BHOPAL: LESSONS FOR TECHNOLOGICAL DECISION-MAKERS

Robert U. Ayres
International Institute for Applied Systems Analysis
Laxenburg, Austria

Pradeep K. Rohatgi
University of Wisconsin
Milwaukee, WI, USA

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FOREWORD

This paper was not written at IIASA; but the first author, Professor Ayres, is currently an active IIASA staff member. In view of IIASA's long record of significant contributions to both risk analysis and environmental problem-solving, it seems likely that many members of the IIASA community, past and present, will be interested in this paper. Hence, it is being reprinted for convenient dissemination, with the kind permission of the original publisher.

T.H. LEE
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Bhopal

Lessons for Technological Decision-Makers

Robert U. Ayres and Pradeep K. Rohatgi

ABSTRACT. The accidental release of methyl isocyanate (MIC) on December 2 and 3, 1984, at the Union Carbide India Limited (UCIL) pesticide manufacturing plant in Bhopal, India, killed at least 1,750 people, and probably as many as 2,500,[1] *while injuring 50,000 or more. This episode appears likely to mark a watershed in the historical relationships between scientists, corporations, governments and communities. Among the many assumptions that will have to be questioned and reconsidered in the wake of this disaster are the following: that it is possible, in principle, to know enough in advance about a complex chemical process to design a totally safe system; that it is possible, in principle, for human workers to operate such a system safely; that it is possible, in principle, for a public agency to regulate such a system effectively (even if it could be designed); and that "fault" in the legal sense can be meaningfully attributed to one among the various actors in the event of a complex system failure. The above questions all arise prominently in connection with the Bhopal tragedy. This paper recounts the key factors insofar as they are known, commenting on the information available to various parties and the decisions that were made. Some general conclusions are drawn at the end.*

Methyl isocyanate (MIC), formula $CH_3-N=C=O$, is an ester of isocyanic acid (HNCO). It was first made from phosgene and methylamine hydrochloride in the liquid phase by Gatterman and Schmidt in 1888, and studied intensively by Slotta *et al.*[2], in the laboratories of IG Farbenindustrie A. G., the German chemical cartel.

Work on the isocyanates was largely centered in Germany until after World War

Robert U. Ayres is Professor of Engineering and Public Policy at Carnegie-Mellon University and Deputy Program Leader of the Technology-Economy-Society Program (TES) at the International Institute of Applied Systems Analysis (IIASA) at Laxenburg, Austria. Prior to 1979, he worked at various "think tanks" and consulting organizations, including the Hudson Institute, Resources for the Future, Inc., and International Research and Technology Corporation. He has written seven books, of which the most recent is The Next Industrial Revolution.

Pradeep K. Rohatgi is currently Professor of Metallurgy at the University of Wisconsin in Milwaukee. At the time of the Bhopal accident, he was Director of CSIR Regional Research Laboratory in Bhopal, Madhya Pradesh, India. He participated in the post-accident assessment of alternative means of disposal of the second tank of MIC at the UCIL plant. Previously he has been Director of the CSIR Regional Research Laboratory, Trivandrum, Kerala, India, and Professor of Metallurgy at the Indian Institute of Science, Bangalore, India.

II, when US and British firms were given access to the research of I.G. Farben,[3] and the cartel was broken up by the occupation authorities. Interest in practical applications of isocyanates grew rapidly, and other chemical firms, including Montecatini in Italy, Monsanto, and Union Carbide (UCC) in the US, became actively involved. Isocyanates contain the unsaturated $-N=C=O$ group, which accounts for their high reactivity. MIC monomer *per se* is the basis of a number of insecticides, including Aldicarb ("Temik"), Baygon, Carbaryl ("Sevin"), and Carbofuran ("Furaden"), and is also a route to the production of polyurethanes, which are widely used in foams, varnishes and plastics.[4] Union Carbide Corporation is one of the two major US producers, mainly from its plant in Institute, West Virginia, near Charleston, which began production about 1967. The only other significant US producer is FMC Corporation. Bayer A.G., a successor of I.G. Farben, also produces MIC in Dormagen, Federal Republic of Germany, and in Antwerp, Belgium.

Production in Bhopal by UCIL using UCC technology began on a small scale in 1977–78 (see Figure 1). Production by UCC in the US in 1980 was about 20,000 tonnes, compared to 1,000 tonnes produced by Union Carbide India Limited at peak output. Demand—hence production—dropped sharply after 1981, and the Bhopal plant was operating at barely half its capacity when the accident occurred on the night of December 2/3, 1984.

Chemistry

Several phosgene-based manufacturing processes are described in the literature.[5] In one, monomethylamine (CH_3NH_3) reacts in the gas phase with phosgene ($COC1_2$) at about 275° C without a catalyst, yielding a mixture of MIC (CH_3NCO) and HC1, which subsequently recombines in the low temperature condenser (25°) to yield methyl carbamoyl chloride ($CH_3NHCOC1$) or MCC. The MIC can then be recovered by thermally decomposing the MCC and preferentially removing the HC1, *e.g.*, by heating with lime as in the original process of Gatterman and Schmidt or by reacting with pyridine at 115°.[6] The proprietary process reportedly used by UCC apparently occurs in the liquid phase: Phosgene is passed into monomethyl amide MMA solution in an inert solvent (*e.g.*, chloroform) at 30°–50° where the reaction takes place and MIC is released as vapor and collected.[7] The Bayer process does not start from phosgene, but from dimethyl urea and diphenyl carbonate.[8] MIC has the basic structure $CH_3-N=C=O$.

It is volatile (boiling point 39°C) and the vapor is heavier than air (vapor density 2.0). It is rated as highly toxic (TLV = .02ppm), highly flammable, and quite unstable, with a near maximum combined health-fire-stability hazard rating of 4-4-3. (By comparison, phosgene has a rating of 4-0-2 with a TLV of .01 ppm, while carbon monixide has a rating of 4-4-1 with a TLV of 50 ppm.)[9]

Carbamates are esters of carbamic acid. The carbamate insecticides are synthesized by reacting MIC with phenols or naphthols. There is an alternative route that begins with a vapor phase reaction of phenol or naphthol with phosgene, followed by reaction with MMA. Ironically, this has been rejected by the chemical industry in favor of the use of liquid MIC, because it would require gaseous phosgene to be kept in storage. The basic carbamylation reaction is

$$CH_3-N=C=O + ROH \longrightarrow CH_3\text{-}N\text{-}C\text{-}RO + OH$$

The reaction of MIC with water is important in regard to the statements that follow. There are three major routes leading to monomethylamide (MMA), 1,3 dimethylurea and 1,3,5 trimethylbiuret respectively:

$$CH_3N=C=O + H_2O \longrightarrow CH_3NH_2 + CO_2$$

$$2CH_3N=C=O + .H_2O \longrightarrow CH_3NH\overset{\overset{0}{\|}}{C}NHCH_3 + CO_2$$

and

$$3\ CH_3N=C=O + H_2O \longrightarrow CH_3NH\overset{\overset{O}{\|}}{C}CH_3N\overset{\overset{O}{\|}}{C}NHCH_3 + CO_2$$

The mix of reaction products depends upon the relative concentration of MIC and water. A small amount of water added to liquid MIC is likely to produce trimethylbiuret predominantly. Both of the latter two compounds are said to be relatively harmless. It is important, however, to note that large amounts of heat are produced., *viz.*, 580 BTU per pound of MIC or 3,700 BTU per pound of H_2O. Thus one major hazard in handling MIC is contact with water.

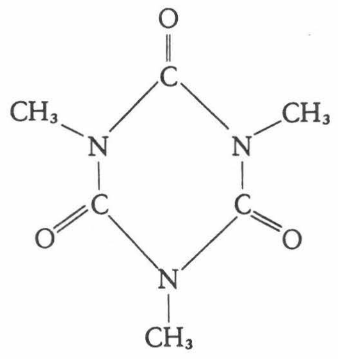
Another important set of reactions are the polymerization reactions. According to one hypothesis, assuming the standard anionic initiation mechanism, an anion "X" attacks the MIC molecule forming an MIC nitrogen anion.

$$X^- + CH_3N=C=O \longrightarrow CH_3N^-\overset{\overset{O}{\|}}{C}\ X$$

This, in turn, can subsequently react with another MIC molecule, and then a third, yielding the linear trimer:

$$\underset{\underset{CH_3}{|}}{N^{(-)}}-\overset{\overset{O}{\|}}{C}-\underset{\underset{CH_3}{|}}{N}-\overset{\overset{O}{\|}}{C}-\underset{\underset{CH_3}{|}}{N}-\overset{\overset{O}{\|}}{C}-X$$

The chain can be terminated as a cyclic trimer (releasing the initiating anion in the process) or it can continue to grow linearly. The heat of formation of the linear polymer is 345 BTU per pound. It is an amorphous solid (actually a substituted form of nylon 1). The cyclic trimer has the structure:



It is a crystalline solid with heat of formation of 540 BTU per pound. Generally speaking, at low initiator concentrations and/or temperatures an amorphous polymer form is favored, while at higher temperatures/concentrations the crystalline trimer form is favored. The rapidity of the process and the path (*i.e.*, to trimer or polymer) is very sensitive, however, to the presence of catalysts. Many metallic chlorides and alkoxides are known to catalyze polymerization. Ferric chloride ($FeCL_3$) is known to be particularly active. Chloride ions (from any source) can act as initiators. Weak organic bases, such as tertiary amines, can also apparently catalyze resinous (linear) polymerization.

In fact, there is apparently some evidence that "ultrapure" MIC may be capable of auto-catalytic (self) polymerization. The mechanism has apparently not been determined, but it is known to be strongly temperature dependent. Trimerization proceeds up to 200 times faster at 25°C than at 0°.[10] This explains the importance of refrigeration in MIC storage which will be discussed later.

In contrast to "pure" MIC, there is evidence that "commercial-grade" MIC is quite difficult to polymerize, although specifications are not given in any published source. In fact, when UCC began production in 1967, only one compound (hexamethylene triamine) was known to be an effective polymerization catalyst.[11] On the other hand, a number of possible catalysts that were tested in the lab were ineffective. No case of autocatalytic polymerization of the commercial-grade MIC was known to have occurred prior to Bhopal. This fosters the supposition that contaminants normally found in commercial-grade MIC tend to act as stabilizers or inhibitors. Unfortunately, neither the stabilizing contaminants nor the mechanism have ever been precisely identified, although UCC conducted some research in the hope of finding inhibitors.[12]

Commercial-grade MIC, as produced by UCC, typically contained contaminants, including methylene chloride (CH_2C1), chloroform ($CHC1_3$), carbon tetrachloride ($CC1_4$), MCC (CHNHCOCl), and phosgene ($COC1_2$). Much attention has been focused on the role of phosgene, in particular, as an inhibitor of the polymerization reaction. Its concentration in commercial-grade MIC is said to average about 200–300 ppm, although the range in different samples can vary by nearly an order of magnitude. The comparative stability of commercial-grade MIC was generally attributed to the presence of trace amounts of phosgene, although the exact mechanism by which inhibition could occur remains quite obscure.[13]

The role of MCC traces is also unclear, since MCC can decompose to MIC and HC1 by the reaction

$$RNHCOC1 \longrightarrow R-N=C=O + HC1,$$

leaving excess chloride ions. It is known that this mechanism can initiate polymerization of the MIC in the presence of carbon steel, although it is apparently inhibited by the presence of methyl pyrophosphoric acid (UCC patent, 1970).

Safety Features Embodied in the System at Bhopal

Based on the known reactivity of pure MIC, especially in the presence of zinc, tin, copper and iron, UCC's operating manual[14] specified bulk storage in drums or tanks of stainless steel (type 304 or 316), or steel lined with nickel or (pin-hole free) glass. In practice, only stainless steel seems to have been used, both for tanks and drums. Tubes and containers for sampling could be made of chlorofluorinated plastics (Teflon or Kel-F). Contact with any other materials, including plastics, was strictly prohibited.

Instructions for bulk storage of MIC specified underground tanks (SS 304 or 361) encased in concrete. Further requirements included:

- Tank size to be at least double the maximum volume to be stored, or a stand-by tank to be available;
- Inert atmosphere (nitrogen gas) at 2–10 psi over atmospheric pressure;
- Refrigeration to maintain a temperature near 0°C (certainly, below 15°C);
- Coolants must not react with MIC (chloroform or one of the chlorofluorocarbons are acceptable);
- Regular, scheduled inspection and cleaning of valves and piping is imperative; and
- Storage time was limited to 12 months maximum.

The UCC operating manual stressed the toxicity and hazardous nature of MIC, including the fact that exposure could lead to fatal pulmonary edema, and specified the use of protective rubber suits and air-breathing equipment for personnel engaged in sampling or testing operations where some possibility of a leak or spill might exist.

In the Bhopal plant of UCIL, there were three double-walled stainless steel MIC tanks, each capable of holding 60 tonnes of liquid. These were designated Tanks 610, 611 and 619. The tanks were designed to be refrigerated and interconnected so that MIC in tank 610 (which leaked) could have been bled into Tank 619.[15] All these tanks were also embedded in concrete, as shown in Figure 1. The major pipe connections to Tank 610 are shown in Figure 2.

In addition to the refrigeration system and stand-by tank, there were four backup safety systems, shown schematically in Figure 3.[16] There were:

- A vent gas caustic scrubber, capable of neutralizing about eight tonnes of MIC per hour at full capacity. (Figure 4 and Figure 5).

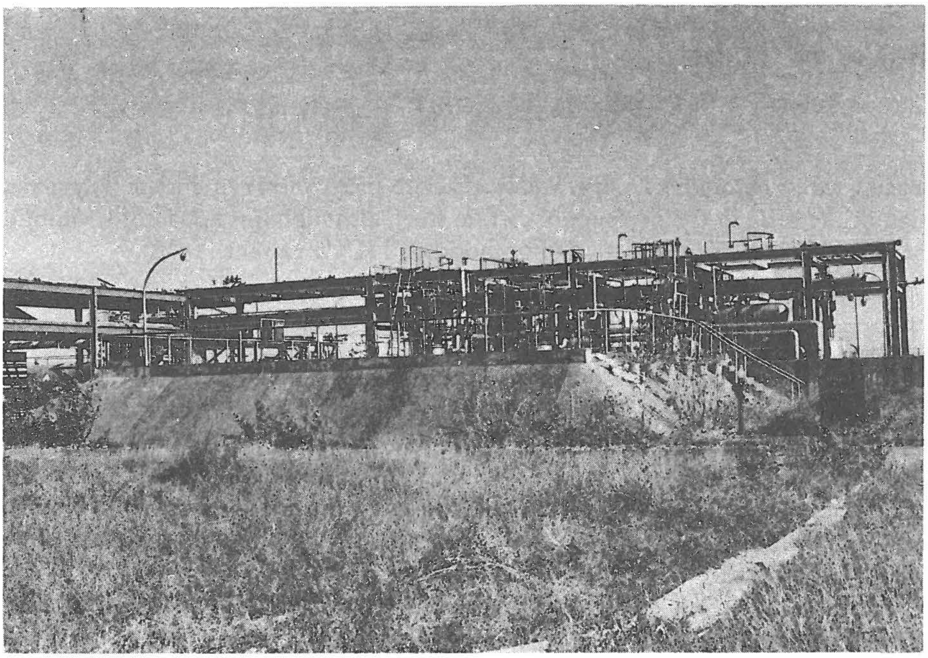


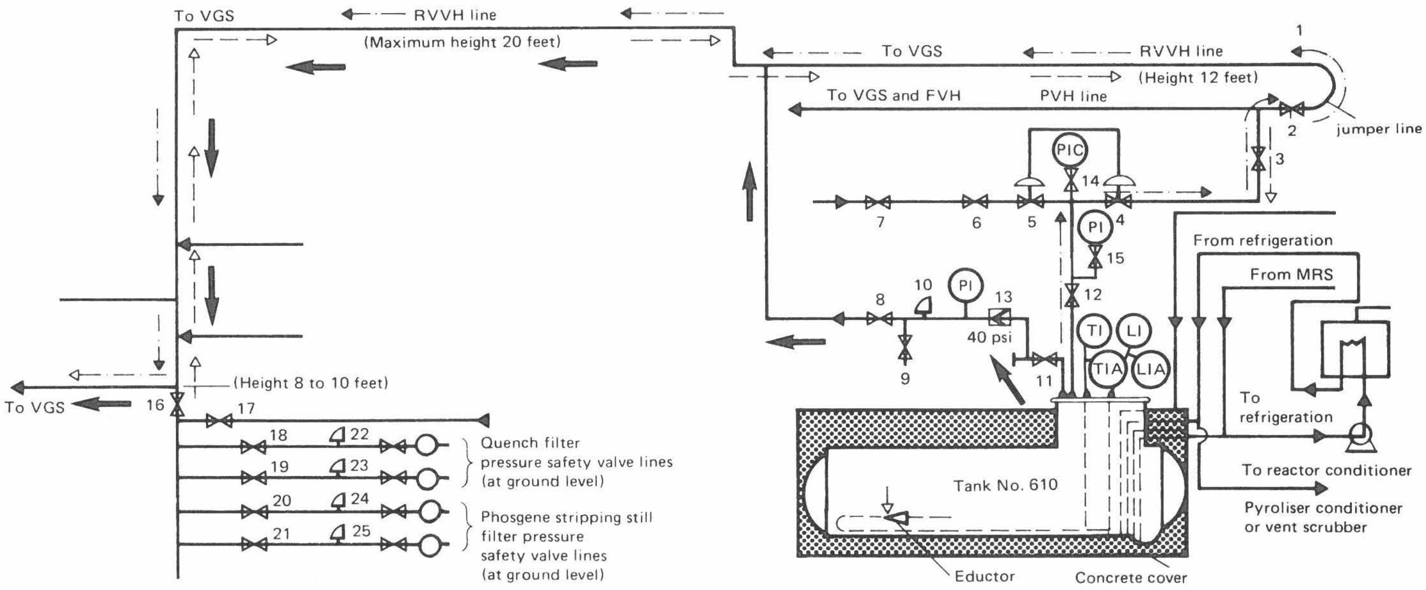
FIGURE 1. MIC Storage Tanks

- A flare tower, designed to burn escaping gases from the scrubber and/or the MIC unit itself, also shown in Figure 5.
- A "water curtain," capable of "knocking down" small amounts of escaping MIC which were not neutralized by the scrubber or the flare up to 12–15 meters above the ground. The jets could reach as high as 35 meters, but only if operated individually.
- A siren, intended to alert the staff and the surrounding community in the event of an uncontrolled leak.

The operating technicians hired when the plant was first built (1977) were reportedly graduates in chemistry or chemical engineering with the equivalent of at least two years of college (US equivalent), plus a six-month training period provided by Union Carbide.[17] Educational standards and staffing levels were relaxed somewhat in recent years when the Bhopal plant began losing money.

Chronology of Events the Night of December 2/3

At the time of the accident, the refrigeration system had been disconnected for several months, apparently to save electric power. Although the MIC operating manual specified a *maximum* of 15°C, the "normal" temperature in the tanks was reportedly around 20°. The vent gas scrubber was also down for maintenance at the time of the accident, and its supply of caustic soda was allegedly low. In addition, the gas vent flare was disconnected, and one section of the pipe leading to it had



Key:

1. Interconnection 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. RVVH isolation valve
9. RVVH bleeder valve
10. Relief valve for MIC tank
11. First RVVH isolation valve for MIC tank
12. First PVH isolation valve for 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. Down-stream isolation valves for filters

22, 23, 24, 25. Bleeder valves

RVVH - relief valve vent header
PVH - process valve vent header
VGS - Vent gas scrubber
FVH - flare vent header
MRS - MIC reactor side
——▷ Route of water ingress
◁·—· Route of gas leakage before 0030 hrs
◀━━ Route of gas leakage after 0030 hrs

FIGURE 2. RVVH and Bleeder Values
Source: *Business India* 2(25): 3–10 (1985)

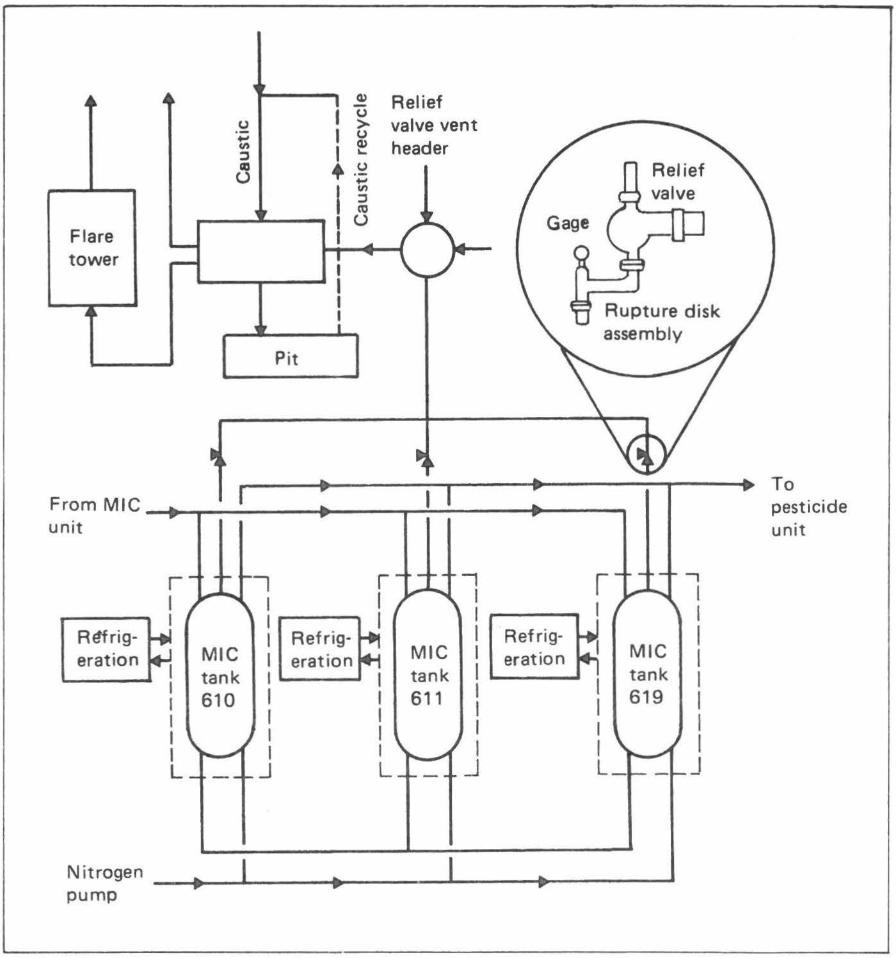


FIGURE 3. Tank and Safety Feature Layout
Source: *Chemical & Engineering News* 3–25 (1985)

been removed and not replaced. On the evening of December 2, Tank 610 (from which the MIC escaped) contained 40 to 50 tonnes (out of a 60-tonne capacity), while Tank 611, adjacent, was thought to contain 15 tonnes, on the basis of shipping records. Later, during the neutralization of residual MIC, it turned out that Tank 611 actually contained nearer to 21 tonnes. Tank 619, the stand-by tank, contained less than one tonne of "off-spec" MIC, although the level gauge had showed it to be about 20% full.[18] Evidently many of the gauges were not working properly.

A routine pipe-washing operation in the MIC unit was started about 10:30 in the evening on December 2, just before the shift change. The pipes being washed were connected to the tank via a relief valve vent header (RVVH), which was normally closed. There were two possible routes, as shown in Figure 2. It appears, however, that the RVVH isolation valve was defective. Two other valves that should have

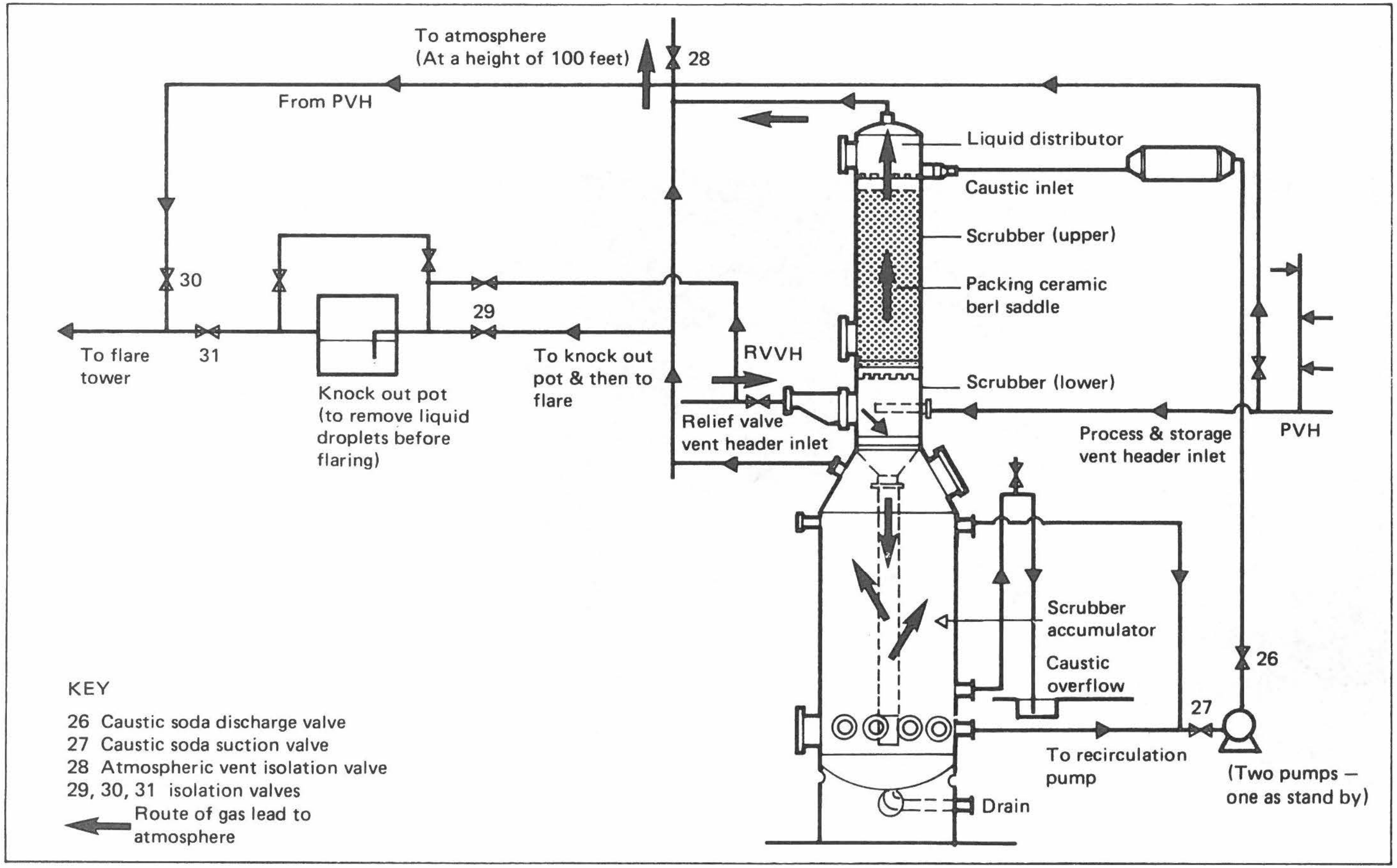


FIGURE 4. MIC Scrubber
Source: *Business India* 2(25): 3–10 (1985)

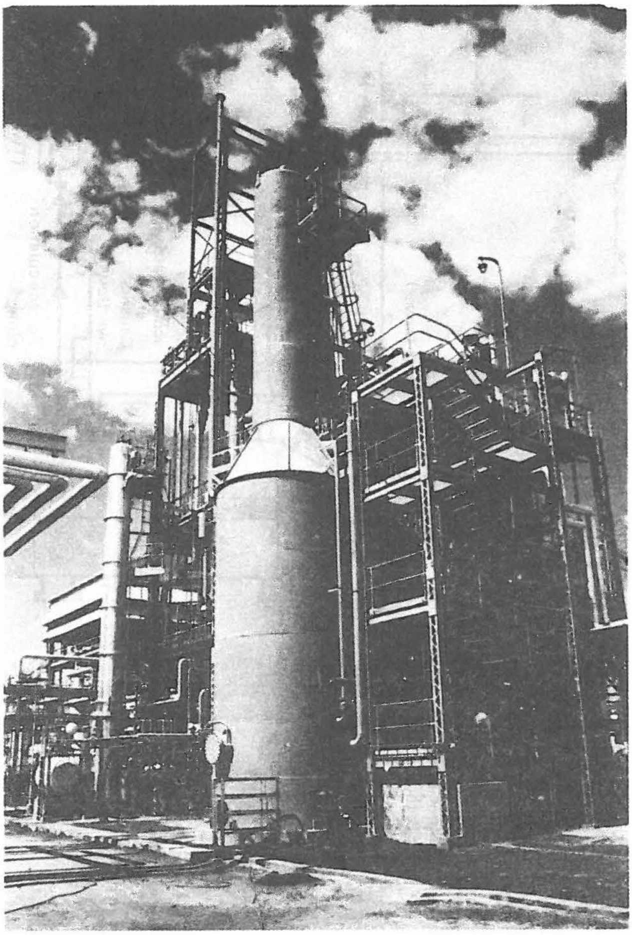


FIGURE 5. MIC Scrubber and Flare Tower

been closed, moreover, had been left open to connect the RVVH line with the process vent header (PVH) line.[19] In addition to the valves, a further protection against water leakage into the MIC tank via the header is a metal sheet known as a "slip blind," which was supposed to be inserted adjacent to the RVVH isolation valve to seal off the rest of the system from the section being washed. According to R. Khan, the employee who was ordered to wash the pipe at 9:30 p.m. on December 2, the slip blind had not been inserted.[20] S. Qureshi, the MIC supervisor on the night shift, later checked the daily maintenance sheet and found no instruction to insert the slip blind, though there was a note to the night shift to wash the pipe.[21]

The first sign of possible trouble in Tank 610 was noticed when the night shift came on duty at 11 p.m.[22] The pressure gauge in the control room showed 10 psi (above atmospheric) as compared to the recommended pressure of 2 to 3 psi. This was at the upper end of the so-called "normal" range. The temperature in the tank

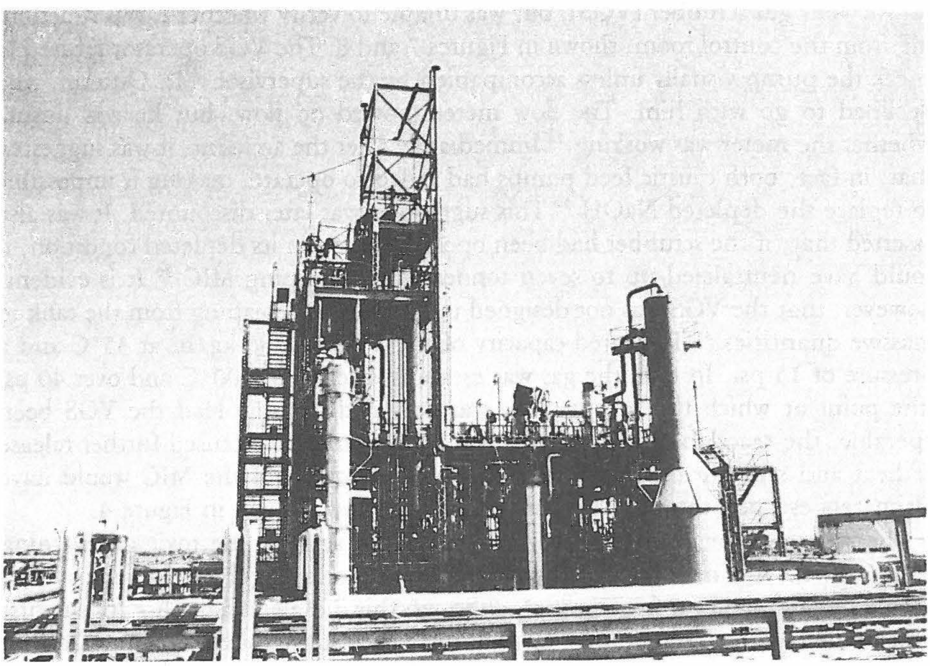


FIGURE 6. MIC Plant with Scrubber in Right Foreground and Vent Stack in Center

was also above 20°C. Both the MIC supervisor and the control room operator, S. Dey, apparently assumed that the instruments were faulty.[23] In any event, nothing was done to follow up their observations.

At 11:30 p.m. December 2, the staff in the utility area of the plant noticed a slight irritation in the eyes, suggesting an MIC leak, and began to look for the source. Small leaks occurred from time to time, and were not necessarily regarded as significant.[24] A continuous drip was observed on the outside of the MIC unit, however, and one worker, V.N. Singh, reported it to the MIC supervisor, Mr. Qureshi, at 11:45 p.m. The supervisor did not treat the report as urgent, and decided not to deal with it until after the next scheduled tea break.[25] At 12:40 p.m. on December 3, the control room operator, Mr. Dey, again checked the pressure gauge for Tank 610 and noticed that it was approaching 40 psi. The temperature gauge was then reading above 25°, the top of the scale. At about 12:45 a.m., loud rumbling noises were heard from the tank. The concrete around Tank 610 had cracked—which implies temperatures approaching 400°C—and the safety valves ruptured as the pressurized gas escaped in a fountain from the top of the vent stack, shown in Figure 6. At 12:45 a.m., the water-washing line (which had been running since 10:30 p.m.) was finally turned off by Mr. Qureshi.[26] Gas may have continued to escape from the vent stack until 2:30 a.m. on December 3.

The operating staff never opened the valve connecting Tank 610 to the stand-by Tank 619, reportedly because the level gauge already showed it to be partially full.[27] The control room operator, Mr. Dey, claimed to have tried to turn on the caustic vent gas scrubber (VGS), but was unable to verify whether it was functioning from the control room, shown in Figures 7 and 8. The VGS operator refused to check the pump visually unless accompanied by the supervisor, Mr. Qureshi, who declined to go with him. The flow meter showed no flow, but he was unsure whether the meter was working.[28] Immediately after the accident, it was suggested that, in fact, both caustic feed pumps had failed to operate, making it impossible to replace the depleted NaOH.[29] This suggestion was later discounted. It was also asserted that, if the scrubber had been operated, even in its depleted condition, it could have neutralized up to seven tonnes of the escaping MIC.[30] It is evident, however, that the VGS was not designed to handle MIC escaping from the tank in massive quantities.[31] The rated capacity of the VGS was 86 kg/hr at 35°C and a pressure of 15 psi. In fact, the gas was escaping at close to 400°C and over 40 psi (the point at which the rupture disk was designed to fail). Had the VGS been operable, the reaction of MIC with caustic soda would have caused further release of heat and still greater pressures.[32] In this case, much of the MIC would have ultimately escaped through the caustic soda overflow, shown in Figure 4.

The control room supervisor, Mr. Dey, did not activate the toxic gas warning siren until 12:50 a.m., when MIC was actually seen escaping from the vent stack.[33] It only remained on for five minutes, although this did alert the police for the first time to the fact that "something" was wrong.[34] The external siren was turned off, in accordance with established operating procedures, and not turned on again full blast until 2:30 a.m., when it was already too late for many people living nearby to

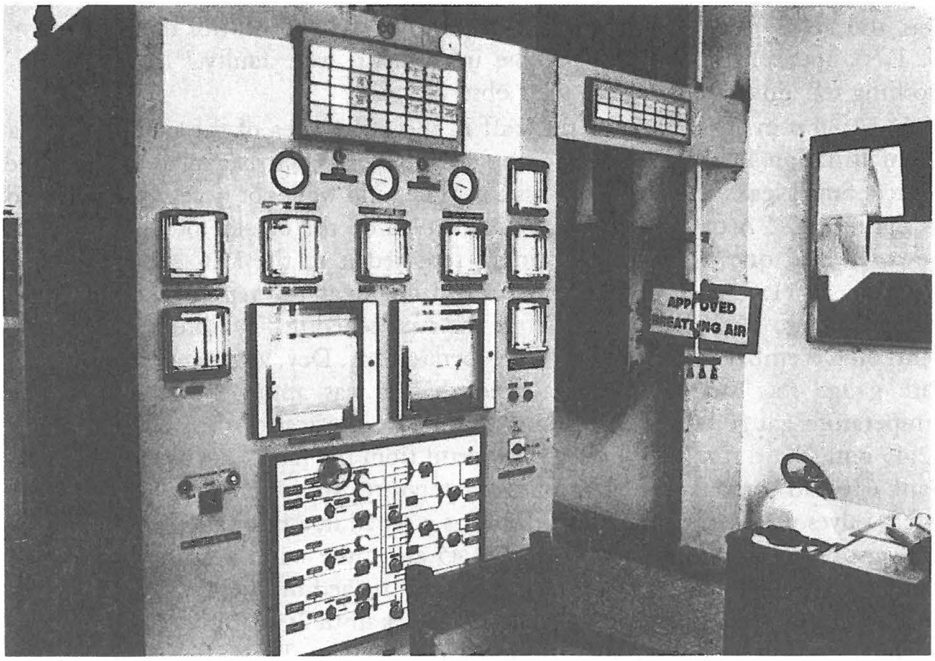


FIGURE 7. Typical Control Panel (Note Black Fungus on Walls—Evidence of High Humidity.)

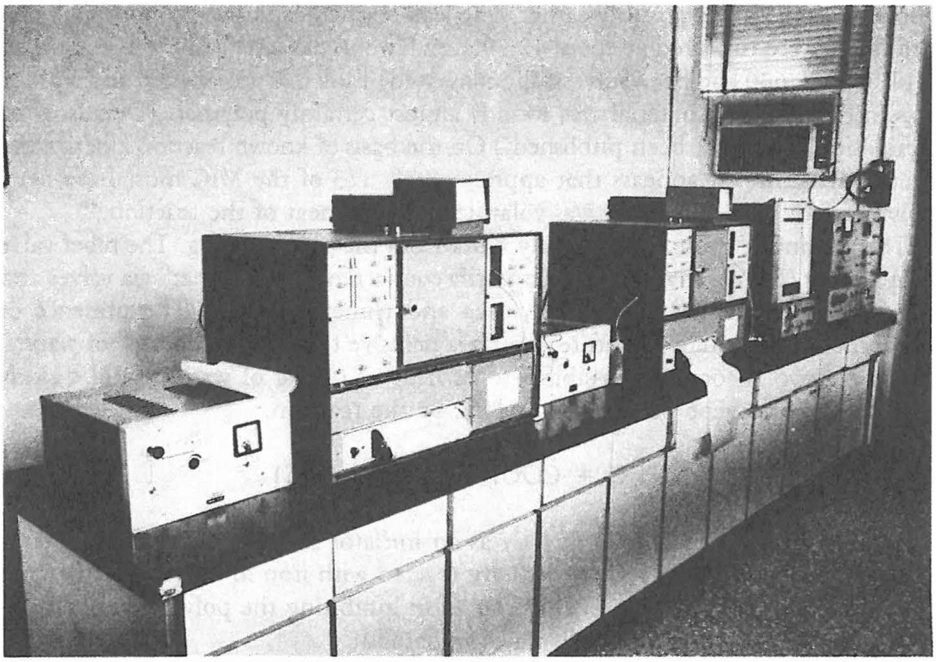


FIGURE 8. Control Room Equipment (Note the Airconditioning unit in the wall and the mandatory surge-protection device.)

escape.[35] The assistant plant manager, S.P. Choudhary, was called at home by Mr. Qureshi at 1 a.m. Choudhary ordered the vent flare turned on, but was told that it was not operable. (This was just as well. The flare, like the VGS, was not designed for a major leak. Had it been turned on, the result would have been a violent explosion).[36]

The plant manager, J. Mukund, was not informed of the leak until 1:45 a.m., and he heard of it—not from one of his employees—but from the city magistrate.[37] A system of "walkie-talkies" maintained at the plant for such emergencies was never used that night.[38] Telephone calls from the Bhopal police to the plant apparently were answered, but elicited no useful information.[39] By 1 a.m., most of the workers had left the plant, in any case. Mr. Qureshi, the MIC supervisor, was unable to find his oxygen mask—someone had removed it. At 1:30 a.m., he ran to the boundary fence and broke his leg climbing over it. Mr. Dey, however, remained safely in the control room all night until the next afternoon. Four buses on the premises, intended to help evacuate employees and/or local residents, were also never used that night.[40]

The Cause of the Chain Reaction in Tank 610

It is now virtually certain that the MIC in tank 610 began a polymerization reaction triggered by water sometime before 11 p.m. The heat generated by the reaction caused the temperature and pressure to rise. Low-level emissions apparently began about 11:30 p.m., or possibly earlier. The leak reached explosive proportions when the valves were ruptured at about 12:30 a.m. Two weeks later (after the remaining MIC in Tank 610 had been successfully converted) Tank 610 was opened and a probe was inserted. Solid material was found, almost certainly polymer. (Details of its composition have not been published.) On the basis of known reaction kinetics and thermodynamics, it appears that approximately 1/3 of the MIC must have been polymerized. The remainder was volatilized by the heat of the reaction.[41]

The proximate cause was probably water from the pipe washing. The relief valve vent header (RVVH) had been temporarily connected by a "jumper" via valves and reacted to product MMA, dimethylurea and trimethylbiuret. (The presence of these chemicals would constitute a fairly conclusive tell-tale "signature" of water.) There are two theoretical possibilities. As little as 0.5 kg of water would quickly remove any phosgene present in the MIC by the reaction:

$$H_2O + COCl_2 \rightarrow CO_2 + 2HCl$$

The resultant HC1 might act directly as an initiator for the polymerization reaction. Alternatively, the HC1 might have reacted with iron in microscopic flaws in the stainless steel of the tank. Thus, far from inhibiting the polymerization reaction, phosgene could conceivably have triggered it.

Assuming the more straightforward hydration reactions, it would have taken 1.5 tonnes of water to produce enough heat to vaporize the 50 tonnes of MIC.[42] This could only be accounted for if all the valves between the water hose connection and the MIC tanks had been wide open. Another possibility still open at the time of writing, however, is that another contaminant of some sort entered the MIC tank, either via the nitrogen line or from the scrubber, and catalyzed the reaction. This can only be determined by an analysis of the solid material in the tank.

Design Defect, Management Error, or Operator Error?

As already noted, several major safety systems (refrigeration, scrubber and flare) were not operational on the night of the accident (Figure 9). A number of instruments were faulty, and some valves were not working or were improperly set. This may reflect design flaws in the equipment, although operation/maintenance failures also bear a share of responsibility. The MIC escaped into the air from a vent 33 meters above the ground, well above the water curtain. Both the VGS and the flare were inadequate to deal with the leak, as noted already. The designers evidently did not anticipate an MIC release of anywhere near the magnitude that actually occurred.

In retrospect, at least five categories of improvements could have been incorporated into the system design. They are as follows:

- An automatic alarm should have been triggered by rapid changes in pressure or temperature in the tank. This could have alerted the operators earlier—perhaps early enough to activate some of the other by-pass and/or protective systems more effectively.

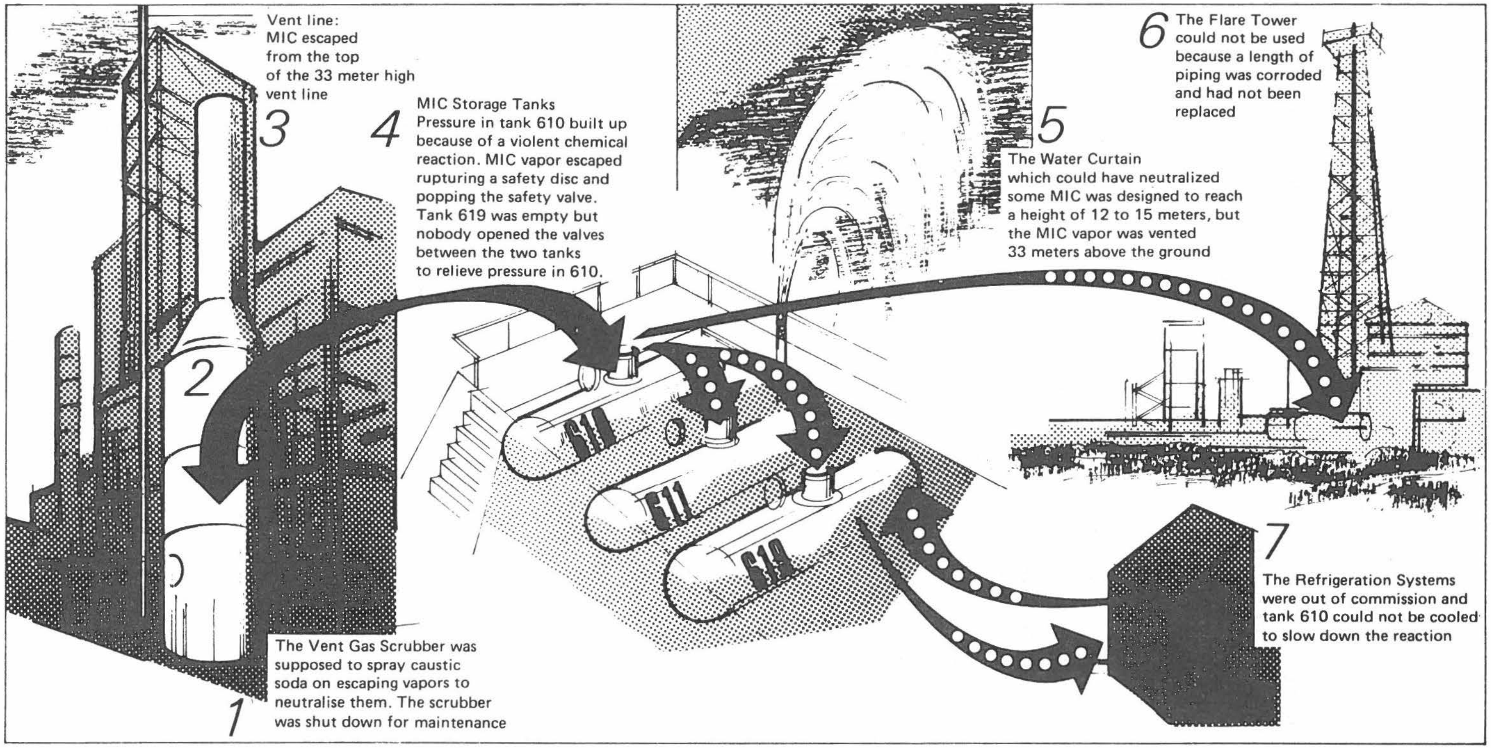


FIGURE 9. The Fail-Safe Failure

- All electrical equipment (*e.g.*, pumps) should have been provided with battery power or effective protection from voltage and frequency excursions.
- The tanks should have been smaller or the scrubber should have been much larger. It could also have been designed to turn on automatically, triggered by gas flow. Also a safety interlock system could have been devised to prevent the disconnection of the scrubber and/or the refrigeration unit while the storage tanks contained MIC. (This would obviously complicate the maintenance problem, however.)
- A back-up system could have been provided to divert effluent from a massive leak into an area that could be flooded with large volumes of water and quickly neutralized. (Such a system exists on the Bayer plants in Germany).
- The MIC tanks probably should not have been encased in concrete. In fact, storage drums would have been much safer altogether, since the one remedial action that might have helped matters in the absence of the refrigeration, scrubber and flare was water-cooling the tank from the outside. During the accident, this was impossible.

There has been much discussion in the media as to whether the Bhopal plant design was or was not of the same design as the UCC plant at Institute, West Virginia. It was not identical, of course, being a much smaller plant. In fact, detailed design was not done by UCC, but by the Indian subsidiary of a London-based engineering firm, Humphreys and Glasgow Consultants Ltd., based on a UCC "design package." All construction was carried out by Indian firms using Indian materials. There has also been comment in the press about a multi-stage "computerized early warning system" that allegedly exists at UCC's West Virginia plant, but not in the UCIL Bhopal plant. This appears to be something of a red herring. No computer can, under present conditions, take the place of responsible human operators on duty. Early warning could have been accomplished by simpler and more reliable means.

In general, electrical and electronic equipment does not function as reliably in India as in the US, due to dust, humidity (which causes insulation to deteriorate, for instance), and wide and unpredictable fluctuations in voltages and frequency of the electric power supply (see Figures 7 and 8). To rely heavily on electronic systems could actually compound the risks unless such systems were consistently protected by airconditioning and provided with reliable independent power supplies.

Management failures that can readily be pinpointed at the operational level include:

- The disconnection of the refrigeration system (contrary to explicit instructions in the UCC manual), apparently to save electricity.[43]
- The decision to operate the MIC unit while both the scrubber and the flare were down for maintenance and while jumper valves 1 and 2 were temporarily open and while the bleeder valves were clogged (hence the need for washing).
- The failure to insert a slip blind prior to washing the pipe. This latter may be attributable to inadequate training or sloppy procedures in the plant.

- Failure to open the valve between tank 610 and the spare tank, 619.
- Failure to provide clear and adequate warning to the public in the event of the accident. Failure to utilize walkie-talkies, buses and other available equipment for emergency evacuation use. Failure to provide helpful information about protective measures to authorities or to the public.

The major planning failure, in retrospect, was the failure to imagine a "worst case" scenario and to take it seriously. Higher management was too lax in enforcing safety related policies, and the plant was not designed to cope with a major leak. Communication between the plant management and the Bhopal public was nil. Given the fact that nobody in the plant itself died, and the simplicity of the basic emergency breathing procedure (a wet cloth over the face), it is particularly hard to see why the necessary information was not made quickly available to the public authorities and to the people living nearby. Evidently even the supervision level employees, such as Mr. Qureshi, forgot what they had been taught under the pressure of the events.

The typical excuse for secrecy is that firms working with dangerous materials do not want to create "unnecessary" alarm and fear. (This was apparently the reason for turning off the first alarm after only five minutes.) Alternatively, UCC may have been trying to minimize the spread of information about MIC for competitive reasons. In the Bhopal case, the consequences of too much secrecy were themselves catastrophic. Even the local Bhopal scientific community was ignorant of what was being done in the UCIL plant. An effective public information program would have been relatively inexpensive. Its complete absence is hard to excuse. Even such a simple measure as sending a sound-truck through the streets instructing people to breathe through wet cloths would have saved hundreds or thousands of lives.

A further criticism that might also be made of the UCC management is that they went into large-scale production of MIC-based pesticides without having done enough basic research on the stability of the chemical.[44] After the accident, when there was serious concern about the MIC in Tanks 611 and 619, neither UCC nor Bayer definitely knew of an effective inhibitor for the polymerization reaction.

Top management laxity has also been alleged. A 1982 report by three visiting UCC experts, released by Chairman Warren Anderson shortly after the accident, noted several safety violations, including the following significant ones:

- "Filter cleaning operations performed without slip blinding process lines. Leaking valves could create serious exposures during this process."
- "Leaking valves have been fairly common. Team members observed one case in which an MIC shut-off valve was leaking so severely that even evacuation of the line above the valve was not adequate to prevent MIC release when a blind flange was removed. . . ."
- "It appears that it would be possible to contaminate the tank with material from the vent gas scrubber."
- "The pressure gauge on the phosgene tank was bad."

The report was evidently sent to the UCIL Bhopal management in September 1982. It is unclear what specific actions were subsequently taken on its recommendations. The works manager, J. Mukund, stated, in an interview with *The Times of India*, that all the improvements called for in the report had been taken care of.[45] This assessment now appears to have been much too optimistic.

It is true, as many critics have pointed out, that the parent firm UCC "could impose its will" in general terms and "could veto actions it did not approve of" (if it knew of them). No large firm attempts to manage distant plants in detail from headquarters; that is what plant managers are hired to do. What the higher level managers attempt to do is define policy, define measures of financial performance, and define objectives. Managers at lower levels are judged in terms of these things. It is virtually certain that UCC did put pressure on UCIL to reduce the losses of the Bhopal plant, but quite unlikely that top management would try to specify just how this was to be done in any level of detail. There were no American advisers resident at Bhopal after 1982.

UCC was, of course, represented on the Board of UCIL. None of the Directors, however, were technical experts, nor were they concerned with operations. Only one, an executive vice president of UCC, was based in the US. The others were based in UCC's Far Eastern regional headquarters in Hong Kong. Indeed, even within the Bhopal plant itself (and in other Indian plants), the disciplinary powers of senior management are more limited than is the case in the US. "Social" legislation in India makes it illegal for an employer to fire employees except in cases of "major infractions" of the rules. It is, consequently, more difficult to enforce rules from the top down—especially when they appear to be arbitrary and the employees are not convinced of their necessity by personal experience.

It is all the more difficult to enforce rigid in-plant maintenance standards when employees live in a society where the electric power system fails several times a week,[46] the telephone system is always overloaded and on the verge of collapse (as it is in Bhopal), spare parts can take months to be delivered, and nobody seems to be able to do very much about these things.

The critical lesson for others may be this: that human beings will not, as a rule, pay adequate attention to safety based on statistical evidence of risk alone. People generally learn best by experience, as the young child learns not to touch a hot stove. People can—and do—learn to behave with reasonable caution so as to avoid accidents of kinds they have personally experienced or seen at first hand. This stimulus-response mechanism for learning caution depends on feedback between accidents and safety related-activities. Study after study reveals that new safety regulations in all countries are adopted largely after major accidents—not in advance of them. Shutting the barn door after the cow escapes seems to be an irremediable human trait. Obviously this mechanism works best in avoiding repetitions of small- to medium-sized accidents that are reasonably frequent, *i.e.*, they have occurred before. Humans seem to be unwilling to be proportionally more careful to avoid larger but rarer calamities of kinds they have never personally experienced.[47] The fact that a complex system has not (yet) failed massively is perhaps regarded subconsciously as evidence that it is fail-safe. This, in turn, leads to laxity.

The Role of Public Authorities

Government agencies traditionally regulate industrial activities involving hazardous and toxic materials. One obvious and appropriate form of such regulation is land-use zoning. If there is a risk of accident—no matter how remote—people should not be allowed to live close to the facility. In Bhopal, the zoning permitted residences near the plant. In fact, there was a densely populated slum of squatters immediately adjacent to the plant. But most of the squatters had arrived after the plant was built (originally outside the city), and Union Carbide had neither the responsibility nor the means to remove them. There were many calls in the Indian press for such plants to be built far from cities on barren land. But the fact is that city authorities invariably prefer employment opportunities to be near at hand. So it was in Bhopal.

There was a failure on the part of the city and provincial governments in this regard. In fact, Bhopal deliberately extended its city limits in 1979 to include the plant site. Moreover, in May 1984, Chief Minister Arjun Singh of the State of Madhya Pradesh, of which Bhopal is the capital, retrospectively regularized all illegal squatters in the city of Bhopal and made them legal owners.[48] The people who lived in the squatter slum near the plant were most attracted to the vicinity by the possibility of employment and by the availability of water.[49]

Another traditional form of government regulation is safety and health inspection. The Bhopal plant design was approved in detail before construction by the government of the state, and detailed modification plans were periodically turned over to various agencies, such as the Central Electricity Board.

There is no question that the governmental bodies had access, in principle, to qualified experts, though the determination to use their services is in doubt. It is the responsibility of the Department of Labor to inspect all facilities for health and safety, especially those handling hazardous materials and potentially dangerous processes. There were at least six serious accidents at the plant before December 1984, including a fatal one in December 1982.[50] The latter prompted the state government to commission an independent report by Dr. S. Siddiqi, the head of the chemistry department of a local science college. The Labor Minister of Madhya Pradesh denies having seen the report.[51] Inspections appear to have been very few and superficial notwithstanding several articles in the local press criticizing safety practices at the Union Carbide plant in detail. In fact, the journalist who wrote the articles, R.K. Keswani,[52] virtually predicted the accident, but local authorities did not respond to his allegations.

Ultimately it must be the responsibility of government to perform the inspection function. It was not performed adequately at Bhopal, if it was performed at all.[53] Moreover, beyond inspection, it is the government's responsibility to enforce the correction of deficiencies. This was not done.[54] The Madhya Pradesh Department of Labor has 15 inspectors, based in Indore, responsible for inspecting 8,000 factories throughout the largest state in India. Only two inspectors were based in Bhopal. Each inspector was responsible for visiting over 400 plants per year in 200 working days, and all travel has to be by public transportation. Given this workload, it is hardly surprising that inspections were superficial and enforcement minimal. It must be noted also that, relative to some others, the UCIL plant was regarded by the inspectors as a model of safety, having had only one fatal accident in recent years.

A third—and less straightforward—role of government is the licensing of products. Ironically, the Central Insecticides Board of the government of India was

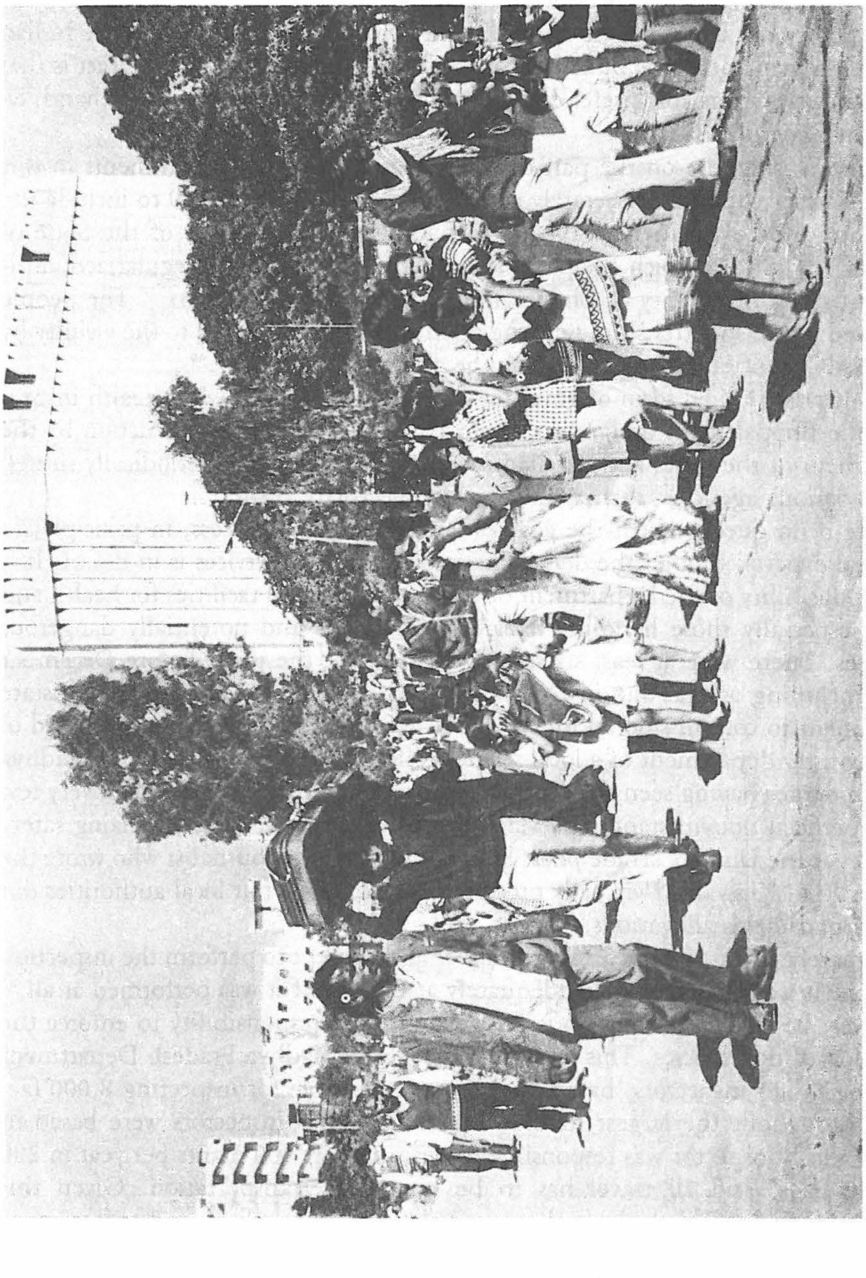


FIGURE 10. Bhopal Residents Flee Disaster Area

planning to withdraw Carbaryl (Sevin) and Aldicarb (Temik)—both based on MIC—from the list of approved insecticides. But the reasons for the proposed deregistration related to hazards associated with use, not manufacture.

This raises an obvious question: Should the federal authorities (in India or the US) undertake to register and control dangerous processes *per se*? It would certainly appear prudent to be especially wary of processes involving chemicals that are capable of self-sustaining chain reactions (such as explosives), or chemicals that are toxic, or both. This question will not be pursued here, since it obviously raises many others that would take us beyond the scope of this paper.

Implications for Legal Fault-Finding

From unexpected small causes—or unlikely combinations of causes—major consequences sometimes result. The circumstances that permitted the Bhopal tragedy to occur—and made it so devastating—would have seemed almost prohibitively unlikely until they actually happened. This may explain why so many journalists, lawyers and members of the public have apparently adopted a "conspiracy" theory[55] to the effect that the various errors of omission or commission by various parties somehow implied criminal dereliction on the part of higher-level UCIL management in India and/or UCC management in the United States. Others may differ, but the facts, as we understand them, do not seem to support this notion.

It seems, however, that the vehemence with which the theory of criminal conspiracy has been promoted reflects a related idea that is very widely held. It is that, *whenever something goes wrong in a man-made system, some person (or firm) must be, by definition, guilty of negligence—or worse—and held individually (or corporately) responsible.* For those who hold this "zero-sum" view of fault, the only question to be resolved is the identity of the guilty party and the degree of guilt.[56] Was the negligence gross or minor? Was there malicious intent? In the Bhopal case, it looks increasingly as though UCC is going to be held "strictly liable," essentially for allowing its Indian subsidiary to operate independent of day-to-day supervision by US engineers and for manufacturing a toxic chemical in a "less developed" country. If these are crimes, many firms must surely be guilty of one or both.

We find this implication disturbing. It is akin to the notion that scientists are morally responsible for any and all future uses of their discoveries, no matter how perverted. It admits no possibility of innocent miscalculation, confusion, or random error. It implies that failure to anticipate every possibility and allow for it is tantamount to negligence. It assumes infinite perfectibility of men, organizations and machines, and potentially infinite liability for the consequences of imperfection.

To be sure, there may very well have been negligence by individuals at UCIL, Bhopal, at higher levels in UCIL, and even at UCC. But it also seems quite possible that most of the failures had quite innocent explanations. If this is true—or could be true—the idea of finding and attributing fault to one party may be fundamentally inappropriate for several reasons. For one thing: If UCC is found guilty of "gross negligence" (as various US attorneys for the plaintiffs hope), for "selling something to developing countries when they know it is going to be used in an unsafe manner",[57] all other parties to the tragedy, including the negligent government authorities, are in effect found innocent. Melvin Belli, one of the leading plaintiff's attorneys, claims that he hopes "to teach Union Carbide and others similarly situated a lesson not to do this again, and to straighten up and fly right."[58] More likely, UCC may be forced to spend the next eight years or so defending itself from legal attacks at great cost in money and management time (albeit profit for lawyers) and, as a consequence, neglect its fundamental business. In fact, this has already happened to a significant degree in the years since the accident.

It has been seriously suggested that multinational corporations should impose tougher safety and environmental standards on their subsidiaries in the less developed countries (LDCs) than in their own countries, on the grounds that implementation is likely to be sloppy. Were this to be done, it would immediately be criticized (justifiably) as a barrier to technology transfer. It is quite clear, in the case of India, at least, that low-cost technology transfer has a high priority and that India is unwilling to accept foreign constraints on its use of imported technology. (India has refused to sign the nuclear nonproliferation treaty for precisely this reason.)

If Belli and his colleagues are successful in the US courts, the most likely lesson for UCC and others "similarly situated" will be to pull back sharply from investments in LDCs like India. This would hardly be in the latter's long-term interest. Such an outcome would, moreover, perpetuate intolerably paternalistic relationships between "developed" and "developing" countries.

Implications for Decision-Makers

It is sufficiently clear from the facts presented that none of the parties—plant designers, operators, company management, or responsible public officials—anticipated the real possibility of an accident of the magnitude of the one that actually occurred. This may seem strange in view of the fact that all the significant component elements of the accident had happened repeatedly, including corroded pipes, pump failures, leaky valves, staff failures to follow procedures specified in the operating manual, systems down for maintenance, and even the major leaks of MIC and phosgene which had happened previously one or more times. The adverse weather conditions (an atmospheric inversion) were unusual, but by no means unprecedented. The only "new" factor was the combination of so many systems and human failures of various kinds at one point in time.

In retrospect, it is obvious that major mistakes were made, and some of them were certainly avoidable and should have been avoided. This is true in nearly all cases of major accidents. But we argue that the implicit conclusion that all mistakes are avoidable is unwarranted and questionable. Yet this assumption pervades the "human factors" literature. For example, consider the following sentence taken from an article by Meister in the *Handbook of Industrial Engineering.*[59]

> Since the worker is merely part of the production system, which has been consciously and deliberately designed, it stands to reason that *those who designed the system are responsible for any inadequacies occurring in it* [Meister's italics]."

The same assumption also obviously underlies the legal concept of "strict liability," under which hundreds of lawsuits have been filed against UCC in the US courts.

It is argued here, on the contrary, that while the probability of operator error can often be reduced, there is no evidence whatever that it can be eliminated altogether, except in a totally automated plant. Even in the latter case, human errors can and will inevitably crop up in fundamental systems design, systems software, and systems maintenance. Human errors are fundamentally "caused" by human variability, which cannot be designed away. In fact, voluminous research—motivated by the perceived need to make nuclear reactors "safe"—suggests that the inherent probability of error (whether of commission or omission) under the most favorable conditions tends to be around 10^{-3} and certainly higher than 10^{-4}. [60] This can be taken optimistically as evidence that "humans are quite reliable,"[61] but it also justifies a negative interpretation; it appears that even the most practiced and motivated operator will make an error at least once in 10,000 opportunities, and probably much more often. Unfortunately, in emergency situations the error probability increases sharply. Under extremely difficult or life-threatening circumstances (as at Bhopal), the probability of human error increases to the order of 25%.[62]

One unavoidable conclusion of these facts (as this paper takes them to be) is that, while safety factors can be introduced and multiplied, truly "fail-safe" design is a contradiction in terms. Accidents will happen, and human error—at some level—is almost always the "cause." Two corollaries emerge. One is that *every* complex system involving humans is a candidate for failure. The dependence of present-day society on such systems is a form of Russian roulette. (This applies conspicuously to military and space systems, which are extraordinarily complex, and correspondingly unsafe.)

The second corollary is that "fault-finding" may be quite inappropriate in many cases. This is not to suggest that true negligence is not blameworthy, but that *not all errors are due to negligence.* In the Bhopal case, one might conclude that operating the MIC unit without the refrigeration unit or the VGS was negligent. Even if both systems had been fully functional, however, it appears likely that the accident would have occurred anyhow. It was the untoward combination of plugged bleeder valves (#22, #23, #24 and #25 in Figure 2) and open "jumper" valves (#1 and #2 in Figure 2) that seems to have allowed a large quantity of water to flow into the MIC tank. The polymerization and pressure rise might have been somewhat slower with the refrigeration system operating, but the MIC would have escaped anyhow. Some of it might then have been neutralized by the VGS, to be sure, but the accident would still have been very serious.

The worst error in retrospect was the decision to turn off the "outside" siren after only five minutes (according to UCIL policy), rather than allowing it to continue as a warning to the community. This undoubtedly cost hundreds of lives. But it was a decision made by a relatively low-level employee under extreme pressure where the "right" choice was directly contrary to formal company policy. The policy itself was wrong, of course, as seen with benefit of hindsight. But this was most likely because those who framed it never conceived of an accident of such magnitude.

Although it is impossible to design perfect fail-safe systems, it is possible to proliferate back-up safety systems, at added cost, to reduce the probability of a catastrophic failure below any specified level. The next and harder question facing a manager or decision-maker is "how much safety is 'enough'?". The answer is implicitly provided by human society, in terms of its willingness to divert resources from "pure" consumption purposes into safety or environmental protection. Economists, in turn, tend to seek indirect measures of the degree of willingness-to-pay for catastrophe-avoidance and/or compensation. The value-of-life controversy is essentially an argument as to how much society is willing to pay to save life under various conditions and circumstances. Unfortunately, human societies are extremely inconsistent in this regard, so that widely divergent estimates can be found in the literature. More direct means of addressing the issue, using decision theoretic methods, are now being developed into the emerging subdiscipline of quantitative risk assessment or QRA.[63]

The Bhopal example illustrates another problem that standard decision theory has not adequately addressed to date. It is the problem of deciding how much "insurance" to buy to prevent low-probability/high-liability events. In the standard management paradigm, decisions are made among optional investment alternatives, subject to a given distribution of probabilities of gains and losses for each option.[64] In comparison with even a remote (say, one in 10,000) possibility of a billion dollar loss, however, such an investment would immediately be ruled out by any rational decision-maker unless he could be sure of being able to buy collectible insurance to cover the entire liability.

The fact that UCC may have had a chance in 1984 to increase its liability insurance from $200 million to $300 million for an incremental annual premium of $36,000 (but declined to do so) suggests what management thought "maximum liability" might be.[65] Under hoped-for circumstances, the plant would earn some profit (gains), although there is always a risk of taking losses instead. Normally the maximum loss that would be considered is the difference between expenditures and revenues—at worst, the whole investment might be written off (*e.g.*, in the case of an "Edsel"). But the case where profits are limited and the loss can be many times the amount of the investment is normally not considered by conservative businessmen; it is a completely new feature of the economic landscape.

A related question is the following: By how much could the probability of such a catastrophe have been reduced if a "worst case" scenario had been used as a basis for the design? (Obviously this was not done.) And how much would it have added to the capital cost? The follow-on question for corporate decision-makers is: Would the investment make economic sense if the additional safety factors had to be factored into the cost estimate? For the government and the public, the question is whether the additional safety systems should be mandated by law. A third question also arises: whether potential liabilities and costs of avoidance may not have grown to the point where certain industries will simply be abandoned by rational investors. The nuclear power, chemical and pharmaceutical industries all appear to be potentially in this category (not in the near future, perhaps, but in a decade or so). Manufacturers are already abandoning manufacture of some pharmaceuticals; extreme shortages of certain flu vaccines and whooping cough (pertussis) vaccine have occurred because of court decisions imposing liability on the manufacturers for side effects that occur in a small number of cases. In the chemical industry, too, it is not inconceivable that large manufacturers will begin to abandon certain processes and products altogether. Dangerous processes might then become the exclusive province of small, "fly-by-night" operators with no attachable assets that would attract the legal ambulance chasers.

Even if the above scenario is too apocalyptic, it is apparent that the potential economic benefits of investments in plant safety have been grossly underestimated in recent years as the financial implications of court decisions based on "strict liability" have not been fully appreciated by industry. Chemical companies will certainly have to reorient internal resource allocation substantially away from product and process R&D and/or capacity expansion and into plant safety. This will not be done voluntarily or in the public interest. It will be done because legal departments and the insurance companies will insist upon it. Technological innovation in the affected industries will thus be slowed.

There are predictable downstream consequences: Chemical firms will earn less profit and invest less. They will grow more slowly and create fewer jobs. Consumers will lose future benefits they would otherwise have enjoyed. In particular, farmers—who depend upon the continuous development of new insecticides to replace the ones that insects have developed resistance to—will experience increased losses. In the very long run, these indirect consequences of slower technological progress could well outweigh, in human terms, the Bhopal tragedy itself.

Notes

1. Many deaths occurred among refugees who escaped from Bhopal into surrounding areas where no systematic identification count was possible. Estimates as high as 5,000 have appeared in the press, but cannot be taken too seriously.
2. K.H. Slotta and Lorenz, *Berichte der Deutsche Chemische Gesellschaft* 58B:1320, 1925; K.H. Slotta and R. Tscheschka, *Berichte der Deutsche Chemische Gesellschaft* 60B:1021–1027 1927; K.H. Slotta and R. Tscheschka, *Berichte der Deutsche Chemische Gesellschaft*, 60B:295–304, 1927; and K.H. Slotta and R. Tscheschka, *Berichte der Deutsche Chemische Gesellschaft* 62:137–145, 1929.
3. See, for example, "Interview with Professor Otto Bayer," British Intelligence Objectives Subcommittee (BIOS), Report no. 719, Item no. 22 (London: His Majesty's Stationery Office, 1946. The subject of this interview was isocyanate chemistry.
4. J.H. Saunders and K.C. Frisch, *Polyurethane Chemistry and Technology* (New York: Wiley Interscience, 1962).
5. R.G. Arnold, J.A. Nelson and J.J. Verbanc, *Chemistry Review* 57:47–76 (1957); J.H. Saunders and R.J. Slocombe, "The Chemistry of the Organic Isocyanates," *Chemical Reviews* 43:205–218 (1948); and S. Patai, ed., *Chemistry of Cyanates and Their Derivatives* (New York: John Wiley & Sons, 1977).
6. Saunders and Slocombe, *op. cit.*
7. C. Deva Kumar and S.K. Mukherjee, "Methyl Isocyanate: Profile of a Killer Gas," *Science Today*, January 1985.
8. German Patent #1,126,371 (March 1962); and Radhika Ramaneshan, "Government Responsibility for Bhopal Gas Tragedy," *Environment* 19(50):2109–2110 (December 1984).
9. TLV = Threshold Limit Value. The hazard scale increases from 0 to 4. Data from the UCC operating manual, as cited by Ramaneshan, *op. cit.*
10. R.A. Mashelkar, Personal Communication with Robert U. Ayres, January 1985.
11. J.A. Tarricone, C.R. Neumeyer and W.P. Ter Horst, Methyl Isocyanate Polymer and Process Therefor, US Patent #3,300,432 (1967).
12. MCC Catalyzes MIC Polymerization in Steel—Inhibited by Methyl Pyrophosphoric Acid, US Patent #3,488,375 (1970).
13. In the days after the accidental release, a team of Indian scientists led by Dr. S. Vardarajan, Director-General

of the Indian Council of Scientific and Industrial Research, was considering options for the safe disposal of the remaining MIC in storage. The possibility of adding more phosgene as an inhibitor was very seriously considered (speech given by Dr. Vardarajan at the Indian Science Conference in Lucknow, UP, India, January 1985). Both UCC and Bayer, however, strongly advised against this option. UCC recommended carrying out the conversion to Sevin by reaction with alpha naphthol, which was finally done on December 15, 1985.

14. The UCC manual has not been published, but it has been obtained by reporters and extensively quoted in various news media, including *India Today* and *The New York Times.*
15. Sreekant Khandekar and Suman Dubey, "City of Death," *India Today* (cover story), December 1984.
16. *Ibid.*
17. *Ibid.*
18. Stuart Diamond in *The New York Times*, January 27 to February 3, 1985.
19. *Ibid.*
20. Bharat Bushan and Arun Subramanian, "Bhopal: What Really Happened?," *Business India*, February 25 and March 10, 1985.
21. Diamond, *op. cit.*
22. *Ibid.*
23. *Ibid.*
24. *Ibid.*
25. Mr. Qureshi subsequently stated that it was his understanding at the time that the reported leak was water, not MIC (Bushan and Subramanian, *op. cit.*).
26. Bushan and Subramanian, *op. cit.*
27. *Ibid.*
28. *Ibid.*
29. Pradful Bidwai, "A Deadly Day in Bhopal," *Times of India* News Service, December 1984.
30. Khandekar and Dubey, *op. cit.*
31. Bushan and Subramanian, *op. cit.*
32. *Ibid.*
33. Khandekar and Dubey, *op. cit.*
34. *Ibid.*
35. Actually, people should have stayed at home, closed their eyes, and breathed through a wet cloth. This simple procedure—if known—would have saved almost all the lives that were lost (Vardarajan, *op. cit*). In any case, there was no way for the people living nearby to know what the siren signified, since it was sounded 20 times a week on the average (Diamond, *op. cit.*).
36. Bushan and Subramanian, *op. cit.*
37. Khandekar and Dubey, *op. cit.*
38. *Ibid.*
39. Bidwai, "Safety Measures . . ." and "Deadly Delay," *op. cit.*
40. *Ibid.*
41. Vardarajan, *op. cit.*
42. *Ibid.*
43. On this point, there is a dispute. Some unnamed Bhopal staffers claim that this was done only after gaining approval from UCC in the US. This has been denied by UCC spokesman (Diamond, *op. cit.*). On technical matters, the Bhopal plant had direct liaison with the UCC plant at Institute, West Virginia. It is not known whether the dismantling of the refrigeration service was actually approved by anybody at UCC, especially since it was specifically prohibited by the operating manual.
44. Vardarajan, quoted by Diamond, *op. cit.*
45. Bidwai, "Deadly Delay," *op. cit.*
46. The fact that electric pumps failed and instruments often did not work is a strong indication that the vagaries of the electric power supply and the climate may have been a major cause of the problems at Bhopal. Heavy duty motors do not normally need maintenance, but they do need protection from power surges, frequency fluctuations, and excessive humidity. As confirmation of this hypothesis, even electric bulbs are known to last only 200 hours, on average, in India. Unreliability may be attributed to another factor, however: the prevalence of illegal, unmetered users (many of them rural water pumping systems) that cut in and out of the power system at random times.
47. A good illustration of this is the fact that people continue to build houses on or near known volcanoes and/or earthquake zones, *i.e.*, the San Andreas fault, Mount Vesuvius, and Mount Pele.
48. Khandekar and Dubey, *op. cit.*
49. Most industrial facilities in India have one or more outside water faucets for landscaping purposes. Squatters make use of such water sources and are generally allowed to do so by plant owners. For this reason, unoccupied land adjacent to any factory is quickly taken by squatters, regardless of where the plant is located.

50. Ramaneshan, *op. cit.*
51. Khandekar and Dubey, *op. cit.*
52. Raj Kumar Keswani, *Jansatta*, June 1984.
53. Ramaneshan, *op. cit.*
54. *Ibid.*
55. Because of the then-recent assassination of Prime Minister Indira Gandhi, one of the first possibilities that occurred to the Bhopal authorities on December 3 was that of deliberate sabotage. This notion, however, seems to have been quickly dismissed. Another wide rumor circulated in the Indian press was to the effect that UCC, through UCIL, was engaged in research on "crop warfare" for unstated—but presumably sinister—purposes.
56. Press coverage contributes to this simplistic view. During UCC's first major press conference (December 13), the following exchange took place (Thomas J. Lueck, "Crisis Management at Carbide," *The New York Times*, December 1984): Reporter (Rick Kilmer, Station WINE, Brookfield, Connecticut): "I think you've said that the company was not liable to the Bhopal victims."
    UCC Spokesman (Jackson Browning): "I didn't say that."
    Reporter: "Does that mean you are liable?"
    UCC Spokesman: "I didn't say that either."
    Reporter: "Then what did you say?"
    UCC Spokesman: "Ask me another question."
    Reporter: "Under what circumstances would you not be liable?"
    The UCC Spokesman decline to answer.
57. Melvin Belli quoted in *Business Week*, December 1984.
58. *Ibid.*
59. David Meister, "Reduction of Human Error," *Handbook of Industrial Engineering* (New York: Wiley, 1982).
60. L.V. Rigby and A.D. Swain, "Effects of Assembly Error on Product Acceptability and Reliability" in *Proceedings, 7th Annual Reliability and Maintainability Conference*, American Society of Mechanical Engineering, New York, July 1968.
61. Meister, *op. cit.*
62. A.D. Swain, *Design Techniques for Improving Human Performance in Production* (1977), available from the author, 712 Sundown Place, SE, Albuquerque, New Mexico 87107.
63. *E.g.*, M. Granger Morgan, "Choosing and Managing Technology-Induced Risk," *IEEE Spectrum* 18:52–60 (December 1981).
64. Evolving legal doctrines in the US have changed the profit-loss trade-offs dramatically. The possibility exists that UCC may be held liable for damages in the hundreds of millions or billions of dollars. This is far more than the $25 million investment and would threaten UCC's survival and the jobs of all its employees worldwide. Over its planned lifetime of perhaps 10 years, the Bhopal plant of UCI might have targeted something like 20% return on investment, or a total of $50 million, of which only about half would have belonged to UCC, as 51% owner of UCI. (This would be optimistic; in actual fact, the plant had been losing money since 1982.)
65. *Business Week*, December 1984.