A common misconception lingering today is the toxic chemical release in Bhopal, India was an extreme, outlier event. However, when the public record is considered a familiar picture emerges. What follows is a careful and recent evaluation of information that has slowly been released into the public domain over the past twenty-seven years. The warnings this assessment offers are of considerable interest and concern for all organizations responsible for the lives of others.

Methyl isocyanate (MIC) release in Bhopal, India

Union Carbide began producing MIC in Bhopal, India on February 5, 1980 [1]. MIC is a highly reactive intermediate chemical that Union Carbide used to manufacture various pesticides. It is also a very lethal substance that can be harmful or fatal if inhaled or absorbed through the skin [2]. MIC reacts exothermically with a variety of potential contaminants including rust and particularly water [3].

Routine maintenance activities were taking place in the factory on the evening of December 2, 1984. Sometime around 10:45 PM, a large quantity of water began entering a chemical storage tank containing over 40 tons of MIC. The reaction mixture inside the tank started progressively warming up as conditions moved closer to a thermal runaway reaction.

Water continued entering the tank until shortly after midnight (December 3, 1984) when the thermal runaway reaction took place. This caused the MIC storage tank's pressure gauge (Fig. 1) to suddenly spike above scale [4]. Although this drew attention to the tank, it was too late to stop the catastrophic loss of process containment.

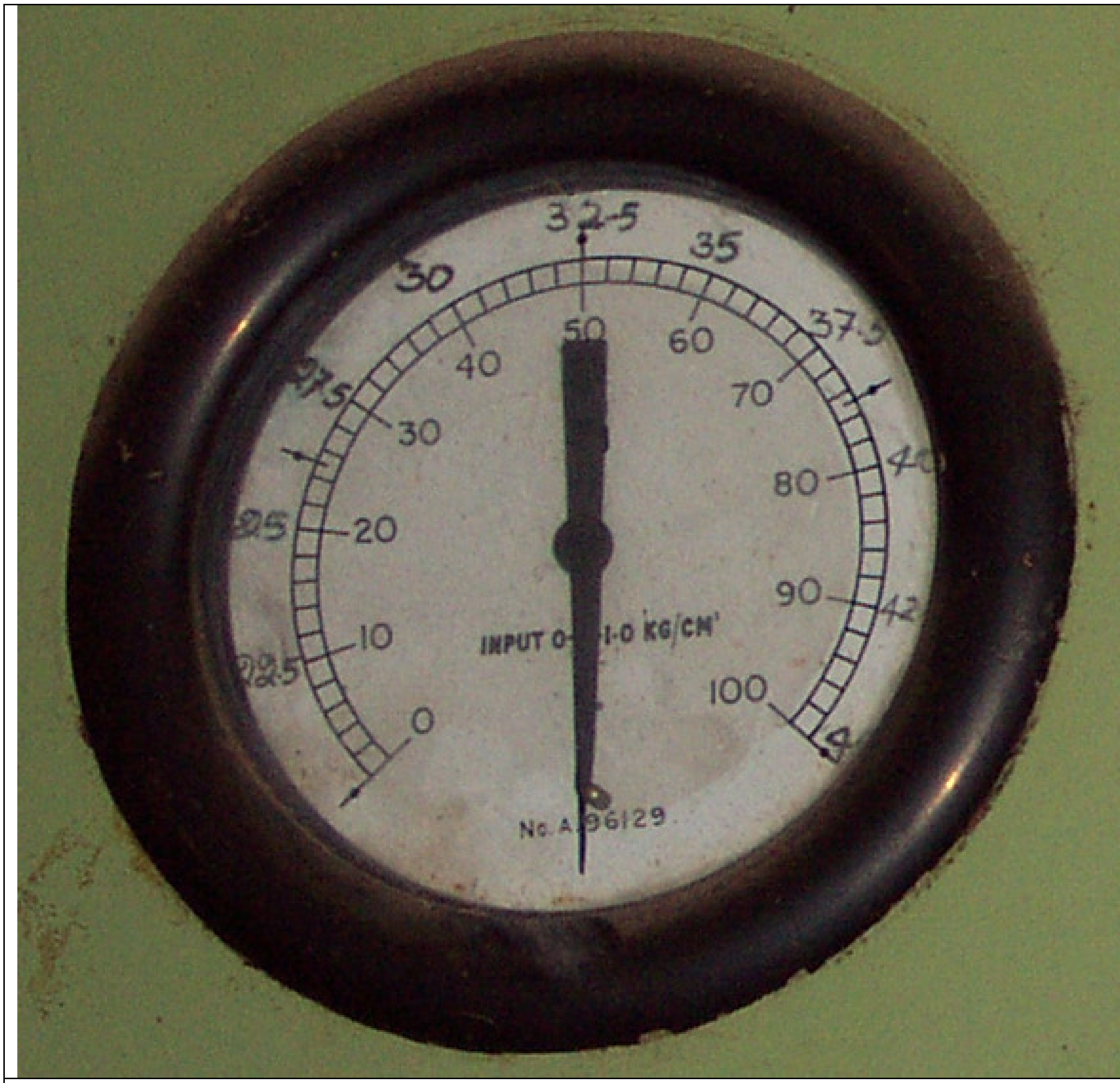

Fig. 1: MIC Storage Tank 610 Control Room Pressure Gauge

Shortly after the runaway reaction occurred, hot MIC vapor burst through the tank's automatic pressure relief system and into the Relief Valve Vent Header (RVVH) [5]. Although this prevented an explosion, a major release involving up to 40 tons of toxic MIC drifted downwind into the surrounding community. By morning, thousands of people and animals were dead [6].

Systems that should have prevented the release including a refrigeration unit and alarms failed. None of the safety equipment capable of containing the potential release or at least minimizing its consequences had worked either. The factory never reopened and Union Carbide, once an undisputed leader in the chemical manufacturing industry, struggled to survive before selling off its remaining business in 1999 [7].

About MIC

Carbon steel is incompatible with MIC [8]. Rust (Fe_2O_3) catalyzes the exothermic MIC trimerization reaction [9] shown in Fig. 2 [10]. This reaction forms a nuisance deposit that can clog pipes [11]. Therefore, stainless steel is recommended in MIC service [12]. In theory, more economical carbon steel components could be substituted when protected by a corrosion inhibitor such as nitrogen [13]. If so, then the inert gas would be critical for mechanical integrity (corrosion and fouling resistance). However, stainless steel represents an inherently safe choice that mitigates the reactivity hazard associated with carbon steel [14].

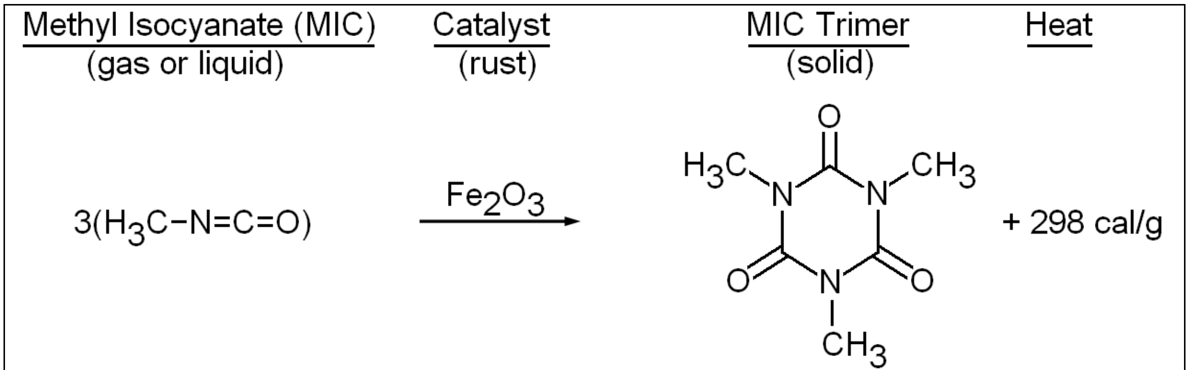

Fig. 2: MIC trimerization reaction

Design elements

In March 1985 Union Carbide issued an investigation report that includes an MIC storage tank Piping and Instrumentation Diagram (P&ID) [15]. The P&ID (Fig. 3) shows how the MIC storage tanks in the Bhopal factory were designed. This P&ID provides information that explains how equipment reliability contributed to the Bhopal disaster.

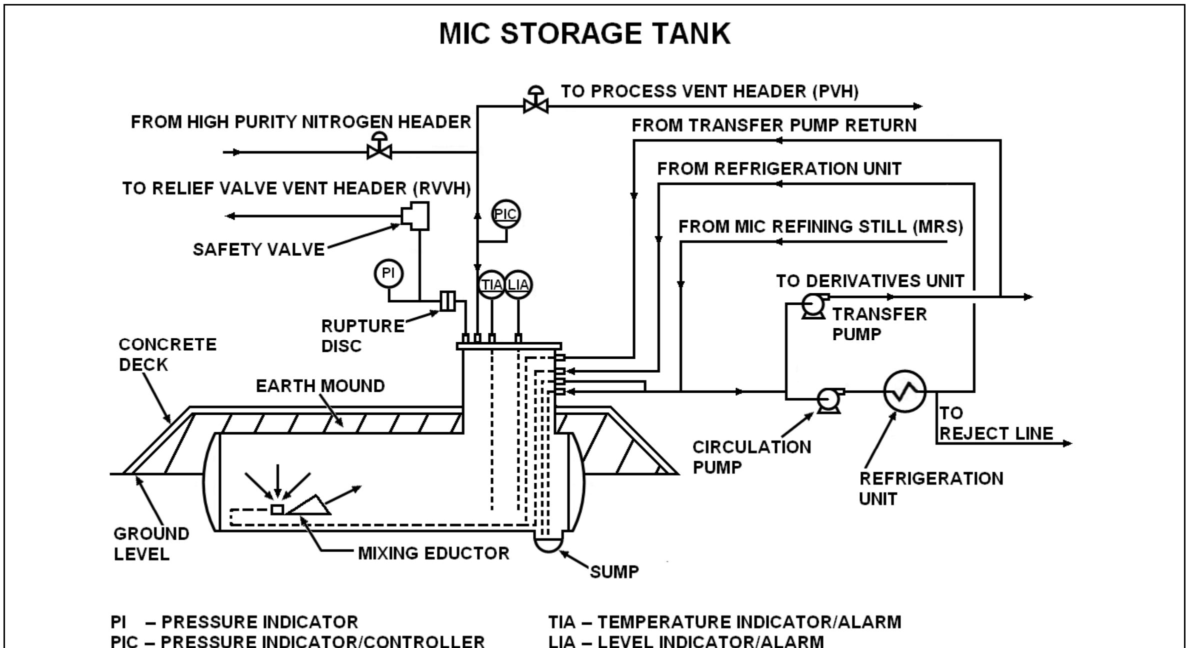

Fig. 3: MIC Storage Tank P&ID

The MIC produced at the factory was stored in two stainless steel storage tanks, designated as Tanks 610 and 611 [16]. An identical tank (Tank 619) received contaminated material from either Tank 610 or 611 on an emergency basis only [17]. Tank 619 provided extra storage volume to allow for an adequate response to a potential thermal runaway reaction [18]. A nitrogen blanket [19] was kept inside the MIC storage tanks to maintain slight pressure [20] while continuously purging MIC vapor into the Process Vent Header (PVH).

The P&ID shows that the tanks were equipped two centrifugal pumps. Each pump had a specific function. The "Transfer Pump" exported stored MIC into the Derivatives Unit as needed to produce pesticides. The "Circulation Pump" processed MIC through a fluorocarbon-based refrigeration system [21]. The refrigeration system kept the MIC storage temperature near 0 °C [22] to prevent a thermal runaway reaction [23].

The MIC pumps were connected to four (4) flanged nozzles on the side of each tank head (Fig. 3). The four nozzles appearing on the P&ID correspond to the actual nozzles installed on the MIC storage tank heads (Fig. 4). Both pumps circulated MIC to and from the bottom of the tank through the internal pipe extensions shown on the P&ID. The discharge lines returning to the tank made it possible for the MIC pumps to operate continuously without ever being shut down. This was the expectation; especially for the circulation pumps needed for uninterrupted MIC refrigeration.

Fig. 4: MIC Storage Tank 610 Side-Head Nozzle Configuration

Procedures

The factory suffered from a series of chronic MIC leaks [24]. MIC is a highly volatile compound [25] that presents an immediate exposure hazard upon its release [26]. For reference purposes, the 8-hour threshold limit value (TLV) for MIC is 0.02 ppm [27] compared to a 10 ppm TLV for H_2S. MIC could therefore not safely be released into the environment [28].

Although the Transfer Pumps were provided to export MIC into the Derivatives Unit, there is no record of their use at any time while the factory was in operation. Instead, an alternative transfer method was developed to exclude the pumps. This method involved raising the MIC Storage Tank pressure to at least 14 psig with nitrogen [29]. These conditions provided an alternative pathway for MIC in the storage tank to travel into the Derivatives Unit (Fig. 5). This practice minimized the potential for Transfer Pump seal failures to expose factory workers to the lethal process [30]. Therefore, it was an inherently safer alternative.

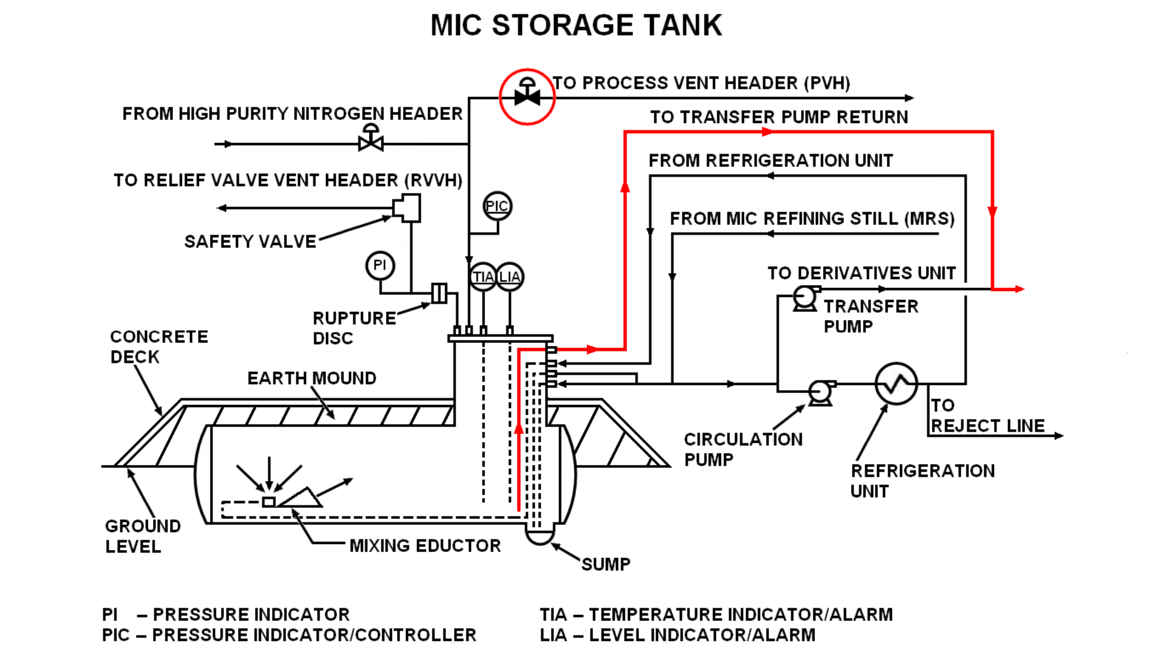

Fig. 5: Alternative MIC Storage Tank Operating Method

However, non-standard operating procedures [31] may address one hazard while introducing others. In this case, pressurizing the tanks in order to bypass the Transfer Pumps required isolating the tanks from the PVH. As the P&ID shows, this practice interrupted excess nitrogen flow into the PVH [32].

Loss of excess nitrogen flow was an issue because the PVH and RVVH were made of carbon steel [33]. Both pipe headers were routed to a Vent Gas Scrubber (VGS) system to contain chemical vapors that might otherwise escape into the atmosphere. The vent header inlet pipes were configured such that they entered above the VGS caustic overflow line (Fig. 6). Therefore, air migrated into the atmospheric VGS when nitrogen was isolated to pressurize the MIC storage tanks. Afterwards, the inert environment inside the PVH and RVVH ceased to exist. The vent lines started to corrode [34], which produced rust. Rust catalyzes the formation of MIC trimer deposits according to Fig. 2.

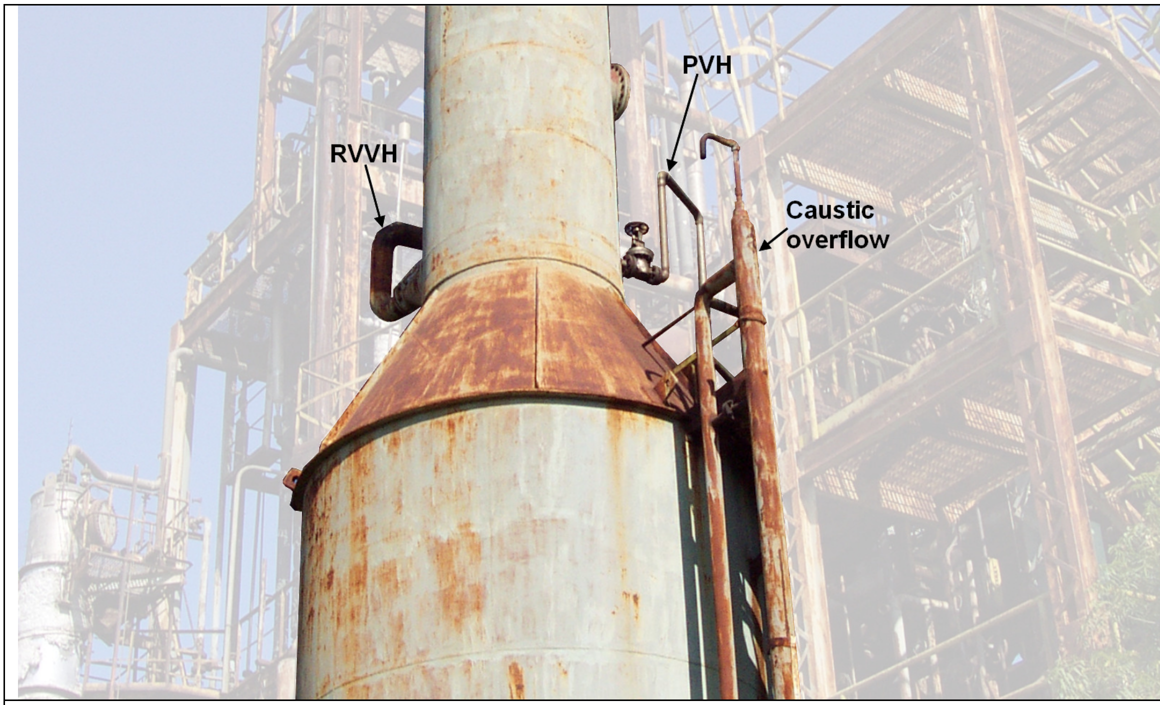

Fig. 6: Vent Gas Scrubber Pipe Configuration

After sealing the tanks, other MIC vapor sources continued venting into the PVH [35]. This prompted the creation of a maintenance procedure to remove MIC trimer deposits polymerizing inside the PVH and RVVH. The procedure involved flushing out the MIC trimer deposits with water [36].

Although MIC could still be exported without the Transfer Pumps, there was no way to refrigerate MIC without operating the Circulation Pumps. A seal failure on or before January 7, 1982 [37] provided a maintenance opportunity to "upgrade" the original metallic seal with a more fouling resistant, but weaker ceramic seal [38]. In MIC fouling service (reactive environment), using a ceramic seal may seem logical. But if a force-related failure mechanism is causing unacceptable seal performance, then a lower strength ceramic material may not be the best choice [39].

On January 9, 1982 the fragile ceramic substitute seal was shattered in an unprecedented catastrophic failure [40]. This failure produced a massive MIC release that sent about twenty-five workers to the hospital with serious injuries [41]. Three days later (January 12, 1982) a formal declaration was issued that the refrigeration system was being shut down [42]. In doing so, a third non-standard operating procedure that involved running the plant without MIC refrigeration was introduced.

Disabling instruments and alarms

After shutting down refrigeration system, the MIC storage temperature varied from about 15 °C to 40 °C [43]. This new operating range exceeded the 11 °C MIC Storage Tank high temperature alarm setting (Fig. 7) [44]. Therefore, the high temperature alarms were disconnected [45]. Likewise, the actual temperature inside the tank was unknown [46] after shutting down the refrigeration system because the control room temperature gauge (Fig. 8) was not scaled to operate above +25 °C. Similarly, the normal operating pressure inside the tank increased from less than 2 psig [47] with an unobstructed tank vent open to the PVH [48] to about 25 psig [49] after bypassing the MIC Transfer Pumps.

Fig. 7: MIC storage Tank 610 High Temperature Panel Alarm

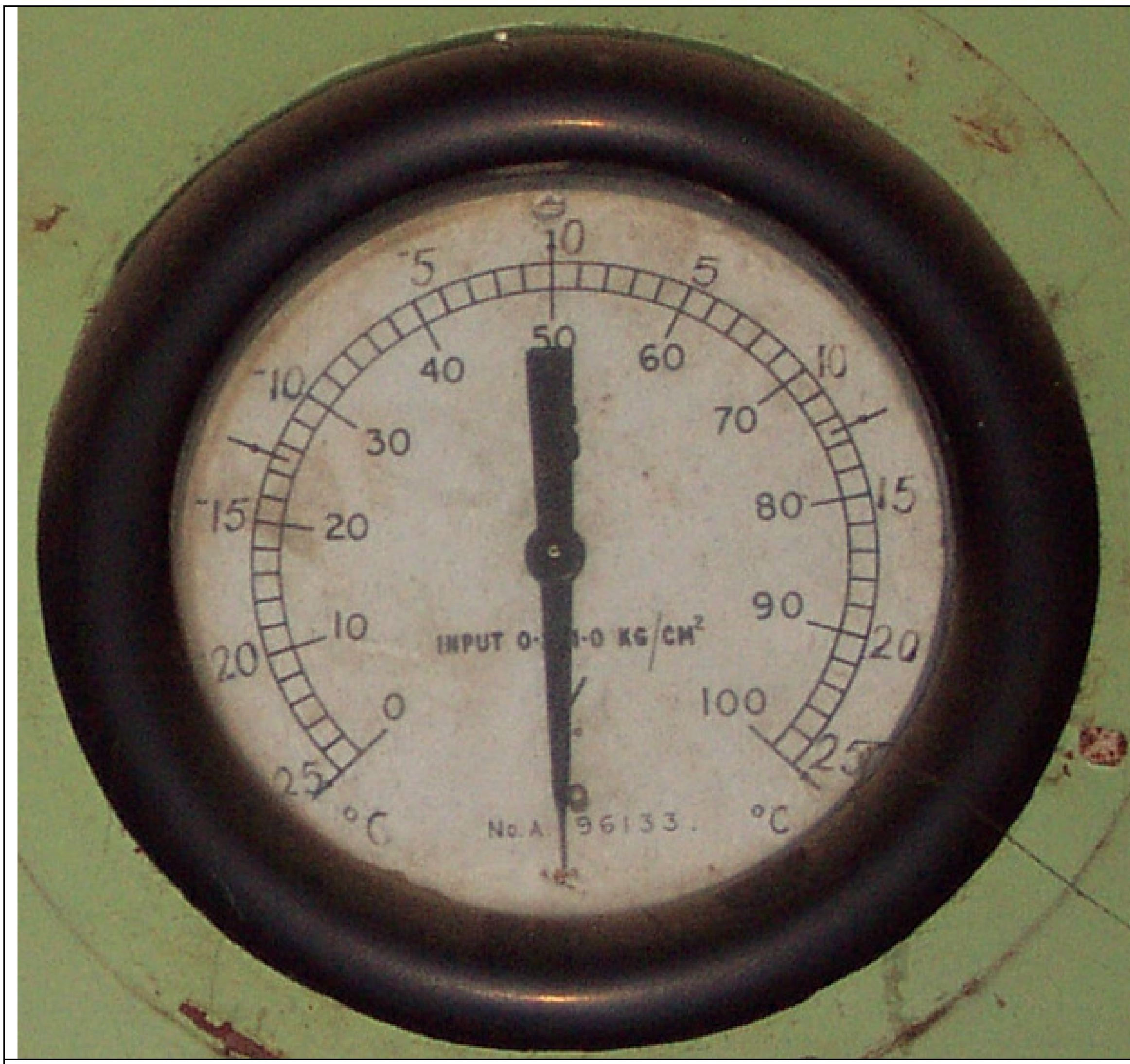

Fig. 8: MIC Storage Tank Control Room Temperature Gauge

In April 1982, factory workers printed hundreds of handouts expressing their concern about decisions being made inside the factory that might influence the community outside the factory [50]. In May 1982, an audit team from the United States arrived in Bhopal to perform an independent safety audit [51]. The audit report included several recommendations to assist with managing the MIC pump hazards:

- Install a nitrogen purge system with low flow alarms at an *alternative* MIC system venting into the PVH [52] (presumably to restore the inert environment inside the PVH and RVVH without operating the Transfer Pumps),
- Equip centrifugal pumps with dual seals [53],
- Provide water spray protection for the MIC pumps in the storage area, for vapor cloud suppression [54].

The audit team complimented the factory's creative approach to improving workplace safety with non-standard operating and maintenance procedures [55]. This might explain why the decision to shut down the refrigeration system four months earlier was not questioned [56]. Accordingly, the factory's safety manuals were rewritten in 1983 and 1984 to reflect actual operation without MIC refrigeration [57].

The fateful night

On the evening of December 2, 1984 the vent lines were corroded and choked with MIC trimer deposits [58]. The pipes were being flushed with water to remove the MIC trimer deposits [59]. MIC trimer deposits form in the presence of rust. Rust forms on carbon steel pipes not protected by an inhibitor. The inhibitor (nitrogen) was isolated from the PVH and RVVH in order to pressurize the MIC storage tanks. The MIC storage tanks were pressurized to bypass the Transfer Pumps.

Somehow, water entered Tank 610 which contained over 40 tons of MIC. Under normal circumstances, this would have activated the tank's high temperature alarm. But the high temperature alarm was disconnected when the refrigeration system was shut down. Likewise, the control room MIC temperature gauge could not be trusted because it normally read above scale without refrigeration. The refrigeration system was shut down almost three years before the incident [60] to manage the potential hazards resulting from pump seal failures. The contamination event inside Tank 610 remained hidden while the reaction mixture continued warming up.

Tank 610's vent valve was leaking on the evening of December 2, 1984 [61]. This made it impossible to pressurize the tank with nitrogen. However, the pressure inside the MIC storage tank increased as the reaction mixture evolved more vapors into the PVH [62]. Although the control room pressure gauge seemed to be within normal range for a sealed tank [63] the tank was not sealed [64]. Therefore, contamination was not detected until a thermal runaway reaction took place, which sent the tank's pressure soaring above the relief valve setting [65]. Although factory workers responded immediately, by that time it was too late.

The refrigeration equipment and process alarms were provided to prevent a thermal runaway reaction should the MIC be contaminated by *any* means. But process safety was compromised in an attempt to manage personal exposure hazards represented by potential pump seal failures.

Can we learn more from Bhopal?

Bhopal forever changed the way industry approaches Process Safety Management (PSM). Increasing clarity around the events leading up to the release complements and reinforces these important lessons. Time has allowed us to take an even closer look at regrettable choices that resulted in disabling the system provided to *prevent* the scenario that resulted in the release. Most industry professionals no doubt plainly see from this examination that we encounter the same situations at work every day. Perhaps this is the message behind "Recognized and Generally Accepted Good Engineering Practices" (RAGAGEP). The decisions we make throughout the life of a process, especially before its construction, can and will affect us as well as all those who follow.

As an industry professional you will make decisions daily that as a whole define your process safety identity. We can't tell you what the right answers are. It is therefore important to allow your conscience be guided by what took place in Bhopal. This is where Bhopal has even more redeeming value. With these thoughts in mind, the focus is on advice provided by a more recent examination:

- When you choose not to investigate a chronic failure, remember Bhopal.
- When the right choice is not the most economical choice, remember Bhopal.
- When choosing to accept actual operation because you cannot get expected or design operation, remember Bhopal.
- When designing a solution that manages a hazard instead of eliminating it, remember Bhopal.
- When tempted to execute a procedure the way you think it should be written instead of how it is actually written, remember Bhopal.
- When thinking about substituting engineered equipment with people, remember Bhopal.
- When you perform a safety audit, remember Bhopal.
- When redesigning a system to make it "safer," remember Bhopal.
- When operators have concerns with a decision you are about to make, remember Bhopal.
- When making changes for the sake of improving personal safety, remember Bhopal.

Finding your identity

After twenty-seven years there are two prevailing theories that may explain how water contaminated the MIC storage tank. A better understanding of the events leading up to the incident supports the conclusion that it really does not matter exactly how the water got in [66]. However, the explanation you favor is governed by your process safety identity. If you believe that a single event can cause a process safety incident of extraordinary magnitude, then the cause was probably sabotage. But if you believe that significant process safety failures result from a complex series of interacting events that may include design defects, repeat failures, workaround procedures, and missed warning signals then maybe the cause was inadequate process isolation during routine maintenance. Perhaps even during a maintenance procedure required to contain the process in a factory like yours.

What can you do?

When you report for work tomorrow, remember Bhopal. And when you return to the comfort of your home, convince yourself it's because you did.

Photo credits

Figures 1, 6, 7, and 8: Dennis Hendershot
Figure 4: Paul Cochrane

The authors

Kenneth Bloch (processreliability@gmail.com) is a PHA/Loss Control Engineer who specializes in petrochemical industry incident investigation and failure analysis. He speaks regularly at AFPM, API, and AIChE process safety symposiums on experiences that help prevent process safety failures in the manufacturing industry. Mr. Bloch graduated with honors from Lamar University in Beaumont, TX in 1988.

Briana Jung (jungbriana@gmail.com) is a Senior Operations Engineer in the petrochemical industry. She is a certified PHA facilitator with over ten years of process plant troubleshooting and optimization experience. Ms. Jung graduated from the University of Minnesota with a B.S. in Chemical Engineering in 2001.

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