Inherently Safer Process Design Philosophy

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For presentation at the
Israel Institute of Petroleum and Energy Conference
Herzlia, Israel
5-6 May 1999

17 July, 1999

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> *Man masters nature not by force, but by understanding.*
>
> — **Jacob Bronowski** (1908–1974)

ABSTRACT

Inherently safer product and process design represents a fundamentally different approach to safety in chemical manufacturing. The process designer is challenged to identify ways to **eliminate** the hazards associated with the process, rather than to develop add-on barriers to protect people from the hazards of the manufacturing process and its materials. This is best accomplished early in the product and process design cycle, but it is never too late to apply inherently safer design concepts. However, the process designer must also recognize that most processes have many hazards, and must always retain a broad perspective when evaluating options. Design alternatives which reduce or eliminate one hazard may create or increase the magnitude of others. The designer must apply good judgment and appropriate analytical and decision making tools to allow him to select the best overall process alternative, considering all of the hazards.

Definition of an Inherently Safer Process

What is an "inherently safer" chemical process? "Inherent" means "existing in something as a permanent and inseparable element, quality, or attribute" (American College Dictionary, 1967). A chemical process is described as **inherently safer** if it reduces or eliminates one or more hazards of the process, and this reduction or elimination is accomplished through changes that are permanent and inseparable.

To understand this definition, it is essential to understand the meaning of the word "hazard." CCPS (1992) defines hazard as "an inherent physical or chemical characteristic that has the potential for causing harm to people, property or the environment.” A hazard is intrinsic to the material, or to its conditions of storage or use. Some specific examples of hazards include:

- Phosgene is toxic by inhalation
- Acetone is flammable
- A cylinder of compressed air at 30 bar pressure contains a significant amount of potential energy

We cannot change these hazards — they are basic properties of the materials or the conditions of usage. However, we can change the materials or conditions. The inherently safer design philosophy challenges the process engineer and chemist to eliminate the hazard by changing the process, rather than to accept the hazard and control it with add-on safety features such as safety interlocks, operating procedures, training, and emergency response systems. Changing a process to eliminate or reduce hazards is a more reliable and robust approach to risk management. Add-on safety features cannot ever be 100% reliable, and there is always some potential for an accident. In many cases, an inherently safer design will also be more economical, eliminating the costs associated with installing, operating, and maintaining add-on safety devices and systems.

History

On December 14, 1977, Trevor Kletz, who was, at the time, safety advisor for ICI Petrochemicals Division, presented the annual Jubilee Lecture to the Society of Chemical Industry in Widnes, England. His lecture, “What you don’t have, can’t leak,” was the first clear discussion of the concept of inherently safer chemical processes and plants (Kletz, 1978).

Following the Flixborough explosion in 1974, there was increased interest in chemical process industry safety, from within the industry as well as from government regulatory organizations and the general public. Much of the focus of this interest was on controlling the hazards associated with chemical processes and plants through improved procedures, additional safety interlocks and systems, and improved emergency response. Kletz proposed a different approach — change the process to eliminate the hazard completely or reduce its magnitude. If this could be accomplished, elaborate safety systems and procedures could be eliminated.

In 1985 Kletz brought the concept of inherent safety to North America. His paper “Inherently Safer Plants” (Kletz, 1985), won the Bill Doyle Award for the best paper presented at the 19th Annual Loss Prevention Symposium, sponsored by the Safety and Health Division of the American Institute of Chemical Engineers. Since then, Dr. Kletz has continued to actively promote the concept of inherent safety throughout the world. Interest in inherently safer chemical processes and plants has grown over the years since 1978, and that growth has been particularly rapid in the 1990s (Kletz, 1996). In 1995 and 1996, there were more than 30 papers and presentations related to inherently safer chemical processes given at six different meetings, conferences, and congresses sponsored by the American Institute of Chemical Engineers and the Center for Chemical Process Safety. At the same time, there were numerous other papers and presentations on the subject throughout the world. Inherently safer design is also receiving attention from government and regulatory organizations in the United States and Europe (Ashford, 1993; Lin, et al, 1994; Mansfield, 1994), joint industry-government working groups such as the INSIDE Project in Europe (Rogers, et al, 1995; Mansfield, 1996a, 1996b; INSIDE Project, 1997), and environmental and public interest organizations (Tickner, 1994). Hendershot (1997a) reviews efforts to encourage inherently safer chemical process design in the United States.

Inherent Safety and Process Risk Management

Risk is a measure of human injury, environmental damage, or economic loss in terms of both the incident likelihood and the magnitude of the loss or injury, or damage (CCPS, 1989). Thus, any effort to reduce the risk arising from the operation of a chemical processing facility can be directed toward reducing the likelihood of incidents (incident frequency); reducing the magnitude of the injury, damage, or loss should an incident occur (incident consequences); or some combination of both. In general, the strategy for reducing risk, whether directed toward reducing frequency or consequence of potential accidents, can be classified into four categories. These categories, in decreasing order of reliability and robustness, are:

- ***Inherent*** — Reducing or eliminating hazards by using materials and process conditions which are less hazardous.
- ***Passive*** — Reducing or eliminating hazards by process and equipment design features which reduce either incident frequency or consequence without the active functioning of any device.
- ***Active*** — Using controls, safety interlocks, and emergency shutdown systems to detect potentially hazardous process deviations and to take corrective action.
- ***Procedural*** — Using operating procedures, administrative checks, emergency response, and other management approaches to prevent incidents, or to minimize the effects of an incident.

Risk control strategies in the first two categories, inherent and passive, are more reliable and robust because they depend on the physical and chemical properties of the system rather than the successful operation of instruments, devices and procedures. Inherent and passive strategies are not the same, and are often confused. A truly inherently safer process will reduce or completely eliminate the hazard (Kletz, 1991a), rather than simply reducing its impact. Table 1 gives some specific examples of the four risk management strategy categories. These categories are not rigidly defined, and some strategies may include aspects of more than one category.

CCPS (1998) provides a series of excellent checklists describing common failure modes for equipment commonly used in the chemical process industries. The book also provides suggestions for inherent, passive, active, and procedural approaches for managing the risks associated with the failures described. The checklists cover the following types of equipment:

- Vessels
- Mass transfer equipment
- Heat transfer equipment
- Dryers
- Fluid transfer equipment
- Solids handling and processing equipment
- Fired equipment
- Piping and piping components
- Solid-fluid seperators
- Reactors

Table 1: Examples of Process Risk Management Strategies (CCPS, 1993)

Risk Management Strategy Category	Example	Comments
1. Inherent	An atmospheric pressure reaction using non-volatile solvents which is incapable of generating any pressure in the event of a runaway reaction.	There is no potential for overpressure of the reactor because of the chemistry and physical properties of the materials.
2. Passive	A reaction capable of generating 150 psig pressure in case of a runaway, done in a 250 psig reactor.	The reactor can contain the runaway reaction. However, 150 psig pressure is generated and the reactor could fail due to a defect, corrosion, physical damage or other cause.
3. Active	A reaction capable of generating 150 psig pressure in case of a runaway, done in a 15 psig reactor with a 5 psig high pressure interlock to stop reactant feeds and a properly sized 15 psig rupture disk discharging to an effluent treatment system.	The interlock could fail to stop the reaction in time, and the rupture disk could be plugged or improperly installed, resulting in reactor failure in case of a runaway reaction. The effluent treatment system could fail to prevent a hazardous release.
4. Procedural	The same reactor described in Example 3 above, but without the 5 psig high pressure interlock. Instead, the operator is instructed to monitor the reactor pressure and stop the reactant feeds if the pressure exceeds 5 psig.	There is a potential for human error, the operator failing to monitor the reactor pressure, or failing to stop the reactant feeds in time to prevent a runaway reaction.

Note: These examples refer only to the categorization of the risk management strategy with respect to the hazard of high pressure due to a runaway reaction. The processes described may involve trade-offs with other risks arising from other hazards. For example, the non-volatile solvent in the first example may be extremely toxic, and the solvent in the remaining examples may be water. Decisions on process design must be based on a thorough evaluation of all of the hazards involved.

Inherent Safety and the Process Life Cycle

All processes and products have a life cycle, as shown in Figure 1 (Bollinger, et. al., 1996). The life cycle begins with discovery at the research stage. Then a process grows through stages of process development, design and construction, and matures with operations, maintenance, and modification. The life cycle is not complete until the process is shut down and the plant decommissioned, a stage that often does not receive the attention that it should.

We should begin to search for inherently safer process options **early** in the process life cycle, and **never stop**. The best opportunities for impacting process design occur early in invention and development, ideally when selecting the product and process chemistry (Hendershot, 1998). As stated by the United States National Research Council (Design, 1988), “Few basic decisions affect the hazard potential of a plant more than the initial choice of technology.” Early in development there is a great deal of freedom in the selection of chemistry, raw materials, process intermediates, unit operations, plant location, and other design variables. As the process moves through its life cycle, it becomes more difficult and expensive to change the basic process. Exploring inherently safer alternatives may require more resources during the early stages of development than is otherwise the case. However, the resulting understanding will, in many cases, minimize or eliminate the need for safety devices and systems and reduce total life cycle cost. For example, if a chemist can discover a way to eliminate a highly toxic material such as hydrogen cyanide (HCN) from a chemical synthesis route, the process design and operating engineers will not have to concern themselves with protecting operators and other personnel from contact with HCN which might leak from any one of the hundreds of flanges, valves, pump seals, and other potential leak points in a large plant.

To be most effective, an inherent safety program should have the objective of creating an awareness of inherent safety in a broad range of chemists and engineers involved in the development of products and processes throughout an organization. The inherently safer way of doing things should become a way of thinking and working. Perhaps the critical moment in the life of any idea occurs immediately after the idea springs into a person’s head. Does he/she pursue the idea, file it away for further thought, discuss it with a colleague, or just forget it as having no further interest? If everyone in the organization understands that inherently safer products and processes are valued and desired, it is much more likely that ideas with the potential to develop into inherently safer systems will survive this critical moment, and will grow and mature.

The best opportunities for development of inherently safer processes come early in the process life cycle. However, it is never too late to consider inherently safer alternatives. Major enhancements to the inherent safety of plants which have been

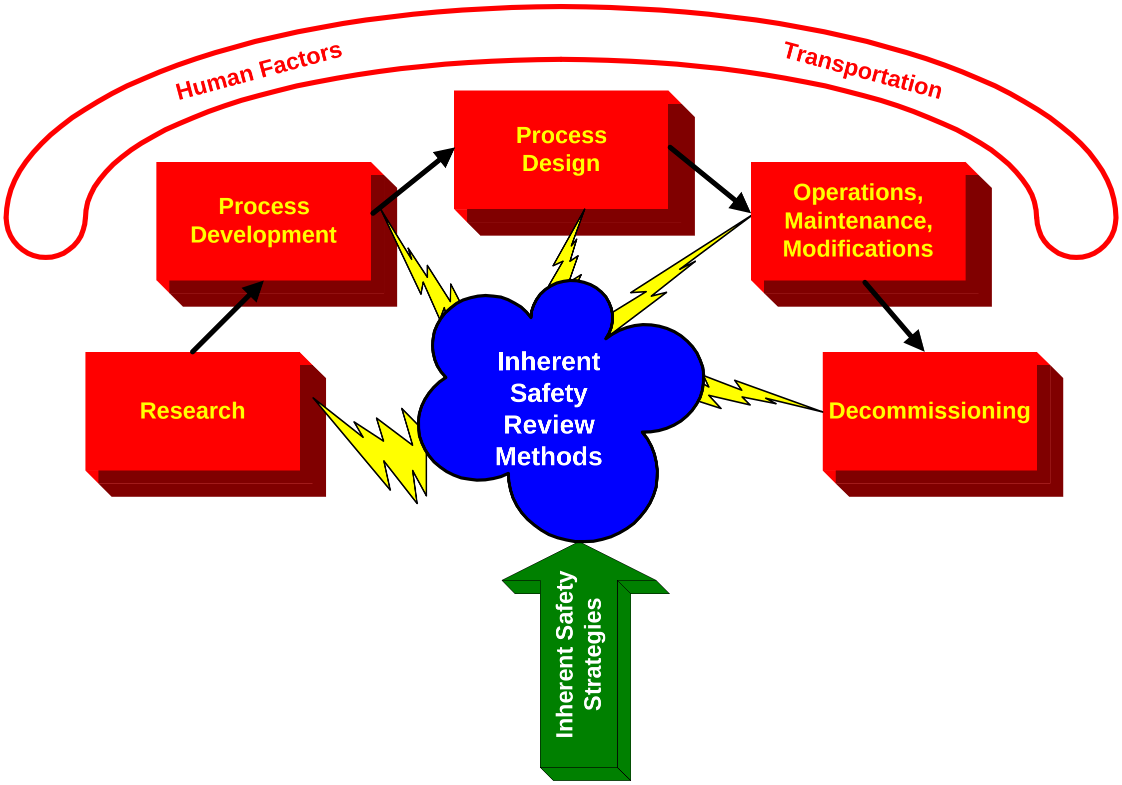

Figure 1: Process Life Cycle Stages

operating for many years have been reported (Wade, 1987; CCPS, 1993; Carrithers, et. al., 1996; Reizel, 1996).

Inherent Safety Conflicts

In many cases, the inherent safety advantages of one process are clear when compared with alternatives. One or more hazards may be significantly reduced, while others are unaffected or only marginally increased. However, all chemical processes have a number of hazards associated with them, and an alternative which reduces or eliminates one hazard may increase a different hazard. For example, process A uses flammable materials of low toxicity, and process B uses non-combustible materials which are volatile and highly toxic. Which process is inherently safer? The answer to this question will depend on the specific details of the process options. In addressing such questions, it is essential that **all** hazards be identified and understood.

An inherently safer process offers greater safety **potential**. However, selection of an inherently safer technology does not ensure that the actual utilization of that technology will result in a safer operation. The traditional strategy of providing layers of protection for an inherently hazardous process can be quite effective, although the expenditure of resources to install and maintain the layers of protection may be very large. In some cases the benefits of the inherently more hazardous technology will be sufficient to justify the costs required to provide the layers of protection required to reduce the risk to a tolerable level. However, even when we determine that the benefits of an inherently less safe technology justify its use, we must always continue to look for inherently safer alternatives. Technology continues to evolve and advance, and inherently safer alternatives which are not economically attractive today may be very attractive in the future.

CCPS (1993) and Hendershot (1995) review a number of specific examples of inherent safety tradeoffs

Resolving Inherent Safety Conflicts

Deciding among a number of process options having inherent safety advantages and disadvantages with respect to different hazards can be quite difficult. The first step is to thoroughly understand all hazards associated with the process options. Process hazard analysis and evaluation techniques, including past history and experience, interaction matrices, what if, checklists, what if/checklists, hazard and operability (HAZOP) studies, and others are appropriate tools (CCPS, 1992). The hazard identification step is perhaps the most important, because any hazard which is not identified will not be considered in the decision process.

Once the hazards have been identified, the process options can be ranked in terms of inherent safety with respect to all identified hazards. This ranking can be qualitative, placing hazards into consequence and likelihood categories based on experience and engineering judgment (CCPS, 1992). More quantitative systems can also be used to rank certain specific types of hazard. For example, Hendershot (1997b) describes a set of quantitative risk index tools for evaluating five inherent safety characteristics of chemical processes:

- Fire and explosion — Dow Fire and Explosion Index (Dow, 1994b)
- Acute toxicity — Dow Chemical Exposure Index (Dow, 1994a)
- Chronic toxicity — In-house index
- Environmental — Environmental Risk Management Screening Tool, ERMST® from Four Elements, Inc., Columbus, Ohio, USA.
- Transportation — ADLTRS® Transportation Risk Screening Index from Arthur D. Little, Inc., Cambridge, Massachusetts, USA.

Unfortunately, none of these indices consider the full range of hazards. To get an overall assessment of the process options, it is necessary to use several indices and combine the results. Edwards, et. al. (1996) describe some initial work on an overall inherent safety index, combining and weighing a variety of separate inherent safety characteristics. In Europe, the INSIDE Project, a joint industry and government effort, developed an inherent safety tool kit which will provide a set of quantitative indices for evaluating inherent safety characteristics of processes (Mansfield, 1996b, INSIDE Project, 1997).

Sometimes the consequences of hazardous incidents can all be expressed in a common measure; for example, dollar value of property damage, total economic loss, risk of immediate fatality due to fire, explosion or toxic material exposure. In this case, the techniques of quantitative risk analysis (CCPS, 1989) may be useful in assessing the relative magnitude of various hazards, and in understanding and ranking total risk of process options. In many other cases, it is not readily apparent how the potential impacts from different hazards can be translated into some common scale or measure. Formal decision making tools can be useful in understanding and prioritizing hazards and potential impacts, particularly if the hazards vary greatly in type of consequence or impact. These tools introduce additional rigor, consistency, and logic into the decision process. CCPS (1995) reviews decision aids and tools, with special emphasis on how they can be employed in making chemical process safety decisions.

Inherently Safer Design Strategies

Approaches to the design of inherently safer processes and plants have been grouped into four major strategies:

Minimize	Use small quantities of hazardous substances
Substitute	Replace a material with a less hazardous substance
Moderate	Use less hazardous conditions, a less hazardous form of a material, or facilities which minimize the impact of a release of hazardous material or energy
Simplify	Design facilities which eliminate unnecessary complexity and make operating errors less likely, and which are forgiving of errors which are made

These strategies are discussed in detail by Bollinger, et. al. (1996), IChemE and IPSG (1995), and in a somewhat modified form by Kletz (1984, 1991b, 1998) and CCPS (1993).

Summary

Inherently safer design represents a fundamentally different approach to chemical process safety. Rather than accepting the hazards in a process, and then adding on safety systems and other barriers to manage those hazards, the process designer is challenged to reconsider the process and eliminate the hazards. If the designer cannot eliminate the hazards, he/she is then challenged to minimize or reduce them as much as possible by modifying the process, rather than by adding external layers of protection. Inherently safer approaches to process design are most effectively applied early in the process life cycle, but it is never too late to consider inherent safety.

In considering inherently safer design alternatives, it is essential to remember that there are often, perhaps always, conflicting benefits and deficiencies associated with the different options. Chemical processes usually have many potential hazards, and a change which reduces one hazard may create a new one, or increase the magnitude of a different existing hazard. It is essential that the process designer retain a broad overview of the process when considering alternatives, that the designer remain aware of **all** hazards associated with each process option, and that appropriate tools are applied to chose the best option.

Acknowledgments

This paper is summarized from the book *Inherently Safer Chemical Processes: A Life Cycle Approach* (Bollinger, et. al., 1996), published by the Center for Chemical Process Safety (CCPS) of the American Institute of Chemical Engineers (New York). I would like to thank the members of the CCPS Inherently Safer Process Subcommittee — Donald E. Park, Albemarle Corporation (Co-Chair); Arthur M. Dowell III, Rohm and Haas Texas Incorporated (Co-Chair); Robert E. Bollinger, CCPS; David G. Clark, DuPont; Daniel A. Crowl, Michigan Technological University; Rodger M. Ewbank, Rhône-Poulenc, Inc.; William K. Lutz, Union Carbide Corporation; Steven I. Meszaros, American Home Products Corporation; and Everett D. Wixom, Exxon Chemical Company — for their review, comments, and suggestions which greatly improved the quality of this discussion.

References

The American College Dictionary (1967). New York: Random House.

Ashford, N. A. (1993). *The Encouragement of Technological Change for Preventing Chemical Accidents: Moving Firms from Secondary Prevention and Migration to Primary Prevention*. Cambridge, MA: Center for Technology, Policy and Industrial Development, Massachusetts Institute of Technology.

Bollinger, R. E., D. G. Clark, A. M. Dowell, R. M. Ewbank, D. C. Hendershot, W. K. Lutz, S. I. Meszaros, D. E. Park, and E. D. Wixom (1996). *Inherently Safer Chemical Processes: A Life Cycle Approach*, ed. D. A. Crowl. New York: American Institute of Chemical Engineers.

Carrithers, G. W., A. M. Dowell, and D. C. Hendershot (1996). “It’s Never Too Late for Inherent Safety.” *International Conference and Workshop on Process Safety Management and Inherently Safer Processes*, October 8-11, 1996, Orlando, FL, 227-241. New York: American Institute of Chemical Engineers.

Center for Chemical Process Safety (CCPS) (1989). *Guidelines for Chemical Process Quantitative Risk Analysis*. New York: American Institute of Chemical Engineers.

Center for Chemical Process Safety (CCPS) (1992). *Guidelines for Hazard Evaluation Procedures, Second Edition With Worked Examples*. New York: American Institute of Chemical Engineers.

Center for Chemical Process Safety (CCPS) (1993). *Guidelines for Engineering Design for Process Safety*. New York: American Institute of Chemical Engineers.

Center for Chemical Process Safety (CCPS) (1995). *Tools for Making Acute Risk Decisions With Chemical Process Safety Applications*. New York: American Institute of Chemical Engineers.

Center for Chemical Process Safety (CCPS) (1998). *Guidelines for Design Solutions for Process Equipment Failures*. New York: American Institute of Chemical Engineers.

The Design of Inherently Safer Plants (1988). *Chemical Engineering Progress,* (September), 21.

Dow Chemical Company (1994a). *Dow's Chemical Exposure Index Guide*. 1st Edition. New York: American Institute of Chemical Engineers.

Dow Chemical Company (1994b). *Dow's Fire and Explosion Index Hazard Classification Guide*. 7th Edition. New York: American Institute of Chemical Engineers.

Edwards, D. W., D. Lawrence, and A. G. Rushton (1996). "Quantifying the Inherent Safety of Chemical Process Routes." *5th World Congress of Chemical Engineering*, July 14-18, 1996, San Diego, CA, Vol. II, 1113-1118. New York: American Institute of Chemical Engineers.

Hendershot, D. C. (1995). "Conflicts and Decisions in the Search for Inherently Safer Process Options." *Process Safety Progress* 14, 1 (January), 52-56.

Hendershot, D. C. (1997a). "Putting Inherent SHE on the Map in the USA." *Inherent SHE: The Cost Effective Route to Improved Safety, Health and Environmental Performance*, 16-17 June, 1997, Kensington Hilton Hotel, London, London: IBC UK Conferences Limited.

Hendershot, D. C. (1997b). "Measuring Inherent Safety, Health and Environmental Characteristics Early in Process Development." *Process Safety Progress* 16, 2 (Summer), 78-79.

Hendershot, D. C. (1998). "Inherent Safety Strategies for Process Chemistry." *Chemical Health and Safety* 5, 4 (July/August), 18-22.

INSIDE Project. (1997). *Inherent SHE: The Cost Effective Route to Improved Safety, Health and Environmental Performance*, 16-17 June, 1997, Kensington Hilton Hotel, London, London: IBC UK Conferences Limited.

The Institution of Chemical Engineers (IChemE), and The International Process Safety Group (ISPG) (1995). *Inherently Safer Process Design*. Rugby, England: The Institution of Chemical Engineers.

Kletz, T. A. (1978). "What You Don't Have, Can't Leak." *Chemistry and Industry* (6 May), 287-292.

Kletz, T. A. (1984). *Cheaper, Safer Plants, or Wealth and Safety at Work*. Rugby, Warwickshire, England: The Institution of Chemical Engineers.

Kletz, T. A. (1985). “Inherently Safer Plants.” *Plant/Operations Progress* 4, 3 (July), 164-167.

Kletz, T. A. (1991a). “Billiard Balls and Polo Mints.” *The Chemical Engineer*, 495 (25 April), 21-22.

Kletz, T. A. (1991b). *Plant Design for Safety*. Bristol, PA, USA: Taylor & Francis.

Kletz, T. A. (1996). “Inherently Safer Design — The Growth of an Idea.” *Process Safety Progress* 15, 1 (Spring), 5-8.

Kletz, T. A. (1998). *Process Plants: A Handbook for Inherently Safer Design*. Bristol, PA, USA: Taylor & Francis.

Lin, D., A. Mittelman, V. Halpin, and D. Cannon (1994). *Inherently Safer Chemistry: A Guide to Current Industrial Processes to Address High Risk Chemicals*. Washington, DC: Office of Pollution Prevention and Toxics, U. S. Environmental Protection Agency.

Mansfield, D. P. (1994). *Inherently Safer Approaches to Plant Design*. Warrington, Chesire, U. K.: United Kingdom Atomic Energy Authority.

Mansfield, D. P. (1996a). “Viewpoints on Implementing Inherent Safety.” *Chemical Engineering* 103, 3 (March), 78-80.

Mansfield, D. P. (1996b). “The Development of an Integrated Toolkit for Inherent SHE.” *International Conference and Workshop on Process Safety Management and Inherently Safer Processes*, October 8-11, 1996, Orlando, FL, 103-117. New York: American Institute of Chemical Engineers.

Reizel, Y. (1996). “Inherently Safer Process: An Integral Part of PSM Implementation.” *International Conference and Workshop on Process Safety Management and Inherently Safer Processes*, October 8-11, 1996, Orlando, FL, 320-328. New York: American Institute of Chemical Engineers.

Rogers, R. L., D. P. Mansfield, Y. Malmen, R. D. Turney, and M. Verwoerd (1995). “The INSIDE Project: Integrating Inherent Safety in Chemical Process Development and Plant Design.” *International Symposium on Runaway Reactions and Pressure Relief Design*, August 2-4, 1995, Boston, MA, ed. G. A. Melhem and H. G. Fisher, 668-689. New York: American Institute of Chemical Engineers.

Tickner, J. (1994). “The Case for Inherent Safety.” *Chemistry and Industry* (3 October), 796.

Wade, D. E. (1987). “Reduction of Risks by Reduction of Toxic Material Inventory.” *Proceedings of the International Symposium on Preventing Major Chemical Accidents*, February 3-5, 1987, Washington, D. C., ed. J. L. Woodward, 2.1-2.8. New York: American Institute of Chemical Engineers.