1. Introduction

1.1 OBJECTIVES, INTENDED AUDIENCE, AND SCOPE OF THIS BOOK

1.1.1 Objectives

The primary objective of this book is to provide a tool that can be used by any industrial company that handles hazardous chemicals to better understand inherent safety concepts and provide guidelines on how to implement them. The goal of this book is to provide practical guidelines for illustrating and emphasizing the merits of integrating research, development, and design into a comprehensive approach that balances safety, capital, and environmental concerns throughout the life cycle of the process. The authors hope that this book will help influence the next generation of engineers, chemists, and current practitioners and managers in the field of chemical processing.

Inherent safety is a powerful and effective means of reducing hazards and risk, versus managing risk by adding layers of protection. A hazard eliminated is one that then doesn't need to be addressed, which may have many direct and indirect benefits. Responsible companies understand the concept and apply it wherever and whenever it may be useful throughout the life cycle of the process. Companies who have an internal motivation to apply inherent safety routinely to the fullest capacity "as a way of doing business" recognize that doing so is beneficial.

In 1996, the Center for Chemical Process Safety (CCPS) published the first edition of its inherent safety concept book. Lessons learned in the ensuing years, combined with the fact that inherently safer design (ISD) was becoming more widely accepted, prompted CCPS to update the concept book in 2009. In the subsequent years, inherent safety has been of greater interest to industry, government, and the public as a concept to reduce hazards. In fact, several governmental entities have mandated consideration of inherently safer design for certain facilities. In the United States, for example, specific regulations exist now for Contra

Costa County in California, the State of New Jersey, and the U.S. Environmental Protection Agency.

Clearly, there is an ongoing need for more guidance, especially in practical, step-wise approaches to conduct inherently safer design studies. This edition builds on the philosophy provided in the first two concept books. It also provides guidelines and approaches to using these concepts with recent research, practitioner observations, new examples and industry methods.

1.1.2 Intended Audience

This book is written for those interested in the application of inherent safety strategies to process safety in industry. It is intended for facility site managers, process safety experts, engineers, chemists, regulators, research and development groups, process development teams, engineering educators and others responsible for workplace safety.

1.1.3 Scope

This book includes key principles on inherent safety and guidelines for how to implement them. It also includes guidance on how to conduct inherent safety studies as well as how to apply inherent safety to an organization's process safety management processes. It also briefly covers the history, research, and basic concepts of inherent safety. The methods described in this book may be widely applicable to inherent safety as it relates to process safety, environmental, and security issues.

1.2 INTEGRATION OF THIS GUIDANCE WITH OTHER CCPS GUIDANCE

Inherent safety is an integral component of process risk management. It is a foundation topic to managing chemical risks and has been referenced in other CCPS guideline books including:

- *Guidelines for Safe Storage and Handling of Reactive Materials*, 1995.
- *Layer of Protection Analysis, Simplified Process Risk Assessment*, 2001.
- Guidelines for Identifying and Analyzing the Security Vulnerabilities of Fixed Chemical Sites, 2003.
- *Guidelines for Risk-Based Process Safety*, 2007.

- *Guidelines for Hazard Evaluation Procedures, Third Edition, with Worked Examples*, 2007.
- *Guidelines for Engineering Design for Process Safety, Second Edition*, 2012, includes a section (Chapter 5.2) on inherently safer design.
- *Guidelines for Implementing Process Safety Management Systems, Second Edition*, 2016.
- *Guidelines for Siting and Layout of Facilities, Second Edition*, 2018.
- *Guidelines for Integrating Process Safety into Engineering Projects*, 2019.

1.3 ORGANIZATION OF THE BOOK

The book is written with the key principles for inherent safety in the body of the book. Tools for implementing the approach, as well as indicative examples and checklists, are included in the appendices. The guidelines begin with an explanation of the concept of Inherent Safety (IS) and then explain its role in Process Risk Management.

Chapter 2 introduces the topic of inherent safety. The key terms and the philosophy behind inherent safety are described. The different ways in which inherent safety is applied can be categorized into "strategies." These strategies—**minimize, substitute, moderate, and simplify**—are discussed in detail in Chapters 3 through 6. Human factors are an extremely important subset of the **simplify** strategy, and Chapter 6.11 of this book presents a detailed discussion of human factors as related to inherently safer design for the human-machine interface. Chapter 7 outlines how each of the four IS strategies can be applied to traditional protection layers.

"Inherently safer" is a way of thinking and, to successfully implement it, this thinking must be well-understood and continually employed wherever possible. Improved understanding of the process may result in a better, more reliable, and even more productive and profitable process that produces higher quality products. Processes should be reviewed for hazards and risks periodically throughout their life cycle. Chapters 8 discusses review methods to do this. Chapter 9 discusses the role of inherent safety in chemical process security. Chapter 10 presents available methods for implementing inherently safer strategies. These can either be independent, special studies, done periodically or before a major project or change is undertaken, or opportunistically applied into day-to-day process risk management strategies. Chapter 11 describes the relationship between the four main IS strategies, i.e., *Substitution, Minimization, Moderation, and Simplification* and each element of a PSM/Risk-Based Process Safety (RBPS) program. Chapter 12 addresses tools available to assist with implementing these IS strategies.

Chapter 13, entitled "Inherently Safer Design Conflicts," describes the conflicts that often develop between the various attributes of safety, operability, cost, as well as other risk parameters and the ways to understand and make decisions considering those constraints. With the advent of regulations requiring inherent safety consideration or implementation, Chapter 14 was written to help guide regulators and industry through the various considerations and challenges of IS.

Chapter 15 contains worked examples of IS study methods and case studies to show a step-wise process that can be followed for an IS evaluation. It also gives practical examples of successful implementation.

Lastly, Chapter 16 describes potential future IS initiatives, including needs, research, expected practice issues, and regulatory issues.

1.4 HISTORY OF INHERENT SAFETY

Inherent Safety is a modern term for an age-old concept: to progress towards eliminating or reducing hazards rather than accepting and managing them. This concept goes back to prehistoric times. For example, building villages near a river on high ground, rather than managing flood risk with dikes and walls, is an inherently safer design concept.

There are many examples of milestones in the application of inherently safer design. For example, in the United States back in 1866, following a series of explosions involving the handling of nitroglycerine, which was being shipped to California for use in mines and construction, state authorities quickly passed laws forbidding its transportation through San Francisco and Sacramento. This action made it virtually impossible to use the material in the construction of the Central Pacific Railroad.

The railroad desperately needed the explosive to maintain its construction schedule in the mountains. Fortunately, a British chemist, James Howden, approached Central Pacific and offered to manufacture nitroglycerine at the construction site. This is an early example of an inherently safer design principle – *minimize* the transport of a hazardous material by in-situ manufacture at the point of use. While nitroglycerine still represented a significant hazard to the workers who manufactured, transported, and used it at the construction site, the hazard to the general public from nitroglycerine transport was eliminated. At one time, Howden was manufacturing 100 pounds of nitroglycerine per day at railroad construction sites in the Sierra Nevada Mountains. The Central Pacific Railroad's experience with the use of nitroglycerine was quite good, with no further fatalities directly attributed to use of the explosive during the Sierra Nevada construction (Ref 1.22 Rolt), (Ref 1.2 Bain).

By today's standards, little about 19th Century railroad construction would qualify as safe, but the in-situ manufacture of nitroglycerine by the Central Pacific Railroad did represent an advance in inherent safety for its time. A further, and probably more important advance occurred in 1867, when Alfred Nobel invented dynamite by absorbing nitroglycerine on a carrier, greatly enhancing its stability. This is an application of another principle of inherently safer design – *moderate*, by using a hazardous material in a less hazardous form (Ref 1.9 Henderson).

A milestone event in process safety and inherent safety was the 1974 Flixborough explosion in the United Kingdom that caused twenty-eight deaths. On December 14, 1977, inspired by this tragic event, Dr. Trevor Kletz, who was at that time safety advisor for the ICI Petrochemicals Division, presented the annual Jubilee Lecture to the Society of Chemical Industry in Widnes, England. His topic was "What You Don't Have Can't Leak," and this lecture was the first clear and concise discussion of the concept of inherently safer chemical processes and plants.

Following the Flixborough explosion, interest in chemical process industry (CPI) safety increased, from within the industry, as well as from government regulators 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 instrumented systems and improved emergency response. Kletz proposed a different approach—to change the process to either eliminate the hazard completely or sufficiently reduce its magnitude or likelihood of occurrence to eliminate the need for elaborate safety systems and procedures. Furthermore, this hazard elimination or reduction would be accomplished by means that were inherent in the process, and thus, permanent and inseparable from it.

Kletz repeated the Jubilee Lecture two times in early 1978, and it was subsequently published (Ref 1.14 Kletz 1978). In 1985, Kletz brought the concept of inherent safety to North America. His paper, "Inherently Safer Plants" (Ref 1.13 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 (AIChE).

Since 1978, interest in inherently safer chemical processes and plants has grown, and that growth was particularly rapid in the 1990s (Ref 1.15, Kletz, 1996). Inherent Safety received additional attention from the chemical industry because of several major industrial accidents. Some examples are:

- Mexico City (1984) – a series of explosions in an LPG terminal killed approximately 500 people and destroyed the facility. A contributing factor was the very high quantity of LPG stored onsite at the terminal, which was in an urban area. Applying IS strategies may have reduced the LPG quantity onsite, making the propagation of the event and the impacts less severe.
- Bhopal, India (1984) – the worst disaster in the history of the chemical industry occurred when water entered a storage tank containing methyl isocyanate (MIC). The resulting reaction generated heat and pressure, lifting the tank relief valve and releasing highly toxic MIC vapors into the city. Exact casualty figures are disputed, but tens to hundreds of thousands of people were exposed. In 1994, the official Indian government estimate of fatalities was 4,000 (Ref 1.8 Hendershot). The two-step process required MIC to be stored onsite. Applying IS strategies by interconnecting the process would have eliminated the need to store MIC altogether.

- Charleston, West Virginia (2008) – debris from a fire and explosion in a pesticide manufacturing facility narrowly missed damaging a neighboring storage tank containing methyl isocyanate (MIC). The company embarked on a redesign of the MIC storage and handling processes at the plant, incorporating IS techniques, eliminating above-ground storage, greatly reducing overall stored volume, and simplifying the internal logistics of MIC handling. (Ref 1.20 NAS). In this case, the MIC tank was not damaged and there was no release of MIC. However, applying IS strategies may have reduced the total quantity onsite.
- West, Texas (2013) - An ammonium nitrate explosion occurred at fertilizer storage and distribution facility while emergency services personnel were responding to a fire at the facility. Fifteen people were killed, more than 160 were injured, and more than 150 buildings in the nearby town of West were damaged or destroyed, raising questions about the siting of the facility relative to populated area (Ref 1.24 CSB). This event highlighted the debate about the explosiveness of Fertilizer Grade Ammonium Nitrate (FGAN) and whether an inherently safer option could be developed and used.

In addition, a reflection on these incidents using Kletz's seminal 1978 paper over thirty years later provides a glimpse what has been learned from these incidents and how effectively managing their hazards and risks can be addressed (Ref 1.25 Vaughen 2012a).

Inherent safety has received considerable research attention from academia, industry, government and regulatory organizations (Ref 1.1 Ashford) (Ref 1.17 Lin) (Ref 1.18 Mansfield), joint industry-government working groups, such as the INSIDE (INherent SHE In DEsign) Project in Europe (Ref 1.21 Rogers) (Ref 1.19 Mansfield), and environmental and public interest organizations (Ref 1.23 Tickner).

In a similar manner, the work of Etowa et al. (Ref 1.5 Etowa) sought to clearly identify the inherent safety features using the Dow Fire & Explosion Index and the Dow Chemical Exposure Index – two commonly used tools in process safety management for relative risk ranking. Goraya, et al. (Ref 1.6 Goraya) developed and validated a methodology for incident investigation that makes explicit use of the principles of inherent safety in determining the root causes of an incident. By means of an illustrative example, Gupta et al. (Ref 1.7 Gupta) provided evidence of the linkages between inherent safety and the cost of process safety. Their work helps to establish a clear business case for the use of inherent safety principles in management efforts directed at enhancing process safety.

Further motivation for the current research is found in the comments of employees who have reviewed the field of inherent safety and inherently safer design, including (Ref 1.3 Bollinger), (Ref 1.7 Gupta), (Ref 1.12 Kletz), (Ref 1.10 Khan) and (Ref 1.26 Vaughen 2012b). For example, Khan and Amyotte (Ref 1.10 Khan) have remarked that the various elements of process safety management can be seen to have at least a partial basis in inherent safety. This fact has been recognized by companies that have incorporated inherent safety as a "named feature" in their safety management documentation and have developed internal standards for the use of inherent safety principles. Yet the term *inherent safety* is typically not named as such in the general description of process safety management systems. Per Bollinger, et al. (Ref 1.3 Bollinger), explicit use of inherent safety terminology within such management systems is a possible means of furthering the adoption of inherent safety principles in industry.

Over the years, the interest in inherent safety from government, industry, and the public has increased. Inherent safety's promise has produced heightened expectations and it is seen almost as a panacea to reducing risks in the chemical process industries as the public becomes aware of the concept. Inherent safety is incorporated into safety and security regulations in parts of the United States at the local, state, and federal levels. Inherent safety has been proposed as a leading requirement for chemical security regulations in the U.S. Congress. To better clarify and more precisely define the terminology, the US Chemical Security Analysis Center (CSAC) of the Department of Homeland Security (DHS) contracted with CCPS to provide a technology-based definition of Inherently Safer Technology (IST) (Ref 1.4 CCPS/DHS).

Some of the best compilations of information on IS can be found in the works of (Ref 1.14 Kletz 1978), (Ref 1.15 Kletz 1996), (Ref 1.16 Lees) and the final report of the INSIDE (INherent SHE in DEsign) project in

Europe (1997) (Ref 1.21 Rogers). Khan and Amyotte (Ref 1.10 Khan) provide an excellent summary of the applications of IS. The second edition of Process Plants: A Handbook for Inherently Safer Design (Ref 1.11 Kletz, 2010) is a practical guide for plant engineers for incorporating IS techniques in their operations. The aforementioned 2012 National Academy of Sciences report on the “Use and Storage of Methyl Isocyanate (MIC)” at Bayer CropScience (Ref 1.20 NAS) is an excellent case study of IS principles applied to an existing chemical manufacturing facility.

1.5 REFERENCES

1.1 Ashford, NIA. The Encouragement of Technological Change for Preventing Chemical Accidents: Moving Firms From Secondary Prevention and Mitigation to Primary Prevention, Massachusetts Institute of Technology, 1993.

1.2 Bain, D. H. *Empire Express: Building the First Trans-continental Railroad*. New York: Viking, 1999.

1.3 Bollinger, R. E., Clark, D. G., Dowell, A.M., Ewbank, R. M., Hendershot, D.C., Lutz, W. K., et al. (1996). Inherently Safer Chemical Processes: A Life Cycle Approach (D. A. Crowl, Ed.), American Institute of Chemical Engineers, 1996.

1.4 Center for Chemical Process Safety, Report: Definition for Inherently Safer Technology in Production, Transportation, Storage, and Use, Chemical Security Analysis Center, Science & Technology Directorate, U.S. Department of Homeland Security (DHS), 2010.

1.5 Etowa, C. B., Amyotte, P.R., Pegg, M. J. and Khan, F.I., Quantification of inherent safety aspects of the Dow indices. Journal of Loss Prevention, 15, 477-487, 2002.

1.6 Goraya, A., Amyotte, P.R. and Khan, F. I, An inherent safety-based incident investigation methodology. Process Safety Progress, 23 (3), 197-205, 2004.

1.7 Gupta, J. and Edwards D. W., A simple graphical method for measuring inherent safety, Journal of Hazardous Materials, 104, 15-30, 2003.

1.8 Hendershot, D.C. An overview of inherently safer design. Risk Management: The Path Forward: 20th Annual CCPS International Conference, Atlanta, GA, 2005.

1.9 Henderson, D. C, and Post, R.L. (2000). Inherent safety and reliability in plant design. In Beyond Regulatory Compliance, Making Safety Second Nature. Mary Kay O'Connor Process Safety Center 2000 Annual Symposium. College Station, TX: Texas A&M University.

1.10 Khan F.I. and Amyotte, P.R., How to make inherent safety practice a reality. The Canadian Journal of Chemical Engineering, 81, 2-16, 2003.

1.11 Kletz, T., Amyotte, P., Process Plants – A Handbook for Inherently Safer Design, 2nd Ed., CRC Press, 2010.

1.12 Kletz, T.A., Inherently safer design—Its scope and future. Process Safety and Environmental Protection, 81(B6), 401-405, 2003.

1.13 Kletz, T.A. Inherently safer plants. Plant/Operations Progress 4 (3), 164-167, 1985.

1.14 Kletz, T.A. What you don't have, can't leak. Chemistry and Industry, 287-292, 1978.

1.15 Kletz, T.A., Inherently safer design: Achievements and prospects, International Conference and Workshop on Process Safety Management and Inherently Safer Processes, October 8-11, 1996, Orlando, FL (pp. 197-206), American Institute of Chemical Engineers, 1996.

1.16 Lees, F.P., Loss Prevention in the Process Industries, 2nd Ed., Butterworth-Heinemann, 1996.

1.17 Lin, D., Mittelman, A., Halpin, V. and Cannon, D., Inherently Safer Chemistry: A Guide to Current Industrial Processes to Address High Risk Chemicals, U. S. Environmental Protection Agency, 1994.

1.18 Mansfield, D.P., Inherently Safer Approaches to Plant Design, United Kingdom Atomic Energy Authority, 1994.

1.19 Mansfield, D.P., Viewpoints on implementing inherent safety. Chemical Engineering, 103 (3), 78-80, 1996.

1.20 National Academy of Sciences (NAS), The Use and Storage of Methyl Isocyanate (MIC) at Bayer CropScience, National Academies Press, 2012.

1.21 Rogers, R.L., Mansfield, D.P., Malmen, Y., Turney, R.D., and Verwoerd, M. (1995). The INSIDE Project: Integrating inherent safety in chemical process development and plant design. In G.A. Melhem and H.G. Fisher (Eds.). International Symposium on Runaway Reactions and Pressure Relief Design, August 2-4, 1995, Boston, MA (pp. 668-689). American Institute of Chemical Engineers, 1995.

1.22 Rolt, L.T.C, The Railway Revolution: George and Robert Stevenson (pg.147). New York: St. Martin’s Press, 1960.

1.23 Tickner, J. The case for inherent safety. Chemistry and Industry, 796, 1994.

1.24 U.S. Chemical and Hazard Investigation Board (CSB), West Fertilizer Company Fire and Explosion, Final Report, 2013.

1.25 Vaughen, B. K., and Klein, J. A., What you don’t manage will leak: A tribute to Trevor Kletz. Process Safety and Environmental Protection, 90, 411-418, 2012a.

1.26 Vaughen, B. K., and Kletz, T. A., Continuing our process safety management journey. Process Safety Progress, 31(4), 337-342, 2012b.