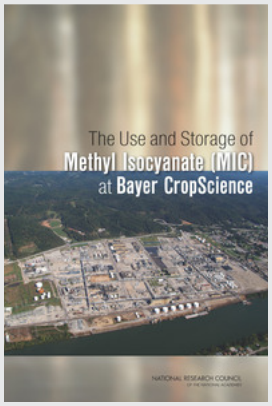


# The Use and Storage of Methyl Isocyanate (MIC) at Bayer CropScience (2012)

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# The Use and Storage of **Methyl Isocyanate (MIC)** at **Bayer CropScience**

Committee on Inherently Safer Chemical Processes:
The Use of Methyl Isocyanate (MIC) at Bayer CropScience

Board on Chemical Sciences and Technology

Division on Earth and Life Studies

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Any opinions, findings, conclusions, or recommendations expressed in this publication are those of the authors and do not necessarily reflect the views of the organizations or agencies that provided support for the project.

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The Committee on Inherently Safer Chemical Processes: The Use of Methyl Isocyanate (MIC) At Bayer CropScience would like to thank the many technical, chemical, and engineering experts who contributed to the integrity of this report through the submission of informative materials and attendance of committee meetings. The committee would like to acknowledge Amy McCormick and Lucy Sciallo-Tyler of the U.S. Chemical Safety and Hazard Investigation Board; Steven Smythe, Patrick Ragan, Connie Stewart, Cindi Lester, Walter Martin, and the staff of the Bayer CropScience facility in Institute, West Virginia; Scott Berger, Center for Chemical Process Safety; Randall Sawyer, Contra Costa County; George Famini and George Emmett, Department of Homeland Security Analysis Center; John Carberry, Carberry EnviroTech; Matthew Blackwood and Larry Zuspan, Kanawha Putman Emergency Planning Committee; Craig Mattheisson, U.S. Environmental Protection Agency; and Warren Woomer of Charleston, South Carolina. We would also like to thank West Virginia State University in Institute, West Virginia for hosting the committee members and National Research Council staff for an open public comment session. Our thanks to all those who participated in the comment periods and who contributed information in support of the committee's data-gathering efforts.

# Acknowledgment of Reviewers

This report has been reviewed in draft form by persons chosen for their diverse perspectives and technical expertise in accordance with procedures approved by the National Research Council's Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making the published report as sound as possible and to ensure that it meets institutional standards of objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following for their review of this report:

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Although the reviewers listed above provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations, nor did they see the final draft of the report before its release. The review of this report was overseen by **David Bonner**, Stematix, Inc. and **W. Carl Lineberger**, University of Colorado at Boulder. Appointed by the National Research Council, they were responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authors and the institution.

# Contents

# Summary

**The use of hazardous chemicals such as methyl isocyanate can be a significant concern to the residents of communities adjacent to chemical facilities, but is often an integral, necessary part of the chemical manufacturing process. In order to ensure that chemical manufacturing takes place in a manner that is safe for workers, members of the local community, and the environment, the philosophy of inherently safer processing can be used to identify opportunities to eliminate or reduce the hazards associated with chemical processing. However, the concepts of inherently safer process analysis have not yet been adopted in all chemical manufacturing plants. This report presents a possible framework to help plant managers choose between alternative processing options—considering factors such as environmental impact and product yield as well as safety—to develop a chemical manufacturing system.**

In 2008, an explosion at the Bayer CropScience chemical production plant in Institute, West Virginia, resulted in the deaths of two employees, a fire within the production unit, and extensive damage to nearby structures. The accident drew renewed attention to the fact that the Bayer facility manufactured and stored methyl isocyanate, or MIC—a volatile, highly toxic chemical (see Box 1) used in the production of carbamate pesticides and the agent responsible for thousands of deaths in Bhopal, India, in 1984. In the Institute incident, debris from the blast hit the shield surrounding a MIC storage tank, and although the container was not damaged, an investigation by the U.S. Chemical Safety and Hazard Investigation Board found that the debris could have struck a relief valve vent pipe and caused the release of MIC to the atmosphere. The Board's investigation also highlighted a number of weaknesses in the Bayer facility's emergency response systems. In light of these concerns, the Board requested the National Research Council convene a committee of independent experts to write a report that examines the use and storage of MIC at the Bayer facility, and to evaluate the analyses on alternative production methods for MIC and carbamate pesticides performed by Bayer and the previous owners of the facility.

Following the 2008 accident, Bayer halted MIC production while completing safety modifications, such as reducing onsite inventory of MIC and building underground storage facilities. Then, in 2011—with the National Research Council study already underway—the Environmental Protection Agency cancelled registration of aldicarb, a carbamate pesticide known commercially as TEMIK that is produced using MIC. Shortly afterwards, Bayer announced that production of certain carbamate pesticides was no longer economically viable for the company and would cease at the end of 2012. In the meantime, Bayer intended to finalize modifications to the MIC plant at Institute and restart manufacturing of aldicarb, carbaryl (another carbamate pesticide known commercially as SEVIN), and the intermediatematerials required for their production (including MIC) in mid 2012.

**BOX 1**
**What Is MIC?**

MIC (methyl isocyanate) is a volatile, colorless liquid that is extremely flammable, and potentially explosive when mixed with air. MIC reacts with water, giving off heat and producing methylamine and carbon dioxide. The liquid and vapor are toxic when inhaled, ingested, or exposed to the eyes or skin. The release of a cloud of MIC gas caused the Bhopal disaster in 1984, killing close to 3,800 people who lived near the Union Carbide India Limited plant in Bhopal, India.

In February 2011, amid concerns about the safety of restarting MIC processing at the Institute, West Virginia plant, a group of local residents filed suit against Bayer. On March 18, 2011, Bayer announced that it no longer intended to restart production of MIC. In a press release, the company stated that "uncertainty over delays has led the company to the conclusion that a restart of production can no longer be expected in time for the 2011 growing season" (see Box 2).

In response to these developments, the National Research Council report's authoring committee felt it necessary to change their approach to addressing the tasks they had been given. In particular, it became apparent that a full review of technologies for carbamate pesticide manufacture was less relevant, as the pesticides would no longer be produced at the Institute plant. In addition, it became clear that a full analysis of manufacturing and energy costs would require greater time and resources than were available for the study. Instead, the committee focused on a limited number of possible alternative production processes, presenting trade-offs with particular attention to safety considerations. Because deciding between alternative processes requires consideration and weighing of a number of different factors, including safety, one possible framework for evaluating these complex decisions is presented.

**BOX 2**
**MIC Storage and Use in the United States**

The Bayer CropScience facility in Institute, West Virginia was the only site in the U.S. that stored large quantities of MIC. The chemical is generated during chemical manufacturing at another chemical facility in Texas, but at this facility the chemical is used up in the next stages of the reaction moments after being produced. MIC is still produced at several other chemical facilities worldwide.

## MAKING THE USE OF HAZARDOUS CHEMICALS SAFER

Within the chemical engineering community, the use of process safety management—a methodology for controlling hazards across a facility or organization to reduce the frequency or consequences of an accident—is a standard practice required by the Occupational Safety and Health Administration. The goal of process safety is a systematic approach to safety that involves the proactive identification, evaluation, mitigation, or prevention of chemical releases that might occur as a result of failures in the process, procedures, or equipment. Process Safety Management ensures that facilities consider multiple options for achieving a safe process, and carefully weigh the possible outcomes of each decision, and the Process Safety Management Standard, promulgated by the Occupational Safety and Health Administration in 1992, lists 14 mandatory elements—ranging from employee training to process hazard analysis—to building a chemical processing system.

One approach for considering each of the options for safer processing is to consider a hierarchy of hazard control. The hierarchy contains four tiers: inherent, passive, active, and procedural, described below. Considering these possible hazard control methods in turn can help identify options for process design or modifications to improve process safety.

***Inherent:*** The inherent approach to hazard control is to minimize or eliminate the hazard, for example by replacing a flammable solvent with water to eliminate a fire hazard, rather than accepting the existence of hazards and designing safety systems to control them (see Box 3). There are four strategies to consider when making any chemical process inherently safer:

- *Substitute*—Use materials, chemistry, or processes that are less hazardous.
- *Minimize*—Use the smallest quantity of hazardous materials feasible for the process, reduce the size of equipment operating under hazardous conditions such as high temperature or pressure.
- *Moderate*—Reduce hazards by dilution, refrigeration, or process alternatives which operate at less hazardous conditions reduce the potential impact of an accident by siting hazardous facilities in locations far from people or other property.
- *Simplify*—Eliminate unnecessary complexity, and design "user-friendly" plants.

***Passive:*** Passive safety systems are those that control hazards with process or equipment design features without additional, active functioning of any device. For example, a containment dike around a hazardous material storage tank is a passive system to restrict a chemical spill to a limited area.

***Active:*** Active safety systems control hazards through systems that monitor and maintain specific conditions, or are triggered by a specific event. Examples of active systems include a sprinkler system that is triggered by smoke or heat.

***Procedural:*** Procedural safety systems control hazards through personnel education and management. Such systems include standard operating procedures, safety rules and procedures, operator training, emergency response procedures, and management systems.

Only the inherent tier of process safety management invites consideration of the elimination or minimization of a given hazard; the other tiers are focused on control of an existing hazard. Although a valuable tool, consideration of inherently safer processes is not currently a required component of the Occupational Safety and Health Administration's Process Safety Management Standard.

See Box 4 for the alternative production methods considered by Bayer. Each possible approach presents its own costs and benefits. For example, a non-MIC-based process for production of aldicarb (option 2) means that there is no risk of worker exposure to MIC. However, some non-MIC-based processes could result in lower purity in the aldicarb, which could negatively affect the characteristics of the final commercial product. Just-in-time production of gaseous MIC product (which falls under option 3) would eliminate the risk of catastrophic release of that material within the community, but it would require a significant re-design of the facility and would, in its current form, result in a final product with lower purity than the existing process.

In evaluating the alternatives, considering costs and benefits such as risk, cost, quality of final product, and community perception, no one method outperformed all others in every category. The process ultimately chosen by Bayer poses higher risks to the surrounding community due to the volume of MIC stored at the facility, but it also considerably decreases the amount of wastewater generated by the process, thereby reducing health risks to the community from damage to local surface water quality (see Box 5).

**BOX 3**
**Emergency Preparedness and Inherently Safer Processes**

Inherently safer processes can help reduce demands on emergency services. Specifically, applying the inherently safer principle of substitution reduces vulnerability if a chemical release occurred; minimization reduces the quantity of chemical available for release; and moderation decreases the temperature and pressure of release.

However, the implementation of inherently safer processes can sometimes transfer risk to new sites. For example, reducing the storage of hazardous chemicals at a chemical facility may make it necessary to increase the number of shipments of chemicals to the site to meet process requirements, with the potential to increase the risk of a chemical release along the transportation route. While the emergency services in a community that houses a chemical processing facility would likely be prepared for the possibility of a chemical release, sites along the transportation route would likely have fewer resources to support an emergency response.

## IMPLEMENTING INHERENTLY SAFER PROCESS ASSESSMENTS

Inherently safer process assessments can be valuable components of process safety management that can help a facility consider the full range of options in process design. However, inherently safer process assessments will not always result in a clear, well-defined, and feasible path forward. Although one process alternative may be inherently safer with respect to one hazard—toxicity of by-products, for example—the process may present other hazards, such as an increased risk of fire or more severe environmental impacts. Choosing between options for process design involves considering a series of tradeoffs and developing appropriate combinations of inherent, passive, active, and procedural safety systems to manage all hazards. Some hazards will be best managed using inherent methods, but others will inevitably remain and be effectively managed with other process safety management systems.

Although the philosophy of inherently safer processes applies at all stages of processing, the available options and the feasibility of implementing them can change over the course of a technology's life cycle. For this reason, it is easiest to implement inherently safer process design before process technologies have been chosen, facilities built, or customers have made commitments based on products with particular characteristics. As a product moves through its life cycle, these and other factors may limit options, make changes more difficult, or involve more people and organizations in the change.

In order to build an inherently safer system, each stage of the process life cycle should be considered:

**Selection of basic technology:** Identify inherently safer options for chemical synthesis.

**Implementation of selected technology:** How will the chosen process chemistry be implemented? Can hazardous operating conditions be minimized? Can impurities and by-products be avoided to eliminate purification steps?

**Plant design:** Considerations include plant proximity to the surrounding population, in-plant occupied areas, sensitive environmental areas, and the general layout of equipment on the plant site.

**Detailed equipment design:** Minimize the inventory of hazardous material in specific pieces of process equipment. Consider the impact of equipment layout on the length and size of piping containing hazardous materials. Consider human factors in the design of equipment to minimize the potential for incorrect operation and human error.

**Operation:** Use inherently safer processing principles in ongoing process safety management activities such as management of change, incident investigation, pre-startup safety reviews, operating procedures, and training to identify new opportunities for inherently safer processes.

## Challenges in Measuring Inherent Safety

There are tools to measure the degree of inherent safety of a given process or processing alternative, but there is no current consensus on the most reliable metrics. Some metrics consider the likelihood of different hazards such as fire, explosion, or toxicity using penalty factors assigned based on the severity of the hazard to calculate an overall hazard index. However, the origin and justification of this relative scale is unclear, and these indexes are not designed to be adjusted readily in order to reflect the variation in preferences among attributes or willingness to tolerate risk that different constituencies may exhibit. For example, a company owner may be willing to tolerate a small risk of a spill that could have health effects in the community if the alternative involved a much higher risk of a fire that would seriously damage the facility, whereas members of the community may not accept such a tradeoff, and employees of the firm (who place some value on keeping the facility intact in order to retain their jobs) might fall somewhere in between the owner and the community.

## Choosing Between Alternative Processes: A Framework for Decision Making

Choosing between multiple process alternatives with conflicting trade-offs is a concern faced by any chemical processing facility. When no option is clearly favorable to the others, the question arises as to what decision-making framework a company could use to consider the trade-offs of process choices from an inherently safer perspective.

## Employing Decision in Inherent Safety Assessments

As currently performed, a potential concern with using inherently safer process analysis is that it may become focused too narrowly, and as a consequence, may overlook certain outcomes. Even when multiple outcomes are recognized, they may be inappropriately weighted. For example, existing indexes for assessing inherently safer processes cannot capture the preferences of all decision makers, and the many trade-offs, uncertainties, and risk tolerances are hidden from view as implicit assumptions rather than explicit chosen parameters. One possible method for incorporating these preferences is to draw upon multi-criteria decision analyses, which use mathematical constructs to assess and evaluate stakeholder input to play a role in developing weighted comparisons between options.

One example of decision theory analysis is multi-attribute utility (MAU) theory. This is not a new idea to the chemical community—in 1995, the Center for Chemical Process Safety (CCPS) published a book that suggested this and other decision aids could be used to support process safety assessments. However, though employed regularly in other sectors, these decision aids have yet to take hold in the chemical process industry. Key obstacles to their use include lack of familiarity with the tools among chemical process industry decision makers and the fear that the methods are either too simplistic or too costly to use. Nonetheless, the report's authoring committee found that decision analysis techniques could prove valuable for strengthening the integration of safety concerns into decision-making in the chemical process industry. The use of these techniques could benefit not only the communities at risk from safety breaches, but also the

**BOX 4**
**Alternative Methods for Producing MIC and Carbamate Pesticides**

The report's authoring committee reviewed Bayer's assessment of alternative processes for the manufacture of MIC and carbamate pesticides and considered the alternatives and trade-offs. The alternative processes Bayer considered fall into the following broad categories:

1. Continue with the current process
2. Adopt an alternative process that does not involve MIC
3. Use an alternative process for MIC production that would consume MIC immediately, and therefore onsite storage of MIC would not be required
4. Reduce the volume of stored MIC, and the risks associated with transporting MIC from site to site, by re-arranging process equipment

**BOX 5**
**Inherently Safer Process Assessments at Bayer CropScience**

Because the view of what constitutes an inherently safer process varies among professionals, the chemical industry lacks a common understanding and set of practice protocols for identifying safer processes. In its presentations to the report's authoring committee, Bayer stated that inherently safer processing is an integral part of its process safety management strategy. However, the committee found that inherent safety considerations were not explicitly stated in Bayer's process safety management records. Bayer performed hazard and safety assessments and made business decisions which resulted in MIC inventory reduction, elimination of aboveground MIC storage, and adoption of various passive, active, and procedural safety measures. However, these assessments did not explicitly incorporate the principles of minimization, substitution, moderation, and simplification that are the basis of inherently safer processes.

Without an emphasis on incorporating inherently safer processes into process safety management, it is unlikely that these concepts would become part of corporate memory, and therefore they could be forgotten or ignored over time. It would be beneficial for Bayer to formally incorporate inherently safer process assessments into the company's process safety management system and training, and to record such assessments as part of its audit review processes.

industries themselves, as decision-making techniques can help with the identification of profitable safety solutions that otherwise could be overlooked.

A formal plan from the Chemical Safety Board or other appropriate entity for incorporating decision theory frameworks into inherently safer process assessments could help chemical facilities adopt inherently safer processes. A working group including experts in chemical engineering, inherently safer process design, decision sciences, and negotiation could identify obstacles and identify options for tailoring methods from the decision sciences to process safety assessments.

## POST-INCIDENT PROCESS ASSESSMENT

Incident investigation is one of the mandatory elements of the Occupational Safety and Health Administration's process safety management standard. Comprehensive protocols and advice are available for conducting investigations of chemical process incidents. These guidelines emphasize the need for a process safety management system to be simultaneously retrospective and prospective, with incident investigation providing the vital bridge between the lessons of the past and safer designs and operation in the future.

Incorporating the principles of inherently safer processes into incident investigations can help prevent future potential incidents that may have similar causes. Over time, findings from inherently safer process assessments performed in the wake of accidents may identify trends in process design that could be used to improve future systems. Findings from an investigation may also be of use when refining the models that support existing inherently safer process assessments. A post-accident inherently safer process assessment may also help identify unanticipated hazards within a process, which could help inform the redesign or rebuild of the facility.

**BOX 6**
**Summary of Findings, Conclusions, and a Recommendation**

**Process Safety Management and Inherently Safer Process Assessments at Bayer CropScience**

Although claimed to be an integral PSM component, inherent safety considerations are incorporated into Bayer's PSM efforts in an implicit manner that is dependent on the knowledge base of the individual facilitating the particular activity (e.g., process hazard analysis or PHA).

Bayer and its predecessors did seek to reduce risks associated with MIC, and those efforts did incorporate some aspects of risk reduction associated with ISP principles. However, Bayer did not make statements or provide documentation indicating that it had engaged in a systematic effort to incorporate ISP into the decision-making process.

Bayer and its predecessors evaluated trade-offs among the alternatives, but while this analysis provides a very useful starting point for a comparison of technologies, it excludes factors that may be important in the decision, from the perspective of both the company and the community.

Bayer CropScience did perform Process Safety assessments, however, Bayer and the legacy companies did not perform systematic and complete ISP assessments on the processes for manufacturing MIC or the carbamate pesticides at the Institute site. Bayer and the previous owners performed hazard and safety assessments and made business decisions that resulted in MIC inventory reduction, elimination of aboveground MIC storage, and adoption of various passive, active, and procedural safety measures. However, these assessments did not incorporate in an explicit and structured manner, the principles of minimization, substitution, moderation, and simplification. The legacy owners identified possible alternative methods that could have resulted in a reduction in MIC production and inventory, but determined that limitations of technology, product purity, cost, and other issues prohibited their implementation.

### Inherently Safer Process Assessments and Decision Making

Inherently safer process assessments can be a valuable component of process safety management. However, the view of what constitutes an inherently safer process varies among professionals, so the chemical industry lacks a common understanding and set of practice protocols for identifying safer processes.

Consistent application of ISP strategies by a company has the potential to decrease the required scope of organizational emergency preparedness programs by reducing the size of the vulnerable zones around its facilities. Such reductions are achieved by reducing the toxicity of the chemicals being used or produced, the quantity of the chemicals being stored, and the conditions under which they are being stored.

As currently performed, a potential concern with using ISP analysis is that it may become focused too narrowly, and as a consequence, may overlook certain outcomes. Even when multiple outcomes are recognized, they may be inappropriately weighted.

The committee recommends that the Chemical Safety Board or other appropriate entity convene a working group to chart a plan for incorporating decision theory frameworks into ISP assessments. The working group should include experts in chemical engineering, ISP design, decision sciences, negotiations, and other relevant disciplines. The working group should identify obstacles to employing methods from the decision sciences in process safety assessments. It should identify options for tailoring these methods to the chemical process industry and incentives that would encourage their use.

### The Use of Inherently Safer Process Assessments in Post-Incident Investigations

The principles of ISP assessment can be used to good effect in conducting an incident investigation when the objective is the prevention of potential incidents having similar fundamental, underlying (root) causes.

# Technical Summary

In 2008, an explosion and fire at a chemical production plant owned by Bayer CropScience (Bayer) in Institute, West Virginia resulted in the deaths of two employees and renewed attention to the onsite manufacture and storage of methyl isocyanate (MIC). MIC is a highly toxic inhalation hazard, and a large release of the chemical in Bhopal, India in 1984 resulted in the immediate deaths of over 3,000 people. In Institute, MIC was manufactured and stored onsite beginning in 1966 for use in the production of carbamate pesticides. These pesticides, including aldicarb (Temik) and carbaryl (Sevin), have been or are used for both agricultural and residential control of pest insects.

Although no part of the MIC production or storage processes at the Institute facility played a role in the 2008 incident, the U.S. Chemical Safety and Hazard Investigation Board (CSB) found during its investigation that debris from the explosion hit the shield surrounding an aboveground storage container of MIC. The Board determined that, had the debris followed a different path, a relief valve vent pipe on the tank could have been damaged, which could have resulted in a release of MIC to the atmosphere. The investigation also highlighted a number of weaknesses in the Bayer facility's emergency response systems and restart procedures within the affected production unit. In light of these concerns, Congress directed the CSB to consult with the National Academy of Sciences for a study to examine the use and storage of MIC at the Bayer CropScience facility. The statement of task was finalized after a public comment period held by the CSB, and it can be found in Appendix A.

In brief, the task was divided into three parts: (1) review current industry practice for the use and storage of MIC, including consideration of the key lessons of the Bhopal incident; (2) review current technologies for producing carbamate pesticides; and (3) examine the use and storage of MIC at the Bayer CropScience facility in Institute, West Virginia. The third part of the task was the most complex, containing the following subparts:

3.1. Identify possible approaches for eliminating or reducing the use of MIC in the Bayer carbamate pesticide manufacturing processes;

3.2. Estimate the projected costs of alternative approaches identified above;

3.3. Evaluate the projected benefits of alternative approaches identified above;

3.4. Compare this analysis to the inherently safer process assessments conducted by Bayer and previous owners of the Institute site; and

3.5. Comment, if possible, on whether and how inherently safer process (ISP) assessments can be utilized during post-incident investigations.

## STUDY CONTEXT

Data gathering and report preparation were performed during a period of legal activity and community concern related to the facility and its production of MIC. When the study began in September 2010, the CSB investigation was not yet complete, and Bayer had begun efforts to reduce onsite inventory of MIC, and a new underground storage facility was being built for MIC in light of that reduction. In August 2010, Bayer announced that, because of the U.S. Environmental Protection Agency's decision to cancel registration of aldicarb, the company would cease production of aldicarb by late 2014. This decision was followed up in January 2011 by a decision to shut down production of MIC by 2012 and cease production of aldicarb and two other pesticides, methomyl and carbaryl. At the time, Bayer intended to restart production of MIC in February 2011, after the plant modifications were complete, to continue production until the 2012 end date. However, also in February, a group of local residents filed suit against the company citing concerns about the restart process and MIC storage and manufacture onsite. This resulted in a court order to halt the restart process pending an evidentiary hearing, although preparations in anticipation of restart were allowed to continue. The court process continued through the month of February, and on March 18, stating that, "uncertainty over delays has led the company to the conclusion that a restart of production can no longer be expected in time for the 2011 growing season",[1] Bayer announced that it no longer intended to restart production of MIC or aldicarb.

In addressing the statement of task, the committee began by considering how to address Task 3 and determining the data-gathering required. In addressing Task 3, the committee quickly determined that a detailed, full analysis of all alter-

[1] Bayer. 2011. Bayer CropScience Announces Decision Not to Resume MIC Production. Bayer Press Release: March 18, 2001 [online]. Available: www.bayercropscience.com/bcsweb/crop protection.nsf/id/84634C20BB57C2D3C125785700503244.

native chemistries available for the production of aldicarb and carbaryl, including their manufacturing and energy costs, would require significantly greater investments than were available for the study. The investment required to fully analyze any one alternative is typically a multi-million dollar expenditure, and further, costs are highly dependent on the facility design, and accurate financial analysis requires specialized tools and information that is often unavailable to the public. In addition, in light of the de-registration of aldicarb and subsequent cessation of MIC, aldicarb, and carbaryl production at the Institute plant, the value of a full literature review for the chemical manufacturing community was reduced as the information available from such a review would have no longer have a potential use for the facility.

With these limitations in mind, the committee chose to focus on a select set of possible alternative production processes for aldicarb and carbaryl. These chosen alternatives had been evaluated by Bayer and the facility's legacy owners, and as a result, information about the chemistry and possible manufacturing processes were available for each. This approach reduced further the value that a literature review, which would be limited in its scope to information about manufacturing processes available in the open literature. As a result of these various factors, the committee chose to focus its efforts primarily on Task 3 and addressed Task 2 only in the context of the chosen alternative production processes.

In this report, the selected alternatives and associated trade-offs are presented, with particular attention to safety considerations. In addition, the context in which these trade-offs must be evaluated (financial, regulatory, etc.) is discussed. Finally, because deciding between alternative processes requires consideration and weighing of a number of different factors, including safety, one possible framework for evaluating these complex decisions is presented. Within this summary, the committee's findings, conclusions, and recommendation have been highlighted in bold text. They have also been aggregated in Box 6 at the end of the summary chapter.

## INHERENTLY SAFER PROCESS ASSESSMENTS AND PROCESS SAFETY MANAGEMENT

Within the chemical engineering community, the use of process safety management (PSM) systems is considered standard practice. PSM is a methodology composed of a number of different elements that, when evaluated as a whole, support organizational safety culture and practices. Although the "elements" or components of any given PSM system may vary somewhat between countries and organizations, the fundamental structures remain similar. Within the United States, Occupational Safety and Health Administration (OSHA) administers the Process Safety Management Standard, which has fourteen mandatory elements relating to, among other things, training, documentation, incident investigation, compliance audits, and process hazard analysis. Although companies are required to address those 14 elements, they are not limited to them. PSM is most effective at supporting a safe environment when it is contained within an overall organizational structure that encourages a culture of safety among its employees.

Within the element of process hazard analysis, employers are required to, "identify, evaluate, and control the hazards involved in the process" (29 CFR § 1910.119). To accomplish control of hazards, companies can consider a hierarchy of hazard control with the tiers of inherent, passive, active, and procedural controls. Only the inherent tier invites consideration of elimination or minimization of a given hazard; all other tiers are focused on control of an existing hazard. It is important to remember, however, that making a system inherently safer through, for example, substitution may result in a shift from one hazard or risk to another, and the full impact of any change on the overall hazard analysis should be considered as part of the decision-making process. The context in which an inherently safer process assessment is performed is important as this can affect the way that a given risk or hazard is weighted against another in the analysis. Although a valuable tool, consideration of ISPs is not a required component of OSHA's PSM Standard.

## INHERENTLY SAFER PROCESS ASSESSMENTS AT BAYER CROPSCIENCE

To address the task, a great deal of information was received from Bayer regarding the use and storage of MIC at the facility under their management and the management of the legacy companies, particularly Union Carbide and Rhône Poulenc. This information was examined in order to assess whether ISP assessment or its principles of substitute, minimize, moderate, and simplify were mentioned or evaluated within the analysis of different processes and synthetic routes. In addition, the role that ISP or its principles play in the PSM systems of Bayer and the legacy companies was evaluated. Although materials relating to the alternatives and their evaluation were provided to the committee for review in good faith, the documentation was rather disjointed and discontinuous, with documents ranging from undated handwritten notes without attribution to in-depth type-written analyses of findings. The assessments presented here are drawn from these documents and from the academic and patent literature, and information gaps within the historic documents could result in gaps within these assessments.

In the course of the study, Bayer presented the company's approach to PSM, stating that ISP is an integral part of its PSM analysis. However, **although claimed to be an integral PSM component, inherent safety considerations are incorporated into Bayer's PSM efforts in an implicit manner that is dependent on the knowledge base of the individual facilitating the particular activity (e.g., process hazard analysis or PHA)**. Although an implicit system of ISP incorporation does not mean an absence of a commitment to inherent safety, it does mean that the commitment is not visible to the extent that might be considered desirable.

A risk of this implicit approach is that the ISP components and principles do not become part of corporate memory, and this can lead to missed opportunities for incorporation of ISPs and design into the production facility.

Over the course of the study, the committee reviewed documentation describing the history of the plant and alternative assessments performed by Bayer and the legacy owners of the facility. **The committee finds Bayer and its predecessors did seek to reduce risks associated with MIC, and those efforts did incorporate some aspects of risk reduction associated with ISP principles. However, Bayer did not make statements or provide documentation indicating that it had engaged in a systematic effort to incorporate ISP into the decision-making process.**

Several decisions regarding process safety were made over the years by the owners of the Institute plant. Most of these decisions involved adding additional safety protections to existing processes, rather than changes to the underlying process. **Bayer and its predecessors evaluated trade-offs among the alternatives, but while analysis provides a very useful starting point for a comparison of technologies, it excludes factors that may be important in the decision, from the perspective of both the company and the community.**

**The committee concludes that Bayer CropScience did perform process safety assessments; however, Bayer and the legacy companies did not perform systematic and complete ISP assessments on the process for manufacturing MIC or the processes used to manufacture pesticides at the Institute site. Bayer and the previous owners performed hazard and safety assessments and made business decisions that resulted in MIC inventory reduction, elimination of aboveground MIC storage, and adoption of various passive, active, and procedural safety measures. However, these assessments did not incorporate in an explicit and structured manner, the principles of minimization, substitution, moderation, and simplification. The legacy owners identified possible alternative methods that could have resulted in a reduction in MIC production and inventory, but determined that limitations of technology, product purity, cost, and other issues prohibited their implementation.**

## INHERENTLY SAFER PROCESS ASSESSMENTS

Within the statement of task, the NRC was specifically asked to compare its analysis of alternative approaches for eliminating or reducing MIC "to the inherently safer process assessments conducted by Bayer and previous owners of the Institute site." This required consideration of the industry's current understanding of ISPs and assessments as well as the approaches used by Bayer and the legacy companies. Drawing upon the expertise within the committee membership as well as that of the publications from the Center for Chemical Process Safety, the Department of Homeland Security, and other material available in the literature, the following findings, conclusions, and recommendation were developed.

**Inherently safer process assessments can be a valuable component of process safety management. However, the view of what constitutes an ISP varies among professionals, so the chemical industry lacks a common understanding and set of practice protocols for identifying safer processes.** Experts in ISP agree on the components that define ISP, but that understanding has not yet become common among the rest of the professional community. Although the general concept of ISP has made it into the community, the specifics are not well known outside of the expert group. One particular barrier for use of ISP assessments that has been noted by expert chemical engineers is a lack of effective methods for analyzing risk-based trade-offs. ISP assessments can be challenging because of the interconnected nature of chemical manufacturing processes, e.g., care must, taken that a risk reduction in one process element does not result in an unexpected risk transfer to a different element. One possible approach for addressing this issue is the use of multi-attribute or -criteria decision analysis, which is described briefly in the next section.

Note that ISP analysis has the potential to reduce the impact of incidents by addressing some common concerns in emergency preparedness and response. In many cases, for example, emergency response units will spend the majority of their training on appropriate response to the most common incident rather than the most catastrophic incident. This is not unexpected in light of funding constraints and the difficulties posed in coordinating the multitier, multiorganization response required for training for large-scale incidents or releases. However, it is just these large-scale incidents that pose the greatest risk to emergency responders. **Consistent application of ISP strategies by a company has the potential to decrease the required scope of organizational emergency preparedness programs by reducing the size of the vulnerable zones around its facilities. Such reductions are achieved by reducing the toxicity of the chemicals being used or produced, the quantity of the chemicals being stored, and the conditions under which they are being stored.**

## PRODUCTION OF MIC AND CARBAMATE PESTICIDES: ALTERNATIVES ASSESSMENT

Four possible categories of alternatives for the manufacture of carbamate pesticides were considered: (1) continuing with the existing process, (2) adopting an alternative chemical process not involving MIC, (3) using an alternative process for MIC production that would consume MIC immediately and thus not require storage, and (4) reducing the volume of stored MIC and the risks of transporting MIC from one facility within the site to another by rearranging process equipment. Note that the task was not to determine the best course of action but to consider and compare these alternatives and the trade-offs posed by each option with respect to costs and benefits to the company and community.

Each possible approach presents its own costs and benefits. For example, a non-MIC-based process for production of aldicarb means that there is no risk of worker exposure to MIC. However, that same non-MIC-based process could result in lower purity of the final material, which could result in greater risk of worker exposure to hazardous dust. Just-in-time production of MIC through a gaseous product would eliminate the risk of catastrophic release of that material within the community, but it would require a significant redesign of the facility and would, in its current form, result in a final product with lower purity than the existing process. In evaluating all of the alternatives, it became clear that no one method outperformed all others in every category of cost and benefit.

The above paragraph highlights some of the technical costs and benefits, but when evaluating alternative approaches, nontechnical considerations should also be considered. One example of this is the perception of the choice by the surrounding community. The facility in Institute, West Virginia, as is true for many chemical manufacturing facilities, exists in close proximity to the surrounding community. In such situations, it is important to recognize the influence that local communities can have on corporate decision making, whether welcomed by the company or not. For example, the suit filed by some members of the local community against Bayer played a role in the company's decision to cease MIC and aldicarb production before the anticipated 2012 stop date. This is an example of how the perception of risk posed by the facility by the members of a surrounding community can affect whether a material or process is readily accepted, and the nature of the relationship between the community and the company may influence that risk perception.

At a basic level, a neutral or positive relationship between a facility and its community allows for open discussion about risks and responses. It allows for a sense of trust that the experts on site are operating with care and consideration. A negative relationship can influence the community perception of risk, lead to distrust, and create an environment of defensiveness and lack of engagement on important issues relevant to everyone involved.

The process ultimately chosen for the Institute site by the facility's owners, although posing higher risks to the surrounding community due to the volume of MIC stored, decreases the amount of wastewater produced as compared with other methods and thus decreases potential damage to local surface waters.

Deciding between multiple process alternatives with conflicting trade-offs is a concern faced by any company. It is clear that the development of a method that companies could use to weigh all of the trade-offs involved when considering process choice from an inherently safer design perspective would be a useful tool for evaluating these concerns. **A potential concern with using ISP analysis is that it may become focused too narrowly, and as a consequence, may overlook certain outcomes.** Even when multiple outcomes are recognized, they may be inappropriately weighted. Both of these problems can result in a choice that does not reflect the optimal conclusion or the decision makers' preferences.

To assist the chemistry community in addressing the last of these findings, which as mentioned above has been noted as a barrier to performing inherently safer process assessments, the committee highlighted a method of decision analysis, multi-attribute utility (MAU) theory. This method was considered as an option for addressing appropriate weightings of multiple outcomes of an ISP analysis or assessment and to assist with placement of the findings of that analysis within the context of a full analysis of all costs and benefits associated with a process. MAU theory provides one possible framework for incorporating input and relative weightings from multiple perspectives and stakeholders, and as such, could be an aid for decision making. As a result, **the committee recommends that the U.S. Chemical Safety Board and Hazard Investigation Board or other appropriate entity convene a working group to chart a plan for incorporating decision theory frameworks into ISP assessments. The working group should include experts in chemical engineering, ISP design, decision sciences, negotiations, and other relevant disciplines. The working group should identify obstacles to employing methods from the decision sciences in process safety assessments. It should identify options for tailoring these methods to the chemical process industry and incentives that would encourage their use.**

## INCIDENT INVESTIGATION AND EMERGENCY RESPONSE

In examining the potential utility of ISP assessments to incident investigation, it becomes clear that **the principles of ISP assessment can be used to good effect in conducting an incident investigation when the objective is the prevention of potential incidents having similar fundamental, underlying (root) causes.** It is possible that over time, findings from ISP assessments performed in the wake of an accident could identify trends in process design that could be used to improve future systems. Findings from an investigation may be of use when refining the models that support existing ISP assessments. A post-incident ISP assessment may help identify unanticipated hazards within a given process that could inform the rebuild or redesign of the facility.

# 1

# Introduction

In August 2008, an explosion of a pressurized vessel, known as a residue treater, at the Bayer CropScience (Bayer) facility in Institute, West Virginia resulted in the deaths of two plant employees, a fire within the production unit, and extensive damage to nearby structures.[1] Of particular relevance to this report, one of the structures hit by debris from the explosion was an aboveground 6,700-gallon storage tank of methyl isocyanate (MIC) protected by a steel "blast mat". The tank was located approximately 70 feet from the site of the explosion and, at the time, contained approximately 6.8 tons of liquid MIC, a volatile, toxic chemical. The proximity of this tank to the explosion caused concern, given that a release of over 40 tons of MIC from a chemical facility in Bhopal, India in 1984 resulted in the immediate death of more than 3,000 people in the vicinity and additional mortality and morbidity of 100,000-200,000 individuals. (See Chapter 2 for more information.)

During an investigation of the 2008 explosion in West Virginia by the U.S. Chemical Safety and Hazard Investigation Board (CSB), the proximity of the tank to the explosion and the protections surrounding it were given careful consideration. Although the MIC tank at the Bayer facility was protected from the heat and debris of the blast by the steel protective shield, the CSB determined from its investigation that "had the residue treater traveled unimpeded in the direction of the day tank and struck the shield structure just above the top of the MIC

[1] A full discussion of the accident and its subsequent investigation by the United States Chemical Safety and Hazard Investigation Board (CSB) can be found in the Board's January 2011 report number 2008-08-I-WV, "Investigation Report: Pesticide Chemical Runaway Reaction Pressure Vessel Explosion (Two Killed, Eight Injured)".

day tank, the shield structure might have impacted the relief valve vent pipe. A puncture or tear in the vent pipe or MIC day tank head would have released MIC vapor into the atmosphere above the day tank." (CSB, 2011)

In 2009, while the investigation was still underway, John Bresland, Chairman of the CSB, stated in testimony before Congress,

> Although the MIC tank and the blast mat escaped serious damage on August 28, there is reason for concern. This was potentially a serious near miss, the results of which might have been catastrophic for workers, responders, and the public. . . . There are hypothetical scenarios where the MIC storage tank could have been compromised during the August 28 explosion, either by powerful projectiles or by a collision with the residue treater vessel, had it traveled in that direction. Any release of MIC into the atmosphere is cause for great concern." (Bresland, 2009)

As a result of this information and additional testimony provided at the hearing, the Chairman of the House Committee on Energy and Commerce, requested that the CSB (Waxman et al., 2009):

1. "Conduct an investigation to determine options for Bayer to reduce or eliminate the use or storage of MIC at its West Virginia facility by switching to alternative chemicals or processes and the estimated cost of these alternatives;
2. Determine whether Bayer has adequately examined the feasibility of switching to alternative chemicals or processes;
3. Provide in its final report specific recommendations for Bayer and its state and federal regulators on how to reduce the dangers posed by onsite storage of MIC; and
4. Brief our staff on the Board's findings and recommendations at the end of its investigation."

As a result of this request, the 111th Congress provided funds to the CSB "for a study by the National Academy of Sciences [NAS] to examine the use and storage of methyl isocyanate including the feasibility of implementing alternative chemicals or processes and an examination of the cost of alternatives at the Bayer CropScience facility in Institute, West Virginia" (H.R. Rep.No.111-316, 111st Cong., 1st Sess. [2009]). This report presents the findings and conclusions of the NRC study committee convened to perform this examination.

## STATEMENT OF TASK

On August 26, 2009, Bayer announced in a press release (Bayer CropScience, 2009) that it would "reduce methyl isocyanate (MIC) storage by 80 percent" at the facility and eliminate aboveground storage of MIC. The company stated that it would cease production of MIC-based products within a year, and that it would "continue to evaluate the feasibility of further measures, which may also include the use of alternative process technologies." MIC production and primary storage occurred at the East Carbamoylation Center along with the manufacture of carbaryl and aldicarb. The aboveground MIC storage and production of methomyl, thiodicarb, carbosulfan, and carbofuran were in the West Carbamoylation Center. Everyday, MIC was transferred from the primary storage facility to the aboveground day-use storage tank. By ceasing production of methomyl and carbofuran, Bayer was able to remove the need for the aboveground tank. This change allowed for reduction in storage capacity. In addition, a new MIC underground storage facility would be built in the East Carbamoylation Center to accommodate the change in production quantity.

In April 2010, in response to the mandate from Congress and acknowledging the 80 percent reduction plan, the CSB issued a draft statement of task for the National Academies in the *Federal Register* and solicited public comment on the language. The National Academies began its work in early September 2010 under the finalized statement of task, which can be read in Box 1.1 and Appendix A. This report contains the consensus findings, conclusions, and recommendation developed in response to this task.

## DEVELOPMENTS IN WEST VIRGINIA

A number of significant changes occurred at the Bayer facility during the course of the study. A timeline of the events can be found in Figure 1.1, and additional details are provided below.

On August 16, 2010, prior to the National Research Council (NRC) beginning its work, Bayer announced that, as part of an agreement with the U.S. Environmental Protection Agency, it would voluntarily cancel the registration of aldicarb (Temik) for use in or on the remaining crops for which the pesticide was being used, including potatoes, citrus, cotton, and peanuts. As part of the phase-out agreement, farmers would be allowed to continue to use aldicarb on potatoes and citrus until the end of 2011.

For all other crops, production would end by December 2014, distribution and sale of aldicarb would end by December 2016, and growers' stocks should be exhausted by August 2018. Citing this agreement and global restructuring of its parent company, on January 11, 2011 Bayer announced that "the production of certain carbamates is no longer economically viable for Bayer CropScience." (Bayer CropScience, 2011b) The company's intention was to finalize the modifications to the MIC plant at Institute; restart manufacturing of aldicarb, carbaryl, and the intermediate materials required for their production, including MIC; and continue manufacturing those materials until mid-2012.

On January 20, 2011, the CSB released its report on the 2008 accident. Key findings from the investigation identified weaknesses in the following areas: the process hazard analysis, the pre-startup safety review, the startup procedures for

**BOX 1.1**
**Statement of Task for the Committee on the Use and Storage of Methyl Isocyanate (MIC) at Bayer CropScience**

The National Research Council will produce a detailed written report, conclusions, and recommendations where appropriate on the following subjects:

**1.** Review the current industry practice for the use and storage of methyl isocyanate (MIC) in manufacturing processes, including a summary of key lessons and conclusions arising from the 1984 Bhopal accident and resulting changes adopted by industrial users of MIC.

**2.** Review current and emerging technologies for producing carbamate pesticides, including carbaryl, aldicarb, and related compounds. The review should include:

2.1. Synthetic methods and patent literature

2.2. Manufacturing approaches used worldwide for these materials

2.3. Manufacturing costs for different synthetic routes

2.4. Environmental and energy costs and trade-offs for alternative approaches

2.5. Any specific fixed-facility accident or transportation risks associated with alternative approaches

2.6. Regulatory outlook for the pesticides including their expected lifetime on the market

**3.** Examine the use and storage of MIC at the Bayer CropScience facility in Institute, West Virginia:

3.1. Identify possible approaches for eliminating or reducing the use of MIC in the Bayer carbamate pesticide manufacturing processes, through, for example, substitution of less hazardous intermediates, intensifying existing manufacturing processes, or consuming MIC simultaneously with its production.

3.2. Estimate the projected costs of alternative approaches identified above.

3.3. Evaluate the projected benefits of alternative approaches identified above, including any cost savings, reduced compliance costs, liability reductions, reduced emergency preparedness costs, and reduced likelihood or severity of a worst-case MIC release or other release affecting the surrounding community.

3.4. Compare this analysis to the inherently safer process assessments conducted by Bayer and previous owners of the Institute site.

3.5. Comment, if possible, on whether and how inherently safer process assessments can be utilized during post-incident investigations.

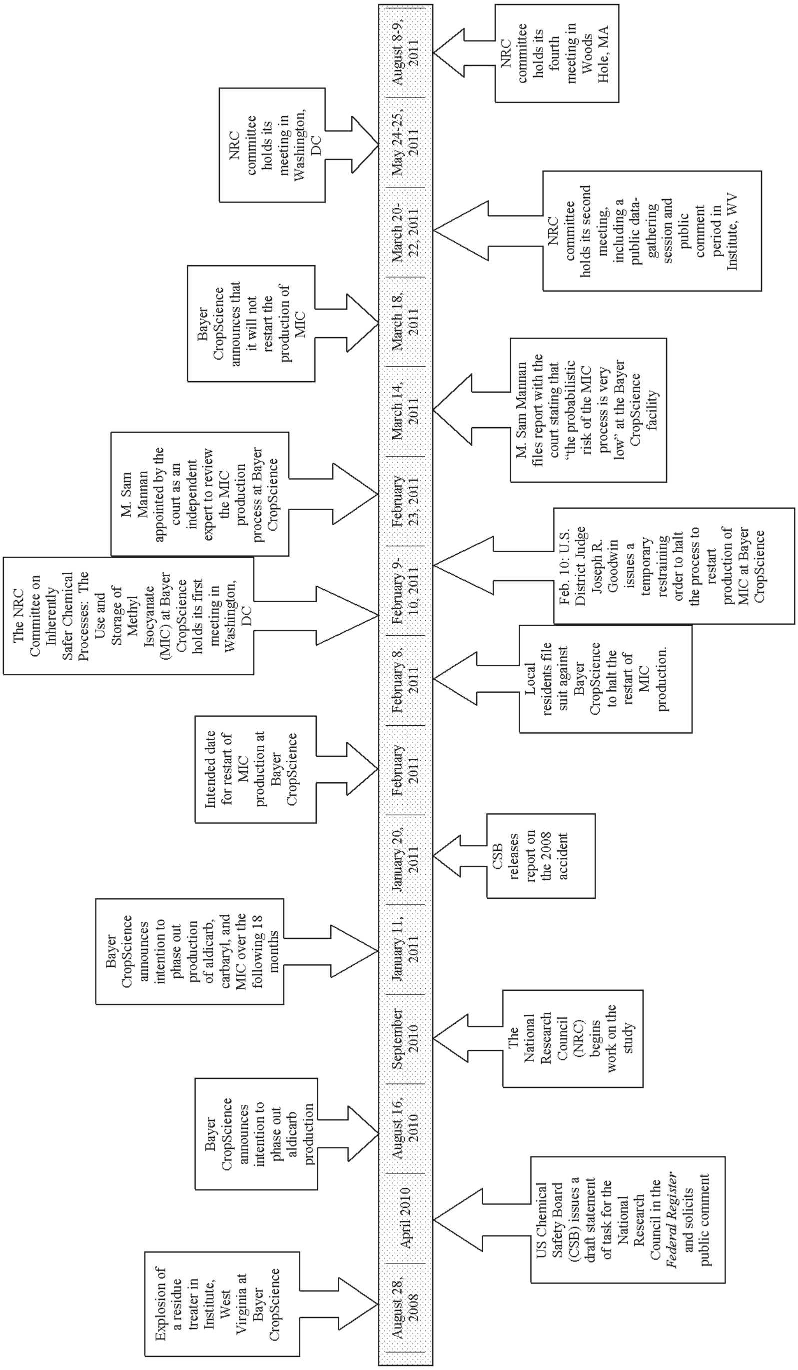


FIGURE 1.1 Timeline of events.
SOURCE: NRC Staff/Committee Generated

the methomyl unit, the MIC day tank shield structure design, emergency planning and response, environmental monitoring, and regulatory oversight of the facility (CSB, 2011). The report provided an overview of the alternative MIC technologies considered by Bayer and the plant's previous owners. The CSB also noted in the report that the board was considering the impact of Bayer's announcement to cease production of MIC on the NAS study. In the end, no changes were made to the NAS study or its statement of task as a result of the announcement.

Bayer intended to restart production of MIC to support production of aldicarb in February 2011. On February 8, 2011, local residents filed suit against Bayer in order to halt the restart of production until certain criteria were met, which resulted in a temporary restraining order to halt the process to restart production of MIC at the Institute facility and scheduled an evidentiary hearing for February 25, 2011 (Case 2:11-cv-00087 Document 16).

On February 12, Bayer requested clarification and cancellation of the judge's order, citing a need to continue pre-startup work related to its "MIC Safety Enhancement Project." The request noted activities such as completion of operator training and drafting of standard operating procedures for the new systems as well as completion of activities to support compliance with recommendations made by the CSB and other federal and local organizations (Case 2:11-cv-00087 Document 24). The judge indicated that the company could continue its work on the safety system, but he also noted that, "The court finds it remarkable that the defendant has yet to complete a wide array of safety measures, in light of the announcement in open court that but for the [temporary restraining order], MIC would have been produced within seven days at the Institute facility. Indeed, the defendant's counsel indicated that Bayer was 'in the process of startup right now,' and that Bayer was 'commissioning equipment'" (Case 2:11-cv-00087 Document 26).

As part of the court proceedings, M. Sam Mannan, a chemical engineering professor from Texas A&M University and recognized expert in chemical process safety, was appointed by the court as an independent expert to review the MIC production process at Bayer CropScience. Professor Mannan was accepted by both the plaintiffs and the defendants in the suit. Mannan's report was delivered to the court on March 14. On the basis of his assessment of the facility and on evaluation of two possible release scenarios (a condenser tube springing a 5-mm leak and deliberate sabotage), Professor Mannan concluded that "the probabilistic risk of the MIC process is very low." (Case 2:11-cv-00087 Document 92-4).

Finally, on March 18, 2011, Bayer CropScience announced that it would not restart the production of MIC. In a press release, the company stated that, "uncertainty over delays has led the company to the conclusion that a restart of production can no longer be expected in time for the 2011 growing season" (Bayer CropScience, 2011a), and this resulted in a dismissal of the case. These events were occurring as the committee was holding its data-gathering sessions.

- Meeting 1: February 9-10, 2011, in Washington, DC.
- Meeting 2: March 20-22, 2011, at West Virginia State University in Institute, West Virginia. Included public comment period and a visit to the Bayer facility.
- Meeting 3: May 24-25, 2011, in Washington, DC.
- Meeting 4: August 8-9, 2011, in Woods Hole, Massachusetts.

In addressing the statement of task, the committee began by considering how to address Task 3 and determining the data-gathering required. While it initially seemed that information from the literature review in Task 2 could be useful in addressing Task 3, the committee quickly determined that a detailed, full analysis of all alternative chemistries available for the production of aldicarb and carbaryl, including their manufacturing and energy costs, would require significantly greater investments than were available for the study. The investment required to fully analyze any one alternative is typically a multi-million dollar expenditure, and further, costs are highly dependent on the facility design, and accurate financial analysis requires specialized tools and information that is often unavailable to the public. In addition, in light of the de-registration of aldicarb and subsequent cessation of MIC, aldicarb, and carbaryl production at the Institute plant, the value of a full literature review for the chemical manufacturing community was reduced as the information available from such a review would no longer have a potential use for the facility.

With these limitations in mind, the committee chose to focus on a select set of possible alternative production processes for aldicarb and carbaryl. These chosen alternatives had been evaluated by Bayer and the facility's legacy owners, and as a result, information about the chemistry and possible manufacturing processes were available for each. This approach reduced further the value of a literature review, which would be limited in its scope to information about manufacturing processes available in the open literature. As a result of these various factors, the committee chose to focus its efforts primarily on Task 3 and addressed Task 2 only in the context of the chosen alternative production processes.

In this report, the selected alternatives and associated trade-offs are presented, with particular attention to safety considerations. In addition, the context in which these trade-offs must be evaluated (financial, regulatory, etc.) is discussed. Finally, as deciding between alternative processes requires consideration and weighing of a number of different factors, including safety, one possible framework for evaluating these complex decisions is presented. Note that much of the information to perform the analysis of trade-offs was drawn from documentation provided by Bayer CropScience from the company's archives and those of the previous owners of the facility. As many of these processes were in active use until very recently, much of the information was previously considered proprietary.

## STRUCTURE OF THE REPORT

This report consists of eight chapters.

Chapter 2 provides an overview of the incidents in Bhopal, India, which is called for in Task 1.

Chapter 3 provides an overview of carbamate pesticides and their history in Institute, West Virginia and includes important information about changes in the plant design related to production of the pesticides and their precursors.

Chapter 4 contains an introduction to Inherently Safer Processes (ISP) and ISP assessment and describes the role such concepts and assessment can play in process safety management. This background information is necessary context for the analysis provided for the remaining chapters.

Chapter 5 addresses Tasks 3.1-3.3 by presenting an assessment of alternative methods for production of MIC, aldicarb, and carbaryl. The chapter also discusses the many factors that influence decision making in chemical manufacturing. This last point led the committee to consider a broader framework in which alternatives and trade-offs could be considered in corporate decision making. One possible framework for decision making is discussed in Chapter 6.

Chapter 7 compares the process analyses performed at the Institute facility by Bayer CropScience and the legacy owners as specifically called for in Task 3.4.

Chapter 8 addresses Task 3.5 and considers the use of ISP assessments in post-incident investigations.

After reading the findings from the CSB report, visiting the plant and talking with Bayer CropScience personnel, and listening to testimony from the public comment periods, it became clear that consideration of the context in which any ISP or process hazard assessment is performed is essential to allow for a complete analysis. To address this need, the discussions in Chapters 5 and 7 also touch on the role that an organizational safety culture plays in creating a safe operating environment and the broader context in which chemical plants operate, including local communities and policy concerns.

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# 2

# Bhopal and Chemical Process Safety

## INTRODUCTION

No discussion of inherent safety processes (ISPs), process safety management (PSM), and methyl isocyanate (MIC) is complete without a discussion of the history and legacy of the Bhopal incident and the lessons learned. In what has been described by many as the "world's worst industrial disaster", over 40 tons of MIC was released at a Union Carbide India Limited (UCIL) plant in Bhopal, India on December 2, 1984 (Dhara and Dhara, 2002; Broughton, 2005). Much has been written on the disaster, and this report does not endeavor to repeat or evaluate that work but rather to provide an overview of the event and a discussion of the key lessons of process safety learned from the disaster as necessary context for the report. Chapter 3 discusses the use of MIC at the Bayer CropScience facility in Institute, West Virginia.

## METHYL ISOCYANATE

The UCIL facility in Bhopal, India was a manufacturing facility for carbamate pesticides that had a design similar to the plant in Institute, West Virginia, and it had been manufacturing MIC on site since 1980. As an intermediate step to the production of these pesticides, the facility stored a large quantity of MIC on site, although it was not actively manufacturing the material at the time of the incident. MIC itself is a volatile, colorless liquid with a pungent odor. It is extremely flammable, potentially explosive when mixed with air, and reacts exothermically with water to form methylamine and carbon dioxide. The liquid and vapor are toxic when inhaled, ingested, and if eyes or skin are exposed. Its vapor pressure is high at 54 kPa at 20ºC, its boiling point is 39ºC, and the vapor density is greater than that of air, meaning that the liquid volatilizes readily and the vapor will stay near ground level. When stored, the liquid is kept between –10°C and 0°C in order to maintain a low vapor pressure and to prevent exothermic self-polymerization.

## THE BHOPAL DISASTER

On the night of the incident, December 2, 1984, at 11:00 p.m. local time, while many of the Bhopal residents were asleep, it was reported that a plant operator noticed a small MIC gas leak and increased gas pressure inside a storage tank. This leak and pressure were due to water that had entered the storage vessel. At the time, critical refrigeration for the storage system had been moved to another area in the plant, and without refrigeration to slow the reaction of MIC with water, the temperature and pressure rapidly rose within the storage vessel. As the temperature rose, the MIC began to self-polymerize, adding to the heat and pressure. The vapor was first routed to a scrubber for the vent gas that should have neutralized at least some portion of the vapor, but this unit was not active.[1] The vapor should then have passed to a flare tower to be destroyed, but the tower was out of service for maintenance because of pipe corrosion. Shortly after midnight, a safety valve opened, sending a MIC gas plume into the air (Broughton, 2005). An emergency water curtain intended to react with the MIC in case of such a release was not designed to manage a release of that scale and was also suffering from corrosion, which likely reduced its efficacy.

More than 40 tons of MIC was released into the impoverished community that surrounded the facility. As the plume traveled through the area, the severe acute irritant effects caused residents living nearby to become disoriented and anxious. In their attempt to escape from the chemical, residents ran out of their homes directly into the gas cloud, which resulted in increased exposure to the chemical. Reportedly, close to 3,800 residents were killed immediately. Thousands more, with estimates of up to 100,000-200,000 people in and surrounding that community, have experienced significant morbidity and mortality, including being partially or totally disabled, and experiencing premature death (Andersson et al., 1990; Beckett, 1998; Hood, 2004; Broughton, 2005; Mishra et al., 2009).

From reports on the event, it is clear that the Bhopal facility was operating with reduced safety standards and equipment. Specifically, the unavailability of the refrigeration, scrubber, flare tower, and water curtain, led Broughton (2005) to conclude that the Bhopal facility operated with "safety equipment and proce-

[1] The caustic in the scrubber was warm the next morning, indicating that some of the MIC could have actually reacted with the system despite being offline, but it was not sufficient to control the release.

dures well below the safety standards found at its sister plant in Institute, West Virginia"; and "the local government, although aware of some of the safety problems", was reluctant to enforce stronger safety and air pollution standards for fear of losing a large employer. Multiple reports on the incident (ICFTU-ICEF, 1985; Shrivastava, 1987; Broughton, 2005; Mannan, 2005) have identified root causes for the disaster that are tied to human and management factors in addition to the technical factors described above. Specific concerns include a lack of responsiveness to safety concerns identified during inspections, poor management of change in response to new procedures, reduced staffing on site and high turnover among employees, and deficiencies in equipment maintenance and operation, including emergency equipment and procedures.

## RISKS ASSOCIATED WITH MIC

The health risks of MIC exposure involve injuries to the ocular, respiratory, gastrointestinal, reproductive, and nervous systems (Beckett, 1998; Dhara and Dhara, 2002; Broughton, 2005). Autopsies performed on 300 victims of the disaster showed lesions that were severely necrotized on the upper respiratory tract lining, the lung capillaries, alveoli, and bronchioles. In addition, the autopsies revealed edematous and enlarged lungs, hemorrhages, bronchopneumonia, and acute bronchiolitis (Dhara, 2000; Broughton, 2005). The acute health effects, particularly those reported and observed in residents 0 to 6 months after the Bhopal disaster, were primarily injuries from the intensely irritating effect of MIC on the cornea and included severe ocular burning, persistent watery eyes, pain, ulcers, and photophobia. Lesions related to respiratory tract toxicity were seen in both the upper and lower respiratory tracts, and included chest pain and pulmonary distress, pneumonitis, pulmonary edema, and pneumothorax. Gastrointestinal problems included persistent diarrhea and persistent abdominal pain (Dhara and Dhara, 2002; Broughton, 2005). Genetic health effects included increased chromosomal abnormalities. Acute psychological health effects included neuroses, anxiety, and adjustment reactions; and acute neurobehavioral effects reported and observed were impaired audio and visual memory, psychomotor coordination, reasoning and spatial coordination (Broughton, 2005).

Chronic and long-term health risks of MIC exposure, particularly 1 to 25 years after the Bhopal incident, also involved injuries to the ocular, respiratory, and other organ systems, including reports of long-term injuries to the reproductive and nervous systems. In published reviews and clinical studies of the health effects from exposure to MIC during the early and late recovery periods of the Bhopal incident, scientists reported persistent watering of the eyes, eyelid infections, corneal opacities, chronic conjunctivitis, tear secretion deficiency, and cataracts (Andersson et al., 1990; Dhara and Dhara, 2002; Broughton, 2005; Mishra et al., 2009). Decreased lung function, restrictive and obstructive airway disease, chest pain, dyspnea, wheezing, and allergic bronchoalveolitis were also identified as the chronic and long-term respiratory health symptoms related to MIC exposure (Andersson et al., 1990; Beckett, 1998; Dhara and Dhara, 2002; Broughton, 2005; Mishra et al., 2009). Long-term reproductive health risks include increased spontaneous abortions, increased perinatal and neonatal mortality, menstrual cycle alterations, decreased placental weights, and increased chromosomal alterations (Beckett et al., 1998, Dhara and Dhara 2002, Mishra et al., 2009). Neurological symptoms include depression, impaired associative learning, motor speed and precision, and muscle aches (Dhara and Dhara, 2002; Mishra et al., 2009).

## LESSONS FROM BHOPAL

### Process Safety Management

Although equipment failures increased the severity of the Bhopal disaster, these failures and the poor emergency response to the incident are indicative of serious flaws in the management of the facility, and these flaws are considered a root cause of the incident. These factors will not be discussed in detail here as they have been the topic of many previous papers and reports (for example, Bowander et al., 1985; Shrivastava, 1987), but the recognition of these organizational and human factors concerns has contributed to the response of the chemical community described here. The incident served as a catalyst for the chemical industry, government, chemical engineers, professional organizations, and various stakeholders to develop and adopt stronger and improved standards and practices for chemical process safety. As described by one process safety expert: "*A significant impact of Bhopal was to make everybody—corporate management, government, communities—aware of the potential magnitude of a chemical accident*" (West et al., 2004). It is in this context that the widespread use and acceptance of the concept, "process safety," and later, chemical process safety, was embraced and adopted as a standard practice in the industry. The heightened awareness resulted in new regulations for process safety; best-practices initiatives, such as Responsible Care;[2] and an increased concern about the potential to export the risk as well as the benefits of technology to developing countries as the chemical industry expanded around the globe. The goal of process safety is to develop a systematic and comprehensive approach to safety that involves the proactive identification, evaluation, and mitigation or prevention of chemical releases that might occur as a result of failures in the process, procedures, or equipment (Kletz, 1998).

In 1990, two major developments in U.S. process safety occurred: the publication of a proposed standard from the Occupational Safety and Health

[2] Responsible Care is a global program initiated by the Canadian Chemical Producers' Association in 1985 as a voluntary, industry-driven program to support improvements in health, safety, and environmental practices in the chemical industry.

Administration (OSHA), titled "Process Safety Management of Highly Hazardous Chemicals," and the passage by the U.S. Congress of the Clean Air Act Amendments (CAAA) of 1990. The CAAA provided regulatory oversight of process safety in the chemical industry to OSHA and the U.S. Environmental Protection Agency (EPA). In particular, CAAA identified 14 minimum elements that the OSHA Process Safety Management Standard must require of employers (see Box 2.1). The final PSM standard was promulgated in 1992 by OSHA and is enforced by that office in coordination with EPA. The standard emphasizes the management of hazards through a comprehensive program that integrates management technologies, practices, and procedures and includes 14 mandatory elements that correlate to the CAAA requirements (see Box 2.2). Under CAAA, EPA has responsibilities relating to the prevention of accidental release, inventories of chemicals, and development of risk management plans (RMP), among other things.

EPA, as directed by the CAAA, established its risk management program rule requiring companies that use toxic and flammable substances to develop and submit an RMP that must be revised and resubmitted every 5 years. A third major provision of the CAAA was the creation and establishment of the U.S. Chemical Safety and Hazard Investigation Board (CSB), an independent federal agency patterned after the National Transportation and Safety Board, to investigate major chemical accidents at fixed facilities (P.L. 101-549§ 304, 104 Stat. 2576 [1990]).

The Bhopal disaster also resulted in changes from within the chemical engineering and chemical industry communities. The American Institute of Chemical Engineers (AIChE) launched a major initiative in February 1985 to improve and bring attention to the practices of process safety (Bollinger et al., 1996). AIChE focused on becoming a resource for information about process safety, providing training and education, advancing the state of the art in process safety, and promoting process safety as a key industry value. An AIChE task force was formed in March 1985, and its members proposed initial objectives to establish guidelines for hazard evaluation procedures; guidelines for bulk storage, handling, and transportation of toxic and/or reactive materials; and good plant operating procedures and training. As a result of these objectives, the AIChE Council officially approved the establishment of the Center for Chemical Process Safety (CCPS). The CCPS was fully established as a separate organization from AIChE in September 1985, with a director, part-time staff consultants in the industry, and close to 40 charter corporate members. In 1989, CCPS outlined 12 elements of process safety management in its book *Guidelines for Technical Management of Process Safety*, and these have been serving as the foundation for process safety programs, standards and regulations throughout the chemical industry in the United States, and around the world (Mannan, 2005). These elements are listed in Box 2.3.

In the chemical process industry, managing risks through the use and implementation of these program elements of process safety management and the

**BOX 2.1**
**CAAA Process Safety Management Standard Requirements**
**(P.L. 101-549§ 304, 104 Stat. 2576 [1990])**

1. Develop and maintain written safety information identifying workplace chemical and process hazards, equipment used in the processes, and technology used in the processes;
2. Perform a workplace hazard assessment, including, as appropriate, identification of potential sources of accidental releases, identification of any previous release within the facility that had a potential for catastrophic consequences in the workplace, estimation of workplace effects of a range of releases, and estimation of the health and safety effects of such a range on employees;
3. Consult with employees and their representatives on the development and conduct of hazard assessments and the development of chemical accident prevention plans and provide access to these and other records required under the standard;
4. Establish a system to respond to the workplace hazard assessment findings, which shall address prevention, mitigation, and emergency responses;
5. Review periodically the workplace hazard assessment and response system;
6. Develop and implement written operating procedures for the chemical processes, including procedures for each operating phase, operating limitations, and safety and health considerations;

mandated requirements of OSHA and EPA generally assumes that the chemical hazard risk already exists and is accepted. The assumption is that once the risk is accepted, it does not go away. Unless the management system is actively monitoring company operations and taking proactive approaches to correct potential problems, the opportunity for an unwanted event to occur will manifest. The "best practice" methods for managing risks are found in the elements and components of PSM, which are widely accepted and used worldwide.

## Community Right-to-Know

Another important regulatory impact of the Bhopal disaster was the passage of the Emergency Planning and Community Right-to-Know Act (EPCRA, also

7. Provide written safety and operating information for employees and employee training in operating procedures, by emphasizing hazards and safe practices that must be developed and made available;
8. Ensure contractors and contract employees are provided with appropriate information and training;
9. Train and educate employees and contractors in emergency response procedures in a manner as comprehensive and effective as that required by the regulation promulgated pursuant to section 126(d) of the Superfund Amendments and Reauthorization Act;
10. Establish a quality assurance program to ensure that initial process-related equipment, maintenance materials, and spare parts are fabricated and installed consistent with design specifications;
11. Establish maintenance systems for critical process-related equipment, including written procedures, employee training, appropriate inspections, and testing of such equipment to ensure ongoing mechanical integrity;
12. Conduct pre-startup safety reviews of all newly installed or modified equipment;
13. Establish and implement written procedures managing change to process chemicals, technology, equipment and facilities; and
14. Investigate every incident that results in or could have resulted in a major accident in the workplace, with any findings to be reviewed by operating personnel and modifications made, if appropriate.

SOURCE: OSHA, 2000.

known as SARA Title III because it is Title III of the Superfund Amendments and Reauthorization Act of 1986). This bill came about as a result of both the Bhopal disaster in 1984 and a release of aldicarb oxime that occurred at the Union Carbide plant in Institute, WV in 1985. The release in Institute resulted in the hospitalization of approximately 100 individuals, and occurred shortly after the re-start of production following a hiatus in response to the Bhopal release. EPCRA, managed by EPA, defines the community right-to-know obligations of government, industry, and Tribal authorities with respect to emergency response planning and hazardous and toxic chemicals in the area. The Act has three subtitles: Emergency Planning and Notification, Reporting Requirements, and General Provisions. Some important elements of the Act follow:

**BOX 2.2**
**Elements of OSHA's Process Safety Management Standard**

- **Process safety information.** Employers must complete a compilation of written process safety information before conducting any process hazard analysis required by the standard. Process safety information must include information on the hazards of the highly hazardous chemicals used or produced by the process, information on the technology of the process, and information on the equipment in the process.
- **Process hazard analysis.** Employers must perform an initial process hazard analysis (hazard evaluation) on all processes covered by this standard. The process hazard analysis methodology selected must be appropriate to the complexity of the process and must identify, evaluate, and control the hazards involved in the process.
- **Operating procedures.** Employers must develop and implement written operating procedures, consistent with the process safety information, that provide clear instructions for safely conducting activities involved in each covered process. Activities to be covered include initial startup, normal operations, temporary operations, emergency shutdown, emergency operations, normal shutdown, and startup following a turnaround, or after an emergency shutdown.
- **Employee participation.** Employers must develop a written plan of action to implement the employee participation required by PSM. Under PSM, employers must consult with employees and their representatives on the conduct and development of process hazard analyses and on the development of the other elements of process management, and they must provide to employees and their representatives access to process hazard analyses and to all other information required to be developed by the standard.
- **Training.** Each employee presently involved in operating a process or a newly assigned process must be trained in an overview of the process and in its operating procedures. The training must include emphasis on the specific safety and health hazards of the process, emergency operations including shutdown, and other safe work practices that apply to the employee's job tasks.
- **Contractors.** Contract employers involved in maintenance, repair, turnaround, major renovation or specialty work, on or near covered processes are required to train their employees to safely perform their jobs. The contract employers must document that employees received and understood training, and assure that contract employees know about potential process hazards and the work-site employer's emergency action plan, assure that employees follow safety rules of the facility, and

advise the work-site employer of hazards that contract work itself poses or hazards identified by contract employees.

The facility employer must obtain and evaluate information regarding the contract employer's safety performance and programs. The employer also must inform contract employers of the known potential fire, explosion, or toxic release hazards related to the contractor's work and the process; explain to contract employers the applicable provisions of the emergency action plan; develop and implement safe work practices to control the presence, entrance, and exit of contract employers and contract employees in covered process areas; evaluate periodically the performance of contract employers in fulfilling their obligations; and maintain a contract employee injury and illness log related to the contractor's work in the process areas.

- **Pre-startup safety review.** A safety review is mandatory for new facilities and significantly modified work sites to confirm that the construction and equipment of a process are in accordance with design specifications; to ensure that adequate safety, operating, maintenance and emergency procedures are in place; and to ensure that process operator training has been completed. Also, for new facilities, a process hazard analysis must be performed and recommendations resolved and implemented before startup. Modified facilities must meet management-of-change requirement.
- **Mechanical integrity.** Employers must establish and implement written procedures to maintain the ongoing integrity of process equipment, including pressure vessels, piping systems, relief and vent systems, emergency shutdown systems, controls, and pumps. Employees involved in maintaining the ongoing integrity of process equipment must be trained in an overview of that process and its hazards and trained in the procedures applicable to the employee's job tasks.
- **Hot work.** Hot work permits must be issued for hot work operations conducted on or near a covered process.
- **Management of change.** Employers must establish and implement written procedures to manage changes (except for "replacements in kind") to process chemicals, technology, equipment, and procedures, and change to facilities that affect a covered process. Employees and contract employees who operate a process and maintenance must be trained in the change prior to startup of the process or the affected part of the process.
- **Incident investigation.** PSM requires the investigation of each incident that resulted in, or could reasonably have resulted in, a catastrophic release of a highly hazardous chemical in the workplace. The investigation must be initiated as promptly as possible, but not later than 48 hours

*continued*

**BOX 2.2 Continued**

following the incident. The investigation must be by a team consisting of at least one person knowledgeable in the process involved, including a contract employee if the incident involved the work of a contractor, and other persons with appropriate knowledge and experience to investigate and analyze the incident thoroughly.

- **Emergency planning and response.** Requires employers to develop and implement an emergency action plan. The emergency action plan must include procedures for handling small releases.
- **Compliance audits.** Employers must certify that they have evaluated compliance with the provisions of PSM at least every three years to verify that the procedures and practices developed under the standard are adequate and are being followed. The compliance audit must be conducted by at least one person knowledgeable in the process and a report of the findings of the audit must be developed and documented noting deficiencies that have been corrected. The two most recent compliance audit reports must be kept on file.
- **Trade secrets.** Employers must make available all information necessary to comply with PSM to those persons responsible for compiling the process safety information, those developing the process hazard analysis, those responsible for developing the operating procedures, and those performing incident investigations, emergency planning and response, and compliance audits, without regard to the possible trade secret status of such information. The employer may require from those persons to enter into confidentiality agreements not to disclose the information.

SOURCE: Adapted from OSHA (2000).

- the creation of local and state emergency planning committees (LEPC and SERC, respectively),
- the requirement for plant operators to notify local and state officials in the event of a significant release of toxic materials,
- the requirement for plant operators to report inventories of all onsite chemicals for which an MSDS exists to state and local officials and local fire departments,
- the requirement for plant operators to submit a Toxic Release Inventory Form annually, and
- the protection of "trade secrets" contingent on approval by the EPA.

EPCRA, Responsible Care, and the continuing evolution of PSM systems

**BOX 2.3**
**12 Elements of Process Safety Management Defined by CCPS**

1. Accountability: Objectives and Goals
2. Process Knowledge and Documentation
3. Process Safety Review Procedures for Capital Projects
4. Process Risk Management
5. Management of Change
6. Process and Equipment Integrity
7. Human Factors
8. Training and Performance
9. Incident Investigation
10. Company Standards, Codes and Regulations
11. Audits and Corrective Actions
12. Enhancement of Process Safety Knowledge

are manifestations of another, less-well-defined legacy from Bhopal: the change in community and industry perceptions of hazardous and toxic materials and the risks they pose to personnel onsite and the local population surrounding chemical facilities. The effects of the MIC release in 1984 are still felt in Bhopal, India, and by the Dow Chemical Company, which purchased the facility from Union Carbide in 2001. Within Institute, WV, it would be naive to not recognize the impact the Bhopal release had, and continues to have, on the area, and it is clear that the release and its aftermath have affected local community relationships with the current and former owners of the facility.

The nature of the relationships between a chemical company and its surrounding community and onsite personnel can and do influence the range of business decisions that a company can make. This relationship is discussed in greater detail in Chapters 6 and 7 in the context of external factors that affect decision-making. To emphasize the importance of these relationships, the committee notes here that in 1985, the DuPont facility in LaPorte, TX actually began onsite production, although not storage, of MIC. In describing the implementation of this process, Mr. John Carberry stated that its success was due in part to the site manager's "long standing, strong, broad community and governmental relations" and because the company recognized that it needed to, "[m]anage community and governmental relations to insure a smooth acceptance of the new process" (Carberry, 2011). To address this need, DuPont pro-actively involved the community in discussions about the change in procedures at multiple points during the decision-making process. This engagement with the community was credited with creating a relationship where objections could be voiced and addressed without community protest.

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# 3

# Industrial Production and Use of MIC at Bayer CropScience

The statement of task calls for an examination of the use and storage of methyl isocyanate (MIC) at the Bayer CropScience facility in Institute, West Virginia. This chapter provides an overview of the history of the plant, with a particular focus on processes relating to MIC and the pesticides it is used to synthesize. Alternative methods of producing these materials are presented in Chapter 5.

## HISTORY AND CHARACTERISTICS OF THE SITE

The 460-acre, multitenant Institute Manufacturing Industrial Park is located 9 miles west of Charleston, West Virginia. The facility is on the Kanawha River to the south, abuts Route 25 and Interstate 64 to the north, and the West Virginia State University to the east. Transportation to and from the site is provided by barge, rail (located adjacent to the river), and truck.

West Virginia State University is the oldest extant institution in the immediate vicinity. Established in 1891 as a land grant college, the university enrolls 3,145 students on a 91-acre campus adjacent to the Institute industrial park (U.S. News, 2010). (See Figure 3.1)

Originally home to the Wertz Field Airport, the site was converted to a synthetic rubber production plant by the U.S. Government Defense Corporation during World War II. Originally designed, built, and managed by the Carbide and Carbon Chemicals Corporation (a subsidiary of Union Carbide) and the U.S. Rubber Company, the facility has had a number of owners. Union Carbide Corporation (UCC) purchased the chemical manufacturing operations plant in 1947, which it used to produce a variety of chemicals including butanol, olefins, plasticizers, and acetic acid. The plant also produced some fungicides, although

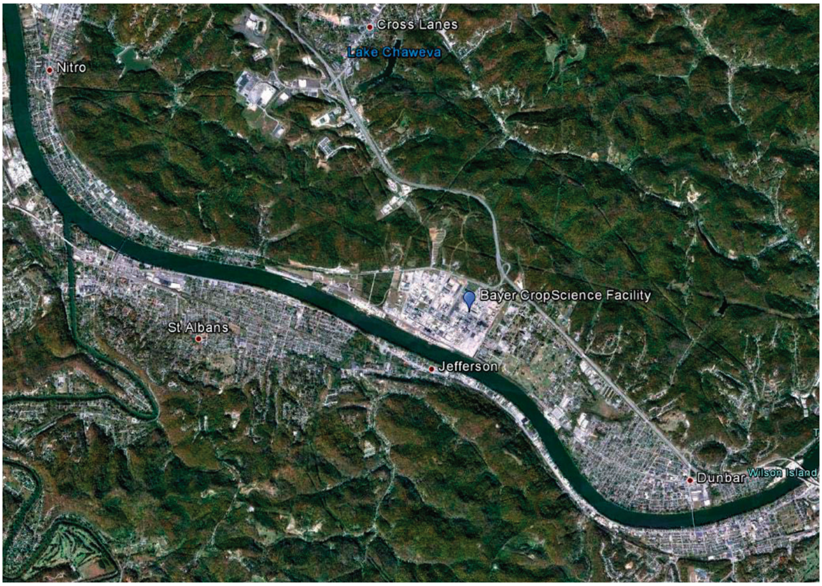




FIGURE 3.1 Google™ Earth satellite images of the facility at Institute, West Virginia and the surrounding area (accessed April 14, 2012). (a) The region around Institute, West Virginia (b) the Bayer CropScience facility and local area.
SOURCE: Google Earth satellite image: ©Google 2012.

this was initially a small portion of the plant's operations. In the 1960s, UCC expanded operations, including construction of facilities to produce carbamates and to allow for production of new synthetic intermediates for other companies (Woomer, 2000). Rhône-Poulenc purchased UCC's agricultural division, including the Institute site, in 1986. In 2000, Aventis (formed by a merger of Rhône-Poulenc and AgrEvo) took over management of the facility. Finally, Bayer CropScience acquired the facility in 2002 (CSB, 2011). Bayer CropScience is a global provider of insecticides, herbicides, and fungicides. Independently operated within Bayer, AG, Bayer CropScience is headquartered in Germany. The company employs about 20,700 workers in over 120 countries (Bayer CropScience, 2011c). The U.S. headquarters are in Research Triangle Park, North Carolina.

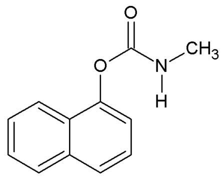
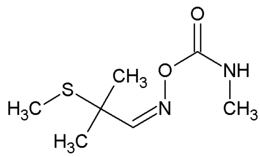
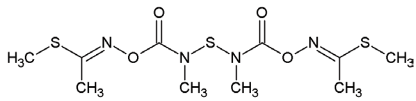
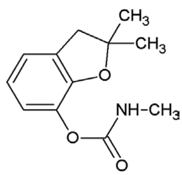
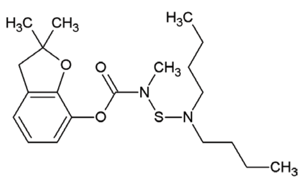
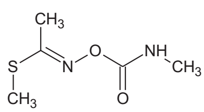
In 2008, the facility hosted seven tenants. Bayer CropScience owned and operated 9 of the 16 production units on the site. Two production units, owned by Adisseo and FMC Corporation, were also operated by Bayer. The remaining units were owned and operated by Dow Chemical, Catalyst Refiners, Reagent Chemical, and Praxair, respectively. Bayer employed approximately 85 percent of the 645 workers employed at the facility (CSB, 2011).

## HISTORY OF CARBAMATE INSECTICIDE MANUFACTURING

The focus of production at the Bayer plant in 2008 was on carbamate pesticides, which have been shown to be effective against a variety of pests. The general structure of carbamate pesticides is $R_1NHCOOR_2$, where R represents alkyl or aryl groups. The facility in Institute manufactured a number of different carbamates over the years. The processes for manufacturing these materials have changed over time, some of which have implications for process safety. What follows here is a description of some of the major changes at the facility, and Appendix B contains a detailed timeline of modifications. The major carbamate products are summarized in Table 3.1.

Carbamate pesticide production in Institute began in the 1960s with carbaryl. Carbaryl is a broad-spectrum pesticide and is used in a variety of commercial and residential settings for control of pests such as beetles, crickets, fleas, ticks, and moths (U.S. EPA, 2004). Production of MIC also began during that decade, although at that time it was only manufactured for use at other facilities and for sale to other companies rather than for use onsite. That changed in 1976 with the production of aldicarb in Institute. Aldicarb had previously been produced in Woodbine, Georgia, and although final formulation and packaging of the material continued at that site, synthesis of the pesticide was moved to Institute. While sharing basic carbamate chemistry with carbaryl, for reasons that are discussed in Chapter 5, production of aldicarb was carried out by a chemical pathway using phosgene and MIC. Aldicarb is primarily used to control nematodes and sucking insects in crops such as cotton, beans, and peanuts (U.S. EPA, 2010). The method for production of carbaryl was changed in 1978 from one that used naphthyl-

TABLE 3.1 Trade Names and Structures of Pesticides Manufactured at the Bayer CropScience Facility

| Pesticide | Trade Name | Structure |
|---|---|---|
| Carbaryl | Sevin |  |
| Aldicarb | Temik |  |
| Thiodicarb | Larvin, CropStar |  |
| Carbofuran | Furadan |  |
| Carbosulfan | Marshal |  |
| Methomyl | |  |

chloroformate (NCF) as a starting material to one that used MIC. That year also saw the startup of a second, larger MIC unit to provide for the growing demand for aldicarb and changes to carbaryl production.[1] In the early 1980s, carbamate

[1] At that time, the facility shipped MIC around the world to customers in France, India, Brazil, and the United States, and to accommodate international demand, Union Carbide built a MIC unit in Bhopal in the late 1970s, with startup in 1980.

insecticide manufacturing was expanded to include methomyl (an intermediate feedstock sold internationally) and thiodicarb (an agricultural insecticide and ovicide used against cotton bollworms and budworms made from methomyl) (U.S. EPA, 1998), both of which required MIC for production.

The MIC and phosgene production units, along with the units that were used to manufacture aldicarb and carbaryl, were all co-located in the East Carbamoylation Complex (ECC). Production units for methomyl and thiodicarb were located in the West Carbamoylation Complex (WCC). The ECC and WCC are highlighted in Figure 3.2. Liquid MIC was stored in underground refrigerated pressure vessels in the ECC where it was manufactured. It was later used as a chemical feedstock there or at the WCC to which it was transferred at night and stored for later use.

On December 3, 1984, in response to the release in Bhopal, the MIC facility in Institute was shut down for several months while Union Carbide installed $5 million worth of safety equipment and enhancements (Los Angeles Times, 1985), which included increased MIC destruction capacity.

However, the Institute site itself suffered an accident on August 11, 1985,

FIGURE 3.2 The Bayer CropScience facility. The circle on the left marks the methomyl production unit, where the aboveground storage tank was located, in the West Carbamoylation Complex. The circle on the right marks the methyl isocyanate production unit in the East Carbamoylation Complex.
SOURCE: Smythe, 2011.

when 4,000 pounds of aldicarb oxime and methylene chloride were released, resulting in 136 people being sent to 5 local hospitals. No fatalities were reported, though 29 individuals were held for observation for one or more days (Houston Chronicle, 1985; Baron et al., 1988).

Following Bhopal, shipments of MIC from Institute to U.S. customers were curtailed. Two of these customers were FMC, a manufacturer of the carbamate pesticides carbofuran and carbosulfan and DuPont. In 1986, FMC built production units for carbosulfan and carbofuran in the WCC (Woomer, 2000). DuPont developed a process for manufacturing MIC as a feedstock that was almost instantaneously reacted into final product, thereby eliminating the need to purchase or store MIC. That same year, 1986, Rhône-Poulenc bought Union Carbide's Agricultural Products Division.

In 1993 a $50 million Institute modification project carried out various changes to the facility related to MIC, phosgene, and chlorine safety (Ward, 1994). As part of that project, MIC capacity was reduced by more than 80 percent to 22 million pounds per year. This change was largely justified as a consequence of DuPont and other customers no longer requiring the product, which had previously been stored in batches of 240,000 pounds. Additional details about these changes can be found in Chapter 5.

In 1999, Rhône-Poulenc purchased the carbofuran and carbosulfan manufacturing facilities owned by FMC and established the Carbamate Excellence Center at Institute, and a new carbamate process, the oxamyl process, was added. In December of that year, Rhône-Poulenc SA merged with Hoechst AG to form Aventis. The Institute site became the largest site in North America for Aventis CropScience (Woomer, 2000). In 2001, EPA performed a series of inspections at the facility and identified a set of violations of environmental laws (EPA, 2009). Also in 2001, the facility was purchased by Bayer, thus moving the Institute plant to its current ownership, Bayer CropScience. As the legal successor to Aventis, Bayer settled with EPA regarding the 2001 violations in February 2009 with an agreement to pay a $112,500 penalty and to spend over $900,000 on supplemental environmental projects. As part of the settlement, Bayer CropScience neither admitted nor denied the allegations.

By 2008 the Institute plant was the only facility in the United States that manufactured, stored, and consumed large quantities of MIC. Liquid MIC was stored in underground refrigerated pressure vessels in the ECC, where it was manufactured before being used—either as a chemical feedstock there or at the WCC to which it was transferred at night and additionally stored. Each pressure vessel was insulated and had double-wall construction, with leak detection in the annulus between the inner and outer wall. The transfer from the ECC to the WCC occurred through a 2,500-foot, insulated, aboveground piping system to an aboveground "day tank" located on the southwest corner of the WCC. The stainless steel tank, with a maximum capacity of 6,700 gallons, held approximately 37,000 pounds of MIC at its normal 75 percent operating capacity. A number of safety features were incorporated into the day-tank design. The tank was filled once per day, and the pipes connecting the ECC to the WCC were purged after the transfer. The MIC was chilled, with methyl isobutyl ketone (MIBK) used as the chiller fluid because, unlike the water-ethylene glycol mixtures typically used in chillers, MIBK does not react with MIC and therefore poses less risk in case of a chiller leak. Fire suppressants were installed to prevent thermal reactions. Air monitors were in place to detect MIC leaks. Finally, the tank and top piping connections were surrounded with a blast blanket to prevent debris from striking the tank and to provide a thermal shield in case of fire (CSB, 2011).

Each of the pesticides being manufactured onsite at Institute used different production processes: aldicarb was produced in a batch reactor, carbaryl in a continuous fixed-bed reactor, methomyl in a continuous plug flow reactor, and carbofuran used a solventless process. All of these processes were designed to use liquid MIC. The pesticides had different seasonal patterns of production, and there was considerable variation in the facility's MIC consumption over time—between 5,000 and 100,000 pounds per day over the course of their history. To regulate carbamate production and minimize startup/shutdown issues for MIC production, the facility maintained an inventory of up to 200,000 pounds of MIC—approximately 10 days of normal production or 3 days of high production (Martin, 2011).

On August 28, 2008, an uncontrolled chemical reaction inside a methomyl unit residue treater in the WCC caused the vessel to explode violently, causing the deaths of two employees. See the next chapter section (History of Emergency Preparedness and Accidents) for more information. As a result of the accident and the damage to the WCC, production of methomyl, MIC, and the carbamate-based pesticides ceased, pending investigation and evaluation of the production unit.

In March 2009, EPA made a decision to ban the use of carbofuran pesticides (74 Fed.Reg.11,551 [2009]) leading to the decision by Bayer CropScience to stop production at Institute of all but two of the carbamate pesticides: aldicarb and carbaryl. Dropping the other products led to substantial reductions in the need for MIC, and so 2009 MIC production was only 9 million pounds, with planned 2010 production of 11.5 million pounds (Martin, 2011).

In August 2009, Bayer announced a $25 million investment program "for further enhancing operational safety" (Bayer CropScience, 2009) at the facility, and as part of this program, the carbamate pesticide production would cease in the WCC approximately a year after the announcement. This would remove the need for the aboveground storage tank and for the transfer of MIC from the ECC to the WCC. Production would be limited to aldicarb and carbaryl, both of which were produced in the ECC.

As part of the modification plan the decision was made to reduce by 80 percent the maximum amount of MIC being kept in storage on the Institute site, with additional passive and active safety systems on MIC production to minimize risks. Additional details will be provided in Chapter 5, but briefly, the MIC-production changes included building a new storage unit for the MIC with underground tanks; incorporation of a steam-ammonia curtain in the building's perimeter to assist in controlling leaks, should they occur; and other passive and active safety controls.

In 2010 Bayer reached an agreement with EPA to voluntarily cancel its registration of aldicarb, with production of the pesticide to end in 2014 and distribution and sales to end in 2016 (EPA, 2010; Ward, 2010). Citing this agreement and global restructuring of its parent company, on January 11, 2011 Bayer announced that "the production of certain carbamates is no longer economically viable." (Bayer CropScience, 2011b) The company's intention at that time was to continue to make modifications to the MIC plant at Institute; restart manufacturing of aldicarb, carbaryl, and the intermediate materials required for their production, including MIC; and continue manufacturing those materials until mid-2012.

In February 2011 a group of Kanawha Valley residents filed suit to stop Bayer CropScience from restarting its production of MIC at the Institute plant until EPA and OSHA completed comprehensive plant inspections. A preliminary injunction was granted, halting Bayer's planned restart of MIC production (Ward, 2011). On March 18, 2011, Bayer CropScience announced that it would not restart the production of MIC. In a press release, the company stated that, "uncertainty over delays has led the company to the conclusion that a restart of production can no longer be expected in time for the 2011 growing season." In light of this decision, the company said it would proceed with decommissioning the MIC and carbamate production units at Institute, as well as closing the Woodbine facility, which had continued to finalize the aldicarb formulation and packaging since 1976 (Bayer CropScience, 2011a).

## HISTORY OF EMERGENCY PREPAREDNESS AND ACCIDENTS

The Kanawha River Valley is the home of an extensive network of chemical and other manufacturing facilities and represents one of the highest concentrations of such industries in the United States. In 1954, these industries established the Kanawha Valley Emergency Planning Committee (KVEPC) following an explosion of an acrolein tank car. An explosion of an ethylene oxide distillation column in 1955 damaged parts of the Institute facility and led to a major safety review by the management (Woomer, 2000). After that, such safety reviews were conducted internally to the plant and its management until the Bhopal accident. Following Bhopal, public concern in the Kanawha Valley about chemical accidents increased, and with passage of the Emergency Planning and Community Right-to-Know Act (EPCRA, see Chapter 2), the Kanawha/Putnam Local Emergency Planning Committee (KPEPC) was established in 1987 (KPEPC, 2011). At the same time, local public concern about MIC led to the establishment of the organization People Concerned About MIC (PCMIC, 2011).

In 1992, the KPEPC initiated the Kanawha Valley Hazard Assessment Project, which examined "worst-case" scenarios for all chemical plants in the valley. The compilation of scenarios were presented during a June 3-4, 1994 workshop held in Charleston, West Virginia under the title "Safety Street: Managing Our Risk Together (Worst Case Scenario Presentations)." This was the first time such an activity had been held in the area, and according to the organizers, it was well received by the community (OECD, 1997). The materials identified a release from the MIC unit as one of worst-case scenarios associated with the Rhône-Poulenc-owned facility; the other two noted chemicals associated with the facility were phosgene and chlorine, the latter being used in the production of phosgene. The risk management plan from Rhône-Poulenc identified the worst case as the full release of 253,600 pounds of MIC from the ECC belowground storage tank. According to the analysis, such a release would exceed ERPG-2 (emergency response planning guidelines) levels out to a distance of 28 miles (at concentration of 0.5 ppm) and ERPG-3 levels out to a distance of 9 miles (5 ppm) (Fortun, 2001, pp. 66-67). ERPG-2 levels indicate the "maximum airborne concentration below which it is believed that nearly all individuals could be exposed for up to 1 hour without experiencing or developing irreversible or serious health effects or symptoms which could impair an individual's ability to take protective action"[2], while ERPG-3 levels indicate the "maximum airborne concentration below which it is believed that nearly all individuals could be exposed for up to 1 hour without experiencing or developing life-threatening health effects".[3] This constitutes the largest scenario vulnerability zone of any chemical used in the valley at the ERPG-2 level and nearly largest vulnerability zone at the ERPG-3 level.

At the time of the 1992 analysis, Rhône-Poulenc had just completed a 1.5-year study called Project Michelle (1989-1990) (as cited in Ward, 1994) which focused on improving the safety of thee MIC processes, including considering whether to put a "bubble" over the entire MIC unit to contain any leaks. Rhône-Poulenc had numerous active (and some passive) systems in place to reduce the risk associated with the MIC unit. These included:

1. **Process design.** An emergency dump tank for safe transfer of MIC from a leaking vessel, a scrubber to destroy MIC in the storage tank, a flare tower to destroy MIC from process vents, backup control room instruments, automatic MIC isolation valves to stop leaks, diking and spill collection sumps, a fire deluge system, MIC leak detection alarms, safety relief valves to protect vessels from overpressure, a diesel generator for backup power, sealless pumps for managing liquid MIC, fire protection for pipe rack transfer lines, and an independent nitrogen supply to prevent cross contamination.

2. **Equipment design.** A double-walled underground storage tank, special pressure vessels, blast material protection for the aboveground MIC storage

[2] AIHA Definition
[3] AIHA Definition

facilities, stainless steel construction, barriers to protect pipelines over roads, and double-walled pipelines with leak detection analyzers on critical transfer lines.

**3. Safety reviews and procedures.** Process hazard analysis completed every 5 years, ongoing safety reviews for design changes, operational reviews completed for all process changes, and safety review teams that included safety experts, engineers, union operators, and union maintenance personnel. It also established procedures and training inspection, emergency response and incident investigation systems (Fortun, 2001, p. 67).

Between 1989 and 1993, although the facility had no EPA-reportable releases (threshold of 10 pounds), it did report 13 leaks of between 1 and 10 pounds, and 30 leaks of less than 1 pound to the local emergency authorities. In 1993, Rhône-Poulenc was fined by OSHA for alleged safety violations that occurred during a non-MIC-related explosion and fire within the methomyl manufacturing unit, which was located near the aboveground MIC storage unit. The incident claimed the life of one plant worker and injured two others. OSHA investigators concluded that the company tried to boost pesticide production without regard for safety (Ward, 1994). The Institute Community Liaison Committee (CLC) commissioned a review of the incident investigation by PrimaTech, Inc. in 1993 (PrimaTech, Inc., 1993).

This incident caused considerable concern within the community, and the president of West Virginia State College,[4] Hazo Carter, wrote to the plant manager stating,

> As president of West Virginia State College, I am quite concerned about the safety of the more than 5,000 students, faculty, staff, and community residents due to recent accidents and frequent spills at the Institute Rhône-Poulenc plant. I was especially concerned to read that a tank holding 30,000 pounds of methyl isocyanate [MIC] gas was within 250 feet of the explosion and fire. The severity of this situation makes it imperative that every precaution be taken to prevent accidents from happening and that immediate notification be given to us if such accidents should occur in the future. (Carter, 1993)

In December 1994, following that explosion, Rhône-Poulenc completed the Institute Modification Project, involving $50 million in improvements. These improvements included: moving the phosgene unit closer to the MIC process to reduce the distance phosgene has to travel in pipes; adding a new cooling system for MIC tanks, using chloroform, rather than water-based brine; adding redundant warning systems to detect leaks and to monitor pressure,

[4] West Virginia State College became West Virginia State University in 2004.

temperature, and possible water-contamination at concentrations as low as 2 ppm; upgrading the scrubber and flare systems; and adding another backup generator (Ward, 1994).

The U.S. Chemical Safety and Hazard Investigation Board (CSB) report on the 2008 incident states that,

> [t]he five-year accident history for the RMP-regulated chemicals reports an accident that released approximately 15 pounds of phosgene (October 1999), another that released less than 1 pound of chlorine (May 2000), and a third that released approximately 3,000 pounds of liquid chloroform (August 2001). Each resulted in one or more worker exposures, and the phosgene release prompted a shelter-in place-alert. However, the company reports none of the releases involved offsite consequences (CSB, 2011).

Following its acquisition of the Institute facility from Aventis CropScience, Bayer CropScience completed 20 projects to enhance process safety and economic competitiveness, with particular attention paid to the phosgene and MIC units. These changes included a new, downsized phosgene unit, reductions in pipeline capacity in chlorine lines, downsizing the MIC unit to match lower demands (since inventory of MIC required for production was reduced by 80 percent since mid-1980s), modernizing equipment and instrumentation to safeguard the purity of the components used in the MIC process, additional emergency neutralization processes, and updated transfer processes.

### 2008 Accident in Methomyl Facility

As described in an earlier section, the production requirements and schedules varied for the different pesticides manufactured at the plant, and the methomyl process (located in the WCC) was only operated periodically in response to seasonal demand for the product. These gaps in the production schedule provided opportunities to perform repairs and system upgrades. In 2008, Bayer upgraded the methomyl control system and replaced the residue treater with a stainless steel tank during one of these downtimes. The process was restarted in August, with operations personnel, engineering staff, and contractors working around the clock to complete system upgrades. Dwindling supplies of methomyl and an increase in demand for thiodicarb created pressure to restart the operation (CSB, 2011). On August 28, 2008, amid startup procedures, an explosion occurred, resulting in the deaths of two plant operators and considerable damage to the WCC. A full investigation of the incident was performed by the CSB and the results of that investigation reported in 2011. An overview of key events and findings from that report is provided here.

The upgrades on the methomyl control system were significant, and as a consequence, the restart procedures were not routine. At the time of the startup, critical procedures had not been completed. In particular, process computer system engineers had not verified the functionality of all process controls and instruments in the new control system, and changes to standard operating procedures that were needed because of changes to system controls had not yet been finalized. In addition, the staff struggled with significant problems as they attempted to bring each subsystem online, including a missing valve on a solvent line, non-operational heat tracing on a process line, a broken stem on a vapor condenser water cooling system valve, and many problems tuning control loops and calibrating instruments for the newly installed computer control system. These problems were further complicated by the operators' lack of familiarity with new methomyl work station functions and changes to some process variables (CSB, 2011).

The explosion originated in the new residue treater in the methomyl production unit. The methomyl was synthesized in solvent through a series of steps. In the final stage, the solvated methomyl was transferred to a crystallizer, where an "anti-solvent" was added to cause the product to precipitate. The solid methomyl was then separated from the solvent via centrifugation. The remaining liquid, consisting of solvent, residual methomyl, and other compounds resulting from the synthesis, was transferred to a "flasher," where the solvent was separated from the other materials and recycled in the production process. After separation of the solvent, the remaining material (residual solvent, up to 22 percent methomyl, and impurities) was transferred to the residue treater. The role of the residue treater was to decompose the remaining methomyl in this liquid to a concentration of no more than 0.5 percent. At that point, this flammable liquid could then be burned for fuel within the facility.

By August 28, methomyl production had begun, although the residue treater had not yet been brought online. There were multiple issues with the production startup that operators were endeavoring to fix, one of which was that the system was depleting solvent faster than expected. This created a need to get the solvent recovery system on line as quickly as possible to replenish the solvent. Because the last stage in the solvent recovery process was the residue treater, that system also needed to be brought online. When beginning the startup of the recovery system, operators failed to prefill the residue treater to the minimum operating level and to heat the liquid to the minimum operating temperature before adding the methomyl. Decomposition of methomyl is an exothermic reaction, therefore it was necessary for safe operation of the system to control of temperature and solvent levels. A control system was designed to prevent addition of methomyl until the solvent was at minimum volume and temperature, but the operators bypassed the safety devices during the startup. In addition, samples taken from the liquid coming from the crystallizer indicated that methomyl concentrations were as much as eight times greater than the specified operating limit, the staff did not have time to review the laboratory results and were unaware of the problem (CSB, 2011).

At 10:25 PM, the residue treater high-pressure alarm sounded, and in response, a control board operator directed two outside operators to check the vent system of the residue treater. Eight minutes later, the vessel exploded and initiated a fire that burned for 4 hours. The explosion killed both operators who were sent to inspect the unit; two other workers onsite and six firefighters were treated for possible toxic chemical exposure at a local hospital.

The Kanawha-Putnam County Emergency Management Director advised more than 40,000 residents, including the resident students at the West Virginia State University directly adjacent to the facility, to shelter-in-place for more than 3 hours (Huntington News Net., 2011). During the emergency, the Bayer CropScience emergency response organization failed to provide timely and accurate information about the incident. In part this was because, continuous air monitors located in and around the production units to detect MIC leaks had malfunctioned in May, causing spurious alarms. The system had not been repaired and restarted even though the MIC storage tank had been refilled. In addition, fence-line monitors were inadequately designed and located for detecting MIC releases (CSB, 2011).

## Emergency Response After 2008

In the wake of the accident, the emergency response systems in place at the facility and in the surrounding area were examined, and a number of recommendations were made by CSB in the areas of communication and planning. The report also noted efforts by local emergency responders (Metro 9-1-1), KPEPC, and Bayer to improve communication between the three groups in the event of an emergency. These efforts included direct telephone lines installed from the facility to Metro 9-1-1 headquarters, development of a method for e-mailing residents in case of a release, increasing call center capacity, and introducing a 15-minute rule for calling an advisory shelter-in-place if an event has been reported but no additional information is available from the facility. Conversations with Matthew Blackwood and Larry Zuspan, representatives from KPEPC in 2011 and testimony provided by Chief Joseph Crawford before Congress in 2009 confirmed that changes to emergency response have been made since the 2008 explosion. CSB also advised modifying KPEPC's Basic Plan and/or the Functional Annex 16, Chemical HazMat Response, to ensure clear delineation of onsite and offsite authority in case of an incident. The relevant changes within the two documents were adopted by KPEPC in May 2011.

In February 2009, as part of a settlement with EPA to resolve issues identified in 2001 at the facility, Bayer agreed to support the following activities as part of supplemental environmental projects (CIC, 2009):

- Funding for a breathing air system for the Kanawha Valley Emergency Preparedness Training Center;

- Equipment for the St. Albans, Jefferson and Institute fire departments;
- Training courses for Kanawha Valley emergency responders; and
- Enhancements for emission dispersion modeling programs for the Metro 9-1-1 center.

Note that informal feedback was received after the public meeting in Institute, West Virginia from a local volunteer firefighter. He expressed concern about availability of emergency equipment in all jurisdictions in the Kanawha Valley. This question was later raised to KPEPC representatives, who stated that they had no knowledge of any particular concern but that efforts were underway to acquire equipment for local fire departments. It is beyond the scope of this study to look further into this question, but asking local personnel for additional input may aid in identification of any gaps in coverage or, if no such gaps are apparent, assist in dissemination of information about available resources.

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# 4

# The Concepts of Inherently Safer Processes and Assessment

## INTRODUCTION

The committee was asked to consider the processes used by Bayer CropScience to manufacture methyl isocyanate (MIC) and carbamate pesticides in Institute, West Virginia, and compare its analysis to "the inherently safer process assessments conducted by Bayer and previous owners of the Institute site." Whereas the preceding chapter provided an overview of the plant and its history to provide background on the development of the processes, this chapter provides an overview to the concept of inherently safer processes (ISPs) and describes the role of ISPs in a process safety management (PSM) system as background for the analysis of the decisions made during those developments. Chapter 5 contains the analysis of alternative methods for production of MIC and the carbamate pesticides produced in Institute, including consideration of ISPs. This chapter also provides an introduction to the role that ISP analyses can play in decision-making. More information about the broader context in which companies manage decision making, and a suggested framework for approaching that process in complex scenarios, is presented in Chapter 6.

## THE ISP CONCEPT

ISP is best described as a philosophy for engineering design of material processing plants, rather than a specific set of technologies or processes. The ISP philosophy can be applied at all stages in the life cycle of a manufacturing plant, from early process invention and research, through development, plant design, operation, and eventual shutdown and demolition, and at all levels of design detail.

It is an approach that encourages the designer to attempt to eliminate or minimize hazards (physical, inhalational, etc.) identified at each stage in the process life cycle, and at every level of process and plant design, rather than accepting the existence of the hazards and designing safety systems to control those hazards. It may not always be feasible to eliminate or reduce hazards, but the ISP philosophy requires that this be attempted before moving on to specification of risk management equipment and procedures. Note that describing a process as "inherently safer" can only be done in the context of specific hazard or subset of hazards and that *management of all hazards must be considered in order to design a safer process*. Thus, a substitution (inherent) might eliminate one type of hazard but require the development of new standard operating procedures (procedural) to manage a different one.

The terms "inherently safer processes" (ISPs),[1] and variations such as "inherently safer technology" (IST) and "inherently safer design" (ISD) were first used in discussions about PSM in the 1970s after serious process industry incidents around that time.[2] These incidents focused industry, government, and public attention on PSM, and resulted in the initial development of many of the PSM techniques and regulations that are in common use throughout the world today.

The ISP philosophy was first fully articulated in 1977 by Trevor Kletz, a senior safety advisor for Imperial Chemical Industries (ICI). That year Kletz presented the Jubilee Lecture to the Society of Chemical Industry in Widnes, England, which he titled "What you don't have, can't leak." In his talk, Kletz challenged the practice of storing large quantities of flammable or toxic materials at manufacturing plants and questioned the need for the use of elevated temperatures and pressures in processing (Kletz, 1978). He also suggested that risk management efforts should aim at elimination of hazards where feasible, instead of using safety systems and procedures to manage the risk. This should be accomplished, for example, by reducing the amounts of hazardous material used in processes, using less-hazardous materials, or developing technology that allows for processes to proceed under milder conditions. Kletz described this as "inherently safer."[3]

In subsequent years, a set of principles for ISPs were established within the chemical community, an effort supported by Kletz (1984, 1985, 1991, 1998) and others in the chemical industry (Puranik et al., 1990; Ashford, 1993; Windhorst, 1995; Mannan, 2005; See also additional references at the end of this chapter). As

[1] The term "inherently safer processes" is used here in accordance with the language of the statement of task.

[2] These included a 1974 explosion at a chemical plant in Flixborough, England that resulted in the deaths of 28 and injuries to another 36 individuals and a 1976 chemical release at Seveso in Milan, Italy that sickened many in the surrounding area.

[3] In his 1977 lecture, Kletz used the term "intrinsically safer." This was later changed to "inherently safer" to avoid confusion with the use of "intrinsically safe" to describe electrical equipment designed to meet specific hazardous area classification requirements.

the principles spread and were adopted, many examples of their implementation emerged. The Center for Chemical Process Safety (CCPS) aggregated this information in the book *Inherently Safer Chemical Processes: A Life Cycle Approach* (Bollinger et al., 1996; CCPS, 2008b). The early versions focused primarily on general concepts, but as acceptance of ISPs by the professional community has grown, the later versions extended the scope to provide more specific guidance on application of those concepts to process design. Today there are a number of working definitions of ISPs, some of which are presented in Box 4.1. In general, these definitions are quite consistent and reflect a consensus of the engineering community on what ISP means.

**BOX 4.1**
**Definitions of Inherently Safer Processes**

**CCPS (2008b, p. 11).** "Inherent safety is a concept, an approach to safety that focuses on eliminating or reducing the hazards associated with a set of conditions. A chemical manufacturing process is inherently safer if it reduces or eliminates the hazards associated with materials and operations used in the process and this reduction or elimination is permanent and inseparable. The process of identifying and implementing inherent safety in a specific context is called inherently safer design. A process with reduced hazards is described as inherently safer compared to a process with only passive, active, and procedural controls. An inherently safer process should not, however, be considered 'inherently safe' or 'absolutely safe.' While implementing inherent safety concepts will move a process in the direction of reduced risk, it will not remove all risks. No chemical process is without risk, but all chemical processes can be made safer by applying inherently safer concepts."

**Kletz and Amyotte (2010, p. 4).** "Intensification, substitution, attenuation, and limitation of effects produce *inherently safer design* because they *avoid* hazards instead of controlling them by *adding* protective equipment. The term *inherently safer* implies that the process is safer because of its very nature and not because equipment has been added to make it safer. Note that we talk of inherently safer plants, not inherently safe ones, for we cannot remove all hazards."

**State of New Jersey and Contra Costa County, California.** New Jersey, in its Toxic Catastrophe Prevention Act (TCPA) (NJDEP, 2009), and Contra Costa County, California, in its Industrial Safety Ordinance

*continued*

**BOX 4.1 Continued**

(Contra Costa Health Services, 1999), require consideration of ISPs as part of their regulation of hazardous industrial facilities. Both regulations cite the 1996 CCPS definition of ISP (Bollinger et al., 1996) (the regulations were issued before publication of the second edition of the CCPS book), which is substantially the same as the 2008 definition above, although not as concisely stated.

**U.S. Department of Homeland Security/CCPS.** The U.S. Department of Homeland Security (DHS), concerned about the potential for intentional release of hazardous materials by terrorist attack, has been interested in ISP as an approach to chemical security. In 2010, the Chemical Security Analysis Center of DHS asked the CCPS to develop a scientific definition of IST (CCPS, 2010, p. Exec 1). A summary of that definition is:

> Inherently Safer Technology (IST), also known as Inherently Safer Design (ISD), permanently eliminates or reduces hazards to avoid or reduce the consequences of incidents. IST is a philosophy, applied to the design and operation life cycle. . . . IST considers options, including eliminating a hazard, reducing a hazard, substituting less hazardous material, using less hazardous process conditions, and design a process to reduce the potential for, or consequences of, human error, equipment failure. . . . IST's are relative. A technology can only be described as inherently safer when compared to a different technology, including a description of the hazard or set of hazards being considered, their location, and the potentially affected population. . . . IST's are based on an informed decision process. Because an option may be inherently safer with regard to some hazards and inherently less safe with regard to others, decisions about the optimum strategy for managing risks from all hazards are required. The decision process must consider the entire life cycle, the full spectrum of hazards and risks, and the potential for transfer of risk from one impacted population to another.

## HIERARCHY OF HAZARD CONTROL

PSM is an interactive, ongoing method for controlling hazards across a facility or organization, with the overall goal of reducing the frequency and/or consequence of an incident. As described in Chapter 2, within the United States, requirements for PSM exist under the Occupational Health and Safety Administration's (OSHA) process safety management standard (OSHA, 29 CFR 1910.119). The PSM standard lists 14 mandatory elements ranging from employee training to process hazard analysis to change management. In practice, PSM is a system that necessitates consideration of multiple options for achieving a safe process and the possible outcomes from each of those options. For example, when determining which hazard management strategy is the best option for a given situation, it is important to understand the effect that any one change in process design may have on all classes of hazard and how that change may affect the type of control strategy required to maintain a safe working environment.

One approach for acknowledging and addressing these trade-offs is to consider a hierarchy of hazard control. The hierarchy contains four tiers, *inherent*, *passive*, *active*, and *procedural*, which are described briefly below.[4,5] Considering these possible hazard control methods in turn can help identify options for process design or modifications to improve process safety.

## Inherent

The inherent approach to hazard control is to minimize or eliminate the hazard. Substituting water for a flammable solvent to eliminate the fire hazard is an example. CCPS identifies four ISP strategies to consider when designing or modifying a process (CCPS, 2008b). As adapted from that volume, one can:

Substitute—use materials, chemistry, and processes that are less hazardous;

Minimize—use the smallest quantity of hazardous materials feasible for the process, reduce the size of equipment operating under hazardous conditions, such as high temperature or pressure;

Moderate—reduce hazards by dilution, refrigeration, process alternatives that operate at less-hazardous conditions; reduce potential impact of an accident by siting hazardous facilities remotely from people and other property; or

Simplify—eliminate unnecessary complexity, design "user-friendly" plants.

Kletz and Amyotte (2010, pp. 16-17) use somewhat different terminology and identify more specific categories (which can be mapped into the four CCPS categories above), but the basic philosophy remains the same. As stated in that reference:

> One person's *intensify* may be another's *minimize*. Someone's *attenuate* may be someone else's *moderate*. You may wish to consider *segregate* as a measure

[4] As with the terminology regarding inherent safety categories, these classifications fall along a spectrum of process safety approaches, and people may disagree about the category into which a particular design falls. For example, some might consider that a high pressure reactor design capable of containing a runaway reaction is an inherently safer design. Others would call this a passive strategy because the hazard—the high pressure from the runaway reaction—still exists, although it is robustly contained by a high pressure vessel.

[5] Not that the use of these terms is not limited to chemical process safety but are also used in consideration of nuclear facility design and management.

> separate from inherent safety; your colleague may consider it a form of *limitation of effects*….the characteristics of a user-friendly plant are sometimes not sharply divided and may merge into one another. Process design, like life, is seldom linear.

The following definitions will be familiar to many in the process industry. These have been summarized and adapted from the 2008 publication *Inherently Safer Chemical Processes: A Life Cycle Approach*, 2nd Edition from the AIChE Center for Chemical Process Safety, and similar definitions can be found in many reference texts on process safety.

### Passive

Passive safety systems are those that control hazards with process or equipment design features without additional, active functioning of any device. For example, a containment dike around a hazardous material storage tank limits a spill to an enclosed area because of the geometry and construction of the dike, and no action is required to provide this function.

### Active

Active safety systems control hazards through controls and systems designed to monitor and maintain specific conditions or to be triggered by an event. Active systems include process controls, safety instrumented systems (SIS), and mitigation systems. A sprinkler system put in place to extinguish a fire is an example of an active system designed to minimize consequences. A control system that regulates solvent flow into a reactor vessel and prevents overflow is an example of a monitoring system.

### Procedural

Procedural safety systems control hazards through personnel education and management. Such systems include standard operating procedures, safety rules and procedures, operator training, emergency response procedures, and management systems. For example, an operator may be trained to monitor the solvent level in a reactor vessel and to shut off the feeds to the tank if the volume exceeds a given quantity.

In general, inherent and passive strategies are the most robust and reliable, requiring the least monitoring or interaction to be effective, but incorporation of strategies from all tiers of the hierarchy should be considered and incorporated as needed for comprehensive PSM. Note that all process safety controls have the potential to reduce the probability or likelihood that a worst-case accident occurs. However, the incorporation of ISP concepts into process design also has the potential to provide assurance that, should a worst-case release occur (i.e., the entire chemical inventory under worst meteorological conditions), an absolute upper bound to the magnitude of an offsite release exists, and that this upper bound is less severe than the worst-case accident resulting from conventional passive, active, and procedural controls.

When performing a process safety assessment, one should consider each level of this process safety "hierarchy" in turn. Quite logically, if the hazard can be controlled with a system that emphasizes inherent safety, active controls will not be necessary. However, since ISP is defined in the context of a specific hazard, the risk of introducing new hazards must be considered. For example, one can describe a process alternative as inherently safer with respect to the acute toxicity of a particular raw material when compared with another alternative. This statement does not say anything about the relative inherent safety characteristics of the two processes with respect to other hazards (fire, explosion, reactive chemistry, chronic toxicity, environmental impact, etc.). These hazards may be greater, reduced, or remain essentially unchanged between the two process alternatives, and the ISP for one hazard may also introduce new concerns.

Thus, it will always be necessary for process plant designers and operators to develop rigorous PSM systems incorporating the appropriate combination of inherent, passive, active, and procedural safety systems to manage *all* hazards. Some will be best managed using inherent methods, but others will inevitably remain and be effectively managed with other PSM systems. One must never assume that it is unnecessary to worry about all elements of PSM because one "inherently safer" process has been implemented.

## INCORPORATING ISP INTO THE PROCESS LIFE CYCLE

The philosophy of ISP applies at all stages, but available options, or the feasibility of implementing those options, change over the course of a technology's life cycle. Every life cycle begins with initial research and product/process conception, and then moves through process development, conceptual plant design, scaleup, engineering and detailed plant design, plant construction, startup, and ongoing operation and future modification (Hendershot, 2011a,b). In each of these phases, different kinds of choices and decisions are made by chemists, engineers, and other technologists. Both the second edition of the CCPS book, *Inherently Safer Chemical Processes: A Lifecycle Approach* and the recent volume by Kletz and Amyotte contain examples of how such analyses can be incorporated into a process hazard analysis, including examples from industry, and each contains additional citations for more information. These descriptions will not be reproduced here. The purpose of this section is not to provide a step-by-step description of how such analyses can be done, but to provide the reader with a broad overview of the elements of the analysis as context for the rest of the report.

There is potential synergy between process simulation and understanding ISP characteristics of a process. Process simulation is a mathematical representation of industrial chemical processes, often used in process design, control, and optimization. Simulations assist engineers in evaluating process alternatives and to identify possible options to, for example, reduce energy consumption, minimize waste, perform cost and benefit studies, and maximize profitability. These tools provide information about process operating conditions and inventory in-process equipment, both of which are important factors in understanding ISP. It may be possible to more explicitly incorporate ISP considerations into process simulation tools, e.g., the inventory of hazardous materials for different process options. Linking process simulation models to accident consequence and likelihood models would have the potential to facilitate the investigation of potential benefits of process alternatives being studied.

It is clear that the best opportunity for implementing ISP into a facility is early in the life cycle of a product or process. At that early stage, process technologies have not been chosen, facilities have not been built, and customers have not yet evaluated product samples or made commitments based on products with particular characteristics. As a product moves through its life cycle, these and other factors may limit options, make changes more difficult, or involve more people and organizations in the change. Development of an ISP, as with the development of any new process, requires extensive resources, including for example, expert personnel, laboratory facilities, pilot plant facilities, and significant financial expenditures, and modifications can become more costly when the process involves modification of an existing facility.

Some typical process life-cycle stages and some examples of ISP options that are best considered at an early stage include:

- **Selection of basic technology.** Consider ISP options for the chemical synthesis route, raw material and chemical intermediate hazards, energetic reactions, etc.
- **Implementation of the selected technology.** Consider how the chosen process chemistry will be implemented. Can hazardous operating conditions be minimized through better catalysts or other changes in operating conditions? Can impurities and by-products be avoided to eliminate purification steps? What specific unit operations are required? What is the order of processing steps?
- **Plant design.** Consider ISP aspects of plant proximity to the surrounding population, in-plant occupied areas, and sensitive environmental areas; the general layout of the equipment on the selected plant site; and the number of parallel systems and size of those system (Hendershot, 2010a).
- **Detailed equipment design.** Minimize the inventory of hazardous material in specific pieces of process equipment. Consider the impact of equipment

layout on the length and size of piping containing hazardous materials. Consider human factors in the design of equipment to minimize the potential for incorrect operation and human error (Hendershot, 2010a).

- **Operation.** Use ISP principles on ongoing PSM activities such as management of change, incident investigation, pre-startup safety reviews, operating procedures, and training to identify new opportunities for ISP.

It is important to consider the entire footprint of a process when evaluating ISP options. Is risk actually reduced, or is it transferred somewhere else, perhaps increasing overall risk? One example used to demonstrate this concept relates to the balance of onsite storage versus increased deliveries of hazardous material (Hendershot, 2006; CCPS, 2010). If a plant reduces the size of a hazardous material storage tank, would the smaller tank size require a change from shipment of the material to the plant in railroad tank cars to much smaller trucks? Such a change could then result in a greater number of shipments overall to meet process requirements (one rail car can hold approximately an order of magnitude more material than a truck). With the additional shipments traveling by road instead of rail, the change in storage tank size could result in greater overall risk from release, depending on details of the transportation route.

It is also important to recognize that an ISP assessment is often not going to result in a clear, well-defined, and feasible path forward for a company. It is a useful philosophy that can help a company reduce its risk and provide structure for consideration of the full range of options in process design. The results of any analysis, however, have to be considered in context. For example, as already described, the inherent safety of one hazard may be reduced and another increased depending on size of a shipment or the mode of transportation of the shipment, or risk may shift from one community well equipped to respond to an emergency to one less able to do so. The cost to eliminate a hazard completely may be prohibitive, but introducing a well-designed passive control system may be feasible. Consideration of these and other, broader trade-offs (community perception, product quality requirements, etc.) should be factored into any final decision.

## ADDITIONAL CONSIDERATIONS

As stated in Manuele (2003), "An organization's culture consists of its values, beliefs, legends, rituals, mission, goals, performance measures, and sense of responsibility to its employees, to its customers, and to its community, all of which are translated into a system of expected behavior." When the philosophy of ISP is incorporated into the culture of an organization, it becomes one of the cultural norms that guide behavior within that organization. Consideration of ISP can then be incorporated into all process and design activities rather than being considered an additional check-the-box exercise.

CCPS (2008) highlighted elements within organizations that can encourage successful adoption of ISP as part of the organizational culture. The first of these is **integration of ISP into the PSM system**. This should include consideration of ISP at all stages in the process life cycle, particularly at three key stages: product and process development, conceptual facility planning and early design, and during routine operation (including modifications and incident investigation). The second element is **education and awareness**. ISP is a philosophy of design; its application should extend beyond just engineering design to plant operation activities. Identifying opportunities to eliminate or reduce hazards should be part of the job for everyone involved in the design and operation of a process facility. This can only happen if there is a broad awareness and understanding of ISP concepts and principles, and these require that education and supporting documentation be made available to personnel.

## RELATIONSHIP BETWEEN EMERGENCY PREPAREDNESS AND ISP

Emergency preparedness (EP is often considered to be an alternative to ISP strategies because EP is a procedural control). However, as is the case with active, passive, and other procedural controls (e.g., personnel training), EP can—and should—be implemented concurrently with ISP, e.g., where Horng et al. (2005) recommended combining source reduction with warning systems to reduce chlorine risks in Taiwan. A closer examination reveals that EP and ISP are closely linked because the latter can be used to reduce the magnitude of incident demands on the onsite and offsite emergency response organizations by reducing the size of the vulnerable zones (VZs) around chemical facilities. Specifically, applying ISP principles to the EPA (1987) procedure for calculating VZs shows that *substitution* decreases VZ size by reducing source toxicity (i.e., level of concern), whereas *minimization* achieves this objective by reducing the quantity available for release, and *moderation* reduces VZ size by decreasing the temperature and pressure of a release.

Smaller VZs reduce the demands on the emergency response organizations by reducing the size of the population at risk. Of particular importance is the fact that smaller VZs often mean that there are smaller *special populations* at risk—such as residents of schools, hospitals, nursing homes, jails, and athletic stadiums (see Lindell and Perry, 2006, Table 1, for a list of special facilities). Special populations generally have more logistical impediments to implementing population protection actions such as evacuation (Van Willigen et al., 2002) and, probably to a lesser extent, sheltering in-place (Sorensen et al., 2004).

Although the adoption of ISP strategies can have a positive effect on nearby offsite risks, it is important to recognize that they can have a negative effect on more remote offsite risks by transferring rather than reducing total risk (see CCPS, 2008b, p. 212). This risk transfer occurs when reducing onsite chemical inventory has the unintended consequence of increasing the number of shipments and thus increasing the probability of releases on transportation routes. This can have an adverse impact on emergency response because releases from onsite sources, by their very nature, take place at locations where they are expected to occur and where there are (relatively) ample resources for emergency response. Releases during transportation, by contrast, take place at unexpected locations where there are likely to be fewer resources to support an emergency response. For example, the sites of transportation incidents will lack the detection and monitoring systems that are often installed around fixed-site facilities. Moreover, the primary responders to transportation incidents will be public sector hazardous materials response teams that are likely to have a relatively limited knowledge of any given chemical, given that hundreds of chemicals might pass through their jurisdictions. By contrast, facility personnel often handle only a few chemicals and thus usually have a deeper knowledge of these chemicals' characteristics and behavior.

Additional information about the relationship between ISP and emergency response and emergency preparedness can be found in Appendix C.

## OPTIONS FOR INCORPORATING ISP IN PSM

There are two common approaches to formal consideration of ISP: independent, stand-alone ISP reviews and incorporation of ISP into existing process safety review activities.

### Independent ISP Reviews

An independent ISP review is conducted by a team that uses knowledge of chemistry, engineering, operation, process safety, and other relevant expertise to examine a process with the objective of understanding its hazards and finding ways to eliminate or reduce those hazards. The review can be done at any stage in the process life cycle from early product and process development through operating facilities. The more established the process, the more difficult and costly it becomes to take advantage of ISP opportunities involving the basic process technology. Thus, early consideration of ISP in product and process selection is important. Major renovation of established facilities also provides an opportunity to reevaluate the basic process technology from an ISP perspective.

The most important tool for an ISP review is an extensive checklist to help the team think about strategies and how they might apply to the process being considered. ISP reviews can draw upon any of the traditional process safety review techniques (e.g., HAZOP,[6] What If, and Checklists) to identify hazards,

[6] HAZOP (Hazard and Operability Analysis) is a method of systematic evaluation of existing processes and operations developed for process hazard analysis and commonly used within the chemical industry.

and then use ISP checklists and principles to help identify opportunities to eliminate or reduce hazards. (See, CCPS, 2008b.) Some organizations have also incorporated incident consequence modeling into these reviews to help the review team understand the magnitude of a potential incident arising from the hazard and the potential benefit of ISP approaches to reducing the incident's consequences. It is important to remember, however, that there are limitations to the use of checklists, and they should be considered only one element of the review and evaluation process.

### Incorporation into Process Safety Reviews

Designers and operators of processing facilities use a series of health, safety, and environmental reviews at various stages in process design, development, and operation as a part of their PSM procedures. The goal is to identify hazards, and in many cases, the focus is on managing or mitigating the hazards through add-on safety devices and procedures once they have been identified.

To include ISP considerations, the protocols for conducting these reviews need to specifically require consideration of ISP opportunities as a part of these reviews. Additional, ISP-specific guide words can be added to guide word-based methodologies, such as HAZOP to encourage ISP consideration. ISP considerations also can be incorporated into all PSM activities, for example, management of change, incident investigation, pre-startup safety reviews, operating procedures, human factors reviews, and any other activities that generate lists of hazards and potential incidents. The important thing is to make sure that the participants in the activity are encouraged and trained to focus initially on eliminating and reducing hazards instead of managing and controlling hazards. This may not always be possible or feasible, but the participants should look for those opportunities rather than just assume that the hazards are present and design systems and procedures to control them.

These two approaches complement each other, and strong PSM programs incorporate both pieces.

## MEASURING INHERENT SAFETY

When incorporating ISP into the PSM system, it would obviously be helpful to have a method for evaluating the inherent safety of any given approach. To that end, a relatively large number of ISP assessment tools exist for attempting to measure the degree of inherent safety of a given process or processing alternative, but there is no current consensus on ISP metrics. These techniques have been reviewed by, among others, Lees (Mannan, 2005, pp. 32.11-32.18), Khan and Amyotte (2003), Khan et al. (2003), and Kletz and Amyotte (2010). Most of these reviews have originated in the academic arena, and in general, these indices have not been applied in industry because they are in early stages of development and their value has not been accepted. One potential problem is that many of the proposed indices consider many different kinds of process hazards—fire, explosion, acute toxicity, chronic toxicity, temperature, pressure, etc.—and use penalty factors to create an overall hazard index. **This means that the creator of the index has applied some kind of evaluation of the relative importance of different hazards**. If, as is often the case, the origin and justification for the relative importance are unclear, appropriate use of the index can be challenging.

One of the earliest efforts to develop an assessment tool was the approximately decade-old INSIDE (*IN*herent *S*HE [Safety, Health, Environment] *I*n *DE*sign) project conducted in Europe, and which resulted in INSET (*IN*herent *S*HE *E*valuation *T*ool), a toolkit "to identify inherently safer design options throughout the life of a process and to evaluate the options" (CCPS, 2008a). There are also well-known process safety methodologies such as checklist and what-if analyses that have been adapted for ISP consideration, primarily in terms of identifying hazards that could be addressed by the principles of inherent safety.

Well-established indexing methods such as the Dow Fire and Explosion Index (F&EI) (Dow Chemical Co., 1994b), the Dow Chemical Exposure Index (CEI) (Dow Chemical Co., 1994a), and the Mond Index (Doran and Greig, 1993) have numerous inherent safety aspects associated with their calculation procedures. The F&EI is a tool designed to help rank hazards in terms of relative physical damage in case of fire or explosion at a facility, and the CEI is a tool to aid in ranking the acute health hazard potentials of materials in the event of an airborne chemical release. The F&EI contains many elements related to ISP—for example, inventory of flammable or combustible material, high temperature, high pressure, exothermic reaction chemistry. However, the F&EI only considers fire and explosion hazards. The CEI was designed to consider material toxicity. Although these indexes have some value in characterizing the inherent safety of a plant, neither was developed with the intention of measuring inherent safety. The Mond Index is similar to the Dow F&EI, but is designed to address a wider range of materials and process and storage configurations.

Etowa et al. (2002) quantified the ISP features of both Dow indexes (F&EI and CEI) and demonstrated the beneficial impact of the principles of minimization, substitution, and moderation. The work of Edwards and coworkers at Loughborough University in the United Kingdom resulted in one of the first indexes designed specifically to address ISP opportunities—the prototype index of inherent safety, or PIIS (Edwards and Lawrence, 1993; Edwards et al., 1996).

Over the past decade there has been a proliferation of ISP indexing procedures and assessment methodologies appearing in the process safety literature. Table 4.1, adapted and updated from Kletz and Amyotte (2010) presents a summary of the literature in the area from 2002-2010.

Observations on the entries in Table 4.1 (again adapted from Kletz and Amyotte, 2010) include the following:

TABLE 4.1 Examples of Development of ISP Assessment Methodologies and Their Application and Extension, 2002-2010

| Reference | Contribution |
|---|---|
| Adu et al. (2008) | Comparative evaluation of various methods for assessing EHS hazards in early phases of chemical process design. |
| Al-Mutairi et al. (2008) | Linking of inherent safety and environmental concerns with optimization of process scheduling. |
| Carvalho et al. (2008) | Method for identifying retrofit design alternatives of chemical processes. Uses Inherent Safety Index (ISI) developed by other researchers. |
| Cordella et al. (2009) | Further development of procedure for decomposition product analysis (Cozzani et al., 2006) to account for acute and long-term harm to human health, ecosystem damage, and environmental media contamination. |
| Cozzani et al. (2006) | Procedure for assessment of hazards arising from decomposition products formed due to loss of chemical process control. Applicable to consideration of substitution principle. |
| Gentile et al. (2003) | Fuzzy-logic-based index for evaluation of inherently safer process alternatives with the aim of linking to process simulation. |
| Gupta and Edwards (2003) | Graphical approach for evaluating inherent safety based on earlier developed Loughborough Prototype Index of Inherent Safety (PIIS). |
| Hassim and Hurme (2010a) | An Inherent Occupational Health Index was developed to assess the health risk of process routes during the process research and development stage. The index can be used to compare process routes or to determine the level of inherent occupational health hazards. |
| Hassim and Hurme (2010b) | The Health Quotient Index (HQI) was developed for assessment during the preliminary process design phase. This index quantifies a worker's health risk from exposure to fugitive emissions by using data from process flow diagrams. This method can be used to quantify the level of risk from a process or to compare alternative processes. |
| Hassim and Hurme (2010c) | The Occupational Health Index (OHI) was developed for assessment during the basic engineering stage. "This method relies on the information available in piping and instrumentation diagrams and the plot plan." The health aspects considered are chronic and acute inhalation risks, and dermal/eye risk. |
| Hassim and Hurme (2010d) | This method estimates inhalation exposures and risks and can be used early in the design stages by utilizing process flow diagrams. The risk of chemical exposure can be evaluated through either the "hazard quotient method or calculating the carcinogenic chemicals intake and the resulting risk of cancer." |

TABLE 4.1 Continued

| Reference | Contribution |
|---|---|
| Hassim and Edwards (2006) | Process Route Healthiness Index (PRHI) for quantification of health hazards arising from alternative chemical process routes. Application is in early stages of chemical plant design. |
| Hurme and Rahman (2005) | Discussion of implementation of inherent safety throughout process life-cycle phases. Use of ISI developed earlier. |
| Khan and Amyotte (2004) | Integrated Inherent Safety Index (I2SI). |
| Khan and Amyotte (2005) | Further development of I2SI to include cost model. |
| Kossoy et al. (2007) | Use of nonlinear optimization method to select inherently safer operational parameters for given configuration of reactor equipment and materials. Primary concern is cooling failure. |
| Landucci et al. (2007) | Procedure and indexes for evaluating inherent safety at preliminary process flow diagram (PFD) stage for hydrogen storage options. |
| Landucci et al. (2008) | Further development of PFD method (Landucci et al., 2007) by use of quantitative key performance indicators (KPIs) to remove subjective judgment. |
| Leong and Shariff (2008) | Further development of iRET (Shariff et al., 2006) to incorporate a quantitative inherent safety level (ISL), thus enabling integration of design simulation software with an Inherent Safety Index Module (ISIM). Application is again at the preliminary design stage. |
| Leong and Shariff (2009) | Evolution of ISIM (Leong and Shariff, 2008) to a Process Route Index (PRI) for comparison and ranking of different routes to manufacture the same product based on hazard potential of routes. |
| Meel and Seider (2005) | Use of game theory to achieve inherently safer operation of chemical reactors. |
| Palaniappan et al. (2002a) | "Methodology for the integrated inherent safety and waste minimization analysis during process design." |
| Palaniappan et al. (2002b) | Indexing procedure for inherent safety analysis at process route selection stage. |
| Palaniappan et al. (2002c) | Indexing procedure for inherent safety analysis at process flowsheet development stage. Discussion of *i*Safe, an expert system for automating procedures developed by Palaniappan et al. (2002b,c). |
| Rahman et al. (2005) | Comparative evaluation of three ISIs with expert judgment at process concept phase. |
| Rusli and Shariff (2010) | This paper presents the Qualitative Assessment for Inherently Safer Design (QAISP) method for application during preliminary design. This qualitative method combines hazard review techniques with inherently safer design concepts to generate inherently safer plant options/proactive measures. |
| Shah et al. (2003) | SREST (substance, reactivity, equipment, and safety technology) layer assessment method for environment, health, and safety (EHS) aspects in early phases of chemical process design. |

*continued*

TABLE 4.1 Continued

| Reference | Contribution |
|---|---|
| Shariff and Leong (2009) | This paper proposes a method of evaluating inherent risk within a process as a result of the chemicals used and the process conditions. Through integration with HYSYS, the method can be used as early as the initial design stages to determine the probability and consequence of possible risk due to major accidents. |
| Shariff and Zaini (2010) | This paper reports on the development of Toxic Release Consequence Analysis Tool (TORCAT), a "tool for consequence analysis and design improvement via inherent safety principle by utilizing an integrated process design simulator with toxic release consequence analysis model." |
| Shariff et al. (2006) | Integrated Risk Estimation Tool (iRET) for inherent safety application at preliminary design stage. iRET links the design simulation software HYSYS with an explosion consequence model. |
| Srinivasan and Kraslawski (2006) | Application of TRIZ methodology for creative problem solving to design of inherently safer chemical processes. |
| Srinivasan and Nhan (2008) | Inherent Benign-ness Indicator (IBI), a statistical-analysis-based method for comparing alternative chemical process routes. |
| Tugnoli et al. (2009) | A quantitative inherent safety assessment method is presented. This method utilizes process flow diagrams in early design stages. The result of the assessment is a quantification of the inherent safety of the process scheme by a set of key performance indicators. |

SOURCE: Adapted from Kletz and Amyotte (2010) and supplemented with additional citations from the literature from late 2009-2010.

- Many of the methods deal specifically with the early concept and route-selection stages of the design process.
- Some of the approaches use sophisticated mathematical and problem-solving techniques such as fuzzy logic.
- There has been a growing trend to link inherent safety with environmental and health issues in an effort to achieve an integrated approach.
- There have been attempts to incorporate inherent safety assessment into process design simulators, and these efforts should be encouraged.
- Some of the indexing methods have been in existence long enough for comparative evaluations to be made among them.

When commenting in 2005 on potential barriers to wider adoption of inherently safer design principles in the process industries, Edwards (2005) noted that the issue may not be the availability of ISP assessment tools but rather the limited use of these tools by industry. Reasons might include the subjective judgment required by some of these tools and also their attendant complexity (Kletz and Amyotte, 2010). In 2011, it appears that the same availability of tools, yet limited uptake by industry, exists. Additional concerns surround the incorporation of ISP and PSM analysis into the business decisions a company must make. This is discussed in greater detail in Chapter 6.

Another approach that considers some important aspects of ISP, is consequence analysis of potential incidents. Estimates of the potential impact of an incident will include evaluation of the effect of inventory of hazardous material, flammable and toxic properties, plant operating temperatures and pressures, plant location, and other factors. Designers considering ISP alternatives for a process can model consequences associated with potential design options and understand whether the proposed ISP options have a significant impact on incident consequences. However, modeling and evaluating potential probabilities and impacts of system failures (worst-case accidents) can present their own challenges, especially with regards to modeling human behavior. This can lead to flawed evaluations in terms of emergency response and risk communication needs. This is described in greater detail in Box 4.2.

**BOX 4.2**
**ISP and Probability Safety Analysis**

Assessments about the safety of systems comprising conventional active, passive, and procedural controls are typically based on probabilistic safety analyses (PSAs) that estimate the probability of a worst-case accident from three inputs. These are (1) a probabilistic safety model (e.g., a mathematical model such as a fault tree or event tree) that identifies the events, such as process component and engineering safety feature (ESF) failure, that are required to produce a release; (2) the estimated probabilities of those events; and (3) the logical interrelationships among those events. The probabilistic safety model is used to combine the estimated probabilities of the individual events (component or ESF failure) to produce the estimated probability of the worst-case accident.

Once a probabilistic safety model has been developed, it can be used to compare the accident probabilities associated with different plant/process designs. Ultimately, the mathematical model is often used to determine when the probability of the worst-case accident has been decreased to a level that is acceptable to plant management. However, it is important to recognize that any mathematical model is a simplification of reality that ignores factors the analyst considers to have minimal effects on the probability of an offsite release. In addition, probabilistic

*continued*

**BOX 4.2 Continued**

safety models sometimes ignore factors for which there are no available data or for which there is no established procedure for including them in the analysis.

One common problem in probabilistic safety models is that they are applied to systems composed of both people and technical systems but only the technical (equipment) components are modeled. This problem is being addressed in techniques that address human reliability (e.g., Swain and Guttman, 1983; Gertman et al., 2005; Spurgin, 2010) but human reliability is not always considered in plant PSAs.

Another common problem in probabilistic safety models is that the builders of the model often assume that the events in the model are independent. This assumption is violated when a common cause can fail multiple process components or ESFs, such as when an earthquake simultaneously fails a pipe carrying a toxic chemical, the secondary containment for that pipe, the flare tower, and the water curtain. Less obviously, the independence assumption is violated when a single operator fails to properly control multiple ESFs, a single maintenance person fails to properly maintain multiple ESFs, a single manager fails to properly supervise multiple operators or maintainers, or when an organizational unit's safety culture tolerates inadequate performance. Such dependencies could be included in the model, but often this is not done.

The neglect of human reliability and event dependence in probabilistic safety models leads to systematic underestimates of incident probabilities. However, such underestimates will not create significant problems when two system designs being compared that are very similar in their susceptibility to human error and common-cause failures. This is because in such cases comparison of similar system designs by subtraction of the failure probability of one system from the failure probability of the other yields the correct *difference* even if both of the *absolute* estimates are biased. For example, suppose the estimated failure probability for System 1 is $P_{E1}$ (which equals $P_{T1}$ - $P_B$, where $P_{T1}$ is the true failure probability for System 1 and $P_B$ is the bias due to omitted error causes) and, similarly, the estimated failure probability for System 2 is $P_{E2}$ (which equals $P_{T2}$ - $P_B$, where $P_{T2}$ is the true failure probability for System 2 and $P_B$ is again the bias due to omitted error causes). The difference between the estimated failure probabilities for the two systems is unbiased as long as the omitted error causes are the same in both systems because $P_{E2} - P_{E1} = (P_{T2} - P_B) – (P_{T1} - P_B) = P_{T2} - P_{T1}$. The difference between the estimated failure probabilities for the two systems is unbiased as long as the omitted error causes are the same in both systems because $P_{E2} - P_{E1} = (P_{T2} - P_\varepsilon) – (P_{T1} - P_\varepsilon) = P_{T2} - P_{T1}$. By contrast, the absolute estimates of failure probability (i.e., the differences of $P_{E2}$ and $P_{E1}$ from zero) are biased to the extent that failure causes have been omitted from the probabilistic safety model. This illustration explains why it is so important to compare probabilistic safety analyses of (relatively) similar systems and to be very skeptical of estimates of absolute failure probabilities. Unless the failure modes for both systems are identical, the bias in each estimate may not be the same in which case the probability models may not be useful even for comparing alternative systems unless they are corrected to account for common-cause failures and human errors.

One consequence of underestimating the failure probability of a conventional system of active, passive, and procedural controls is that such underestimates make ISP strategies seem to be less advantageous than they would be if the failure probability of a conventional system of active, passive, and procedural controls were accurately estimated. If the magnitude of the underestimate were known to be small, then there would be little reason to be concerned about it. However, the magnitude of the underestimate is not known, but the evidence from published post-accident investigations suggests that it might be sufficiently large that conventional strategies of active, passive, and procedural controls are being chosen in situations where ISP strategies might produce significantly greater levels of safety at reasonable cost. To avoid this problem of underestimation, PSAs need to more carefully consider human reliability, common-cause errors and, in particular, organizational safety culture.

Another consequence of underestimating the failure probability of a conventional system of active, passive, and procedural controls is that such underestimates can lead to a neglect of offsite emergency response and emergency preparedness because of the belief that they are unnecessary. Consequently, plant personnel have insufficient familiarity with offsite agencies emergency plans and procedures to work effectively with them when emergencies occur. This can lead to major problems in the implementation of warning and protective actions (shelter in place or evacuation) of nearby residents.

Finally, underestimating the failure probability of a conventional system of active, passive, and procedural controls hinders risk communication with other stakeholders. In many cases, community groups focus on the worst-case accident and have relatively little interest about the estimated probability of that event. By contrast, plant personnel typically focus on the (estimated) low probability of a worst-case accident and believe that this justifies a low priority for what they consider to be only marginally greater safety at significantly greater cost. The disagreements are likely to be particularly acute if community groups mistrust plant management and, thus, have low confidence in the effectiveness of a conventional system of active, passive, and procedural controls.

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# 5

# MIC and Pesticide Production at the Institute Plant: Alternatives Assessment

## INTRODUCTION

In this chapter, possible alternative methods for production of methyl isocyanate (MIC) and carbamate pesticides at the Bayer CropScience facility are presented. This chapter directly addresses Tasks 2 and 3.1 of the committee's statement of task. Before beginning, however, it is important to address two points.

First, when the committee began its work, there was an assumption that Bayer CropScience would be restarting production of MIC and the carbamate pesticides. Were that to be done, then a "[r]eview [of] current and emerging technologies for producing carbamate pesticides, including carbaryl, aldicarb, and related compounds." (SOT, Task 2) would potentially have value for the company. During the course of the study, however, Bayer CropScience (Bayer) announced they would not be restarting production of MIC. This was based on a combination of the factors described in Chapters 1 and 3 including deregistration of aldicarb, carbosulfan, and carbofuran with the U.S. Environmental Protection Agency (EPA) and the continued economic viability of the other pesticides manufactured at the facility. In light of these changes, the committee determined that an in-depth review of the field as a whole would provide little value to the sponsor or the reader beyond what a targeted review of processes considered by Bayer and the legacy owners of the facility would provide. Thus, the analyses presented in this chapter focus on those processes identified by the current and former owners as most likely to meet the manufacturing needs of the Institute facility.

Second, the process assessments presented here may be incomplete because the analysis is based in large part on materials provided by Bayer CropScience that were generated by former site owners, primarily Rhône-Poulenc. At the first meeting of the committee, Dr. Steven Smythe speaking on behalf of the company, stated that 29 routes to MIC production had been identified, and four had been evaluated in greater detail. Although the materials relating to the alternatives and their evaluation were provided to the committee for review in good faith, the documentation was rather disjointed and discontinuous, with documents ranging from undated handwritten notes without attribution to in-depth typewritten analyses of findings.

Therefore, the process assessments presented here are drawn from documents provided by Bayer and from the current academic and patent literature. Information gaps within the historic documents could result in gaps within these assessments.

## ALTERNATIVES ASSESSMENT

In considering the adoption of a new or redesigned process, it is helpful to break down the impact that the proposed redesign would have on the elements outlined in Chapter 4, namely selection of basic technology, implementation of the selected technology, plant design, detailed equipment design, and impact on operations. The options facing the facility's owners—Bayer CropScience today and the legacy companies in the past—were (1) continuing with the existing process, (2) adopting an alternative chemical process not involving MIC, (3) using an alternative process involving MIC production that would consume MIC immediately (just-in-time) and thus not require storage, and (4) reducing the volume of stored MIC and the risks of transporting MIC from one facility within the site to another by rearranging process equipment. Each of these has implications for the facility as a whole, and the technical considerations for them are presented below. However, a key motivation for this NRC study is to evaluate whether Bayer could have identified a superior process for manufacturing pesticides at the Institute facility that would have reduced risks to the surrounding communities.

Any potential changes proposed by Bayer CropScience were compared to the processes in place in 2008, referred to here as the "existing process," for the chemistry and production methods in place at that time.

### Production of MIC

There are a number of possible methods for production of MIC. This chemistry has been used for decades, and much has been written about the possible paths for production. In light of Bayer's decision to no longer produce or store large quantities of MIC onsite, a full evaluation of every possible alternative method of production is not presented here. Rather, this section describes four methods evaluated by Bayer and previous owners of the facility. The evaluations of these processes and the role those evaluations played in Bayer's decision making are described in Chapter 6.

In 2010, Bayer identified four alternative processes for generating MIC (referred to here as DuPont, cyanate, diphenylcarbonate, and Enichem) based in part on earlier evaluations conducted by prior owners of the Institute site. The company stated that data for their analyses were derived in part from the following sources (Smythe, 2011):

- **The Union Carbide Corporation (UCC) process.** Current operating data and cost
- **DuPont.** Stanford Research Institute Report and internal evaluation performed by Rhône-Poulenc
- **Cyanate.** Patent literature between 1973 and 1985
- **Diphenylcarbonate.** Domagen operating costs and conditions between 1971 and 2002
- **Enichem.** Patent literature from 1975 and internal evaluation performed by Rhône-Poulenc

All four of the processes generate MIC in a gaseous form, rather than a liquid form, which would have necessitated some adjustments to the downstream production processes at Institute to be used directly or incorporation of a recovery step to condense or capture liquid-phase MIC. In addition, none of the processes had been run at a scale similar to the existing MIC process at Institute.

Note that all process flow diagrams below were provided by Bayer CropScience to the committee.

### *The Union Carbide Corporation (UCC) Process in Institute*

The synthetic method for the production of MIC has remained largely unchanged since 1966, when production began in Institute. In this process, developed by Union Carbide, phosgene ($Cl_2CO$) and methyl amine ($CH_3NH_2$, MMA) are combined to form *N*-methyl carbamoyl chloride ($C_2H_4NClO$, MCC), from which hydrogen chloride (HCl) is eliminated to generate MIC. See Figure 5.1.

The MCC generation takes place at high temperature and low pressure in a reactor with a specialized design that permits very fast reaction times and complete conversion of MMA to MCC, followed by a pyrolizer to split MCC into

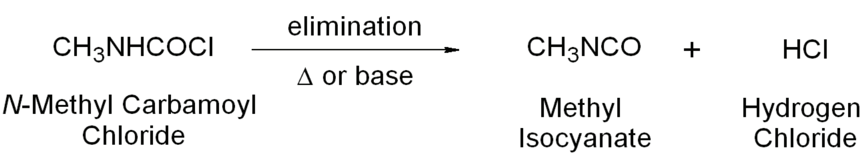


FIGURE 5.1 Synthesis of MIC from *N*-methyl carbomoyl chloride, as used at the Bayer CropScience facility.

MIC and HCl. The pyrolizer has an inclined orientation to separate the HCl from the MIC, avoiding any re-formation of MCC. The process, as used at the Bayer CropScience facility, produced extremely pure MIC (99.9 percent), which was then stored in liquid form before being transferred for use in production of carbamate pesticides. A diagram of the process and the equipment used for production of MIC is shown in Figure 5.2.

### *DuPont Process*

In 1985, DuPont developed a methylformamide oxidation process to make its own MIC when the Union Carbide facility halted production following the Bhopal disaster (Carcia, 1984; Rao, 1985). The DuPont process combines monomethylamine and carbon monoxide to provide *N*-methylformamide (see Figure 5.3). The *N*-methylformamide is then oxidized with oxygen/palladium (through an air intake) at very high temperatures to generate gaseous MIC and water. To prevent the MIC from reacting with the water, it is almost immediately fed into a process to produce methomyl and oxamyl carbamate pesticides.

When Rhône-Poulenc considered the plausibility of developing this method for producing MIC at the Institute facility, concerns, such as whether downstream

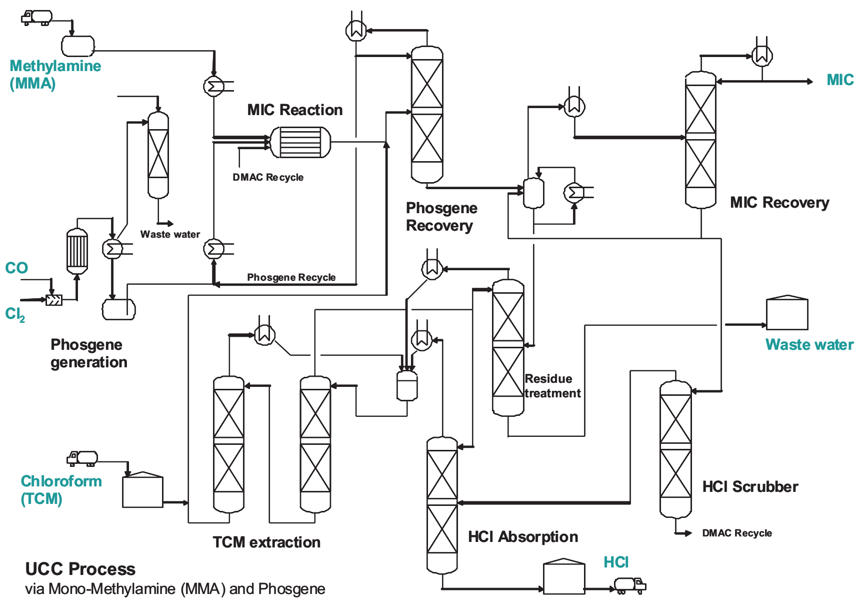


FIGURE 5.2 Process flow diagram for production of MIC via mono-methylamine and phosgene (UCC process).
SOURCE: Smythe (2011).

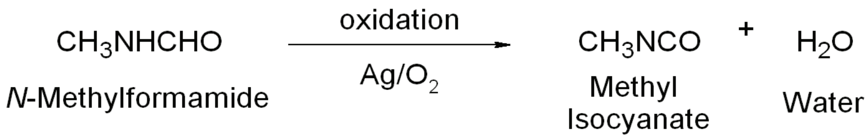


FIGURE 5.3 Synthesis of MIC from *N*-methylformamide, used by DuPont.

pesticide production could continue with the vapor phase MIC or if recovery of liquid MIC was required, had to be considered. If the vapor phase could be used, then this process would have the advantage of using MIC as soon as it is produced (just-in-time production). DuPont's production facility in LaPorte, Texas is able to use vapor phase MIC, so there is no MIC storage on site, and since it is produced as a gas rather than a liquid, only a small amount of MIC is in the system at any given time. However, according to Bayer's analysis, the concentration of impurities in the MIC generated using the DuPont process is higher than with the UCC process.

### *Cyanate Process*

The cyanate process has been used in South Africa, and it is currently used as a method for making MIC in Asian countries. This method combines potassium or sodium cyanate and dimethyl sulfate in an aromatic solvent to generate MIC and potassium or sodium sulfate (See Figures 5.4 and 5.5). This is one of the earliest methods for synthesis of isocyanates reported in the literature, having been discovered by Alfred Wurtz in 1849.

In contrast to the DuPont process, but similar to the UCC process, the cyanate process is a batch process and requires some capacity for storing MIC. The yield of MIC was reported in a patent awarded in 1980 as on the order of 80-85 percent relative to added potassium cyanate (Giesselmann et al., 1980).

An important consideration any company contemplating adoption of this process is the amount of waste generated as a result of this reaction, which is roughly 1.5 kg of solid $K_2SO_4$ or $Na_2SO_4$ waste per kg of MIC produced.

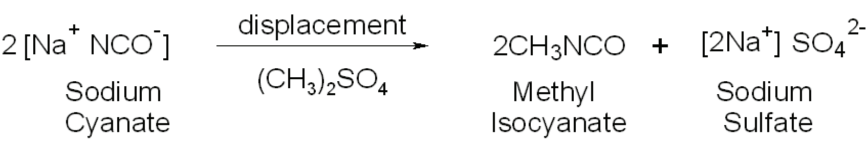


FIGURE 5.4 Synthesis of MIC from sodium cyanate, used in the cyanate process.

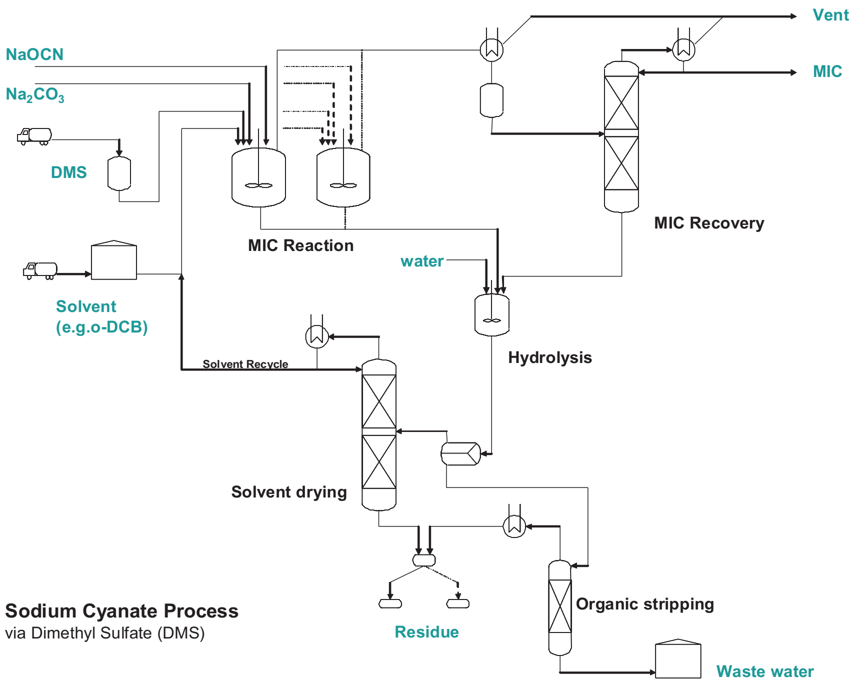


FIGURE 5.5 Process flow diagram for production of methyl isocyanate via dimethyl sulfate and sodium cyanate (cyanate process).
SOURCE: Smythe (2011).

### *Bayer Diphenylcarbonate and Dimethylurea Process*

Bayer used a diphenylcarbonate process to make MIC at its Dormagen plant between 1971 and 2002, combining diphenylcarbonate with dimethylurea (Kober and Smith, 1968). In this method, the dimethylurea and diphenylcarbonate are heated to form MIC and phenol via an exchange-replacement-elimination sequence (See Figure 5.6).

The diphenylcarbonate process has the advantage of not requiring chlorine or phosgene as inputs, but it does generate large amounts of phenol, although this can be recovered by cooling the product mixture and recycling for use in the production of diphenylcarbonate. The diagram in Figure 5.7 shows the process.

### *Enichem Diphenylcarbonate Process*

Enichem, a chemical company based in Europe, also had a process to make MIC that combined diphenylcarbonate with methylamine (Romano et al., 1984;

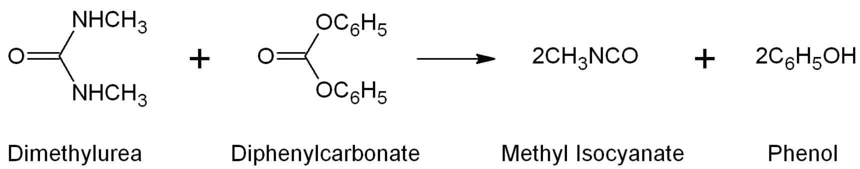


FIGURE 5.6 Synthesis of MIC from diphenylcarbonate and dimethylurea, used in the diphenylcarbonate process.

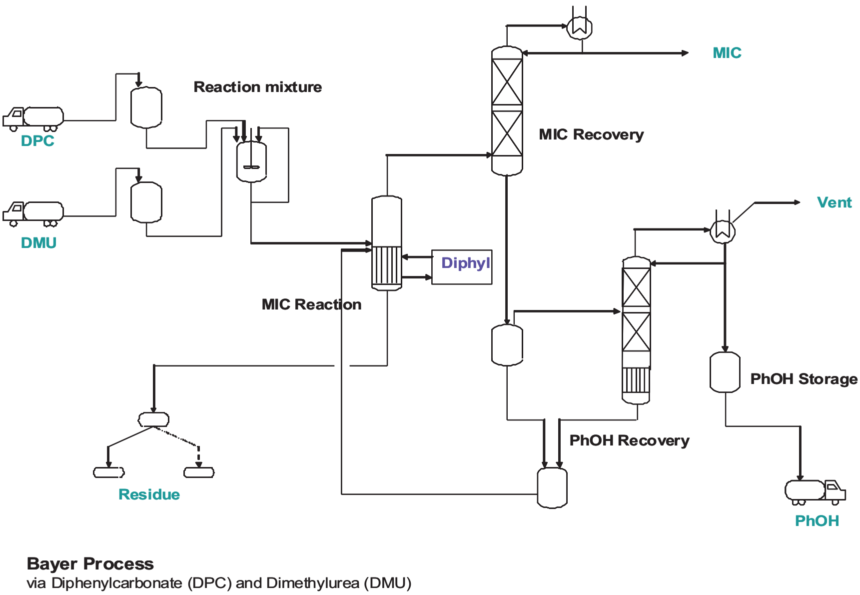


FIGURE 5.7 Process flow diagram for production of MIC via diphenylcarbonate and dimethylurea (Bayer diphenylcarbonate process).
SOURCE: Smythe (2011).

Rivetti et al., 1987) (see Figure 5.8). As with Bayer's diphenylcarbonate process, the Enichem diphenylcarbonate process is essentially a replacement-elimination reaction. The two reactants are mixed and heated to form *N*-methylcarbamate, also known as phenyl-*N*-methylurethane, and phenol. Further heating leads to the elimination of MIC and additional phenol. The mixture is then cooled to remove the phenol and remaining *N*-methylcarbamate allowing MIC to undergo additional purification steps (see Figure 5.9). Because phenol is also a by-product of the Enichem reaction, manufacturers using this method must consider whether to dispose of or recycle this material.

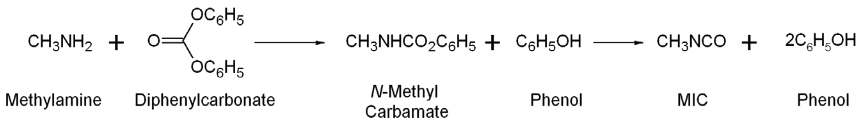


FIGURE 5.8 Synthesis of MIC from diphenylcarbonate and methylamine, used in Enichem diphenylcarbonate process.

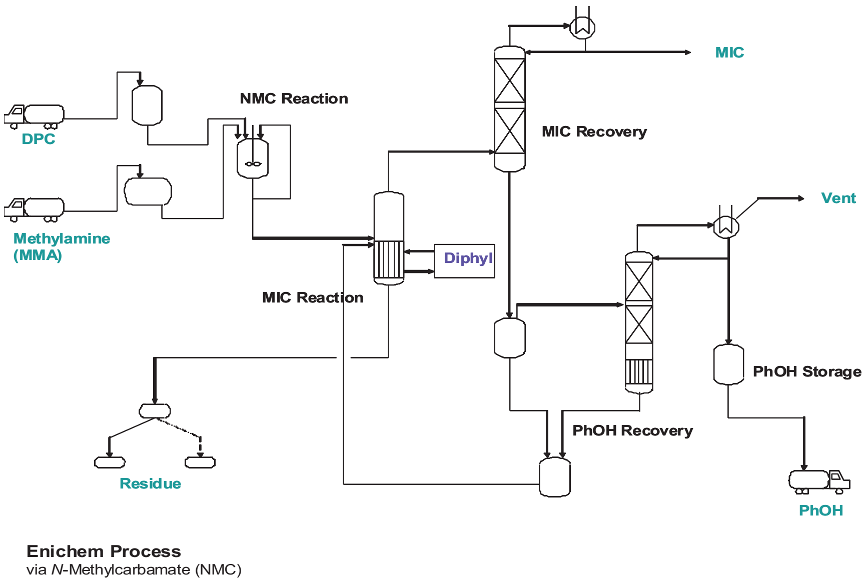


FIGURE 5.9 Process flow diagram for production of MIC via *N*-methylcarbamate (Enichem process).
SOURCE: Smythe (2011).

In the late 1980s, Rhône-Poulenc considered this option in great detail, including the manufacture of diphenylcarbonate onsite from dimethylcarbonate and phenol, which would negate the need for phosgene in the production of diphenylcarbonate. The company then engaged with Enichem to evaluate the feasibility of adopting and licensing this process from Enichem in Institute, West Virginia.

## Carbamate Pesticide Production

MIC was produced at the Institute facility to act as a reactant in the synthesis of carbamate pesticides. In this section the focus is primarily on the possible technical alternatives for production of carbamate pesticides at the Institute facility. The assumption that carbamate production would continue was implicit in the Committee's Statement of Task, which focused on identifying different technologies for producing carbamate pesticides and possible approaches for reducing or eliminating the use of MIC in their production. A broader range of alternatives could be considered, including not making any carbamate pesticides, or even not making any pesticides at all, which reduce safety risks. However, such alternatives could lead to a different set of risks to society—such as, losses of crop production, higher prices for food, possible starvation in developing countries unable to afford higher food costs, etc. Alternative processes that lead to lower quality and reduced effectiveness in the resulting pesticides, also relate to the overall benefits of the pesticide under consideration.

Consideration of the various nonprocess alternatives are discussed briefly in Chapter 6 when ways to quantify the benefits and costs from different production processes are described.

### *Alternative Production Methods for Carbamate Pesticides*

The carbamate pesticides in production in Institute in 2008 were all *N*-monomethyl carbamates, with carbaryl, aldicarb, and thiodicarb the primary pesticides produced onsite. The chemical reactions used to produce these pesticides are summarized in Figure 5.10. There are two reaction types available for the final step in synthesizing carbamate pesticides: additions to MIC and replacements in carbamates and carbonates (second and third equations of 5.10). The different pesticides are characterized by differences in the R group and physical formulations, but the underlying synthetic chemistry is similar. Specific applications of the carbamate synthesis equations are shown in Figure 5.11. An early

$$CH_3NCO + HOR \xrightarrow{\text{addition}} CH_3NHCO_2R$$

$$CH_3NHCOX + HOR \xrightarrow{\text{replacement}} CH_3NHCO_2R + HX$$

$$CH_3NH_2 + OC(OR)_2 \xrightarrow{\text{replacement}} CH_3NHCO_2R + HOR$$

FIGURE 5.10 Possible methods for synthesis of *N*-monomethyl carbamate pesticides. These equations represent the generic forms of the possible synthetic pathways discussed later in this chapter.

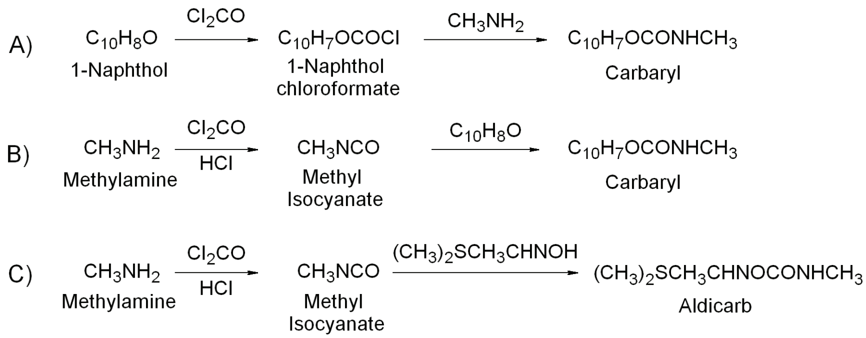


FIGURE 5.11 Synthesis routes for the production of carbaryl (without and with MIC) and aldicarb (with MIC). (A) A synthetic route for production of carbaryl without the use of MIC; (B) A synthetic route for production of carbaryl using MIC; and (C) A synthetic route for the production of aldicarb using MIC.

non-MIC process for carbaryl is shown in the first equation. The MIC-based syntheses of carbaryl and aldicarb are shown in the second and third equations. The most recent processes used by Bayer, DuPont, and Enichem to produce carbamate pesticides (described earlier) all use MIC.

*Carbaryl*

The first carbamate pesticide in production at the Institute plant was carbaryl. This broad-spectrum pesticide has relatively moderate toxicity to mammals, and it is commonly found in both agricultural and residential uses. It has a demonstrated toxicity for aquatic life (EPA, 2004), and environmental release is a concern for users of carbaryl. See Tables 5.1 and 5.2.

Carbaryl was originally produced with a non-MIC-based chloroformate process (see Figure 5.11) using intermediates produced elsewhere, and this process was used for many years (1961-1977). In this reaction, 1-naphthol is reacted with phosgene to create a chloroformate. Reaction of the chloroformate with methylamine results in the formation of carbaryl. In 1978, the production process for carbaryl was changed to use MIC. See Figure 5.12 for a flow diagram of this process. The reasons given for the change were that the chloroformate process was highly corrosive, had lower yield, and generated considerable waste products. One internal report stated that with the change in process, the yield of carbaryl went from 86 percent to 92 percent with respect to 1-naphthol with a purity of 99 percent (Peck, 1978). Production of carbaryl then became the largest volume consumer of MIC at the Institute plant. At one point, because of high demand for the product, 40 million pounds of MIC was produced annually. In 2008, the

TABLE 5.1 Acute Toxicity Categories for Carbaryl

| Guideline No. | Study | MRID No. | Results | Toxicity Category[a] |
|---|---|---|---|---|
| 81-1 | Acute oral—rat (99% a.i.) | 00148500 | $LD_{50}$ for males = 302.6 mg/k; for females = 311.5 mg/kg; combined = 307.0 mg/kg | II |
| 81-2 | Acute dermal—rabbit (99% a.i.) | 00148501 | $LD_{50}$ > 2000 mg/kg | III |
| 81-3 | Acute inhalation—rat (99% a.i.) | 00148502 | $LC_{50}$ > 3.4 mg/L | IV |
| 81-4 | Primary eye irritation—rabbit (99% a.i.) | 00148503 | Not a primary eye irritant | IV |
| 81-5 | Primary skin irritation—rabbit (99% a.i.) | 00148504 | Not a primary skin irritant | IV |
| 81-6 | Dermal sensitization—guinea pig (99% a.i.) | 00148505 | Negative | NA |

[a]I, highly toxic, severely irritating; II, moderately toxic, moderately irritating; III, slightly toxic, slightly irritating; IV, practically non-toxic, not an irritant.
SOURCE: EPA (2004).

process used a continuous fixed bed reactor run for 12 days followed by shutdown for 3 days to dissolve the accumulation of solids from the reactor (Martin, 2011).

### *Aldicarb*

The Institute plant began producing aldicarb in 1976 (equation 5.11). Bayer personnel stated that of all the carbamates being produced at Institute, aldicarb was most clearly dependent on the use of the highly purified MIC generated from the existing Institute process. The primary uses of this pesticide are in early applications in commercial agriculture to control nematodes and sucking insects (U.S. EPA, 2010). In contrast to carbaryl, aldicarb and its metabolites are highly toxic through oral, dermal, and inhalational routes of exposure. Aldicarb is also toxic to fish and aquatic invertebrates. To render it safe to use, the aldicarb was processed into granules that reduced generation of dust and facilitated handling of the material, which in turn reduced exposure to the users.

The MIC-based aldicarb production process used a batch reactor, with an extended cook-out period that generated a complete reaction (see Figure 5.13). This material was then shipped to Woodbine, Georgia for binding onto particles of gypsum. This method necessitated a very clean coating of the pesticide being deposited on the particles of gypsum in the final formulation. Any impurities in the MIC could lead to imperfections in the coating, resulting in serious problems with clumping of the final product in the applicators. Such impurities could also

TABLE 5.2 Typical Human Hazard and Precautionary Statements

| Toxicity Category | Systemic effects (oral, dermal, inhalation toxicity) | Irritation effects (skin and eye) | Sensitizer[a] |
|---|---|---|---|
| I | Fatal (poisonous) if swallowed [inhaled or absorbed through skin]. Do not breathe vapor [dust or spray mist]. Do not get in eyes, on skin, or on clothing. [Front panel first-aid statement required.] | Corrosive, causes eye and skin damage [or skin irritation]. Do not get in eyes on skin, or on clothing. Wear goggles or face shield and rubber gloves when handling. Harmful or fatal if swallowed. [Front panel first-aid statement required.] | If product is a sensitizer: Prolonged or frequently repeated skin contact may cause allergic reactions in some individuals. |
| II | May be fatal if swallowed, [inhaled or absorbed through the skin]. Do not breathe vapors [dust or spray mist]. Do not get in eyes, on skin, or on clothing. [Appropriate first-aid statement required.] | Causes eye [and skin] irritation. Do not get in eyes, on skin, or on clothing. Harmful if swallowed. [Appropriate first-aid statement required.] | |
| III | Harmful if swallowed [inhaled or absorbed through the skin]. Avoid breathing vapors [dust or spray mist]. Avoid contact with skin [eyes or clothing]. [Appropriate first-aid statement required.] | Avoid contact with skin, eyes, or clothing. | |
| IV | No precautionary statements required | No precautionary statements required. | |

[a]There are no categories of sensitization.
SOURCE: 40 CFR § 156.62.

lead to greater formation of dust with correspondingly higher health risks. These issues were identified as a serious problem with most alternative sources of MIC, which tended to produce MIC of lower purity, which would in turn affect production of aldicarb. Figure 5.13 shows a simple process flow diagram for production of aldicarb.

### *Other Carbamates*

Other carbamate pesticides (utilizing MIC) were also in production at Institute in 2008, but were not analyzed by the Committee for reasons described below. These pesticides include thiodicarb (Larvin), carbosulfan (Marshal), methomyl, which used a continuous plug flow reactor; and carbofuran (Furadan), which used a solventless process. The carbofuran unit was owned by FMC and operated by Bayer. When the Committee's investigation began, Bayer had already decided to shut down production of methomyl and carbofuran after the 2008 accident. Pro-

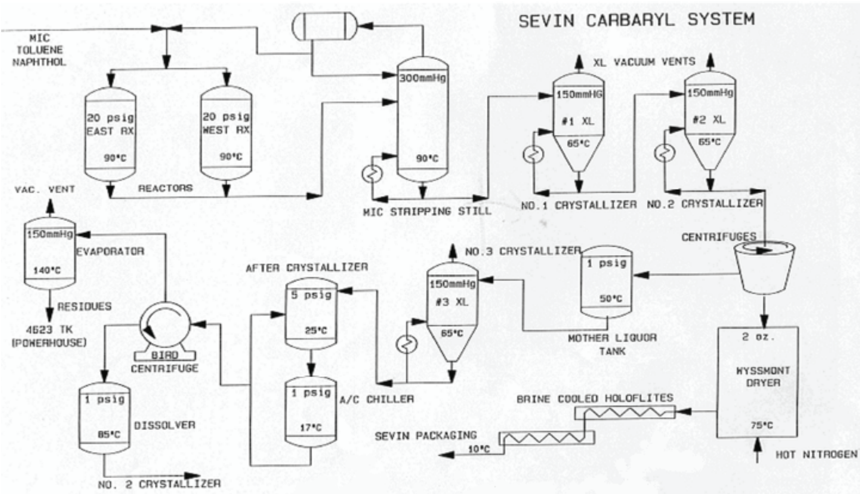


FIGURE 5.12 Basic process flow diagram for production of carbaryl.
SOURCE: Martin (2011).

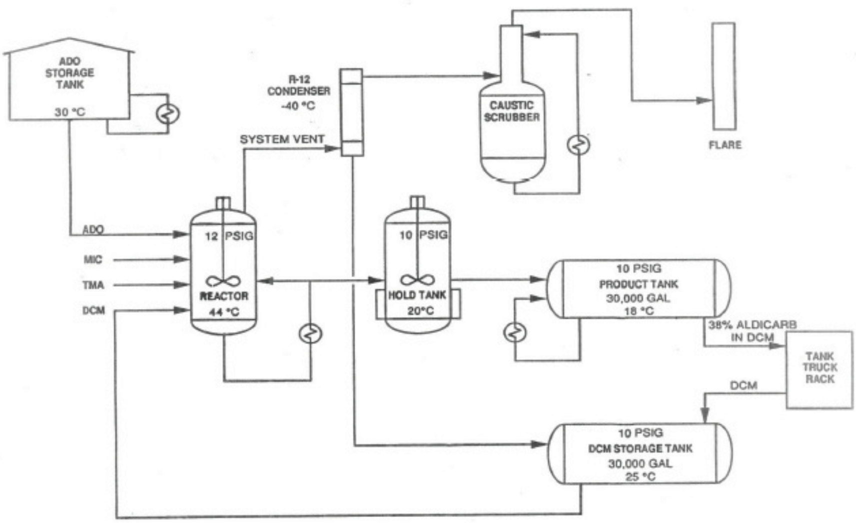


FIGURE 5.13 Basic process flow diagram for production of aldicarb.
SOURCE: Martin (2011).

duction of carbosulfan and thiodicarb continue using methomyl and carbofuran from an external source. The decision to close down those lines was apparently related to their location: those operations were in another part of the plant, requiring a separate MIC storage tank and a long pipe to transfer the MIC to that area.

Of the carbamate pesticides being produced at Institute in 2008, only carbaryl had been produced by a non-MIC process. At the time the present study was initiated, it appeared that a modified MIC process for the synthesis of carbaryl would be restarted at the Institute plant. In that case, a complete and critical review of the literature, patents, and worldwide practice for MIC-based and non-MIC-based *N*-monomethyl carbamate pesticide syntheses could have been appropriate, although such a review would have required considerable time and resources. Given the decision by Bayer to discontinue production of both MIC and *N*-monomethyl carbamate pesticides at the Institute plant, such a detailed review became unnecessary.

## ALTERNATIVE ARRANGEMENTS OF PROCESSES

A key concern with the overall design of the production processes at the Institute plant was the need for storage of considerable amounts of MIC. This arose because of the characteristics of the production processes for MIC and the four carbamate pesticides. To account for the agricultural calendar, the production of MIC was ideally run on a continuous basis through most of the year, with only limited shutdowns (except for one long shutdown in July and August). The different carbamate processes had different schedules. The aldicarb and carbofuran processes ran all year long, whereas the carbaryl, oxamyl, and methamyl processes only required MIC during 4-5 months of the year. In addition, the Institute aldicarb and oxamyl processes ran in batch mode, and the carbaryl process was shut down for a few days every two weeks to dissolve solids from the reactor. Between the seasonal fluctuations and the short-run fluctuations in the carbamate processes, there was considerable variation in the need for MIC over time. The operators at the Institute plant had developed some degree of flexibility in the production rate for the MIC process, roughly a 3:1 (high:low) ratio, but they still relied upon a maximum MIC inventory level of 200,000 pounds to coordinate the MIC and carbamate production over time (Martin, 2011).

At various times the owners of the Institute site considered ways to reduce the amount of MIC being stored onsite. Reductions in MIC storage could offset impacts on the risk of the overall process. Smaller inventories of MIC would reduce the magnitude of damages from a potential accidental release of MIC from storage. However, holding smaller inventories would increase the number of times the MIC and carbamate processes had to be started or stopped, due to halting MIC production when the storage capacity was reached and stopping the carbamate process when the MIC in storage was used up. This could increase the overall risk of the process, because startup and shutdown periods have the greatest potential for accidents (the 2008 methomyl accident happened during process startup) (CSB, 2011).

There were substantial reductions in the maximal MIC storage amounts at the Institute plant, from 1 million pounds at its peak to about 200,000 pounds more recently, as the scale of overall MIC production fell from over 40 million pounds annually in the late 1970s to around 10 million pounds by 2008 (Smythe, 2011). From 1989 to 1991 Rhône-Poulenc conducted an evaluation of alternative approaches to MIC production, including having separate MIC generators attached to each carbamate production line in order to reduce the need for MIC storage. This approach could have reduced the potential damage in the case of an accident because the amount of MIC being stored on each line would be smaller, but there would have been four times as many places for an accident to occur. In the end, the complications associated with having four separate MIC production units was considered to outweigh the benefits of reduced MIC storage, and the production process was not changed. In 1993, Rhône-Poulenc's Institute Modification Project allowed the MIC production unit to operate at reduced rates, permitting a better match between MIC and carbamate production rates without increasing MIC storage. Most recently, in August 2009, Bayer announced plans to reduce the amount of MIC storage from 200,000 pounds to 40,000 pounds, as part of a $25 million investment project that also strengthened the layers of protection around the MIC production and storage units, and eliminated aboveground storage of MIC (Bayer CropScience, 2009).

Another important issue relates to the physical layout of the production process. In the case of the Institute plant, in 2008, the production of carbamate pesticides occurred in two separate areas of the plant, with the aldicarb and carbaryl processes located relatively close to the MIC production area, whereas the carbofuran and methomyl processes were located some distance away, in the West Carbamoylation Complex (WCC). Each night the MIC needed for the next day's carbofuran and methomyl production was transferred to an aboveground holding tank. The proximity of that MIC tank to the explosion in the methomyl production unit in 2008 was a key concern in the investigation of the accident. Bayer's 2009 decision to shut down the WCC helped reduce the risks associated with storing MIC in an aboveground tank and the overnight pumping of MIC to that tank (Bayer CropScience, 2009; Smythe, 2011).

## Technical Considerations

A comparison of different production processes begins with consideration of the underlying chemical reaction. This determines the per-unit variable cost of production, along with energy and capital costs. There may be some uncertainty, especially on the capital costs, as well as a learning curve associated with operating a new production process. These uncertainties provide a substantial advantage for an incumbent production process, along with the cost advantage that no additional capital costs are required to continue using the existing equipment.

Balanced against the costs of production is the revenue to be gained, which is likely to be influenced by the quality of the product. For the four alternative MIC production methods described above (DuPont, cyanate, diphenylcarbonate, and Enichem), purity of the MIC produced was an issue. According to the analysis provided by Bayer, the DuPont process generated considerable impurities at startup, which would have been unacceptable for the high-purity production requirements for the manufacture of aldicarb. Collection and purification of the gaseous MIC prior to use in the synthesis would require storage of a quantity of MIC on site and would, to some degree, reduce the benefit of just-in-time production of the chemical. Adoption of this process at the Institute site also presents additional technical challenges, since it would have required adapting the Institute aldicarb and carbaryl processes to work with gaseous MIC rather than liquid MIC. In addition, as production of aldicarb oxime ran as a batch process, onsite storage of MIC would still be required for at least short periods of time.

The cyanate method could match MIC production more closely to the batch versions of carbamate production. However, in order to accommodate the continuous production units of carbaryl and methomyl, onsite storage would again be required. In addition, the cyanate process is generally run on a much smaller scale than the UCC process; and adapting it to the Institute scale of production would require a very large number of reactors being built on site, which have an increased risk of leaks and equipment failures. Finally, as mentioned previously, the cyanate process generates significant quantities of hazardous waste that would need to be controlled and disposed of appropriately.

The diphenylcarbonate process for MIC production was used by Bayer in Germany until 2002. When that process was phased out, the company lost its in-house expertise. More importantly, however, this process depends on a supply of dimethylurea, which had been purchased from BASF in Germany but was not readily available in the United States. It is unclear whether onsite production of DMU was considered. There were also concerns about the quality of the MIC produced by the process, which could affect the final production of aldicarb. As with the DuPont process, an additional purification step might have resolved this issue, thought this would also have introduced a requirement for some onsite storage capacity. This process also requires the generation of phenol, which is also a hazardous material that must be managed, either by recycling of the material in the process or through treatment and disposal.

The Enichem process, although listed as potentially promising in the late 1980s, also presented some concerns. For example, the process had only been run on a very small scale (less than 5 percent of the level of production at Institute), and there were also concerns about the quality of the MIC that would be produced. The different MIC processes vary considerably in the purity of the product MIC, with the Institute UCC process providing the highest MIC purity, which affects the quality of the resulting carbamate pesticides.

## INFORMATION REQUIRED FOR SCREENING ALTERNATIVES

Performing a comprehensive inherently safer processes (ISP) analysis requires considerable information (see Chapter 4). There are multiple dimensions along which the processes can be compared, and many characteristics of each process need to be taken into account. These comparisons can then be incorporated into the process safety management (PSM) evaluations and, in turn, can affect business decisions. Indirectly, incorporating or developing systems that are "inherently safer" may reduce overall lifetime costs to a company by reducing the possibility of accidental release of hazardous materials from the process, with potential damages to personnel, the production facility, and the surrounding community.

When a company faces a decision about whether or how to change a process, more than the safety elements are considered, although safety could be a deciding factor in whether to move ahead. Some process characteristics are obviously part of any business decision, including the costs of the chemicals, labor and energy requirements, and new capital expenditures, as well as the quality of the product and revenues expected from its production. There can also be environmental impacts anticipated from the process, depending on the nature of the inputs being used and any by-products being generated. Many of these characteristics involve a substantial degree of uncertainty. The underlying chemical reaction may support relatively straightforward calculations of the amounts of different chemical and energy inputs needed for the process, and hence the expected per-unit production costs. The costs of developing and installing new capital equipment for the process will be less certain, as will the steepness of the learning curve when starting a new process. On the other hand, the probability and consequences of a major accident are much less certain, making it difficult to quantify those risks and consider them along with the other characteristics in the final decision-making process.

Any firm approaching a redesign must consider the position of the product in the market and its expected life-cycle. At this point, carbamate pesticides are relatively mature products, with a limited remaining market life, and hence a less desirable focus for new investment. Of the pesticides made at Institute, aldicarb seemed to have fewer competing products, which may help explain why Bayer was initially willing to spend $25 million in 2010 to extend aldicarb production for a limited number of additional years (Bayer CropScience, 2009).

In addition to production costs, the reaction identifies the particular chemicals involved in the process, as either inputs or by-products, and hence the hazards associated with the process. In addition to MIC itself, phosgene and chlorine are commonly used as reactants in carbamate production, and generation of unwanted by-products such as phenol also increases risks. Balanced against the hazards from the chemicals are the safety measures being employed in the process. These add to the costs of running the process, but reduce the risk of accidental exposures, both within the facility and in the surrounding community.

## Regulatory Considerations

A company's decisions about production processes are also strongly influenced by constraints imposed by other entities. For example, manufacturing carbamate pesticides for sale in the United States requires that the pesticide be approved by EPA. The pesticide approval process can take multiple years, and approval is needed when there is a substantial change in the production process for the pesticide. This gives a considerable advantage to an incumbent process that has already been approved by EPA. When Bayer evaluated several alternative methods for producing MIC in 2010, a major drawback of all the alternatives, as identified by the company, was that changing the MIC process would require an EPA review and reapproval of the "new" pesticide, because the purity of the MIC could change. The reregistration process can be lengthy, could result in significant periods of lost production. . . such a gap in production could risk permanent loss of customers (farmers), who would have to switch to alternative pest control measures for at least one growing season.

Government regulation of workplace and environmental hazards can also influence company decisions, given the hazardous nature of the chemicals involved. For example, the creation of EPA and the federal Clean Air Act and Clean Water Act legislation increased pressure to reduce air and water pollution in the 1970s. This pressure to limit pollution helped drive the decision by Carbide to switch away from a highly-polluting (non-MIC) process for carbaryl production to a MIC-based process that generated less pollution. This example highlights the complexities of regulating production processes—efforts to reduce exposures to one set of hazardous chemicals may lead to changes that increase the risks of exposure to other chemicals. For more information about policy initiatives relating to ISP, see Appendix D.

## Company-Community Relationships

Government regulators are not the only source of external pressures on the company's decisions. The local community can also influence the decisions, and the relationship between the company and the surrounding community can be very important in this process.

The relationship between a chemical company and the community that surrounds it is a complex one. Chemical companies manufacture useful products and provide employment for the local communities, but to create these products, most chemical manufacturing processes require use of hazardous materials and/or processes of some form. These hazards are managed through, among other things, process controls, training and education, and management systems. Regulatory structures, professional standards, and other forms of required and voluntary guidance reinforce and encourage safe practices. In case of accidents or leaks, emergency response systems are in place to help minimize the adverse consequences and control the event. Ideally, these protective systems overlap and integrate in such a way that the risks posed by the chemical and physical hazards onsite are as low as possible.

Community perception and understanding of risk and safety are important. For example, when considering responses to accidents or leaks, if an incident large enough to require local emergency response services to respond is a possibility, then a thorough understanding of the potential risks posed is required for development of an appropriate response and training of emergency personnel and community members. At a basic level, a neutral or positive relationship between a facility and its community allows for open discussion about risks and responses. It allows for a sense of trust that the experts onsite are operating with care and consideration. A negative relationship can influence the community perception of risk, lead to distrust, and create an environment of defensiveness and lack of engagement on important issues relevant to everyone involved. This issue has been examined in the literature with respect to community risk perception of nuclear and chemical facilities among other hazards (Starr, 1969, 1981, 1985).

Community perception is built on so-called risk perception "frames," which are closely linked with individual views about how societal decisions should be made (social control frames) and the way they think about a given problem (cognitive frames) (Wildavsky and Dake, 1990; Dake, 1991; Elliott and Hanke, 2003; Gray, 2003; Lewicki et al., 2003). In short, people use different frames, based on background, education, social norms, and the like, to define whether a problem exists and if so, what the problem is. People with different frames may disagree about the problem, its size and scope, and how to address it.

Relevant to chemical manufacturing, one area in which differences in framing exist is in how people view environmental hazards and whether they pose health risks for the community. Researchers working in the field of risk perception have shown that parties confronting environmental hazards develop considerably different frames about the characteristics and intensity of the hazard (Elliott, 1984). Conflicting differences in how technical and lay populations frame risks occur frequently: the former stress prediction and prevention of risks whereas the latter are concerned about risk detection and repairing damage from risks that have occurred. Community perceptions of risk stem from a diverse set of factors ranging from the psychological to social processes of framing, to cultural expectations, and these factors play themselves out within a context of a particular facility and the risks associated with that facility, the relationship between the facility and the surrounding community, and corresponding processes of communication, control, and conflict or collaboration.

With regards to consideration of ISP, discussions between a facility and the community regarding trade-offs between possible alternative manufacturing methods could help the two sides understand their respective risk perceptions and tolerances. These shared understandings could then be used to help develop reporting and emergency response systems, outreach and communication strategies, and other activities in support of maintaining a safe environment and positive relationship. Analysis and discussion of trade-offs is likely to be complex, and decision-aid methods, such as the example described in Chapter 6, could be useful for framing such a discussion by identifying points of disagreement and concurrence among stakeholder groups. The findings from these analyses can be used by companies to aid in decision making by helping to clarify the issues of concern to the members of the community.

A good example of the role communities can play in facility decision-making processes can be seen in a comparison of the community relations at the Institute plant with those at a DuPont plant in La Porte, Texas. DuPont had been producing their methomyl insecticide, Lannate, using MIC shipped from the Institute plant. In 1985, restrictions on transportation of MIC following the Bhopal accident led DuPont to modify their Lannate production process to generate its own MIC. DuPont's good relationship with the surrounding community permitted an open exchange of information about the new process, so that the community was willing to allow DuPont to start producing MIC in the facility, albeit with a process that involved no storage of MIC and only a few pounds of MIC in the process at any one time (Carberry, 2011). In contrast, the poor relationship between Bayer and its surrounding community resulted in a court injunction filed by community members to stop Bayer from resuming MIC production at Institute. This contributed to a complete shutdown of MIC production, even though Bayer had been producing MIC there for many years, had recently spent $25 million installing additional safety features, had reduced MIC storage levels by 80 percent, and was planning to phase out MIC production altogether within a few years. Thus, good community relations are crucial to a facility's gaining local acceptance of their decisions.

Today, decision making for the production, storage, and use of MIC and other hazardous chemicals is predominantly made by facility operators within the context of national, state, and local regulations and requirements. At the same time, the chemical industry has increasingly realized the importance of effective working relations with the communities in which plants are located. One example of this is the Responsible Care program described briefly in Chapter 2. This voluntary program seeks to improve health, safety, and environmental performance in the chemical industry. At the heart of the International Council of Chemical Associations program is an effort for "companies to be open and transparent with their stakeholders—from local communities to environmental lobby groups, from local authorities and government to the media, and of course the general public." Community advisory panels, as well as a wide range of other outreach efforts, have followed.

These efforts by the chemical industry have increased transparency, outreach, and dialogue with stakeholders external to facilities. However, as is seen in the dynamics surrounding questions of safety associated with MIC production and use at Bayer in Institute, West Virginia, these efforts have sometimes failed to produce a convergence of perspectives as to what poses significant risks to the community or how best to manage those risks. Divergent perceptions of risk, a problem common to many facilities that pose some level of risk to the surrounding community, are particularly important when the risks are potentially as substantial as those for chemicals such as MIC or phosgene. In Institute, there are obviously divergent perceptions of the risk posed by large-scale manufacture and storage of MIC at the Bayer facility between individuals working at the facility and at least one subset of the community. The most prominent group advocating for the removal of MIC from the facility is People Concerned about MIC (PCMIC), a group formed after the Bhopal disaster and which has worked toward that goal since that time.

## QUANTIFYING COSTS AND BENEFITS OF ALTERNATIVES

Corporate decision making, at least as modeled by economists, is fundamentally driven by the goal of profit maximization. Nicholson (2005) provides a standard textbook discussion of various terms used in this section, including profit-maximization, capital costs, expected value, and externalities. In terms of the technical considerations mentioned earlier, decision making involves a comparison of the revenues generated by a production process with the costs of that production. At its simplest level, per-unit revenues from the sale of a pesticide could be compared to the per-unit costs of the chemicals and energy needed to produce the pesticide, and so a firm choosing among alternative processes that produced exactly the same product should choose the lowest-cost alternative. This calculation could be complicated by consideration of the capital expenditures associated with the processes, which enter the calculations as a one-time cost rather than a per-unit cost. However, suitable tools are available to deal with that, such as the present discounted value of future costs and revenues, or the annual cost of renting the capital each year.

A profit-maximizing firm should also consider any risks involved in the production process. An accident causing a temporary shutdown in production and extensive repairs will represent a cost to the firm, but a cost with considerable uncertainty attached to it, both in terms of magnitude and probability. One approach would be to assign the "expected value" of the accident (accident cost*probability), and so an accident with $50 million of damages and a three percent chance of happening each year would be assigned an expected annual cost of $1.5 million. It would then be profitable for the firm to implement safety measures that could cut the damages (or the accident probability) in half, as long as those safety measures cost less than $750,000 per year. Firms are often assumed to use expected values to make these calculations, although if the potential risks are extremely large (e.g., complete shutdown of the facility or bankruptcy of the firm), the firm might be "risk averse," equivalent to being willing to pay more than the expected value of the risk for some sort of insurance policy to avoid the risk. In the case of production risk using ISP to avoid the risk entirely would be one way of "buying insurance" against an accident.

From the point of view of the broader society, a key problem with the profit-maximizing decision described above is that the firm would not include in its calculations all the costs borne by people who might be exposed as a result of an accident at the facility. This discrepancy between "private" and "social" costs has been a central topic in Benefit-Cost Analysis (BCA) for many years (see Pigou, 1952 for an early example and Boardman et al., 2010) for a modern textbook approach). BCA is commonly applied to government (and private) decisions to see whether they are in society's best interest (benefits>costs), and is required for major federal regulations (e.g., under Executive Order 13563, January 18, 2011, regulations "must take into account benefits and costs, both quantitative and qualitative").

A firm's decisions about risks, even those involving risks to others, can sometimes coincide with the socially optimal decision. Risks to the facility's workers could, at least in principle, be reflected in compensating differentials—higher wages needed to attract workers to those risky jobs (assuming they know about the risk)—and would be included as a cost in the firm's profit calculations. However, risks affecting people outside the facility would not generally be connected to the firm's costs. Ignoring these external costs, called externalities, can lead a profit-maximizing firm to choose a riskier production process than would be optimal for society as a whole (Nicholson, 2005). One way of forcing firms to "internalize" these external costs (recognize the costs in their decision making) is through legal liability—if those damaged by an accident can sue the firm and collect full compensation for their damages, it provides an incentive for firms to reduce risks.

The existence of externalities provides an economic justification for the activities of regulatory agencies (such as EPA or OSHA) that constrain firms' decisions about utilizing hazardous production processes with high levels of external risks. The presence of regulators imposing penalties for violations of safety regulations can provide an incentive to firms to reduce the risks associated with their production processes. Community groups picketing the facility or organizing boycotts of the firm's products can also impose direct costs on firms using risky production processes. Both types of external pressures, regulatory and community-based, can lead firms to reduce risks, in order to reduce their likelihood of being penalized for those risks.

Corporate Social Responsibility (CSR), whose history is discussed in Carroll (1999) and elsewhere, is another approach to firms' decision making that emphasizes society's role in permitting the firm to operate. CSR sees the firm as having a responsibility to take into account the external effects of its decisions. From this perspective, firms should consider how their decisions could achieve socially-preferred outcomes, considering external costs and benefits even when there are no regulatory or community pressures to do so. Many discussions of CSR describe firms as accepting lower profits in return for social acceptance, but Porter and Kramer (2006) argue that socially responsible decisions can also benefit the firm's long-run profitability, especially if the firm focuses on providing benefits to society using its areas of expertise.

Whatever decision-making process is being followed, one key element in the calculation of the optimal decision is the risk of an accident. This can be complicated, especially when the risk of a substantial release affecting the area outside the facility involves the simultaneous failure of multiple layers of protection. Calculations of such risks often assume that the probability of each layer's failure is independent, so that three layers of protection, each with a 1-in-10,000 risk, would provide an overall risk of 1-in-a-trillion. One lesson from the Bhopal accident is that, at least in that institutional setting, failures to manage risk were correlated across the layers of protection, greatly increasing the risk of an accident. Regulatory decisions under BCA can depend heavily on the calculations of the risk of low-probability events, such as the probability of a large accident at a chemical plant, or the probability of a given person dying of lung cancer after being exposed to air pollutants. A key difference between these two examples lies in the frequency of their observations. Millions of people are exposed to air pollution every year, and the (very small) fraction of individuals who die after the exposure can be calculated, which allows one to determine reasonably precise estimates of the risk's probability. For large industrial accidents, which fortunately rarely occur, calculations of the probabilities involved depend on engineering models of the effectiveness of the different layers of protection. It is not that such calculations cannot be made—they are done regularly as part of both applications of BCA and profit maximizing decisions by firms—but as noted in Box 4.1, there are inherent uncertainties and biases involved.

There is also the sensitive issue of assigning values to the illnesses or deaths of people that could result from a major accident. For profit-maximizing decisions by the firm, these values can be related back to the potential liability costs of an accident, as discussed earlier. For BCA applications, the most common tool is the "value of a statistical life" (VSL). Suppose that a typical worker requires $5,000 extra wages per year in order to accept a risky job that has a 1-in-1,000 chance of a fatal accident during the year. A group of 1,000 such workers would, on average, have suffered one extra death per year—and would have accepted a total of $5 million to bear the risk of that death—so the VSL would be $5 million. Considerable effort has been expended by both academics and regulatory agencies to refine their VSL estimates, as well as to consider whether and how VSL values might vary within the population (see Aldy and Viscusi, 2007 for a recent example). Despite the common use of VSL in these calculations, many are uncomfortable about "putting a dollar value on a life", and regulators face considerable controversy when making adjustments to VSL (see Nelson, 2011 for a discussion of such controversies at EPA).

## IMPLEMENTING METRICS

A fully quantitative inherently safer process (ISP) analysis that assigns values to all the benefits and costs from alternative production processes, including risks of accidents and other uncertain outcomes, would require considerable resources and a level of detail about production costs and risks that were not made available for this study. The owners of the Institute plant have done some comparisons of alternative production processes, although these were not fully quantitative. The most recent example of this sort of analysis at Institute was an analysis of alternative methods of producing MIC, mentioned in above (Smythe, 2011). A summary of the results is shown in Table 5.3. The first thing to note is that the various dimensions in the analysis are described in qualitative terms (high, low, medium), which rules out any sort of fully quantitative analysis of trade-offs across dimensions. The underlying study did include dollar amounts for the per-unit cost of production (summarized here in low/high terms, to avoid revealing any confidential business information), but the other dimensions were qualitative.

This sort of qualitative information could still be valuable in conducting an ISP analysis of the processes and could be used in support of or as a starting point to quantitative analyses. One value would come in identifying cases where option A is "dominated" by option B, that is B performs better on every dimension. This would be unusual, given multiple dimensions, but it helps to rule out clearly unsatisfactory options. A second value comes in helping focus the discussion of trade-offs. Also indicated in Table 5.3 that the Bayer process has low process complexity, low waste generation, and low internal recycle streams. All of these characteristics would tend to make it an "inherently safer" process, relative to the other four. However, the need for a supply of dimethylurea (DMU) was a major obstacle, because it was not available in the United States, made this option unfeasible at the Institute plant. It is unclear whether onsite production of DMU was considered as part of the analysis.

When Bayer explained how this information was used in its decision making about the best MIC production process, major advantages were seen for the incumbent process. The "bottom line" yes/no questions— "adaptation of infrastructure," "R&D required," and "registration required" —played a crucial role in the decision. These all show "no" for the Institute process and "yes" for the four alternative processes. "Adaptation of infrastructure" refers to the potentially large capital costs that would be needed to install the equipment needed for a new process (while the equipment for the existing process is already in place). "R&D required" reflects the uncertainty and learning costs associated with beginning

TABLE 5.3 Comparison of Alternative MIC Production Processes from Bayer CropScience

| Process | UCC | DuPont | Cyanate | DPC/DMC | Enichem |
|---|---|---|---|---|---|
| Internal recycle streams | High | High | High, solvent reflux | Low | Very high |
| Per-unit operating cost | Low | Low | High | High | High |
| Waste and wastewater | Medium | Medium (cyanide) | High (cyanide?) | Low | Medium |
| License fee | No | Yes | Yes | No | Yes |
| Adaption of infrastructure | No | Yes | Yes | Yes | Yes |
| R&D required | No | Yes | Yes | Yes | Yes |
| Registration required | No | Yes | Yes | Yes | Yes |
| Other factors | | Catalyst exchange every 2 weeks | Batch process | External intermediate (dimethylurea) | |
| Raw material properties[a] | MMA (mono-methylamine) : F+, Xn<br>CO:T<br>$Cl_2$: T; Phosgene: T+ | CO:T<br>MMA: F+, Xn | NaNCO:Xn<br>Dimethyl sulfate: T+ | Phenol: T, C | MMA: F+, Xn<br>Phenol: T, C |
| Process complexity | Very High | High | Medium | Low | High |
| Experience | Mature | Mature | Mature | Mature | One Unit? |

SOURCE: Adapted from Smythe, 2011. *a*: F – Very Flammable, F+ – Extremely Flammable, T – Toxic, T+ – Very Toxic, Xn – Harmful, C – Corrosive.

any new production process. The final element, "registration required", confers a unique advantage upon the incumbent process in the case of pesticide production. As noted earlier, the need for EPA to reapprove the "new" version of the pesticide (made using MIC generated by a new MIC production process with different impurities) would cause a delay of months to years (once the agricultural cycle is taken into account) in marketing the pesticide. Since carbamate pesticides are near the end of their marketing life anyway, such a delay could make the shift to a new process uneconomical. If it were possible to keep the old process operating during the EPA review of the new process, "registration required" might be less of an absolute barrier, but that was not the situation faced by Bayer in 2010, and few facilities would have the extra physical space needed to continue running the old process while constructing the new one.

Bayer eventually decided to continue the existing MIC production process, but with an 80 percent reduction in the maximum MIC storage levels (from 200,000 pounds to 40,000 pounds), and other safety enhancements, including the elimination of aboveground MIC storage and the closure of the methomyl facility. The August 26, 2009 news release announcing this decision identified "the concerns of public officials and the site's neighbors" as an important factor and promised to "continue its dialogue and close cooperation with the community and governmental agencies involved" (Bayer CropScience, 2009). This highlights the importance of external pressures on the decision-making process. Bayer personnel indicated that the decision-making process was carried out at the corporate level, including the size of the reduction in MIC storage levels, and the facility's involvement was limited to confirming that a reduction in MIC storage to 40,000 pounds was feasible. In particular, the size of the reduction in MIC storage did not seem to be based on a specific analysis of the potential trade-off between the risks of larger MIC storage capacity and the risks of more frequent startup/shutdown conditions (i.e., why was 40,000 pounds the optimal MIC storage capacity, rather than 30,000 or 60,000 pounds?).

As noted earlier, this study focuses on alternative processes for producing carbamate pesticides at the Institute plant. In these calculations, the relative costs (both production costs and potential accident risks) associated with different processes have been considered, but the decision whether to produce the pesticides at all, which would depend on the overall benefits and costs of pesticide production, was not. Expanding the analysis to include these decisions would require additional information, including the benefits of these particular pesticides to farmers, relative to using other pesticides or no pesticides at all. These benefits may be reflected (at least partially) in the price of the pesticide, and thus be included in the company's decision. Many of the decisions by Bayer in recent years have been of this type: deciding first to shut down the methomyl and carbofuran production lines, then later to stop MIC production altogether, along with the production of additional carbamate pesticides.

Looking again at the four MIC manufacturing processes in light of considerations such as those discussed above, Bayer's predecessors developed a table to help evaluate the trade-offs among the alternatives. Although this table provides a very useful starting point for a comparison of technologies, it excludes factors that may be important in the decision-making process, from the perspective of both the company and the community. For example, it does not include the volume of onsite MIC storage required, the risk of an accidental release into the surrounding community (which is related to storage volumes), the purity of the resulting MIC, or the likelihood of facing a community lawsuit. The next chapter discusses one possible systematic framework for identifying the key attributes that must be included into this type of decision and for analyzing the trade-offs.

## CONCLUSIONS

Several decisions regarding process safety were made over the years by the owners of the Institute, West Virginia plant. Most of these decisions involved adding safety protections to existing processes, rather than changes to the underlying process. **Bayer and its predecessors evaluated trade-offs among the alternatives, but while analysis provides a very useful starting point for a comparison of technologies, it excludes factors that may be important in the decision, from the perspective of both the company and the community.** The only major change in production process was in 1978 from chloroformate to isocyanate in the carbaryl production. For an ISP analysis that focused solely on MIC usage, this was going in the "wrong" direction, but increasing environmental concerns in the 1970s about the level of pollution by-products of the chloroformate process, relative to the isocyanate process, were the driving factor behind that decision. Depending on the extent of environmental damages caused by the pollution from the chloroformate process and the probability and magnitude of the damages from an accidental MIC release, the overall risks generated by carbaryl production at the Institute plant might well have been reduced by the change to using MIC.

Decisions about the production processes at the Institute plant appear to have been driven by business conditions and external pressures, rather than resulting from an application of ISP analysis to the processes. A timeline of these decisions is provided in Appendix B. The earliest example in the data was the establishment of the Union Carbide Reactive Chemicals employee awareness training program and the Kanawha Valley Emergency Planning Committee, following explosions at the site in 1954 and 1955. The 1984 Bhopal accident led to expansion of the MIC destruction capacity and other safety enhancements. Restrictions on the shipment of MIC following Bhopal also led FMC to shift its production of carbofuran to the Institute plant. The 2008 methomyl accident and EPA regulatory decisions led Bayer to not restart the methomyl and carbofuran production lines, and the court injunction and other delays in restarting production eventually led Bayer to close down MIC production at Institute.

The decisions at the Institute plant also demonstrate the importance of various barriers to change in existing production processes. On the cost side, there are investment costs for installing new production equipment and the uncertainty and learning costs associated with beginning a new process. In addition to these cost factors, a key factor in recent decisions at the Institute plant about their carbamate pesticide production process was the requirement for EPA registration of pesticides. This gives a substantial advantage to incumbent production processes, since changing to a new production process for an existing product means a delay in production while the "new" version of the product is being approved by EPA—potentially losing customers as farmers switch to other products during one or more growing seasons.

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# 6

# A Framework for Decision Making

## INTRODUCTION

Chapter 5 presented four alternatives available to Bayer: (1) continuing with the existing process, (2) adopting an alternative chemical process not involving MIC, (3) using an alternative process for MIC production that would consume MIC immediately and thus not require storage, and (4) reducing the volume of stored MIC and the risks of transporting MIC from one facility within the site to another by rearranging process equipment. Table 6.1 summarizes how these four alternatives compare along several key performance features, or "attributes", some of which were captured in Table 5.3 and some of which are additional attributes that could have been considered an analysis of trade-offs. An "X" indicates that the given manufacturing approach is superior to the others along the given attribute. As is clear from this comparison, none of the alternatives is superior to all the others along every attribute. For example, the Institute process, while posing higher risks due to the volume of MIC stored, generates less wastewater than the original non-MIC process used to produce carbaryl, and also has many cost advantages

Given that no alternative clearly dominates the others, the question arises as to what decision-making framework could be used to identify the "best" choice. Benefit-cost analysis (BCA), as described in Chapter 5, assigns dollar values to the different attributes, based on their expected values, adds together all the benefits and costs for each alternative, then chooses the one with the highest net benefits. While Chapter 5 illustrated that valuing uncertain attributes can be difficult in many cases, BCA has been used extensively for many years by government agencies, and certain conventions have been adopted (such as using the value of a statistical life to evaluate fatality risks) to deal with some common attributes.

TABLE 6.1 Multiple Attribute Analysis of Alternative Carbamate Pesticide Production Processes

(1)—Existing Institute Process
(2)—Non-MIC Processes
(3)—Process Producing Gaseous MIC Consumed Immediately
(4)—Alternative MIC-based Process Arrangements, Reducing Onsite Storage

| **Potentially Important Attributes External/Regulatory Pressures** | **Manufacturing Approach** | | | |
|---|---|---|---|---|
| | **(1)** | **(2)** | **(3)** | **(4)** |
| Liability for harm to surrounding communities | | X | X | |
| Community acceptance | | X | ? | |
| Liability for worker injury due to MIC exposure | | X | ? | |
| Liability for worker injury due to dust exposure | X | | | |
| Wastewater disposal requirements | X | | | X |
| Length of time for regulatory approval | X | | | |
| **Internal/Cost Pressures** | | | | |
| Product purity | X | | | X |
| Cost and availability of chemical feedstocks | X | | | X |
| Capital costs | X | | | |
| Equipment O&M costs | X | | | |
| Costs of safety equipment | ? | ? | ? | ? |
| Process corrosivity | X | | | X |
| Process yield | X | | | |
| Availability of in-house expertise | X | | | X |
| Previous experience with large-scale production | X | | | |

NOTE: "X" indicates that the given pesticide manufacturing approach performs better than the others along the given attribute. "?" indicates that information available to the committee was insufficient to evaluate the approach along the given attribute.

The complex, multi-attribute decision-making Bayer and the legacy owners faced when modifying the MIC and carbamate-pesticide production processes is a challenge that will be familiar to many in the chemical industry. Incorporating risk considerations into these analyses can be particularly challenging as the final decision may affect individuals and organizations beyond the company itself, e.g., reducing or increasing requirements for local emergency responders. In fact, several experts in chemical engineering have suggested that the lack of effective methods for analyzing such trade-offs is a major barrier to the widespread use of inherently safer processes (ISP; Khan and Amyotte, 2004). With this in mind, the committee chose to present one possible approach for analyzing these and other trade-offs, while recognizing other methods are also possible.

The alternative to BCA described in this chapter is multi-attribute utility theory (MAUT), one of a suite of methods—or decision aids—developed to assist with complex decision-making involving multiple stakeholders. MAU (described in more detail in the next section) keeps the attributes separate throughout the process and emphasizes the multi-dimensional nature of the decision process. The method recognizes explicitly that different people could assign different values to the different attributes—both in how strongly the person weights different attributes when making the final decision and possibly even in whether the attribute is considered to be positive or negative. By forcing the user to confront the multiple attributes and decide their relative importance, MAU may help clarify a difficult decision (or at least the difficult trade-offs involved). However, MAU is still a relatively unfamiliar process for most companies, which is a disadvantage when it comes to applying the method in real-world cases.

## MULTI-ATTRIBUTE UTILITY THEORY

The need for trade-offs among conflicting objectives under uncertainty is pervasive in many decisions faced by businesses, government agencies, and other organizations. Decision scientists have conceived formal methods for balancing such trade-offs and have established mathematically that these methods yield the choice that maximizes the utility to the decision maker. Many approaches to multiple-criteria decision making are available from the fields of economics and decision analysis, including, for example, analytic hierarchy process (AHP) analysis and fuzzy set theory. Overviews of methods for multi-attribute or criteria decision analysis can be found in Belton and Stewart (2002), Figueira et al. (2005), and DeBrucker et al. (2012). There are strengths and weaknesses for each methodology, and these should be evaluated and understood by any user prior to application. MAU, one example of these analysis methods, assigns a numeric value (utility) representing a specific decision maker's preferences to each of the (multi-attribute) outcomes of each choice under consideration. The discussion below illustrates how MAU could be employed in supporting decision making in the chemical manufacturing industry, while recognizing that the AHP, fuzzy set theory, and other decision-making frameworks also could be considered.

MAU is not a new idea to the chemical community. In 1995, the Center for Chemical Process Safety (CCPS) published a book that suggested that MAU and other decision aids could be used to support process safety assessments (CCPS, 1995). However, these decision aids, although employed regularly in other businesses, have yet to take hold in the chemical process industry. The CCPS's observation from its 1995 book remains true today: "Decision aids have been applied only to a very limited extent in risk decision problems in [the chemical process] industry." The CCPS indicates key obstacles to adopting these tools include lack of familiarity with the tools among chemical process industry decision makers and fear that the methods are either too simple or too costly. Nonetheless, the committee believes that MAU and/or other techniques from decision analysis could prove highly valuable for strengthening the integration of safety concerns into decision making in the chemical process industry. Use of these techniques could benefit not only those at risk due to safety breaches but the industries themselves, as the techniques can lead to the identification of profitable safety solutions that otherwise may have been overlooked. These tools could also assist in strengthening the relationship between companies and communities by providing a framework for requesting and receiving input from external stakeholders. Such input may help identify overlooked concerns or areas where additional communication and outreach could be beneficial for maintaining a safe environment and a positive relationship with the external stakeholders.

This section first provides an overview of MAU theory and its use for analyzing trade-offs in complex decision problems under uncertainty. Then, it describes some limitations of the inherent safety indexes currently being used. Finally, it suggests an approach for employing MAU concepts in ISP assessments focused on improving the choice of chemical manufacturing process. However, as noted previously, MAU theory is not the sole method of approaching these difficult questions, although it is hoped that the discussion here will demonstrate the potential utility of these types of decision aids.

## Decision Sciences and MAU Models: Background

The field of decision sciences emerged from the axioms of rational choice first posed by mathematician John von Neumann and economist Oskar Morgenstern in 1947. Von Neumann and Morgenstern proved that if an agent (decision maker) has preferences with four specific characteristics (completeness, transitivity, continuity, and independence), then there must exist a mathematical equation known as a utility function such that the decision makers' preferences can be captured by maximizing the equation's expected value (von Neumann and Morgenstern, 1947; French, 1986). The utility function is usually designated as $U(\boldsymbol{x})$, where $\boldsymbol{x}=(x_1, \ldots, x_n)$ is a vector representing how well a particular decision option satisfies each of $n$ attributes important to the decision maker. Because the utility function includes multiple attributes, it provides a framework to consider trade-offs among those attributes (for example, among cost, risk, and performance).

Since von Neumann and Morgenstern published the axioms of rational utility, decision scientists have developed systematic methods for characterizing utility functions (see, e.g., Keeney and Raiffa, 1976; French, 1986; Raiffa et al., 2002). Many different mathematical forms for utility functions have been conceived. Each functional form makes certain assumptions about independence of and/or interactions among the conflicting objectives. For example, the simplest type of utility function is linear in all the attributes:

$$U(x_1,\ldots,x_n) = \sum_{i=1}^{n} k_i U_i(x_i) \tag{6.1}$$

In this function, the $U_i(x_i)$ represents individual utility functions for each of the decision maker's *n* objectives, and the $k_i$ represents weights assigned to the different objectives. These weights reflect the value to the decision maker of an option that offers the best possible outcome along objective *i*, while setting all other objectives at their worst possible values. For this type of utility function to accurately characterize preferences, certain strict independence conditions must hold (for details, see Clemen and Reilly, 2001, and other texts on decision theory). In essence, the decision makers' preferences for one attribute cannot change as levels of some other attribute change, even if the outcomes along attributes are uncertain. Another type of utility function, requiring weaker independence conditions, is the multiplicative function, expressed as follows:

$$1 + kU(x_1,\ldots,x_n) = \prod [kk_i U_i(x_i) + 1] \tag{6.2}$$

Several textbooks explain in detail the methods for determining which functional form is appropriate for the decision situation at hand (e.g., Keeney and Raiffa, 1976; Bunn, 1984; Clemen and Reilly, 2001). Formal courses in decision analytic methods are offered in many business and engineering schools. In general, the methods involve the following steps:

- Identifying the fundamental objectives of the decision makers and attributes that can be used to represent progress along each objective;
- Eliciting individual utility functions for each attribute (the $U_i(x_i)$ in the above equations)—functions that may be linear, concave, or convex, depending on the decision makers' risk tolerance;
- Testing the attributes for independence to determine the appropriate functional form (e.g., linear, multiplicative, linear-multiplicative) for the MAU model; and
- Eliciting the scaling constants (the *k* and $k_i$ in the above equations) for the multi-attribute function.

The resulting MAU model will be specific to the decision makers upon whose values it is based, and as a practical matter, it may be difficult for the decision makers to identify their preferred attributes. Adding to the complexity, even if different interest groups can agree on the attributes that should be considered in a decision, they may prefer different trade-offs among the attributes (e.g., willingness to trade cost savings for decreased health hazard) or have difficulty assigning values to the trade-offs, and they may exhibit different risk tolerances (willingness to gamble on outcomes with the potential for high payoff but also high risks of loss). As a result, different utility functions (with different single-attribute utility functions and scaling constants) are needed to reflect the preferences of groups with different values. It is worth noting that some efforts to develop indexes for ISP assessments assume that there is a single correct process design from an inherent safety perspective. However, groups with disparate values may have differing utility functions that may lead to differences in the preferred manufacturing process.

Although multiple MAU models may be needed to reflect different groups' values, these models can be extremely useful in guiding negotiations among groups in conflict (Raiffa et al., 2002). As Clemen and Reilly (2001) point out, "Understanding trade-offs can be crucial for making progress in negotiation settings." By making values explicit, MAU models can reveal similarities and differences in the value structures of groups. As an example, MAU models can be used to identify trade-offs between risk reductions and cost reductions. Keeney and McDaniels (1992) show that a MAU function developed to inform strategic decisions of the British Columbia Hydro and Power Authority (BC Hydro) implies that the company decision makers value a hectare of wilderness lost at $2,500 (see Box 6.1). That is, at least $2.5 million in economic benefits would be needed to justify a company choice that would damage a thousand hectares of wilderness.

Disagreements on certain features of a decision do not always result in different preferred alternatives. That is, a MAU process may reveal that groups in conflict might make similar choices in spite of their different values. When groups do differ in their preferred alternatives, a MAU model can highlight the main features of the decision about which groups disagree, and this may facilitate compromise. Raiffa et al. (2002) provides detailed guidance on the use of MAU models in negotiations among parties in conflict.

Decision analytic methods are now widely employed in business and other applications, from fire department operations planning to nuclear power facility siting (Keeney and Raiffa, 1976; von Winterfeldt and Edwards, 1986; Keefer et al., 2004). The Decision Analysis Society, a specialty group within INFORMS (Institute for Operations Research and the Management Sciences), organizes regular conferences to exchange both academic and practical information on decision analysis and publishes a journal, entitled *Decision Analysis*. Keeney and Raiffa (1976) and von Winterfeldt and Edwards (1986), along with more recent issues of *Decision Analysis*, provide many more practical examples of applications of MAU theory to decision making. The example provided in Box 6.2 shows that firms can "discover" new information about their preferences by using MAU—in this case, an alternative that was preferred in four out of five attributes turned out not to be the optimal choice, because of the high value the firm placed on the fifth attribute.

Note that MAU provides a framework for making rational decisions; it does not necessarily describe how people *actually* make decisions. In fact, substantial research has indicated that individuals often do not act in accordance with the

**BOX 6.1**

**MAU Model Informs Strategic Decisions in the Hydropower Industry**

The British Columbia Hydro and Power Authority (BC Hydro) has used MAU to inform strategic decisions since the late 1980s, when the company commissioned Ralph Keeney and Tim McDaniels to support a comprehensive reassessment of the company's planning processes. Keeney and McDaniels constructed a MAU model that BC Hydro then used to support decisions related to capital equipment upgrades, supply planning, and other corporate strategic issues. Keeney and McDaniels (1992) and Clemen and Reilly (2001) summarize how the MAU model was developed and the values revealed by the model.

First, Keeney and McDaniels interviewed BC Hydro's key decision makers to identify their objectives and sets of attributes for measuring progress toward those objectives. The result was the set of six fundamental objectives and 22 attributes for measuring performance shown in Table 6.2. Next, Keeney and McDaniels assessed a MAU function for combining all of these attributes into a summary measure of utility for the company. The result was a combination linear-multiplicative utility function (see Keeney and McDaniels, 1992). This function then was programmed into a spreadsheet to allow BC Hydro's managers to assess the overall utility of various decision alternatives.

Keeney and McDaniels used the resulting MAU function to illustrate the dollar value, from the company's perspective, of various attributes. For example, they showed that the value of a hectare of wilderness, from the company's perspective, is equivalent to $2,500, so that any process change that would cause such a loss but produce less than $2,500 in expected gain would not be worthwhile. Similarly, they showed that two power outages per year of 2 hours duration each to 20,000 large (commercial and industrial) customers was equivalent to $83 million. Keeney and McDaniels observed that "if BC Hydro had opportunities to reduce expected outages of that nature at a cost less than $83 million, those opportunities would be good investments from the utility's perspective."

After Keeney and McDaniels' MAU decision support model was in place, BC Hydro's Director of Strategic Planning commented,

> The structured set of objectives has influenced BC Hydro planning in many contexts. Two examples include our work to develop a decision framework for supply planning, and a case study of an investment to upgrade reliability. . . . Less obvious has been an evolution in how key senior planners view planning issues. The notion of a utility function over a range of objectives (rather than a single objective, like costs) is evident in many planning contexts. The specific trade-offs in the elicitation process are less important than the understanding that trade-offs are unavoidable in electricity utility decisions and that explicit, well-structured, informed trade-offs can be highly useful. (Keeney and McDaniels, 1992, p. 109, as quoted in Clemen and Reilly, 2001)

TABLE 6.2 Fundamental Objectives and Attributes for Measuring Progress along Objectives Described in Hydropower Case Study in Box 6.1

1. Maximize contribution to economic development
    - 11. Minimize cost of electricity use (mills per kilowatt-hour in 1989 Canadian dollars)
    - 12. Maximize funds transferred to government (annualized dividend payable)
    - 13. Minimize economic implications of resource losses (cost of resource losses in 1989 Canadian dollars)
2. Act consistently with the public's environmental values
    - 21. About local environmental impacts
        - 211. To flora (hectares of mature forest lost)
        - 212. To fauna (hectares of wildlife habitat lost of Spatzizi Plateau quality)
        - 213. To wildlife ecosystems hectares of wilderness lost of the Stikine Valley quality)
        - 214. To limit recreational use (hectares of high quality recreational land lost)
        - 215. To aesthetics (annual person-years viewing high voltage transmission lines in quality terrain)
    - 22. About global impacts (generation capacity in megawatts that results in "fossil fuel" pollution)
3. Minimize detrimental health and safety impacts
    - 31. To the public
        - 311. Mortality (public person-years of life lost)
        - 312. Morbidity (public person-years of disability equal in severity to that causing employee lost work time)
    - 32. To employees
        - 311. Mortality (employee person-years of life lost)
        - 312. Morbidity (employee person-years of lost work time)
4. Promote equitable business arrangements
    - 41. Equitable pricing to different customers (constructed scale, see text)
    - 42. Equitable compensation for concentrated local impacts (number of individuals that feel they are inequitably treated)
5. Maximize quality of service
    - 51. To small customers
        - 511. Minimize outages (expected number of annual outages to a small customer annually)
        - 512. Minimize duration of outages (average hours of outage per outage to small customers)
    - 52. To large customers
        - 511. Minimize outages (expected number of annual outages to a large customer annually)
        - 512. Minimize duration of outages (average hours of outage per outage to large customers)
    - 53. Improve new service (elapsed time until new service is installed)
    - 54. Improve response to telephone inquiries (time until human answers the telephone)
6. Be recognized as public service oriented (constructed scale, see text)

SOURCE: Keeney and McDaniels, 1992.

**BOX 6.2**
**MAU Informs Materials Choices in the Automotive Industry**

As an example of practical application of MAU to inform system design in industry, consider the example of choosing materials for automobile frames and skins presented in Thurston (1990). Thurston designed a MAU model for use by a French automobile manufacturer working on long-range plans for its future vehicle fleets (those to be manufactured in the next 5-10 years). The company's design engineers faced three options for vehicle frame-and-skin systems:

1. Traditional steel uni-body,
2. Internal steel frame with nonstructural external polymer composite skin, and
3. Steel and polymer composite frame with polymer composite skin.

The design engineers were perplexed about which material choice to pursue, because although steel could be produced with the lowest operating cost, it did not perform as well along other attributes (including durability and flexibility) as the other choices. Thurston, in describing this case study, noted, "When decision makers are faced with several alternative systems, each system may be represented as a bundle of seemingly incommensurate attributes. The best choice is not always clear." In this case, the automotive company, with support from decision analysts, used a MAU model to help decide which of the three vehicle frame-and-skin systems maximized the utility to the company, given the need to trade-off cost and performance attributes.

Thurston interviewed the decision makers at the company (in this case, engineering materials design managers focused on long-term fleet planning) to determine which attributes were important in their decision. The decision makers identified five attributes:

1. Capital cost (billions of francs),
2. Operating cost (francs per vehicle),
3. Weight (kg),
4. Corrosion resistance (years of resistance to corrosion), and
5. Design flexibility (number of body styles possible per platform).

With the company's engineers, Thurston then measured the performance of each of the three materials options along these five attributes. Table 6.3 shows the results.

*continued*

**BOX 6.2 Continued**

TABLE 6.3 Alternative Automotive Frame-and-Skin Systems and Their Performance Along Key Attributes

| Design | Capital Cost (Billion Francs) | Operating Cost (Francs per Vehicle) | Weight (Kilos) | Design Flexibility (Number of Bodies per Platform) | Corrosion Resistance (Years) |
|---|---|---|---|---|---|
| Steel Uni-body | 3 | 30 | 500 | 1 | 5 |
| Steel Frame; PC Skin | 2 | 40 | 425 | 5 | 15 |
| Steel and PC Frame; PC Skin | 1.5 | 45 | 350 | 5 | 15 |

SOURCE: Reproduced from Thurston, 1990.

Next, through in-person and electronic surveys of the decision makers, Thurston determined an appropriate form for the MAU function—in this case, multiplicative:

$$KU(\bar{x})+1=\prod_{i=1}^{n}\left(Kk_iU_i\left(x_i\right)+1\right)$$

Thurston then assessed the individual utility functions $U_i(x_i)$ for each of the five attributes, again through surveys of the decision makers, and the scaling constants $k_i$ for each utility function, as well as the overall scaling constant $K$. As an example, Figure 6.1 shows single-attribute utility functions for operating cost and flexibility in number of body types possible per platform.

As shown, these single-attribute functions convert the levels of each option along each attribute to a value between 0 and 1 that reflects the decision makers' tolerance of risk. For example, the concave shapes of these utility functions show that the decision maker is risk averse in preferences for capital costs and flexibility, gaining more from initial incremental cost savings and design flexibility than from subsequent increments.

Figure 6.2 shows the resulting attribute scores and rankings of the three design alternatives. As shown, the steel frame with polymer composite skin option has the highest utility. This result was counter-intuitive to the decision makers, since the polymer composite skin-and-frame option scored highest along four of the five attributes, including capital costs. However, the high variable costs of this latter system outweighed the benefits along the other four attributes. Thus if the decision makers

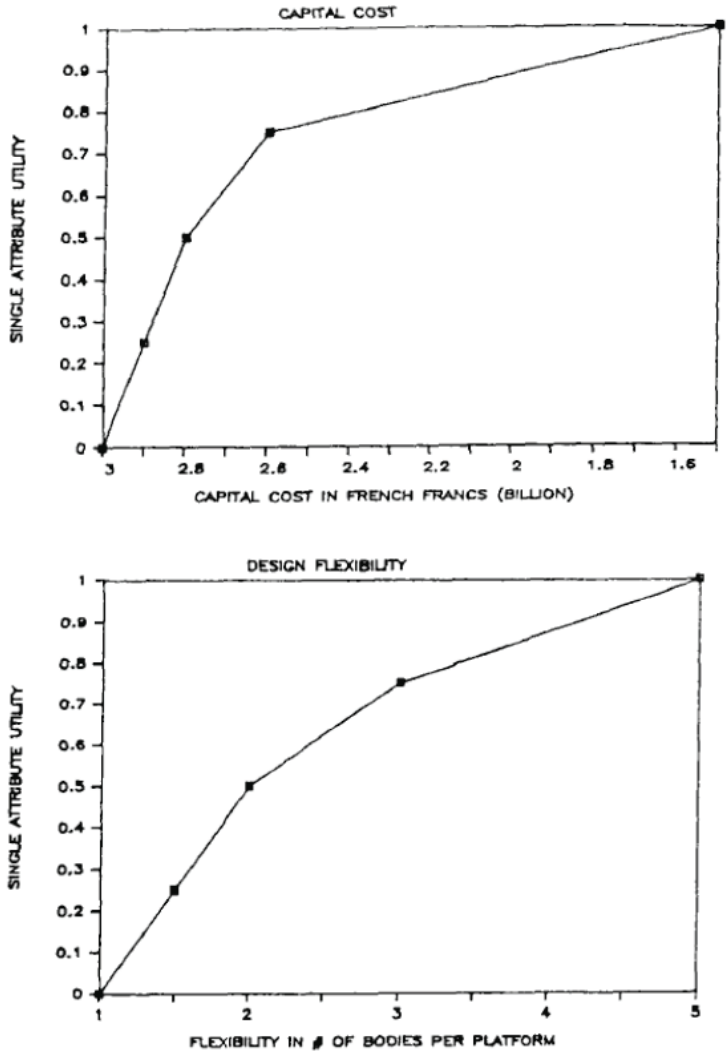


FIGURE 6.1 Single-attribute utility functions for cost and flexibility for the auto industry case study described in Box 6.2. Note that the dots represent points on the utility function assessed through structured interviews with the company's decision makers.
SOURCE: Thurston, 1990.

*continued*

**BOX 6.2 Continued**

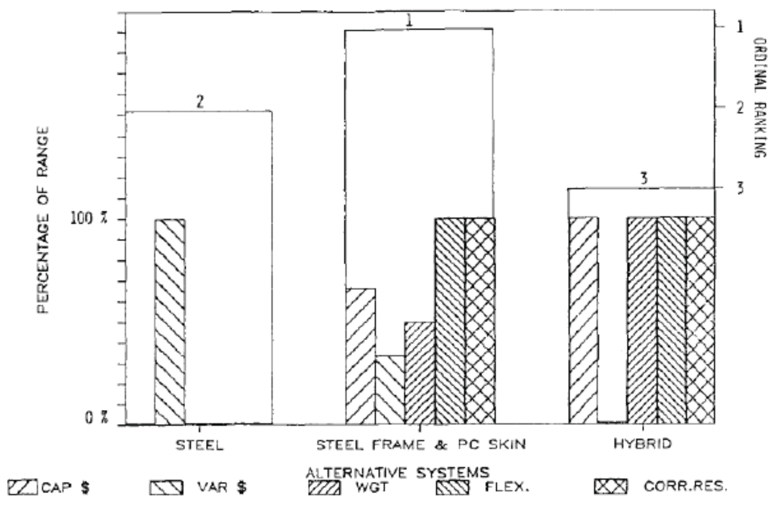


FIGURE 6.2 Attribute levels and final rankings of the alternative auto frame-and-skin designs discussed in Box 6.2.
SOURCE: Thurston, 1990.

had chosen the option that seemed intuitively to be the right choice, this decision would not have accurately reflected their true preferences.

tenets of rational decision theory (Kahneman et al., 1982). Decision analysis, by providing a framework for the decision process, can help overcome the well-known human cognitive limitations that can lead to less-than-optimal decision-making (Clemen and Reilly, 2001). It is also important to recognize that, as with any modeling system, the quality of the data used in the analysis is critical, and care must be taken to ensure that the inputs collected from the various stakeholder communities—utility values for MAU—accurately represent their views.

### Limitations of Existing Inherent Safety Indexes

Chemical engineers in the field of ISP design have conceived a number of summary indexes intended to capture the trade-offs in objectives embodied by different design options. Examples include the integrated inherent safety index (I2SI) and a set of European Union (EU) indexes known as the INSET Toolkit. (For descriptions of these methods, see Chapter 4 and Khan and Amyotte, 2004.) When considered from a formal decision analysis perspective, these indexes have a number of limitations, both theoretical and practical. The main theoretical weakness is that the indexes were not designed to follow the von Neumann-Morgenstern model of rational choice, so there is no guarantee that the index value for a given manufacturing process will be able to reflect a given decision maker's actual preferences and attitudes toward risk. Perhaps more importantly, these indexes—in contrast to a MAU approach—do not allow for the possibility of multiple decision makers with different preferences.

As an example, consider the I2SI index (Khan and Amyotte, 2004). This index is intended to combine assessments of multiple inherent safety attributes into a single numeric value. The equation for computing this index is:

$$I2SI = \frac{ISI_{alt} / PHCI_{alt}}{HI_{base} / PHCI_{base}} \tag{6.3}$$

where $ISI_{alt}$, $PHCI_{alt}$, $HI_{base}$, and $PHCI_{base}$ are all subindexes computed as functions of various process design attributes. For each manufacturing process considered, the ratio $HI_{base}/PHCI_{base}$ is the same, so that when comparing multiple alternatives the above equation reduces to:

$$I2SI = c \times \frac{ISI_{alt}}{PHCI_{alt}} = c \times \frac{Min\{200, \sqrt{\sum_{i=1}^{5} ISI_i^2}\}}{\sum_{j=1}^{10} PHCI_j} \tag{6.4}$$

where $c$ is a constant and the summation terms in the equation represent the attributes listed in Table 6.4. The values for the summation terms are determined from a combination of subjective judgments about the degree to which each process unit satisfies the principles of ISP.

An index such as the I2SI provides a single calculation that cannot be adjusted to reflect the variation in preferences among attributes and willingness to tolerate risk that different constituencies may exhibit. For example, a company owner may be willing to tolerate a small risk of a spill that could have health effects in the community if the alternative involved a much higher risk of a fire that would seriously damage the facility, whereas members of the community may not accept such a trade-off, and employees of the firm (who place some value on keeping the facility intact in order to retain their jobs) may prefer something in between the owner and the community. In addition to putting different weights

TABLE 6.4 Attributes Included in the I2SI (Equation 6.4)

| Attribute Category : Adherence to principles of inherently safer design | |
|---|---|
| Attribute Description | Representation in I2SI Equations |
| Extent to which process **minimizes** use of hazardous materials | $ISI_1 = ISI_m$ |
| Extent to which process **substitutes** safer materials for more hazardous ones | $ISI_2 = ISI_{su}$ |
| Extent to which process **attenuates** risks by operating under safer conditions (e.g., room temperature and pressure) | $ISI_3 = ISI_a$ |
| Extent to which process **simplifies** manufacturing (e.g., by avoidance of multiproduct or multiunit operations or congested pipe or unit settings) | $ISI_4 = ISI_{si}$ |
| Extent to which process **limits** potential negative consequences of out-of-normal operations (e.g., by unit segregation) | $ISI_5 = ISI_l$ |
| **Attribute Category : Need for add-on processes to control hazards** | |
| Attribute Description | Representation in I2SI Equations |
| **Pressure** control required | $PHCI_1 = PHCI_p$ |
| **Temperature** control required | $PHCI_2 = PHCI_t$ |
| **Flow** control required | $PHCI_3 = PHCI_f$ |
| **Level** control required | $PHCI_4 = PHCI_l$ |
| **Concentration** control necessary | $PHCI_5 = PHCI_c$ |
| **Inert venting** necessary | $PHCI_6 = PHCI_{iv}$ |
| **Blast wall** needed | $PHCI_7 = PHCI_{bw}$ |
| **Fire resistance** wall needed | $PHCI_8 = PHCI_{fr}$ |
| **Sprinkler** system necessary | $PHCI_9 = PHCI_s$ |
| Forced **dilution** needed | $PHCI_{10} = PHCI_d$ |

on different attributes, a MAU model can reflect differences in risk tolerances in the form of the utility function: linear functions represent risk neutrality; concave functions represent a preference for gambling on high risks that have potentially high payoffs; and convex functions represent risk aversion (for details, see Clemen and Reilly, 2001).

The existing indexes are the proverbial black box: input a set of numbers based on the process being evaluated, and the index produces a single value for each alternative, which is then used to rank the different alternatives and identify the optimal decision. All of the trade-offs, uncertainties, and risk tolerances are hidden from view because they are implicitly assumed in the underlying calculations, rather than explicitly chosen parameters. Because these indexes implicitly assume one value structure, the effects of alternative value structures on the preference ordering of the alternatives cannot be assessed. Indeed, because the trade-offs in the index are completely opaque (to the analysts as well as to others), it is unlikely that companies will be able to use such indexes to build trust within the communities in which their facilities are located. A more transparent approach, that is, one that makes the trade-offs in attributes and risk tolerances explicit, is needed if the outcomes of ISP assessments are to be widely embraced.

## EMPLOYING MAU MODELS IN ISP ASSESSMENTS

The existing inherent safety indexes could serve as a starting point for building MAU functions to inform process design choices, with inherent safety in mind. For ISP design, fundamental objectives have been described as elimination, minimization, substitution, moderation, and simplification. The indexes provide useful starting points for constructing MAU functions in that they identify a number of the attributes by which progress along these fundamental objectives could be measured. For example, the attributes in the I2SI include costs associated with any damage that might occur due to a safety breach and costs associated with a process control option under consideration. Other attributes that could be included might be the number of fatalities that could occur in an accident and the potential loss of community goodwill (which can lead to additional costs for the company in its future decision-making). CCPS (1996), mentioned at the beginning of this chapter, provides an illustration of the use of MAU to choose a process control device for a hypothetical chemical distillation column.

## EMPLOYING MAU MODELS AT BAYER CROPSCIENCE

MAU and ISP decision-making tools could have been used to inform manufacturing process design choices at numerous points in the history of the Institute pesticide plant, starting with the introduction of MIC to the site in 1978. As noted in Chapter 5, changes to the production process made at the Institute facility were generally considered in response to business conditions or external pressures, without explicit consideration of ISP principles. Several of these decision points could have provided opportunities to introduce MAU approaches, which would have recognized the multi-attribute nature of the decision and the differences in preferences between the firm and the community, perhaps resulting in a decision-making process that would have been more acceptable to the community. That, in turn, might have allowed production to continue at the plant in some form.

Chapter 5 mentions the 1984 Bhopal accident and the 2008 methomyl accident as significant opportunities for broadening the approach to decision making at Institute. Other opportunities arose when the plant changed ownership. Choices that better accounted for the multiple costs and benefits involved—including the costs associated with risks imposed on the community—could have prevented the types of accident risks that persisted until the use of MIC ceased at the site. Without such a multi-attribute decision framework in place, the decisions at the Institute site seem to have focused on production costs and the business risk of interrupting the flow of product to the market, which resulted in the decision to continue with the same basic production process with some modifications rather than adopting an entirely new approach.

This bias in favor of an existing production process is not surprising and may even reflect the optimal decision, especially from the company's point of view. "Steel in the ground" is a powerful motivator. It avoids the up-front capital costs of a new process, along with any uncertainties about how well the process will operate or what its operating cost will be. Critically and objectively reviewing a process that has been in operation for many years can be difficult for those working at a chemical production facility. For example, from a practical standpoint, it is likely that, over time, a given process will have been modified from its initial design. Minor changes in procedures, modifications to existing equipment, and the effect of age and maintenance on the system must be taken into account during the trade-off analysis. This may be challenging if, due to staffing changes or insufficient documentation, the modifications from the initial design have not been recorded. In addition, alternative processes may always seem "hypothetical," and concerns about risks expressed by community members may be ascribed to their lack of understanding of the process and its many layers of safety protections. These factors make it difficult to apply MAU (and ISP) analyses to existing plants in ways that can really identify promising alternatives to the existing process.

Implementing a structured, multi-attribute decision process such as MAU analysis may be easier when designing a new production process or an entirely new facility. In such cases, no incumbent process has an advantage in terms of capital costs or production uncertainties, since all the alternative processes are new and hence hypothetical. In addition, the company may be involved in negotiations with regulators—who, in turn, are considering the concerns of community groups—in order to obtain an operating permit, so the need to address concerns held by those outside the facility will be more salient. During these initial interactions between the facility and its neighbors, a MAU analysis could serve to educate community members about the trade-offs between risks and economic considerations of importance to the company, while informing the company of the community's concerns about different types of production risks.

However, conducting a MAU analysis for the MIC issue would not necessarily have resulted in different decisions by the companies owning the Institute plant. Especially using the company's own valuation on the multiple attributes of the alternatives, continuing with the existing MIC process might well have seemed optimal. The advantage that would be gained from using multi-criteria analysis is that the company would have explicitly identified the most important attributes of the alternative processes and assigned a valuation to those attributes. Using MAU could also have provided a calculation into which the preferences of others (e.g., community members) could easily be incorporated.

## CONCLUSIONS

No one carbamate pesticide production process dominates all the others along every attribute that owners of the Institute site considered or could have considered. However, given the necessary trade-offs, a decision-analysis approach, such as MAU, could have helped the various plant owners consider all aspects of their choices. A decision analysis approach might also have facilitated the communication process between the company and the surrounding community, allowing the two groups to compare their preferences regarding the decision attributes and their potentially differing tolerances and attitudes toward risk. Although the CCPS has advocated for the development of such an approach since 1995, it has not become institutionalized in the chemical process industry. **A new decision-making framework, incorporating some of the work done to develop existing ISP indexes but also allowing explicit consideration of differences in decision makers' preferences across multiple attributes, could assist in the incorporation of ISP considerations into decision making in the chemical manufacturing industry and communication of those considerations to a concerned public.**

Design decisions cannot be strictly objective with regards to ISP as these choices will always require trade-offs among attributes and varying levels of risk; different individuals or constituencies may have different value systems and thus make different trade-offs. However, a new decision framework could support incorporation of the attributes in existing indexes, while adhering, and drawing benefit from, the mathematics of multi-attribute or -criteria decision analysis.

**The committee recommends that the Chemical Safety Board or other appropriate entity convene a working group to chart a plan for incorporating decision theory frameworks into ISP assessments. The working group should include experts in chemical engineering, ISP design, decision sciences, negotiations, and other relevant disciplines. The working group should identify obstacles to employing methods from the decision sciences in process safety assessments. It should identify options for tailoring these methods to the chemical process industry and incentives that would encourage their use.**

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# 7

# Process Safety Management at Bayer CropScience

All safety assessments and practices exist within the context of an organization, and as a result, the environment in which a company operates and the safety culture that it fosters within its walls affect the efficacy of any hazard control system. This chapter presents process safety management (PSM) from both a general perspective and with specific reference to the system implemented at Bayer CropScience (Bayer) and considers the context in which this system operates in Institute, WV. This chapter also addresses Bayer's use of inherently safer process (ISP) assessments conducted by Bayer within their PSM system, as well as the context in which these assessments were considered.

## PSM—GENERAL CONSIDERATIONS

PSM is a concept well familiar to the global chemical engineering community. These PSM systems, described in Chapter 4, are conceptual and management frameworks developed to aid in the control of hazards on site. The components of any given PSM system may vary somewhat between countries and organizations, but the fundamental structures remain similar. These systems make explicit the understanding that controlling a hazard—whether physical, toxic, electrical, etc.—requires a *sociotechnical* system, and therefore, requires engagement at all levels of an organization. For example, if ventilation is required to maintain a safe environment, purchase of the equipment required to provide that ventilation is only one piece of the sociotechnical system. There must also be adequate training of personnel so that they know how and when to use the equipment, monitoring of the equipment's performance and employee's compliance with safety protocols, emergency response protocols in case the equipment fails, periodic auditing of the protocols regarding ventilation by management to proactively identify and address any emerging concerns or new understandings about the risk posed by a given material, etc. These systems have been developed in response to the knowledge that once a hazard and its risks are brought into an environment, the risk "remains, waiting for an opportunity to happen unless the management system is actively monitoring company operations for concerns and taking proactive actions to correct potential problems" (Amyotte et al., 2007).

Having an effective management system for process-related hazards—fire, explosion, and toxic release—is therefore considered by many in the chemical process industries to be a critical corporate objective. Formally, PSM is defined as the application of management principles to the identification, understanding, and control of process hazards to prevent process-related incidents OSHA's PSM standard, 29 CFR § 1910.119. Various approaches exist for PSM. One example is the 1989 system developed by the Center for Chemical Process Safety (CCPS, 1989), which served as the basis for a 12-element system recommended by the Canadian Society for Chemical Engineering (CSChE, 2002). More recently, the CCPS has developed guidance on a 20-element, risk-based approach to managing process safety (CCPS, 2007); see Table 7.1. Within the United States, OSHA administers Process Safety Management of Highly Hazardous Chemicals standard 29 CFR § 1910.119, which defines requirements for handling of those materials. It consists of 16 elements, 14 of which are mandatory.

## PSM AT BAYER CROPSCIENCE

As most companies do, Bayer CropScience has its own PSM system. Bayer's 14-element system is shown in Table 7.2, with noted similarities between this system and the CCPS-developed listing in Table 7.1.

For this discussion, Bayer's element 4, *Process hazard analysis*, is most relevant. This analysis consists of the following steps (Patrick Ragan, Bayer CropScience unpublished material, August 8, 2011):

1. Hazard identification (using a variety of methods including preliminary safety analysis; hazard and operability study (HAZOP); what-if review; checklist review; what-if/checklist review; fault tree analysis; event tree analysis; and failure modes, effects and criticality analysis (FMECA);
2. Severity determination;
3. Probability determination;
4. Risk assessment (using a risk matrix); and
5. Risk management (including application of risk reduction measures).

Within step five, the list of preventive safety measures given includes passive, active, and procedural measures for hazard control, but there is no specific requirement to consider ISP measures.

TABLE 7.1 Risk-Based Process Safety Management System

| Accident Prevention Pillar | Risk-Based Process Safety Element |
|---|---|
| Commit to process safety | Process safety culture |
| | Compliance with Standards |
| | Process safety competency |
| | Workforce involvement |
| | Stakeholder outreach |
| Understand hazards and risk | Process knowledge management |
| | Hazard identification and risk analysis |
| Manage risk | Operating procedures |
| | Safe work practices |
| | Asset integrity and reliability |
| | Contractor management |
| | Training and performance assurance |
| | Management of change |
| | Operational readiness |
| | Conduct of operations |
| | Emergency management |
| Learn from experience | Incident investigation |
| | Measurement and metrics |
| | Auditing |
| | Management review and continuous improvement |

SOURCE: Adapted from CCPS (2007).

TABLE 7.2 Bayer CropScience System for PSM of Hazardous Chemicals

| Focus | Element |
|---|---|
| Commitment | 1. Leadership and culture |
| | 2. Employee participation |
| Understanding risk | 3. Process safety information |
| | 4. Process hazard analysis |
| Managing risk | 5. Operating procedures |
| | 6. Training |
| | 7. Contractors |
| | 8. Pre-Startup safety review |
| | 9. Mechanical integrity |
| | 10. Safe work practices |
| | 11. Management of change |
| Response and corrective action | 12. Incident investigation |
| | 13. Emergency planning and response |
| | 14. Compliance audits |

SOURCE: Provided by Patrick Ragan, Bayer CropScience, on August 8, 2011.

## ISP ASSESSMENTS AT BAYER CROPSCIENCE

**Although claimed to be an integral PSM component, inherent safety considerations are incorporated into Bayer's PSM efforts in an implicit manner that is dependent on the knowledge base of the individual facilitating the particular activity (e.g., process hazard analysis or PHA).** Although an implicit system of ISP incorporation does not mean an absence of a commitment to inherent safety, it does mean that the commitment is not visible to the extent that could be considered desirable.

The disadvantage of an implicit system of ISP is *corporate memory*. The extensive work of Professor Trevor Kletz over several decades of process safety research, practice and writing has clearly demonstrated that organizations do not generally have a long-term memory—at least not a memory longer than about 10 years. Corporate memory resides with individuals, and individuals retire, resign, or otherwise move on to other opportunities. While acknowledging the value of individual memory and active sharing of information between employees, if ISP consideration requirements are not explicitly recorded within the suite of PSM documentation, then such requirements may be forgotten or potentially ignored. It would be beneficial for Bayer to formally incorporate ISP assessment into the company's PSM system and training and to record such assessments as part of its audit and review processes. Doing so would provide regular opportunities to update the assessment protocols in light of any new developments in the area.

As mentioned in Chapter 4, descriptions on how ISP considerations can be incorporated into all elements of a PSM system are available. These include specific suggestions for training initiatives using the various ISP resources. Recommendations are also given regarding compliance audits related to identification and implementation of ISP. Both of these elements (training and audits) would seem particularly relevant to the case of Bayer CropScience and the Institute facility. Documented training of personnel with respect to the concept of inherent safety, for example, would contribute to creating and maintaining a consistent level of knowledge within the organization and formalize corporate memory in this area.

In the course of reviewing the materials provided by Bayer CropScience regarding the alternatives assessment performed by Bayer and the previous owners of the facility and the design of the post-2008 facility redesign, it was clear that safety considerations did come into play in the analysis. However, the focus of the alternatives assessments and the redesign was primarily directed toward managing the hazard rather than eliminating or reducing it, which is consistent with the focus on passive, active, and procedural controls within the PSM. Appendix B provides a detailed history of process changes that occurred at the Institute facility, and points where ISP-type decisions were made are highlighted. A summary of specific examples of the process changes that occurred are listed in Box 7.1. For example, every time a significant reduction of MIC inventory

**BOX 7.1**
**Summary of Process Design Changes with Implications for Safety at the Institute Facility Consistent with ISP Principles**

- Union Carbide Company (UCC) practiced principles of sustainability in 1978 when it switched from the chloroformate process to the isocyanate process for carbaryl production achieving higher yields, less waste, less corrosion, and less environmental impact.
- UCC practiced passive and active safety strategies in 1978 and 1985 in the design of the MIC process featuring refrigerated underground storage, emergency scrubbers, and emergency flares.
- UCC followed ISP principles in its search for alternative chemistries to MIC prior to 1985.
- UCC followed ISP principles in its focus on less hazardous MIC-adducts in 1986 (for remote production to avoid aldisol transportation).
- Rhône-Poulenc practiced passive and active safety strategies in 1988 with MIC incinerator and carbaryl reliability optimization, and ISP principles with MIC downsizing measures (Project MN).
- Rhône-Poulenc followed ISP principles in 1989 to 1991 in the evaluation and design of Enichem phenylmethylcarbamate process with cracking at remote (Project MS) or at four individual carbamate plants in Institute, eliminating MIC storage and transport and reducing total MIC inventory for all carbamate production to a few hundred pounds. However, this process was not implemented.
- Rhône-Poulenc practiced passive and active safety strategies in its 1993 Institute Modification Project.
- The Rhône-Poulenc 1994 Risk Management Plan contains passive, active, and mostly procedural safety elements.
- Bayer followed ISP principles in modeling and analyzing the operational impacts of reducing MIC inventory.
- Bayer MIC Unit Layers of Protection strategy contains mostly passive and active and some inherent safety elements.
- Bayer (Project MINEXT) practiced ISP in 2010 by closing the West Carbamoylation Center and by reducing carbamate production to two products and reducing MIC inventory by 80 percent, and practiced passive and active safety strategies by eliminating aboveground storage, and using double-walled construction, steam-ammonia curtains, and other measures.
- Bayer followed ISP principles in 2010 by evaluating alternative chemistries for the production and use of gaseous (instead of liquid) MIC, including chemistries avoiding the use of phosgene (although none was evaluated to be competitive or timely in the present business environment).
- Bayer also followed ISP principles in 2010 by substituting a non-reactive material for brine in the MIC storage tank refrigeration systems.

occurred, one aspect of the philosophy of ISP (reduction) was implemented, even if that term was not used.

Since ISP was not a formal consideration for the facility's owners, the committee finds that the managers of the facility in Institute missed opportunities to perform full safety assessments. **Bayer CropScience did perform PSM assessments, however, Bayer and the legacy companies did not perform systematic and complete ISP assessments on the process for manufacturing MIC or the processes used to manufacture pesticides at the Institute site. Bayer and the previous owners performed various hazard and safety assessments and made certain business decisions that resulted in MIC inventory reduction, elimination of aboveground MIC storage, and adoption of various passive, active, and procedural safety measures. However, these assessments did not incorporate, in an explicit and structured manner, the principles of minimization, substitution, moderation, and simplification. The legacy owners identified possible alternative methods that could have resulted in a reduction in MIC production and inventory, but determined that limitations of technology, product purity, cost, and other issues prohibited their implementation.**

## ISP ASSESSMENTS—EXTERNAL CONTEXT

Because Bayer implicitly uses ISP practices and principles within their PSM system (e.g., reducing inventory of MIC and acknowledging the safety benefit drawn from that), it is a useful exercise to consider what incentives could exist for the explicit incorporation of ISP assessments into the PSM system. Indeed, within the industry broadly, there are barriers to the formal consideration of ISP including the perception that inherent safety is impractical, or costly, that there is a lack of institutional infrastructure and frameworks for evaluating inherently safer processes, and a lack of standards and guidance measures for existing operations (CCPS, 2008). The purpose of this section of the report is not to endorse one method or another for encouraging the adoption of ISP. Rather it is to provide a brief overview of possible drivers and barriers to formal, explicit consideration of ISP by a company.

One possible mechanism for overcoming these barriers is through professional standards within the field of chemical engineering. **Inherently safer process assessments are a valuable component of process safety management. However, as noted in Chapter 4, at this time the view of what constitutes an inherently safer process varies among professionals, so the chemical industry lacks a common understanding and set of practice protocols for identifying safer processes.**

Externally, industry standards could affect the formal incorporation of ISP into PSM. It is clear that companies look to professional organizations, such as CCPS, for guidance on these issues. Alternatively, were ISP to be incorporated into the standards of the American Chemistry Council Responsible Care Program, for example, it would likely encourage adoption of ISP concepts into PSM methodologies.

Of course, regulatory policy could drive companies' adoption of ISP analyses. In Chapter 4, Box 4.1 presented definitions of ISP, including two drawn from regulatory policy initiatives within the United States that require consideration of ISP. In reviewing those policies, it is clear that the link between ISP strategies and the framework set down by cleaner production and pollution prevention regulations is seen as a starting place for considering the role of ISP in context (Zwetsloot and Ashford, 2003). It is important to remember, however, that the effective implementation of ISP relies on the awareness of the professional, technical community, and studies (Wilson et al., 2008; Copsey, 2010) have highlighted the need to improve links between workforce preparation and industry knowledge of inherently safer strategies for risk reduction.

In the United States, companies are required to have PSM systems in place for handling of highly hazardous chemicals. However, the elements of OSHA's PSM (29 CFR § 1910.119) standard do not require any explicit consideration of ISP. Rather the requirements accept the presence of a hazard, and the risks that may come with its use, and are thus directed to the tiers of the PSM hierarchy geared toward control and management of the hazard and its risk rather than elimination of the hazard itself. The PSM elements required by OSHA were presented in detail in Chapter 2 and are listed in Table 7.3.

The U.S. Environmental Protection Agency (EPA) policy has considered the possibility of inherent safety at least since the early 2000s, but measures regarding chemical accident prevention have tended to focus on prior planning and "inspection and . . . corrective and preventive maintenance." (Ashford and Zwetsloot, 1999). Therefore, the concept of safety planning is far from new, but

TABLE 7.3 Fourteen Required Elements of OSHA's PSM Standard

- Process safety information,
- Process hazard analysis,
- Operating procedures,
- Employee participation,
- Training,
- Contractors,
- Pre-startup safety review,
- Mechanical integrity,
- Hot work,
- Management of change,
- Incident investigation,
- Emergency planning and response,
- Compliance audits, and
- Trade secrets.

the far-reaching ramifications of ISP appear to require a greater degree of planning and technological investment than do traditional safety strategies that tend to be "failsafe" rather than "foolproof." (Ashford and Zwetsloot, 1999).

The difficulties of implementing ISP also can be observed in the EPA Risk Management Program (RMP) (EPA, 2001), which is still intentionally more oriented to risk management than risk prevention (Malloy, 2008), and as a policy matter does not mandate ISP. Nevertheless, companies dealing with hazardous chemicals must develop accident prevention plans during hazard emergency response planning, but this policy does not extensively involve stakeholders outside of firms (CCPS, 2009).

Other pertinent regulations and laws include the Pollution Prevention Act (PPA), which is not primarily directed at accidents (Ashford and Caldhart, 2010), and the Department of Homeland Security's Chemical Facility Anti-Terrorism Standards (CFATS) (Malloy, 2008). The post-September 11 approach is particularly amenable to ISP (CCPS, 2009), because the unpredictable nature of terrorist attacks may create challenges for traditional assessments based on internal production risks. However, regulatory bodies have tended to conclude that ISP shift rather than prevent risks (Malloy, 2008). This is an important critique that warrants further research, because of the possibility that inherently safer technology may lead to the reallocating of risk to other areas of the production process (Hendershot, 2010).

The previous paragraphs were a brief overview of the policy context for ISP. More information, including international initiatives, can be found in Appendix D.

Finally, in regard to the perception of cost barriers to ISP, it is important to recognize that for most established manufacturing processes, the materials in use, whether hazardous or not, are cost competitive, and shifts to lower risk technology or process design can involve costs and uncertainties for companies (CCPS 2009). This being the case, these cost issues, and/or the perception of them, present a major practical barrier for industry to adopting safer processes (Malloy, 2008). However, greater production stability associated with inherently safer technology may lead to "greater reliability of production" and operations economies (Ashford and Zwetsloot, 1999; Malloy, 2008), which, if applicable, can be seen as an overall benefit to the company. As discussed earlier in this report, however, the costs associated with redesigning an existing facility mean that the barriers posed by these costs will be much lower when incorporated into an initial design or as part of a planned, significant modification of an existing site.

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# 8

# Post-Incident Retrospective Process Assessment

Part 3.5 of this study's statement of task was to "[c]omment, if possible, on whether and how inherently safer process assessments can be utilized during post-incident investigations." Unlike the preceding chapter, this portion of the task looks beyond Bayer and requires broad consideration of the application of inherently safer process (ISP) assessments under these circumstances. The conclusion from the analysis presented here is that **the principles of ISP assessment can be used to good effect in conducting an incident investigation when the objective is the prevention of potential incidents having similar fundamental, underlying (root) causes.** Examples are provided to demonstrate how this might be done and the extent of current practice in this regard. This chapter also provides information regarding emergency response systems and discusses how ISP assessments could be used to improve and support effective emergency planning and response.

## INCIDENT INVESTIGATION—AN ESSENTIAL COMPONENT OF A SAFETY MANAGEMENT SYSTEM

As noted in Chapter 7, incident investigation is not a one-time, stand-alone event, but instead a necessary element within a functioning process safety management (PSM) system. Indeed, it is one of the mandatory elements of OSHA's PSM standard, which requires, "the investigation of each incident that resulted in, or could reasonably have resulted in, a catastrophic release of a highly hazardous chemical in the workplace" (Department of Labor, 2000).

Comprehensive protocols and advice are available for conducting investigations of chemical process incidents (e.g., CCPS, 2003). Such guidelines emphasize the need for a PSM system to be simultaneously *retrospective* and *prospective*, with incident investigation providing the vital bridge between the lessons of the past and safer designs and operation in the future (CCPS, 2003). This point is expanded upon in the following sections.

**Relationship Between A Priori and Post-Facto Assessment**

Although advance preparation is essential, incident investigations are conducted after the fact—that is, after a loss-producing event or a near-miss has occurred. In conducting a post-incident process assessment, it is important to avoid the problem of *hindsight bias*. Hindsight bias, known commonly as "Monday morning quarterbacking" or "20-20 hindsight" is the tendency to view events as more foreseeable or more inevitable *after the fact* than they actually would have appeared at the time actions needed to be taken (Fischhoff, 1975; Blank et al., 2007; Louie et al., 2007). In particular, anyone who is judging the safety of a facility after an incident has information that was not available to those who conducted any pre-incident process assessment. Although most people recognize it would be unfair to use later information to second-guess earlier decisions, research on hindsight bias cited above has shown that cognitive biases can limit our ability to recognize the additional information that we have acquired after the event. While such new information should never be ignored, it is important to acknowledge that critical factors may not have been obvious before an incident, because this can help identify new opportunities for analysis, monitoring, communication, etc.

The chain of events that produced a chemical release is obvious in retrospect because it happened, even though it might not have been obvious in prospect because safety analysts failed to imagine that such an event chain could happen. In such cases, it is important to judge what the safety analysts could *reasonably* have been expected to anticipate by examining the safety analyses conducted in other facilities. If facilities with similar designs had also failed to anticipate that chain of events, then those conducting a pos-tincident process assessment should be wary of the effects of hindsight bias. However, if facilities with similar designs had anticipated that chain of events, then those conducting a post-incident process assessment should be less concerned that their analyses are being affected by hindsight bias.

Alternatively, it might be that the *probability* (rather than the possibility) of that chain of events might seem more likely in retrospect than in prospect because a pre-incident safety assessment underestimated the probability that such an event chain could happen. In this case, it is important to balance the possibility that the post-incident process assessment is being affected by hindsight bias against the possibility that any pre-incident process assessment was affected by *optimistic bias* (Weinstein, 1989), also known as comparative optimism (Klar and Ayal, 2004). In other words, the pre-incident process assessment might have assumed that engineered safety features would not fail, that emergency operating procedures would be implemented effectively, that everyone at risk would receive warning messages, and so on. Aside from any erroneous assumptions about the quality of the facility design, there is ample documentation that facilities "as built" and "as maintained" typically differ—sometimes substantially—from their original designs (as evidenced by the Bhopal tragedy). Further, operational and design changes over the life of a facility can introduce new hazards not anticipated by the original designers; this illustrates the need for an effective management-of-change protocol within an overall PSM system. Consequently, preincident process assessments can provide unrealistically optimistic estimates of incident probabilities.

Issues of hindsight, and hindsight bias, are critical when the focus of an investigation is solely on a given incident itself, perhaps for reasons relating to litigation or disciplinary measures. It is precisely this retrospective nature of incident investigation, however, that gives this PSM element its dominant role in learning from experience. As noted in CCPS (2007), the process of incident investigation involves reporting, tracking, and investigating incidents, together with management of the development and documentation of recommendations arising from investigations. If the sole purpose is simply to establish guilt and assign blame to plant personnel, the result will not only be ineffective recommendations but also missed opportunities to prevent repeat occurrences. CCPS (2007) further comments that a much more effective approach to incident investigation is to develop recommendations that address systemic causes. In other words, it is the management system deficiencies (often termed *root causes*) that need to be identified in an effort to avoid not just the same or a similar incident from happening again, but also incidents that could occur because of the existence of deeper, management-system causation factors. Examples in this latter category would include shortcomings in any of the elements of a PSM system.

Because PSM involves a suite of considerations that complement one another, efforts directed at a particular element can have a positive effect on one or more other elements. For example, commitment to a strong process safety culture will undoubtedly affect all remaining PSM elements as previously discussed in Chapter 7. It is difficult to envisage senior managers searching for PSM system deficiencies during an incident investigation without those same managers being fully committed to ensuring a sound safety culture; Sutton (2008) has demonstrated this strong correlation between root-cause analysis through incident investigation and the development of a company's safety culture. Similarly, hazard identification and risk analysis, which by their nature are a priori activities, can be used to inform the process of incident investigation, a post facto activity as previously mentioned.

A tool commonly used to identify process hazards is a checklist of relevant concerns. Table 8.1 gives a partial listing of items drawn from the ISP checklist found in Appendix A of CCPS (2009). The recommended questions in

TABLE 8.1 Partial ISP Checklist (adapted from CCPS, 2009)

| ISP Alternative | a | b | c | d | e |
|---|---|---|---|---|---|
| MINIMIZE | | | | | |
| Can hazardous raw materials inventory be reduced? | | | | | |
| Can hazardous in-process storage and inventory be reduced? | | | | | |
| Can hazardous finished product inventory be reduced? | | | | | |
| Can alternative equipment with reduced hazardous material inventory requirement be used? | | | | | |
| SUBSTITUTE | | | | | |
| Is this hazardous process/product necessary? | | | | | |
| Is it possible to completely eliminate hazardous raw materials, process intermediates, or by-products by using an alternative process or chemistry? | | | | | |
| Is an alternative process available for this product that eliminates or substantially reduces the need for hazardous raw materials or production of hazardous intermediates? | | | | | |
| Is it possible to substitute less hazardous raw materials? | | | | | |
| MODERATE | | | | | |
| Is it possible to limit the supply pressure of hazardous raw materials to less than the maximum allowable working pressure of the vessels to which they are delivered? | | | | | |
| Can the process be operated at less severe conditions for hazardous reactants or products by considering improved thermodynamics or kinetics to reduce operating temperatures or pressures? | | | | | |
| Can process units for hazardous materials be designed to limit the magnitude of process deviations? | | | | | |
| SIMPLIFY | | | | | |
| Can equipment be designed such that it is difficult or impossible to create a potential hazardous situation due to an operating or maintenance error? | | | | | |
| Can passive leak-limiting technology be used to limit potential loss of containment? | | | | | |
| Has attention to control system human factors been addressed through logical arrangement of controls and displays that match operator expectations? | | | | | |

NOTES: a = Applicable (Y/N), b = Opportunities/Applications, c = Feasibility, d = Current Status, e = Recommendation.
SOURCE: Adapted from CCPS (2009).

Table 8.1—which provide explicit, structured consideration of the four key ISP principles (minimization, substitution, moderation, and simplification)—can be asked at virtually any stage of process design and operation to identify potential hazards and suggest remedial actions. They can also be asked at the stage of incident investigation with the aim of root-cause prevention. This point is elaborated upon in the following paragraph and later in this chapter.

Kletz and Amyotte (2010) have commented that reports of incident investigations often deal only with the immediate causes of the incident (i.e., the triggering events), but not with ways of avoiding the hazard. If an investigation protocol is designed primarily to determine why control of hazards was lost, it is unlikely that emphasis will be placed on examining why the hazard was tolerated and whether it could have been avoided in the first place. A primary function of effective incident investigation must therefore be to challenge company personnel to question the basic technology underlying the affected materials, equipment, and processes.

Several questions have been posed by Kletz and Amyotte (2010) to motivate incident investigators and investigation teams to think of less obvious ways of preventing process incidents. These questions, given below in adapted form, raise issues similar to the checklist questions listed in Table 8.1:

- *What* is the purpose of the operation involved in the incident?
  *Why* do we do this?
  *How* else could we do it?
  *Who* else could do it?
  *When* else could we do it?
  *Where* else could we do it?
  *What* could we do instead?
- *What* equipment failed?
  *How* can we prevent failure or make it less likely?
  *How* can we detect failure or approaching failure?
  *How* can we control failure (i.e., minimize consequences)?
  *What* does this equipment do?
  *What* other equipment could we use instead?
  *What* could we do instead?
- *What* material leaked (exploded, decomposed, etc.)?
  *How* can we prevent a leak (explosion, decomposition, etc.)?
  *How* can we detect a leak or approaching leak (etc.)?
  *What* does this material do?
  *What* material could we use instead?
  *What* safer form could we use the original material in?
  *What* could we do instead?
- *Which* people could have performed better? (Consider people who might supervise, train, inspect, check, or design better than they did, as well as people who might construct, operate, or maintain better than they did.)

*What* could they have done better?

*How* can we help them to perform better? (Consider training, instructions, inspections, audits, etc., as well as changes to design.)

*What* could we do instead?

Kletz and Amyotte (2010) further challenge incident investigators to keep a more general, overarching set of questions in mind when following their established investigation protocol. These questions are as follows:

- Did a lack of application of the principles of ISP play a role in incident causation?
- Would minimization, substitution, moderation, and simplification have helped to prevent the incident or mitigate the consequences?
- How effective were the available passive and active engineered safety devices with respect to prevention and mitigation?
- How effective were the available procedural safety measures with respect to prevention and mitigation?
- Were recommendations made to avoid the hazards and to permanently remove them wherever possible?

## AN APPROACH TO ISP-BASED INCIDENT INVESTIGATION

The discussion in the preceding section demonstrated that similar questions can and should be asked during both hazard identification and incident investigation. A structured use of checklist questions is, however, required for effective performance of the tasks of identifying hazards and investigating incidents.

Hazard identification/risk analysis and incident investigation are distinct PSM elements. Because PSM is underpinned by the concept of continuous improvement, it stands to reason that the use of ISP principles in conducting these activities will lead to opportunities for refinement of the ISP assessment methodologies. Mahnken (2001) has illustrated the general use of case histories arising from incident investigations to enhance process hazard analysis methodologies such as the familiar HAZOP (*HAZ*ard and *OP*erability study). Similarly, Khan (2006) has demonstrated how case histories can assist in identifying the need for improved hazard identification—particularly with respect to thermal stability of reactive materials and the potential for runaway chemical reactions. Khan (2006) further comments that "it is . . . necessary to make full use of all opportunities at the conceptual stages of process development and design to reduce the frequency of accidents in the chemical process industries." This is essentially a call for early ISP consideration and an examination of the effectiveness of preincident ISP assessments based on the findings of post-incident investigations.

Formalized approaches to ISP-based hazard identification are available in the process safety literature—for example, the protocol for use of ISP checklist questions in conducting a process hazard analysis (PHA), which is described in Appendix B of CCPS (2009). In a similar vein, Goraya et al. (2004) have proposed the ISP-based protocol for incident investigation shown in Figure 8.1. Key features of this approach are as follows (Goraya et al., 2004):

- Incorporation of a basic framework utilizing best practices drawn from industry;
- Adoption of an integrated approach that considers all potential categories of loss (people, property, production, and environment; "property" meaning assets and "production" meaning uninterrupted business operation);
- Classification of evidence collected after the incident into convenient data categories as appropriate with respect to data fragility (position, people, parts, and paper);
- Use of a loss causation model for identification of factors which distinguishes between "immediate causes, basic causes, and lack of management control factors" (i.e., management system deficiencies);
- Introduction of inherent safety guidewords or "mind triggers"(minimize, substitute, moderate, and simplify) at both the initiation and completion of the protocol, in an attempt to encourage ISP considerations during the collection of data and the development of recommendations, respectively;
- Use of explicit inherent safety checklist questions structured around key ISP principles (see, for example, Goraya et al., 2004; CCPS, 2009; Kletz and Amyotte, 2010) during root-cause analysis; and
- Adoption of a layered approach for making recommendations.

It is the last three items in the above list that make the protocol of Goraya et al. (2004) explicit in its consideration of ISP. The final item in particular, which was first introduced to the process safety community by Professor Trevor Kletz, is critical to the integration of ISP within the investigation protocol. As described previously in this chapter, it should be well-understood that the root causes of process incidents are typically management system deficiencies; this accounts for the third layer of recommendations shown in Figure 8.1. It is of course necessary to take immediate action to remove existing hazards following an incident; hence the first layer of recommendations in Figure 8.1. ISP, by its very nature, requires an attempt to avoid hazards and to permanently remove them wherever possible. It is therefore fundamentally impossible to address the second layer of recommendations in Figure 8.1 without explicit consideration of the principles of ISP. A positive result of second-layer ISP recommendations is thus the identification of opportunities for overall design improvements during facility rebuild in the case of significant asset loss. Such ISP opportunities represent a specific application of the well-established need to make general process improvements on the basis of both incident data (Leggett and Singh, 2000) and lessons learned from major incidents (Balasubramanian and Louvar, 2002).

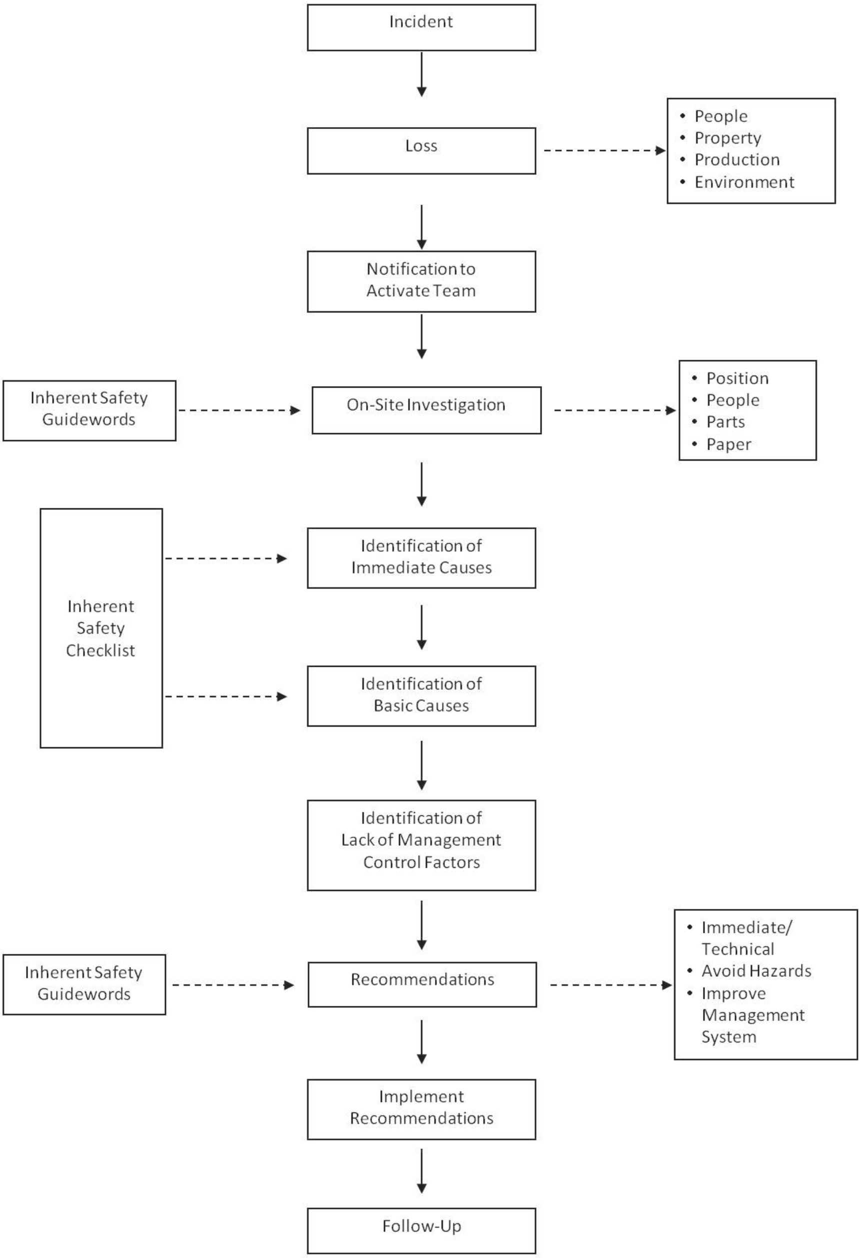


FIGURE 8.1 Inherent safety-based incident investigation methodology.
SOURCE: Goraya et al. (2004).

However, the implementation of ISP improvements resulting from second-layer recommendations will not necessarily be seen as a practical approach by all decision makers. Sociologist Andrew Hopkins has addressed this issue in his recent book on high-reliability organizations (Hopkins, 2009). He comments that although a focus on incident investigation recommendations that are deemed practical to implement will at least increase the likelihood of action being taken, it will not ensure that more fundamental (and potentially more costly) system enhancements will be undertaken.

Hopkins (2009) gives the example of additional training being provided to air traffic controllers who had made procedural errors, as opposed to removing hazards by making changes to the computer software running the air traffic control consoles, which had been identified as the root-cause source of error. Such system-wide improvements to the underlying technology, although resource-intensive and requiring comprehensive risk assessment, remain the best response to hazards identified during an incident investigation (Hopkins, 2009).

As discussed in Chapter 7, the principles of inherent safety have broad application to all elements of a PSM system. This point is repeated here as a reminder that ISP enhancements can be beneficial to all PSM aspects—not only those involving hazard identification, risk analysis, and incident investigation (Amyotte et al., 2007; CCPS, 2009; Kletz and Amyotte, 2010).

## LONG-TERM TRENDS IN INVESTIGATION RESULTS

The documentation resulting from investigations by the U.S. Chemical Safety and Hazard Investigation Board (CSB) represents some of the most accessible process incident information available in the public domain. As noted on its Web site (www.csb.gov), CSB is an independent, nonregulatory federal agency charged with investigating industrial chemical incidents. Such incidents are investigated by a team of CSB employees, and from the evidence collected, root and contributing causation factors are identified. With this information, the CSB creates sets of recommendations for various bodies such as facility managers, regulatory agencies, and technical associations. Following a completed investigation, documentation in the form of a full investigation report, case study, safety bulletin, or urgent recommendations are made available on the CSB Web site. These documents often have accompanying video support and are widely recognized as valuable learning tools for improving safety in the process industries.

An analysis of these publicly available CSB reports has recently been undertaken by Amyotte et al. (2011), primarily from the perspective of the actual and potential use of ISP principles in incident investigations. Approximately 60 reports covering the period 1998-2010 were reviewed; this resulted in the identification of numerous ISP examples related to incident prevention and consequence mitigation. These findings were often implicitly referenced in the documentation (i.e., not named as inherent safety per se), with a growing trend in recent years toward explicit use of ISP terminology when identifying causation factors and making recommendations. Particularly noteworthy in this latter regard are the BP Texas City (CSB, 2007), Valero McKee (CSB, 2008), and Xcel Energy (CSB, 2010a) investigation reports, as well as the urgent recommendations resulting from the Kleen Energy (CSB, 2010c) and ConAgra (CSB, 2010b) investigations.

In accordance with the concept that ISP is not a stand-alone approach to risk reduction, the review of CSB reports by Amyotte et al. (2011) also identified a significant number of actual and potential measures related to the other categories in the overall hierarchy of controls. The majority of the non-ISP safety features were related to procedural safety, followed by active engineered devices and, to a lesser extent, passive engineered devices. These results were determined to be generally consistent with the work of Kidam et al. (2010), who reviewed 364 chemical process industry incident descriptions in the Failure Knowledge Database maintained on the Japan Science and Technology Web site. The analysis by Amyotte et al. (2011) identified investigation lessons similar to those given by Kaszniak (2010) in his independent review of CSB reports, and by Yang et al. (2009) in their analysis of case histories (including a small subset of CSB investigations).

It is not known whether other organizations that conduct process incident investigations have adopted ISP as an integral component of their investigation protocols. It does appear, however, that at least one such organization—the CSB—has made a conscious attempt to explicitly utilize the concept and principles of ISP during post-incident investigations. As noted by Amyotte et al. (2011), this is a welcome trend that should be encouraged and widely adopted in the process industries. Expanded use of ISP considerations during process incident investigations is predicated on widespread knowledge and understanding of the inherent safety concept itself. Continued educational (e.g., Hendershot, 2006; Hendershot and Murphy, 2008) and training (e.g., IChemE, 2005) efforts in this regard are therefore imperative.

## CONCLUSIONS

This chapter has provided a review of incident investigation from both a general perspective as a key element of a PSM system and with specific ISP considerations in mind. Incident investigations are most useful in the process industries when they are conducted with the objective of determining root causes. Such causes typically reside at the level of management system deficiencies and are often related to shortcomings in hazard identification and risk assessment protocols. Explicit incorporation of the principles of ISP can play an important role in the efficacy of an incident investigation protocol.

Lessons learned from incident investigations—both general and those specific to ISP—can also have a beneficial impact on PSM overall. Such lessons can be used to make systemic improvements involving all categories in the hierarchy of controls and to help identify previously unforeseen hazards in a given process or industry sector. Because incident investigation acts within a management system based on continuous improvement, it is to be expected that investigation results will provide valuable input to the methodologies being used to predict hazards and prevent their occurrence.

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# Appendixes

# Appendix A

# Statement of Task

The National Research Council will produce a detailed written report, conclusions, and recommendations where appropriate on the following subjects:

1. Review the current industry practice for the use and storage of MIC in manufacturing processes, including a summary of key lessons and conclusions arising from the 1984 Bhopal accident and resulting changes adopted by industrial users of MIC.
2. Review current and emerging technologies for producing carbamate pesticides, including carbaryl, aldicarb, and related compounds.
   The review should include:
   2.1 Synthetic methods and patent literature
   2.2 Manufacturing approaches used worldwide for these materials
   2.3 Manufacturing costs for different synthetic routes
   2.4 Environmental and energy costs and trade-offs for alternative approaches
   2.5 Any specific fixed-facility accident or transportation risks associated with alternative approaches
   2.6 Regulatory outlook for the pesticides including their expected lifetime on the market
3. Examine the use and storage of MIC at the Bayer CropScience facility in Institute, West Virginia:
   3.1 Identify possible approaches for eliminating or reducing the use of MIC in the Bayer carbamate pesticide manufacturing processes, through, for example, substitution of less hazardous intermediates,

intensifying existing manufacturing processes, or consuming MIC simultaneously with its production.

3.2 Estimate the projected costs of alternative approaches identified above.

3.3 Evaluate the projected benefits of alternative approaches identified above, including any cost savings, reduced compliance costs, liability reductions, reduced emergency preparedness costs, and reduced likelihood or severity of a worst-case MIC release or other release affecting the surrounding community.

3.4 Compare this analysis to the inherently safer process assessments conducted by Bayer and previous owners of the Institute site.

3.5 Comment, if possible, on whether and how inherently safer process assessments can be utilized during post-accident investigations.

# Appendix B

# Carbamate Pesticide and Methyl Isocyanate Timeline

**4 June 1954:** Acrolein tank car explosion and 1955 ethylene oxide distillation column explosion at the Institute site led to the establishment of the Union Carbide Reactive Chemicals employee awareness training program and the Kanawha Valley Emergency Planning Committee.

**1958:** Carbaryl (Sevin) commercialized by Union Carbide (UCC); production by chloroformate process (phosgene + 1-naphthol → 1- naphthol chloroformate; naphthol chloroformate + methylamine → carbaryl) (None of the intermediates were made at Institute).

**5 January 1961:** First shipment of carbaryl from Institute.

**1966:** Methomyl introduced (and registered in 1968) by DuPont; production by isocyanate process (methomyl oxime + methyl isocyanate → methomyl).

**1966:** UCC startup of MIC Unit 1 for use in carbamate pesticides (other than carbaryl).

**1976:** UCC aldicarb (Temik) production started in Institute East Carbamoylation Center; production by isocyanate process (aldicarb oxime + methyl isocyanate → aldicarb).

**April 1978:** UCC startup of new Syngas plant and MIC Unit 2 (Total Unit 1 and Unit 2 capacity: 42M lb/yr MIC).

**1978:** UCC carbaryl production changed to isocyanate process (phosgene + methylamine → methyl isocyanate; methyl isocyanate + naphthol → carbaryl) in Institute East Carbamoylation Center; isocyanate process claimed to involve higher overall yields, fewer losses from hydrochloride adduct by-products, less waste and environmental impact, and fewer and less severe corrosion problems.

**1978:** Sophisticated drum-filling operation enables MIC to be shipped to customers in France, India, Brazil, and United States.

Literature describes four general routes to carbaryl (http://www.exchemistry.com/sevin.html):

1. 1-naphthol + phosgene then + methylamine (chloroformate process),
2. 1-naphthol + methyl isocyanate (isocyanate process),
3. 1-naphthol + methyl carbamoyl chloride, and
4. 1-naphthol + dimethyl urea.

In principle, these four approaches may also apply to any of the carbamates; as far as is known, however, only the chloroformate process was used as an alternative to the isocyanate process, and that was for carbaryl, and that was abandoned.

**1979:** UCC shuts down MIC Unit 1 because of lower projected demand.

**1984:** UCC methomyl and Larvin production started using isocyanate process in Institute West Carbamoylation Center on old olefins site.

**1984:** Toluene diisocyanate site converted to Miscellaneous Carbamates Unit for aldicarb, Standak, Broot, and Zectran.

**3 December 1984:** Bhopal accident.

**1985:** MIC destruction capacity and other safety enhancements added at Institute.

**23 April 1985:** Boros (UCC) report on possible research alternatives:

1. Aqueous medium for aldicarb oxime + MIC reaction (similar to DuPont 1970 patent).
2. Onepot process for aldoxycarb (aldicarb oxime + methyl isocyanate (water) → aldicarb; aldicarb + H2O2/HCOOH → aldoxycarb [Standik]).
3. General process for carbamates: ROH + CO + CH3NH2 (Pd/O2) → carbamate + H2O (caustic, chlorine, phosgene, MIC eliminated; need high Pd productivity and recovery) (based on Asahi Chemical article in Journal of Organic Chemistry, 1984).

4. Use of MIC/NaHSO3 solid adduct (reported 27 July 1976) instead of MIC demonstrated for carbaryl, aldicarb, methomyl, and carbofuran.
5. Conversion of methyl formamide to MIC over dehydrogenation catalyst (Sun Ventures & DuPont, 1976).
6. Review of 55 MIC patents between January 1944 and July 1979 reveal primary method of MIC production to be phosgenation of methylamine followed by either (a) HCl removal by some separation technology, or (b) HCl removal by reaction with an acid receptor.
7. NaOCN + dimethyl sulfate → MIC + sodium sulfate (cyanate process) (Deutsche Gold patent; operated by Sunko, June 1980).

**June 1985:** DuPont, given loss of availability of bulk MIC, develops methyl formamide oxidation process for MIC(g) production and integrates with continuous methomyl process for minimum MIC inventory.

**11 August 1985:** Accidental release of aldicarb oxime and methylene chloride in Miscellaneous Carbamates Unit (aldicarb plant) (Lead in part to new OSHA safety program for chemical plants and EPA Chemical Emergency Preparedness Program).

**January 1986:** FMC, given the loss of availability of bulk MIC, starts production of carbofuran (Furadan) (operated by UCC on old ethyl alcohol site) in Institute West Carbamoylation Center; production by isocyanate process (carbofuran phenol + methyl isocyanate → carbofuran).

**1986:** UCC updates MIC patent review (July 1979-December 1985); patent activity shifting to MIC "carriers":

1. Phosgenation of methylamine followed by pyrolysis of methyl carbamoyl chloride (traditional route; little patent activity);
2. Phosgenation of ureas (Philagro);
3. Thermal decomposition of carbamic acid esters (Bayer, EniChemica);
4. Thermal decomposition of trisubstituted ureas (Bayer);
5. Thermal decomposition of oxazolidinones (Agency of Industrial Science and Technology);
6. Thermal decomposition of oxalamate (BASF);
7. Thermal decomposition of N-substituted acetylacetamides (Bayer);
8. Thermal decomposition of dialkylmalonamides (Bayer);
9. Thermal decomposition on N,N'-disubstituted allophanates (BASF);
10. Thermal decomposition of organosilicon intermediates (Soviet publications);
11. Thermal decomposition of reversible boron-MIC adducts (Vertac);
12. Dehydrogenation of N-methylformamide (DuPont);
13. Methylation of metal cyanate (Degussa, FMC);

14. Acetyl chloride and sodium azide (USSR); and
15. Amination of chloroformate (Hungary).

Recommended UCC research alkyl carbamates, boron compounds, and silyl carbamates.

**March 1986:** UCC report on pyrolysis of aryl *N*-methyl carbamates to MIC.

**~1986:** UCC report on concept to react diphenyl carbonate and methylamine to make phenylmethylcarbamate based on EniChemica technology.

**October 1986:** In a meeting with Nor-Am Chemical, UCC discloses that although it had been working on a phenyl methylcarbamate (and butylphenyl methylcarbamate) process for shipment to make aldicarb at Woodbine, Georgia, Brazil, and France, it discovered that it could ship aldisol (aldicarb/methylene chloride solution) instead, and therefore was less interested in the phenyl methylcarbamate process.

**December 1986:** Rhône-Poulenc (RP) buys Union Carbide Agricultural Products Division

**March 1987:** Study by Schering Agrichemicals related to local Michigan production of carbamates given the loss of availability of bulk MIC (small scale: 1M lb/yr final product).

Three basic approaches:

1. Via MIC from onsite MIC generation,
2. Via methyl carbamoyl chloride from methylamine phosgenation (without pyrolysis), or
3. Via methyl carbamoyl chloride from methyl formamide and sulfuryl chloride.

In turn, three cases were considered for onsite MIC generation:

1. Sodium cyanate + dimethyl sulfate (Sunko);
2. Methyl formamide oxidation (DuPont); and
3. Diphenyl carbonate processes (two versions):
    a) Diphenyl carbonate + methylamine (EniChemica and Union Carbide),
    b) Diphenyl carbonate + dimethyl urea (Bayer).

Concluded changing to EniChemica process had 5- to 6-year payback vs. continued Sunko contract manufacture; recommended continue sulfuryl chloride route development.

**April 1988:** RP evaluates DuPont methyl foramide oxidation route to MIC production.

**October 1988:** RP Project MN:

1. MIC vent gas incinerator,
2. Carbaryl reliability and optimization,
3. Comparison of UCC and RP syngas and phosgene technologies, and
4. MIC downsizing (use of new discrete simulator software package).

**31 January 1989:** RP Project MS (presentation to Perez and Robirds) (preparation of MIC and aldicarb at Woodbine to eliminate aldisol transport from Institute to Woodbine).

Two MIC processes considered:

1. Cyanate process (NaOCN + dimethyl sulfate → MIC) (semibatch)
   Pros: Low MIC inventory (200 lb or less); dimethyl sulfate to be made by RP
   Cons: Dimethyl sulfate transportation; NaOCN availability; high variable costs; environmental protection concerns

2. DuPont methyl formamide oxidation process (methyl formamide + O2 → MIC + H2O)
   Pros: DuPont technology; cost depends on methyl formamide cost, but lower than cyanate process
   Cons: Need for pilot plant; Long development and startup time; lower MIC quality could risk lower aldicarb quality; needs "miracle" process and technology relationship with DuPont
   Also considered transfer of Woodbine formulation capabilities to Institute (except gypsum granulation) and maintaining existing MIC and aldicarb technologies in Institute; this was the preferred alternative

**1989:** RP consideration of Enichem technology for phenyl methylcarbamate technology for individual MIC production at each carbamate process.

**July 1989:** RP discussion of two alternative routes to diphenyl carbonate for Enichem process:

1. Phenol phosgenation
2. Phenol + CO + $O_2$

**December 1989:** RP further discussions of Enichem MIC technology at Institute

1. Manufacturing and inventory cost analysis,
2. Concept and objectives,
3. MIC generators/users interface,

4. Quality program, and
5. Impact on plant operaion.

Expected MIC inventories: 150 lb of methomyl, 300 lb of carbaryl, 50-300 lb of aldicarb.

**January 1990:** RP considers MIC minimization (identified as "Bayer alternative" based on diphenyl carbonate + dimethyl urea) as well as MIC containment alternatives.

**10 July 1991:** RP report on Enichem-RP technical meeting on dimethyl carbonate, diphenyl carbonate, and MIC

1. Dimethylcarbonate is made from methanol, CO, and $O_2$ over Cu and Pd;
2. Diphenylcarbonate is either made from phenol and phosgene or phenol, CO, and $O_2$, or by transesterification of dimethylcarbonate with phenylacetate;
3. Phenylmethylcarbamate is made from diphenylcarbonate and methylamine to be cracked at each carbamate process to MIC.

**December 1991:** RP designs (but does not build) a new MIC plant for Institute based on phenylmethylcarbonate production, storage, and distribution to various carbamate processes to be cracked to gaseous MIC.

**18 August 1993:** An explosion in the methomyl/Larvin plant killed one employee and critically injured two others. RP was charged with 27 safety violations including failure to properly maintain, inspect, and test piping systems and other equipment. OSHA fined RP a record $1.6 million.

**1993:** RP conducts $50M Institute Modification Project (IMP) related to MIC, phosgene, and chlorine safety. Aspects include chlorine unloading, chlorine transfer, phosgene production, elimination of hard-to-clean small diameter piping, MIC refining system and phosgene separation system leak detection, water leak detection by analysis for $CO_2$, reduce number of make tanks, field storage tank modifications, MIC transfer line changes, methylamine storage relocation, local storage of caustic for MIC destruction, standby emergency diesel electric generator; allow MIC production unit to operate at reduced rates (700-4000 lb/hr); new MIC instrumentation; replace Crane canned pumps with external recirculation with Sundyne canned pumps with internal recirculation; radiation shields for MIC and $Cl_2$ transfer lines near fire hazards; control room air safety; replace Karbate reboilers with tantalum; MIC make analyzers; piperack crossing barriers; MIC capacity reduced to 22M lb/yr.

**1994:** RP MIC Risk Management Plan.

Process design

1. Emergency dump tank available for safe transfer of product from leaking vessel,
2. Scrubber will destroy MIC from any storage tank,
3. Flare tower will destroy MIC vapors from process vents,
4. Backup control room instruments,
5. Automatic MIC isolation valves stop leaks,
6. Diking and spill collection sump,
7. Fire deluge system,
8. MIC leak detection alarms,
9. Safety relief valves protect vessels from over pressure,
10. Diesel generator for backup power,
11. Sealless pumps for pure liquid MIC,
12. Fire protection for pipe rack transfer lines, and
13. Independent nitrogen supply to prevent cross contamination.

Equipment design

1. Double-walled underground storage tank,
2. Pressure vessels coded by ASME,
3. Blastmat protection on aboveground MIC storage facilities,
4. Stainless steel construction,
5. Pipelines over roads protected by barriers, and
6. Double-walled pipelines with leak detection analyzers on critical transfer lines.

Safety reviews

1. Process hazard analysis completed every five years,
2. Ongoing safety reviews for design changes,
3. Operational reviews completed for all process changes, and
4. Safety review team includes safety experts, engineers, union operators, and union maintenance personnel.

Procedures

1. Strictly enforced inventory limits,
2. Annual review of operating procedures,
3. Personnel safety procedures, and
4. Strictly enforced cross-plant transfer procedure.

Training

1. Skilled union operators are trained and qualified,
2. Maintenance personnel are fully trained, and

3. Hazard communications training provided for all personnel, including contractors.

Mechanical Integrity
1. Periodic testing and inspections for tanks, columns, heat exchangers, pumps, instruments, pipes.

Emergency Response
1. Dedicated in-plant Emergency Operations Center,
2. Trained Incident Commander onsite,
3. Trained emergency squad onsite at all times,
4. Plant-wide notification system,
5. Dispersion modeling system,
6. Regular meetings and coordination with community responders,
7. Onsite dispensary and doctor,
8. Periodic unannounced drills,
9. Courtesy notification to METRO of minor releases, and
10. Plant can activate community alarm (Good Samaritan Agreement).

Incident Investigation
1. Formal investigations conducted for significant events,
2. Reporting procedures for all events, and
3. Conducted with operators, union, and safety representatives.

Audits
1. In-plant audits,
2. Corporate audits,
3. Job observation,
4. Auditing for critical safety procedures, performed by each department,
5. CMA Responsible Care self-audits conducted annually, and
6. Ongoing risk assessment process.

**12 August 1996:** AgrEvo evaluation of Kuo-Ching (Taiwan) MIC production MIC made batchwise by cyanate process (NaOCN + dimethyl sulfate); two batch lines; 1000kg/batch; no overnight storage.

*Has/Does:* Scrubbers, dump tanks, backup control room instruments, automatic MIC isolation valves, diking, fire deluge system, pressure relief valves, backup diesel power, gravity flow for MIC, mechanical seals on agitators, fire protection for transfer lines, periodic process hazard analysis, safety reviews for design and equipment changes, operational reviews for process changes, safety review team expertise, inventory limits, annual review of procedures, personnel safety procedures, enforced plant procedures, trained and qualified operators, trained maintenance, hazard communications, testing and inspection for leaks, trained emergency squad, emergency notification system, coordination with community emergency responders, unannounced drills, community alarm, formal incident investigation, reporting procedure, investigations conducted with operators and safety representatives.

*Does Not Have/Do:* Heat transfer fluid inert to MIC, MIC leak detection alarms, double-walled storage tanks, blastmat protection on aboveground storage tanks, double-walled pipelines, dedicated in-plant emergency operation center, onsite trained incident commander, onsite dispensary and doctor.

AgrEvo expressed unspecified concerns over conditions of the MIC unit and a renovation was promised.

**March 1999:** RP purchases FMC carbofuran and carbosulfan manufacturing facilities and establishes Carbamate Excellence Center.

**November 1999:** RP begins production of new carbamate Oxamyl in Miscellaneous Carbamates Unit.

**December 1999:** Rhône-Poulenc agricultural products division merged with Hoechst Shering AgrEvo to form Aventis CropScience.

**October 2001:** Aventis CropScience sold to Bayer to become Bayer CropScience.

**October 2002:** Bayer conducts safety analyses of MIC and carbamate operations.

**2002:** Bayer MIC Inventory Reduction Conclusions.

1. Increased unavailability of MIC could lead to operational delays in consuming units;
2. Limiting maximum MIC capacity would lead to increased shut down start up cycles for MIC unit;
3. Points 1 and 2 are inversely proportional; and
4. Forcing MIC inventory levels down appears feasible, but costly for MIC manufacture and downstream consumers.

**28 August 2008:** Bayer methomyl residue treater accident.

**May 2009:** Carbofuran banned by the U.S. Environmental Protection Agency.

**2009:** Bayer MIC production 9M lb.

**5 April 2009:** House Energy and Commerce Committee asks U.S. Chemical Safety and Hazard Investigation Board to investigate alternative MIC technologies.

**26 August 2009:** Bayer announces $25 M plant modification. Modification plan includes the following (Martin, 2011).

*Bayer MIC Unit Layers of Protection*
Primary measures:

1. Process design.
2. Equipment, piping, and instrumentation standards:
    a. Exotic materials of construction throughout the process to minimize corrosion.
3. Operator training and experience, mature, well-documented procedures.
4. Online analysis allows verification of MIC quality before adding to storage tank:
    a. MIC purity must be maintained to minimize the probability and rate of undesirable reactions;
    b. Multiple analyzers based on diverse technologies used to monitor MIC quality both before and after entering storage tanks; and
    c. Proper levels of adverse reaction inhibitors are maintained in underground storage.
5. MIC storage tanks are located underground:
    a. Tank integrity is protected by jacket and vault.
6. MIC tanks are maintained at low temperatures, minimum needed pressure, and are instrumented with redundant pressure, level, temperature, and temperature rate of rise alarms:
    a. Temperature rise is an indication of loss of refrigeration and/or reaction;
    b. Higher temperature increases the rate of reaction for undesirable reactions; and
    c. Pressure indicates venting due to contaminated MIC and/or loss of refrigeration.
7. Buffered cooling with non-reactive solvent for all MIC storage:
    a. Prevents contamination with reactive coolant.
8. Canned rotor pumps are used for refined MIC service:
    a. Prevents seal leakage to the environment even at trace levels.
9. Dedicated nitrogen supply for MIC services which can also provide a backup for instrument air.
10. Distillation condensers are placed high in the structure to avoid reflux pumps.
11. Structured process hazards analysis by HAZOP method.
12. The refined MIC has online analysis for water and major impurities:
    a. Provides early detection of water contamination in the event of a leak in the condenser or vent condenser.
    b. Both make stream and storage tanks in building are covered.

13. Continually charged MIC transfer lines outside MIC unit process structure are double-walled:
    a. Adds additional structural integrity to the transfer lines,
    b. Prevents small leakage from welds and flanges or from corrosion,
    c. Annulus is nitrogen swept and the sweep gas analyzed for organics for early detection, and
    d. Steam/ammonia curtain around MIC process structure to mitigate any leaks within structure.
14. Transfer from MIC underground tank to carbaryl unit is done continuously using double walled pipe. The MIC goes directly into the reaction loop around the continuous carbamoylation reactor. There is no MIC storage in the carbaryl unit.
15. Transfer from MIC underground tank to the aldicarb unit is also done continuously using double-walled pipe.The MIC goes directly into the batch aldicarb reactor and there is no MIC storage in the unit.

Secondary measures:

1. Emergency vents to scrubber then to flare:
    a. MIC-bearing emergency vents have two buffers before the environment.
2. Sufficient caustic to destroy all stored MIC in the unit:
    a. Emergency equipment operates even in loss of site power and utilities.
3. Diesel generator provides backup power for controls and pumps needed to destroy MIC:
    a. Allows operation of all equipment necessary to destroy MIC, even in the event of a complete electrical power outage, utility outage; and
    b. Sphere nitrogen can quickly be set to supply unit instrument air header.
4. Ambient air monitors are provided to detect MIC/phosgene release:
    a. Provides an early warning of fast-developing releases;
    b. Includes sweeps on double-walled equipment and piping; and
    c. Covers process structure and storage building.
5. An emergency dump tank as large as the single largest MIC tank is provided:
    a. Provides an additional storage location in case of an emergency around the MIC storage tanks; and
    b. The tank is always empty, with a nitrogen blanket, is double-walled construction, and is underground.

*Bayer Phosgene Handling Considerations*

1. Phosgene product is condensed using chilled solvent.

2. Small condenser accumulator is in place to provide a buffer to prevent CO reaching the MIC process.
3. All liquid phosgene vessels and piping are double walled.
4. Phosgene product is transferred to the MIC unit phosgene vaporizer by pressure to avoid pumps.

**2010:** Bayer planned MIC production: 11.5M lbs

**2010:** In response to House Energy and Commerce Committee request to investigate alternative MIC technologies, Bayer evaluated five most promising alternatives:

1. Current Bayer (UCC) process MIC(l): (phosgene + methylamine)
2. Diphenylcarbonate process MIC(g): (diphenyl carbonate + dimethyl urea based on Bayer 1971-2002 Dormagen operating data)
3. Enichem process MIC(g): (diphenylcarbonate + methylamine based on RP 1989-1990 evaluation)
4. Cyanate process MIC(g): (NaOCN + dimethyl sulfate based on Russian/Japanese 1973-1985 patent literature)
5. DuPont process MIC(g): (methyl foramide oxidation based on SRI and RP evaluation).

The carbaryl process needed to be modified to handle gaseous MIC in the last four alternatives.

*Evaluation Summary*

Diphenylcarbonate (Bayer)

*Pros*

- Investment smaller than Enichem process,
- Good chemical stability of diphenylcarbonate,
- Residue amount smaller than Enichem process, and
- Lower storage requirements than Enichem process.

*Cons*

- Rely on competition for supply of raw material (dimethylurea from BASF);
- Handling of other toxic materials (e.g., phenol);
- Impact of MIC quality on product quality and hence registration likely (new registration, if at all, requires 2-3 years); in addition, impact on aldicarb formulation highly likely because of its complexity and sensitivity to low level of impurities;
- Impact on manufacturing technologies for aldicarb and carbaryl; significant amount of process development required for adaptation (2-3 years);
- Large amount of equipment required;
- Diphenylcarbonate plants have been shut down more than 10 years; no in-house know-how available any longer; learning curve expected to be steep.

Enichem

*Pros*

- No need for chlorine and phosgene, and
- Reduction of MIC inventory.

*Cons*

- Impact of MIC quality on product quality and hence registration likely (new registration, if at all, requires 2-3 years); in addition, impact on aldicarb formulation highly likely because of its complexity and sensitivity to low level of impurities;
- Impact on manufacturing technologies for aldicarb and carbaryl: significant amount of process development required for adaptation (2-3 years);
- Utilization of recycle phenol (no experience of Enichem technology at large scale available);
- Effluents quantities and qualities (residual phenol); and
- Learning curve to be absorbed.

Cyanate

*Pros*

- Currently used by most of the Asian suppliers at small scale, it has the advantage to produce MIC on demand: one batch of MIC for one carbamoylation batch.

*Cons*

- Includes handling of other toxic materials (e.g, DMS);
- Produces large amount of waste (6 kg per kg MIC);
- For large quantities such as 4,000 Mt/year and the need to feed large continuous units like carbaryl or methomyl, high level of MIC inventory is required;
- MIC can only be produced in batch, requiring a large number of large-batch reactors; technology involves more equipment than currently at Institute, increasing safety risk;
- Impact of MIC quality on product quality and hence registration likely (new registration, if at all, requires 2-3 years); in addition, impact on aldicarb formulation highly likely because of its complexity and sensitivity to low level of impurities;
- Impact on manufacturing technologies for aldicarb and carbaryl: significant amount of process development required for adaptation (2-3 years); and
- Learning curve will be steep.

DuPont

*Pros*

- DuPont Technology produces MIC from air oxidation of methylformamide; MIC is available diluted in $N_2$ streams.

*Cons*

- MIC quality is different, impacting product quality and hence registration (new registration, if at all, requires 2-3 years); in addition, impact on aldicarb formulation highly likely because of its complexity and sensitivity to low level of impurities;
- Impact on manufacturing technologies for aldicarb and carbaryl: significant amount of process development required for adaptation (2-3 years);
- Because of a mix of batch and continuous process, MIC inventory needed;
- Process streams may contain traces of toxic materials (e.g., HCN); and
- Supply of raw material (methylformamide) in the hands of competitors (BASF and DuPont).

Conclusions

Only DuPont process shows competitive manufacturing cost, but:

- Unknown impact of by-products on product quality and registration;
- Unknown impact of wastes on Institute waste handling facilities; and
- Low catalyst lifetime (frequent shutdowns).

Recommendation

Continue with the existing MIC technology at Institute but reduce manufacturing to two products (aldicarb and carbaryl) allowing downsizing of the MIC plant and reduction of MIC inventory by 80 percent.

**2010:** Bayer $25M Project MINEXT to reduce inventory by MIC 80 percent

1. Passive and active safety systems:
   a. Underground storage, double-walled construction; SS inner shell;
   b. Refrigerated MIC storage;
   c. Adjacent empty dump tanks;
   d. Scrubbers and flare system independently capable of destroying MIC in process and storage;
   e. Double-walled piping with annular nitrogen purge;
   f. Air monitoring;
   g. Automated control system; automated safety supervisory system, trained operators, and technical professionals; and
   h. Steam-ammonia curtain to mitigate phosgene or MIC leaks;
   i. Leak detection and repair process for extremely small leaks.

**11 January 2011:** Bayer announces plans to restart the East Carbamoylation Center and the new reduced MIC inventory system for aldicarb and carbaryl production, but for a period of no more than 2 years.

**18 March 2011:** As a result of legal challenges and delays that meant missing the production window to meet demand for the 2011 growing season, Bayer announces decision not to restart aldicarb, carbaryl, or MIC production facilities and to permanently shut down the East Carbamoylation Center, ending all MIC and carbamate pesticide production at Institute.

# Appendix C

# Emergency Response and Emergency Preparedness

Emergency response is commonly conceived as providing an additional layer of protection that goes beyond engineered safety features (ESFs) such as water curtains and flare systems (CCPS, 2009). That is, the emergency response is intended to be independent of all ESFs so that it can perform even if those systems fail. Indeed, an effective emergency response involves linked onsite and offsite emergency response organizations that perform emergency assessment, hazard operations, population protection, and incident management actions. On the basis of federal guidance for nuclear and chemical emergency preparedness (USNRC/FEMA, 1980; NRT, 1987, 1988), Lindell and Perry (1992, 2006, 2007) defined *emergency assessment* as actions taken to define the nature and magnitude of an event by evaluating conditions in the facility and the surrounding physical environment—especially plant conditions, chemical releases, and meteorological conditions (McKenna, 2000). *Hazard operations* consist of preventive and corrective actions to control leaks, spills, fires, and stabilize containers (Lesak, 1999). *Population protection* includes the use of personal protective equipment and safe havens to protect facility personnel. In addition, it includes offsite actions such as warning people in potentially affected areas to shelter in-place or evacuate, providing evacuation transportation support and traffic management, establishing public shelters (congregate care facilities for those who lack the funds to pay for hotels/motels or nearby, and providing medical treatment for those who are injured (Perry and Lindell, 2007). Finally, *incident management* ensures that emergency assessment, hazard operations, and population protection actions are undertaken in a timely and effective manner and that responders have sufficient resources—including support staff, equipment, and facilities—to do their jobs. Effective incident management provides coordination between onsite and offsite emergency response organizations through a mutually agreed emergency classification system and standardized forms for continuing emergency assessments. In addition, coordination between onsite and offsite organizations is facilitated by mutual adoption of organizational structures such as the Incident Command System (DHS, 2008).

People sometimes erroneously assume that major disasters are just larger versions of routine emergencies, and so available personnel can improvise a satisfactory response using available resources. In fact, major disasters involve both quantitatively larger and qualitatively different demands that arise from tasks that are not performed, and resources that are not available, during routine operations. Thus, emergency planners need to follow a systematic process that develops accurate assessments of incident demands and community capabilities, identifies the gaps between demands and capabilities, and develops a strategic plan for reducing this gap (Lindell and Perry, 2007). Specifically, they must use hazard/vulnerability analysis to identify, in advance, what are the abnormal incident demands that should be expected and what are the novel emergency response functions that will need to be performed in response to these demands. In addition, they need to identify the organizations that will perform these emergency response functions and the resources those organizations will need in order to perform their emergency response functions.

Emergency operations plans and procedures can be developed by following guidance from the federal government (NRT, 1987, 1988; FEMA, 2010) and chemical industry (CMA, 1985), national standards (NFPA, 2010), and accreditation programs (EMAP, 2010). These documents are sometimes misinterpreted to suggest that the development of paper plans and procedures is a sufficient condition for adequate emergency preparedness. Instead, development of written plans and procedures should be considered to be a necessary, but not a sufficient, condition. At minimum, plans and procedures need to be supplemented by periodic audits to ensure that they are current (e.g., telephone numbers are up to date) and that equipment is properly maintained (e.g., portable instruments are charged and calibrated).

In addition to developing emergency operations plans and procedures, emergency planners need to conduct training needs assessments to identify any tasks that are critical, infrequent, and difficult (Goldstein and Ford, 2002). *Critical* tasks are those that are essential to protecting the health and safety of facility personnel, offsite responders, and the offsite population. In addition, although some emergency response tasks are the same as ones performed during normal operations, it is important to identify which of them are performed *infrequently* and therefore provide few opportunities for emergency responders to practice and develop skilled performance. Finally, some tasks might be *difficult* to perform because of their cognitive, psychomotor, or physical demands. Effective emergency preparedness requires identifying these infrequent, critical, and difficult tasks, selecting the appropriate personnel for each position in the emergency response organization, and providing the levels of initial and refresher training needed to ensure emergency responders continuing proficiency. Like safety training, emergency response training can be accomplished in a number of different ways that address workers' abilities and performance motivation (Lindell, 1994). Because of the significant uncertainties about disaster demands, emergency planners need to provide training that facilitates emergency responders' ability to improvise so that they can develop incident action plans that adapt to the distinctive circumstances of each emergency (Ford and Schmidt, 2000; Mendonça and Wallace, 2004).

Finally, effective emergency preparedness programs rely on methods such as drills, exercises, and minor incidents. Individual responder drills—as well as tabletop, functional, and full-scale exercises—need to be reviewed by qualified evaluators. Critiques of these drills and exercises can be used not only to identify needs for additional individual training but also can be used as opportunities for organizational learning. That is, these critiques can be used as the basis for revising plans, procedures, and selection and training programs.

## DEVELOPING AND MAINTAINING EMERGENCY PREPAREDNESS

To identify organizational and contextual factors associated with establishing and maintaining emergency preparedness, we conducted a search for articles on emergency preparedness at chemical facilities. This search yielded a number of scholarly articles on emergency preparedness but most of them provide recommendations for developing facility emergency preparedness rather than examining factors that influence its development and maintenance. Of the few articles that discuss changes in facility emergency preparedness, most examine the effects that major incidents such as Bhopal exert on subsequent laws and regulations with which chemical facilities must then comply (e.g., Belke and Dietrich, 2005; Joseph et al., 2005; Gerbec and Kontic, 2009). Only two studies have examined factors influencing emergency preparedness at chemical facilities. Quarantelli et al. (1979) found that larger companies had more extensive planning processes than smaller ones, and Lindell and Perry's (1998) examination of hazardous materials—handling firms in Los Angeles, California, found that all facilities in the study were more likely to engage in hazard assessment and emergency preparedness measures than hazard mitigation measures in the year after the 1994 Northridge Earthquake. Moreover, they substantially increased their implementation of hazard mitigation measures such as plant site, plant design, process modification, external hazard protection, chemical substitution, and administrative controls during that time period. Surprisingly, however, there was no evidence of a relationship between experienced damage and implementation of these mitigation measures.

A broader literature on organizational emergency preparedness reveals that businesses generally engage in limited levels of emergency preparedness (Mileti et al., 1993; Drabek, 1994a; Dahlhamer and D'Sousa, 1997). As was the case in the Quarantelli et al. (1979) study, the most reliable indicator for predicting organizational emergency preparedness is organizational size (Drabek, 1991, 1994a,b; Dahlhamer and D'Souza, 1997; Perry and Lindell, 2007). In addition, some studies have found evidence of a positive relationship between disaster experience and business emergency preparedness (Dahlhamer and Reshaur, 1996; Dahlhamer and D'Souza, 1997; Webb et al., 2000). Finally, some studies on organizational emergency preparedness have found that other characteristics, including business age, scope (local vs. national) and type may correlate with degree of emergency preparedness, but at this time, the findings are inconsistent across studies.

There has been a substantially smaller amount of research on the conditions that facilitate community emergency preparedness (Lindell and Perry, 2001, 2007). An analogue of management support, support from senior elected and appointed officials, as well as the wider community, is an important element in community emergency preparedness but other elements are also important (Lindell and Perry, 2006, 2007). These include hazard exposure/vulnerability, community resources, extra-community resources, routine staffing/organization, and the type of planning process adopted. In addition, EPA performed a systematic study of community preparedness for chemical accidents and found that there was often poor coordination between plants and communities as well as few communication protocols in place for emergency response (Rogers and Sorensen, 1991; Sorensen and Rogers, 1988). All of these factors directly or indirectly affect individual outcomes for those participating in the community emergency preparedness system (job satisfaction, organizational commitment, organizational attachment, and organizational citizenship), as well as organizational outcomes such as the quality, timeliness, and cost of products such as hazard/vulnerability analyses, community capability assessments, emergency plans and procedures, training programs, and risk communication programs.

## SUMMARY

Effective emergency response requires pre-incident emergency preparedness to ensure that onsite and offsite emergency response organizations have adequate staffing, training, and resources. There is extensive guidance available for developing and maintaining emergency preparedness, but the level of organizational emergency preparedness is generally modest. It appears that a major impediment is that many organizations underestimate the demands of a major incident, or overestimate their ability to improvise an effective response, or both. Additional impediments to the development of effective emergency preparedness programs are perceptions that emergency preparedness is "an intractable problem and that disaster reduction policies lack clear and measurable performance objectives" (Waugh, 1988). These problems are exacerbated by the disparity between the costs and benefits of effective emergency preparedness programs; such programs have substantial short-term costs but only "pay off" in the long term. The limited amount of existing research suggests that organizational emergency preparedness is usually determined by factors such as organizational size and disaster experience, but other factors also need to be examined (Lindell and Perry, 2007).

ISP strategies can avoid some of the shortcomings of organizational emergency preparedness programs by reducing the toxicity of the chemicals being used or produced, the quantity of the chemicals being stored, and the conditions under which they are being stored. However, chemical facility designers need to consider the potential for ISD strategies to transfer risks from communities surrounding fixed-site facilities to those on transportation routes where the lower quantities released are likely to be at least partially offset by lower levels of emergency preparedness.

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# Appendix D

# Policy Context of Inherently Safer Processes

*This appendix is an expansion of the discussion of the external policy context contained in Chapter 7. The purpose of this appendix is not to endorse any regulation or policy. Rather it is to provide a brief overview of the policy context in which inherently safer process assessments exist today.*

## U.S. FEDERAL AND STATE REGULATIONS

The U.S. Occupational Safety and Health Administration (OSHA) and Environmental Protection Agency (EPA) are the two main federal government bodies that administer regulations that potentially mandate, or encourage, inherently safer processes. Of these, OSHA is more relevant inside the plant because of its concern with the immediate safety of workers, whereas EPA regulations focus more on potential ramifications to more general environmental health and safety (Fallon et al., 2007; Malloy, 2008).

### Occupational Safety and Health Administration

The OSHA process safety management of highly hazardous chemicals standard (29 CFR § 1910.119) requires companies handling listed hazardous chemicals to conduct a process hazard analysis (PHA), and develop a safety plan in accordance with 29 CFR 1910.119 (see also Fallon et al., 2007). It is therefore potentially an institutional vehicle for the development of inherently safer processes in hazard planning at OSHA-supervised facilities, although it does not necessarily mandate such an approach.

Within the process safety management standard, section 1910.119(c) mandates employee participation in the elaboration of safety plans. The section states: "Employers shall consult with employees and their representatives on the conduct and development of process hazards analyses and on the development of the other elements of process safety management in this standard." (29 CFR 1910.119 c) Despite this language the extent and methods of employee consultation are not described in the regulation. Buttressing employee participation in hazard management could be an effective organizational strategy for implementing inherently safer design in facilities with high risk for hazardous events, and warrants further research.

## Environmental Protection Agency (EPA)

EPA policy has considered the possibility of inherently safer processes at least since the early 2000s, but measures regarding chemical accident prevention have tended to focus on prior planning and "inspection and to corrective and preventive maintenance" (Ashford and Zwetsloot, 1999). Therefore, the concept of safety planning is far from new, but the far-reaching ramifications of inherently safer processes appear to require a greater degree of planning and technological investment than do traditional safety strategies that tend to be "failsafe" rather than "foolproof" (Ashford and Zwetsloot, 1999).

The difficulties of implementing inherently safer design can be observed in the EPA Risk Management Program (RMP) (EPA, 2001), which is still intentionally more oriented to risk management than risk prevention (Malloy, 2008), and as a policy matter does not mandate inherently safer processes. Nevertheless, companies dealing with hazardous chemicals must develop accident prevention plans during hazard emergency response planning, but this policy does not extensively involve stakeholders outside of firms (CCPS, 2009).

Other pertinent regulations and laws include the Pollution Prevention Act (PPA), (which is not primarily directed at accidents) (Ashford and Caldhart, 2010), and the Department of Homeland Security's Chemical Facility Anti-Terrorism Standards (CFATS) (Malloy, 2008). The post-September 11 approach is particularly amenable to inherently safer design (CCPS, 2009), because the unpredictable nature of terrorist attacks may create challenges for traditional assessments based on internal production risks. However, regulatory bodies have tended to conclude that inherently safer design shifts rather than prevents risks (Malloy, 2008). This is an important critique that warrants further research, because of the possibility that inherently safer technology may lead to the reallocating of risk to other areas of the production process (Hendershot, 2010).

## EUROPEAN SAFETY REGULATIONS

### Renewed European Policy for Chemicals

The European Union's Renewed European Policy for Chemicals (REACH) 2007 amendments (EC, 2006) require a registry system for hazardous chemicals, based on the "principle of substitution" (Garcia-Serna et al., 2007). Although REACH is primarily concerned with chemical toxicity, it also contains hazard prevention components. REACH is being gradually phased in, and technical support on risk reduction is available

Initially the REACH program was supervised by the European Chemicals Bureau (ECB) (Garcia-Serna et al., 2007), but in 2008 ECB was superseded by the European Chemicals Agency, which now runs a central database and registration procedure. The program, is aimed at both producers and downstream users, and will mandate the progressive substitution of the most dangerous chemicals within a much larger system of registration. The crux of how REACH works in the case of dangerous chemicals is as follows:

Substances with properties of very high concern will be made subject to authorization; the Agency will publish a list containing such candidate substances. Applicants will have to demonstrate that risks associated with uses of these substances are adequately controlled or that the socioeconomic benefits of their use outweigh the risks. Applicants must also analyze whether there are safer suitable alternative substances or technologies. If there are, they must prepare substitution plans, if not, they should provide information on research and development activities, if appropriate. The Commission may amend or withdraw any authorization on review if suitable substitutes become available (EC, 2007).

### Seveso and Seveso II

In the EU, the Seveso Directive (96/82/EC) revised the framework directive on Major Accident Hazards of Certain Industrial Activities, and for the first time promoted inherently safer processes as the recommended strategy for plant safety reports (Ashford and Zwetsloot, 1999; Zwetsloot and Ashford, 2003). In the late 1990s reforms were made, titled Seveso II (most recently updated in 2005). Seveso II is more directly oriented toward inherently safer processes than is the case for similar regulations in the United States.

Under Seveso II, an operator must present a conceptual model for avoiding hazardous incidents, as well as documentation supporting the effectiveness of the safety plan (SFK, 2001). A more detailed comparison and examination of Seveso II's mechanics is outside the scope of this appendix but Seveso II should be a priority for future research.

It is also worth mentioning that Seveso II has important land use ramifications. The different models of adoption of its directives in different EU member countries could provide interesting case studies for comparison (Basta et al., 2008). A preliminary review has found some evidence that European land use regulations are more explicitly oriented to creating frameworks for safer siting (Landucci et al., 2008). While further research into their details is required, two noteworthy examples are:

a) "Decreto Ministeriale 9 Maggio 2001, Suppl. Ord. G. U. n.138 del 10/06/01, Requisiti minimi di sicurezza in materia di pianificazione urbanistica e territoriale per zone interessate da stabilimenti a rischio di incidente rilevante." (Landucci et al., 2008)
b) "Major Accident Commission, Technical Committee for Plant Safety (SFK/TAA Germany), Guidance SFK/TAA-GS-1, Recommendations for separation distances between establishments under major accidents ordinance and areas requiring protection within the framework of land use-planning (in German), Bonn (D), 2005" (Landucci et al., 2008)

These regulations, and other similar ones, are potentially helpful illustrations of how local and county governments within the EU comply with Seveso II.

For example, France employs a consequences-based approach, focusing on damages thresholds, whereas the Netherlands and the United Kingdom regulate on the basis of a risk-based approach, using "calculated risk indexes" (Cozzani et al., 2006).[1] The former of these two methods tends to be more conservative, and prioritizes the reduction of inventories of hazardous materials. Therefore, although risk assessment can provide a starting point for analysis, a consequences-based approach may be more amenable to the creation of inherently safer land-use policies related to the siting of hazardous facilities (Cozzani et al., 2006). What is particularly different about the European approach, when compared with the U.S. approach, is the fluidity of the integration of land-use policy into safety policy.

### Example: United Kingdom

The United Kingdom is involved in various policies to promote safer design. Health and Safety Executive's (HSE) *Policy and Guidance on Reducing Risks as Low as Reasonably Practicable in Design* (HSE, 2003). It is a national level approach to assess safety management at the workplaces. This policy uses language suggesting an approach favoring inherent safety. However, more definite conclusions will require further research and comparison with OSHA regulations in the United States.

[1] The U.S. Chemical Facility Anti-TerrorismStandards (72 Fed. Regist. 17688 [2007])) also uses risk-based performance safety.

The UK also has a system of hazard prevention regulation in line with Seveso II, such as the Installation Handling Hazardous Substances Regulations (NIHHS), Control of Major Accidents Hazards Regulation (COMAH), the Planning Act 1990, and the Planning (Hazardous Substances) Regulations 1992 (Basta et al., 2008). Therefore, not only does the UK currently undertake workplace safety regulations that potentially promote inherently safer processes, but land-use planning also interfaces with hazard planning (Basta et al., 2008). Coordination for these planning processes occurs under the auspices of the HSE, which takes a risk-oriented approach to chemical releases, but consequences-oriented approach to energy sector related risks (Basta et al., 2008).

## U.S. STATE REGULATIONS

### New Jersey

New Jersey claims to be the first state to have implemented anti-terrorism and inherently safer process design into chemical plant regulation (Politicker NJ 2005), and the NJ Toxic Catastrophe Prevention Act Program is well discussed in current literature (see, e.g., CCPS, 2009). At present there are two primary pieces of legislation under which inherently safer systems and technology are regulated in the state: the New Jersey Domestic Security Preparedness Act (NJ OHSP, 2001) and the Toxic Catastrophe Prevention Act (TCPA) (NJ DEP, 2009; Fallon et al., 2007). New Jersey has the oldest and most developed toxic hazard regulation system in the United States, and its concept of inherently safer processes now extends to all registered facilities. TCPA was first passed in 1986, but only took force in 1988, and it now regulates all facilities using more than 10,000 pounds of listed hazardous substances per year (Fallon et al., 2007). The Bhopal accident inspired the first iteration of the TCPA, and the September 11, 2001, terrorist attacks led state officials to explore expansion the program to include concepts approximating inherently safer process requirements (CCPS, 2009).

TCPA is overseen by the New Jersey Bureau of Release Prevention. Facilities must submit an offsite consequences report to the Bureau, while the State Domestic Security Preparedness Task Force[2] oversees those regulations related to DSPA (Fallon et al., 2007). Using the CCPS' framework, New Jersey established a concept of inherent safety based on reducing hazardous chemical stocks, finding less hazardous substitutes, using hazardous materials in their least dangerous form possible, and designing equipment with aims at eliminating equipment and human error (TCPA as cited in Fallon et al., 2007).

The Task Force oversaw the important task of developing sector-specific industry best practices in conjunction with leading facilities. Now, TCPA facilities must, under a 2005 New Jersey executive order, comply with the Task Force's

[2] Overseen by the New Jersey Office of Homeland Security and Preparedness (OHSP).

best practices (Fallon et al., 2007).[3] For TCPA facilities, compliance involves conducting a review, and produces a reviewable assessment, of the viability of implementing inherently safer strategies and technology during mandatory vulnerability assessments related to antiterrorism regulations (CCPS, 2009). This review was a 120-day process and only led to 19 percent of facilities finding new measures, and less than half made no new recommendations. However, CCPS notes that the existing hazard reduction framework had been in place since the 1985 introduction of the TCPA, and many facilities may have already incorporated most practicable inherently safer policies. In sum, inherent safety reviews must be undertaken in all TCPA-regulated processes, and also in the case of vulnerability assessments under New Jersey state security requirements.

In terms of creating an institutional environment to facilitate compliance, various consultants are now engaged in providing services to companies regulated under the New Jersey regulations, including, for example, Accu-Tech (2011) and Chilworth (2011). Moreover, New Jersey keeps data and plans prepared under the TSPA and DSPA confidential and privileged (P.L. 1963, c. 73 (C.47:1A-1 et seq; CCPS, 2009). This policy decision stems from a desire to create trust between facilities and regulators. Under the antiterrorism executive order, the New Jersey Domestic Security Preparedness Task Force submitted an inherently safer technology (IST) checklist to facilities hosting hazardous processes, which is one method recommended by Amyotte et al. (2007). Those authors also recommended policies based upon carefully designed guidewords—such as minimize, substitute, moderate, and simplify—that can be incorporated into hazard management planning to improve compliance with checklists. The idea behind checklists and guidewords is standardizing the concepts of inherent safety within the culture of facilities design and process management. On that note, one benefit of the longevity of New Jersey's program is the potential to examine its effectiveness at standardizing the culture of inherent safety, which may prove necessary in creating programs to encourage more wide spread adoption of inherently safer design and technology.

## California

### *Contra Costa County*

Contra Costa's legislation[4] (County Ordinance Chapter 450-8) provides an additional layer of regulation for facilities that are already under California Accidental Release Prevention (CalARP) and EPA supervision (CCPS, 2009). The Contra Costa Industrial Safety Ordinance (ISO) dates from 1998 after a series

[3] However, under DSPA the number of reporting facilities is much greater, and over 800 facilities had to provide special vulnerabilities assessments (Fallon et al., 2007).

[4] The Industrial Safety Ordinance has also been adopted by the City of Richmond, which is in Contra Costa County.

of incidents spurred resident concern (Malloy, 2008). Like New Jersey, Contra Costa is also home to a national-level concentration of chemical plants, which brought heightened safety scrutiny, along with the need to protect the economic base the plants provide.

These facilities must submit their safety plans to the county and show, through supporting documentation, that they have "to the greatest extent feasible" implemented safer systems (Malloy, 2008 and County Ordinance Chapter 450-8.016(d)(3)). Under the Contra Costa Program Guidance document, determinations that inherently safer options are not feasible are more strictly scrutinized than in New Jersey. For a facility not to implement an inherently safer process requires conflict with the law, a financial analysis demonstrating economic infeasibility, or an analysis based upon generally accepted engineering principles that risk will increase (Malloy, 2008). This requires weighing the circumstances, and in practice is designed to elicit proof that facilities have identified and acted to minimize hazard. However, at early stages of the Contra Costa program, efforts were limited by a lack of guidance as to expectations and best practices regarding inherently safer systems. CCPS has identified the publication of guidelines as important in fostering reasonable expectations about feasibility (CCPS, 2009).

The Contra Costa County program is also much smaller than the New Jersey program, including only nine facilities (seven in the county and two in the City of Richmond): "two Air Products facilities (within the Shell Refinery and the Tesoro Refinery), ConocoPhillips Rodeo Refinery, Air Liquide-Rodeo Hydrogen Plant, General Chemical West's Bay Point Works, Shell Oil Martinez Refinery and Tesoro Golden Eagle Refinery. The City of Richmond's Industrial Safety Ordinance (Municipal Code Chapter 6.43, RISO) is almost identical (except for the 2006 amendment) to the County's Industrial Safety Ordinance. The two facilities located in Richmond that are subject to this ordinance include: Chevron Richmond Refinery and General Chemical West's Richmond Works" (Contra Costa Health Services, 2011a).

Another important difference between the New Jersey initiative and that in Contra Costa is that the CalARP Program Guidance Document[5] (compliance plan document) is administered by the Contra Costa Health Services Department, and not a security-oriented or industry-oriented regulator. However, the program's key elements are very similar to New Jersey's and include a 5-year incident history, an offsite consequence analysis, process hazard analysis, 3-year compliance audits,[6] emergency response planning, and a risk management plan (Contra Costa Health Services, 1998).

Newer elements of the program include more focus on "human factors," including safety culture assessments and security vulnerability analysis (Contra

[5] http://cchealth.org/groups/hazmat/california_accidental_release_prevention_guidance_document.php.

[6] The county is currently in its fourth round of audits.

Costa Health Services, 2011b). County administrators claim that major accidents and releases have declined at a steady rate since the ISO's implementation in 2000.[7] It should be noted that in the Contra Costa and New Jersey programs, limited public access to information about the facilities creates barriers to rigorous external evaluation of their performance (Malloy, 2008; CCPS, 2009).

Beyond Contra Costa County, other California policies do appear to be relevant to inherently safer concepts. These include the Cal/EPA Green Chemistry Initiative, the California Accidental Release Prevention Program (CARPP), and the Silicon Valley Toxic Gas Ordinance.

## Green Chemistry

California Assembly Bill 1879 directs the California Department of Toxic Substances Control (DTSC) to create a system for reducing, substituting, and in some cases banning chemicals of concern (Heartney and Norris, 2008). A "Green Ribbon Science Panel" has been established to advise the California Green Chemistry Initiative (CA DTSC, 2011), which will include a Toxics Information Clearing House. This is a more stringent pollution reduction program than the EPA's Toxic Release Inventory (TRI), because it gives state regulators the ability to target specific chemicals, and design management and reduction processes for them throughout their lifecycle, including the "design, manufacturing, and distribution processes." (CA DTSC, 2008a,b) This legislation is primarily concerned with exposure.

### *California Accidental Release Prevention (CalARP) Program*

The CalARP Program requires risk management plans for facilities, as well as assessments of seismic risks, but does not explicitly mandate inherently safer design. It is a program similar to EPA's Risk Management Program, although stricter and more detailed. One notable difference is the emphasis on stakeholder involvement in the planning process (Sawyer, 2010; Contra Costa Health Services, 2012). On the subject of worker involvement, the regulation requires training and information on safety management planning. However, this process is not central to the regulations, although, the programs administrators do include the following language in a document titled "Agency Guidance":

> Never forget about who's actually running the plant: it's the "hourly" workers. As CalARP Program regulators, we're typically only interacting with plant manage-

[7] The graphs provided do not include four major chemical accidents or releases (MCAR), which occurred in November 2010 but produced limited effects to the community, nor do they include transportation-related events. This is an important gap in the data, given arguments that reducing onsite storage risk may increase transportation-related risks.

> ment, engineers, and "salaried" RMP/PSM staff. In theory, these people know how their plant operates and ultimately make decisions on process changes. In reality, it's the hourly workers who really know the nuances of the operation, and can be invaluable in foreseeing the effects of any proposed modifications. This is one area of the Prevention Program where both the plant manager and the youngest apprentice should be regarded on the same level. Make sure that the plant manager and the hourly workers are both somehow included in this employee participation plan. Don't forget about contractors too, although if there's going to be some major change, chances are that contractors are going to be involved as part of the mix at the management level anyway.[8] (CA OES, 2005).

*Santa Clara County Toxic Gas Ordinance*

In Silicon Valley, Santa Clara County has implemented a Toxic Gas Ordinance to control dangerous conditions related to toxic gases. The ordinance dates from 1990 (Stanford University, 2009). This is a targeted program within the semi-conductor industry.

## SELECTED INTERNATIONAL GUIDELINES

### United Nations Environmental Program (UNEP)

The United Nations Environment Program (UNEP) has produced *A Flexible Framework for Addressing Chemical Accident Prevention and Preparedness* (UNEP, 2009). Discussing the role of stakeholders, UNEP specifically mentions that one role of industrial management is to promote inherently safer processes. The UN's direct role in managing chemical accident hazard is minimal, but it does have the capability of promoting common practices and discourse in a globally consolidating industry. Therefore, implementation of inherently safer production within globally fluid supply chains could be aided by the UN framework.

### Organisation for Economic Cooperation and Development (OECD)

Organisation for Economic Cooperation and Development (OECD) has produced a detailed set of guidelines (OECD Guiding Principles for Chemical Accident Prevention, Preparedness, and Response) for developing hazard management planning, and safety procedures in the relevant industries of its member countries. Although the document is not organized around the concept of inherent safety, it does state that: "Public authorities should encourage industry to take measures to improve safety, for example by utilizing the principles of inherently safer technol-

[8] See California Regulations: http://www.oes.ca.gov/Operational/OESHome.nsf/PDF/CalARP%20Guidance%201-31-05/$file/CalARPGuid1-05.pdf.

ogy." (OECD, 2003) Furthermore, the OECD recommends the establishment of safety performance indicator (SPI) programs.

What distinguishes the OECD program from others is its extensive and detailed discussion of risk and hazard identification between facilities and stakeholder groups, including workers, the general public, and management. It is also noteworthy that the guidelines involve stakeholders in the assessment of acceptable community risks in the production process.

### International Labor Organization (ILO) Guidelines

The International Labor Organization (ILO) has developed a set of workplace safety guidelines, incorporating a Plan Do Check Act (PDCA) system (SFK, 2001). What distinguishes the ILO model is a focus on employee participation in the creation of health and safety management systems (ILO, 2001). Further research could compare the ILO guidelines with actual practices at chemical plants in the United States.

## GENERAL COMMENTS

Barriers include the perception that inherent safety is impractical or costly, the lack of institutional infrastructure and frameworks for evaluating inherently safer processes, and a lack of standards and guidance measures for existing operations (CCPS, 2009).

In order to prove more effective than existing practices, inherently safer programs must be distinguished from mitigation focused on "engineered safety" (device-centered) and "procedural safety" (behaviorally-centered) (Amyotte et al., 2007). Moreover the literature focuses on the benefits of beginning the planning process as early as possible in the production lifecycle (Mary Kay O'Connor Process Safety Center, 2002).[9]

Current programs, such as those found in New Jersey and Contra Costa County, include broad mandates which might be improved through focusing efforts for improvements on more discrete elements of the production and technology development process. Given that some studies have found that nearly 45 percent of incident causation is attributable to process and equipment integrity and process knowledge failures (Amyotte et al., 2007), these could be crucial phases of process to focus efforts for promoting inherent safety.

[9] Malloy (2008) notes that some industry groups (DHS and American Chemical Council) criticize the concept of inherent safety because of its vagueness, arguing that it could lead to arbitrary penalties and results that actually increase facility risk.

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# Appendix E

# Meeting Agendas

**Inherently Safer Chemical Processes:**
**The Use of Methyl Isocyanate (MIC) at Bayer CropScience**
**The National Academy of Sciences**
**Keck Center**
**500 Fifth Street, N.W., Room 100**
**Washington, DC 20001**

**AGENDA**

**February 9, 2011**

**10:30 a.m.** Welcome
- Elsa Reichmanis, Committee Chair

**10:35 a.m.** Overview of the National Academy of Sciences Study
- Kathryn Hughes, National Research Council

**10:50 a.m.** Context of the Study and Overview of CSB Investigation
- Amy McCormick and Lucy Sciallo-Tyler, U.S. Chemical Safety and Hazard Investigation Board (Study Sponsors)

**11:30 a.m.** Lunch
- Lunch available in the Keck Center Atrium on the 3rd floor

**12:30 p.m.** Overview of the use of MIC at Bayer CropScience
- Steven Smythe, Bayer CropScience

**2:30 p.m.** Overview of Inherently Safer Chemical Processes and Practices
- Scott Berger, Center for Chemical Process Safety, AIChE
- Randall Sawyer, Contra Costa County

**3:20 p.m.** Break

**3:30 p.m.** Defining Inherently Safer Processes at DHS
- George Famini and George Emmett, DHS Chemical Security Analysis Center

**4:00 p.m.** Public Comment Session
- Please sign up to speak during the public comment session
- All comments limited to 3 minutes

**4:30 p.m.** Transition to Just-in-Time Production of MIC
- John Carberry, Carberry EnviroTech

**5:15 p.m.** Adjourn Open Session

**Inherently Safer Chemical Processes:**
**The Use of Methyl Isocyanate (MIC) at Bayer CropScience**
**West Virginia State University**
**Alumni Center**
**Institute, WV 25112**

## AGENDA

**March 21, 2011—WVSU Alumni Center**

**6:15 p.m.** Public Comment Session
- Please sign up to speak during the public comment session
- All comments limited to 3 minutes

Welcome
- Elsa Reichmanis, Committee Chair

Overview of National Academy of Sciences Study
- Kathryn Hughes, National Research Council

**8:15 p.m.** Adjourn Open Session
- Note: May adjourn earlier if no additional comments

**March 22, 2011—WVSU Alumni Center**

**11:20 a.m.** Presentation—Bayer CropScience
- EHS and Training Procedures and Policies

**12:30 p.m.** Adjourn Open Session

**Inherently Safer Chemical Processes:**
**The Use of Methyl Isocyanate (MIC) at Bayer CropScience**
**National Academies Keck Center**
**500 Fifth Street, NW, Room 100**
**Washington, DC 20001**

**AGENDA**

**May 24, 2011—Keck Center, Room 105**

**9:30 a.m.** Kanawha Putman Emergency Planning Committee (via telephone)
- Matthew Blackwood et al.

**10:15 a.m.** Overview of the EPA Risk Management Program (tentative)
- Craig Mattheisson, EPA

**Inherently Safer Chemical Processes:**
**The Use of Methyl Isocyanate (MIC) at Bayer CropScience**
**National Academies Jonsson Center**
**Woods Hole, Massachusetts**

**AGENDA**

**August 8, 2011**

**11:00 a.m.** Patrick Ragan, Bayer CropScience
- Vice President Quality, Health, Safety and Environment, North America

# Appendix F

# Biographies of Committee Members

**Elsa Reichmanis** (NAE) is a professor of chemical and biomolecular engineering at the Georgia Institute of Technology. Prior to joining Georgia Tech, she was director of materials research at Bell Labs, Alcatel-Lucent. She is noted for the discovery, development, and engineering leadership of new families of lithographic materials and processes that enable very large scale integration manufacturing. Her research interests include the design and development of polymeric and hybrid organic/inorganic materials for electronic and photonic applications. A particular focus relates to organic/polymer semiconducting materials and processes for plastic electronics and photovoltaics. She is the recipient of several awards, was elected to the National Academy of Engineering in 1995, and has participated in several National Research Council (NRC) activities. She currently serves as a member of the National Science Foundation (NSF) Math and Physical Sciences Advisory Committee, she recently served as cochair of the NRC Board on Chemical Sciences and Technology, and was a member of the Visiting Committee on Advanced Technology of the National Institute of Standards and Technology (NIST). She is an elected member of the Bureau of the International Union for Pure and Applied Chemistry (IUPAC). She has been active in the American Chemical Society throughout her career, having served as 2003 President of the Society. In other technical activities, she served as a member of the Air Force Scientific Advisory Board and is an associate editor of the ACS journal, *Chemistry of Materials*.

**Paul Amyotte** is a professor of chemical engineering in the Department of Process Engineering and Applied Science, and the C.D. Howe Chair in Engineering, at Dalhousie University, Halifax, Canada. He holds a bachelor's degree from the

Royal Military College of Canada, a master's from Queen's University, and a Ph.D. from the Technical University of Nova Scotia, all in chemical engineering. He is a fellow of the Chemical Institute of Canada, the Engineering Institute of Canada, and Engineers Canada. He is a past president of the Canadian Society for Chemical Engineering and of the Association of Professional Engineers of Nova Scotia, and is a past chair of the Canadian Engineering Qualifications Board. He is the editor of the *Journal of Loss Prevention in the Process Industries,* and has recently served as chair of the Safety and Security Strategic Projects Panel of the Natural Sciences and Engineering Research Council of Canada. Dr. Amyotte's teaching, research, and practice interests are in the areas of process safety, inherently safer design, and dust explosion risk reduction. He has consulted to industry, government, and academia in these and related areas, and has published or presented approximately 180 papers in the field of industrial safety. Recent research accomplishments and professional engagements include the delivery of keynote lectures at the 2010 Mary Kay O'Connor Process Safety Center Annual Symposium and Nanosafe 2010 (International Conference on Safe Production and Use of Nanomaterials), expert testimony at the U.S. Chemical Safety and Hazard Investigation Board public hearing on the Kleen Energy natural gas explosion (June 2010), and coauthorship with Professor Trevor Kletz on the second edition of *Process Plants: A Handbook for Inherently Safer Design* published by the Taylor & Francis Group in 2010.

**Peter Beak** (NAS) is CAS Professor Emeritus at the University of Illinois at Urbana-Champaign. Dr. Beak's research interests are in synthetic, structural, and mechanistic organic chemistry, new reaction processes, synthetic methodology, and reactive intermediates, and his work has clarified the effect of molecular environment on structure—stability relationships, provided new reactions that are widely used for chemical synthesis, and identified novel reactive intermediates. His current research involves the determination of reaction trajectories in atom-transfer reactions and asymmetric synthesis. Dr. Beak has held editorships, lectureships, and leadership positions in professional organizations. He has received a number of awards, lectured around the world, and served as research advisor for more than 100 graduate and postdoctoral students. Dr. Beak served on the NRC committee that authored the 1995 edition of Prudent Practices in the Laboratory. Dr. Beak is a member of the National Academy of Sciences (elected in 2003) and the American Academy of Arts and Sciences. He received his B.A. from Harvard University in 1957 and his Ph.D. from Iowa State University in 1961 and then joined the faculty at Illinois.

**Michael L. P. Elliott** is the associate director, Center for Quality Growth and Regional Development, and associate professor, with joint appointments to the Schools of City and Regional Planning and Public Policy at the Georgia Institute of Technology. He is a cofounder and has served as codirector of both the

Consortium on Negotiation and Conflict Resolution and the Southeast Negotiation Network. Dr. Elliott's work, both as a researcher and mediator, focuses on community engagement, environmental dispute management, risk perception and management, and environmental planning and policy. His particular expertise lies in the design and evaluation of environmental dispute resolution and participatory processes, and in the mediation of public policy disputes, especially as they relate to toxics and their management. In these capacities, he has worked regionally on issues ranging from specific conflicts over solid and hazardous waste and the siting and managing of locally unwanted facilities to the design of local and regional policies for managing environmental risk, natural resources, and the quality of growth. Nationally, he has worked with agencies such as the U.S. Environmental Protection Agency, the National Park Service, the Army Environmental Policy Institute, the U.S. Council on Environmental Quality, and the President's Conference on Cooperative Conservation. Internationally, he has provided consultations and training for resolving environmental and land disputes in Estonia, Israel and Palestine, Nicaragua, Kazakhstan, and Germany. Dr. Elliott received his B.S. and Ph.D. from Massachusetts Institute of Technology and his M.C.P. from the University of California, Berkeley.

**Wayne B. Gray** holds the John T. Croteau Chair in Economics at Clark University, where he has taught since 1984, when he received his Ph.D. in economics from Harvard University. Dr. Gray is also a research associate at the National Bureau of Economic Research and the director of the Boston Census Research Data Center. He has served as a member of the U.S. Environmental Protection Agency's (EPA's) Advisory Council for Clean Air Compliance Analysis, the Science Advisory Board for Massachusetts' Executive Office of Environmental Affairs, and a National Research Council committee examining proposed changes in EPA's New Source Review program. Dr. Gray's research focuses on the effectiveness and economic impact of government regulation of environmental and workplace hazards, including studies on productivity, investment, and plant location, working with plant-level data for steel mills, oil refineries, and pulp and paper mills. He has examined regulation of air and water pollution, and measured the effects of enforcement on compliance status and pollution emissions. He has also written several papers on the effectiveness of Occupational Safety and Health Administration enforcement activity, examining impacts on regulatory compliance, workplace injuries, and exposures to hazardous substances.

**Dennis C. Hendershot** has been a staff consultant for the Center for Chemical Process Safety (CCPS) since 2005, and serves as editor of the monthly CCPS *Process Safety Beacon*. Mr. Hendershot spent 35 years working for Rohm and Haas Company, in process research and development for a variety of agricultural, chemical, acrylic monomer, and polymer processes. Since the late 1970s he has worked in development and implementation of process safety management programs, including HAZOP, fault tree analysis, quantitative risk analysis, incident investigation, and process risk management systems. From 2005 through 2008, Mr. Hendershot worked with Chilworth Technology as a principal process safety specialist. Mr. Hendershot is a fellow of the American Institute of Chemical Engineers (AIChE), a fellow of the Center for Chemical Process Safety, and a member of the American Chemical Society. Mr. Hendershot was chair of the Safety and Health Division of AIChE, and a member of the AIChE Board of Directors. He has chaired a number of subcommittees of CCPS, including inherently safer design, risk assessment, hazard evaluation procedures, reactive chemistry, risk tolerance criteria, and undergraduate education. Mr. Hendershot has received the AIChE Doyle Award for the best paper presented at the annual Loss Prevention Symposium twice (1989 and 2002), and received AIChE's Walton-Miller Award for contributions to process safety in 2006. In 2000, the Mary Kay O'Connor Process Safety Center at Texas A&M University presented Mr. Hendershot with its Merit Award for contributions to Process Safety.

**Andrea Kidd Taylor** is a lecturer at the Morgan State University (MSU) School of Community Health and Policy (SCHP) in Baltimore, Maryland. She has more than 25 years' experience in occupational and environmental health and safety. Before joining the MSU faculty, Dr. Taylor served a 5-year term on the U.S. Chemical Safety and Hazard Investigation Board (CSB), a board established under the Clean Air Act Amendments of 1990 to investigate chemical accidents at fixed facilities, an appointment that she received from President Clinton with confirmation by the U.S. Senate. Prior to the CSB, she worked as an industrial hygienist and occupational health policy consultant for the United Auto Workers in Detroit, Michigan. Dr. Taylor serves as an executive board member of the American Public Health Association and as a member of the Beyond Pesticides/National Coalition against the Misuse of Pesticides Advisory Board. She formerly served as a member of the U.S. Presidential Advisory Committee on Gulf War Veterans' Illnesses and as a health representative on the National Advisory Committee on Occupational Safety and Health (NACOSH). She has authored many publications, including articles that highlight minority workers, chemical safety, and disease and injury prevention. Dr. Taylor was selected by the MSU-SCHP students in 2007 and 2009 to receive the Golden Apple Award for excellence in teaching and advising. Her research interests are occupational and environmental health and safety interventions and policies, indoor air quality in public schools, minority workers, and the prevention of environmental exposure to pests and pesticides.

**Michael K. Lindell** has a graduate degree in Social Psychology from the University of Colorado (1975) with a specialty in disaster research and has completed hazardous materials emergency responder training through the Hazardous Materials Specialist level. Dr. Lindell has nearly 40 years of experience in the field of emergency management, during which time he has conducted 47 major research projects, many funded by the National Science Foundation, on the processes by which individuals and organizations respond to natural and technological hazards. In addition, he has had extensive experience in providing technical assistance to government agencies, industry groups, and private corporations in development of emergency plans and procedures. Professor Lindell organized and chaired an American Society of Civil Engineers Specialty Conference on Hazardous Facilities and served twice as Secretary of the Executive Committee for the ASCE Council on Natural Disaster Reduction. He co-chaired the organizing committee for a conference on protective action decision making in nuclear power plant accidents and was a member of the steering committee for a similar conference on protective action decision making in chemical emergencies. He participated in NSF's Second Assessment of Research and Applications on Natural Hazards, serving as a member of the committee on Preparedness and Response, and chairing the committee on Adoption, Implementation, and Evaluation of Hazard Adjustments. He has served on eight consultant panels for the International Atomic Energy Agency in developing planning guidance for response to nuclear and radiological incidents, has made presentations to five National Research Council panels, and served as a member of two National Research Council panels—Disasters Research in Social Sciences and Assessing Vulnerabilities Related to the Nation's Chemical Infrastructure. Professor Lindell has made nearly 200 presentations before scientific societies and short courses for emergency planners, as well as being an invited participant in workshops on risk communication and emergency management in the United States and internationally. He has written extensively on emergency management and is the author of more than 80 technical reports, 100 journal articles and book chapters, and 10 books/monographs. The latter include a book on risk communication in multiethnic communities (Sage, 2004) and a textbook on community emergency planning (Wiley, 2007). Professor Lindell is currently a member of the federal Advisory Committee on Earthquake Hazards Reduction and is completing his term as editor of the *International Journal of Mass Emergencies and Disasters.*

**Jacqueline MacDonald Gibson** is an assistant professor in the Department of Environmental Sciences and Engineering at the University of North Carolina, Chapel Hill. She conducts interdisciplinary research on the quantification of risks due to environmental contamination and on the quantitative comparison of policy options for controlling environmental risks. As an example, she is the principal investigator for a study to assess public health risks due to environmental contamination in the United Arab Emirates and to develop a national strategy to reduce those risks. Dr. MacDonald Gibson earned a dual Ph.D. degree from the Department of Engineering and Public Policy and the Department of Civil and Environmental Engineering at Carnegie Mellon University in 2007. Prior to returning to school in 2003 to study for her Ph.D., she was a senior engineer at the RAND Corp. While at RAND, she served as liaison to the White House Office of

Science and Technology Policy. She also previously was associate director of the Water Science and Technology Board, a unit of the National Research Council of the National Academy of Sciences. In those previous positions, she led a range of studies including assessment of options for improving potable water service to small U.S. communities, evaluation of regulatory requirements for the remediation of contaminated groundwater, assessment of research priorities for new environmental remediation technologies, evaluation of research on alternative methods for detecting and cleaning up landmines, and evaluation of risk assessment methods for sites contaminated with unexploded military ordnance. She has given briefings on these and other topics to a variety of federal officials, members of Congress and their staffs, and institutional advisory boards. Dr. MacDonald Gibson earned an M.S. degree from the Department of Civil and Environmental Engineering at the University of Illinois, Urbana-Champaign, and a B.A. in mathematics from Bryn Mawr College.

**Jeffrey J. Siirola** (NAE) is currently retired from the Eastman Chemical Company where he was a technology fellow in Eastman Research in Kingsport, Tennessee. His areas of interest include chemical process synthesis, computer-aided conceptual process engineering, engineering design theory and methodology, chemical process development and technology assessment, resource conservation and recovery, sustainable development and growth, artificial intelligence, nonnumeric computer programming, and chemical engineering education. Dr. Siirola is secretary and a member of the Board of Directors of the Accreditation Board for Engineering and Technology. He is also a trustee and past president of CACHE (Computer Aids for Chemical Engineering Education), and a member of the American Chemical Society, the American Association for Artificial Intelligence, and the American Society for Engineering Education. He has served on numerous National Science Foundation and National Research Council panels, and on the advisory boards of several journals and chemical engineering departments. Dr. Siirola is a member of the National Academy of Engineering and was the 2005 president of the American Institute of Chemical Engineers. He received a B.S. in chemical engineering from University of Utah in 1967 and a Ph.D. in chemical engineering from the University of Wisconsin-Madison in 1970.

# Appendix G

# Acronyms

| | |
|---|---|
| **ACS** | American Chemical Society |
| **AHP** | Analytic Hierarchy Process |
| **AIChE** | The American Institute of Chemical Engineers |
| **ASCE** | Council on Natural Disaster Reduction |
| | |
| **BCA** | Benefit-Cost Analysis |
| **BC Hydro** | British Columbia Hydro and Power Authority |
| | |
| **CAAA** | U.S. Congress of the Clean Air Act Amendments |
| **CACHE** | Computer Aids for Chemical Engineering Education |
| **CalARP** | California Accidental Release Prevention |
| **CARPP** | California Accidental Release Prevention Program |
| **CCPS** | Center for Chemical Process Safety |
| **CEI** | Dow Chemical Exposure Index |
| **CFATS** | Department of Homeland Security's Chemical Facility Anti-Terrorism Standards |
| **CLC** | The Institute Community Liaison Committee |
| **CMA** | Chemical Manufacturers Association |
| **COMAH** | Control of Major Accidents Hazards Regulation |
| **CPS** | Chemical Process Safety |
| **CSB** | U.S. Chemical Safety and Hazard Investigation Board |
| **CSR** | Corporate Social Responsibility |
| | |
| **DHS** | U.S. Department of Homeland Security |
| **DSPA** | New Jersey Domestic Security Preparedness Act |

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|---|---|
| **DTSC** | California Department of Toxic Substances Control |
| **ECB** | European Chemicals Bureau |
| **ECC** | East Carbamoylation Complex |
| **EHS** | Environment, Health and Safety |
| **EP** | Emergency Preparedness |
| **EPA** | U.S. Environmental Protection Agency |
| **EPCRA** | Emergency Planning and Community Right-to-Know Act (also known as SARA Title III) |
| **ERPG** | Emergency Response Planning Guidelines |
| **ESF** | Engineering Safety Feature |
| **EU** | European Union |
| **F&EI** | Dow Fire and Explosion Index |
| **FMECA** | Fault Tree Analysis; Event Tree Analysis; and Failure Modes, Effects and Criticality Analysis |
| **HAZOP** | Hazard and Operability Analysis |
| **HCl** | Hydrogen Chloride |
| **HQI** | Health Quotient Index |
| **HSE** | Health and Safety Executive |
| **IBI** | Inherent Benign-ness Indicator |
| **ICI** | Imperial Chemical Industries |
| **ILO** | International Labor Organization |
| **INFORMS** | Institute for Operations Research and the Management Sciences |
| **INSET** | *IN*herent *S*HE *E*valuation *T*ool |
| **INSIDE** | *IN*herent *S*HE [Safety, Health, Environment] In DEsign |
| **iRET** | Integrated Risk Estimation Tool |
| **ISD** | Inherently Safer Design |
| **I2SI** | Integrated Inherent Safety Index |
| **ISI** | Inherent Safety Index |
| **ISIM** | Inherent Safety Index Module |
| **ISL** | Inherent Safety Level |
| **ISO** | The Contra Costa Industrial Safety Ordinance |
| **ISP** | Inherently Safer Processes |
| **IST** | Inherently Safer Technology |
| **IUPAC** | Bureau of the International Union for Pure and Applied Chemistry |
| **KPEPC** | Kanawha/Putnam Local Emergency Planning Committee |
| **KPIs** | Key Performance Indicators |
| **KVEPC** | Kanawha Valley Emergency Planning Committee |

| | |
|---|---|
| **LEPC** | Local Emergency Planning Committees |
| | |
| **MAU** | Multi-Attribute Utility |
| **MAUT** | Multi-Attribute Utility Theory |
| **MCC** | **N-**Methyl Carbomoyl Chloride |
| **MIBK** | Methyl Isobutyl Ketone |
| **MIC** | Methyl isocyanate |
| **MMA** | Mono-Methylamine |
| | |
| **NACOSH** | National Advisory Committee on Occupational Safety and Health |
| **NAS** | National Academy of Sciences |
| **NCF** | Naphthylchloroformate |
| **NIST** | National Institute of Standards and Technology |
| **NIHHS** | Installation Handling Hazardous Substances Regulations |
| **NRC** | National Research Council |
| **NSF** | National Science Foundation |
| | |
| **OECD** | Organisation for Economic Cooperation and Development |
| **OHI** | Occupational Health Index |
| **OSHA** | United States, Occupational Safety and Health Administration |
| | |
| **PCMIC** | People Concerned about MIC |
| **PDCA** | Plan Do Check Act |
| **PFD** | Process Flow Diagram |
| **PHA** | Process Hazard Analysis |
| **PIIS** | Loughborough Prototype Index of Inherent Safety |
| **PPA** | Pollution Prevention Act |
| **PRI** | Process Route Index |
| **PRHI** | Process Route Healthiness Index |
| **PSAs** | Probabilistic Safety Analyses |
| **PSM** | Process Safety Management |
| | |
| **QAISP** | Qualitative Assessment for Inherently Safer Design |
| | |
| **REACH** | European Union's Renewed European Policy for Chemicals |
| **RISO** | The City of Richmond's Industrial Safety Ordinance |
| **RMP** | Risk Management Program |
| | |
| **SERC** | State Emergency Planning Committees |
| **SFK/TAA** | Major Accident Commission, Technical Committee for Plant Safety (Germany) |
| **SIS** | Safety Instrumented Systems |

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|---|---|
| **SPI** | Safety Performance Indicator |
| **SREST** | Substance, Reactivity, Equipment, and Safety Technology |
| **TCPA** | Toxic Catastrophe Prevention Act |
| **TORCAT** | Toxic Release Consequence Analysis Tool |
| **TRI** | EPA's Toxic Release Inventory |
| **UCC** | Union Carbide Corporation |
| **UCIL** | Union Carbide India Limited |
| **UNEP** | United Nations Environment Program |
| **VSL** | Value of a Statistical Life |
| **VZs** | Vulnerable Zones |
| **WCC** | West Carbamoylation Complex |