From Reports to Insights: Identifying Contributing Factors to Process Safety Incidents in New Chemical Safety Board (CSB) Incident Reports

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Abstract: As process safety incidents continue to occur in industries causing death and damage, it is important to identify trends that lead to loss of containment. In this work, we review 81 process safety incidents across a variety of industries to find the root causes. Incidents were categorized according to 18 different contributing factors, based off the Center for Chemical Process Safety (CCPS) elements of risk-based process safety. The most common factors were asset integrity and human factors. The incidents that involved human factors were analyzed through the lens of the Phoenix human reliability analysis (HRA) model, to test whether the model helps explain human failure events in process safety incidents across a variety of industries. The model helped in identifying mechanisms of failure and performance influencing factors but had blind spots regarding cooperation between teams.

1. INTRODUCTION

The process safety field has progressed significantly since the Bhopal disaster in 1984, which brought attention to process safety and lead to the creation of the Chemical Safety Board (CSB) in the United States. Despite this attention and progress, process safety incidents continue to occur, causing death, injury, and damage to facilities, and so it continues to be important to investigate process safety incidents.

One way to prevent process safety incidents is to investigate past incidents and investigate conditions that lead to the failure that should be avoided, taking a "lessons learned" approach. The process safety field continues to advance, iterating on methods to analyse past events[1], and identifying trends across multiple incidents[2, 3, 4]. This paper will analyse process safety events in a manner similar to Bhusari et al[3] which categorized incidents by the type of root cause.

These papers identify human and organizational factors as contributing to a significant number of incidents, with Ness, 2015[2] identifying the importance of company culture and management systems in preventing incidents, and Bhusari et al.[3] found the most common factors to be Safety Culture and Emergency Preparedness and Response, however Wang et al.[4] found the most significant contributing factors to be Design and Preventative Maintenance, with factors like Safety Culture and Operating Procedures to be still prevalent. Overall, this shows a trend of company culture and management to be significant factors in process safety incidents.

One of class of contributing factor, human factors, is analysed more in depth in the field of human reliability analysis. This field has created multiple models to identify different types of human failures and why those failures occur[5, 6, 7, 8, 9]. La Fata et al. found that while there is significant and growing research on both process safety and HRA, there is little research on HRA in the process industry [10]. Of the research that focuses on HRA in the process safety industry, most focus on the petrochemical industry, either creating HRA frameworks for the petrochemical [11, 12] or offshore oil and gas[13, 14] industries or conducting eye-gaze tracking studies on the human failure rate in control rooms [15, 16, 17, 18].

This paper will focus on a set of incidents reported on by the CSB that occurred recently, between 2020 and 2025. We will classify incidents by contributing factor, and then further investigate the most found root causes to find issues repeatedly causing process safety incidents.

2. DATA: U.S. CHEMICAL SAFETY BOARD (CSB) INCIDENT REPORTS

The Chemical Safety Board (CSB) is a US government agency that investigates accidental chemical releases from companies that result in death, injury, or significant property damage. In 2020, the Accidental Release Reporting Rule went into effect which required all fixed facilities to report accidental chemical releases resulting in deaths, serious injuries, or property damage over $1 million. The CSB has released summaries of 81 of the incidents in three different volumes.
These summaries cover events disclosed under the Accidental Release Reporting rule that the CSB did not to conduct a full investigation on. The incidents span from March 2020, when the reporting rule went into effect, to January 2025. In total, the summarized incidents resulted in 14 fatalities, 65 serious injuries, and $3.5 billion in property damage.

3. METHODS

3.1. Phase 1: Overall Analysis of Reports: Operating Phase, Contributing Factors

To analyse the set of incident reports by the CSB, we read the set of reports and classified each incident by incident, using the North American Industry Classification System (NAICS) by looking both at how the facility was described in the report and researching the company. Each incident was also classified according to the operating phase during the release, as normal operation, maintenance, startup, shut down, or temporary operations, as defined in **Table 1**. The phase of operation at the time of incident was decided based of information in the report.

Table 1: Definition of operating phases

Phase of Operation	Definition
Normal Operation	The normal processes, including any maintenance work that occurs on equipment in operation
Maintenance	Maintenance work on process equipment while the normal process is not occurring, including routine procedures
Startup	Restarting a part or a whole of a process, including any releases that occur after startup but due to conditions occurring in startup and not normalized before the release
Shut Down	Shutting down a part or a whole of a process before the incident occurs, whether planned or unplanned
Temporary Operations	Processes that are temporary measures due to a process upset

We categorized the incidents by the phase of the chemical release, whether solid, gas, liquid, or two phase. The phase was categorized as the phase of the chemical after the release so a liquid under pressure that vaporized upon release would be classified as gas.
The hazard types used to classify the incidents were explosion, fire, toxic, thermal, and pressure. Each incident was classified with only one hazard type, whichever was the most specific to the incident. An incident involving an explosion and fire, would be classified as an explosion.
For each incident, we created a causal chain was that broke apart the incident into individual events, decisions, and preexisting conditions and linked events or conditions by causality. This causal chain was then used to find the main cause of the incident.
Using the fourteen contributing factors from Bhusari et. al [19] plus four more factors, as defined in **Table 2**. The added contributing factors are safeguards controls & layers of prevention, contractor management, pre-startup safety review, and external events. Each event was assigned one primary contributing factor that lead directly to the incident. Any other contributing factors that were involved for an incident were labelled as secondary contributing factors, regardless of the number.

Table 2: Contributing Factors Used in Analysis, based on Bhusari et. al

Contributing Factor	Definition or description

Safety culture	CCPS defines safety culture as “the common set of values, behavior, and norms at all levels in a facility or in the wider organization that affect process safety.” A weak safety culture implies lack of leadership, lack of a common understanding of everyone's responsibilities regarding safety, ineffective supervisory oversight, placing production before safety, ineffective safe management systems, and not measuring proper personnel and process safety metrics.
PHA	PHAs (Process Hazard Analysis) use methodologies including but not limited to Checklist, What if, HAZOP (Hazard and Operability) study, and FMEA (Failure Mode and Effects Analysis). They are commonly done by a team consisting of representatives of operations, engineering, maintenance, and so on. In the US, compliance with OSHA PSM requires they be performed at least every 5 years.
Mechanical integrity	The inspection, testing and maintenance of process equipment must consider the hazards and risks of the operations, including such equipment as vessels, storage tanks, piping systems, relief systems, controls, alarms, and emergency shutdown systems. Best practices include written procedures and a schedule for inspections and testing to ensure fitness for use during equipment lifetime.
Emergency and preparedness response	Equipment, processes, and training must be capable of handling emergencies such as spills, fires, explosions, hurricanes, security breaches, and so on. Best practices include written procedures, defined teams with clear roles and periodic training and drills, which may include appropriate external parties.
Personnel Training	Comprehensive program of on the job training (OJT) and informative/technical training of employees and contractors (including supervisors). Program must be documented and include periodic refresher training and assessment of competency.
Operating Procedures	Written operating procedures aligned with process safety that provide clear step-by-step instructions for safely performing tasks involved in each process. Typically include operating limits, safety and health considerations, and safety systems, for multiple operating modes—initial start-up, normal operations, shutdown, and so on as noted by OSHA PSM.
Preventive Maintenance	Preventive maintenance is the periodic inspection of equipment to reduce the likelihood of its failure or performance degradation. This is to ensure the equipment is safe to operate and to fix issues thus preventing major hazards due to equipment malfunctioning.
Management of Change	CCPS defines Management of Change (MOC) as “a process to ensure changes do not inadvertently introduce new hazards or unknowingly increase risk of existing hazards.” MOC includes a review and authorization process for evaluating proposed adjustments to facility design, operations, organization, or activities prior to implementation to make certain that no unforeseen new hazards are introduced and that the risk of existing hazards to employees, the public, or the environment is not unknowingly increased.
Work permit System	A work permit system is a formal written system used to control certain types of work (hot work, work at height or confined spaces, etc.) that are not part of routine operations and potentially hazardous. The document typically specifies the work to be done and the precautions to be taken to mitigate hazards, typically reviewed, and signed off on by site supervision.
Regulations and Regulatory Oversight	There are varieties of regulations (OSHA, EPA, DHS, etc.) that protect people in and outside the site, as well as the environment. May include periodic regulatory inspections/audits. While this does not directly cause incidents, regulations set a minimum standard for operators.
Design	Designs should consider RAGAGEP (Recognized and Generally Accepted Good Engineering Practices), reflecting hazards, safety systems and instrumentation. It is often subsequent modifications to the design that lead to the introduction of unintended hazards.

Human & Organizational Factors	Human and organizational issues, such as equipment related (eg, valve location, lighting), sufficient staffing, as well as broader organizational issues. Shortcomings can result in accepted “normalization of deviance” by operators.
Hazard Awareness and Identification	The process of identifying all hazards in the workplace that can cause potential harm to personnel, environment, or processes and eliminating these hazards to reduce workplace incidents (eg, ventilation and gas monitoring). It is commonly done by a hazard assessment survey of operations, process safety information like safety data sheets (SDS), proper housekeeping for cleaner and safer workplace, equipment and materials, recording incidents and near misses, and so on.
Facility siting	Proximity of facilities to the public, as well as location of on-site plant personnel to hazards. Considers analysis of consequences of flammable and/or toxic hazardous materials.
Contributing Factors	This Element ensures that contractor workers are vetted for their specialized services and can perform their work safely using facility standards [20].
Safeguards, Controls, & Layers of Prevention	Any device, system, or action that interrupts the chain of events following an initiating event or that mitigates the consequences of an event, engineered mechanisms and administrative policies, or independent devices, systems, or actions that are provided to reduce the likelihood and severity of an undesired event [20].
Pre-startup Safety Review	A systematic and thorough check of a process prior to the introduction of a highly hazardous chemical to a process. The PSSR must confirm the following: Construction and equipment are in accordance with design specifications; Safety, operating, maintenance, and emergency procedures are in place and are adequate; A process hazard analysis has been performed for new facilities and recommendations have been resolved or implemented before startup, and modified facilities meet the management of change requirements; and training of each employee involved in operating a process has been completed [20].
External Events	Event caused by (1) a natural hazard-earthquake, flood, tornado, extreme temperature, lighting, etc.; or (2) man-induced events-aircraft crash, missile, nearby industrial activity, sabotage, etc., or (3) an interruption of facilities such as electric power or process air [20].

3.2. Phase 2: A Focus on Human and Organizational Factors as a Contributing Factor to Incidents

The second phase of the investigation involved looking further into the events that involved human factors, as primary or secondary contributing factors. In order to further investigate those incidents, the Pheonix HRA framework was used [21]. This framework classifies potential incidents into different Human Failure Events (HFE) which occurs via Crew Failure Modes (CFM) in which different Performance Influencing Factors (PIF) are involved. The HFE are split into different phases, the information gathering stage, decision making stage and action stage.

The Bayesian networks identified by Ekanem[21] in the context of nuclear power plant (NPP) control room operations were used to investigate incidents with sufficient reported detail that included failure due to human factors. The PIFs on the Bayesian networks that were noted in the incident reports was marked, along with the HFE and CFM involved.

4. RESULTS

4.1. Phase 1: Results of Overall Analysis

The three volumes of reports from the CSB cover incidents involving a wide range of industries, covering 13 different sectors as defined by the 3-digit NAICS codes. The most frequent industries involved were Petroleum and Coal Products Manufacturing, and Chemical Manufacturing, the traditional topics of process safety. A third of the incidents were in different industries, including utilities, food paper and other manufacturing.

Table 3: Incidents by Industry Sector

Industry Sector	NAICS code	Count
Petroleum and Coal Products Manufacturing	324	28
Chemical Manufacturing	325	27
Utilities	211	5
Paper Manufacturing	322	5
Food Manufacturing	311	8
Other Manufacturing	(312, 321, 327, 332)	4
Other Non-manufacturing	(213, 486, 493, 563)	4

Figure 2 shows the phase of operation at the time of the incident, with 41 out of 81 of the incidents occurring during normal operation. During a plant being shut down for maintenance, 25 incidents occurred. However, each incident was also classified according to whether maintenance actions were taken during and leading up to the incident, and a total of 34 incidents involved maintenance actions, of which 10 incidents occurred during normal operation.

Figure 1: Phases of operation involved in CSB incident reports

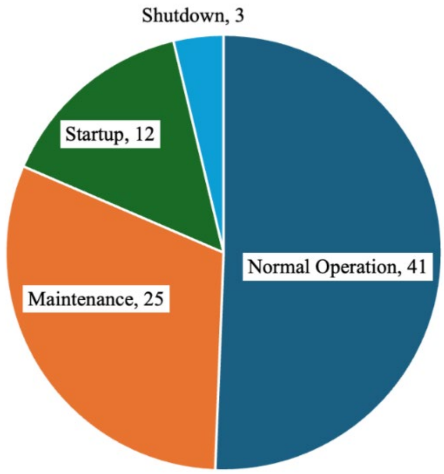
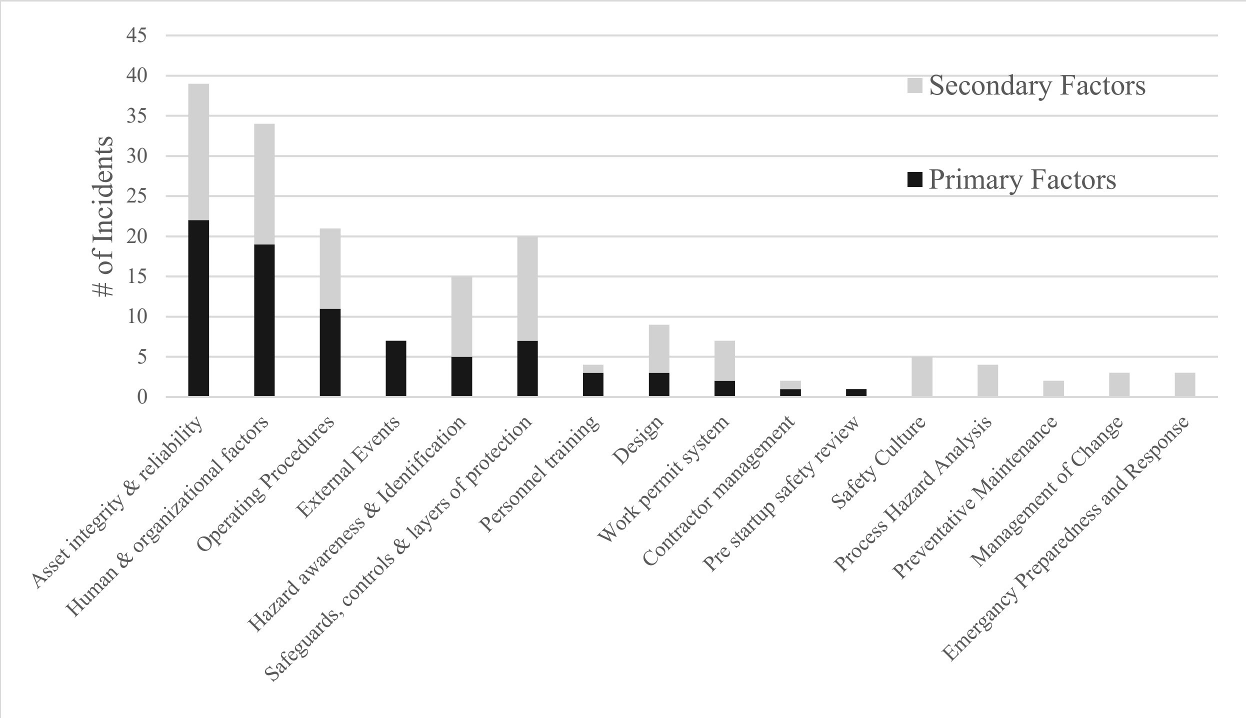


Figure 3 shows the factors by the number of times they occurred as a primary or secondary factor. The factor most frequently identified as the primary contributing factor was asset integrity & reliability, with 22 incidents being primarily caused with a failure of asset integrity. Similarly, 19 incidents were primarily caused by failures in human & organizational factors. A total of 11 incidents were caused due to issues with operating procedures, whether due to missing, incomplete, or incorrect operating procedures. In Figure 2, the number of incidents which can be attributed to each contributing factor as primary or secondary is shown. Some factors, such as hazard awareness, safeguards, controls and layers of prevention, design, or contractor management, were more common as a secondary factor than a primary factor and other factors including safety culture and process hazard analysis were only identified as secondary factors to the incidents and were not identified as the primary factor in any incident studied. No incidents were identified to include failures in facility siting or in regulations or regulator oversight.

Figure 2: Number of Incidents involving primary and secondary factors



The most prominent contributing factors, Asset Integrity & Reliability and Human & Organizational Factors, were the both the most common as primary factors and as secondary factors. These contributing factors were both investigated in more detail to gain more insight into patterns causing process safety incidents. One thing to note is that the numbers of primary factors and secondary factors are not the same, as some incidents only had one identifiable contributing factor which became the primary factors, whereas some had multiple contributing factors from different categories, and as such had two or three secondary factors.

Figure 3: Heatmap of prevalence of secondary factor by primary factor

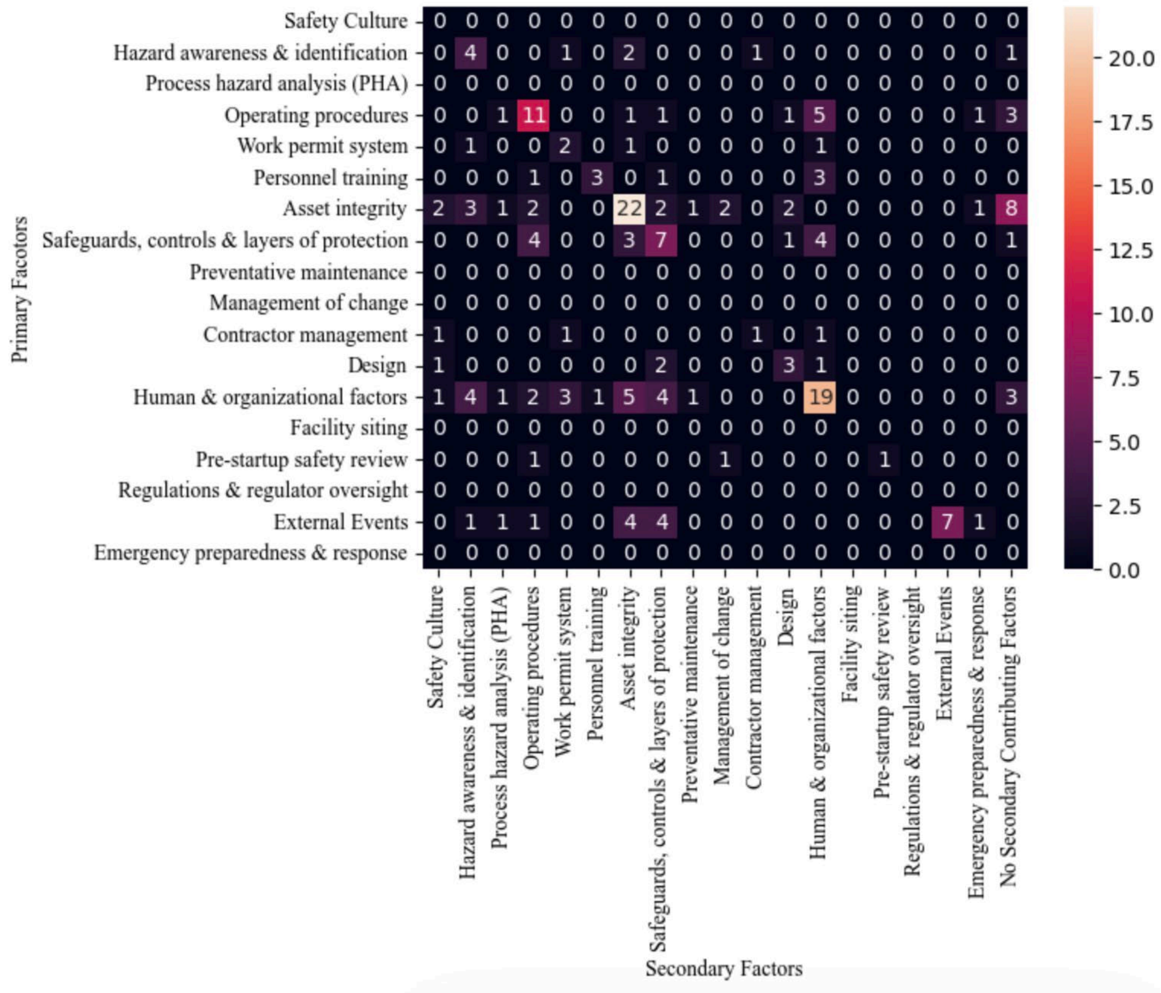


Figure 4 shows the linkage of each primary factor with the other factors as secondary factor, with the total number of incidents with that primary factor in the diagonal. For incidents with asset integrity as a primary factor, the secondary factors were evenly distributed across nine secondary factors. When human and organizational factors was the primary factor, the most common secondary factors were asset integrity, hazard awareness and identification, and safeguards and layers of prevention. One clear connection occurred between operating procedures as a primary factor and human and organizational factors as a secondary factor– five out of the eleven incidents attributed to operating procedures also involved human factors. This follows expectations because operating procedures are a performance influencing factor for human failure events [23].

4.3. Phase 2: Human Factors

The most frequent human failure modes from the Pheonix HRA[23] were "inappropriate strategy chosen" occurring in nine incidents, "procedure step omitted" occurring in five incidents, and "incorrect operation of component/object" occurring in five incidents. These frequencies are shown in Figure 6 and Table 5. There was a significant overlap between incidents involving human factors and operating procedures.

Table 4: CFMs by Frequency

Information Stage	I1	Key alarm not responded to (intentional and unintentional)	3	7
	I2	Data not obtained (intentional)	1	
	I3	Data discounted	0	
	I4	Decision to stop gathering data	0	
	I5	Data incorrectly processed	0	
	I6	Reading error	1	
	I7	Information miscommunicated	2	
	I8	Wrong data source attended to	0	
	I9	Data not checked with appropriate frequency	0	
Decision-making Phase	D1	Plant/system state misdiagnosed	1	17
	D2	Procedure misinterpreted	0	
	D3	Failure to adapt procedures to the situation	1	
	D4	Procedure step omitted (intentional)	5	
	D5	Inappropriate transfer to a different procedure	1	
	D6	Decision to delay action	0	
	D7	Inappropriate strategy chosen	9	
Action Phase	A1	Incorrect timing of action	3	10
	A2	Incorrect operation of component/object	5	
	A3	Action on wrong component/object	2	

4.4. Phase 2: Bayesian Network Modeling

Overall, we were able to implement the Pheonix HRA method to the incidents we studied. The factors that were mentioned in the reports as leading up to the human failure were almost all mentioned as expected performance influencing factors (PIFs) for the identified human failure event (HFE). However, the exception to this was from the Charleston, Tennessee Silicon Tetrachloride release incident, where, because the failures were due to coordination between two teams, there were elements not represented by the Bayesian networks. The line opening was performed by a contractor contrary to company requirements, so it is unclear if the contractors had the responsibility or the company workers to ensure the piping was cleaned and isolated. Due to this, it is difficult to evaluate what other factors led to the inaction as the two groups had different factors. Thus, the Bayesian networks would result in different PIFs leading to the identified CFMs depending on the team that is the subject of the analysis. This highlights the need for further research on modeling multi-party human reliability analysis.

We modeled three of the incidents in which human and organizational factors were the primary factor using Bayesian networks guided by the CFMs and HFEs from the Pheonix HRA framework. These incidents were the Meraux, Louisiana refinery fire, the Charleston, Tennessee silicon tetrachloride release, and the Rincon, Georgia hot water release

5. CONCLUSIONS

In this work, we surveyed three volumes of reports by the U.S. Chemical Safety Board covering 83 incidents involving chemical releases in 29 states. These incidents spanned multiple industries including the petrochemical, chemical, and food manufacturing among other industries. We classified the primary and secondary contributing factors to each incident by constructing a chain of events diagram for each of the events described in the investigative reports. Through this approach, we determined that the most frequent contributing factors were human and organizational factors, mechanical integrity, operating procedures, and safeguards, controls & layers of protection. Many of the mechanical integrity issues

were failures of equipment such as piping and valves. We found a significant overlap between human factors and operating procedures, explained by inadequate operating procedures being a factor that can contribute to human failure events.
For the incidents where human factors were a contributing factor, we applied the Pheonix HRA framework to identify a crew failure mode and potential performance influencing factors. Most of the incidents we modeled had failures in the decision-making phase, where the decision on how to act in the situation was made incorrectly. The model helped identify potential performance influencing factors, the factors mentioned in the reports matched with the and highlighting several that could have had an impact, but where not mentioned in the report. However, the framework did not clearly apply to human & organizational factors involving multiple distinct groups, such as outside contractors and employees of the operating company/entity.

6. FUTURE WORK

Human and organizational factors are a major cause of safety incidents in the process industries. However, structured human reliability analysis in these industries is an understudied area. Additional structured modeling of human failure events in the process industries holds the potential to reduce the likelihood and impact of these events. Human reliability analysis should be studied further outside of control rooms. The existing HRA frameworks should be evaluated for their ability to model events that occur with the interaction between multiple teams. If no frameworks are found that can sufficiently model inter-team work, a new HRA framework should be created or an existing framework modified to model human and organizational factors occurring in inter-team work. Such an approach would help engineers and decision-makers develop effective mitigation strategies against incidents that are attributed to human and organization factors.

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