What Went Right

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Learning from process industry case histories is most often centred on management system elements and equipment components (including safety devices), and the actions of personnel that led to the failure of them achieving their intended functions. Hence there can be a tendency to focus on things that went wrong. In this paper we explore the idea of focusing on things that went right – on events, resources, and concepts in which there is strong evidence of process safety success. It is concluded that learning lessons in this manner can serve as a helpful complement to the more traditional avenue of learning from process safety failure.

Keywords: case histories; lessons learned; process safety communication; process safety success

Introduction

As process safety researchers and practitioners, we often find ourselves living in a world of things that went wrong. This is not unexpected given that our primary goal is to keep hazardous materials contained so as to avoid process fires, explosions and toxic releases. One of our key tools for reducing process risk is to study case histories and learn relevant lessons that enable us to avoid having things go wrong in our own plant.

It can also be helpful, although potentially more difficult, to take a step back and consider what did not go wrong – i.e., what went right. The context for this need is provided by the following quote: *Process safety is a relatively young and evolving field largely – and unfortunately – advanced by tragic events that, ironically, underscore the importance of the field only after the fact. Even today, in light of many serious industrial incidents and the resulting losses of property and life, a disturbing school of thought exists: if nothing bad happens, it is because there are no hazards, and if there are no hazards, then there is no need to take preventive measures* (MKOPSC, 2012).

The current author had occasion to reflect on process safety successes during the final stages of preparing the sixth edition of Professor Trevor Kletz's book, *What Went Wrong? Case Histories of Process Plant Disasters and How They Could Have Been Avoided* (Kletz and Amyotte, 2019). Unlike the book title, there is no question mark in the title of the current paper. This is because the list of things described here as having gone right in process safety is a personal list consisting of events, resources and concepts that were instrumental in writing the aforementioned text (Kletz and Amyotte, 2019). The objective of this paper is to identify and celebrate these things that went right. Motivation for the paper comes from the global challenge of transforming information into knowledge, and communicating process safety success stories to those who so often find themselves dealing with things that went wrong.

Fortuitous events that have occurred in the field of process safety include the: (i) life's work of Trevor Kletz (October 23, 1922 – October 31, 2013), (ii) formation and continued funding of the US Chemical Safety Board (CSB), (iii) partnership of the Institution of Chemical Engineers (IChemE) Safety Centre and the Mary Kay O'Connor Process Safety Center (MKOPSC) in developing a vision of the future of process safety, (iv) founding of the Journal of Loss Prevention in the Process Industries in 1988, (v) acknowledgement of the importance of an information/knowledge management and communication paradigm, and (vi) promotion of a systems approach to major accident prevention.

In addition to the above occurrences, helpful and authoritative resources in the field of process safety include the: (i) IChemE Loss Prevention Bulletin, (ii) IChemE/BP Process Safety Series, (iii) safety culture books written by Professor Andrew Hopkins, (iv) books and guidelines prepared by the Center for Chemical Process Safety (CCPS), as well as the Process Safety Beacon, and (v) various symposium series established by leading organizations such as the IChemE, CCPS, MKOPSC, and European Federation of Chemical Engineering (EFCE) Working Party on Loss Prevention.

Attention is also drawn to concepts that have gained increasing prominence in recent years, including: (i) process safety applications in laboratories, pilot plants, and other manufacturing facilities, (ii) process security, (iii) domino effects, (iv) Natech (natural hazard triggering technological disasters) events, and (v) black swan events.

The current paper addresses each of the six events, five resources, and five concepts by briefly explaining their roles in process safety assurance and providing illustrative examples of what went right. The discussion in the following sections is based, in part, on the treatment in Kletz and Amyotte (2019) with relevant excerpts. The hierarchy of controls is used where appropriate to categorize successful risk reduction measures in terms of inherently safer design (ISD), passive engineered safety, active engineered safety, and procedural safety.

Process Safety Events and Successes

Key process safety events and some indicators of success are described first.

Professor Trevor Kletz (1922 – 2013)

The name *Trevor Kletz* is synonymous with process safety; his life's work led to significant advances in many of the field's most important topics: inherent safety, hazard identification, incident investigation, lessons learned, and so on. Reading anything written by Trevor – including his autobiography (Kletz, 2000) – will be a positive step on the road to success in one's process safety endeavours. He was, in the words of the late Professor Sam Mannan, *a visionary and a trailblazer, the likes of whom come in our midst only every few centuries* (Mannan, 2015).

In Kletz (2012), Trevor wrote: *I have been involved in process safety for many years and the history of the subject as I see it depends to some extent on my own history*. He is, of course, correct. Figure 1 illustrates both the reason for his appointment as ICI safety adviser in the late 1960s, and the successful results of the measures he introduced during his tenure in that role. Trevor was quick to credit others for the changes and improvements they were also making over the period shown in Figure 1 (Kletz, 2012).

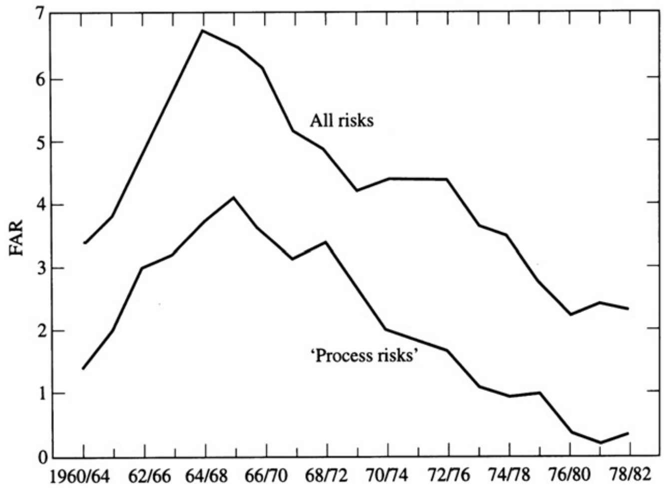

Figure 1 ICI fatal accident rate (FAR) from 1960 to 1982 (Kletz, 2012; with permission).

US Chemical Safety Board

As noted on its web site (www.csb.gov), the United States Chemical Safety and Hazard Investigation Board (Chemical Safety Board or CSB) is an independent, non-regulatory federal agency charged with investigating industrial chemical accidents. Such incidents are investigated by a team of CSB employees, and from the evidence collected, root and contributing causation factors are identified. With this information, the CSB creates sets of recommendations for various bodies such as facility managers, regulatory agencies and technical associations. Following a completed investigation, documentation is made available on the CSB web site, often with accompanying video support. CSB products are widely recognized as valuable learning tools for improving safety in the process industries. Twenty years after achieving operational status in 1998, the CSB continues to receive its budget from the US government (in spite of funding threats in the past couple of years).

CSB reports of investigation are a rich source of information on process safety shortcomings in all categories of the hierarchy of controls. Some reports also offer lessons on the proper functioning of safety devices and their potential for effective mitigation (Amyotte et al., 2018). For example, witness the performance of the blast blanket – a steel-rope mesh ballistic shield (see Figure 2) – protecting the aboveground methyl isocyanate (MIC) day storage tank at a pesticide production facility (CSB, 2011). Although fragments from a vessel that had exploded in an adjacent unit struck the blast blanket, and the shield was subjected to intense radiant heat from the fire caused by the explosion, the day tank itself was not damaged during the incident (CSB, 2011).

Similar to passive devices such as the above mentioned blast shield, properly designed and functioning active measures can work well to prevent or mitigate process incidents. For example, an explosion suppression system (see Figure 3) installed on a dust collector at an ink manufacturing facility performed as planned when a dust explosion occurred in the collector (CSB, 2015). Detection of the incipient pressure rise led to activation of the suppression system and injection of inert sodium bicarbonate, thus preventing structural failure of the dust collector (CSB, 2015).

Figure 2 MIC day tank blast shield structure at Bayer CropScience plant (CSB, 2011).

Figure 3 Dust collector at US Ink facility, with explosion suppression canister in centre foreground (CSB, 2015).

IChemE Safety Centre and Mary Kay O'Connor Process Safety Center

As noted on its web site (www.icheme.org/knowledge/safety-centre), the IChemE Safety Centre (ISC) is a not-for-profit multi-company, subscription based, industry consortium, focused on improving process safety; the ISC shares, analyzes and applies safety. In its relatively short lifetime (about six years as of 2019), the organization has made significant contributions in advancing process safety research and practice.

The Mary Kay O'Connor Process Safety Center (MKOPSC) was established in 1995 in memory of Mary Kay O'Connor, a University of Missouri-Columbia graduate in chemical engineering. She lost her life on October 23, 1989 in an explosion at the Phillips Petroleum plant in Pasadena, TX where she was an Operations Superintendent. Funding for the Center comes from an endowment in memory of Mary Kay O'Connor as well as consortium revenue and contract projects. (See the MKOPSC web site – psc.tamu.edu – for these and other details on the Center.)

Partnership between the ISC and MKOPSC in recent years has led to joint sponsoring of process safety symposia, as well as development of a vision of process safety titled *Process Safety for the 21st Century and Beyond* (MKOPSC/ISC, 2017). This document builds on an earlier vision of process safety research (MKOPSC, 2012), the development of which was co-ordinated by the MKOPSC. One of the features of MKOPSC/ISC (2017) is a description of key process safety challenges facing four broad groups: academia, regulators, industry, and society; competency was identified as a concern for all groups (explicitly for three and by implication for academia). A measure of the success possible through such visioning exercises can be found in the competency matrix given in the guidance document (ISC, 2018) subsequently published by the ISC. Partnerships between safety organizations can therefore be effective in both needs identification and solution recommendation.

Journal of Loss Prevention in the Process Industries

The Journal of Loss Prevention in the Process Industries (JLPPI) was established in 1988 by founding editor Phil Nolan and founding regional editors Stan Grossel and Toshisuke Hirano. Their vision was to create an archival, peer-reviewed journal devoted solely to loss prevention in the process industries with an emphasis on chemical and process plant safety. (In the interest of full disclosure, the current author is one of the editors of JLPPI.) The process safety research and practice communities are fortunate to also have other archival process safety journals in which to publish and from which to learn, most notably Process Safety and Environmental Protection (PSEP) and Process Safety Progress (PSP).

In accordance with the current paper's theme of process safety success, the following JLPPI references are introduced:

- Fthenakis (2001): The author describes an incident involving atmospheric release of nitrogen tetroxide and nitric acid vapours from a railcar tank in a Louisiana chemical facility. In drawing an analogy with the 1984 Bhopal tragedy, he comments on the key differences in the Louisiana incident that prevented fatalities: (i) a low population density around the plant, (ii) released material that was less toxic than MIC, and (iii) effective actions of first responders (fire department and law enforcement). Whether by design or good fortune with respect to the first two items, they do show the efficacy of the ISD principles of moderation (limitation of effects) and substitution, respectively. The third item shines a positive light on procedural safety measures.

- Nelson and Van Scyoc (2009): The authors examine risk management practices in the power generation and aerospace industries, which focus on achievement of success rather than avoidance of loss. In their words: *…people (and organizations and entire industries) who fear failure (atychiphobia) sometimes obsess about failure so much that they miss opportunities to succeed* (Nelson and Van Scyoc, 2009).

- Landucci et al. (2016): The authors offer a comprehensive treatment of the role of safety barriers in reducing the risk of domino or knock-on effects. (See section 4.3.) They describe the requirements for prevention of domino escalation factors, and how, for example, successful activation of active fire protection systems does not necessarily guarantee such prevention. Here, we are reminded of the fact that each mitigation measure in an event tree offers two possible paths – one based on failure of the device or procedure, and one based on success.

Information/Knowledge Management and Communication Paradigm

The current author has previously argued that process safety assurance has entered a paradigm of contextualizing information to facilitate knowledge management and communication. This follows on successive earlier paradigms identified by others: technical safety improvements, human error/human factor considerations, a management focus on Health, Safety and Environment (HSE), safety management systems, and safety culture (Kletz and Amyotte, 2019). This is not to say that we do not need new technical and concept-driven solutions to meet the challenges of process safety assurance. It is simply to say that we need to manage and communicate our current solutions more effectively.

While addressing the importance of maintaining an awareness of the total cost of major accidents, Gupta (2015) produced a list of 45 cost items for the Bhopal tragedy in terms of human, environmental, and economic factors. As expected, all are negative and are directly attributable to the failure of safety devices, procedures, and management systems. Perhaps only one item – a reduction in accident costs for other companies – can be viewed through the lens of partial success. Taking information on the multitude of major accident costs, embodying this information within the psyche of an organization, and communicating the knowledge so gained to all stakeholders by means of a well-managed campaign, might create opportunities for incident prevention. Of course, these actions do nothing to ease the plight of the people affected by the MIC release at Bhopal.

Further thoughts on paradigm success measures were given by Guy Colonna (Senior Director, Engineering with the National Fire Protection Association) in his banquet speech during a recent industrial explosions symposium (Colonna, 2018). He spoke of NFPA's Fire & Life Safety Ecosystem *as a way to engage in discussions with our stakeholders in order to imbed fire and life safety into their operations – whether it's a hospital, office building, hotel and conference center, shopping mall, or industrial facility* (Colonna, 2018). In addressing his audience of scientists and engineers, he further commented: *A common theme emerging from forums such as this is those of you in attendance here represent the "haves" while in many cases those most in need of the information being presented are those not here, the "have nots."* (Colonna, 2018). He then touched on the importance of sharing information on current technology and lessons learned with all stakeholders, and concluded with a quote from Winston Churchill: *Success is the ability to go from one failure to another with no loss of enthusiasm* (Colonna, 2018).

Systems Approach

The technical literature is replete with comprehensive listings and discussion of major process accidents (e.g., Mannan et al., 2012). Why these low-frequency, high-consequence incidents continue to occur with alarming regularity has also been addressed. Silva (2016) gives the following reasons: (i) new technology, (ii) loss of knowledge due to inadequate training, procedures, and information, and (iii) failure to incorporate new knowledge such as lessons learned. Amyotte et al. (2016) describe seven core concepts for their prevention: (i) the creation of paradigm-enhancing organizations (such as those described in the current paper), (ii) inherently safer design, (iii) awareness of the total cost of major accidents (per section 2.5), (iv) consideration of the broader societal and cultural aspects of major accidents, (v) process safety culture (see section 3.3), (vi) process safety competency (per section 2.3), and (vii) dynamic operational risk management.

One might reasonably question whether adequate consideration of the above technological, cultural, societal, and knowledge-based issues will be enough to assure process safety in today's complex systems. Three papers published in the AIChE Journal over the past decade offer some interesting perspectives. A relevant quote from each paper is given below:

- *Process safety is really a problem in process control – it is only a broader version of the same theme and objectives underlying control* (Venkatasubramanian, 2010).
- *Accidents occur when…process safety-imposed constraints are violated, and given that these constraints are imposed on the operational state of a chemical plant as a system, one concludes that process safety is a problem that must be addressed within the scope of an operating plant seen as a system* (Leveson and Stephanopoulos, 2013).
- *…new approaches are needed. One new path being taken is to use a system-analysis approach to safety, instead of a component reliability approach* (Davidson, 2018).

It remains to be seen how successful a control-driven, system-based approach will be in preventing major process incidents. Anecdotally, however, there does seem to be a current and renewed emphasis on avoidance of loss of <u>control</u> (in addition, to or in place of, avoidance of loss of <u>containment</u>).

Process Safety Resources and Successes

Key process safety resources and some indicators of success are now described.

Loss Prevention Bulletin

The Loss Prevention Bulletin (LPB) is published six times per year by the Institution of Chemical Engineers in the UK. It is a valuable source of actual plant case histories and technical articles on industrial hazards and best practices for process risk reduction. As such, the LPB is a key resource for a company to enhance its approach to learning process safety lessons without having to experience the hardship of a loss.

A recent LPB safety practice article poses the following question: *Hazard identification – can power engineers learn from the process industries?* (Clay, 2017). The author concludes the paper by answering in the affirmative (with important caveats): *Intelligent use of these* [process industry hazard identification] *techniques, appropriately selected and competently executed, may help power engineers to deploy exciting new power technologies safely and efficiently* (Clay, 2017). It is interesting to note the potential for success with respect to the power generation industry learning from the process industries, just as Nelson and Van Scyoc (2009) comment on similar potential for the process industries to learn from the power generation industry.

IChemE/BP Process Safety Series

The IChemE/BP process safety series is a series of short books written by BP and again published by the Institution of Chemical Engineers in the UK. They give practical advice on a wide range of topics: (i) hazards of air and oxygen, (ii) hazards of trapped pressure and vacuum, (iii) safe tank farms and (un)loading operations, (iv) hazards of nitrogen and catalyst handling, (v) hazards of water, (vi) hazards of steam, (vii) LNG fire protection and emergency response, (viii) hazardous substances in refineries, (ix) liquid hydrocarbon tank fires: prevention and response, (x) control of work, (xi) safe ups and downs for process units, (xii) safe furnace and boiler firing, (xiii) hazards of electricity and static electricity, (xiv) safe handling of light ends, (xv) hazards of oil refining distillation units, (xvi) confined space entry, and (xvii) hotel fire safety.

These examples of successful implementation of safety measures are taken from the series:

- <u>Passive:</u> In discussing the risk of contact with overhead cables, the following advice is given: *In most areas, there is no mechanical safeguard for protection of overhead electrical lines from crane booms. However, in refineries and chemical plants, it is good practice to install warning girders over roads before electrical lines or pipe-racks* (BP, 2006). This passage is followed immediately by two photographs representing failure and success. One picture shows a truck boom striking an unprotected natural gas pipeline, while the other shows warning girders in place on both sides of a pipe-rack.
- <u>Active and ISD:</u> In discussing the location of remote isolation valves, the following advice is given: *The valves should be fire-proofed and located as close as possible to the inventory (if possible inside vessel, if not welded on vessel outlet pipe, or on 1st flange after vessel). When possible, it is good practice to locate the first flange on liquid lines far away from the storage vessel, so any fire from a flange leak will not impinge on the vessel…*(BP,

2007). This passage is followed immediately by a photograph showing the location of the first flange for a spherical tank scenario in accordance with the above guidance. The following text accompanying the picture has clear ISD overtones: *Note that there is no gasket, bolted flange or manual and control valve under the vessel, therefore minimizing incidents in direct contact proximity of large inventory. The number of liquid line piping connections to the bottom of the tank is also minimized compared to the majority of spherical tanks…*(BP, 2007).

Safety Culture Books

Professor Andrew Hopkins of the Australian National University is a prolific author on the subject of safety culture. His book, *Safety, Culture and Risk. The Organisational Causes of Disasters* (Hopkins, 2005) offers an accessible introduction to the topic for scientists and engineers of virtually any discipline or background. The concepts of safety culture, collective mindfulness, and risk-awareness are presented from a practical perspective using a case-study approach with a rigorous theoretical underpinning.

The case histories in Hopkins (2005) generally deal with safety culture deficiencies – for example, the Glenbrook (Australia) train crash and the Royal Australian Air Force F111 fuel tank deseal/reseal program. Brief mention is made, however, of the success of the US nuclear aircraft fleet in developing and employing a flexible culture in which decisions during peak periods of landing and take-off are made by personnel best equipped to do so (even though they may be at the lower end of the normal chain of command). This example provides a lead-in to Hopkins' later study of HROs (high reliability organisations) and safety success in sectors such as air traffic control and the nuclear industry (Hopkins, 2009).

Center for Chemical Process Safety Publications

The Center for Chemical Process Safety or CCPS (www.aiche.org/ccps) conducts global efforts to disseminate information through avenues such as symposia and conferences (e.g., the annual Global Congress on Process Safety, in conjunction with the AIChE Safety & Health Division; see section 3.5). CCPS also produces numerous guidelines and concept books, and works to build competency through educational packages, training courses and certification. The Process Safety Beacon is one such valuable resource.

As described in Kletz and Amyotte (2019), the Beacon is a monthly one-page newsletter produced by the CCPS, which is available in the AIChE magazine Chemical Engineering Progress and through email subscription. The Beacon is intended as a resource for plant operators and other manufacturing personnel. The aim is to deliver process safety messages by presenting real-life examples, the lessons learned, and the practical measures that can be taken to prevent similar incidents from occurring.

The December 2015 issue of the Process Safety Beacon is titled *Stop! Look! Listen!* (Beacon, 2015). The theme is one of applying to process facilities the caution typically given on signage at railroad crossings that do not have gates or warning lights. The idea is to stop periodically, look around, listen to the sounds of the plant, and take action based on what you see and hear (Beacon, 2015). Four examples are given, including the following: *An engineer noticed accumulated dust as well as a dust cloud near equipment containing combustible solids. Electrical equipment and sources of electrostatic sparks presented potential ignition sources for an explosion. The equipment was stopped, the room was cleaned, and corrective actions to contain the dust were implemented* (Beacon, 2015).

One can surmise that key to success in this case would be the engineer's knowledge of the underlying chemistry and physics of the process with which they were working. This would include knowing about the fire triangle – knowing that combustible dusts can act as the fuel for an explosion, that the oxygen in air is generally readily available as an oxidant, and that even relatively low-energy electrical or electrostatic sparks can ignite many combustible dusts. It would also include knowing about the explosion pentagon (Figure 4) – knowing that mixing of a combustible dust with air can be achieved by any number of dispersion mechanisms leading to primary or secondary explosions, and that the confinement for overpressure development can come from process equipment itself, the walls of a room, or even turbulence-generating obstacles in the path of an accelerating flame.

A second example of successful intervention by plant personnel is given in the following passage: *An operator walking past a reboiler recirculation pump on a distillation column thought that the pump was making unusual noises. The pump was inspected and contained fragments of metal. These were found to be parts of tray supports from the column, a number of which had corroded and failed* (Beacon, 2015).

Perhaps in this case a key factor in the operator taking action was an aversion to normalizing deviation; odd noises from equipment were not accepted as simply the cost of doing business but were treated as an opportunity to make right something that could be wrong and about to fail. The existence of a strong reporting culture also seems plausible here. Otherwise, why would the operator bother to point out something that might well not have been a problem at all?

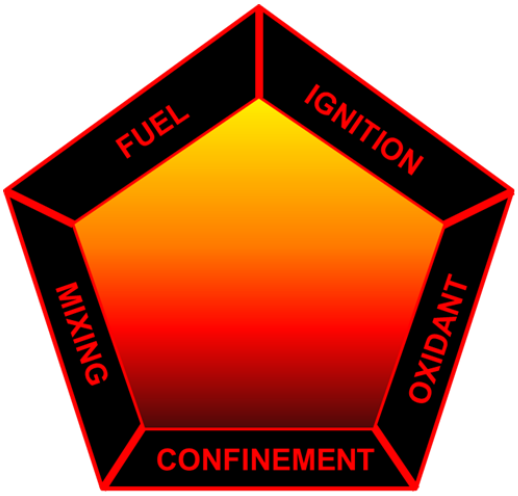

Figure 4 Explosion pentagon (Kletz and Amyotte, 2019).

Process Safety Symposia

As noted in the introduction to the current paper, there are numerous process safety conferences organized on a regular schedule throughout the world. All solicit papers on case histories. Most of these deal with process accidents in which there has been significant loss – in keeping with the theme that we learn best through failure (our own or that of others).

There are a few exceptions to the above generalization. The paper by Cheung et al. (2014), presented at the 10th Global Congress on Process Safety, presents both negative and positive examples with respect to process safety culture (per section 3.3):

- At one refinery, a Stop Work Authority (SWA) initiative was designed to empower employees to *call time-out whenever they are uncomfortable with the safety of anything that might be going on* (Cheung et al., 2014). It was found that the SWA program worked well for maintenance tasks having occupational safety impacts, but was less effective for operational issues having process safety impacts.
- At another refinery, the process safety culture greatly benefited from features such as operators routinely taking a rotation in a process safety group, new workers immediately being trained to build process safety competencies, and corporate leadership maintaining competency programs and equipment budgets.
- In a petrochemical facility, the process safety culture greatly benefited from features such as a management vision that had remained consistent from initial start-up, empowerment of workers to take lead roles in writing procedures and reporting near-misses, and an investment in strong process safety management competencies.

Process Safety Concepts and Successes

Finally, key process safety concepts and some indicators of success are described.

Other Industries and Applications

It has become increasingly clear in recent years that a process safety management mindset, system and approach can be beneficial in a variety of applications in addition to those typically found in the process industries. It is not only personnel in petrochemical plants and oil refineries who are exposed to the risk of fire, explosion, and acute health effects. Classrooms, laboratories, pilot plants, bioprocessing facilities, and electronics manufacturing plants are all vulnerable to some of the same hazards as the chemical process industries (Kletz and Amyotte, 2019).

In the aptly titled article, *Why Scary Lab Accidents Happen*, Uva (2017) describes a laboratory demonstration involving sodium metal, water, methanol, an exothermic reaction, and an explosion. No member of the student audience was harmed because the experiment had been conducted in a two-way fume hood and the protective pane on the student-side was fully closed. The instructor was less fortunate (although not severely injured) because the window on the instructor-side of the fume hood was partially open. This is a good reminder that passive barriers cannot perform their intended function if they are not in place.

The author further comments: *What probably works best is a physical environment designed to minimize accidents* (Uva, 2017). Several desirable features recently observed by the author in a university chemistry laboratory are then given. These safety measures can be seen to cover most levels in the hierarchy of controls:

- Each experiment was being conducted under a lineup of fume hoods.
- The fume hoods were separated from the student work stations by a wide walkway.

- The work stations were all behind Plexiglass shields and faced the fume hoods (allowing the students to observe their experiments while writing).
- The chemical stockroom was separated from the lab, easily accessible, and managed by someone with a good sense of housekeeping.
- The likelihood of students working alone was minimized by the common work and lab areas.

Process Security

The term safety is often used when we talk about random events, while security is used in relation to deliberate actions (Rausand, 2011). The primary distinction between safety and security is, therefore, whether there is an intentional aim of doing harm – this being the case with security (Rausand, 2011). Process security issues have existed for many decades; it is only in the past couple that they have attracted widespread public attention and received the concerted efforts of specialists (Kletz and Amyotte, 2019).

Moreno et al. (2018) have recently conducted a review of 300 global security-related incidents. Their analysis includes both physical security and cyber security issues, the latter largely associated with oil and gas (i.e., energy/power) facilities. Table 3 in Moreno et al. (2018) gives descriptions of several process security incidents in which significant loss occurred. In two cases, some measure of consequence mitigation was achieved by the prompt actions of both plant personnel and firefighters. A third example further demonstrates the necessity and potential success of an effective emergency response program and competent emergency responders. In a case of terrorism at a lower-tier Seveso-rated industrial gas plant, responders and plant staff extinguished fires, closed leaking gas bottles, and apprehended the third party. Damage, although not inconsequential, was limited to a building roof and some production equipment.

Domino Effects

The domino effect can be described as: *a sequence of accidents…in which a primary accident, usually a fire or an explosion, triggers further accidents with an overall escalation of the consequences of the event* (Li et al., 2017).

Section 2.2 detailed the successful avoidance of a domino effect involving the MIC day tank at a pesticide production facility. Figure 5 gives a post-incident view of the passive barrier (blast shield) that prevented further harm. Had the shield failed, or had missile fragments from the original explosion struck an unprotected part of the day tank, the consequences could have been disastrous. (There is much more that could be related about this incident than space permits here. Readers are referred to CSB, 2011).

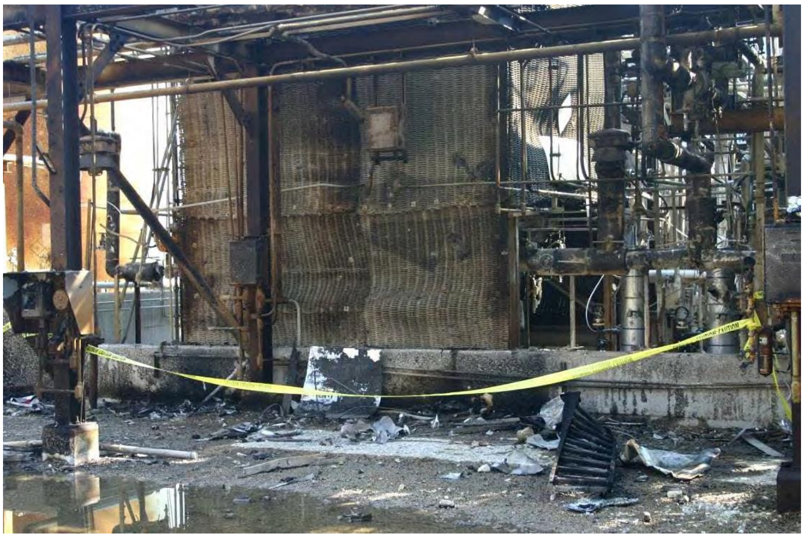

Figure 5 Post-incident view of MIC day tank blast shield at Bayer CropScience plant (CSB, 2011).

Natech Incidents

In the chemical process industries, Natech events are process incidents in which loss of containment occurs not, for example, as a result of overfilling or overpressuring a storage tank, but as a consequence of a naturally occurring and typically severe disturbance (hurricane, earthquake, tsunami, etc.). Natechs (Natural Hazard Triggering Technological Disasters) have obviously been around for decades; it is only in recent years, however, that the term has been become fairly widespread and intensive research into these events has been undertaken (Kletz and Amyotte, 2019).

In their review of the 1994 Milford Haven thunderstorm in the UK, Krausmann and Cruz (2017) describe the Natech effects on a large oil refinery. Lightning strikes initiated a series of accidents in which power loss and dips resulted in the release and ignition of flammable vapours. Although 26 nonserious injuries were suffered by on-site personnel and there was significant asset loss and business interruption, further disaster was averted because of several factors (Krausmann and Cruz, 2017):

- Action was taken to cool nearby vessels containing flammable material, thereby preventing domino escalation.
- Accident mitigation was facilitated by on-site and county firefighting teams.
- The alkylation unit next to the fluidized catalytic cracking unit or FCCU (which was the original unit involved in the accident) was unaffected. This was attributed to the design, construction, and operation of the alkylation unit to high safety standards.

Additionally, the accident occurred on a weekend when fewer employees were at work. This, of course, is sheer chance; rolling the dice and hoping for good luck is clearly no substitute for effective design and emergency response measures.

Black Swan Events

It is unfortunate that the term "black swan" (an "unknown unknown") has found its way into the vocabulary of process safety. These are events for which it is claimed there could have been no preventive action, given that they are highly improbable and therefore unpredictable. There should, however, be no surprises with respect to catastrophic occurrences in the process industries unless knowledge deficiencies exist (Kletz and Amyotte, 2019).

Such deficiencies are often rooted in a failure to recognize or pay attention to the warning signs preceding an incident. This was not the case in December 2004 when 10-year old Tilly Smith was credited with saving over 100 lives on a resort beach in Thailand. She recognized the warning signs of an impending tsunami by observing the receding sea. She then warned her parents and the hotel staff who evacuated hotel guests to a safer location (McCusker, 2008). Both the alertness of Ms. Smith, and the decisive actions of those who believed her, exemplify *what a proactive business risk mindset is about – keen awareness of individuals of the presence of risks, and the timely implementation of effective risk mitigation actions* (McCusker, 2008). There is a clear lesson here for the process industries – a lesson that is based on success, not failure.

Concluding Remarks

In a recent and comprehensive treatment of domino effects, the following introductory comments in one of the chapters are made: *Failure is often a better teacher than success. Thus, past accidents always contain a lesson to learn from them. The survey of accidents is a way to search why and how accidents occur and to determine which are the most common sequences they follow. The study of specific accidents shows what went wrong and which measures should be applied to avoid it in the future. Both approaches are helpful in improving the safety and efficiency of industrial plants and activities* (Casal and Darbra, 2013).

There can be little if any argument with the opinions expressed in the above passage. The thesis of the current paper is simply that while failure may indeed be a better teacher than success, there are still valuable lessons that can be learned from successful intervention and proactive behaviour of practitioners, researchers, regulators, and organizations. It does seem, though, that one has to look a bit deeper to find these success stories.

Dedication

The author's work on this paper is dedicated to the memory of Professor M. Sam Mannan (1954 – 2018), Executive Director of the Mary Kay O'Connor Process Safety Center, Texas A&M University.

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