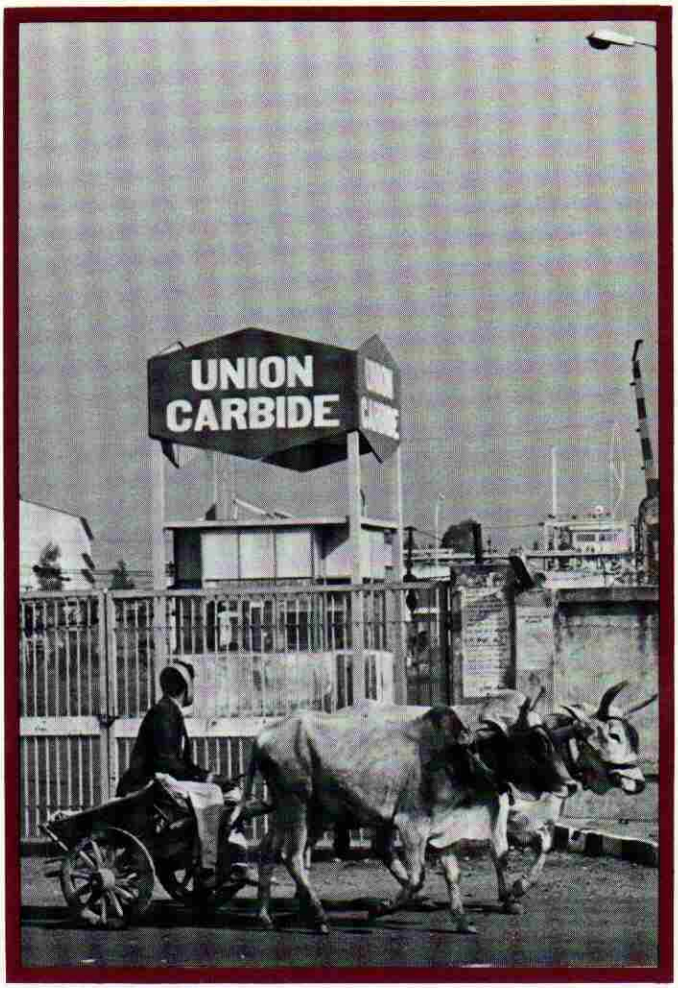
In the aftermath of the catastrophe, what can we learn from history's worst industrial accident?

AVOIDING FUTURE BHOPALS



By B. Bowonder, Jeanne X. Kasperson, and Roger E. Kasperson

Runaway chemical reactions are rare events, particularly in this heyday of the redundant and "defense-in-depth" safety design for complex, high-risk technologies. Yet during the chill of night between December 2 and 3, 1984, a statistically improbable worst-case scenario moved from the computer simulations of the risk assessors and played itself out on the unsuspecting citizens of Bhopal, India. A parade of failures—in design, in maintenance, in operation, in emergency response, and in management—conspired with a southerly wind and a temperature inversion to push a lethal cloud of methyl isocyanate (MIC) out to kill and injure thousands of people, animals, and plants in the area (see Figure 1 on page 9). By sunrise, the unprecedented horror had catapulted Bhopal to the head of history's roll of industrial disasters (see Table 1 on page 8).

The inevitable spate of articles and conferences on the perils of technology transfer is in full force. Postmortems on the accident are likely to proliferate for some time as the courts and the risk analysts puzzle over the catastrophic chain of collapses, each trivial in its own right, that sent MIC on its destructive path.

Indeed, much is at stake in the responses to the accident, for the postmortems may select the "wrong" lessons and thus fail to avert future calamities, place unwarranted crippling restraints on the chemical industry, or impede the flow of needed and generally beneficial technology to developing countries. The chemical industry, with a job-related lost-workday incidence of 2.43 per 100 full-time workers in 1983 (compared with an all-industry incidence of 6.84), is an undisputed leader in industrial safety.[1] Union Carbide Corporation, the parent company involved in the disaster at Bhopal, has more than twenty years' experience in the safe manufacture, use, transport, and storage of MIC (to say nothing of a

host of other hazardous products). With a cadre of scientists and technicians and an institutional structure for environmental protection, India is better equipped than other developing countries to manage hazardous technologies. Given this framework, other industries in other places are more likely candidates for catastrophic disasters. Thus it is essential to understand how and why this particular surprise occurred at Bhopal if we are to ward off future similar tragedies.

Survivors search to identify relatives among the dead.

Jobs and Self-Sufficiency

Union Carbide was scarcely an unwelcome intruder in Bhopal. The Indian government promoted the siting of industries in less developed states such as Madhya Pradesh where Bhopal is located. Eager to attract major industries, Madhya Pradesh leaders offered incentives to companies that would bring jobs and indigenous manufacturing to its unindustrialized cities; Union Carbide, for example, built on government land for an annual rent of less than $40 an acre. A plant that would manufacture the carbaryl pesticides to fuel India's ongoing green revolution was particularly welcome as another step toward self-sufficient food production. Hence the 1970 decision of Union Carbide of India Limited (UCIL) to manufacture the pesticide Sevin in an advanced facility in central India was met with great fanfare.

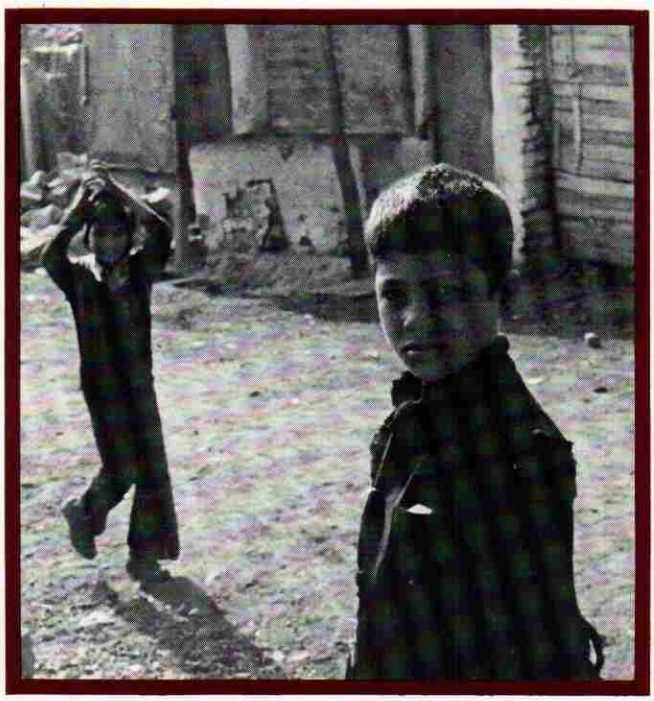
Sevin, manufactured from MIC, had received the endorsement of the Indian Council of Agricultural Research. Use of the pesticide decreases insect damage of cotton, lentils, and other vegetables by as much as 50 percent. Even in the wake of the accident, few serious observers have suggested that India do away with Sevin and other carbaryl pesticides which, ironically, are substitutes for "more dangerous" DDT and organophosphates. Given the high toxicity[2] of MIC (see Table 2 on page 11), however, it is clear that the chemical requires, at all stages, special handling commensurate to the risk.

It is easy to contend that high-risk facilities have no place in densely populated urban areas. Yet such a facility is apt to attract squatter settlements to its gates, whether it be a liquefied-natural-gas facility in Mexico City, a petrochemical complex in Cubatão, Brazil, or a pesticides factory in Bhopal. The showpiece UCIL factory and other industries that set up shop in Bhopal surely contributed to the staggering rise in population—from 350,000 in 1969, to 700,000 in 1981, to over 800,000 in 1984. As a Union Carbide official recently put it:

In India, land is scarce and the population often gravitates towards areas that contain manufacturing facilities. That's how so many people came to be living near the fences surrounding our property.[3]

It is also, of course, how risks come to fall so disproportionately on the poor.[4]

The showpiece factory never lived up to its promise of production and jobs for the area. A drought in 1977 forced many farmers to take out government loans, many of which began to fall due in 1980. The farmers then exchanged the expensive Union Carbide pesticides for others less costly and less effective. Meanwhile, the Indian government was



(Above left) The Union Carbide plant at Bhopal, India; (right) children in the squatter community around the plant. (Photos: Wil Lepkowski)

TABLE 1

MAJOR INDUSTRIAL DISASTERS IN THE TWENTIETH CENTURY

YEAR	ACCIDENT	SITE	NUMBER OF FATALITIES
1921	Explosion in chemical plant	Oppau, Germany	561
1942	Coal-dust explosion	Honkeiko Colliery, China	1,572
1947	Fertilizer ship explosion	Texas City, USA	562
1956	Dynamite truck explosion	Cali, Colombia	1,100
1974	Explosion in chemical plant	Flixborough, UK	28[a]
1975	Mine explosion	Chasnala, India	431
1976	Chemical leak	Seveso, Italy	0(?)[b]
1979	Biological/chemical warfare plant accident	Novosibirsk, USSR	300
1984	Natural gas explosion	Mexico City	452+[c]
1984	Poison gas leak	Bhopal, India	2,500[d]

[a]3,000 evacuated
[b]700 evacuated, hundreds of animals killed, 200 cases of skin disease
[c]4,258 injured, 31,000 evacuated
[d]100,000 evacuated, 50,000 severely impaired

SOURCES: Patrick Lagadec, *Major Technological Risk: An Assessment of Industrial Disasters* (New York: Pergamon Press, 1982); Sailesh Kottary, "Whose Life Is It Anyway?" *The Illustrated Weekly of India* (30 December 1984–5 January 1985), 8; "Union Carbide Halts Production of Pesticide Gas," *Financial Times* (London), 5 December 1984, 1.

providing incentives for small-scale manufacturers to produce pesticides that they could afford to sell at half the price of Union Carbide products. In addition, inexpensive, nontoxic synthetic pyrethroids made their debut, and sales of traditional pesticides began to drop throughout the industry. The Bhopal operation, never very profitable, broke even in 1981 but thereafter began to lose money. By 1984 the plant produced less than 1,000 of a projected 5,000 tons and lost close to $4 million. UCIL, contemplating selling the operation, began to issue incentives for early retirement and cut back on its workforce. Many of the skilled workers left for securer pastures. Things were not going well.

Early Warnings

Whether cost-cutting measures and the departure of skilled personnel caused lapses in safety is difficult to ascertain. Nevertheless, the Bhopal plant experienced six accidents—at least three of which involved the release of MIC or phosgene, another poisonous gas—between 1981 and 1984. These accidents scarcely presaged the catastrophic release, but taken together they surely could have pointed to safety problems at the plant. Indeed, a phosgene leak that killed one worker on December 26, 1981, generated an official inquiry, but the findings (filed three years later) gathered dust in the Madhya Pradesh labor department until after the Bhopal accident, when two officials lost their jobs for having failed to act upon the report's safety recommendations.[5]

Meanwhile, a local journalist warned that the plant's proximity to Bhopal's most densely populated areas was inviting disaster. In 1982 Rajkumar Keswani took on UCIL in a series of articles in the Hindi press. "Sage, please save this city," "Bhopal on the mouth of a volcano," and "If you don't understand, you will be wiped out," the headlines warned.[6] On June 16, 1984, he tried again, this time with what he calls "an exhaustive report on the Union Carbide threat." "The alarm fell on deaf ears," he wrote one week after the Bhopal accident.[7]

A 1982 safety audit by an inspection team from the parent company cited a number of safety problems, including the danger posed by a manual control on the MIC feed tank, the unreliability of certain gauges and valves, and insufficient training of operators.[8] UCIL claims to have corrected the deficiencies, but auditors have never confirmed the corrections.

Just before the accident in Bhopal, Union Carbide Corporation's safety and health survey of its MIC Unit II plant in Institute, West Virginia, cited 34 less serious and 2 major concerns, the first of which was the "potential for runaway reaction in unit storage tanks due to a combination of contamination possibilities and reduced surveillance during block operation."[9] Why the parent company, which owns 50.9 percent of the Bhopal plant, failed to share with its subsidiary its two major concerns (the second was the serious potential for overexposure to chloroform) is unclear. Some Union Carbide officials contend that the different cooling systems—brine at Institute and Freon at Bhopal—made the hazard communication unnecessary, but this is difficult to square with the recommendation:

The fact that past incidences of water contamination may be warnings, rather than examples of successfully dealing with problems, should be emphasized to all operating personnel.[10]

Equally puzzling is the parent company's earlier overriding of an alleged UCIL protest against the installation of such large storage tanks—15,000 gallons—at Bhopal.[11]

In any event, MIC sat in storage at the Bhopal plant for at least three months prior to the accident.[12] Such storage invites disaster, for the tiniest ingress of water, caustic soda, or even MIC itself is sufficient to set in motion an exothermic (heat-producing) chemical reaction.[13] One Indian scientist has even hypothesized that the reaction at Bhopal began slowly and imperceptibly at least two weeks before the fateful night in which it reached violent runaway proportions.[14]

Accident Analysis

Some time shortly before the 10:45 P.M. shift change at the Bhopal plant on December 2, 1984, water and/or another contaminant entered MIC storage tank 610 (see Figure 2 on page 11), thereby triggering a violent chemical reaction and a dramatic rise in tem-

perature and pressure. It is not known whether the incoming control room operator was aware that the 10:20 P.M. tank pressure read 2 psi (pounds per square inch), but the 11:00 P.M. reading of 10 psi does not seem to have struck anyone as unusual. Nor should it have, since normal operations ran at pressures between 2 and 25 psi.

By the time the operator did take notice of the rising pressure—from 10 psi at 11:00 P.M. to 30 psi at 12:15 A.M.—the reading was racing to the top of the scale (55 psi). Escaping MIC vapor ruptured a safety disc and popped the safety valve. On the heels of this initial release came a series of compromises and failures of virtually all the safety systems designed to prevent release (see Box on page 34). The deadly gas spewed out over the slums of Bhopal.

Some of the details surrounding the release remain sketchy, yet it is possible to construct a reasonably plausible analysis of the accident. Figure 3 (on page 31) depicts the accident in terms of a general model that views hazards as threats to humans and to things they value (see *Environment,* September 1978, page 16 for the model developed by the Hazard Assessment Group at Clark University's Center for Technology, Environment, and Development). Hazards, which arise out of human wants, develop in stages and end in unintended and undesired consequences. The stages flow into each other much like a succession of reservoirs, each leading to the next. Each linkage in this causal chain presents an opportunity for intervention via control measures designed to arrest the evolution of the hazard.

In the case of the Bhopal accident, the basic *human need* for food generated a *human want* of increased food supply through pest control (i.e., the manufacture and application of pesticides). The particular *choice of technology* at Bhopal was the indigenous manufacture, using MIC, of carbamate pesticides. As Figure 3 indicates, this choice of technology entailed, at least implicitly, a series of important choices, ranging from the basic selection of chemical over biological pest control to a series of considerations relevant to the storage of toxic materials and the scale of technology. These decisions fundamentally shaped the inherent hazard that was set off by the *initiating event,* the contamination of MIC.

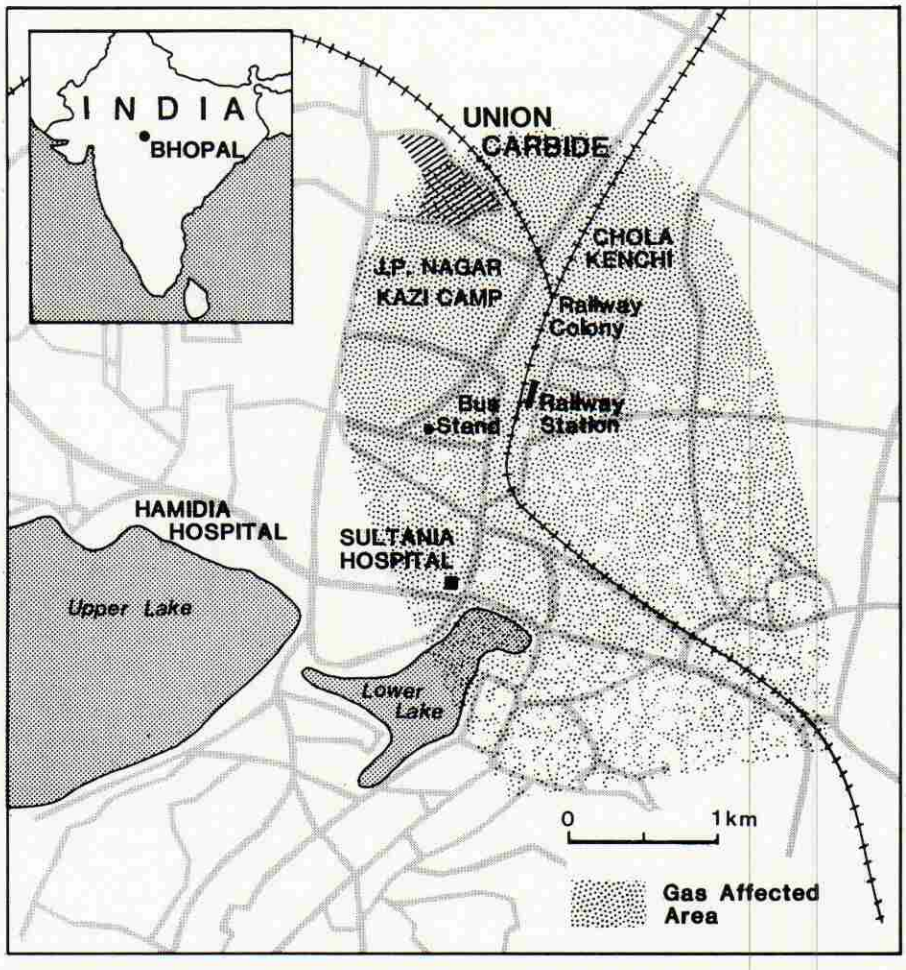


FIGURE 1. Extent of MIC dispersal at Union Carbide's Bhopal site.
SOURCE: Clark University Cartography Lab.

All the while, standard means to *prevent exposure*—remote siting, exclusion zones or so-called greenbelts, early-warning and emergency-response systems, evacuation plans, and hazard communication—never materialized at Bhopal. The surprise release of poison gas thwarted any concerted effort to *prevent consequences.* For want of instructions to breathe through a wet towel, scores of people died ghastly deaths. For lack of information on the toxicity of MIC, Bhopal's medical community was hard put to *mitigate consequences.* Figure 4 (on page 33) shows how these contributors at each stage of the accident in effect hurried a low-probability hazard along to catastrophic consequences.

Consequences of the Accident

More than six months after the accident, even the early (acute) consequences of the accident are not well defined and the longer-term (chronic) effects are very uncertain. Estimates of

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A Leak at Institute, West Virginia

Is Safer Safe Enough?

The leak on August 11, 1985, of methylene chloride and aldicarb oxime at Union Carbide's plant in Institute, West Virginia, attests to the vulnerability of back-up safety systems that fail even in the face of $5-million worth of upgrading.

The Institute plant resumed operations in May 1985 after undergoing extensive retrofitting and modernization that plant officials had touted as a precautionary measure, a way to make a "safe plant safer." In place were a new chemical process that would lower intrinsic risk by reducing the quantities of MIC in transport and a spanking new computerized warning system that would pinpoint the speed and direction of any airborne chemical release. A review by EPA essentially endorsed the company's confidence that the plant posed no major risk to the surrounding community.

But by the time the noxious gas mixture had dropped in unexpectedly on four communities and sent at least 135 people to the hospital, assurances that Bhopal "couldn't happen here" rang hollow. Once again, an intruder—steam this time—entered the jacket surrounding an unusual storage vessel, triggered a temperature and pressure rise that overwhelmed three gaskets on the tank, thereby producing a leak that eluded the multilayered safety system and escaped directly into the atmosphere. The high pressure also ruptured a safety valve, so that additional gas flowed to a neutralizer and a flare tower, two back-up safety devices that only partially destroyed the vapor. As at Bhopal, another safety system, the water spray, was insufficient to arrest off-site migration of the gas. That some gas by-passed the safety systems altogether and escaped directly into the atmosphere and some gas sneaked past both the scrubber and the flare has posed the potential need to retool valving and piping systems throughout the chemical industry.

Just as MIC had surprised Bhopal, the gas mixture announced its own arrival—before the public siren sounded, before anyone notified local authorities, before the emergency-response teams got wind of it. The newly installed cloud-dispersion computer modeling was not programmed to track an aldicarb oxime leak. In short, exposure preceded the activation of any plans to prevent it.

These multiple failures in the face of the intense corporate and public scrutiny lavished on this particular plant—perched as it is in a setting conducive to high safety performance—will confound the management of catastrophic risk in developing countries. No technological or managerial quick fix is equal to overcoming the vulnerability, pervasive even in well-conceived safety systems; the flaws in design; the inadequacies in computer modeling (or failure to input relevant data); the human reluctance to acknowledge failure when it does occur (no one wants to sound the siren); and the intrinsic limitations in the depth of regulatory inspection, review, and enforcement.

R.E.K. and J.X.K.

human fatalities range from 1,400 to 10,000 (see Table 3 on page 12). The Indian government's official count as of June 1985 of 1,762—based on death certificates—undoubtedly underestimates the toll because many people fled from the city and died in outlying regions, the deaths occurred disproportionately among people living in the nearby squatter settlements about whom little information exists, and the upcoming elections provided incentive for official minimization of the number of fatalities.

More recently, Asoke K. Sen, the Indian law minister, put the fatalities at more than 2,000,[15] closer to the more widely accepted estimate of 2,500. This figure, based on body counts conducted by members of the press, is subject to errors in observation and tabulation and also misses the deaths that occurred outside the city. Because the exodus from the city was extensive within 24 hours of the release, a significant number of fatalities may have escaped count.

The Medico Friends Circle estimated at least 4,000 deaths, based on the sale of death shrouds in the week following the accident. Other estimates have reached 10,000, but they are based on impressionistic information. Estimation is confounded further because over 80 percent of the deaths occurred outside the hospitals. Only 438 deaths are recorded in the various hospitals on December 3 and 4.[16] Although a precise breakdown of age among the fatalities is unavailable, the deaths were disproportionately concentrated among children and especially infants.

Information on the number of people exposed to MIC as well as on the long-term health effects from exposure is even less available. (Vegetation analyses are under way and may improve understanding of MIC's effects.) The most widely accepted estimates indicate that 200,000 persons were exposed, and that 50,000 to 60,000 received substantial exposture.[17] Law Minister Sen recently indicated that doctors have treated 200,000 persons for exposure and 17,000 persons in Bhopal have been permanently disabled, largely from lung ailments.[18] Evidence of continuing physiological effects—including abnormally high blood levels of carboxyhemoglobin and methemoglobin, low vital lung capacity, neurological abnormalities, widespread gastritis, and vomiting—is accumulating. At the time of the accident, the German toxicologist Max Daunderer warned about the stages of MIC's effects—irritated eyes, skin, and lungs during the first four to seven days, serious central nervous system effects developing after three to four weeks, and then delayed central nervous system disorders, including paralysis.[19] The degree of reversibility or irreversibility of these effects, however, is not known.

The Indian Council of Medical Research is coordinating a massive data-gathering effort on long-term morbidity conducted by the All-India

Institute of Medical Science, the V.P. Patel Chest Institute, the Industrial Toxicology Research Centre, and the KEM Hospital in Bombay. Meanwhile, widespread distribution (often without medical supervision) of antibiotics and corticosteroids, as well as widespread malnutrition and chronic diseases among many victims, have complicated the assessment of MIC's effects on morbidity. Studies aimed at defining potential genetic and carcinogenic effects are only beginning and results will require another three to five years. Although MIC passed the Ames test,[20] the U.S. National Toxicology Program is planning an ambitious series of animal studies to elucidate long-term effects on respiratory, reproductive, and immune systems.[21]

Special concern exists over possible damage to women's health. Amidst accounts of abnormally high levels of uncommon vaginal discharge, excessive menstrual bleeding, retroverted position of the uterus with severe restricted mobility, and other disorders, the press has alleged that government and medical teams are avoiding women's health complaints. Junior gynecologists and midwives in hospital maternity wards have reported unusually high numbers of premature or underweight babies and physical deformities among the 20 to 30 infants born daily in Bhopal.[22] Despite the sketchy evidence, some local doctors had advised a number of the 1,000 women who were pregnant at the time of the accident to undergo abortions,[23] advice which a government services department has contested. The Indian Council of Medical Research recently reported that a study of the effects of MIC exposure on fetal growth in some 500 babies does not indicate fetal damage.

Effects of the accident on mental health are acknowledged but are the least studied. Reports of mental trauma and other psychiatric effects persist, yet there is no systematic program for monitoring or treating mental health problems. A distinguished group of psychiatrists who visited Bhopal several weeks after the accident acknowledged weakly that people were indeed suffering from anxiety and depression, but it was difficult to attribute these symptoms to the accident.[24] More recently the King George Medical College has found widespread mental disorders among the Bhopal population.

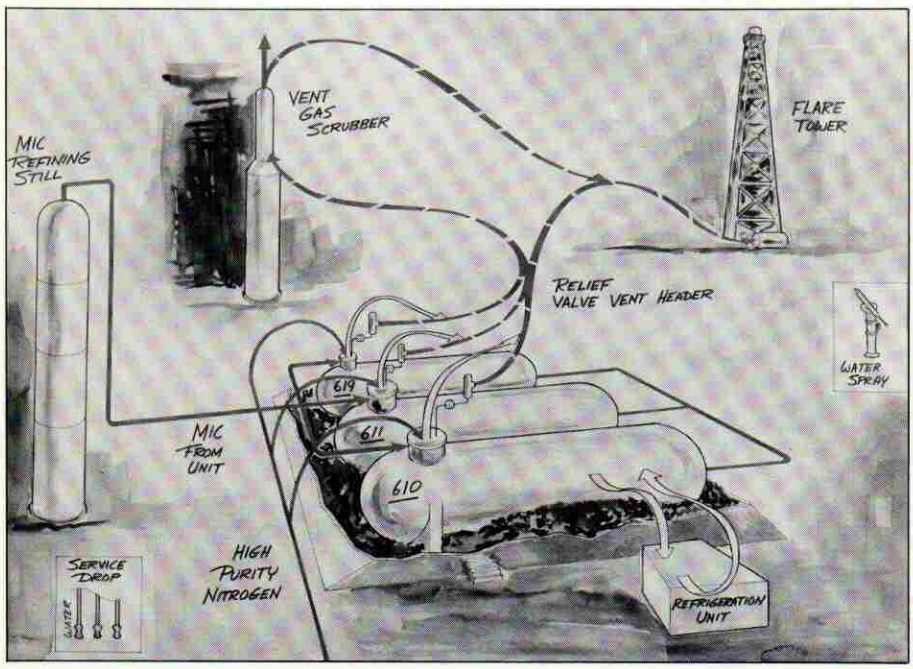


FIGURE 2. MIC tanks at the Bhopal pesticide plant.
SOURCE: Union Carbide Corporation

TABLE 2
WORKPLACE LIMITS TO CHEMICAL EXPOSURES

CHEMICAL	PARTS PER MILLION[a]
Carbon monoxide	50.00
Chloroform	25.00
Methylamine	10.00
Benzene	10.00
Acetic acid	10.00
Cyanogen	10.00
Phosgene	0.10
Methyl isocyanate	0.02

[a]Time-weighted averages for 8-hour exposure
SOURCE: American Conference of Governmental Industrial Hygienists (ACGIH), *TLVs: Threshold Limit Values for Chemical Substances and Physical Agents in the Work Environment and Biological Exposure Indices with Intended Changes for 1984–1985.* (Cincinnati: ACGIH, 1984).

Other damages and burdens add to the human health problems. Some 70,000 to 100,000 persons left the city for distances up to 50 kilometers, with resulting disruption and economic loss. An estimated 1,600 animals died on the first and second days after the accident, posing a serious disposition problem—eventually solved by digging a 1-acre burial pit 5 kilometers from the city. Ecological effects—among the least understood of the accident's long-term effects—include apparent damage to certain vegetation, animal, and fish species but not to others and are under study through the Indian Council of Agricultural Research.

What of the relief efforts to avert further health and ecological effects? Despite the remarkable emergency performance of the Indian medical system, many victims of Bhopal are suffering further harm. As often happens in disasters, the nonaffected residents of Bhopal show a general lack of interest for the victims, many of whom are poor immigrants, not from Bhopal.

Numerous private relief organizations appeared quickly on the scene, administered their aid, and departed. The Indian and Madhya Pradesh governments preside over an uneven relief program, consisting of small doles of money, recently scheduled to be revised to $180 per affected family (from $833 for each death and $12–$240 for each

TABLE 3
MAJOR HUMAN AND ENVIRONMENTAL CONSEQUENCES OF THE BHOPAL ACCIDENT

CONSEQUENCE	SOURCE	ESTIMATED NUMBER AFFECTED	BASE OF ESTIMATE
Mortality	Indian government	1,762	Death certificates
	Independent Indian agency	1,400	Residential survey
	Delhi Science Forum	5,000	Survey of hospitals
	Newspapers and magazines	2,500–10,000	Body counts, unsystematic interviews of doctors, victims, and local officials
	Medico Friends Circle	4,000	Sale of death shrouds
	Asoke Sen (Indian law minister)	2,000	Unspecified
	Indian officials and embassy personnel[a]	5,000	Unspecified
Morbidity	Newspaper reports	200,000 exposed; 50,000–60,000 suffering ill effects	Survey of hospitals and interviews with medical doctors
	Delhi Science Forum	20,000 severely affected in lungs and eyes	Survey of hospitals, medical doctors, affected areas, and victims
	Newspaper reports	Effects on women's health: excessive vaginal discharge, excessive menstrual bleeding, retroverted position of the uterus, cervical erosion and inflammation; unusually high numbers of premature or underweight births, physical deformation among 20–30 daily births	Reports from survey of two Indian camps
	Indian Council of Medical Research	No indication of adverse fetal effects	Survey of 500 babies born since the accident
	Asoke Sen	17,000 persons in Bhopal permanently disabled, largely from lung ailments. Doctors have treated 200,000 (25% of Bhopal's population)	Unspecified
Mental Health Effects	King George Medical College	168 mental cases, especially of neurotic depression or anxiety neurosis	Study of one clinic in affected area
	BusinessIndia	193 suffering from mental disorders (22.6% of survey; majority are women under 45 years of age)	Survey of 855 patients in 10 government hospitals
Evacuation	Newspaper reports	70,000 people left Bhopal before 14 December 1984	400 buses evacuated people for 2 days; interviews with officials, residents, and evacuees
Nonhuman Mortality	*BusinessIndia* and government sources	1,047 animal fatalities; therapeutic treatment to 7,000; delayed poisoning in poultry; breakage and deformation in various phytoplankton cells; change in pigmentations of chlorophyceal algae; fish suffering anemic conditions; 1,600 animals and several fishes found dead (790 buffaloes, 270 cows, 483 goats, 90 dogs and 23 horses); some insect species killed; certain trees lost all leaves; other vegetation in vicinity of plant turned black	Body counts and field observations
Economic Loss	Ishwar Das (Indian relief commissioner)	800 small-scale manufacturing units and about 20,000 shops and establishments suffered business loss; jobs lost from closing of plant, death or incapacitation of wage earners, short-term evacuation costs, uncompensated medical expenses (no quantitative estimates available)	Government survey

[a]Reported by *Chemical and Engineering News*, 11 February 1985.

SOURCE: Clark University Center for Technology, Environment, and Development

person suffering injury or illness, depending upon its severity), and a free ration package of 12 kilograms of cereals, one-half kilogram of oil, and one-half kilogram of sugar per adult each month plus 200 milliliters of milk daily per child. But of the 18,000 families expected to receive compensation, only half have been identified by June 1985 and of these only 4,000 had actually received payment.[25]

The Indian government announced in June 1985 that 1,500 housing units and a 100-bed hospital would be built to accommodate the most seriously ill Bhopal survivors.[26] But despite the substantial efforts by the Indian government and a reported $27 million expenditure by the Madhya Pradesh state government, the relief effort falls short of what is needed.

Hazard Management

The Bhopal accident raises a number of basic issues for the management of industrial hazards in general and for disaster prevention in developing countries in particular. The more prominent of these are characterized below.

Choice of Technology

Few basic decisions affect hazard potential more than the initial choice of the technology. In the case of Bhopal, the choice involves the long-term storage of MIC, a chemical so extremely hazardous that some countries expressly prohibit long-term storage. Bayer AG, a large multinational corporation, manufactures MIC in West Germany and in Belgium, but the process uses the nontoxic intermediates dimethyl urea and diphenyl carbonate and involves no dangerous phosgene or chlorine. Moreover, Bayer promptly converts MIC into end products that are safe to store,[27] and temperature and pressure gauges on the tanks automatically control inconsistencies and can immediately trigger an alarm system.[28] France prohibits domestic manufacture of MIC and requires that special MIC storage drums be maintained in separate sheds equipped with automatic water sprinklers and sensitive gas detectors.[29] England allows only one company to handle MIC and the gas must be stored at a site two miles out of the town of Grimsby.[30] Such alternative technologies, replete with added automated safeguards, pose a lower inherent risk of catastrophic releases than the dangerous process chosen for the Bhopal plant.

Until 1978 UCIL did not store MIC at Bhopal. At that time U.S. corporate headquarters decided, apparently to promote efficiency, to utilize a technology that favored large inventories of MIC, despite its high toxicity and in the face of reservations from the Indian subsidiary. The decision to store MIC at Bhopal was taken without apparent considerations of the particular safety issues posed by a location in India as compared with one in North America. In addition, the Bhopal plant relied on manual, labor-intensive controls while Union Carbide's plant in Institute, West Virginia, used a computerized monitoring system. These basic choices about the technology to be employed and the extent of needed safeguards at the Bhopal plant contributed ultimately to the disaster that occurred.

Siting and Land-Use Control

Bhopal is situated in central India, and the plant site is astride main rail lines leading north to New Delhi, west to Bombay, east to Calcutta, and south to the cotton-growing areas near Madras. For Union Carbide, the area was one of the few regions without an electricity shortage; as well, Bhopal's 10-mile-long Upper Lake provided an ample water supply for manufacturing chemicals, and a ready pool of labor existed in the city.

Since India has no policy on the siting of hazardous industries, no one contested the location of the plant a scant two miles from the center of the city. Although the state department of Town and Country Planning was aware of the plan to manufacture and store MIC, it approved the location and, in preparing the Bhopal Master Plan in 1975, subsequently classified the plant as "general" rather than "obnoxious" and did not require it to relocate to a more remote site (although 16 other smaller industries were relocated).[31] Indeed, in the aftermath of the accident, the Indian press engaged in controversy over whether an official who may or may not have issued an eviction order in 1975 was consequently transferred.[32]

The absence of an exclusion zone or land-use control around the plant exacerbated the high risk of the location. Bhopal is one of the fastest-growing cities in the world: between 1961 and 1981 its population increased by nearly 75 percent per decade, crowding people living in primitive huts onto government lands. The state government, having failed to prevent the population growth adjacent to the plant, compounded the problem by conferring legal status on those living in the squatter settlements in April 1984 so that they could vote in the December elections. This action was taken with knowledge of the accidents that had occurred at the plant and of the highly critical results of the 1982 safety investigation conducted by Madhya Pradesh.

Risk Management

The Bhopal plant employed defense in depth, layers of safety systems in-

(continued on page 31)

Avoiding Future Bhopals

(continued from page 13)

tended to prevent major releases even in the face of individual system failures. Its five major safety systems were:

- ***the refrigeration system.*** The MIC storage tanks were connected to a refrigeration system that circulates the liquid MIC and keeps it cool. In the event MIC becomes contaminated, the refrigeration slows the reaction that may occur, thereby increasing the time available for safety response.
- ***the spare tank.*** One of the three 60-ton tanks at the plant is always left empty so that, in the event of an accident, MIC from a leaking tank can be diverted to the spare.
- ***the flare tower.*** A 30-meter-high pipe located a short distance from the MIC unit is used to burn toxic gases high in the air, thereby rendering them harmless.
- ***the vent gas scrubber.*** A tall, rocket-shaped unit is intended to detoxify any releasing gas by spraying it with caustic soda solution and converting it into a harmless vapor.
- ***the water curtain.*** The plant was equipped with a network of water-spouts that, in the event of an accident, shoots jets of water 12 to 15 meters in the air forming a water curtain around the gas leak. The water neutralizes the MIC vapor to form dimethyl urea or trimethylbiuret, both comparatively safe substances.

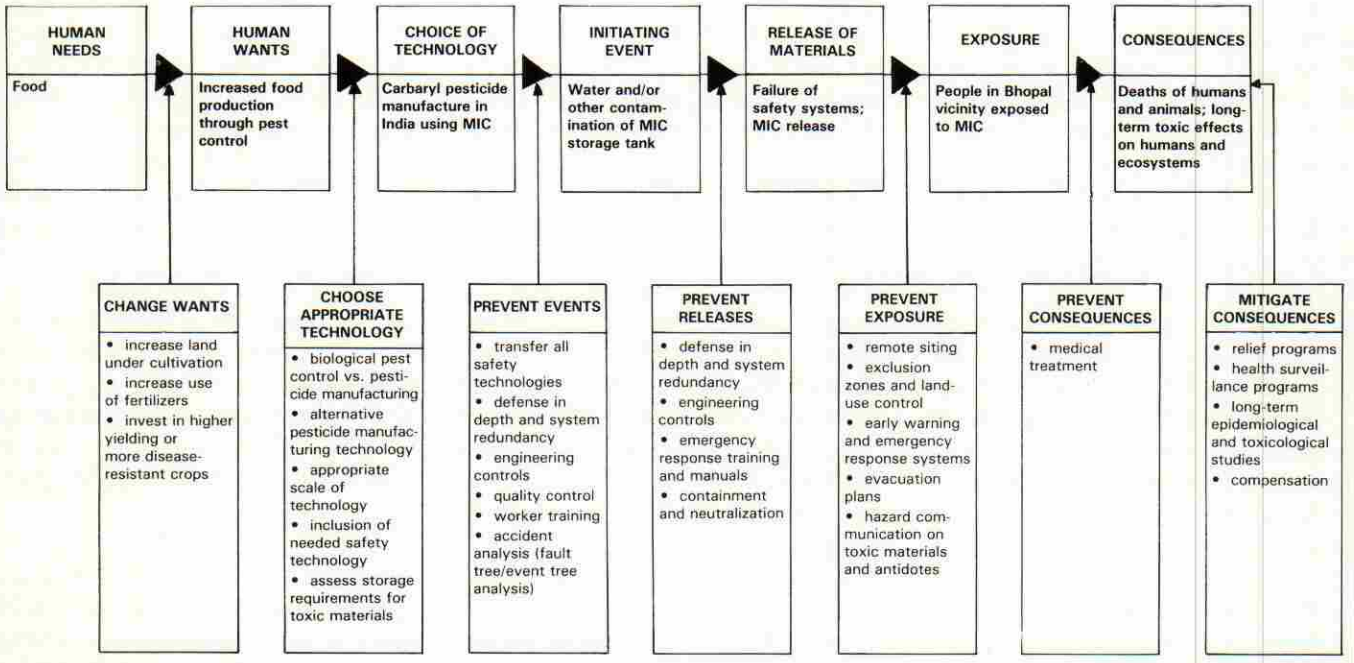
Even if one or several of these systems were to fail, the others should successfully protect against any massive offsite release.

The Bhopal accident testifies to the vulnerability of even well-founded safety philosophy to diverse implementation failures and human error. At the time of the accident, with or without Union Carbide's authorization, the refrigeration system was not working. The use of a requisite spare tank—which may or may not have been empty—required that the operator manually open the valves connecting the two tanks, an operation taking no more than three minutes. In the confusion of the accident, however, the valves were not opened. The vent gas scrubber, on standby mode since October 23, 1984, failed, possibly because the operators neglected to augment the flow of caustic soda required to neutralize MIC. The flare tower designed to burn off escaping gas was under maintenance (because of pipe corrosion) and thus inoperative. And the spouts designed to shoot jets of water into the air to quench a gas leak could not cope with the gusher of MIC some 35 meters high. In short, design errors, sloppy maintenance, poor safety practices, inadequate operator training, and human error hopelessly compromised a many-layered safety system that should have worked.

Emergency Preparedness

Bhopal was ill-prepared for the disaster. No emergency manuals or evacuation plans were available to local officials who, along with nearby hospital officials, were not aware of the toxic substances at the plant, their degree of toxicity, potential health effects, or the recommended medical treatment. The exposure had occurred before the warning siren sounded (some hours after the

FIGURE 3. The causal structure of hazard: Application to the Bhopal accident.



SOURCE: Clark University Center for Technology, Environment, and Development.

beginning of the release), and no public warnings were issued. No information on the movement of the gas cloud—broadcast to the factory workers—alerted people in the vicinity about the best direction in which to flee. Tragically, people poured out of their homes and ran *toward* the factory. Although Union Carbide Corporation headquarters sent a telex on December 5, 1984, indicating that victims might be given amyl nitrite, sodium nitrite, or sodium thiosulphate if cyanide poisoning (a possible sequela to MIC exposure) were suspected, UCIL did not divulge it to the public, arguing that administration of an antidote for cyanide would create widespread panic.[33] Even basic instructions to breathe through a wet towel, which could have saved the lives of hundreds, were never forthcoming.

Given the lack of emergency preparations and critical information during the crisis, the response by India's medical system was nothing short of remarkable. Granted, much of the treatment was strictly symptomatic, but even timely eyewashes warded off some serious injury. It happened that the accident occurred two miles from the region's biggest, best staffed, and best stocked hospital (Hamidia). Although its capacity was 760 beds, the hospital admitted 1,900 seriously ill patients the first day after the accident and eventually treated more than 70,000 victims. By the second and third day, 35 mobile medical teams, each consisting of 2 doctors, a nurse, a pharmacist, and paramedics, were operating outside the hospitals. Quickly the medical resources of Bhopal—500 doctors, 5 major hospitals, and 22 clinics—were supplemented by hundreds of doctors, nurses, and paramedics flown in from the outside.

Amazingly, doctors never ran out of needed medicine and drugs in the aftermath of the accident. The location of the accident and the "fast, intelligent, comprehensive marshalling of manpower, supplies and equipment"[34] carry a sobering message. Had the spontaneous Indian medical response been more limited, had the medicines not been available, or had the accident occurred in other parts of the developing world lacking India's medical capabilities, the fatalities could easily have reached as high as 70,000.[35]

Institutional Issues

More dramatically than Three Mile Island, Seveso, or Mexico City, the Bhopal accident has highlighted a host of far-reaching institutional problems. Although India is more advanced technologically and institutionally than most developing countries, the key legislation covering industrial hazards (the 1948 Factories Act) is geared toward mechanical rather than chemical hazards. Enforcement of environmental occupational health standards has been left to the state governments and is weak or nonexistent. It is noteworthy, for example, that among 250,000 textile workers in India, not a single case of byssinosis has ever been reported.[36]

The Madhya Pradesh labor department employs 15 factory inspectors for more than 8,000 factories, and those employed at the Bhopal office are mechanical engineers with little knowledge of chemical hazards.[37] Although the Madhya Pradesh government commissioned an investigation of the serious 1982 accident at the Bhopal plant, no corrective actions resulted. Trade union action on behalf of worker safety in India is also rare. Finally, although India has some active environmentalists, developing societies generally lack a well-developed network of environmental groups to contest and watch over policy and law enforcement—a key resource in developed countries.

The accident also points up the absence of export controls over the transfer of hazardous industries to developing countries. Heretofore, much attention has focused on the export of hazardous technological products. The extent to which U.S. regulatory systems function to review safety issues involved in the transfer of technology is currently unclear. In addition, the Reagan administration has rescinded the Carter administration's Executive Order 12264, which placed restrictions on the export of hazardous substances. Similarly, at the international level, there is a general absence of codes and legal mechanisms to oversee the operation of multinational corporations.

All told, as Thomas Gladwin so aptly put it, "The firm's technological reach had exceeded its managerial, cultural, and institutional grasp."[38]

Learning From Bhopal

Definite conclusions concerning the long-term lessons of the Bhopal accident must necessarily await fuller information and the analyses that are in process. Such efforts will certainly diminish many of the problems that thwarted effective hazard management at Bhopal, but some of the deeper problems will require a longer time frame to resolve.

Values in Conflict

The Bhopal accident spotlights an inherent tension between values in the *policies* surrounding the transfer of technology to developing countries and in the very *nature* of complex technologies. The Union Carbide plant came to Bhopal as part of an Indian plan for self-sufficiency in agricultural production and for industrialization of its underdeveloped regions through a labor-intensive technology transfer. But assuring the prevention of catastrophe will probably require tightening controls by parent companies, which possess the overwhelming capability and knowledge for controlling industrial risks. Regulatory systems, whether in developed or developing countries, will always find it difficult to replicate such resources. Thus the management of catastrophic hazards presses for centralized control by the parent corporation and extensive automation; at the same time, participatory economic development presses for decentralized control, indigenous resource development, and labor-intensive production.

Transfer of Technology

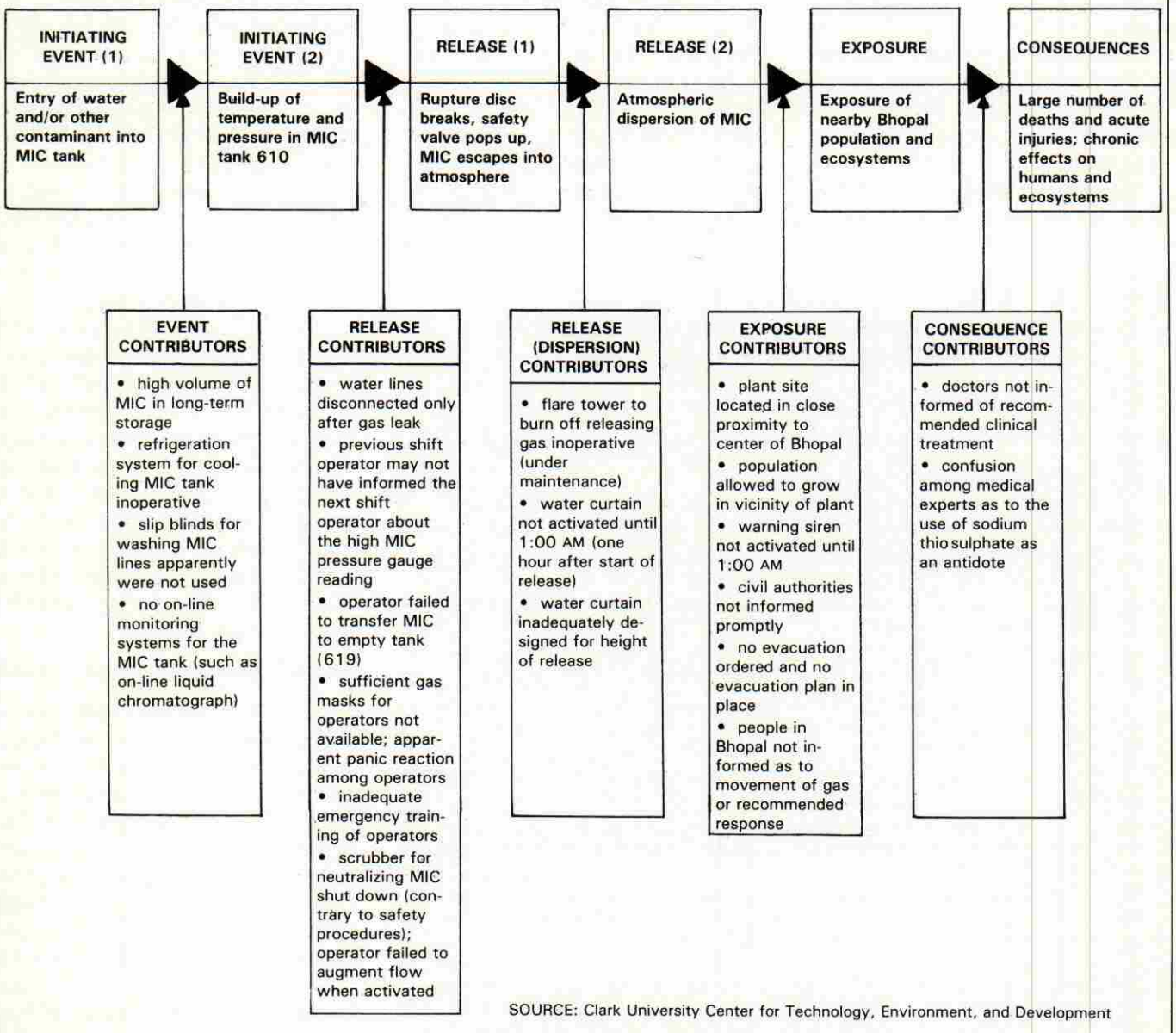
Probably no decision will more profoundly affect the balance of benefits and risks than the choice of technology to be transferred to developing countries. Whether in bioengineering, chem-

icals, energy, or transportation, the technology in question will enhance development and economic gain only at some price in risk. But in response to the Bhopal accident, the flow of needed technology to developing societies may be impeded. Indeed, capital spending for developing countries by U.S. chemical companies has been falling since 1981.[39]

The choice-of-technology mistake at Bhopal was not the transfer of the modern formulation plant for bulk pesticides needed for Indian agriculture. Rather it was the construction of such a large MIC-based plant of this particular design (the most advanced pesticide plant in the developing world); the choice of a particular production process that carried higher inherent risk for a catastrophic accident; the choice of a scale of plant and equipment (designed to produce 5,000 tons a year) that involved large inventories of highly toxic substances; and the failure to incorporate technological designs and practices for defense-in-depth protection against major accidents.

In the future, economic considerations alone should not drive the choice of the imported technology. Rather they should be meticulously balanced with opportunities for risk minimization. In order to determine a safety goal, the realities of the developing country will have to be confronted. At Bhopal these included a shortage of experienced operating, maintenance, and management personnel, and major structural obstacles to effective emergency response. The transfer of an *equivalent* safety goal is likely to involve

FIGURE 4. Detailed model of contributors to the Bhopal accident.



SOURCE: Clark University Center for Technology, Environment, and Development

different and *higher,* not identical, supporting safety systems.

Siting Hazardous Facilities

Past industrial disasters, including the Mexico City explosion and the Three Mile Island accident, have taught that remote siting provides a major protection against potential catastrophes. Particularly where engineered safeguards may be compromised through poor maintenance and equipment failure or operator error, physical distance —by affording greater dilution of the release and increased time for responses —offers an overall redundancy in safety. The tragic loss of life at Bhopal was concentrated in the densely populated squatter settlements located within three kilometers of the plant. A remote site for the plant or an exclusion zone of three kilometers at the Union Carbide plant might have averted most of the fatalities.

One apparent message from Bhopal would call for remote siting of facilities that carry the potential for rare but catastrophic events. Such a policy must be augmented by control over population growth around the facility. Short of truly remote sites, well-considered locations and land-use controls can provide important means of disaster minimization. Exclusion zones similar to those surrounding nuclear plants (in India as well as elsewhere) should be provided, with the size of the zone determined by comprehensive, site-specific risk analyses. Use of company buses can readily overcome the problem of access to needed labor pools.

Risk Assessment

The past 10 years have witnessed a major development in the methods of probabilistic risk analysis (PRA), particularly for the nuclear industry. It is high time that other industries, including the chemical industry, begin to catch up. The U.S. Nuclear Regulatory Commission has recently summarized the current status of these techniques and their potential contributions for plant design and maintenance.[40] These methods are likely to be more extensively used in Europe as chemical plants prepare the various safety studies required by the Seveso Directive, the European Economic Community's response to the 1976 accidental dioxin release at Seveso, Italy.

Although the absolute numerical values produced by such analyses should be viewed cautiously, the PRAs now being widely performed for nuclear power plants (and some other industrial facilities) have considerable power for identifying potential accident sequences that could lead to catastrophic consequences. These analyses should be more widely used in the licensing process for technologies with catastrophic-risk potential. They should be comprehensive in scope—covering manufacturing operations, intermediate steps, storage, and transportation of materials—and should more effectively integrate behavioral and cultural considerations, going beyond current practice. (Even in the nuclear case, human behavior data bases remain underdeveloped.)

A comprehensive risk analysis, such as that for the Canvey Island petrochemical complex in England[41] or the Rijnmond petrochemical authority in Holland,[42] should not only assess major risks but also identify cost-effective opportunities for risk reduction. Leading candidates for such analyses would be the petrochemical complexes at Baroda in India[43] and in the Cubatão Valley in Brazil,[44] where the major ingredients for industrial disaster exist.

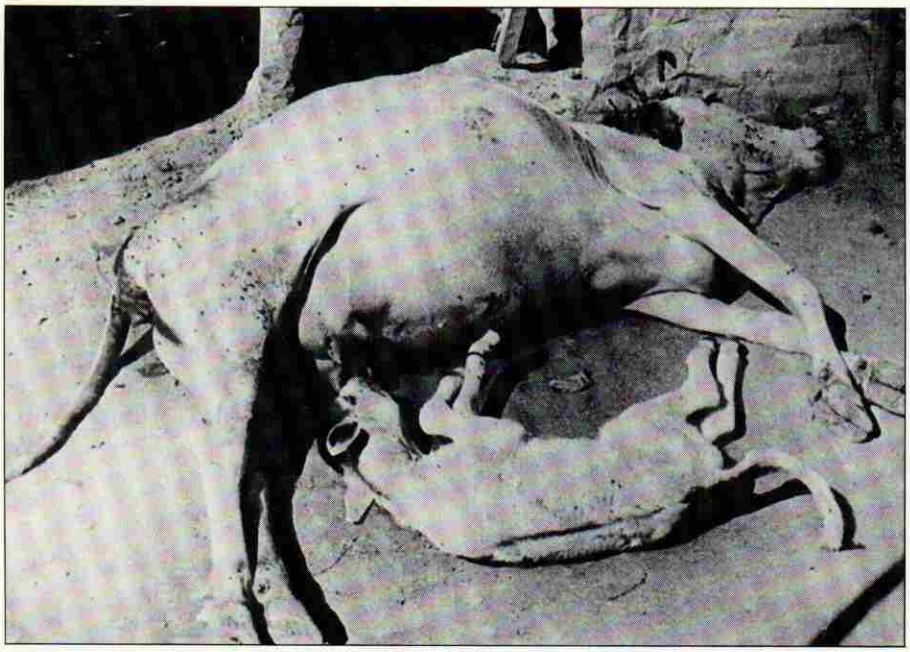
Hazard Communication and Response

Some of the clearest failures in the Bhopal accident involved inadequate information flow and emergency preparedness. These failures occurred at various levels: inadequate worker understanding of MIC's toxicity and health threat; lack of knowledge by local government and medical officials of the plant's chemicals and their hazards; poor information during the accident to guide nearby residents; and lack of advice to local medical personnel as to recommended treatments.

MAJOR FINDINGS OF UNION CARBIDE CORPORATION INVESTIGATION TEAM (March 1985)

1. The incident was the result of a unique combination of unusual events.
2. The team believes that the safety valve remained open for approximately two hours before it reseated. During that period more than 50,000 pounds of MIC vapor and liquid escaped through the safety valve.
3. The team's hypothesis is that the reaction in the tank occurred when a substantial amount of water was introduced into tank 610.
4. The exact source of water is not known, but laboratory work demonstrated that 1,000 to 2,000 pounds of water would have accounted for the chemistry.
5. The refrigeration system provided to cool the MIC in the storage tank had been nonoperational since June 1984.
6. It is not known whether the 2-psi pressure reading observed 40 minutes earlier by the operator on the previous shift had been communicated to the new operator.
7. The vent gas scrubber had been on standby mode since October 23, 1984. The return to an operating mode was dependent on the operator's being alerted to a problem and taking prompt action to activate the circulating pump.
8. The flow meter did not register a circulation of caustic solution in the vent gas scrubber.
9. The increase in temperature (of the MIC tank) was not signaled by the tank high-temperature alarm, since it had not been reset to a temperature above the storage temperature.
10. Extensive experimentation suggests that residues in tank 610 are attributable to the reaction at high temperature of MIC with large amounts of water, higher than normal amounts of chloroform, and an iron catalyst.

SOURCE: Union Carbide Corporation, *Bhopal Methyl Isocyanate Incident Investigation Team Report* (Danbury, Conn.: Union Carbide Corporation, 1985).



A dead cow and calf in Bhopal. In addition to the human fatalities, the MIC cloud killed some 1,500 animals.

There was also no evacuation plan, and some workers may have escaped danger only because the door they chose to flee through happened, fortuitously, to open north rather than south, although some reports say that an announcement warned workers of the wind direction.[45]

An important lesson of the accident at Bhopal is how formidable the social, cultural, and institutional impediments are to effective hazard communication and emergency response programs. Such impediments include slow bureaucratic response, cultural differences in chemical experience, and underdeveloped social communication networks. That the state government only convened at its normal meeting time, 10 hours after the accident, to handle the emergency indicates the need to change the basic societal structure for responding to hazards. Bhopal has only one telephone per one thousand people, running water for only a few hours per day, few street signs or traffic lights, and crowded 12-foot-wide thoroughfares in which cows, goats, water buffaloes, taxis, and horse-drawn carriages travel simultaneously in both directions.[46] Local residents, with little experience with chemicals as part of everyday life and with no direct information provided by the plant, viewed the plant as producing "medicine for the crops" and not substances harmful to people.[47]

Preventive maintenance to avoid accidents is a concept largely foreign to Indian culture. Although most workers at Bhopal had seen industry information on the hazards of MIC,[48] few understood it; nearly all underestimated the toxicity. And the lack of any local- and state-level emergency response organization made coordinated response to the accident impossible. In short, safe here is likely not to be safe there.

Institutional Changes

The accident at Bhopal clearly reveals that at various levels institutional safeguards are inadequate. Multinational corporations will need to do more than conduct the initial reviews of toxic substance storage and handling as they did in the several months following the accident. They will need to reexamine, and undoubtedly increase, their capabilities in formal risk assessment for safe plant siting, design, and management. Most will require new resources to appraise both catastrophic risk and the relevant societal and cultural factors. This upgrading should be modeled after the Institute for Nuclear Power Operations, which was established after the Three Mile Island incident, and should consider the use of simulators in operator training.[49] The corporate codes of social responsibility will also need to address explicitly the lessons from Bhopal and then act on the more demanding obligations by improving auditing, monitoring, and compliance programs.

Host countries will need to institute licensing and regulatory structures that are sensitive to their own "risk carrying capacities." They will need to stipulate more stringent requirements for highly toxic substances or for industries possessing potential for other catastrophic accidents. Such controls should emphasize the development of hazard data bases,[50] which will need to be linked for easy communication and exchange of information. The Bhopal accident also highlights the need for more openness by both the host government and corporations in siting decisions, environmental impact assessments, accident inquiry reports, and basic information on hazards. India has no provision for public participation or public hearings, and most governmental and official documents are confidential. The "right to know" principle, if applied in India and other developing countries, would afford additional protection to workers and public.

The Nature of Response

As the Bhopal tragedy nears its first anniversary, broad-based efforts to avoid such future accidents have begun in earnest. Nearly all the large chemical corporations have examined catastrophic risk potential and safety practices at their plants in North America and abroad and have discovered problems, particularly with the size of chemical inventories. This has lead to changes in corporate policies governing storage and emergency-response planning.[51] A task force of the U.S. Environmental Protection Agency reviewed the issue of airborne toxic substances, recommended reinforcement of the national contingency plan for emergency

The siting of the Union Carbide plant and other factories in Bhopal surely contributed to the increased population around the pesticide factory. (Photo: Wil Lepkowski)

response, and underscored the need to strengthen hazard communication. At the same time, the task force decided against special restrictions on the chemical industry.[52]

As well, the World Bank has reviewed all of its major projects that have potential environmental impacts and is developing hazard-prevention guidelines, due this month, based on the Seveso Directive. The Chemical Manufacturers Association has established two new programs designed to increase member company and local community emergency response and the flow of hazard information to local officials and publics.[53] In 1985 a number of multinational corporations joined with the U.S. Agency for International Development and the World Environment Center in Project Aftermath, an assessment of information and technical assistance needs for industrial hazard management in some forty countries.[54]

These undertakings are a start, but it is essential to recognize that no quick fix exists to erase the problems that led to the Bhopal accident. Advances in formal risk analysis have yet to permit definitive quantification of accident probabilities and sequences for complex technologies. The cultural and social impediments to well-intentioned plans remain poorly understood and only weakly incorporated into safety programs. Corporations and regulatory agencies alike change slowly.

Previous experience in disease prevention attests to the long time frames and the degree of determination necessary for fundamental gains. The European effort to implement the corrective measures set forth in the Seveso Directive will not reach fruition until 1989, some thirteen years after the accident. Despite the massive response by industry and government to the Three Mile Island accident, the extent of safety upgrading achieved and the degree to which attitudes toward safety have been altered remain uncertain six years after the event. So, too, one should expect the depth of the problems posed by Bhopal to require a decade of determined response, the adequacy of which will require testing over the long term. Moreover, it should surprise no one, as the accident recedes from societal attention and urgency, that conflicting values will tend to erode early progress in resolving the issues raised by the Bhopal accident, in developed and developing countries alike.

Of critical importance is the creation of a culture of safety among those who transfer technology to developing countries, those who woo it for the development of their national economies and localities, and those who manage it when it arrives. The continuing agony of the Bhopal victims argues poignantly that the magnitude of response be commensurate with the tragedy that necessitated it.

ACKNOWLEDGMENT

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Roles Along the Rivers

(continued from page 20)

404 permits were required for wetland activities and directed the Corps to broaden its jurisdiction to include wetlands.[8] Since then, many courts have held that wetlands are "waters of the U.S."[9]

Although the Section 404 program has reduced filling both in coastal wetlands and along larger rivers, disagreements continue between the Corps, FWS, and EPA on the scope of regulated activities and standards for permitted uses. Coordination between this program and NFIP has also been limited.

The Wild and Scenic River Program

In order to protect free-flowing rivers of exceptional natural value, Congress in 1968 authorized a National Wild and Scenic River System.[10] Once a river is included in the system, federal water projects are prohibited there. Fee and easement acquisition may be used to protect the adjacent lands. Designation of rivers for the system has slowed to a trickle—five since 1978. Only 65 rivers, with river segments totaling 7,200 miles are included in this system. This is only a portion of the 1,500 river segments totaling 62,000 miles that the National Park Service has identified as possessing exceptional natural values of the sort that potentially qualify them for inclusion in the national system. Again, little coordination has taken place between this program, NFIP, and the Section 404 program.

State River Management

States often establish standards that are more restrictive than federal standards. When viewed from a single federal management perspective—for instance, flood hazard reduction—development at a specific site may be acceptable. It is only seen as undesirable when the combination of natural hazards and special values is considered—a perspective more common at the state level.

Four types of restrictions characterize state programs on the use of waters and adjacent lands, although the restrictions usually apply to only a small number of rivers or river segments and adjacent lands. First, state regulations may prohibit dams, although the prohibitions do not apply to federal government projects unless the river has been incorporated in the federal Wild and Scenic River System. State regulations also set performance standards to reduce flood losses on most major floodplains and performance standards to protect wetlands, water quality, wildlife, and scenic and recreational values. Finally, state regulations specify setback distances for structures and minimum lot sizes.

In general, more progress in managing river corridors has been made at the state level than at the federal one. This has been achieved through a variety of programs.

Floodplain Management Programs

At least 31 states have adopted programs that regulate fills and structures in the 100-year floodplain.[11] These programs either directly regulate fills and