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PROCESS SAFETY MANAGEMENT (PSM): A REVIEW

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Abstract

Despite having clear regulations and Process Safety Management (PSM) system in place, major disasters have been taking place in several chemical and process industries globally. This study attempts to scan the earlier research studies and body of knowledge related to PSM and its elements with the objectives of analysing extant research, for practical insights and establishing new research ideas towards effective PSM. An exhaustive search was carried out across various bibliographic databases for selection of scientifically published papers and relevant books for reading and documenting the review through systematic writing. The study found that earlier research was predominantly focused on few PSM elements while other areas are yet to be explored. Further research can be undertaken to identify the causatives factors or root causes of the industrial incidents. This review offers several contemporary management insights and specific research ideas which can help both process safety professionals and researchers.

Keywords: Process Safety Management (PSM); Risk Management; Hazard and Operability Studies (HAZOP); Process Hazard Analysis (PHA); Process Safety Information (PSI): Mechanical Integrity: Management of Change.

1. INTRODUCTION

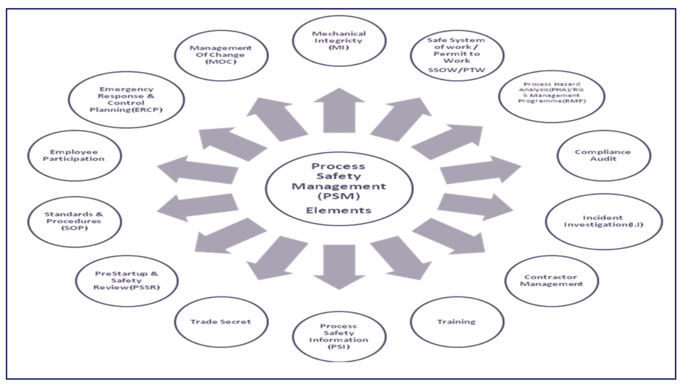
In today's global scenario, industrial disasters are perceived to be on the rise both in magnitude and frequency. Global data on reported disasters shows an increase of about 60% over the previous years (Frank P Lees, 2003). The severities of these incidents are very high, causing huge damage to the business, society, and environment. Despite huge development in safety management system with various methodologies developed to identify and control risks, the incidents especially in chemical process industries handling hazardous chemicals are on the rise. Repeated incidents and disasters in oil & gas as well as chemical process industries were not on control which necessitated OSHA to frame Process Safety Management (PSM) system (29 CFR 1910.119). PSM plays a vital role provided it is correctly implemented, audited, and reviewed as stipulated in OSHA PSM 29 CFR 1910.119 section (a) to section (p).

Section 2 in this paper provides a brief overview and functions of PSM, while section 3 states the objectives of this literature review. Section 4 describes the research methodology adopted for the literature review including the keywords/search terms used in identifying relevant studies, bibliographic databases accessed in search of research papers on PSM and the criteria adopted for selecting papers for review of literature. Section 5 focuses on literature review and analysis wherein the current outlook of PSM research has been captured, research insights related to PSM and its elements were described and presented in a tabular form. Aligned with the research objectives section 6 deals with findings on review of available literature and discusses the scope for future research with respect to various research gaps identified. Sections 7 and 8 offers scope for future research and ideas/directions towards identifying causative factors/root causes for incidents in PSM implemented process and chemical industries.

2. PROCESS SAFETY MANAGEMENT (PSM) – AN OVERVIEW:

Process Safety Management (PSM) is a systematic analytical tool or line of defense focused to prevent process related incidents and release of any hazardous substances by reducing the process risks as low as reasonably practicable level.

Fig 1: Elements of Process Safety Management (PSM)



Source: Loss prevention in Process Industries (Frank p Lees 2003)

PSM is a management system to identify, understand, and control the hazards and to eliminate or minimize chemical process related injuries/illness/release of hazardous chemicals.

In a Nutshell:

- ✓ Process Safety Management is an ongoing activity – Never ends.
- ✓ Process Safety Management is a process – Not a project.
- ✓ Process Safety Management is not a onetime fix.
- ✓ Process Safety Management is a way of improving safety and operability.

- ✓ Process Safety Management is not only management activity – involves everyone including contractors.
- ✓ Process safety Management is continual improvement in process operation and safety as risk can never be zero.

Process Safety Management has 14 important elements. For effective functioning of this management system all the elements are required to be effective and coordinated during implementation, plant operation, modification / management of change (MOC) and till demolition including start-up and shutdown.

3. RESEARCH BACKGROUND AND OBJECTIVES

Safety incidents are occurring in the Chemical and Process industries despite PSM implementation. Despite having clear regulations and PSM system in place, major disasters have taken place globally. Bhopal disaster in India (Gupta et al, 2003; Sam mannan, 2011), piper alpha disaster in North Sea offshore platform (Ian Waldram, 2013), Bunce field explosions (Sam Mannan, 2011) and flixborough explosions (Venart 2014) are few major disasters which clearly show the ineffective implementation of PSM programme. Identifying the causative factors / root causes for PSM failures and understanding relevant scientific solutions can help in effective PSM implementation. As a first step, the extant literature associated with PSM research can be reviewed to know the focus of earlier research, gain insights for advanced practice and future research, and identify triggers that provide new research ideas/ directions towards effective PSM. This literature review is, therefore, focused on scanning the earlier research studies and body of knowledge related to PSM and its elements with the following research objectives:

a) Bibliographic analysis of the extant research related to PSM and its elements.

b) Annotate the PSM literature and present summary of practical research insights.

c) Identify new directions and scope for future research towards effective PSM.

4. RESEARCH METHODOLOGY

As part of the literature review, this study gathered the previous scientific knowledge pertaining to PSM towards the above stated research objectives. An exhaustive search was carried out across various bibliographic databases using relevant keywords and focused search terms. It was followed by the selection of scientifically published papers and relevant books for reading, referring, and documenting the review through systematic writing along with the summary of extant literature and directions for future research.

The research began with identifying keywords and focus search terms across PSM elements applying Boolean search methods in various bibliographic databases such as Ebscohost and research gate and professional resources like Elsevier, AIChE and Science Direct. The papers chosen for the review were based on the implicit quality of the journal and aligned with the stated research objectives. Over 150 research papers related to process and general safety management in Chemical and Process Industries published by Science direct, Centre for Chemical Process Safety (CCPS), American Institute of Chemical Engineers (AIChE) and other publishers published during 1995 - 2021 were reviewed, documented, and analysed to: 1) understand the professional journal publications and their contributions in the PSM research; 2) identify the trend of publishing during the period considered for review; and 3) identify the major focus areas in PSM research and publication, provide an overview of research insights having practical insights, and research gaps that could be explored in future for effective PSM.

5. BIBLIOGRAHIC ANALYSIS

Research in PSM has been published by various professional journals in the domain. Figure 2 shows the journal wise share of PSM research published. The journals "Professional Safety" and "Chemical Business" have contributed significantly to PSM research and publishing. Research in PSM domain was naive and limited until 2010. Later the research became significant and more papers were published upto 2015. Figure 3 shows the trend line of research and publication activity in PSM domain.

Fig : 2 Journal Wise Share of PSM Research Publshed

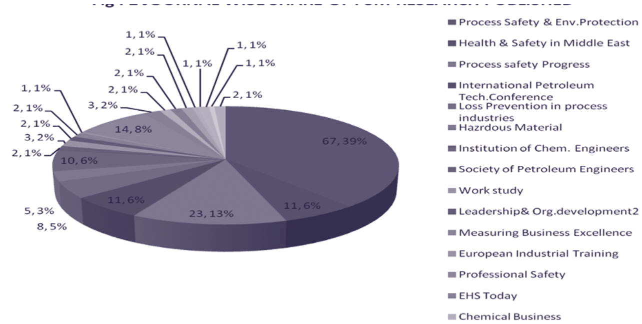
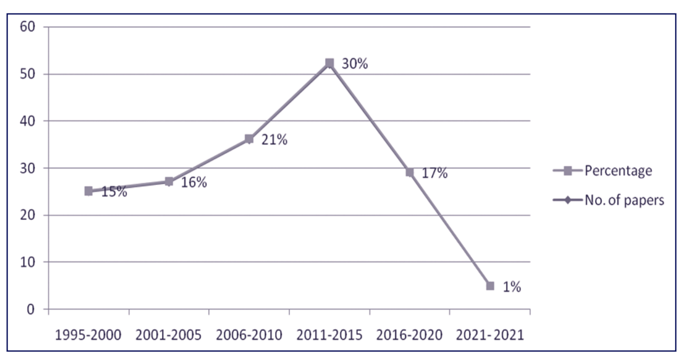


Fig : 3 Trend Of Research Papers Published During 1995-2021



6. LITERATURE REVIEW AND ANALYSIS

On selecting the research papers based on the above said criteria, meticulous focus was given in understanding the essence in implementation and practising process safety management (PSM) & its elements. The ensuing sub-sections highlights key insights and findings of various research studies across different areas and/or elements of PSM.

6.1 Process Hazard Analysis / Risk Management Programme (PHA/RMP) : Assessing and managing the major risks on identifying the invisible hazards and having best practices of plant safety including compliance to codes, standards and procedures with human competence are the core values of PSM (Sharon Cave, 2013; Katherine, 2013; Teresa Budworth, 2013). PSM performance shall be achieved with various risk assessment tools including fuzzy risk assessment of rare events for industrial disasters and its risk aversion by computing the limits (Waddington et al, 2013; Mirilarasami et al, 2011 and Enrico Zio et al, 2013). Risk Management Programme is thorough, orderly, and systematic approach to identify, evaluate, and control chemical process, storage and handling of highly hazardous chemicals (Pasman *et al*, 2009 and Karthikeyan, 2009).

Various methodologies are used to assess process hazards such as application of chain of events analysis, its control systems and the errors and calculation of fire & explosion index for loss control (Mike Brown, 2003; Timothy et al 2009 and Gupta *et al*, 2003). An accident Hazard Index is a multi-attribute method for process industry hazard rating (Khan et al, 2000). Loss prevention was done with systematic hazard identification, prediction, and prevention (SHIPP) creating an accident model to improve the effectiveness of PSM with safe operation and process reliability (Mimi Hossim, 2010; Samith et al, 2011; Louver, 2008; and Angela, 2009). Various risk assessment and risk control methodologies are used including six step basic risk assessment, computer aided evaluation and fire and explosion index to improve plant safety & reliability (Adnan et al, 2013 and Maintyn et al, 2009). Risk based safety measures considering process variables and domino effects can use accident damage assessment module, a tool of consequence assessment can be applied (Luciano et al, 2019; Paul et al 2019; Abdul Aziz et al, 2019 and Renan et al, 2020). Oil & Gas and chemical process industry apply base risk assessment tools like Hazard and Operability studies (HAZOP), Layer of Protection Analysis (LOPA) and control the risk As Low as Practicable (ALARP) as predictive approach for continual improvements in health & safety management (Lin Cui *et al,*2008; Raymond, 2008; Annamaria et al, 2011).

6.2. Mechanical Integrity (MI) : Inherent safer design, technical integrity, risk-based inspection and maintenance, engineering risk control techniques applied are major contributors for preventing equipment failure in process industry incidents (David, 2013; Thomas, 2012; Khan *et al,* 2004; Kletz, 2003). As design is a contributor to process incidents, inherent safer design of chemical process, process equipment, accessories, warning, and safety system are to be based on assessed risk in process facilities (Chang *et al*, 2011; Kamarizan *et al,* 2012 and Rajagopalan *et al*, 2012). Facility sitting using risk mapping on plant grid areas and facility layout based on worst case scenarios like toxic release shall be considered to optimise plant safety (SeughJung *et al*, 2010, Diaz *et al,* 2010; Dalzel, 2003; Angela, 2007, Gupta *et al,* 2003 and Unnikrishnan, 2013). Criticality assessment and analysis of process equipment with adequate inspection intervals will improve the mechanical integrity of process equipments (Peter et al, 2020; Alzabi et al, 2015; Julio et al, 2012 and Brown, 2021). Optimal plant layout, inherent safer equipment, and process design along with suitable facility sitting for storage and handling of hazardous chemicals will effectively reduce the risk and ensures safer plant (Muhammad et al, 2019; Federica et al, 2021; Renshaw, 2013; and Liaw, 2019).

6.3. Process Safety Information (P.S.I.) : Process safety information (PSI) assessment plays a vital role in preventing process related incidents which can be seen in process safety progress since last two centuries (Law et al, 2006; Jack et al, 2008; Katherine, 2013; Paul et al, 2007 and James, 2009). The basic information required to analyse and control the risks associated with chemical process operation from design to construction, commissioning, operation, modification and demolition of chemical process plants in a safe manner are material safety data sheet (MSDS), piping & instrumentation diagram (P&ID), relief system design, process chemistry, safe levels of storage tank, safe upper and lower levels of critical parameters, emergency trip/inter-lock system, material of construction, design standard & codes (ANSI/UL/FM/ISI/API/SIL), equipment data sheet and electrical classifications (Karthikeyan, 2009). Process safety information deficiencies are to be encountered with clear hazard communication system as same as that of global harmonised system implemented for clear communication of hazardous chemicals (Liaw, 2019).

6.4. Incident Investigation (I.I) : Incident Investigation is a crucial part of PSM program. Resolutions and corrective actions must be documented and viewed by all concerned employees (Karthikeyan, 2009 and OSHA 29CFR 1910.119 guidelines). Process incidents are investigated using root cause analysis; failure modelling and the same shall be applied for investigating process incidents to prevent recurrence of similar incidents (Rinfeng et al, 2012; Gupta, 2003; Crawley et al, 2003; David et al, 2012 and Sutton, 2008). Near-miss Incident management in the chemical process industry plays a vital role, if identified, reported, analysed, and controlled (James et al, 2008). Compliance to recent development in fire & explosion index and clear post incident review will further reduce process related incidents (Dale et al, 2009 and Leong et al, 2012). Lessons learnt from piper alpha disaster, Buncefield fire & explosion, Bhopal tragedy, flixborough and multiple case histories of domino accidents to be controlled and prevented for non-recurrence of process related incidents (Waldram, 2013; Sam, 2011; Mannan *et al*, 2008; Mannan *et al*, 2007 and Venart, 2004).

6.5. Training (TRG) : Training plays a vital role in safe operation of process plants. Process plant incidents can also be prevented with perfect knowledge management, safety training, blended training & practices during routine and non-routine activities including start-up & shutdown operations (Diliddo et al, 2013; Oyetola et al, 2012; Mohamed, 2013; and Toby, 2012). Accident minimisation is possible with good training strategies by pooling knowledge and improving safety for contracted works (Charles, 2017 and Patrizia et al, 2015) and orientation training is appropriate to get familiarised with worksite (Brian, 2018).

6.6. Emergency Response & Control Planning (ERCP) : Many provisions of process safety management focus on preventing incidents from occurring. It is statistically impossible to have zero incidents. Hence preparations and resources should be in place to minimize injury / exposure to worker and loss of property. Emergency action plan for entire plant on various possible scenarios must be developed and implemented. Written procedures to handle probable emergencies like hazardous material release / spill / fire and explosion should be in place and employees are trained. Emergency planning and response plays a key role in disaster management during emergencies related to process nature, hazardous materials used to include shelter in place (Mannan et al, 2000; Katherine, 2012 and Kulkarni et al, 2011).

6.7. Contractor Management : Contractors play a key role from construction, commissioning, operation, modification; start up, shutdown, maintenance operations till demolition, risk mitigation with effective contractor management dealing with multicultural workforce in process plants handling hazardous chemicals, which becomes very important to prevent / minimize industrial incidents (Ahmad et al, 2012 and Gamal et al, 2011). Therefore, employer's moral duty is to provide safe work environment to contract employees so that they can perform their job safely without any incident while handling hazardous chemicals, maintenance of equipments in routine or non-routine basis. They are to be made aware of equipments handled and hazards associated with, chemicals handled in work area and precautions to be adhered, personal protective equipments to be used, work or operating procedure with respect to job and training on specialized job and emergency evacuation procedures (Karthikeyan, 2009 and CCPS, 2007).

6.8. Employee Participation : Process Safety Management (PSM) is not a management program handled by management. It is a program involving everyone in the organization. All managers, employees and contract workers are responsible for successful implementation, review, and continual improvement of PSM (Karthikeyan, 2009 and CCPS, 2007). Successful process safety implementation is feasible with only positive safety culture and safety performance. Safety culture, therefore, needs to be improved at workplace to reduce work related incidents (Behari, 2018 and Shahid et al, 2017). Positive safety culture can be achieved only by employee participation, management commitment, visible leadership, clear demonstration with clear attitudinal approach to prevent incidents in process plants (Ian Donald et al, 1996).

6.9. Compliance Audit : Auditing is a critical part of every successful management system. Observing the performance with the established standards will only reveal the gap, required to be bridged. Process Safety Management system and program effectiveness needs to be audited and evaluated by trained, knowledgeable and impartial competent auditors and team. Management must establish a regular schedule for periodic audits; the results are analyzed, reviewed and implemented for corrective and preventive action (CAPA) (Karthikeyan, 2009 and CCPS, 2007). Compliance audit, one of the most important elements in PSM is complying to legal requirements, codes, set standards, procedures, and review of the same post safety audit for implementation of CAPA (Rob James et al, 1994 and Ju lynne et al, 2010). PSM goal can be achieved only when a correct compliance audit is in place (Brian, 2021).

6.10. Safe System Of Work (SSOW) / Permit To Work (PTW): Work permit is a written document, authorization to perform non routine work in chemical process industries in a safe manner. Work permits contain important information like area of work and exact location, nature of work to be performed, permit validity with specific timings, hazards identified and control measures in place, personnel involved in the job, precautions to be complied, personal protective equipments to be used, emergency procedure and evacuation plan, oxygen and toxic gas levels, standby person details as necessary, chemical lines isolation details, electrical power / energy isolation, responsible work supervisor details and other job specific instructions (CCPS, 2007 and Karthikeyan, 2009). Types of work permits used in non-routine operation which are highly hazardous in nature if not organized in a safe way in chemical process industries are cold work or general work permit, working at height, excavation work permit, confined space entry permit, electrical / energy isolation work permits (LOTO), hot work permit, hazardous line breaking permit and loading /unloading of hazardous chemicals permit. Routine and non-routine operations pose enormous risk in process plants leading to major disasters and the same shall be prevented more effective SSOW for routine operations and PTW for non-routine operations (Iliffe et al, 1999).

6.11. Management of Change (MOC): Anything differs from original design specification is known as change. Managing change is very important to prevent incidents. The implications on safety are enormous. Bhopal disaster stands a testimony to this. Managing changes to technology, hazardous chemicals, facilities, and personnel in a chemical industry are not the same as managing in any other industries. Contemplated changes to a process must be thoroughly evaluated to fully assess the impact on employee's safety and health. Written procedures must be established when such changes take place. Few of the changes that needs MOC applications are reducing reactor settling time, changing catalyst type or concentration, process parameters, changing inspection methods, changing carbon steel to stainless steel, replacement of ball valve with gate valve, change in material of construction, change in impeller size, and increase / decrease in number of chemical plant operators per shift (Davepoint, 2012; Manuele, 2012; Robert, 2016; CCPS, 2007 and Karthikeyan, 2009). Management of change (MOC) plays a key role in process safety management system. Non-compliance to MOC and non-coordination with other required elements leads to disasters and the same can be achieved by bench marking MOC practices in process plants (Keren et al, 2002). Management of change, a mandatory safeguard and key to safety to be exercised whenever a small change is taking place in the process, equipment, and technology (Davepoint, 2012; Manuele, 2012; and Robert, 2016).

6.12. Summary of Research Insights for Practice : Various generic and specific practical insights extracted from earlier research works in Process Safety Management (PSM) are presented in the form of tabulation. As research works available in the extant literature were predominantly observed within each specific PSM element, the corresponding research insights (shown in Table 1) are tabulated.

Table 1: Research Insights from the Literature

Sl. No	Description	PSM Element	Focus	Practical Insights from the Earlier Research
1	Process Hazard Analysis	Risk Management	Various risk assessment & risk control methodology, facility sitting, Standards &Procedures	1. Fuzzy risk assessment and risk aversion by computing the limits of rare events will help in boosting the PSM performance. 2. Accident Hazard Index is a multi-attribute method for process industry hazard rating. 3. Chain of events analysis, its control systems & the errors and calculation of fire & explosion index for loss control are used to assess process hazards. 4. six step basic risk assessment, computer aided evaluation and fire and explosion index to improve plant safety &reliability. 5. Quantitative risk assessment, mechanism analysis, Hazard, and operability studies (HAZOP), quick risk assessment, dynamic safety analysis using boe-tie mapping and layer of protection analysis (LOPA) are applied in chemical process and oil& gas industries. 6. Chemical hazard recognition with a pre assessment about hazardous chemicals, identifying its reactivity hazards and taking adequate control measures will reduce the risks in process industries
2	Mechanical Integrity	M.I.	Equipment failure, Engineering. techniques for failure education, Inherent safer design.	1. Inherent safer design, technical integrity, risk-based inspection and maintenance, engineering risk control techniques applied are major contributors for preventing equipment failure in process industry incidents. 2. Criticality assessment and analysis of process equipment with adequate inspection intervals will improve the mechanical integrity of process equipment. 3. Inherent safer equipment and process design along with suitable facility sitting for storage and handling of hazardous chemicals will effectively reduce the risk and ensures safer plant.
3	Process Safety Information	P.S.I.	Process risk assessment	1. PSI assessment plays a vital role in preventing process related incidents which can be seen in process safety progress since last two centuries. 2. PSI deficiencies are to be encountered with clear hazard communication system as same as that of global harmonised system implemented for clear communication of hazardous chemicals
4	Incident Investigation	I.I.	Root cause analysis, Earlier Incidents and lessons learnt, facility sitting, anatomy of domino accidents.	1. Process incidents are investigated using root cause analysis, failure modelling and the same shall be applied for investigating process incidents to prevent recurrence of similar incidents. 2. Near miss Incident management in the chemical process industry plays a vital role, if identified, reported, analysed, and controlled 3. Compliance to recent development in fire & explosion index and clear post incident review will further reduce process related incidents
5	Training	Training	Operation knowledge Management, Safety training, Chemical Engineering Practices, Shutdown operation.	1. Process plant incidents can also be prevented with perfect knowledge management, safety training, blended training & practices during routine and non-routine activities including start-up & shutdown operations. 2. Training to contract workmen is very important specially the orientation training to get familiarised with worksite. 3. Accident minimisation at large industries is possible with good training strategies by pooling knowledge and improving safety for contracted works

6	Emergency Response & Control Planning	ERCP	Protection of workplace during emergencies, Disaster risk management	1. Emergency planning and response plays a key role in disaster management during emergencies related to process nature, hazardous materials used to include shelter in place. 2. Disaster management in chemical industries plays vital role in minimizing the damage to industry and environment.
7.	Contractors Management	CM	Contractors dealing with multi-cultural workforce	1. Effective contractor management dealing with multicultural workforce in process plants handling hazardous chemicals becomes very important to prevent/minimize industrial incidents.
8	Employee Participation	Employee Participation	Safety culture and performance	1. Safety culture needs to be improved at workplace to reduce work related incidents. 2. Positive safety culture can be achieved only by employee participation, management commitment, visible leadership, clear demonstration with clear attitudinal approach to prevent incidents in process plants
9	Compliance & Audit	Audit & Review	Role of regulators & Audit review	1. Process safety management goal can be achieved only when a correct compliance audit is in place. 2. Comply with legal requirements, codes, set standards, procedures, and review of the same post safety audit for implementation of corrective actions and preventive actions (CAPA)
10	Safe system of work/ Permit to work	SSOW / PTW	Effective permit to work system	1. Routine and non-routine operations pose enormous risk in process plants leading to major disasters. 2. Disasters can be prevented with more effective safe system of work (SSOW) for routine operations and Permit to work system (PTW) for non-routine operations
11	Management of Change	MOC	Management of change practices	1. Non-compliance to MOC and non-coordination with other required elements leads to disasters and the same can be achieved by bench marking MOC practices in process plants. 2. MOC should be exercised whenever a small change is taking place in the process, equipment, and technology
12	Pre Startup-Safety Review	PSSR	Review of equipment suitability before commissioning.	NIL
13	Standards & Procedures	SOP	Importance of standards and need for procedures	NIL
14	Trade Secret	TS		NIL

7. FINDINGS AND SCOPE FOR RESEARCH

Analysis of the Figure 4 and Table 1 shows that the extant research was predominantly focused in few PSM elements, particularly the Process Hazard Analysis (PHA) / Risk Management Program, Mechanical Integrity (MI), Process Safety Information (PSI), Incident Investigation, and Training. However, research is naïve and limited in elements such as Emergency Response, Contractor Management, Compliance Audit, Employee Participation, and Management of Change. No research was found in PSM elements viz., Pre-Start-up Safety Review, Standards & Procedures, and Trade Secret, which offers immense potential for research and development. Therefore, the PSM domain offers a wide scope for further research on emerging issues in areas like Employee Participation, Contractor Management, Management of Change, etc., while researchers can also study issues related to unexplored elements.

The extant literature though offers specific scientific methods/ solutions for risk assessment and improving mechanical integrity, and highlights the importance of PSM, there are no scientifically published research studies on factors causing the incidents in chemical and process industries. But the literature has indicated that non-coordination with other required elements may lead to disasters (Keren et al., 2002). Non-coordination between the process safety elements, therefore, becomes inevitable to keep the process safe whenever any change takes place in management, chemical process, critical process equipment and technology during routine process operation and non-routine activities. This will ensure the process safety with necessary CAPA in the respective element so that whole PSM functions as intended. There are no studies which have focused on the coordination of PSM elements and failure / effective implementation of PSM system. This leads to proposition of various research ideas discussed in the ensuing section.

8. RESEARCH IDEAS OR PROPOSITIONS

Aligned with the last research objective, the following research ideas are proposed for future research towards identifying the causative factors of incidents in PSM implemented process and chemical industries:

a. Review major incidents / disasters occurred in oil & gas and chemical process industries practicing PSM, nation / international vide for the last 20 – 25 years.

b. Review the incident reports/ case studies and identify the causative factors pertaining to PSM elements.

c. Compare whether the causative factors are similar for all types of industrial disasters in process industries.

d. Explore whether the causative factor is ineffective implementation of any PSM element(s) or coordination failure of one main element with other elements.

e. Identify the PSM element which is not effectively implemented with respect to its sub-element leading to incidents.

f. Analyse based on incident analysis, how often one element is not coordinated with other which may be one of the significant causative factors for the disaster.

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