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## Guidance to improve the effectiveness of process safety management systems in operating facilities

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### ABSTRACT

The Process Safety Management (PSM) systems at the operating facilities in the Oil & Gas and in Chemical manufacturing industries have matured over the years and have become, at most facilities, very robust and sophisticated. These programs are administrated by Process Safety (PS) teams at both the corporate business units and plant levels and have been effective in reducing the number and severity of PS events across the industries over the past 25 years or so. Incidents however are occurring at a regular interval and in recent times several noteworthy PS events have occurred in the United States which have brought into question the effectiveness of the PSM programs at play. These facilities have been applying their PSM programs with the expectation that the number and severity of PS events would decrease over time. The expected result has not been realized, especially in context to those facilities that have undergone the recent incidents. Current paper reviews a few publicly available PS performance reports of Oil & Gas and Chemical manufacturing industries. The authors identified a few factors at play that have led to these PS events based on their experience, literature review, and incident investigation reports. Most of the factors are intertwined with multiple PSM elements and it requires a holistic approach to address them. Each of the factors is described and the path forward is proposed to improve the effectiveness of PSM programs.

### 1. Introduction

Process safety (PS) performance indicators published over the years have shown a substantial decrease in incidents in all Oil & Gas and Chemical manufacturing industries due to the implementation of process safety management (PSM) programs (American Chemistry Council: Responsible Care, 2020a; American Chemistry Council: Responsible Care, 2020b; International Association of Oil and Gas Producers (IOGP), 2019; Marsh, 2019; Marsh et al. (2018)). The O&G and Chemical manufacturing facilities/industries, hereby will be referred to as operating facilities or industries, have invested a great deal in the development and implementation of programs and the training of staff to reduce both the number and severity of incidents occurring in their facilities. These programs have largely been effective in improving PS performance. However, the industries seem to hit a plateau in reducing the number of major incidents. The industries are experiencing fewer significant incidents but those that are occurring are resulting in greater negative impact with negative effects on reputation and public trust.

Despite the improvements in overall PS performance, several

incidents since 2014 were made visible through live media coverage and a few lasted for several days with negative impact not only on the image of the companies involved but also on the industries in general. These incidents undermine the public's trust in industries as good corporate citizens but more importantly bring into question why the PSM programs at play at these facilities are not preventing these incidents from occurring. Under such circumstances, the critical questions to ask are, how successful the established PS programs have been, what are the limits of the current approaches, how can the PSM programs be further improved. The current work reviews the recent incident trends in the industries in the US to provide a clear understanding of the PS performance. It then identifies the factors at play behind the incidents and proposes path forward to overcome these factors and improve the effectiveness of PSM programs.

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## 2. Recent trends

### 2.1. Trends according to marsh

Marsh's 'The 100 Largest Losses 1978–2017' provides a list of the 100 largest property damages that have occurred over the time globally due to incidents in the petrochemical industry, refineries, gas processing, terminals and distribution and upstream industries, as shown in Fig. 1a (Marsh et al., 2018). These values have been normalized to 2018 dollars with \$136 million dollars being the lowest damage and \$1518 million dollars being the highest. It is apparent from the figure that there has been an increase in the number of high-value losses in the recent years. Values for the US are different, compared to the global perspective. Fig. 1b shows the 26 incidents in the US that were included in the 100 largest losses of property from 1978 to 2017. These are also the most expensive incidents, in terms of property damage, that happened in the US over this period of time. As the figure shows, no incidents have made it to the list after 2008 suggesting there has not been any PS incident greater than 136 million dollars in the US.

An interesting perspective is provided by Marsh's Global Market Index report (Marsh, 2019). The report indicates that in the US there was more than 6% increase in insurance premiums in the third quarter International Association of, 2019, driven by an increase in property values and mostly by increase in premiums for financial and professional liability coverage. The double-digit rise in property pricing for both catastrophic and non-catastrophic exposure was felt by more than two-thirds of property owners. Financial and professional liability costs saw an increase due to increased litigation with event-driven lawsuits expanding to areas such as cyber breaches, social media, and safety (Marsh, 2019). Amongst this, the increase in the financial liability has a greater impact on the overall 6% increase than the property premiums. This can indicate that company reputation or the public perception of the risk imposed by a particular company on their community may have a large influence on the overall risk, and hence on the insurance pricing. With current day communication technologies and influence of social media, this may be another influence that an incident may have on a company.

### 2.2. Trends according to IOGP

The International Association of Oil and Gas Producers (IOGP) is an industry body representing upstream industry with its 85 members globally. According to the (IOGP), the PS event per million work hours among its members companies has decreased over the years, however in recent years, the situation reached a stagnant condition whereby the rate is not decreasing at the same pace as it was doing before (Fig. 2) (International Association of Oil and Gas Producers (IOGP), 2019). The IOGP data indicates that Tier 1 event (following API RP 754) in the offshore and onshore oil and gas industries seem to hit a plateau whereas Tier 2 (following API RP 754) events has been reducing gradually.

### 2.3. Trends in ACC member companies

There are more than 250 companies that are members of the American Chemistry Council (ACC), all of which participate in the Responsible Care which is chemical manufacturing industry's performance initiatives on environment, health, safety and security. ACC reports to have reduced the number of PS incidents significantly by 48% since 2000 (American Chemistry Council: Responsible Care, 2020a). However, the rate of decrease is not apparent in recent times (2008–2018), as shown in Fig. 3a. It should be mentioned that the definition of what was considered as PS events was changed over the time period considered by ACC. There were a total of 254 Tier 1 (following API RP 754) incidents occurred among these companies participating in the Responsible Care program in 2018 (American Chemistry Council: Responsible Care, 2020b). As reported by the ACC, 92% of these incidents were categorized as "low severity" (Fig. 3b). This indicates that for these companies, a significant number of incidents keep occurring, although they have been mostly of low severity.

### 2.4. Ends according to OSHA

The Occupational Safety and Health Administration (OSHA) database indicates the number of incidents that have been reported through OSHA Form 170 whereby OSHA conducts an inspection in response to a fatality or catastrophe (involving 3 or more hospitalizations) because of work-related incident or exposure. According to OSHA database, the

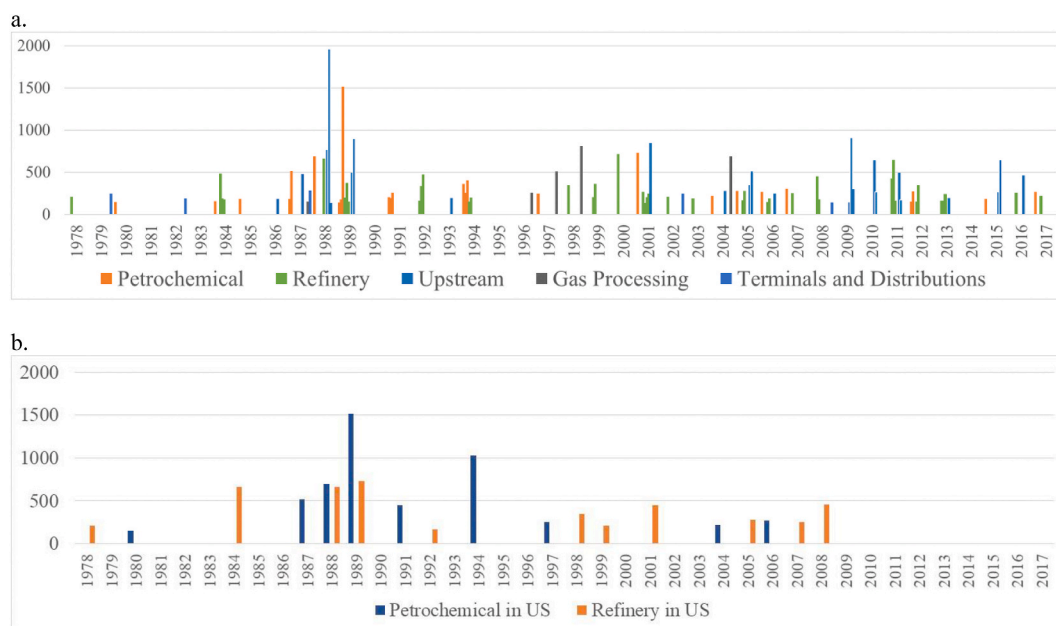
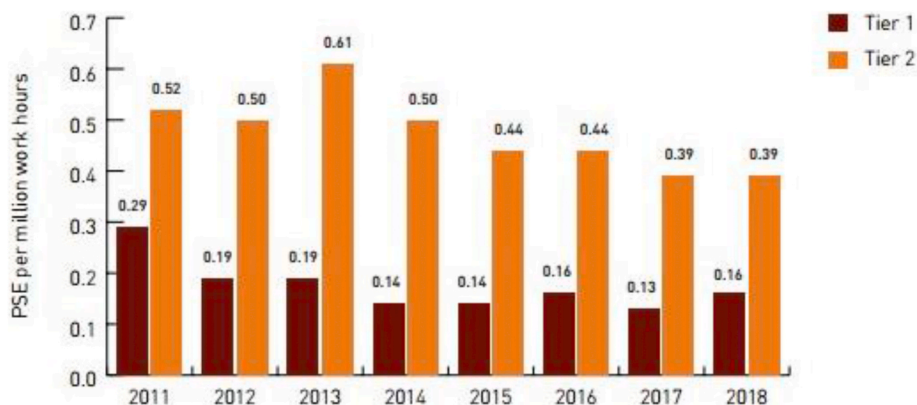
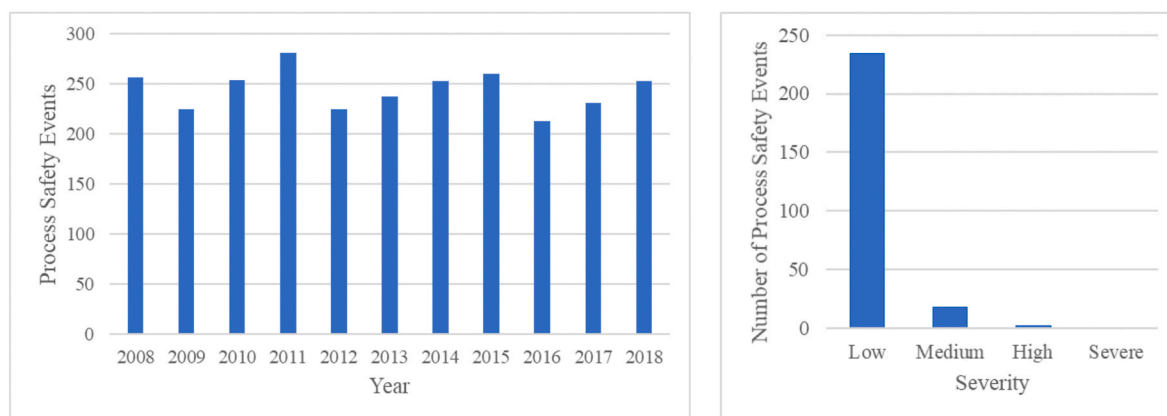


Fig. 1. a. 100 Largest Losses according to Marsh from 1978 to 2017. b. Of the 100 largest property damage according to Marsh from 1978 to 2017, the damages in the US are shown in the Petrochemical and Refinery industries. Post 2008, incidents in the US has not made it to the largest losses list in Marsh et al., 2018.

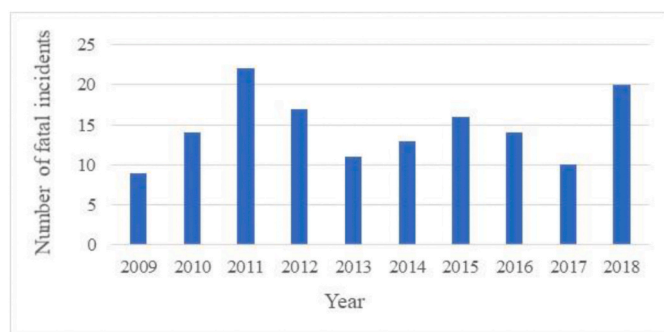


**Fig. 2.** PS events per million work hours among IOGP member companies, showing Tier 1 and Tier 2 data. Data post 2013 carry greater confidence and show that number of Tier 1 incidents per million workhours show unchanging variation, though Tier 2 incidents indicate a slight decrease (International Association of Oil and Gas Producers (IOGP), 2019).



**Fig. 3.** a. Figure showing the number of process safety incidents that have occurred in ACC member companies over the last decade. Although the definition of what constitutes a PSE has been changed starting 2017 to reflect that of API RP 754 definitions, the variation due to the change of definition is expected to be low (American Chemistry Council: Responsible Care, 2020a). b. Data shows the number of PS events in ACC member companies according to their severity in 2018. The severity is measured as defined in API RP 754. 92% of ACC member companies' Tier 1 events have a severity score in the low category. Figures adapted from (American Chemistry Council: Responsible Care, 2020b).

overall catastrophic and fatal incident count, pertaining specifically to the chemical manufacturing industry in the US (NAICS 325 subsector) has not changed in recent years as shown in Fig. 4. Due to the reporting criteria, PS incidents are not reported separately from the occupational incidents. Since the objective of the study is not a quantitative analysis of the incident data, efforts are not given to isolate the PS incident from occupational incidents. With the assumption that PS events stays the same fraction of the total incidents, it is fair to say the number PS



**Fig. 4.** Figure showing trend of fatal and catastrophic incidents over a 10-year period in the chemical manufacturing industry (NAICS code beginning with 325).

incidents has not reduced significantly in recent time.

### 2.5. Recent notable incidents in Texas

Recently, a number of major chemical disasters in Texas have made it to the headlines of several news media at national and state levels, leading to a growing public concern and a subsequent pressure on the reputation of the industries in general within this area. Fig. 5 shows a collection of incident reports obtained from various news media over the years (Kannan et al., 2016). The overall number of incidents have varied over the years, but the coverage garnered by several incidents in 2019 alone has been overwhelming. As advised by Kannan et al., the number incidents reported in the news should not be used as indicator or trend, however, they suggest the growing safety concern incumbent on the neighboring community among the society (Kannan et al., 2016).

Fig. 6 shows some of these major incidents and the impact they have had in 2019 and the beginning of 2020 (Banks, 2020; Chemical Safety and Hazard Investigation Board (CSB), 2019a; Chemical Safety and Hazard Investigation Board (CSB), 2019c; Dempsey et al., 2019; Scherer and Foxhall, 2019; Toal et al., 2019). Many of these incidents resulted in fatalities and injuries, and large fires, some with explosions or long plume hovering over the city of Houston. In two cases, the emergency response was extended for several days (Chemical Safety and Hazard Investigation Board (CSB), 2019c; Toal et al., 2019). As one incident

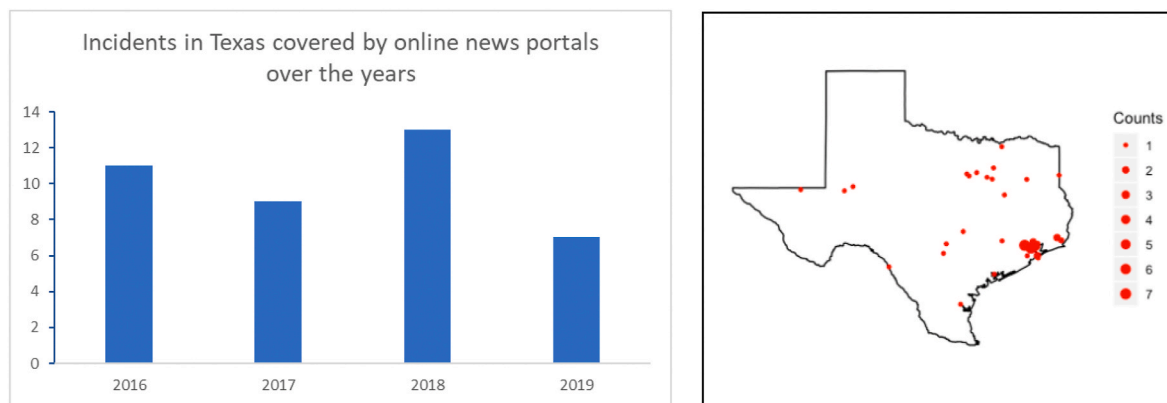


Fig. 5. Figures showing numbers of chemical and petrochemical incidents in Texas that made to the news headlines over 2016–2019 and their locations (based on the data collected by MKOPSC from various news media).



Fig. 6. Timeline of incidents in Texas that have been covered extensively by new media in 2019- early 2020 (Banks, 2020; Chemical Safety and Hazard Investigation Board (CSB), 2019a; Chemical Safety and Hazard Investigation Board (CSB), 2019c; Dempsey et al., 2019; Scherer and Foxhall, 2019; Toal et al., 2019).

made it to the news, the next incident had probably raised more questions and concerns both among regulatory authorities as well as the public. Although some of the incidents (such as fire at ITC, explosion at Watson Grinding) are not part of the Oil & Gas and Chemical manufacturing industries, they involved hazardous substances. Nonetheless, such fire and explosion incidents put negative impacts on the industries.

In summary, it is not the objective to conclude any trend based on the presented data as they seem incomplete. However, there are a few facts that can be extracted:

- No incident occurred in the US of magnitude \$137 million or more in asset damage since 2008 (Marsh et al., 2018).
- Tier 1 incidents (as defined by API PR 754) reported by IOGP have not been reduced significantly in the last decade.
- PS incident (definition changed, recently adopted API RP 754) has been reduced by 48% since 2000 according to ACC (American Chemistry Council: Responsible Care, 2020a). However, in recent years, it became plateaued.

- Fatal and catastrophic incidents (as defined by OSHA) have not been reduced significantly in the last decade.
- Although the presented data involves PS events occurring in different timelines, it essentially conveys one single message that the high consequence events (defined and reported differently such large asset damage, Tier 1 incidents, or fatal and catastrophic incidents) have remained significantly unchanged in recent years.

These PS performance data, however, do not tell us why some of these incidents report so much in the news media and hence public attention in the recent time. It is important to note that severity can also be expressed in terms other than property loss or fatality or Tier 1 incident, such as reputation, financial loss, cost of litigation. As indicated by Marsh's market index, the normalized cost of incidents to current account has consistently increased for many years (Marsh, 2019). Coverage by news media can have a greater impact on such severity of the incident and corresponding cost arising from them can become considerable. It should also be considered that the public expectation or acceptable risk as perceived by public may have changed over the last twenty or so years.

So, these incidents bring into questions whether or nor industry is doing the right thing? What are the precursors to prevent the PS incidents? Is there any limitation to the PSM program or effective PS program implementation? Where should the resources be spent? What are the factors at play? How can we the overall situation be improved?

### 3. Framing an approach to improvement

The questions that need to be asked and answered in a very practical manner are:

- *What are the factors at play behind the current major incidents although the incident rate and severity seem to have hit a plateau over the past several years?*
- *What are the measures that might have an impact on improving the effectiveness of process safety programs at operating facilities and hence result in reducing the incident rate and severity?*

When addressing the issues at hand, one needs to recognize that to do things differently one has to modify circumstances so that the staff at the operating plants and in corporate support groups see things differently to start the improvement process. One cannot resolve issues and problems with the same thought process and approach that created them. While more training is vital, it is only a part of the solution. The solution is to create a paradigm shift to “*look through the eyes of risk*” in all that one does. This means to adopt a risk paradigm in all activities and programs which is currently absent in several areas of operation in industry.

In identifying the factors that are at play and deciding upon the programs as potential solution, the lead author relied upon his life-long experience in the industry and exposure to current industry conditions. The identified factors were then refined and supported by findings from incident investigation reports and extensive literature review. Both factors at play and recommended next steps were presented to the largest state-wide industry body represented by 70 leading chemical companies. Feedback was received from the experts of the PS subcommittee of the industry body and incorporated in the current paper.

Several factors at play are identified, when attempting to rationalize what are the precursors to the recent incident trends discussed above. Each factor is discussed in detail in Section 4.0 and recommendations for implementing solutions to improve the effectiveness of PSM programs at operating plants are proposed and discussed in section 5.0.

## 4. Factors at play

### 4.1. Critical technical decisions taken at inappropriate management level

Critical technical decisions are often left to plant or operations management and are in many cases taken without the benefit of a thorough risk assessment as an important input to those responsible for taking the critical decision (Behie et al., 2017). CSB investigation report on Chevron refinery fire in 2012 recommended to develop an auditable process that will provide the submitter of critical decision to seek further review by his or her manager, who can further elevate and discuss the recommendation with higher level management (Chemical Safety and Hazard Investigation Board (CSB), 2015b). The document includes the ultimate determination of approval, deferral, or rejection, justification determination, and the person or team responsible for that decision. Similar recommendation were observed in other CSB investigation reports on Tesoro Refinery fire (2010) and BP Texas City incident (2005) emphasizing that PS is not effectively incorporated into management decision-making at all levels (Chemical Safety and Hazard Investigation Board (CSB), 2007; Chemical Safety and Hazard Investigation Board (CSB), 2014b). To be effective and serve the best interests of the organizations, the risk assessment process must be embedded at all levels of the company. A rigorous risk assessment process may not avoid all

incidents but rather it certainly will improve the chances of avoiding inappropriate decisions with disastrous outcomes.

A risk assessment process postulates and analyzes a few event scenarios for the possible outcomes of each decision option. The assessment must be led by a senior risk engineer familiar with the operating facility in question and include plant management representatives, operators, operational management representatives and safety professionals. Each of the consequence in each decision scenario is assigned as is the probability of occurrence based on the company's risk matrix and circumstances that exist at the time. In the absence of a company wide risk matrix, a fuzzy risk matrix can be very useful for making complex risk decisions (Hong et al., 2020). The decision that is finally taken must be taken based on the risk level determined. The higher the level of estimated risk of the proposed decision, the higher in the organization management must take the responsibility for the decision. From Fig. 7 below, a decision that places the organization at substantial risk (risk level D and E in the example matrix below) the more senior the management position required to take and sign for the decision. The manager who signs off approval for the decision holds the clear responsibility for the decision. Following this approach, senior and executive management will be fully aware of all critical technical decisions made in the organization and can ensure that the ultimate decision has their approval. In that context, proper knowledge on risk-based decision management is crucial for executives at the higher level of the organization.

### 4.2. Dynamic workforce changes (retirement wave/inadequate PS knowledge among new employees)

The workforce of today is dramatically different from that of yesteryear. It has become increasingly more complex. The active participation of three primary generations in the workforce has given way to a workforce comprised of workers from four or five different generations (Behie et al., 2018). There have been a few studies regarding how the baby boomer's generation can contribute as they grow older, however, it is not well studied how the following generations (generation X and millennials) will cope once the baby boomer generation is gone (Hedge et al., 2006; Silverstein, 2008). Although petrotechnical professionals over 55 years of age made up 19% of the workforce in 2015, reports suggest that this figure will drop to a mere 7% by 2025 (Andrews et al., 2017). It is predicted that there will be a deficit of 10–40 thousand petrotechnical professionals by 2025, as shown in Fig. 8, and this deficit will form a major barrier to the success of many oil and gas companies (Andrews et al., 2017). Companies in the oil and gas and chemical process industries must attract and retain technical staff to be successful. However, because of a demographic gap, these companies must overcome a chasm in the talent pipeline for mid-career professionals.

The dynamics of the changing workforce has resulted in a shortage of skilled workers with less experience on the job. In many of the operating facilities the average number of years of experience on the job is about five years compared to the minimum of eight years required to make consistent decisions (Behie et al., 2018).

It is critically important for the industries to not only to understand the dynamics of the changing workforce but also to establish organizational structures and programs that adjust to meet the changes in the technical workforce of the future. This process needs to start now because significant changes have already begun (Andrews et al., 2017). In order to provide inexperienced operating staff with support, companies should seriously consider bringing back experienced personnel who have retired to coach and mentor young operators to address the learning curve. Specialized training, particularly in PS programs, that stress the responsibilities of the operators to take ownership of implementing process safety at the shop floor should be developed and provided.

Coronavirus (COVID-19) pandemic and crashed oil price have

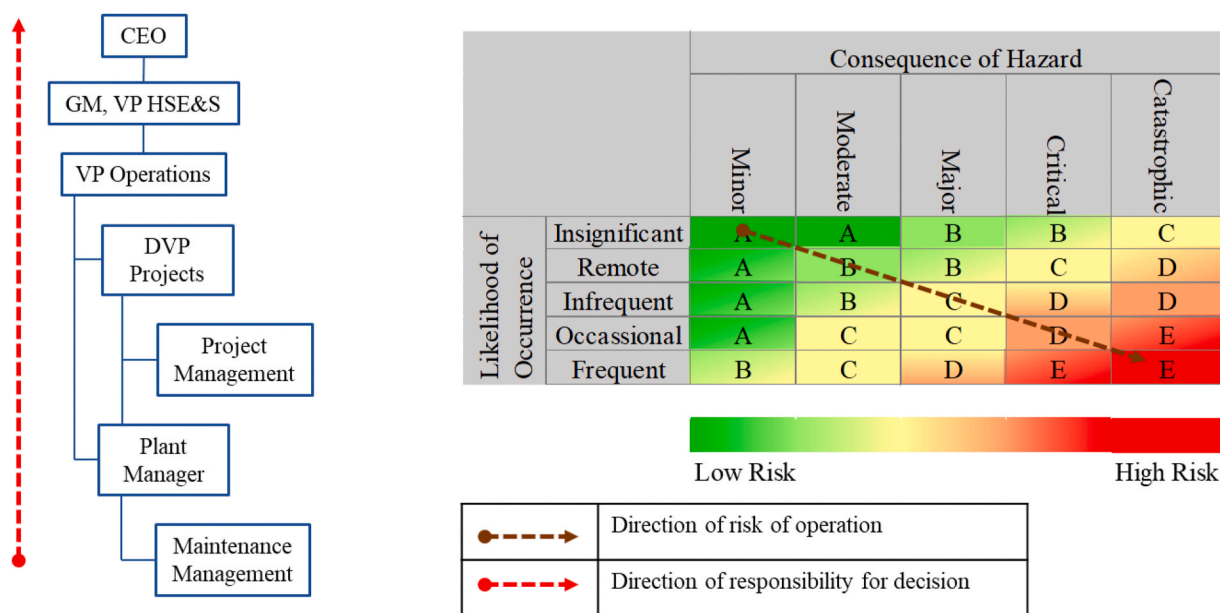


Fig. 7. Management Level Decision Maker- As the risk of an intended operation increases (shown by direction of brown arrow), the responsibility of decision making should be pushed to higher levels of the organizations (direction of red arrow). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

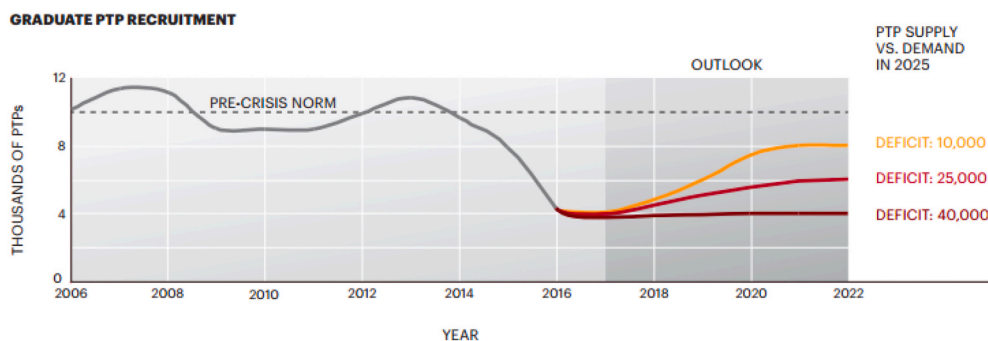


Fig. 8. The Oil & Gas industry will likely face a shortage of petrotechnical professionals when oil production rebounds and there is a growth in the exploration and production sector. Figure shows the predicted upper and lower bounds of this likely deficit during the graduate hiring process (Andrews et al., 2017).

dramatic impact on the Oil and Gas workforce (Chapa, 2020; New Orleans City Business, 2020). Significant number of Oil and Gas workers have been laid off and it is uncertain when the COVID-19 condition or oil price will regain the normalcy. The problems will be exacerbated with prolonged recovery as the laidoff workforce looking for alternate jobs.

#### 4.3. Lack of process safety training/knowledge at all levels of the organization

PS education has been mandated in the Chemical Engineering curriculum in the US in 2011. A few Chemical Engineering schools teach PS engineering course as part of their curriculum while others sprinkled the content throughout their syllabus. However, no process safety courses are currently taught at the technical colleges and trade schools (Dee et al., 2015). As a result, new engineers working in plant operations and the new field level operators and technicians have limited or no training in process safety and the major responsibility of training these new recruits fall on the hiring company itself. From the BP Texas City explosion that occurred in 2005, it was found that the knowledge level and training development plans of the operators were not assured by the management and enhanced safety training beyond the initial job training and refresher training were not provided (Chemical Safety and Hazard Investigation Board (CSB), 2007; Halim and Mannan, 2018).

This factor was a major contributor to this disaster that killed 15 people, injuring 150 and led to substantial financial losses to the company. Several other recent CSB investigation reports, published between 2014 and 2019, issuing recommendations to strengthen the training programs, initial and periodic refresher training, specific hazards and emergency training for all employees and contractors suggested that lack of proper training is still an important issue (Chemical Safety and Hazard Investigation Board (CSB), 2014a; Chemical Safety and Hazard Investigation Board (CSB), 2015a; Chemical Safety and Hazard Investigation Board (CSB), 2017; Chemical Safety and Hazard Investigation Board (CSB), 2018; Chemical Safety and Hazard Investigation Board (CSB), 2019b; Chemical Safety and Hazard Investigation Board (CSB), 2019d). The lack of training in the principles of PSM directly affects the effectiveness of the PS programs at operating facilities since those on the front lines are not trained and hence are poorly positioned to take responsibility for the implementation of process safety in the plant, they work in. It is a critical driver in limiting the effectiveness of facility level PS programs since those on the front lines currently have no responsibility for process safety. With the proper training and redeployment of PS responsibilities, the effectiveness of PS programs will be substantially enhanced with the effect of earlier detection and prevention of PS incidents.

#### 4.4. Reassessing PS programs specific to the management of aging plants

About 173 PS incidents (represents 5.5% of all such incidents) reported between 1996 and 2008 in RIDDOR was attributed to aging plant (Horrocks et al., 2010). The limited information provided in RIDDOR about the underlying causes means that the actual number could be much higher. Across Europe, between 1980 and 2006, 96 major PS incidents (28% of all such incidents) reported in the MARS database are estimated to be due to aging plant resulting in an overall loss of 11 lives, 183 injuries and over 170 million € of economic loss (Horrocks et al., 2010). Although such data is not available for the US industries a comprehensive study on CSB investigation reports from 1998 to 2012 revealed that a considerable number of incidents (8 out of 64) are attributed to aging plant (Baybutt, 2016). As defined by the UK HSE, aging plant may not be considered fully fit for purpose due to age related deterioration in its integrity or functional performance. Aging of an operating facility may indicate the degradation of the material or equipment in use, its overall condition and the change in its condition over time, fatigue, or obsolescence. All these physical states, mechanisms and organizational elements can lead to major accidents (Gyenes et al., 2016). For instance, equipment deterioration over time played a role in Chevron refinery fire, old equipment such as a tank constructed in 1929 failed catastrophically in Allied Terminals Fertilizer tank collapse incident in 2008, use of dated standards and practices played a role in Formosa Plastics in 2005, and outdated technology also has played a role in BP Texas City refinery incident in 2005 (Baybutt, 2016).

Aging plants pose additional challenges to leadership in terms of preventing loss of containment and emergency preparedness. In many aging plants, the PSM has not been able to keep up with the requirements of a degraded system. All plants need to be maintained as they age to ensure that they continue to operate in the manner they were designed. It is critically important that the PSM system designed to inspect, maintain and test critical equipment components are updated as facilities age. In many facilities, the aging of facilities is not the issue but rather lack of improvements in management systems that are not keeping pace with the requirements of aging facilities.

#### 4.5. Failure to focus and monitor the health of preventive barriers in place

About one-third of all CSB incidents and OSHA's PSM covered incidents have issues related to deficiencies in maintenance, inadequate inspection, inadequate preventive maintenance, and no or inadequate mechanical integrity program at all (Baybutt, 2016). Current PSM programs address the integrity of equipment; however, it does not specify any mechanism to ensure the requirements are followed for all safety critical equipment. It only requires compliance with recognized and generally accepted good engineering practices (RAGAGEP). As a result, a wide range of practices are used for assessing the health of safety critical equipment or barriers preventing PS incidents without much consideration of identifying the deeply rooted factors that influence the safety critical equipment or barrier health or understanding what measures can strengthen them. This necessitates identification of best practices for asset integrity program among several industry practices such as risk-based condition monitoring, machine learning-based predictive maintenance. It is important to focus on 'critical' barriers such as pressure safety valves (PSVs), pressure relief systems, emergency shutdown valves (ESDVs), fire and gas detectors and preventers (F&G D&P) systems, process control systems (PCSs) and at the same time, consider the influence of various factors such as maintenance backlog, inhibits/bypasses, deferrals, overdue PMs, MOC program, permit to work practices, conflicting workorders.

Layers of protection implemented on safety critical equipment are designed to bring a process that has moved outside the normal operating envelope back into the safe operating range. The health of critical barriers is reported in several categories for active (hardware and human factors) and passive or support systems (management systems). The focus of

barrier health models currently in use is on the hardware barriers (International Association of Oil and Gas Producers (IOGP), 2016).

The advantage of the barrier health models includes:

- the use plant data for near real-time monitoring of barrier health conditions
- the ability to identify conflicts in work execution plans thus allowing plans to be optimized
- comparison of health of critical components against performance standards
- reports operating plant status (in a risk stoplight format) at all levels (frontline to top executive)

Barrier health models are currently in use on offshore facilities and in onshore facilities with high complexity. Even then, much work still needs to be done to improve these models and for widespread implementation of such models. Apart from looking only at the technical aspects of barrier health assessment, research is also being conducted to incorporate the effect of organizational factors and human and operational influences on the overall effectiveness of the critical barriers in operating facilities.

#### 4.6. Ineffective emergency response plans

Past incidents have demonstrated that effective emergency response can prevent a minor release from escalating into a major incident. Baybutt (2016) reported in the analysis of multiple CSB investigation reports that inadequate emergency preparedness was responsible for the escalating a loss of containment incident into a wide scale disaster of many cases (Baybutt, 2016). Similar observation was made in the recent incidents as well. It took three days to extinguish a fire in a recent incident at Intercontinental Terminal Company (ITC) tank fire at Deer Peres et al. (2016) (Chemical Safety and Hazard Investigation Board (CSB), 2019c). Although there was no injuries or fatalities caused by the fire, the local community experienced severe disruptions resulting in schools and businesses either to close or operate under modified conditions. More importantly, there was a growing concern in the media outlets and other social media regarding the causes behind the prolonged emergency response. In a six-month time, another fire and explosion incident broke out at Port Neches, TX that lasted for eight days and prompted the evacuation of 60,000 residents (Seba, 2019; Toal et al., 2019). Both incidents exposed the lack of emergency preparedness for such major fires at the heart of the world's largest petrochemical cluster. Another aspect of Port Neches fire was that after company officials discovered that asbestos had been released from the blast, they waited 7 h before informing authorities regarding the potential hazards (Bain, 2020). A previous major explosion/fire in Texas, the West Fertilizer explosion demonstrated how important it is for the emergency responders to have the necessary hazard information in order to respond safely and effectively (Chemical Safety and Hazard Investigation Board (CSB), 2016). These incidents have pointed out gaps in the industry's emergency response processes as well as gaps in Local Emergency Planning Committee (LEPC)'s knowledge and understanding leading to lack of information and misinformation being communicated during an incident. The development of a centralized chemical inventory at all operating facilities, and their associated potential hazards and response strategies will be immensely helpful for the first responders. It is uncertain if all community responders are trained and prepared for different types of chemical hazards present in their localities. Another relevant issue might be potential disconnect between PSM system and emergency preparedness and response system. Deficiencies in communication of hazards to responders and local communities early on and their coordination during an emergency can worsen the situation as observed in the past incidents (Chemical Safety and Hazard Investigation Board (CSB), 2019c; Sanicola, 2020).



#### 4.7. External communication

A significant mistrust of industry has developed in the eyes of the public as a result of the substantial increase in major PS events. This mistrust is exacerbated when the incidents go on for several days with ongoing impacts on the public in terms of evacuation, business disruption, air emissions, and water pollution. Miscommunication and/or misinformation, particularly at the beginning of a major incident, and the lack of timely update elevates the level of public mistrust (Bain, 2020). A series of disasters in Texas in the year 2019, as shown in Fig. 5, received wide scale social media coverage, and each incident, although independent, increased the public dissatisfaction more and more due to the small-time gaps between each event. Such events can increase insurance premiums for the companies operating in the region (Sanicola, 2020) and make them more susceptible to lawsuits and civil litigations (Collier, 2020). In such cases, the impact of an incident of small consequence can result in large financial losses to a company.

### 5. Next steps

Based on the identified factors at play, it is evident that these factors do not focus on any single aspect of PSM, but rather encompasses multiple elements and overall PS management systems. A more holistic approach towards implementation of safety management programs is suggested in order to fully appreciate and internalize all the factors at play. These approaches will improve the effectiveness of PS management systems and programs and impact multiple elements altogether. The recommended steps for implementation are discussed next.

#### 5.1. Role of the risk assessment function

For the risk-based decision-making procedure outlined in section 4.1 to become part of management's approach, critical decision making based on risk analysis must be integrated into the management decision making process. The critical decision-making process described above must be followed for all critical technical decisions. The risk assessment process for each decision may only take a few hours to complete with the proper personnel in attendance. As such risk assessments can be completed and the output made available to senior management in short order even for time-critical decisions. There are many examples in the accident record where decisions were made without the benefit of a robust risk assessment and these decisions lead to disastrous outcomes (Behie et al., 2017). To be effective and serve the best interests of organizations, the risk assessment process must be imbedded at all levels of the company.

#### 5.2. Workforce development for operators, engineers, managers, and executives

Incomplete PS knowledge and ownership across an organization can lead to inadequate prioritization and a higher level of risk taking leading to incidents in operational facilities. A structured competency development program is required at all levels of the organization starting from 'shop floor' operators, newly recruited engineers up to top executives. The current status of worker competency and the impacts of changing workplace dynamics need to be assessed and incorporated. Only then can effective training and continuing education programs be implemented that will meet industry requirements.

The current retirement wave has resulted in reduced experience levels in the workplace in many industries. As a result, valuable knowledge on how to ensure safe operations are being lost. Currently, PS courses are taught only in few engineering curricula across the country and not at technical colleges or trade schools. A comprehensive PS certificate program can be a valuable asset for students at both engineering and operator levels as they enter the workforce. PS certificate program for the two-year college program will be an important addition.

This program might also be made available on-line for anyone wanting to improve their knowledge in process safety.

PS responsibility must also be enhanced at all levels of technical management and this can be done effectively in several ways that support the program above. These include the following:

- Incorporating active learning components in operators' training and education
- Holding PS workshops or bootcamps for middle and senior management
- Encouraging new engineering hires to take on-line PS courses and gain certification
- Holding PS workshops for executive management not only to enhance their knowledge in PS but also to stress the critical importance of their support and participation in PS program implementation
- Implement a risk-based decision-making training program

Such training would encompass risk-based decision management with the goal to provide guidance to improve the outcome of the critical technical decisions they will be faced with in the future. Companies can collaborate with institutes or centers that provide an array of courses for continuing education and professional development in the field of process safety and risk management to improve the core process safety knowledge of engineers working in different fields in the industry.

#### 5.3. Process safety vulnerability assessment and identification of best practices

It is crucial to understand the gaps in implementation of a PSM program in an operating facility and to identify best practices for implementation of PSM programs. PSM programs vary widely across operating facilities, ranging from minimal effort given by management to elaborate programs fully supported by management for PS implementation. Companies lagging behind in PS implementation compared to their peers would benefit from identification of best practices in their industry sector that they can implement economically and effectively. Understanding the existing gaps and identification of best practices can happen if companies participate in information sharing. Questionnaires can be developed to understand where a company stands in terms of implementation of PSM programs and what effective measures are in place in peer companies that are successful. These questionnaires can probe into important fields such as mechanical integrity programs, risk management programs, risk evaluation programs, Tier 3 data analysis methods adopted by companies etc. Cooperation among industry members can help to bring out the real picture with the help of such questionnaires. The information will then be analyzed and reported back to the industry on the existing gaps and on the best practices available so that the individual companies can use this information to take measures to implement improvements. A joint effort from industry can have multiple benefits: not only will this help identify best practices but will also enable some companies that have limited resources to learn the most effective way to implement PS practices from the other companies. An example of such an approach is the development of 'Advanced Procedure' through an industry consortium whereby a joint effort is made to identify the best practice of writing procedures that will benefit companies both inside and outside the consortium (Ahmed et al., 2020; Peres et al., 2016). In the long run, this type of approach will help reduce incidents and severity in the industry, thus preserving public trust and industry reputation.

#### 5.4. Process safety management of aging plants

Companies are well advised to review their maintenance management and inspection management systems in light of best practices in their industry sector and update their practices as required as their

plants age. Some practices that should be considered are the use of on-line conditioning monitoring techniques for critical components and machine learning-based predictive maintenance techniques. Management of aging plants also involves improved workforce training in the areas of mechanical integrity, maintenance and inspection data, Tier 3 data, incident investigation reports *etc.* From plants that can be analyzed to identify the weak links in the system. As plants age, facility programs need to be updated and optimized. Optimization dictates that one moves to risk-based inspection programs that includes revisiting internal inspection frequencies to ensure that vessels do not operate under minimum corrosion allowance-conditions. Of critical importance is to identify potential loss of process containment events and ensure response can be taken as early as possible.

### 5.5. Barrier health assessment

Current developments for dynamic barrier health monitoring models allow assessment of increased risk conditions due to impaired barriers through use of various tools. State of the art research techniques (*e.g.*, natural language processing, artificial neural network) are being used to identify causes behind large number of incidents from investigation reports. This knowledge will help identify how various technical, operational, human as well as organizational factors influence barrier failure tendencies, and this can be used to develop causal models (Halim et al., 2018, 2020). Tier 3 data can then be used to understand existing barrier reliability and the information from the facility can be used to update the barrier health model through use of tools that use Bayesian inference. Other methods can involve study of system dynamics and identification of weak signals that indicate a barrier failure is imminent (Halim, 2019; Yu et al., 2020). Use of data regarding MOC, PSSR, planned work on critical component, challenges to safety system/-barriers, bypasses of safety systems, *etc.* can also be used to develop a leading indicator dashboard (Tamim et al., 2017, 2019) of the overall health of the barriers in play. Such dashboard will enable management to take proactive measures to monitor the performance of preventative barriers before they degrade and lead to an incident. The outcome will allow work execution to be optimized and barrier health conditions to be monitored in near real-time. In a broader perspective, this will provide information on operating plant status to all levels, starting from frontline operators all the way up to top executive level. With the advent of data mining processes and artificial intelligence, these tasks need not be time consuming, if initial effort and resources are spent in developing a good robust barrier health model. Such models are currently being used effectively in the offshore oil and gas industry.

### 5.6. Development of robust emergency response plan

A comprehensive emergency response plan (ERP) in accordance with the chemical, fire and natural hazards present in the operating facilities are critical to maintaining safe operations. The ERP should be vetted by the PSM team and communicated and trained with company emergency responders as well as local LEPC's and community emergency response team (Quddus et al., 2018). Although this recommendation does not prevent an incident, it provides the substantial basis and framework to respond with accurate information in a timely manner. Immediate or early detection of a loss of containment incident is critical to preventing escalation. In addition to early on-site detection, effective and timely mutual aid has also shown to be critical in preventing escalation (Cozzani et al., 2007, 2009). Over response is a more effective response than under response to avoid losing valuable time if the requirements of the situation are underestimated.

### 5.7. Risk communication

The series on incidents in 2019 described above have gained considerable media coverage that has led to a significant mistrust of

industry in the eyes of the public, and this is compounded by misinformation and lack of timely information to the public. One major factor in play in this regard is the fact that the public does not understand the difference between hazard and risk. One way to combat public mistrust and miscommunication issues is to develop more effective communication tools and mediums, and to deliver honest and regular updates to the public during a major PS event. Communication tools for different levels of people including K-12 students would improve the awareness of the hazards and how preventive and mitigative barriers can effectively reduce the risk associated with these hazards. These tools can vary widely in terms of delivery from news article, books, podcasts to immersive environment including games *etc.* (Collette and Dempsey, 2016; TEES Mary Kay O'Connor Process Safety Center, 2020). These tools can be shared with employers, employees, policy makers, general public, first responders, and local emergency planning committees (LEPCs) as targeted audiences. Academic and research institutions which are considered as trusted source of information and have experience in developing risk communication tools (such as MKOPSC) are more likely to be more accepted by the target audience as a reliable communication of hazards and risks associated with the operating plants.

## 6. Discussions and conclusions

An analysis of trends obtained from various industry sources showed that over the years, number of incidents have been reduced in the United States, however, the severity of incidents seems to have reached a plateau suggesting further reduction would require strengthening and revitalizing the current PSM programs to improve their overall effectiveness. Apart from damage to property, people and environment, the impact of incidents has far greater impact, affecting reputation of the companies and industries, generating overall mistrust of industry in the eyes of the general public and leading to legal action. Due to the social media and other web-based outlets people have a lot more information than twenty years ago, which makes public more aware of the impact of plant upsets on their surrounding communities.

An important aspect of any PSM program is the compliance with regulatory requirements. OSHA mandated PSM regulation for more than twenty-five years and a few best practices are available from different industry bodies, which typically go beyond regulatory requirement. Most major facilities probably follow the industry standards or their own guidance documents on PSM. It is important that these guidance documents must be developed based on scientific evidences and improved as necessary or updated whenever possible (Halim and Mannan, 2018). For instance, mechanical integrity of PSM requires following recognized and generally accepted good engineering practices for inspection and testing of certain equipment. However, PSM does not guide whether the barrier health management program would be the best option or what specific issues need to be addressed for the maintenance of an aging plant or how the critical decision regarding the maintenance should be made. Most importantly, it might not be required from the PSM guidance, since the nature of these guidance may vary from facility to facility and it would be more appropriate to let the facility decide the best course of action for them. However, enforcement is very crucial for regulations to be effective. An example of lack of enforcement leading to an incident can be explosion at West Fertilizer at West, Texas. Another aspect regarding the PSM is related to covered facility. Two of the incidents (ITC and Watson Grinding) shown in Fig. 6 do not involve operating facilities and it is not very clear if they covered by PSM program or if they are under enforcement.

Over the years, companies have effectively implemented PSM programs to reduce the number of incidents as well their severity. However, more effort needs to be extended to evaluate the effectiveness of PSM by addressing the factors at play as discussed in this paper. The current paper discusses these factors and provides recommendations for future improvements opportunities. An interesting observation from this

research is that although companies might currently be doing well in addressing each of the PSM elements individually, the factors at play identified encompass multiple PSM elements taken together. This indicates that a more holistic approach at implementing effective PSM programs are required and the recommendations provided in the paper intends to do exactly that.

### CRedit authorship contribution statement

**Stewart W. Behie:** Conceptualization, Methodology, Investigation, Formal analysis, Writing - original draft, Supervision. **S. Zohra Halim:** Investigation, Formal analysis, Writing - original draft. **Bill Efaw:** Conceptualization, Writing - review & editing. **T. Michael O'Connor:** Conceptualization, Formal analysis, Writing - review & editing. **Noor Quddus:** Methodology, Investigation, Formal analysis, Writing - original draft, Writing - review & editing.

### Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Conceptualization	Ideas; formulation or evolution of overarching research goals and aims
Methodology	Development or design of methodology; creation of models
Software	Programming, software development; designing computer programs; implementation of the computer code and supporting algorithms; testing of existing code components
Validation	Verification, whether as a part of the activity or separate, of the overall replication/reproducibility of results/experiments and other research outputs
Formal analysis	Application of statistical, mathematical, computational, or other formal techniques to analyze or synthesize study data
Investigation	Conducting a research and investigation process, specifically performing the experiments, or data/evidence collection
Resources	Provision of study materials, reagents, materials, patients, laboratory samples, animals, instrumentation, computing resources, or other analysis tools
Data Curation	Management activities to annotate (produce metadata), scrub data and maintain research data (including software code, where it is necessary for interpreting the data itself) for initial use and later reuse
Writing - Original Draft	Preparation, creation and/or presentation of the published work, specifically writing the initial draft (including substantive translation)
Writing - Review & Editing	Preparation, creation and/or presentation of the published work by those from the original research group, specifically critical review, commentary or revision – including pre- or post-publication stages
Visualization	Preparation, creation and/or presentation of the published work, specifically visualization/data presentation
Supervision	Oversight and leadership responsibility for the research activity planning and execution, including mentorship external to the core team
Project administration	Management and coordination responsibility for the research activity planning and execution
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