The Evolution of Process Safety: Current Status and Future Direction

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Abstract

The advent of the industrial revolution in the nineteenth century increased the volume and variety of manufactured goods and enriched the quality of life for society as a whole. However, industrialization was also accompanied by new manufacturing and complex processes that brought about the use of hazardous chemicals and difficult-to-control operating conditions. Moreover, human-process-equipment interaction plus on-the-job learning resulted in further undesirable outcomes and associated consequences. These problems gave rise to many catastrophic process safety incidents that resulted in thousands of fatalities and injuries, losses of property, and environmental damages. These events led eventually to the necessity for a gradual development of a new multidisciplinary field, referred to as process safety. From its inception in the early 1970s to the current state of the art, process safety has come to represent a wide array of issues, including safety culture, process safety management systems, process safety engineering, loss prevention, risk assessment, risk management, and inherently safer technology. Governments and academic/research organizations have kept pace with regulatory programs and research initiatives, respectively. Understanding how major incidents impact regulations and contribute to industrial and academic technology development provides a firm foundation to address new challenges, and to continue applying science and engineering to develop and implement programs to keep hazardous materials within containment. Here the most significant incidents in terms of their impact on regulations and the overall development of the field of process safety are described.

INTRODUCTION

The body of process safety knowledge has grown impressively over the years. Following the 1984 Bhopal disaster, there has been increased activity in the research and academic community related to process safety in the chemical industry (1). The resulting research articles cover a wide variety of safety topics ranging from clinical studies to estimate toxicity, risk management, design and manufacturing processes, and environmental and regulatory issues. In several countries, long-term research efforts have been undertaken. In the United States and Europe, government funds have been made available to investigate hazardous phenomena and to develop and evaluate test methods and computational tools. Whereas governmental regulations set out minimum programmatic requirements and standards that apply to processing plants, industry has also implemented various programs aimed at improving process safety performance. However, there continues to be a compelling need to increase the competency level of both practicing engineers and new graduates to facilitate process safety performance improvements in industry and government. Thus, a three-way partnership (**Figure 1**) is needed between government, the academic/research community, and industry.

INCIDENTS THAT SHAPED AND INFLUENCED PROCESS SAFETY

Unfortunately, societal approaches to process safety have been and continue to be reactive instead of proactive, risk-based approaches. This seems to be compounded by our failure to learn (2), flawed risk analyses, and lack of overall competency. Some well-publicized events that have shaped and influenced the evolution and development of process safety are summarized below.

Flixborough (1974, United Kingdom)

The Flixborough explosion took place on a Saturday in June 1974. The rupture of a 20-inch bypass, installed as a replacement of a reactor No. 5 owing to a vertical crack, led to the release of large quantities of cyclohexane. Cyclohexane in contact with air formed a flammable mixture and subsequently found an ignition source. This explosion caused the deaths of 28 workers and injured 36 more. The Flixborough disaster was a major influence for process safety initiatives in the United Kingdom. The investigation led to the creation of the Advisory Committee on Major Hazards at the end of 1974. The Committee was in charge of developing new UK regulations for the control of industrial major accident hazards (CIMAH) (3, 4).

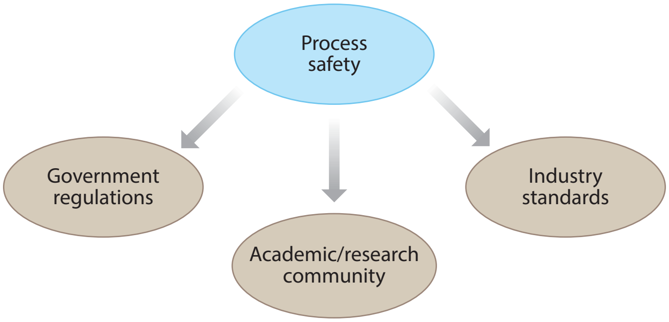

Figure 1

Process safety is an alliance between government, academia, and industry.

Seveso (1976, Italy)

Before the CIMAH regulations could be introduced, another catastrophic incident occurred in Italy in 1976 at the ICMESA (Industrie Chimiche Meda Società Azionaria) chemical plant. A reactor producing trichlorophenol overheated, causing a safety valve to vent and leading to the release of dioxin, an undesired by-product. Preventive measurements to avoid further dioxin contamination included extermination of over 80,000 animals, examination of thousands of people, and allowance of abortion based on the mother's decision (5).

Seveso further catalyzed the enactment of CIMAH regulations, which were finally introduced in 1984. This incident was the major driver for the Seveso I Directive (1982) and its successor regulations, the Seveso II Directive (1996), Seveso II Directive (2003), and Seveso III Directive (2012). Currently, most EU industries with potential for such major incidents are regulated by the Seveso III Directive, the main goal of which is to prevent and control industrial incidents involving dangerous substances (The European Chemical Industry Council, CEFIC)[1] (6).

Bhopal (1984, India)

The unforgettable Bhopal gas tragedy was a wake-up call for the government, the chemical industry, and academia. In 1984, at the Union Carbide Plant in Bhopal, India, a methyl isocyanate (MIC) storage tank was contaminated with water. MIC in contact with water caused an unwanted and fast runaway reaction, which led to a massive release of MIC to the atmosphere. Hundreds of thousands were injured, and estimates of deaths vary between 3,000 and 20,000 (1).

After Bhopal, the Environmental Policy Act (1986) obligated by law that US manufacturing industries report their annual emissions of a wide variety of chemicals (7). In India itself, regulations and policies enacted after this incident included the Air Act (1987), the Hazardous Waste (Management and Handling) Rules (1989), the Public Liability Insurance Act (1991), and the Environmental Protection (Second Amendment) Rules (1992) (3).

Bhopal also provided a wealth of lessons learned, many of which remain true and yet not completely realized or implemented. For instance, some of these lessons stress the importance of inherently safer design; minimization of stocks of hazardous materials; maintenance of protective equipment; siting of high-risk facilities and land-use planning; sharing of hazard and risk information with regulators and emergency responders to help prepare for emergencies; and appropriate application and use of risk assessments.

Following the Bhopal incident, the American Institute of Chemical Engineers formed an industry-technology alliance, the Center for Chemical Process Safety (CCPS), that identifies and addresses process safety needs in the chemical, pharmaceutical, and petroleum industries. Since its inception, CCPS has produced 100 publications that provide guidelines for process safety programs and practices aimed at promoting improved process safety performance.

Piper Alpha (1988, United Kingdom)

The Piper Alpha oil production platform was located in the North Sea off Scotland. In July 1988, a safety relief valve for a spare condensate pump was removed and temporarily replaced with a blind flange by the day-shift operator. Lack of communication between shifts led to catastrophe when the night-shift team had a problem with the primary pump. Unaware of the temporary

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[1] CEFIC. *Process Safety and Seveso*. Retrieved April 29, 2015. **http://www.cefic.org/Policy-Centre/Environment–health/Seveso**.

replacement, the team restarted the spare pump. Most likely, a gas condensate started leaking from the temporary flange, formed a cloud, and ignited. The first explosion occurred in the production deck and was followed by a series of major explosions. The poor safety layout of the platform and the lack of a temporary refuge contributed to preventing the safe evacuation of workers. A total of 167 individuals died in the Piper Alpha incident (8). After Piper Alpha, safety case regulations were developed and implemented in the United Kingdom. Other changes in the offshore industry included the adoption of a permit-to-work system, requirement of a safe place to muster in case of emergencies for everyone on board, and better emergency response training.

Exxon Valdez Spill (1989, United States)

In 1989, approximately 11 million gallons of crude oil were spilled into Alaska's Prince William Sound. The spill occurred when the oil tanker Exxon Valdez hit the Bligh Reef. Although this incident is not one of the largest oil spills in history, its global impacts were significant. The government and the Coast Guard were not prepared to deal with such an incident. Before the spill, the US government had been working for more than 15 years on the Oil Pollution Act; the incident was the catalyst that finally led to its promulgation (7).

Phillips 66 (1989, United States)

On October 23, 1989, in the Phillips 66 Chemical Plant, close to Pasadena, Texas, a valve failure allowed the release of highly flammable gases from a polyethylene reactor. The release was followed by the quick formation of a vapor gas cloud, which led to a massive explosion in less than 90 seconds. The explosion measured more than 3.5 on the Richter scale, killed 23 workers, and injured hundreds of people (3, 8). In the aftermath of the Phillips 66 incident, the Clean Air Act Amendments of 1990 were promulgated, which contained provisions for the Occupational Safety and Health Administration (OSHA) and the US Environmental Protection Agency to develop regulations to protect employees in the workplace and the public and the environment, respectively. OSHA fulfilled its mandate in 1992 by promulgating the Process Safety Management (PSM) regulations. The Environmental Protection Agency published the Risk Management Program regulations in 1996. The Clean Air Act Amendments of 1990 also mandated the creation of an independent federal agency, the US Chemical Safety and Hazard Investigation Board (CSB), with the specific statutory mandate to investigate catastrophic incidents to determine root causes.

On the academic front, the Mary Kay O'Connor Process Safety Center (MKOPSC) was established in 1995 as part of the Engineering Program at Texas A&M University in College Station. MKOPSC is a unique organization and fulfills many roles in process safety. The underlying mission of the Center is "Making Safety Second Nature," and its approach is to create a paradigm shift in the engineers educated by the Center.

BP Texas City (2005, United States)

On March 23, 2005, 15 people were killed and almost 200 were injured owing to a series of explosions and a fire at the BP Texas City Refinery. These explosions and fires began during the start-up of an isomerization unit. A distillation tower was overfilled, causing the pressure safety relief valve to open and leading to the flow of hydrocarbon liquids into a blowdown disposal drum with a stack (which did not have a flare). Flammable hydrocarbons were released, leading to fires and explosions (9, 10). In the aftermath of this incident, OSHA adopted special emphasis programs with regard to refineries. The incident also resulted in the revision of the American Petroleum

Institute's (API's) Recommended Practice (RP) 752 and the development and adoption of several other API Recommended Practices (API RP 753, Management of Hazards Associated with Location of Process Plant Portable Buildings; API RP 754, Process Safety Performance Indicators for the Refining and Petrochemical Industries; and API RP 756, Management of Hazards Associated with Location of Process Plant Tents).

T2 Explosion (2007, United States)

On December 19, 2007, a powerful explosion and subsequent chemical fire killed 4 employees and destroyed T2 Laboratories, Inc., a chemical manufacturer in Jacksonville, Florida. It injured 32, including 4 employees and 28 members of the public who were working in surrounding businesses. Debris from the reactor was found up to one mile away, and the explosion damaged buildings within one quarter mile of the facility (11). In its report, the CSB concluded that there was no requirement for accredited baccalaureate chemical engineering programs to include process safety or reactive hazard awareness in their curricula. As a result, CSB issued a recommendation to the Accreditation Board for Engineering and Technology to include process safety/reactive hazard awareness in their evaluation criteria.

Deepwater Horizon (2010, United States)

On April 20, 2010, the horizontal semisubmersible *Horizon* rig underwent an explosion caused by the catastrophic blowout of the Macondo exploratory well located off the coast of Louisiana in the Gulf of Mexico. The incident killed 11 employees and caused an uncontrolled oil spill that last for almost 90 days (12). The incident impacted industry and regulators around the globe, even spurring an unprecedented reorganization within the US Department of the Interior. The first action taken by the Department was to strengthen regulatory oversight, which included the replacement of the Minerals Management Service with two separate bureaus: the Bureau of Safety and Environmental Enforcement (BSEE) and the Bureau of Ocean Energy Management. Industrial contributions to safety improvement included the creation of spill-response cooperatives; development of new standards; and the creation of the Center for Offshore Safety, in which offshore operators share best practices and work together on the improvement of offshore operations. As a response to the *Deepwater Horizon* blowout, BSEE also sponsored the start-up of the Ocean Energy Safety Institute, an institute designed to conduct dialogue and research among all stakeholders aimed at ensuring safe and environmentally responsible offshore operations. Its mission is to facilitate shared learning, open discussion, and cooperative research among academia, government, nongovernmental organizations, and industry.

West Fertilizer Explosion (2013, United States)

On April 17, 2013, an ammonium nitrate explosion occurred at the West Fertilizer Company storage and distribution facility in West, Texas, 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 were damaged or destroyed. Shortcomings identified after the incident included lack of enforcement inspections, potential improper storage of ammonium nitrate, and absence of land-use planning. Questions were also raised regarding awareness of potential risks and sharing of such information with emergency responders. The US Congress also held several hearings, including a hearing focused on issues regarding "facilities flying under the radar," with regard to regulatory inspection and compliance (13).

CURRENT STATUS OF PROCESS SAFETY

Process safety is a relatively young field; its body of knowledge has grown from a slow start over the past 50 years. After each of the aforementioned disasters, academic and industrial research related to different process safety areas has increased impressively. The main areas of technology development influenced by each of these incidents are depicted in **Figure 2**. In general, in the

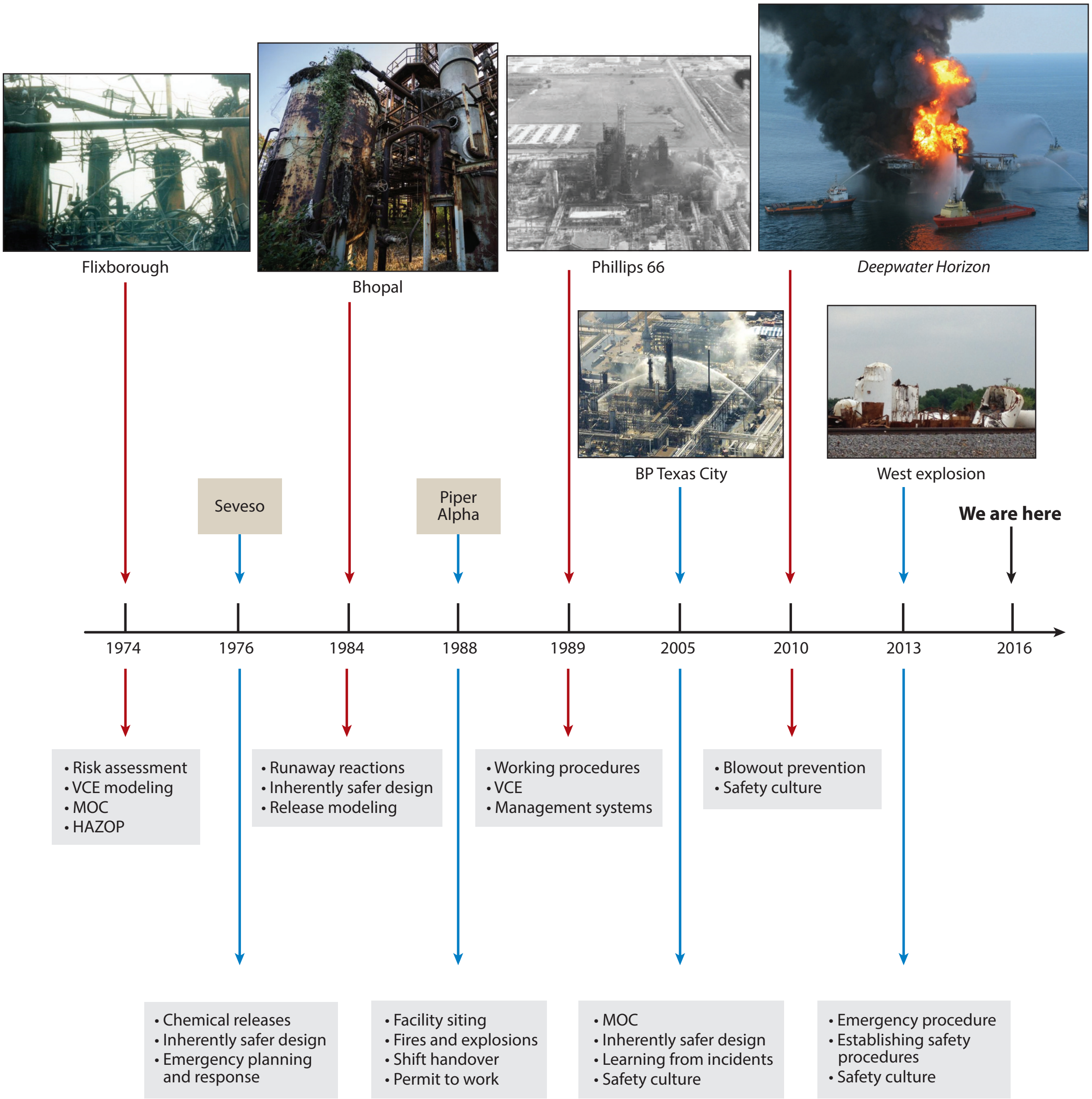

Figure 2

Technology development influenced by major incidents. Abbreviations: HAZOP, hazard and operability study; MOC, management of change; VCE, vapor cloud explosion. Bhopal photo credit: Giles Clarke/Getty Images Reportage.

1970s and early 1980s, most academic and industrial research focused mainly on the technical safety aspect. However, in the late 1980s and early 1990s, the importance of human factors in preventing process safety incidents gained recognition, and in the 1990s and early 2000s, safety management systems began to be incorporated in regulations around the world.

Crowl (14) shared his early experiences in implementing process safety with academia, reporting at an academic conference that process safety research was conducted almost entirely in the industrial domain until the late 1980s. Existing available information was spread throughout a large number of sources but was not readily available. The emphasis was on solving the immediate problems, and deeper and fundamental issues were not analyzed. On the academic side, progress was very difficult because of the challenges of adding new courses to existing curricula. In addition, the academic establishment viewed process safety research as devoid of fundamental or intellectual challenges. This was compounded by lack of funding for process safety research by research agencies. Things gradually improved with the engagement of industrial professionals with academia; workshops, conferences, and a global congress on process safety; and the formation of organizations such as CCPS and MKOPSC and the resulting development of Safety and Chemical Engineering Education (SAChE) materials. As shown in **Figure 3**, the present view toward process safety can be divided broadly into three categories: properties of substances, process technology, and system safety.

Properties of Substances

A hazardous material inherently possesses qualities that can cause devastating situations when exposed to the right conditions. As an example, MCMT (methylcyclopentadienyl manganese tricarbonyl), a reactive substance used in T2 laboratories (15), was involved in an explosion that demolished an entire production site. An effective and systematic study of hazardous properties of substances considers its reactivity, flammability, toxicity, and corrosive effect (16). Understanding

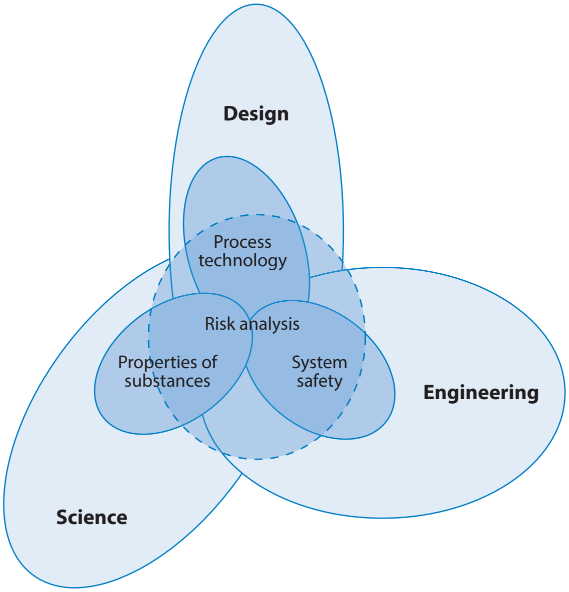

Figure 3

Current view toward process safety.

of the reactive behavior of a chemical depends not only on its inherent properties but also on process conditions and modes of operation. Therefore, the properties of reactive chemicals are studied at various production stages, such as product design (molecular level) (17, 18), laboratory-scale (19–22) and bench-scale operations, pilot plants, and finally at the commercial scale. In the molecular level or the product design, the focus is to create a substance that can replace the existing, more hazardous material. At the laboratory scale, the reactive properties are evaluated so that thermal runaway reactions can be prevented. Adoption of both theoretical and experimental approaches at this stage is crucial because the behavior of a reactive chemical system depends on the scale of operations (23). The validated theoretical models are further tuned during bench-scale operations and pilot-plant studies before the substance is taken to the commercial production stage. The flammability of the substance does not change based on the scale of operations but rather depends on the operating conditions (24). Experimental studies (25–27) are the first stage of estimating flammability. It is not practical to estimate flammability for numerous process conditions or mixtures of materials; therefore, validated theoretical models (28) become important. Toxicity refers to injury or risk to the human owing to exposure to hazardous chemicals (29). The toxicity of the chemicals is defined based on the dose-versus-response studies of different chemicals. The corrosive effect of materials is another important aspect of material properties because many incidents can be prevented if mechanical integrity of the system can be ensured. Other important material properties that are directly related to process safety include, but are not limited to, boiling point, flash point (30, 31), and auto-ignition temperature (32).

Process Technology

The most important focus of process technology is the development of inherently safer design solutions of process components, equipment, and installations (33, 34). It is also involved in increasing the reliability of the system (8) via computer simulations (35) and innovative developments. Most often, process economics drives the technological improvements. Deeper understanding of the substance properties and behavior under process conditions, as well as adequate computer-simulation process methods, is key to reliable prediction of safe operation.

System Safety

Process safety approaches focusing on specific technology or individual equipment are important; however, a holistic approach is also very important. System safety addresses process safety issues using such an approach, considering related procedures development; assignment of safety accountability (tasks, responsibilities); process documentation and knowledge; personnel qualification and training; occupational safety measures; procedures and management of change; incident investigation and risk management; integrity of equipment with inspection and maintenance; compliance with regulations, standards, and codes; and audits. Lately, attention to safety attitude and safety culture (36), involvement of the workforce, and stakeholder outreach have also been intensified.

CHALLENGES IN SOME SPECIFIC AREAS

Computation and Instrumentation

Some specific areas that have received the attention of process safety professionals include application of advanced computational approaches, such as molecular simulations (16, 17), for determining the properties of hazardous material; computational fluid dynamics simulations of hazardous vapor cloud generation and mixing (37); detailed chemical kinetic studies of runaway reactions

(38); electronic and molecular structure modeling to design less hazardous materials (39); and improved instrumentation, such as reduction of sensors' response time and optimized location for detectors (40).

Statistics and Reliability Engineering

To continuously improve the process safety performance of an organization or a unit of the processing areas, statistics and data collection and mining are crucial (41). The old reactive approach to improvement of system safety has shifted toward the predictive or proactive approach; some professionals have adopted a frequentist's approach, whereas others have taken a Bayesian approach. Proponents of the latter believe that Bayesian approaches offer more benefits in determining process safety health because the decision network (Bayesian belief network) continuously updates itself, which enables informed decision-making at all times (42). Further advancements include use of fuzzy logic (33, 43) and artificial neural network models.

Process Equipment System and Control

Historically, the focus of process development was to increase the efficiency of the process in terms of economic growth or improvement. However, in recent times, the focus has been trending toward both economic and safety improvement. Without an improvement in safety features, no development in this area can be claimed as an advancement. Optimizing the process for improved efficiency, automating the process to eliminate human interactions from dangerous operations, and creating remote mitigation systems to control safety breaches are some examples of recent developments in this area (29).

Psychology and Organizational Science

Humans are an integral element of the system (44). However, humans are also very susceptible to making mistakes. The focus in this area is to improve the human-machine interface to reduce human error/factors (45). Safety culture and safety climate also impact the overall performance of the organization. A positive safety culture starts from leadership positions and trickles down to the bottom of the organization. Resilience engineering is another important aspect of process safety (46).

Data Sharing

Data are one important building block for interpreting information and making decisions. Data can be advantageous if used properly and dangerous if not. Data in the field of safety can be used to measure progress, evaluate trends, allocate priorities, perform risk assessment, and improve safety performance. The process of learning from incidents and near misses in industry can be a vital tool, which can be implemented with the assistance of data sharing. Major hurdles in data sharing can be categorized as availability of data, quality of data, and other barriers to data sharing.

Various types of data and information are needed to understand system operability, productivity, and reliability, which ultimately aids in better assessment of risk. Most organizations work in silos, and the data they collect are kept confidential. The main drawback in today's world is nonavailability of a comprehensive data bank for collecting, sharing, and accessing data. A shared database among various organizations could benefit all stakeholders, which would enhance system reliability, performance, and ultimately overall profits. In addition, efforts must be made to overcome barriers such as proprietary issues, legal issues, and standardization of data format.

The trade-off between complexity and ease of access to databases is also a challenge. In addition to confidentiality, contractual barriers also prevent data sharing. However, confidentiality is also important to ensure data sharing, quality, and quantity.

Use of Leading Indicators

The necessity of having a workable set of process safety leading and lagging indicators largely garnered attention after the BP Texas City Refinery explosion in 2005. The Baker panel, led by former US Secretary James Baker III, investigated the overall safety culture and came up with several recommendations to "develop, implement, maintain, and periodically update an integrated set of leading and lagging performance indicators for process safety both for its refineries and for more general use across the refining and chemical industry" (47, p. xvii). CCPS published guidelines on "Process Safety Leading and Lagging Metrics" in December 2007. Leading metrics were defined as "a forward looking set of metrics which indicate the performance of the key work processes, operating discipline, or layers of protection that prevent incidents" and lagging metrics as "a retrospective set of metrics based on incidents that meet an established threshold of severity" (48, p. xvi). These definitions and guidelines inspired the creation of ANSI/API standard (ANSI/API RP) 754: *Process Safety Performance Indicators for the Refining and Petrochemical Industries* (49), which was published in 2010. API represented safety indicator concepts as a pyramid consisting of four tiers: Tier 1 tends to be the most lagging events (e.g., the loss of primary containment), whereas Tier 4 represents the most leading aspects of events (e.g., organizational discipline and management attention toward safety factors). The UK Health and Safety Executive (HSE) also published guidelines to develop process safety indicators (50) in 2006. The concept of dual assurance was established to correlate the safety/risk indicators with process performance and critical risk factors. To support the upstream operations, the International Association of Oil and Gas Producers (IOGP) published a report, "Process Safety: Recommended Practice on Key Performance Indicators" (51), in which guidelines were proposed based on the framework built by API RP 754, UK HSE, CCPS, and the Organization for Economic Co-operation and Development. IOGP highlighted near-miss events, as they can serve as leading and lagging indicators simultaneously and provide both retrospective and forward-looking insights.

Recent studies and experiences revealed that relying too much on lagging indicators or personal safety measures, i.e., total recordable injury rate and/or lost-time injury rate, over leading indicators or process safety parameters is in fact a very risky practice. Lagging indicator data might be useful for organizational benchmarking purposes, but it lacks the potential of revealing true process safety information and safety culture. A report on trends in risk level on the Norwegian Continental Shelf (52) divided major hazard risk indicators within the industry into two categories: precursor events (i.e., hydrocarbon leak, well kick) and barrier elements (i.e., fire detection, gas detection, fire water pump). In 2009, Hopkins (53) discussed the limitations of recommended guidelines (e.g., Baker Panel Report and UK HSE) to differentiate between leading and lagging indicators effectively and stated that process safety indicators should measure the effectiveness of the controls responsible for risk management.

Several analytical works have been undertaken to develop an integrated set of leading metrics using lagging data. Barry & Lehman (54) discussed an approach in which cumulative risks can be predicted up front using work execution and incident data. Interaction between people and the plant was identified as a critical leading element. Forest & Kessler (55) applied Six Sigma tools to find potential leading indicators and established a correlation between leading and lagging indicators. MKOPSC researchers have also conducted investigative studies to determine effective process safety metrics for improved decision-making (56).

Despite all these approaches and guidelines, there remain significant challenges and opportunities to improve the implementation of leading and lagging indicators for improving process safety performance and preventing process safety incidents. One major unexplored area in terms of a safety indicator–based approach would be offshore industries. Several offshore incidents, including Macondo, have exposed the fact that lagging and/or personal safety indicators can be very misleading in terms of high-consequence incident prevention. Wilkinson (57) reviewed all the existing guidelines and concluded that the offshore industry requires additional and careful attention beyond only production-related losses. In May 2014, Mannan et al. (58) published a paper in the *Oil and Gas Journal*, making several recommendations, including that effective use of indicators is required as a preventive measure for blowouts and other drilling incidents.

To improve process safety performance, more focus must be directed on initiating events and barrier performances for developing leading indicator–based process safety approaches. Some of the future research areas include development of uniform definitions and characteristics for leading indicators and near misses, selection of a practical set of leading indicators from limited process data, quantification of selected leading indicators, optimization of barriers based on leading indicators, and validation of developed procedures.

Risk Communication with the Public and Other Stakeholders

The World Health Organization (59, p. 326) defines risk communication as "any purposeful exchange of information about risks between interested parties." As per the United States Environmental Protection Agency (60, p. 1), "risk communication is a dialogue—an interactive process of information exchange—among the Site Team and the community that discusses the nature of risk and other concerns. This dialogue should be a genuine and sincere conversation that aims to identify mutual solutions and respond to public concerns." It is evident from both of these definitions that risk communication is an important two-way communication between the organization/agency and stakeholders. Various types of risks can be communicated to stakeholders including government agencies, statutory authorities, media persons, industry consortiums, and the public. These areas of risk may include the environment, health, and safety. The process of risk communication allows the organization to establish its credibility among its stakeholders by way of exchanging the right information, encouraging participation from interested parties, spreading risk awareness, understanding risk perception of important stakeholders, and thus developing a fruitful joint relationship (59). World Health Organization guidelines (60) examined this process in detail and referred to it as a cyclic process based on the risk management cycle schematic from Chorus & Bartram (61), with risk communication as the central engine for the whole process.

Certain federal laws and regulations in the United States have mandatory risk communication requirements. Many voluntary guidelines and standards in oil and gas also underscore risk communication activities. Some of these regulations include the Comprehensive Environmental Response, Compensation, and Liability Act; Emergency Planning and Community Right-to-Know Act; Occupational Safety and Health Act; National Environmental Policy Act; and Risk Management Program Rule.

As noted by different researchers, generating informed stakeholders is the comprehensive objective of risk communication, and different risk communication approaches have been proposed to achieve this. Two major approaches are found in the literature:

1. The seven developmental stages approach (62), which includes quantifying the right risk, sharing the numbers with stakeholders, explaining the meaning of the numbers to them,

helping them to understand that these risks are similar to the ones accepted before, showing benefits for them, treating them well, and encouraging their participation.

2. The eleven steps approach (63), which includes obtaining organizational support, determining risk communication needs, developing objectives for risk communication, forming communication teams, training team members, evaluating potential audience, evaluating media, designing the risk message, developing a schedule, communicating a plan with organizations, and forming focus groups.

These two approaches have many aspects in common and focus on the management systems methodologies. Nevertheless, it would be beneficial to learn from mistakes or experiences of others, just like we do in cases of incidents. Rowan (64) identified three major challenges of risk communication: knowledge, process, and communication skills. His work described each of these challenges in detail and established the need to overcome each of them to ensure successful risk communication.

McKechnie & Davis (1999) (65) observed that the public has become active in recent years and demands larger participation in the decision-making process. This has created challenges like providing risk information in scenarios of limited data availability, details about the process of risk assessment, various interpretations of use of science in risk communication, different perceptions about acceptable limits of risk, and availability of information to support decision-making. This has led to significant new policies designed to increase relevant public responses and reduce irrelevant ones (66). In the oil and gas industry, an effective risk communication program can help organizations to retain their shareholder value, trust and credibility, and market stake. A strategy to continually improve the risk communication system through audits can help overcome the identified deficiencies in the process and system.

PROCESS SAFETY RESEARCH

Despite a slow start, process safety research has gained a significantly strong footing. Many journals with special focus on process safety research have gained considerable popularity. In addition, mainstream chemical engineering journals, as well as journals in other engineering disciplines, have also started to publish high-impact articles relevant to process safety research and relevant fields. The following is a description of some of the process safety research areas that are receiving attention in these publications.

Abnormal Situation Management

An abnormal situation can be defined as “a disturbance or series of disturbances in a process that cause plant operations to deviate from their normal operating state” (**http://mycontrolroom.com/company/abnormal-situations-management**). Such situations may result in minor to very severe consequences. Hence, it is imperative to identify the cause and execute corrective actions in time to prevent or recover from such situations. An abnormal situation may cause a reduction in production, resulting in financial losses, or even injuries or death. Owing to advancement in process control, the ability to deal with complex systems and situations has increased drastically.

Abnormal situations can be triggered by failures in equipment, people, processes, or some combination of the three. Most occurrences can be prevented if the right technology and expertise are applied to quickly provide the appropriate plant personnel with predictive diagnostic information, thus supplying early detection, guidance, and avoidance of potentially costly problems. As Vedam et al. (67) highlighted, poor abnormal situation management or reaction to abnormal situations has contributed to losses of more than \$20 billion annually to the industry. Also, as Nimmo (68)

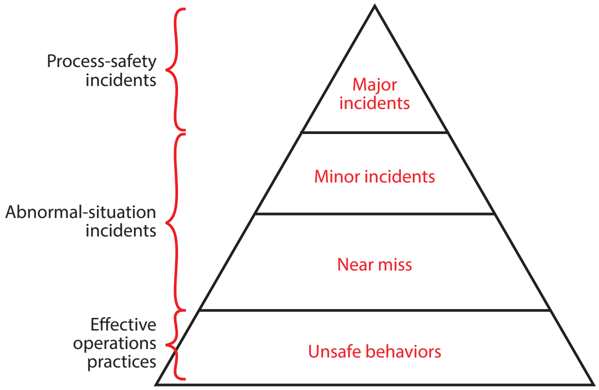

Figure 4

Illustration of the safety pyramid in process safety management (69).

mentioned, the United States–based petrochemical industry could save an estimated \$10 billion annually by detecting, diagnosing, and appropriately dealing with abnormal situations.

Abnormal situation management includes use of all resources—hardware, software, and people—to achieve safer and more efficient operations. Its focus is on operational integrity and human reliability to reduce the frequency of abnormal situations and ultimately improve process safety as well as plant performance. **Figure 4** illustrates the relationship between abnormal situation management and process safety (69). Unsafe behaviors at the bottom could lead to near misses, which could result in process safety incidents. Leading indicators, such as addressing unsafe behaviors and near misses in an appropriate and timely manner, can reduce the overall likelihood of abnormal situations.

Abnormal situation management is one area of research at MKOPSC (70–72). The main aim of this research is to establish and maintain safety of processes with automation and analysis methodologies. Effective application of these methods can reduce production losses, limit downtime, and help to attain stringent safety requirements. The central goal of abnormal situation management is to document all possible normal modes of plant operation and detect deviations from normal behavior. Fault detection and diagnosis have gained central importance in the chemical process industry over the past decade, presenting a need for fault-diagnosis systems, which use the limited process dynamics information and accurately detect, isolate, and identify faults.

Blowout Prevention

With drilling technologies hitting new frontiers and moving to more geographically challenging locations (e.g., ultradeepwater and the Arctic), advancements in blowout control and well-killing methodologies are of utmost necessity. Improvement in blowout preventer design and remotely operated vehicle control for subsea blowout preventer operations are some key research areas. Blowout phenomena and kill techniques have been studied using different simulators, e.g., the dynamic kill simulator *COMASim* (73). Engineered shape-memory alloys were used to test subsea blowout preventer control system and response times (74), and comprehensive risk assessment studies have also been performed in which managed pressure drilling was compared with conventional drilling (75) in terms of safety barriers and hazards. Gas kicks, which are precursors to blowouts, have caught significant attention, and many investigative works have been performed and are currently in progress for their successful and early detection. Some notable approaches for gas kick detection include use of wellhead sonar for acoustic gas detection (76), use of the Microflux®

control for kick detection and control in oil-based mud (77), and use of intelligent (wired) drill pipe for early kick detection (78). Current MKOPSC research efforts include developing analytical or semianalytical mathematical models of uncontrolled fluid flow based on basic physical phenomena (79) and development of leading indicator–based risk models for offshore blowouts.

Engineering Sustainability

The 1981 report "Our Common Future" by the World Commission on Environment and Development (80, p. 41) defines sustainable development as "meeting the needs of the present without compromising the ability of future generations to meet their own needs." Sustainable development deals with the three major aspects of environmental, social, and economic factors. Fenner et al. (81) suggested a sustainable development framework composed of eight key elements: an ethical foundation, justice through participation, a future vision, interlinking scales, system context, holistic financial accountability, maintenance of natural capital, and efficient provision of coordinated infrastructure.

Globally, different engineering professional organizations have recognized the significance of the role of engineering in the promotion of sustainable development. Some examples include the UK Institute of Chemical Engineers in its Melbourne Communiqué (82), the American Society of Civil Engineers (83), and the UK Royal Academy of Engineering (84). Also, many institutes and schools have recognized the contribution of engineers in sustainable development (85). Nevertheless, there is a need to promote curricula and courses related to sustainability in engineering programs (86).

Various tools and approaches are being developed to achieve the goal of sustainable development across engineering departments, regulatory bodies, industrial sectors, and society. Some of the major initiatives are design for environment (87), life cycle assessment (86, 88, 89), sustainability indicators (90), chemical safety strategies (91), exergy analysis (92), and the US Environmental Protection Agency's "Chemical Safety for Sustainability" research plan (93). IPIECA, the Global Oil and Gas Industry Association for Environmental and Social Issues, has published work on sustainable development in areas of oil-spill preparedness, fuels and products, social responsibility, biodiversity, health, and water (**http://www.ipieca.org/**; 94).

As recognized by industry and academic communities, there is a need for innovation in engineering to design sustainable products, processes, and systems. Consequently, sustainable development research has gained momentum and has been discussed at national and international forums at various levels worldwide. Further, advances have been made in laws and regulations, engineering tools/models, and technologies related to sustainability.

Facility Siting

Facility siting is the optimal placement of a chemical or petroleum processing site and arrangement of the units and equipment, taking into account long-term risks from toxic release, fire, and explosion. It gained wide attention after the BP Texas City Refinery explosion in 2005. MKOPSC initiated several studies on how to select a site, how to recognize and assess hazards and risks, and how to lay out the facilities and equipment within that site. Several research efforts have been undertaken to study the various aspects of optimal facility layout, including facility siting under toxic release conditions, considering the effect of wind speed, wind direction, and atmospheric stability via probit functions and Monte Carlo simulations (95); optimal allocation of new facilities with integration of quantitative risk analysis in the optimization formulation (96); and development of a probabilistic approach to prevent a domino effect based on optimal layouts (97). Other interesting work deals with construction of an optimal layout of gas detector networks by using computational fluid dynamics (CFD) simulations and mathematical optimization concepts. Examples include a grid-based plane facility layout optimization study and evaluating facility siting using FLACS (flame acceleration simulator), considering obstacle effects and 3D risk calculation.

Flammability and Combustion

To prevent fires and explosions in chemical industries, a comprehensive knowledge of flammability characteristics of different chemicals and chemical mixtures is needed (e.g., flammability limits, ignition energy, factors affecting burning rates). Explosions of dispersed flammables in air are by far the largest damage-causing phenomena (98). Vapor cloud explosions (VCE) have caused numerous incidents in refineries and chemical plants (e.g., Port Hudson in 1970, Buncefield in 2005). The behavior of combustible gases, vapors, and gas-air mixtures over a large range of concentrations has been investigated for varying conditions and under varying circumstances. Some contemporary works include application of the flammability diagram for evaluation of fire and explosion hazards of flammable vapors (99); evaluation of lower flammability limits of fuel–air–diluent mixtures using calculated adiabatic flame temperatures (100); and prediction of the flammability zone for a fuel, oxygen, and nitrogen mixture with adiabatic flame temperature (101).

For VCE studies, predicting the occurrence of an explosion and its impact through proper analysis of overpressures proved to be an efficient approach. The VCE overpressure prediction methodologies vary from simple empirical models to sophisticated and complex models. CFD models are also widely used for their flexibility and accuracy—FLACS is an example of such a model (102, 103). Study of the transition from deflagration to detonation in VCE is another major area of interest (104) for current research.

MKOPSC has been involved in several key research projects on flammability, electrostatics, measurements of lower and upper flammability limits of substances such as hydrogen and light hydrocarbons, modeling and estimation for flash points and flammability limits, aerosol flammability, and dust explosion. Research conducted by MKOPSC has established correlations between the operating conditions and the drop-size distributions of heat-transfer fluid aerosols and has developed predictive models to relate aerosol droplet sizes and formation distances to bulk pressures, temperatures, fluid properties, orifice sizes, and ambient conditions (105–107). Ongoing research work includes determining (upper and lower) flammability limits for pure hydrocarbon and hydrocarbon mixtures in air at standard and nonstandard conditions (e.g., temperatures, pressures, and concentrations of oxygen and water), flammability and flame propagation in aerosols of high–flash point hydrocarbons, and flammability studies of engineered nanomaterials.

MKOPSC has also carried out fundamental research in the field of dust explosions, which is classified into several categories: dust cloud formation processes, dust cloud ignition processes, flame propagation in dust clouds, and blast wave generation by burning dust clouds. Some notable works cover the effect of particle size polydispersity on the explosibility characteristics of aluminum dust (108), the correlation of the lower flammability limit for hybrid mixtures (109), and shock interaction with dust layers. Preliminary results seem encouraging, but many unresolved issues still need further investigation.

Human Factors

Human factors research has received significant attention from researchers in both academia and industry, but much more remains to be done. Some of the areas currently being addressed are discussed in brief here.

1. Design of control interfaces incorporating human factors: Owing to the level of complexity and automation in today's process plants, it is extremely important to know where to

place manual control/emergency devices while taking into account perception gaps regarding safety. Technological advancement in human-machine interfaces may present a serious drawback by affecting human capability to diagnose and act in critical scenarios, thus leading to human errors. Proper location and appropriate interfaces in the distributed control system control room are extremely important. If human-machine interface limitations are considered based on human factors research, process safety can be enhanced. These approaches have led to the optimization of processes with an appropriate alarm-management system to achieve maximum operator efficiency.

2. Human resource management in high-stress, high–cognition demand environments: This can be an area where process safety intersects with human factors in environments such as offshore and shift operations. Conditioning or institutionalizing of a person's perception can occur after large amounts of time at a facility. Under duress or stress, a person may miss important safety indicators, such as alarms, because they either voluntarily choose to overlook or simply cannot comprehend its importance owing to the stress. Either can be a major hazard and can be overcome by assessing risk and converging human factors.
3. Standardization of safety culture description and development of a framework to measure safety culture: Efforts range from development of survey tools to assess safety culture to defining attributes of best-in-class safety management systems. With regard to the latter, MKOPSC has conducted research to define and quantify the practical attributes of best-in-class safety management systems (110). The research is based on years of study on the underpinnings of a strong safety culture. The authors have identified ten attributes that are important to create a best-in-class safety culture. Instead of expecting one organization to possess all of the attributes or employ all of the techniques identified, the authors suggest that these principles be treated as guidelines that can be used to improve the safety culture in organizations.

Inherent Safety

Inherently safer processes are those that achieve hazard elimination or reduction by means that are permanent and intrinsic components of the process, which means that the process will be safer without requiring additional add-on features (e.g., alarms or safety interlocks). There are four major strategies for the design of inherently safer processes: minimization or intensification, substitution, moderation or attenuation, and simplification. Inherently safer design has been a common denominator in the lessons learned from most of the major incidents in the chemical processing industry. Because of this, it has received a lot of attention from industry and environmental groups. Regarding inherently safer design research, materials properties assessment, in particular flammability, explosivity, and reactivity, received significant attention in the first decade of the 2000s. In the past five years, focus has been given to the study of domino effects and inherently safer layouts.

Liquefied Natural Gas

Liquefied natural gas (LNG) is a mixture of methane and small amounts of ethane and trace impurities (e.g., propane, butane, and N_2), depending on the source of natural gas and specifications of the liquefaction process. Effects of LNG composition, its physical properties, and LNG boiling phenomena are different aspects of LNG safety that ultimately influence the outcome, such as pool fire, flash fire, mitigation strategy, and emergency response. The current status of LNG research in these areas is discussed here.

LNG pool formation. During a loss-of-containment event, LNG will form a liquid pool on water or land, depending on the leakage source. A vapor cloud will be formed as a result of heat transfer to the pool. To determine the consequence of a spill, the vaporization rate of LNG and vapor dispersion must be understood. The estimation of vaporization rate is known as source-term modeling as it is further used as an input to the vapor dispersion model. The composition of LNG plays a strong role in modeling of the vaporization source term. Owing to the high temperature gradient between the spilled substrate and the liquid, LNG will boil violently at the beginning stage of the spill (111, 112). Because methane has a larger relative volatility than other constituents, it will vaporize faster than other components. The resulting liquid has a lower methane concentration and higher impurities than the residual LNG; thus, the bubble point of the residual LNG will increase (112–116). The increase in the bubble point owing to the composition change will affect the temperature difference between the LNG pool and the hot surface and alter the heat-transfer rate. However, a portion of heat is required as sensible heat to warm up the LNG pool, so less heat will be used as latent heat to vaporize the LNG (112, 113). Thus, accurate source-term modeling depends on the LNG composition, the mixture thermodynamics, and the complicated interplay of various physical processes.

LNG vaporization. The LNG vaporization process is also determined by interface physics in a mesoscale. During the vaporization process, bubbles will be generated in different boiling regimes (113, 114). In an actual spill scenario, film boiling occurs first and continues in the spreading front of the pool. As the temperature of the ground decreases, the lowest heat transfer rate is reached (Leidenfrost point). Further decreases in surface temperature cause breaking of the sustained vapor film between the heated ground and boiling liquid. Therefore, the heat transfer rate increases to a maximum (critical heat flux). Subsequent cooling of the ground will decrease the heat transfer rate in the nucleate boiling regime (116–118). Most frequently, the current estimation of the vapor generation owing to LNG spill is based on the initial vaporization rate at the film boiling regime. Heat-transfer correlations are usually used, which results in inaccurate estimation of the vapor source term. Current research efforts focus on using CFD-based methods for accurate vapor-generation estimation (119, 120).

Other studies in LNG facility safety (e.g., prevention and mitigation of an accidental release) involve (*a*) enhancement of LNG vapor dispersion by using a forced convection method, such as water curtain applications; (*b*) use of high-expansion foam to control the pool fire; and (*c*) emergency response and regulatory directions. Both computer modeling and experimental approaches have been used to address the key issues in these areas.

Offshore Risk Assessment

Offshore risk assessment research has several major branches: development and use of indicators, quantitative risk assessment, study of barrier management systems, and incorporation of human and organizational factors into risk models. Several guidelines have been proposed to develop efficient leading and lagging indicators to provide early incident warning and benchmark organizational performances (e.g., API 754, OGP 456, UK HSE guidelines). Vinnem et al. (121) and Skogdalen et al. (122) analyzed offshore risk indicators based on the study of the Norwegian Risk Level project and proposed a set of leading risk indicators with performance-influencing factors. Mannan et al. (58) reviewed incident trends and current practices of developing risk indicators and recommended focusing more on organizational practices and gas kick indicators (i.e., cement failures). MKOPSC is currently analyzing the methodology of incorporating leading risk indicators into the dynamic risk assessment model for offshore blowouts. MKOPSC has also analyzed wellbore integrity in the sustained-casing-pressure (SCP) annulus (123) with a theoretical framework and model for quantitative analysis of SCP-test data.

Some recent studies on offshore risk management include leak frequency modeling (124), incident precursor modeling with dynamic failure assessment (125), and evaluation of the risk object model (OMT; risk modeling—integration of organizational, human, and technical factors) for offshore maintenance works (126). Human cognitive and perceptual capabilities and organizational roles are also being taken into consideration to ensure human-centered design. Incorporation of human and organizational factors into offshore quantitative risk analysis (127), development of a human error probability index based on the SLIM (success likelihood index methodology) approach to analyze human error in offshore operation (128), and use of a Bayesian network to analyze causal relationships on offshore safety assessment (129) are some contemporary works in the field of human and organizational safety factors. MKOPSC is also studying the methodology of integrating human factors in offshore risk assessment.

Quantitative Risk Assessment

UK HSE Research Report 151 (130, p. 2) describes risk assessment as "the process of estimating the likelihood of occurrence of specific undesirable events (the realization of identified hazards), and the severity of the harm or damage caused, together with a value judgment concerning the significance of the results. It therefore has two distinct elements: risk estimation and risk evaluation." Risk analysis is a key feature of modern decision-making, for both government and industry. As shown in **Figure 5**, the risk analysis process has three major elements: risk assessment, risk management, and risk communication (131).

Some of the global regulations that require employers to conduct risk assessments are listed here.

1. United States: US EPA Clean Air Act, Clean Water Act, US Nuclear Regulatory Commission Risk Assessment Regulations, OSHA Process Safety Management (PSM) regulations
2. United Kingdom: Control of Substances Hazardous to Health Regulations 1999, requiring employers to carry out assessments of the risks from exposure to substances hazardous to health, and Control of Major Accident Hazard Regulations 1999, requiring operators of certain major hazard sites to prepare formal safety reports (which implicitly require them to carry out detailed risk assessments) to demonstrate that all necessary measures have been taken to control the off-site risks
3. Australia: Work Health and Safety Regulation
4. Canada: Canadian Center for Occupational Health and Safety Act

Figure 5

Three elements of risk analysis (131).

Risk assessment is of three types:

1. Qualitative assessment involves quality or kind, whereas quantitative assessment is expressed in terms of a number or quantity. In risk assessment studies, a subjective analysis leading to nonnumerical results can be considered as qualitative. The common method used is the ranking or risk matrix approach (132).
2. Semi-quantitative assessment offers an intermediate level between the qualitative evaluation of risk and the mathematical evaluation of risk (quantitative risk assessment) by evaluating risks using a scoring approach. This type of assessment enables more accuracy and consistency over the qualitative risk matrix approach by escaping some of the uncertainties from qualitative risk evaluation (133).
3. Quantitative assessment is a technique used to calculate risk levels for a person, the environment, and the community and compare them with regulatory risk requirements.

Quantitative risk analysis techniques are favored when sufficient experimental and field data are available, as these provide numerical estimations for complex scenarios. Although not yet mandated by US government regulations, quantitative risk analysis is an increasingly preferred method of hazard evaluation based on numerical estimation of incident frequency and consequences. Internationally, there appears to be a gradual trend toward increasing use of quantitative risk assessment methods in the chemical process industry. The various tools and techniques available to conduct quantitative risk assessment are hazard identification (hazard and operability study, failure mode effect analysis, what-if analysis, and preliminary hazards analysis), frequency assessment (fault tree analysis, event tree analysis, Bayesian network analysis, dynamic risk analysis), and consequence assessment (software tools like PHAST and FLACS).

Reactive Chemicals

Improper handling during processing, transport, or storage of reactive chemicals can lead to a runaway reaction. In a runaway reaction, the rapid increase of the reaction rate leads to a rapid temperature increase, which is usually accompanied by evolution of gas and a pressure increase in the vessel. Proper understanding of the behavior of chemical systems under runaway conditions is needed to avoid incidents, such as those that occurred at Seveso and Bhopal. However, with the advance in technology and increase of process complexity, systems with unknown chemistry and reactivity continue to appear. This is one, but not the only, reason why reactive chemistry incidents still happen more than 30 years after Bhopal. The kinetic and thermal behavior aspects of chemical processes must be understood. To enhance this understanding and avoid potential runaway reaction incidents, experimental and theoretical research is needed in both industry and academia. Fundamental understanding of the runaway behavior of unknown systems is usually achieved by adiabatic calorimetry and other calorimetric techniques at different scales (from microscale to pilot plant). In the past decade, researchers have begun to use ab initio principles to address chemical reactivity. In their 2004 publication, Rogers et al. (134) describe the needs and applications for reactive chemicals research.

Resilient Engineered Systems

The word resilience has been defined by various researchers and used in different contexts. It has been applied to fields like biology, ecosystems, and environment. The concept of resilience in safety management is fairly new, and there exists limited literature in this field. The Center for Resilience at The Ohio State University defines resilience as the capacity of a system to survive, adapt, and grow in the face of unforeseen changes, even catastrophic incidents. With the increase in complexity of chemical plants and the increase in the difficulty of predicting potential failures, the desire to design systems resilient to potential faults has increased (135). Process resilience is the intrinsic ability of a system to adjust its functioning prior to, during, or following changes and disturbances, so that it can sustain required operations under both expected and unexpected conditions (136). In general, in the oil and gas industry, the major causes of incidents are not always technical failures. An incident occurs following various types of failures, including management, organization, and human failures.

The concept of resilience is based on a systems approach, and any analysis includes looking at all the components of the system in an integrated manner. It can be considered as a proactive approach that requires continual monitoring and interpretation of different metrics and indicators associated with the system. This method of studying any complex system includes all the details for different components and various levels, supports development of varied relations between components and studies their effects, and enables better management of a complex system. The four major aspects of implementing resilience engineering in a system (137) are anticipation, monitoring, response, and learning; following these four basic principles enables successful implementation of resilience engineering in any complex system. It is important to understand the complexities involved and develop methods to make the system survive, adapt, and organize into new configurations as needed.

Resilience research focuses on understanding the underlying relationship of modes and causes of failures and developing techniques that apply to many types of systems, structures, and products. Holt & Morari (138) categorized process resilience into two categories based on operation modes: steady state and dynamic state. SINTEF (Norway) (139) has explored a set of contribution success factors for early successful recovery of high-risk incidents based on research interviews. They also developed a resilience-based early warning indicator method, which includes a set of contributing success factors and general issues for each of the factors. In the oil and gas business, with changing technology and increasing regulatory standards, process safety and risk management have become challenging. With increasing demand and awareness, both design and operations and technology and organization must be considered in an integrated manner.

Safety Culture

In oil and gas, refining, petrochemical, and other process industries, the social aspects of humans and organizations have gained focus and have begun to be studied through the concepts of safety culture and safety climate. Researchers and industry (140) have used these terms interchangeably. According to Glendon & McKenna (141), the term culture relates to policies or behaviors that exist within an organization, whereas climate associates with certain external aspects as well. It was during the 1970s that the subject of organizational climate attracted the interest of researchers and began to be studied (142–144). Many authors made efforts to bring clarity to the use of the two terms organizational culture and climate (144, 145).

Conventionally, operations and design teams, including the risk assessors, have focused on technical issues to improve process safety performance. However, incidents like Flixborough (1974), Bhopal (1984), Piper Alpha (1988), *Columbia* (2003), and the Texas City Refinery (2005), which continued to happen globally, emphasized the role of cultural issues as contributing causes. Following the Texas City Refinery incident in 2005, the Baker Panel found serious safety culture deficiencies. Further, the official investigation after the *Columbia* disaster stated, “In the Board’s view, NASA’s organizational culture had as much to do with this accident as the External Tank foam” (146, p. 177). These incidents clearly illustrate a requirement for strong process safety culture in any organization beyond maintaining and implementing the PSM regulations and systems.

Mannan et al. (110) describe ten attributes of safety on a higher level that are helpful for prevention of loss of containment: leadership; culture and values; goals, policies, and initiatives; organization and structure; employee engagement and behaviors; resource allocation and performance management systems, standards, and processes; metrics and reporting; a continually learning organization; verification; and auditing. This ideal framework for process safety performance must be applied at different levels of organization (110).

CHALLENGES TO ADVANCING PROCESS SAFETY PERFORMANCE

A lot of progress has been made in advancing technologies and research topics that encourage process safety performance. As the incidents we have discussed show, however, much work remains in the education, research, and practice of process safety. Here we discuss some of the outstanding challenges.

Application of Risk Assessments and Land-Use Planning

Traditional risk-based process safety approaches define risk as frequency of occurrence times the consequence of the incident. Typically, historical data obtained from the site and found in centralized databases are used to calculate the frequency of occurrence, and a combination of simulation approach (e.g., PHAST, CFD models), hazard analysis, and expert judgment is used to estimate the consequence of the incident. Major limitations of such approaches include use of data that are often not specific, data that may not account for current operational changes and environment at a facility, data that do not reflect the physics of failure, and uncertainties in the approaches that cannot be justified in terms of fundamentals of operations.

An effective alternative approach is needed throughout the industry. One possible solution may be data-independent mechanistic approaches that use the reliability of the individual components or processes based on fundamental engineering principles. Characteristics of such approaches should include but are not limited to continuous monitoring of frequency changes based on the first-principle approach, real-time management of operations, and operational parameters calculated on a real-time basis. Once the operational parameters are identified, based on engineering analysis and judgment, reasonable ranges of failure can be assigned. Consequences should be based on performance parameters that reflect changes in layout, behavior of process fluids, and reliability of operations, mapped into a function (e.g., cost). Use of net-present-value analysis can provide a good estimation of cost. The distribution of net-present value can be used to reflect the risk. Reliable quantitative risk assessments should be used for design, operational decision-making, and land-use planning.

Chemical Incident Surveillance

There is a continuing need for the establishment of chemical incident surveillance systems for process safety incidents. There is presently no reliable means for evaluating the performance of industry in limiting the number and severity of accidental chemical releases. There are also limited data with which to prioritize efforts to reduce the risks associated with such releases. Without this information, there are no means to measure the effectiveness of present programs or to guide future efforts. Although individual companies keep data on their safety performance, there is as yet no herd measure of their performance. Such incident surveillance systems could also be used as a resource for trend analysis, performance measures, and lessons learned. This knowledge base could then be used to improve planning, response capability, and infrastructure.

Competency Level of Practicing Engineers

Integration of knowledge is needed for modern industrial practice. The main product of the competency element is an understanding and interpretation of knowledge that helps the organization make better decisions and increases the likelihood that individuals who are faced with an abnormal situation will take the proper action. To accomplish that, we must integrate process safety into the curricula of chemical engineering and other disciplines. This must be done in a comprehensive manner. Although sprinkling process safety elements into various courses may achieve some progress, it has been proven through experience that this approach is very difficult to implement, and even when done properly, it does not accomplish the overall objectives. Instead, a comprehensive approach that relies on making appropriate changes and revisions to different courses and then pulling all the concepts together into a stand-alone process safety course is much more promising. Finally, industry should adopt requirements to assure continuing competency in process safety for all individuals who have to work with the process, including all senior managers, line managers, operators, maintenance personnel, boards of directors, and administrative staff members.

Investments in Fundamental and Applied Research

As indicated in the preceding discussion, a significant number of intellectually challenging process safety problems can be solved only by applying the fundamentals of science and engineering. So, funding agencies and universities alike must pay closer attention to this issue and create new opportunities for advances in process safety research. Some areas that need short-term and long-term research planning and emphasis are

- Application of lean and agile tools to improve safety management and safety culture (e.g., safety stream mapping, safety gamification)
- Design of improved corrosion inhibitors (e.g., for naphthenic acid corrosion)
- Development of guided shallow gas blowout strategies
- Evaluation and management of natural disaster risks in process industry
- Human-centered design
- Inherently safer processes
- New materials (e.g., for flame retardancy)
- Noninvasive pressure measurement for process equipment
- Pipeline leak prevention, detection, and online repairing
- Smart coatings or self-healing polymers for corrosion inhibition
- Predictive models
- Reactive and energetic chemicals
- Smart use of databases

Risk-Based Regulations

Regulations themselves cannot improve process safety performance; instead, regulations should be considered as the minimum standards that can motivate improvement. However, proposed regulations should be based on science and on an understanding of risk. We need to understand whether regulations are doing what we intend them to do. This should be based on risk-based studies to determine hazards/risks. These studies should consider types of facilities, their locations, and the chemicals involved and their quantities to determine what agencies should regulate these facilities.

Once regulations are adopted, there must be strict adherence to the requirements, and there should be comprehensive procedures in place to ensure enforcement. All federal agencies with the responsibility to regulate safety/risk and associated issues should be required to conduct a primary screening to determine their regulatory landscape. Once the regulatory landscape is determined, each federal agency should develop and implement a plan and schedule for ensuring compliance through regular inspections. Inspections can yield positive results only when an adequate number of qualified, trained, and competent inspectors are available. Clearly, in these days of budget restrictions, hiring and training hundreds or thousands more inspectors is going to be a challenge at least and at worst impossible. A cost-effective and viable alternative is third-party certified audits and inspections. This approach has worked for ISO-9000 certifications and other programs. There are market-based approaches through which this regime can be implemented without placing a major burden on the regulatory authority or the regulated community.

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