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Chlorine Safety in Water Treatment: A Study of Causes and Preventive Measures Through Fault Tree and Event Tree Analysis

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ABSTRACT

Accidents in process industries, especially involving hazardous substances like chlorine, pose significant risks to humans, the environment, and property. This paper examines chlorine-related incidents in water treatment plants (WTPs), where chlorine gas is used for disinfection. Typically, WTPs store over 20 chlorine drums, each containing around 930 kg, increasing inherent risks due to chlorine's reactivity and health consequences upon exposure. Incidents such as the Bhopal 2022 case, which hospitalized 15 people, and the Kota Belud 2017 case highlight the importance of safe operation. This study aims to identify the root causes of chlorine-related incidents, assess their impacts, and recommend effective preventive measures to enhance safety. Using Fault Tree Analysis (FTA) to identify root causes and Event Tree Analysis (ETA) to evaluate preventive measures. Major failure causes included equipment damage, corrosion, non-compliance with design specifications, and mishandling. Preventive measures like leak detectors, scrubber systems, and Emergency Shutdown Systems (ESD) significantly reduce risks. If scrubbers fail but ESD works with trained personnel, or if scrubbers work but ESD fails without personnel, the impact remains medium. However, chlorine releases become catastrophic when all measures fail or only leak detectors work without effective mitigation systems.

1. INTRODUCTION

A water treatment plant is a crucial facility for preparing raw water for human consumption. Chlorine is commonly used in the chlorination process at water treatment plants to disinfect water and kill bacteria, viruses, and other microbes. It is one of the facility's key components and is essential to protecting the public from outbreaks of waterborne disease [1-4].

Based on the chlorine properties information, chlorine is a greenish-yellow gas at room temperature with a pungent, suffocating odor [5]. Exposure to chlorine can irritate the nose and throat and can cause respiratory system damage, with permanent loss of function possible in severe cases [6-8]. The American Conference of Governmental Industrial Hygienists (ACGIH), is a non-profit organization that creates guidelines for safe exposure to chemicals and physical agents in the workplace. ACGIH's guidelines are known as threshold limit values (TLVs) chlorine gas exposure at 0.5 ppm averaged over an 8-hour work shift, National Institute for Occupational Safety and Health (NIOSH's) recommended exposure limit (REL) of 0.5 part per million (ppm), and Occupational Safety and Health Administration (OSHA's) permitted exposure limit (PEL) of 1.0 ppm is the workplace exposure limit for chlorine [9]. Chlorine gas is also very reactive, corrosive, and very toxic. Based on the Acute Exposure Guideline Levels (AEGL) [10] issued by the U.S. Environmental Protection Agency (US EPA) informed that this chlorine gas can cause acute lethality effects on human health, and if exposed to chlorine gas to a concentration of 10 ppm in a certain period [11].

On 27 June 2022 in Aqaba Port, Jordan, a major hazard accident happened involving a chlorine tank with a capacity of 25 tons that leaked, resulting in the death of 13 people while 260 people were injured [12-14]. This incident shows the serious effects that chlorine can have if it is not managed safely. Based on the impact of chlorine is very serious, the WTP facility usually stores more than 20 tons of chlorine drums (1 ton or 930 kg per drum) to ensure continuous handling and operation safely.

This study conducts a thorough investigation of chlorine-related occurrences, including their surrounding impacts and underlying primary causes. The investigation systematically identifies and categorizes the root causes, allowing for the integration of preventive measures and probability studies using FTA and ETA [15]. Furthermore, the study emphasizes the importance of continuing to the next level of quantitative evaluation, where reliable methods such as FTA can improve forecast accuracy and risk mitigation strategies [16]. FTA is utilized to understand the causes of failures for improved system design and reduced failure risk. Diverse methods and tools are employed within FTA, including both qualitative and quantitative approaches, for the analysis of failure probabilities, which are crucial for enhancing system reliability [17].

FTA focuses on how systems might fail and the likelihood of those failures occurring. Major failures and their causes are visually represented by FTA, facilitating the prediction of the overall likelihood of system failure [18-21]. Meanwhile, researchers apply ETA to examine the outcomes resulting from the root causes of accidents (identified through FTA) while considering preventive and mitigation measures [22].

ETA begins with a selected initiating event, such as a failure. The elements influencing the outcomes are considered in turn. These could include the system's built-in safety functions, alternate external factors that influence the outcome, or different operator responses. Each is given as one or two options, such as “Yes” for success (a) and “No” for failure (å). The event tree is created by working from left to right, beginning with the initiating event and branching as each aspect is considered in turn [15].

In the study by Renjith et al. [23], FTA was employed to estimate the probability of chlorine release from the storage and filling facilities of a chlor-alkali industry. FTA provided a structured approach to identify potential hazards, specifically focusing on the release of chlorine by mapping out all possible causes and failures that could lead to such an incident. Similarly, Kumar and Singh [24] also utilized FTA to analyze chlorine-related incidents; however, they differentiated their approach by incorporating the α-cut interval-based similarity aggregation method (AIBSAM) to combine expert opinions and calculate the likelihood of failure. In contrast, the study extended the use of FTA beyond evaluating failure probabilities also to assess the consequences of each potential event, while the outcomes in ETA can range from minor to major consequences [15].

The objective of this study is to analyze the causes of chlorine-related incidents in water treatment plants using Fault Tree Analysis (FTA) and Event Tree Analysis (ETA). By examining past chlorine accidents, identifying failure pathways, and assessing the effectiveness of preventive measures, this study aims to propose effective mitigation strategies and ensure safe operations in water treatment facilities.

2. METHOD

2.1 Root cause analysis and preventive measures development in chlorine-related accidents at WTP

Several steps will be used to produce a comprehensive root-cause analysis of the chlorine incident. Figure 1 shows the method for comprehensive root cause analysis for chlorine-related incidents.

The methodology begins with collecting data from accident investigation reports, publications, journals, accident databases, and case studies to comprehensively understand chlorine-related incidents in WTP. This information is systematically evaluated to determine the location, effects, weather conditions, and underlying causes of each incident. Subsequently, the sequence of events leading to each accident is analyzed, focusing on scenarios such as chlorine leaks from drums and pipes, to construct a detailed FTA. Preventative measures are then identified and assessed through ETA, encompassing practices such as regular inspections of chlorine drums and pipe connections. Finally, insights derived from the FTA and ETA are integrated to develop a comprehensive framework of root causes and corresponding preventive measures, aimed at enhancing safety and mitigating risks in WTP operations.

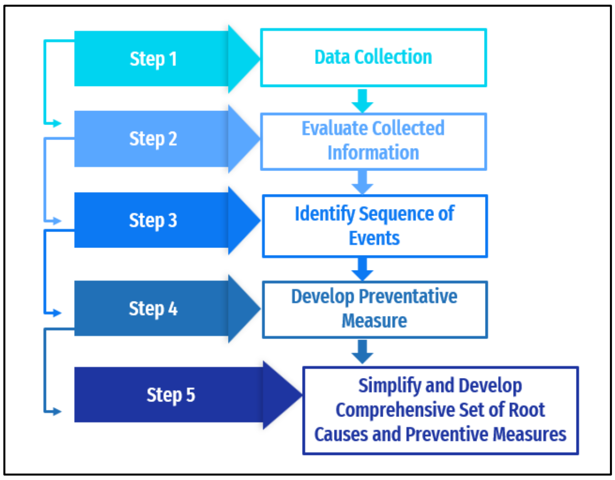
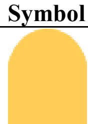


Figure 1. Flowchart of the method for comprehensive root cause analysis of chlorine-related incidents

2.2 Fault Tree Analysis (FTA)

Fault Tree Analysis (FTA) is a deductive method used to identify and analyze factors contributing to an undesired "top event." It traces the causes of the top event through a tree diagram, illustrating their logical relationships. The diagram includes basic events (causes), intermediate events (cause combinations), and gates (e.g., AND, OR) that define how the causes interact to result in the top event. The gate symbols used in FTA are shown in Table 1.

Table 1. The gate symbols used in FTA [25]

Symbol	Meaning	Description
	Logic gate AND	The output event happens only if all input events happen
	Logic gate OR	The output event occurs if any of the input events happen
	Basic event	Failure of a component that has no identifiable primary cause. It is the highest level of detail in the tree
	Undeveloped event	Failure of a component with a primary cause undeveloped because of lack of information
	Intermediate event	A fault event that occurs because of one or more antecedents causes acting through logic gates

2.3 Event Tree Analysis (ETA)

ETA was carried out on the example of a safety procedure for operating on the chlorine gas system by the operator in potential chlorine release. In the event tree method, the analysis starts with finding the causes (threatening factors) that lead to the resulting threats. In the tree event schema, the areas of the event header (description of the initiating events) are extracted. In this case, the method allows analysis of complex safety systems and emergency procedures involving human operators. The event tree is constructed, working from left to right, starting with the initiating event and then branching as each factor is considered in turn. Figure 2 shows that simplified generic event tree [15].

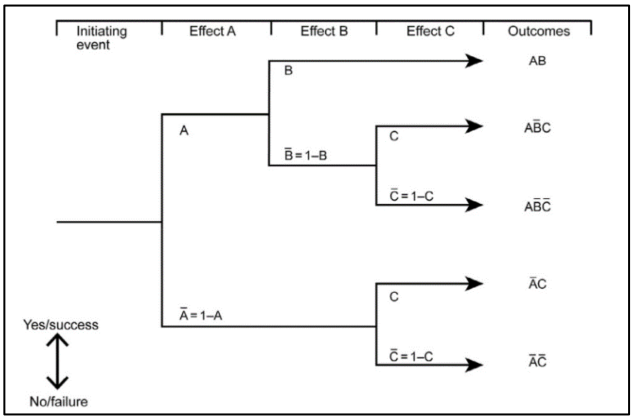


Figure 2. Simplified generic event tree [15]

3. RESULT

3.1 Develop detailed information from each chlorine incident

As a result of identifying chlorine leak incidents at the WTP facility, there are 16 chlorine incidents from the records from the Major Hazard Incident Data Service (MHIDAS) database [26] and five incident cases from the news. However, for this paper, only two chlorine incident cases were selected and analyzed comprehensively. The identified root causes from the two chlorine incidents were developed in FTA and ETA. Table 2 outlines selected cases of these incidents, which occurred at two different WTPs. Specifically, the incidents took place in WTP at Kota Belud Sabah, Malaysia [27] and WTP at Madya Pradesh Bhopal, India [28]. Therefore, this study aims to analyze these cases, seeking commonalities, understanding root causes, and proposing potential preventive measures to enhance safety in water treatment plants.

Table 2. Selected cases of chlorine incidents, which occurred at two different WTPs

	Location & Date of Incident	Land Use Area	Weather Condition	Surrounding Activity	Root Cause
Case 1	Kota Belud WTP, Sabah Coordinate: 6º 21' 20.41" North/ 116º 26' 05.58"East Elevation: 18m July 21, 2017	19490 m^2	Temperature: Day: 34℃ Night: 26℃ Humidity: 82% Wind direction: dominant wind blowing from East & South East direction	0m – 200m: Water treatment plant facility, residential area, villages, commercial area, school 200m – 500m: Sports center, shops, residential area, villages, district office, community hall, mosque, Kota Belud township, light industrial park 500m – 1km: Villages, integrated sewage treatment, shops, school, mosque, wet market, township, residential area	The leak was caused by a hole in one of the valves connected to the chlorine tank, and then managed to stop the leakage by tightening the valve immediately. The failure occurred at the drum / fusible plug/valve.
Case 2	Bhopal WTP, Madya Pradesh, India Coordinate: 23º 24' 19.49" North/ 77º 24' 46.34" East Elevation: 586m October 21, 2022	3797.60 m^2	Temperature: Day: 32℃ Night: 16℃ Humidity: 66% Wind Direction: dominant wind blowing from North & South West direction	0m – 200m: New Vidhan Sabha - Provincial Council, parking area, shop lot, water treatment facility, Nagar Nigam water treatment plant and recreation park 200m – 500m: Hotel, recreational area, township, office building, residential area, and shop lots. 500m – 1km: School, college, residential area, government office, stadium, hospital, temple, shopping mall, hotel, office building, shopping mall, shop lots, and recreational park.	Found that the nozzle of a 900-kg chlorine gas cylinder installed at the water treatment plant in the area had started leaking due to malfunction.

Table 3. Revised, updated, and newly identified root causes of the chlorine incident from Molla and Yusoff [29]

Top Event (B)	C	D	E	F
Chlorine leak & release at drum (B1)	Failure at operation drum and its drum component (C1)	Damage drum and its fittings component drum (D1)	No fittings leak test (E1)	No safe operating procedure (SOP) for fittings (F1) No fittings inspection (F2)
			Fittings hit by hard object (E2)	Fall down from hoist machine (F3) Fall down from forklift (F4)
			Improper handling and storage practice (E3)	Undeveloped event
	Failure from the standby drum and its essential fittings (C2)	Corrosion (D2)	Effect on moisture inside/outside drum (E4)	Undeveloped event
			Contaminants and impurities contribute to corrosion inside the drum (E5)	Undeveloped event
		Not follow the design specification (D3)	Chlorine drums deviate from the international standard design specifications (E6)	Undeveloped event
			No confirmation from procurement standard design (E7)	Undeveloped event
		Mishandling (D4)	No trained person (E8	Undeveloped event
			Human error (E9)	Undeveloped event

Table 4. Equations used to calculate the probability of FTA

Equation System for Top Event (B1) Chlorine Leak and Release
B1 = C1 + C2
C1 = D1 x D2 x D3 x D4
C2 = D1 x D2 x D3 x D4
D1 = E1 + E2
E1 = F1 + F2
E2 = F3 + F4
D2 = E3 + E4 + E5
D3 = E6 + E7
D4 = E8 + E9

3.2 Determine the series of events that led to the WTP chlorine facility accident

According to the same source, potential accidents in chlorine facilities can be caused by leakage in the operating drum C1 and standby drum C2. Since both cases share the same cause, the known sequence of accidents is identical. In the case of the WTP accident in Kota Belud Sabah, the failure occurred in the drum/plug/fuse valve B1, which may have also occurred in C1 and C2. If B1C1 and B1C2 experience failure, the possible causes may include damage to installation components (less than 1 inch) D1, corrosion (internal/external) D2, non-specification of chlorine drum and fittings D3, and mishandling D4. Table 3 highlights the revised, updated, and newly identified root causes of the chlorine incident, as reported by Molla and Yusoff [29]. It seeks to outline the sequence of events that contributed to the chlorine facility accident at the WTP. Figure 3 depicts the FTA developed to analyze chlorine leakage and release from the drum at the WTP. Calculating the probability of the main event in FTA is crucial for assessing risk, improving safety and reliability, and efficiently allocating resources. Hence, the equation used to calculate the probability of the FTA is shown in Table 4.

3.3 Combination of FTA and ETA

Based on Figure 3 and Figure 4, the result of root causes, preventive, and mitigation measures are connected as shown in Table 5. The findings presented in Figure 3 and Figure 4 highlight the nature of the interrelated causes, preventive actions, and mitigation measures for chlorine-related incidents at WTP. Table 5 consolidates this information, illustrating how specific root causes, such as corrosion or equipment failure, align with targeted prevention and mitigation strategies. For example, the use of scrubbers and leak detectors directly addresses the risks posed by chlorine leaks, while regular inspections and staff training reduce issues of improper operation and maintenance. This integrated approach emphasizes the importance of a comprehensive safety framework, where addressing root causes increases the effectiveness of mitigation measures, ultimately increasing operational resilience in WTP facilities.

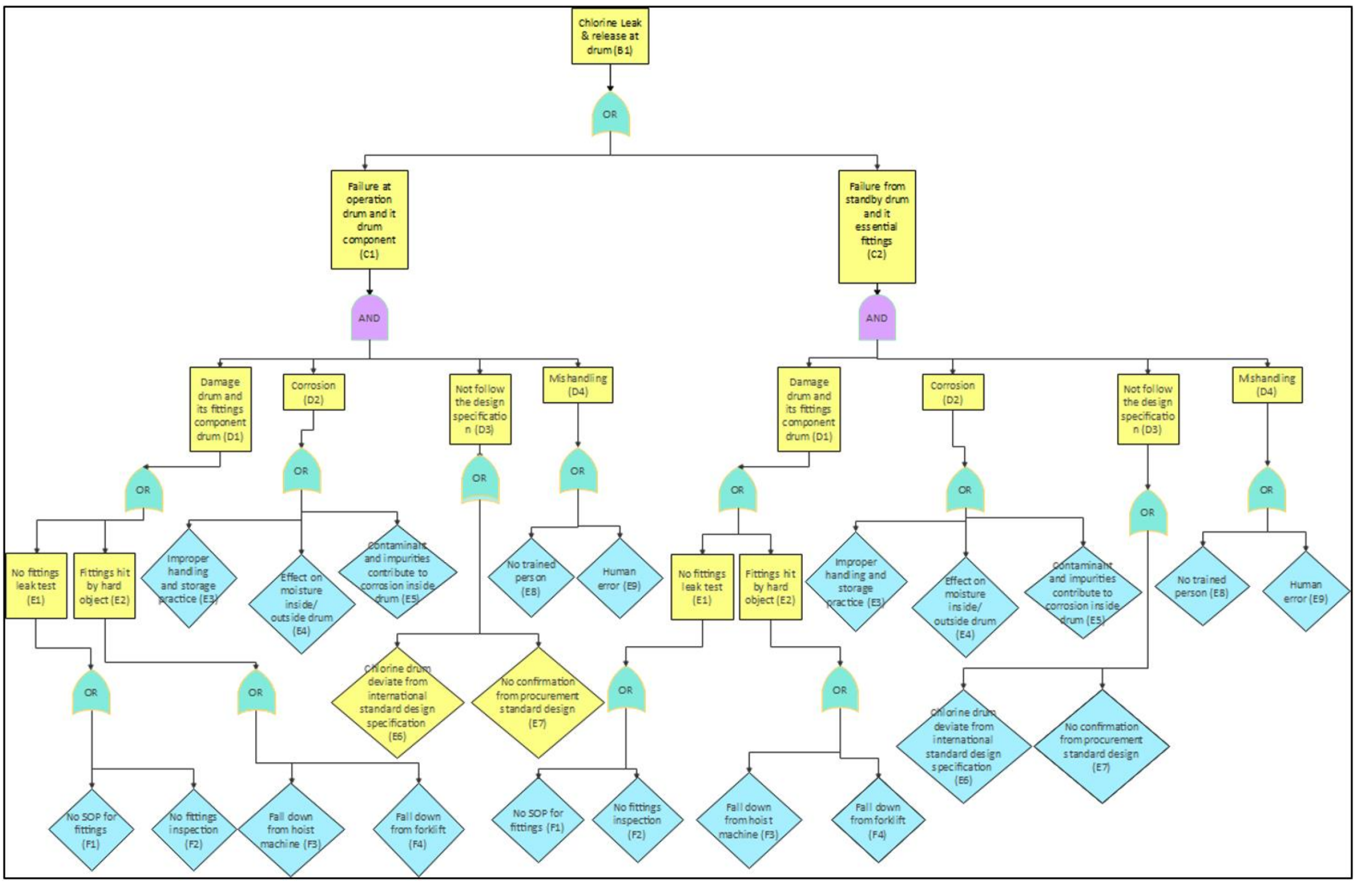


Figure 3. FTA chlorine leak and release at drum in WTP

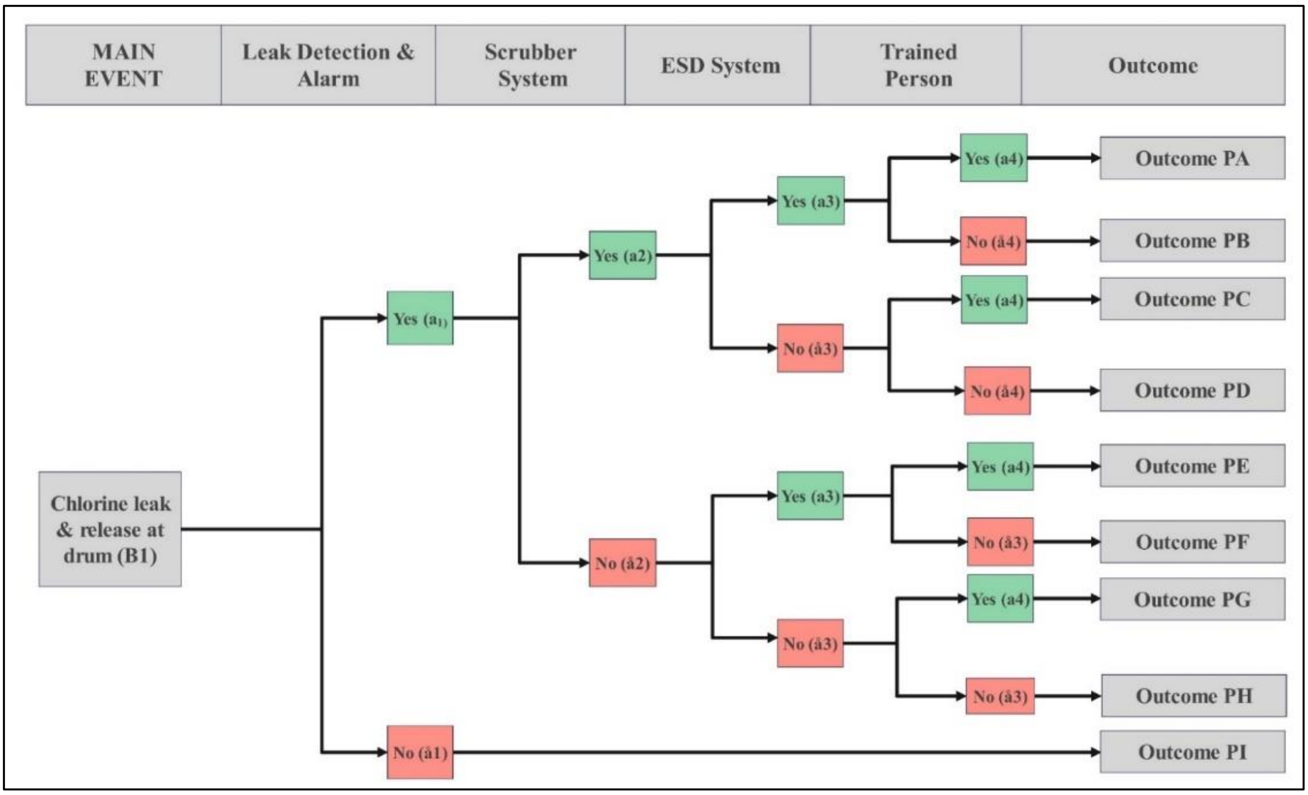


Figure 4. ETA chlorine leak and release at drum in WTP

Table 5. Combination of FTA and ETA results

Multiple Causes	FTA		ETA	
	Equation System	**Top Event**	**Outcome Mitigation Measures**	**Consequences**
Damage drum and its fittings component (D1)	P(D1) = P(E1) + P(E2) P(E1) = P(F1) + P(F2) P(E2) = P(F3) + P(F4)	Chlorine toxic release at operation drum and its drum component P(C1) = P(D1) x P(D2) x P(D3) x P(D4)	$PA = PB_1Pa_1Pa_2Pa_3Pa_4$	The problem of leaks in chlorine drums can be overcome, and the facility is safe ● Safe
			$PB = PB_1Pa_1Pa_2Pa_3P\mathring{a}_4$	Leaks in chlorine drums can be overcome because gas detectors, alarms, scrubber systems, and ESD function well. ● Safe
			$PC = PB_1Pa_1Pa_2P\mathring{a}_3Pa_4$	The leak problem in the drum is still under control; however, the possibility of chlorine being released from the drum or leaking pipeline can still occur and get stuck in the chlorine room due to the ESD malfunctioning. So, the trained person is required to manually minimize chlorine leakage, such as closing the valve and closing the leaking drum in the facility by wearing suitable PPE like a Self-Contained Breathing Apparatus (SCBA) ● Safe
Corrosion (D2)	P(D2) = P(E3) + P(E4) + P(E5)		$PD = PB_1Pa_1Pa_2P\mathring{a}_3P\mathring{a}_4$	The problem of impact and leak effect on the drum can still be overcome even if the ESD fails to function and a trained person is absent. However, the potential impact of an accident could be significant if the chlorine room space is open. ● Under control (mild impact)
Not follow design specification (D3)	P(D3) = P(E6) + P(E7)	Chlorine toxic release from standby drum and its essential fittings P(C2) = P(D1) x P(D2) x P(D3) x P(D4)	$PF = PB_1Pa_1P\mathring{a}_2Pa_3P\mathring{a}_4$	The effects of chlorine accidents are controlled within the onsite perimeter (if chlorine gas is trapped in the chlorine room) facility due to scrubber failure to function properly. However, the impact of chlorine impact on employees can be minimized by trained persons to ensure proper use of PPE and emergency action is more effective. ● Under control (mild impact)
Mishandling (D4)	P(D4) = P(E8) + P(E9)		$PF = PB_1Pa_1P\mathring{a}_2Pa_3P\mathring{a}_4$	The effect of chlorine accidents is significant in the onsite perimeter (if chlorine gas is trapped in the chlorine room) facility due to the scrubber system's failure to function properly. In addition, the impact of chlorine on employees is unlikely to be minimized by no trained persons to ensure proper use of PPE and emergency action is more effective. ● Slightly under control (medium impact)

PG = $PB_1Pa_1P\mathring{a}_2P\mathring{a}_3Pa_4$	The effects of chlorine accidents are likely to be uncontrollable within the onsite perimeter (if chlorine gas is trapped in the chlorine room) facility due to scrubber failure and ESD functioning properly. However, the impact of chlorine on employees can be minimized by ensuring that trained personnel properly use PPE and by implementing effective emergency actions. ● Out of control (medium to severe impact)
PH = $PB_1Pa_1P\mathring{a}_2P\mathring{a}_3P\mathring{a}_4$	The effects of chlorine accidents are potentially severe ● Catastrophic
PI = $PB_1P\mathring{a}_1P\mathring{a}_2P\mathring{a}_3P\mathring{a}_4$	The effects of chlorine accidents are potentially severe ● Catastrophic

4. DISCUSSION

The findings from the FTA and ETA provide a systematic understanding of chlorine-related risks in WTP. From the FTA results, multiple root causes were identified, including damage to drums and fittings (D1), corrosion (D2), deviations from design specifications (D3), and mishandling (D4). Each root cause was further broken down into contributing events (e.g., E1, E2, E3), enabling a quantitative assessment of their probabilities. The analysis highlights the interdependencies between failure mechanisms, such as the combined impact of corrosion and mishandling, emphasizing the importance of addressing these root causes to prevent chlorine leaks.

The ETA results focused on mitigation and prevention measures. Scenarios were analyzed based on the functionality of safety systems, including gas detectors, alarms, scrubbers, and ESD. The outcomes ranged from “safe” to “catastrophic,” depending on the performance of these systems and the involvement of trained personnel. For instance, while functional scrubbers and ESD can significantly reduce risks, their failure, coupled with untrained personnel, may escalate the consequences to catastrophic levels.

The combination of FTA and ETA provided insights into critical failure pathways and their consequences. Table 5 connects these pathways with mitigation measures, illustrating the relationship between specific root causes and outcomes. For example, mishandling (D4) combined with scrubber failure (PF) leads to medium impacts that may be managed through proper PPE and trained personnel, while system-wide failures (PH, PI) result in catastrophic consequences.

The results from Table 5 show the consequences of chlorine release incidents at WTP. The consequences of chlorine-related incidents range from safe operation to catastrophic, depending on the effectiveness of preventive measures. In a safe operation, all systems leak detection, scrubber systems, ESD, and trained personnel function effectively, ensuring chlorine leaks are fully controlled with no significant impact on health, the environment, or operations.

Under a medium impact, partial failures occur. For instance, if the scrubber system fails but ESD functions and trained personnel manage the leak, the ESD ensures that the remaining chlorine is contained and prevented from being released into the atmosphere, while the trained personnel promptly implement emergency procedures following chlorine leak response standards to minimize the impact effectively. Similarly, if the scrubber system works but ESD fails without trained personnel, the impact remains contained within the facility because the scrubber system captures and treats the released chlorine gas, mitigating its toxic effects.

When multiple systems fail, the situation escalates to a medium to severe impact. For example, failures in both the scrubber and ESD systems, combined with limited mitigation, result in partial control with significant risks extending beyond the facility. In the worst-case scenario, a catastrophic event occurs when all preventive measures fail or only the leak detection system functions without effective mitigation or control. This leads to uncontrolled chlorine gas release, causing widespread health impacts, severe environmental contamination, and potential fatalities.

5. CONCLUSIONS

This study analyses two case studies of chlorine-related incidents at WTP to identify causes and evaluate mitigation measures using FTA and ETA. The results show that chlorine leakage can be effectively reduced if critical systems such as leak detectors, scrubbers’ systems, and ESD are functioning optimally. When this system is in operation, the resulting chlorine leak remains contained within the facility, avoiding severe impacts. However, in a scenario where the emergency shutdown system fails, safety can still be maintained through the performance of effective scrubbers, leak detectors, and trained personnel, limiting the consequences to a manageable level. Conversely, the failure of multiple mitigation systems significantly increases the risk of catastrophic outcomes, highlighting the importance of redundancy and robust safety system protocols. Despite these findings, this study is limited to specific case studies and static probability analysis, which may not fully capture dynamic operating conditions or regional variations. Future research should expand the data set to include multiple case scenarios, use dynamic risk modeling techniques, and assess the long-term reliability of safety systems under operational stress. By addressing these gaps, future studies can further refine safety strategies and increase the resilience of WTP facilities to chlorine-related hazards, ensuring sustainable and safe operations worldwide.

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