The evolution of process safety standards and legislation following landmark events: what have we learnt?

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While modern process safety can be dated back to E.I. duPont in the early 1800s with the building of black powder plants including separation distances, and blast zones, the management of process safety has come a long way. Despite this however, we have continued to see many catastrophic incidents occur, across a range of industries. There has been significant learning opportunities from the catastrophes, but are we actually applying the learnings? Exploring the past 40 years history shows a number of landmark process safety events. These events have not only changed our state of knowledge for managing process safety, but have also resulted in standards and legislative change in multiple jurisdictions. This paper explores the significant learnings that came out of the various landmark process safety events and the impact these changes have had on how process safety is managed today. Incidents considered as case studies in this paper include the following:

Flixborough UK (1974), Seveso Italy (1976), Three Mile Island USA (1979), Bhopal India (1984), Piper Alpha UK (1988), Longford Australia (1998), Texas City Refinery USA (2005), Montara Australia (2009), Macondo USA (2010), and Pike River New Zealand (2010) .

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Introduction

As Mark Twain once said, "Name the greatest of all inventors. Accident". As humans, we design, manage and operate increasingly complex systems and processes. Our ability to do this safely is based on what we have learnt along the way and our failures. This paper explores some key process safety incidents that have occurred, and draws links with changes in legislative frameworks and standards as a result. This paper is not a thorough synopsis of the incidents, they can be found in various other resources, nor is it a thorough list of all the learnings and changes that came from the incidents. The author has highlighted what they believe are the key changes and developments.

Some incidents that shaped developments

The incidents reviewed in this paper include the following:

- Flixborough UK 1974;
- Seveso Italy 1976;
- Three Mile Island USA 1979;
- Bhopal India 1984;
- Piper Alpha UK 1988;
- Longford Australia 1998;
- Texas City Refinery USA 2005;
- Montara Australia 2009;
- Macondo USA 2010; and
- Pike River New Zealand 2010.

There are many more incidents that have occurred and in their own way have had an impact on how we manage process safety. For example, the Imperial Sugar Refinery explosion in Georgia, USA in 2008, highlighted the hazards of combustible dusts, however to date there has not been definitive change to how they are legislated in the USA. In fact this evolution has stalled, with the Occupational Health and Safety Administration (OSHA) yet to issue the proposed rule.

Flixborough UK 1974

The Flixborough disaster occurred more that 40 years ago, however it is still considered to be one of the most significant process safety events today, and still perhaps the worst onshore incident in the UK. The Flixborough facility was initially a fertiliser manufacturing site, however in the 1960's it was converted to manufacture an intermediate product used in the production of nylon. The process, operated by Nypro Chemicals, required the oxidisation of cyclohexane, a flammable substance, through six reactors in series, connected with metal expansion bellows. These reactors operated at elevated temperature and pressure (Turney 2014). Approximately two months prior to the incident, the fifth reactor showed cracks and needed to be taken out of service for repair. To enable the process to continue, a section of pipe was inserted where the fifth reactor would have been. Though the fittings from the reactors were 28 inch, a connecting pipe was fabricated in 20 inch pipe and installed between the two reactors. This connection was not subject to design calculations or testing prior to restarting the process. While a scaffold was used to support the pipe, it was not sufficient to withstand the forces exerted by the process. The modification continued in operation, until just prior to the incident, when the process was again shut down to repair a minor leak. On 1 June, the 20 inch temporary pipe failed during the restarting operation, releasing tonnes of boiling cyclohexane, which subsequently ignited. The explosion was estimated to be the equivalent of between 15 and 45 tonnes of TNT. The explosion killed 28 workers, and seriously injured 89 others, both onsite and offsite. The plant was destroyed as well as approximately 2000 buildings nearby.

How Flixborough changed process safety

The United Kingdom government directed a formal investigation into the incident, lead by Roger Parker ESQ, QC, published in 1975, this report, known as *The Flixborough Disaster Report of the Court of Inquiry*, details the complete investigation, as well as several recommendations, which lead the way for some of the current process safety elements we now take for granted.

Parker identified recommendations across a wide range of areas, from procedural, legislative, cultural and technical requirements.

This incident highlighted the need for structured assessment processes when making changes to equipment, what we now call Management of Change (MoC). This is perhaps the most widely known development that came from the incident. Defining requirements that change needs to be engineered, constructed and tested to the same standard as initial design. MoC is commonly accepted in industry as a required and critical system, however the author's observation is that it is often poorly executed, and is still a prominent factor in many incidents. In addition to hardware changes, organisational change management and fatigue were both factors in this incident, these learnings relate to what we now call human factors (HSE 1999).

With approximately 2000 buildings in the surrounding environs damaged or destroyed, it highlighted the need to manage where facilities are sited, with respect to sensitive populations. This need for planning was also picked up after the Seveso incident. It also lead to the wide acceptance of blast proof control buildings.

The Health and Safety at Work Act (HASAWA)1974 was promulgated shortly after this incident. While Flixborough may not have triggered the need to evolve from the old Factors Act, this incident undoubtedly influenced the requirements in the HASAWA.

The author also previously worked in a facility that was designed and constructed by ICI, as its first major development in the years following this incident. This facility had a number of inherently safer designs built in, including a blast proof control room and storage of flammable gases away from the reaction areas as well as the populated areas, to minimise the impact of domino effects. The storage areas also took into account the physical properties of the flammable gas in question being heavier than air, by being located at the lowest point in the facility, and as far away from populated areas a possible. These design principles came from the learnings of Flixborough.

Seveso Italy 1976

On 10 July, an unattended reactor at the ICMESA chemical works in Seveso, Italy, released a gaseous emission of several chemicals. These included sodium salt of trichlorophenol, sodium hydroxide, sodium glyoxides and sodium oxalate, likely propelled by hydrogen. The emissions also included 2,3,7,4- tetrachlorodibenzo - p - dioxin, a highly toxic substance. This release resulted in more than 400 locals being treated for chemical burns. Approximately three weeks after the incident, people in these areas started to be affected with chloracne, a characteristic symptom of dioxin poisoning. Some 17 sq km around the facility was contaminated (Marshall 1992).

The chemical release was the result of an exothermic reaction. The origin of the exotherm is still some cause for conjecture.

How Seveso changed process safety (European Commission 2014)

Following this incident, the European commission developed legislation focusing on prevention and control of major chemical incidents. This is known as the Seveso directive. This was the commencement of goal based legislation, requiring facilities to demonstrate how they would manage their operations safely. The Seveso directive was adopted in 1982, some six years after the incident. The directive was then amended twice in 1987 and 1988 to increase the scope to cover storage of dangerous substances in response to the Bhopal tragedy and the Sandoz fire in Basel Switzerland in 1986.

In 1996, Seveso II directive was adopted, extending the scope again. This included the addition of requirements for a safety management system, emergency planning and land use planning, as well as the requirement on member states to carry out inspections. This was particularly important to demonstrate that this form of performance based legislation is not 'self regulation' as it is often mislabelled. The regulators are required to inspect facilities and can require rectification by the operators. The scope was again extended in 2003 to include risks from storage and processing in mining and from pyrotechnic and explosive substances. This was as a result of three incidents, ranging from an ammonium nitrate explosion, a sodium cyanide leak and a fireworks factory explosion.

Seveso III was adopted in 2012, with a required date for implementation in 2015. This again expanded the scope with respect to the community right to know provisions, as well as increased standards for inspections. Technical changes included a revision of the schedule of chemicals, to bring it into line with the Globally Harmonised System (GHS) for the classification, labelling and packaging of substances and mixtures.

The Seveso directives have also been used as the basis for legislative frameworks outside of the European Union. The Australian framework for major hazard facilities is based on Seveso II and the New Zealand framework is based on the Australian legislation.

Three Mile Island USA 1979

Reactor number two at the Three Mile Island nuclear power plant (TMI-2) suffered a cooling malfunction, which lead to the release of low level radioactive gas (World Nuclear Association, 2012). In the early hours of 28 March 1979, an automatic shutdown of TMI-2 was triggered. During the shutdown, a relief valve stayed open, with the control system indicating it had received the close signal. There was no indication to show the valve had not closed. This lead to the fuel core becoming uncovered, causing the core to overheat and more than a third of the fuel to melt. Due to the type of training the operators had received, and the incorrect and inadequate instrumentation, the operators failed to identify what was occurring. The reactor itself remained intact and contained the damaged fuel, despite the significant meltdown. Public information and poor communication about the incident contributed to the public's fears.

How Three Mile Island changed process safety

The Three Mile Island incident highlighted issues around inadequate instrumentation. The operators had to interpret the operation, rather than have direct signals. For example, seeing a closed signal had been sent, and interpreting that to mean the valve had closed, rather than a signal confirming closure. Also, in their attempts to diagnose what was occurring, they were relying on pressure indication to tell them the volume in the cooling system, rather than a level gauge. The pressure was high, so they believed it was getting full, but in fact the liquid was vaporising, raising the pressure and the level was dropping. Events like this have changed the way facilities are instrumented, with a focus on direct measurement and not interpretation. At the time of the TMI-2 incident, TMI-1 was shut down for refuelling. TMI-1 was eventually restarted some six years after the TMI-2 incident. During this time it received some improvements to address the learnings from the TMI-2 incident. TMI-1 went on to be a safe and reliable reactor.

This incident also changed how we use simulators for training, the approach toward troubleshooting and the establishment of the US based Institute of Nuclear Power Operations (INPO).

Following this incident, public acceptance of nuclear energy suffered a significant drop. This contributed to a decline in nuclear construction in the USA through the 1980s and 1990s.

Bhopal India 1984

The Union Carbide India Limited facility, a 50.9% subsidiary of Union Carbide Corporation, suffered an exothermic reaction in a storage tank containing methly isocyanate (MIC) late on 2 December. At around 00:15 on 3 December, a toxic gas cloud was released from the storage tank and settled over the highly populated town. Thousands died from the exposure that morning and hundreds of thousands were affected. Thirty years on, the site is still standing, in a derelict state, but with significant soil and ground water contamination. The exothermic reaction was caused by water ingress into the MIC tank, however the exact cause of the water entering the tank has never been proven. There are four possible theories for how water entered that tank. These theories were best summarised in the Loss Prevention Bulletin 240 (Macleod, 2014). Regardless of these theories, what is known is that in the lead up to the exotherm, refrigeration had been shut off to the tank, including temperature alarms, caustic circulation had been set to manual, the vent gas scrubber had been set to standby and the flare had been disconnected. This meant that all the installed safety devices to prevent or mitigate an exotherm had been either removed or bypassed, with the exception of the relief valve. This relief valve was the path to atmosphere for the toxic cloud. This incident highlights a number of learnings, ranging from human factors to maintenance and operating standards, corporate governance and operations of joint ventures.

How Bhopal changed process safety

Bhopal is said to be the worst industrial incident the world has seen. As such, the ramifications of the incident changed how the world not only managed chemical incidents, but also how the public accepted, or not, the presence of facilities in their area. In Europe, the original Seveso directive was updated in 1987 following Bhopal, to cover storage of dangerous substances in the scope. In the USA, Bhopal was a triggering event for the development and implementation of the process safety management standard (PSM) (CSB, 2014) as well as the establishment of the US Chemical Safety Board (CSB), though it was not operational until 1998. Industry in the USA also banded together to form the Centre for Chemical Process Safety (CCPS).

Bhopal highlighted the concept of inherently safer design, with it being noted that MIC did not need to be stored on site, it could have been consumed as it was produced. This concept aligns with Kletz's (2001) quote "what you don't have, can't leak." This focus resulted in the reduction of storage for storage sake across many companies globally.

The management and operation of joint ventures was also highlighted in this incident, and it raised questions on how sites are managed and governed. It did not resolve the questions but at least has them in the open. Though Union Carbide corporation owned the majority of shares (50.9%), the remaining shares were owned by the Indian government and Indian minority share holders and the facility was operated by Indian nationals. This amounted to the export of a technology with no direct management of the facility. The exporting of technologies needs to take into account the culture and labour associated with the facilities operation. It is not clear that this occurred in the Bhopal case.

Piper Alpha UK 1988

During the evening of 6 July, an explosion occurred on the Piper Alpha oil rig in the North Sea, owned and operated by Occidental Petroleum (Atherton, Gil, 2008). The immediate cause of the incident was the release of gas, which ignited via a pump discharge line which had its relief valve removed. The open pipe was only loosely blanked providing a path for release when the pump was charged. As a result of this incident, 167 workers lost their lives. The 61 crew who survived jumped from the platform into the North Sea and were rescued by boat. While a significant systemic failure in this incident was due to the permit to work system and inadequate handover communication, there were several other factors which played a part in the escalation of the incident. The platform was originally designed to handle oil, so it was constructed with fire walls, not blast walls, which would have been needed for gas handling. Changes meant that at the time of the incident, the platform handled gas from itself and two other interconnected rigs. The fire walls were quickly destroyed by the initial explosion that occurred (Kletz, 2001). The rig design had not been appropriately risk assessed to determine the need for the blast walls. In addition to this, the workers were not clear on how to evacuate from the rig in an instance like this one. They waited in the accommodation deck to be rescued by helicopter, however no helicopters were able to land with the smoke and fire. The interconnected rigs unable to reach Piper Alpha via radio or onshore management, continued to pump gas to the rig and effectively added the fuel to the fire.

How Piper Alpha changed process safety

Piper Alpha was as significant to the offshore oil and gas industry as Flixborough was to the chemical industry (Kletz, 2001). This incident resulted in safety case legislation not only in the UK offshore industry but also across the world. For example, a number of regimes have safety case type legislation for this industry, including Australia, New Zealand and Brunei. The CSB in the USA has recommended this type of legislation as well, though to date no changes have been adopted. In addition to the legislative framework which emerged from the incident, a number of accepted practices and standards have evolved. Permit to work systems have become more thorough and shift communications have been a constant focus on facilities, both on shore and off. Temporarily inhibiting safety systems such as fire pumps has become more structured. In fact, some insurance companies require the insured to notify them each time a fire system is inhibited and then brought back online. It is now standard practice to do complete risk assessments on new facility design as well as periodic reviews to ensure the facility remains fit for purpose. Much has been written and studied about this incident. The learnings from it shaped the way offshore operations are conducted in various locations across the world.

Longford Australia 1998 (Dawson, 1999)

On 25 September, an explosion and fire took place at the Esso Longford facility, in gas plant one (GP1). This incident resulted in the death of two workers and injuries to eight others. The State of Victoria was also without natural gas supply to consumers and businesses for approximately two weeks following the incident (essential services were supplied).

Hot lean oil was used in a heat exchanger to warm the rich oil. The lean oil pumps had stopped, resulting in the lean oil flow ceasing to the exchanger. This lack of 'warming' caused the temperature in the exchanger to reduce to -48^{o}C, as opposed to the normal operating temperature of 100^{o}C. After several hours, the lean oil pumps were restarted. This commencement of flow resulted in thermal stress on the vessel and it suffered cold brittle fracture. The release of vapour following the fracture then ignited. GP1 was the oldest of the three plants and started operation in 1969. The Parliament of Victoria established a Royal Commission in to the incident, Esso was subsequently prosecuted in the Supreme Court and convicted on 11 counts for various breaches of the Occupational Health and Safety Act 1985. The causes of the Longford incident started well before the fateful day in September 1998. As stated above, GP1 was first operated in 1969. Over the life of the facility, changes had been made, for example, part of GP1 had a distributed control system (DCS) installed to supplement the paper chart recorders and alarm panels in the control room. During the incident, the control room suffered what is known as an 'alarm flood'. This is a situation when the number of alarms registered on the systems is too great for the operator to acknowledge and respond to. It was also noted in the Royal Commission that the training was inadequate as it did not cover the hazard of cold brittle fracture of the equipment should the warm oil flow be lost. In addition to this, an organisational change in the early 1990s had resulted in process engineering support being relocated to the Melbourne office, some two and a half hours drive or a flight away. The engineers were available via phone but were not onsite monitoring the operation and providing advice on a day to day basis. They did not have access to trend data due to the lack of transmitting devices installed at the facility.

How Longford changed process safety

The Longford incident had a profound impact on the legislative regime in Victoria. In 1996, the Federal Government in Australia had issued a *National standard for the control of major hazard facilities*. This standard was based on the Seveso II directive. Under Australian law, these standards are not compulsory as the states have jurisdiction for health and safety law. The legislative framework in Victoria at the time of the incident was found to be inadequate. A series of recommendations were made by Dawson (1999) with respect to the development of a unit in the regulator to focus on major hazard facilities as well as the adoption of the safety case regime as defined in the national standard. Prior to the incident, no state in Australia had referenced or implemented this standard. Following the Longford explosion in 1998, Victoria was the first state to implement a regulation based on this standard. This regulation was introduced into law on 1 July 2000. The development and implementation of a law only 20 months after the incident was extremely quick, demonstrating the public and political pressure that resulted from the incident. Thus, the Longford incident changed the face of major hazard regulation in Australia.

Texas City Refinery USA 2005

On 23 March, 2005, during the start up of the isomerisation unit after a maintenance shutdown, the raffinate splitter tower was overfilled, resulting in high pressure causing the relief valves to open. The flow from the relief valves flowed to a blow down drum. The drum was not designed to handle liquid flow and released heated raffinate out the top of the blow down drum stack. This highly flammable product found an ignition source in the form of a running diesel vehicle with the resulting explosion causing 15 fatalities and 180 injuries (CSB, 2007). The 15 people killed were housed in a temporary trailer office adjacent to the isomerisation unit. Several contributing factors were identified, many of which are common to most incidents such as significant budget cuts to both capital and expense funds resulting in lack of equipment upgrades and reduced staffing. Shift handover was lacking, procedures were routinely not followed, the safety focus was on personal safety and not process safety, training was inadequate as well as poor process displays on control boards and safety systems were not functioning.

How Texas City Refinery changed process safety

While this incident did not result in the change of US legislation regarding process safety, it did result in industry standards changing significantly. Occupied buildings were a significant focus for a range of industries across the world. This incident raised the challenges of managing process safety and not being able to rely on personal safety management and performance indicators. New standards were developed to define how to establish appropriate key performance indicators relating to process safety, namely the American Petroleum Institute Recommended Practice 754 (API RP 754), *Process safety performance indicators for the refining and petrochemical industries*. This recommended practice has been adopted across many countries and industries. Interestingly it has also been widely adopted by the offshore oil and gas industry, even though it states in the scope that it is limited to refining and petrochemical industries. In addition to API RP 754, the Health and Safety Executive (HSE) in the UK as well as the CCPS have released guidance to assist organisation in establishing leading process safety metrics. Ten years on from this incident, leading process safety metrics is still a significant work area for most organisations.

Another significant impact that resulted from learnings out of this incident is the siting of offices and personnel in process plants. Methods for determining the location of buildings and managing the occupancy has also been published by the American Petroleum Institute as

Recommended Practice 753 (API RP 753). This guidance has been adopted by many facilities across the world and the author has personal knowledge of sites that depopulated or had structures reinforced or relocated. There has been many impacts on how process safety is managed following this incident. However the author considers these to be the most notable that have resulted in widespread action globally.

Montara Australia 2009

In the early hours of 21 August, the Montara Wellhead Platform owned and operated by PTTEP Australasia located in the Timor Sea, suffered a well kick, which released oil and gas. This release continued for over 10 weeks. No personnel were injured in the release and subsequent fire. The direct root cause of the incident was determined to most likely be the failure of the casing shoe (Borthwick, 2010). The installation also lacked sufficient barriers against blowout. The Northern Territory Department of Resources was the delegated authority and therefore the regulatory body responsible for regulation of the operation. It was found to have approved the drilling program in July 2009 even though it did not meet accepted industry practice.

How Montara changed process safety

In 2005 the National Offshore Petroleum Safety Authority (NOPSA) was established. At this time, offshore safety regulation was performed by the state and territory governments. However when NOPSA was established, it did not have responsibility for well integrity; this rested with the designated authority of the state or territory regulator. Borthwick (2010) suggested that the resourcing capacity of the Northern Territory government was insufficient to have provided adequate regulatory oversight and compliance. This resulted in the recommendation for a single regulatory body for offshore operations including safety and later environmental matters. Eight months after the Montara blow out, the Macondo incident occurred in the Gulf of Mexico. This incident though not impacting Australia directly, influenced the ongoing development of the new national regulator. The National Offshore Petroleum Safety and Environmental Management Authority (NOPSEMA) was established in January 2012 as a result. Therefore, the Montara incident shaped the face of regulation for offshore oil and gas operations in Australian waters.

Macondo USA 2010

On 20 April, 11 workers were killed when an explosion occurred aboard the deepwater horizon drilling rig in the Gulf of Mexico. The rig was undertaking temporary well abandonment when a blow out occurred. The escaping liquid and gas hydrocarbon ignited. The hydrocarbon continued to flow for some five months, resulting in one of the worst environmental incidents in US history (CSB 2014). This was a classic process safety related incident in that multiple layers of protection failed.

At the time of the incident, the activities were regulated by the Minerals Management Service (MMS) though just prior to the incident, the decision had been made to split MMS into three entities.

How Macondo changed process safety

As a result of the incident on 28 May 2010, a six month moratorium on deep water drilling of the US outer continental shelf was issued (US DoI, 2010), based on deepwater drilling posing 'an unacceptable threat of serious and irreparable harm or damage to wildlife and the marine, coastal and human environment'. As foreshadowed above, a new regulator was formed after the incident to oversee offshore exploration, the Bureau of Safety and Environmental Enforcement (BSEE). This was seen to be more focused on enforcement of legislation.

The CSB have released volumes one and two of the investigation, however volumes three and four are still outstanding. Almost five years on, there is still much debate regarding the most appropriate legislative framework in the US offshore industry. There may still be more standard and legislative change to come from this incident in future years particularly with respect to deepwater drilling activities. The CSB has released recommendations to implement a safety case based regime for off shore oil and gas exploration and production in US waters. This has not eventuated as recommended, however the regulation through BSEE has taken on some goal based elements in a hybrid manner.

Pike River New Zealand 2010

An underground mine explosion occurred on 19 November at the Pike River coal mine (Royal Commission on the Pike River Coal Mine Tragedy, 2012). At the time of the explosion, 31 people were in the mine. Two managed to escape with the remaining 29 trapped. While emergency services initiated rescue efforts, on 24 November a second explosion rocked the mine. At this stage the 29 trapped workers were presumed dead. At the time of writing, their bodies have still not been recovered. The immediate cause of the explosion was the accumulation of methane in the mine which somehow ignited, though the ignition source was not identified. There were multiple underlying causes of this tragedy. The ventilation system was poorly designed with risk not taken into account and it was not even functioning as designed. Routine methane recordings were being taken in the mine but no action was taken to address the dangerously high levels. Financial pressures resulted in some methane detectors being disabled or bypassed to prevent them interrupting production. The method of mining had changed resulting in the liberation of more methane during operations. The investigation of this incident not only found liability with mining company and its board of directors, but also with the inadequacy of the regulator and the regulatory framework in New Zealand.

How Pike River changed process safety

This incident lead to the establishment of a Royal Commission. While the Royal Commission focused on the mine tragedy and therefore the legislation governing underground mining; the incident triggered the change for the entire framework for all industry in New Zealand. The New Zealand government in adopting the Australian model work health and safety act and regulations. This model act and regulations define a safety case, goal setting regime. This initial Australian regulation concerning major hazard facilities was based on the Seveso II directive.

Conclusion

As has been demonstrated, there have been many and varied changes to legislation, standards and industry practice as a result of major incidents that have occurred. The impacts have been wide, ranging across industries and beyond countries. We have seen new regulators established, new legislation enacted, industry standards developed, and the evolution of safety management systems. Individually and collectively these changes have undoubtedly made a difference in the incidents occurring, but not enough. For all of this development however, we still see major incidents occurring as shown with the recent incidents references. While the concepts behind process safety continue to evolve, we must continue to work on learning the lessons and putting the developments into practice. If we do not do this, we are destined to continue to repeat the lessons of the past. The challenge for generations to come is to remember these incidents and the lessons we have learnt so that we do not take retrograde steps in how we manage safety. By linking these incidents to the changes they have generated, it helps to give context to our current operating environments.

Lastly, it is important that we all take heed of the learnings, regardless of the jurisdiction where they occur. we should all strive to learn from the incidents, so we can prevent similar events in our own jurisdiction.

If accident is indeed the name of all inventors, these incidents show how the inventions can be for the benefit of safety, following the accidents.

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