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Accident Analysis Using Fault Tree Analysis: A Case Study of AB Specialty Silicones

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Abstract

Since the Industrial Revolution, industrial production processes have become increasingly complex, involving far more than just simple raw materials. The interaction of two or more incompatible substances can lead to severe consequences, including significant financial losses, environmental damage, and human injuries. Notably, while nearly all industries rely on a wide range of materials, many potential reactions within these processes remain poorly understood. A striking example is the 2019 incident at AB Specialty Silicones, which resulted in considerable human and financial losses. Fortunately, tools and techniques, such as fault tree analysis (FTA), can predict such events effectively.

In this research, we utilized the FTA method to identify the root causes of this accident, focusing on factors that would not have occurred if they had not been combined. By examining the key elements that directly contributed to the incident, we emphasize that proper control of these factors could have prevented it. Industrial accidents not only cause damage to organizations but also significantly impact safety culture and worker morale. To prevent such incidents, risk assessments must be complemented by learning from the experiences of other organizations. This dual approach acts as a shield, enabling companies to manage and control accidents more effectively.

Many studies primarily focus on the statistical analysis of accidents, often overlooking their root causes. This paper aims to address that gap by identifying and analyzing the dimensions of the incident to uncover its underlying factors. It is worth noting that, to date, no specific research has been conducted on the analysis and investigation of incidents in the silicone industry. The results of our research could serve as a foundation for further studies in this field.

Keywords: Fault Tree Analysis Method; Accident Analysis; Accident Modeling; Risk Assessment; Lesson Learning.

1. Introduction

Silicon is a material that possesses special physical and chemical properties, as silicone molecules are helical and their intermolecular forces are very low. This results in high elasticity and flexibility at both low and high temperatures (Métivier & cassagnau, 2019). Due to the characteristics of silicone and its unique properties, the applications of silicone in various fields are increasing day by day, leading to a significant rise in the demand for the production of silicone products as well as silicone molds (Aziz, Fan, Khan, Haroon, & Cheng, 2018). With the expansion of the growing trend of using and producing silicone materials in various industries, we are witnessing an increase in the number of these industries worldwide.

Taking into account the demand for silicone materials, we observe the growth of manufacturing companies and factories to meet this demand. Considering that this industry is younger than many others, it can be said that there are

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many risks that are still unknown or have not been thoroughly researched. In this paper, we aim to identify the existing risks by examining one of the accidents in this industry and helping other companies in this field recognize their work risks.

Accident analysis and investigation are widely recognized as crucial components of comprehensive and efficient safety management. Understanding the various causes embodied in past cases is of vital importance. On this basis, feasible mitigation strategies can be developed to avoid similar mistakes in the future (Wang & Yan, 2019).

During the last few years, researchers have developed many techniques for handling the problems of system safety and risk analysis, including Hazard and Operability Analysis (HAZOP), Fault Tree Analysis (FTA), Event Tree Analysis (ETA), and Failure Mode Effect Analysis (FMEA). All of these techniques share a common objective: to reduce catastrophic risk to an acceptable or tolerable level (Hamza & Hacene, 2019). Among these, we use FTA, a widely applied safety and hazard analysis technique (Ericson, 2015). It is well-structured, precise, and powerful, making it suitable for risk assessment and identifying the basic causes of specific events. It assists the analyst in identifying, evaluating, and analyzing all of the basic causes and paths that lead to the occurrence of a certain event. Furthermore, it shows the interrelationships and interdependencies of hazardous events and their corresponding root causes (Yazdi, et al., 2023). For these reasons, the FTA method is increasingly being adopted across various fields, such as dependability analysis (Kabir, 2017), reliability analysis (Hamza & Hacene, 2019), uncertainty handling (Zarei & Yazdi, 2018) and for risk assessment of train derailment (jafarian & Rezvani, 2012), hotel fires (Hu, 2016), container terminals (sunary & Hamka, 2017) , leaks in storage tanks (Ikwan, sanders, & Hassan, 2021), formal requirements for nuclear reactor protection (Jang, Yoo, & Lee, 2020), and shields for tunnels (Hyun, Min, Choi, Park, & Lee, 2015). Since the FTA method is one of the most versatile methods, it can be used in risk assessment, reliability analysis, incident analysis and in general, throughout the entire life cycle of a system. All the articles mentioned in the above paragraph are informative regarding this issue.

The fault tree itself is a graphic model of the various parallel and sequential combinations of faults that will result in the occurrence of a specific undesired event. The faults can be events associated with component hardware failures, human errors, or any other pertinent events that can lead to the undesired event. A fault tree thus depicts the logical interrelationships of basic events that lead to the undesired event, which is the top event of the fault tree. A fault tree is a complex of entities known as “gates,” which serve to permit or inhibit the passage of fault logic up the tree. The gates show the relationships of events needed for the occurrence of a “higher” event. The “higher” event is the “output” of the gate; the “lower” events are the “inputs” to the gate. The gate symbol denotes the type of relationship of the input events required for the output event (Vesely, Goldberg, Roberts, & Haasl, 1981).

This study provides a novel and focused analysis of industrial incidents within the silicone manufacturing industry, an area highly underexplored in accident analysis literature. Our contributions are as follows: This study provides industry-specific insights, as while fault tree analysis (FTA) has been extensively utilized in various sectors, such as nuclear safety, transport, and construction, its application to the silicone industry is unprecedented. This study pioneers the use of FTA to investigate the AB Specialty Silicones accident, filling a critical gap in safety management literature for this sector. By dissecting the AB Specialty Silicones explosion, this research identifies and highlights risks specific to the silicone manufacturing process, including the inadvertent mixing of incompatible chemicals like potassium hydroxide and TD 6/12 blend. Unlike prior studies that focus on general industrial risks, this work emphasizes chemical-specific hazards and their management. The research proposes targeted recommendations, such as redesigning container systems, improving safety culture, and implementing gas detection technologies, which are tailored to silicone production facilities. These are absent in broader studies, underscoring the study's practical significance. This work synthesizes common root causes from many industries, such as inadequate safety culture and emergency preparedness, and contextualizes them within the unique framework of silicone manufacturing. This cross-industry perspective strengthens the generalizability of findings. Compared to contemporary research in accident analysis, such as (Chen, et al., 2024) on fire risks in construction or (Liaw, Liu, Wan, & Tzou, 2023) on liquefied petroleum gas(LPG) explosion risks, this study diverges by focusing on sector-specific application, as unlike generic frameworks, this study tailors the FTA methodology to uncover risks unique to the silicone industry. It provides comprehensive qualitative analysis, while others, such as (Zhu, Tang, Li, & Fang, 2020), focus on quantitative modeling, this paper emphasizes qualitative root cause identification, which is pivotal for emerging industries with limited historical data. Finally, it offers practical recommendations, as the study bridges theoretical analysis with actionable safety improvements, which are often underdeveloped in similar research.

The description and methodology of the FTA are discussed in Section 2. Section 3 presents details of the incident that occurred at AB Specialty Company. The FTA map of the incident, along with its analysis, is provided in Section 4. The conclusion and recommendations are presented in Section 5.

1.1 Root Cause Finding in Related Research

The Fault Tree Analysis (FTA) method is widely recognized as one of the most precise and reliable approaches for incident analysis. It has been widely and effectively applied across various types of accidents due to its effectiveness in identifying root causes and providing actionable solutions. The validity of FTA is further supported by numerous studies referenced in this research, which highlight its ability to uncover critical underlying factors in incidents. Therefore, utilizing the FTA method in this study not only ensures a comprehensive analysis but also significantly enhances the credibility and reliability of the findings.

Extensive research has identified a variety of root causes across different industries. For instance, in fire incident analyses (Chen, et al., 2024) (Tunçel, Beşikçi, Akyuz, & Arslan, 2023), common root causes included design deficiencies, malfunctioning monitoring equipment, and the accumulation of flammable materials at construction sites. Similarly, in a tanker explosion analysis (Zhu, Tang, Li, & Fang, 2020), factors such as lack of experience, insufficient knowledge and skills, and weaknesses in company safety management policies were identified as major contributors.

Other studies (Liaw, Liu, Wan, & Tzou, 2023) (Sakar & Sokukcu, 2023) have highlighted additional root causes, such as improper management of changes, deficiencies in mechanical integrity, inadequate emergency planning, accidental mixing of incompatible chemicals, material leaks, poor safety culture, and insufficient maintenance of equipment.

By synthesizing the findings from these diverse studies, it becomes evident that while these incidents occur in different industries, certain root causes are consistently observed. These recurring causes, which are visualized in the chart below, emphasize shared challenges in safety management, although their relative impact varies depending on the specific context of each incident.

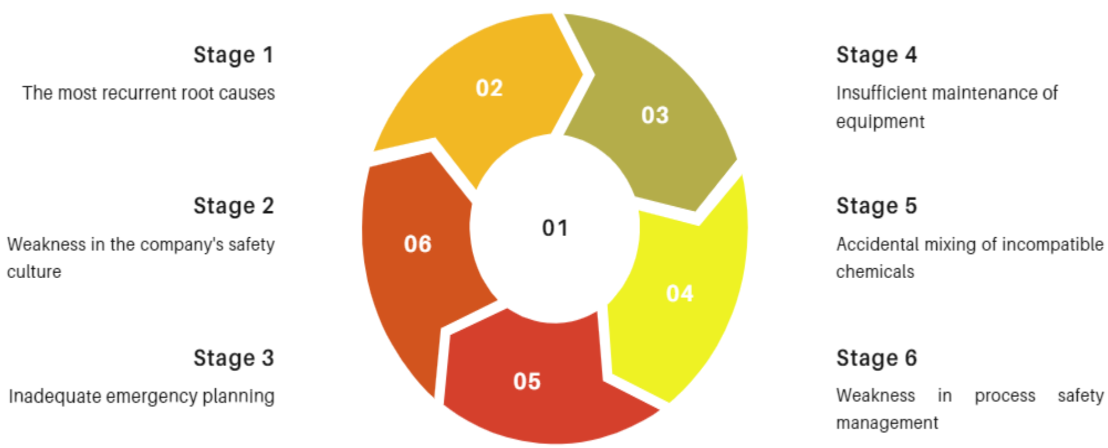

Figure 1. The Most Recurrent Root Causes (Provided by authors)

2. Theory of Fault Tree Analysis Method and Accident Analysis

Fault Tree Analysis (FTA) emerged in the 1960s as a response to the increasing complexity of engineering systems and the need for systematic safety assessments. The method was developed by the U.S. Air Force in an effort to improve the reliability and safety of military aircraft and missile systems. The motivation behind FTA was to provide a structured approach to identifying potential failures in complex systems and understanding how these failures could lead to catastrophic events. FTA is a systematic, deductive analytical tool applied in fields like engineering, safety, and risk management to identify and analyze the potential causes of system failures. By breaking down complex systems into simpler components, FTA helps organizations understand how different failures can interact to lead to undesirable outcomes, thus enabling better decision-making regarding risk mitigation and system reliability. The technique is widely used for both qualitative and quantitative assessment. The qualitative phase results in the minimal cut sets (MCS), which represent the system logic function as Boolean algebra to identify the combination of basic events in component failure modes. An MCS is a combination of basic events that cause the undesired event. The FTA process can be seen in Fig. 1 (Hu, 2016).

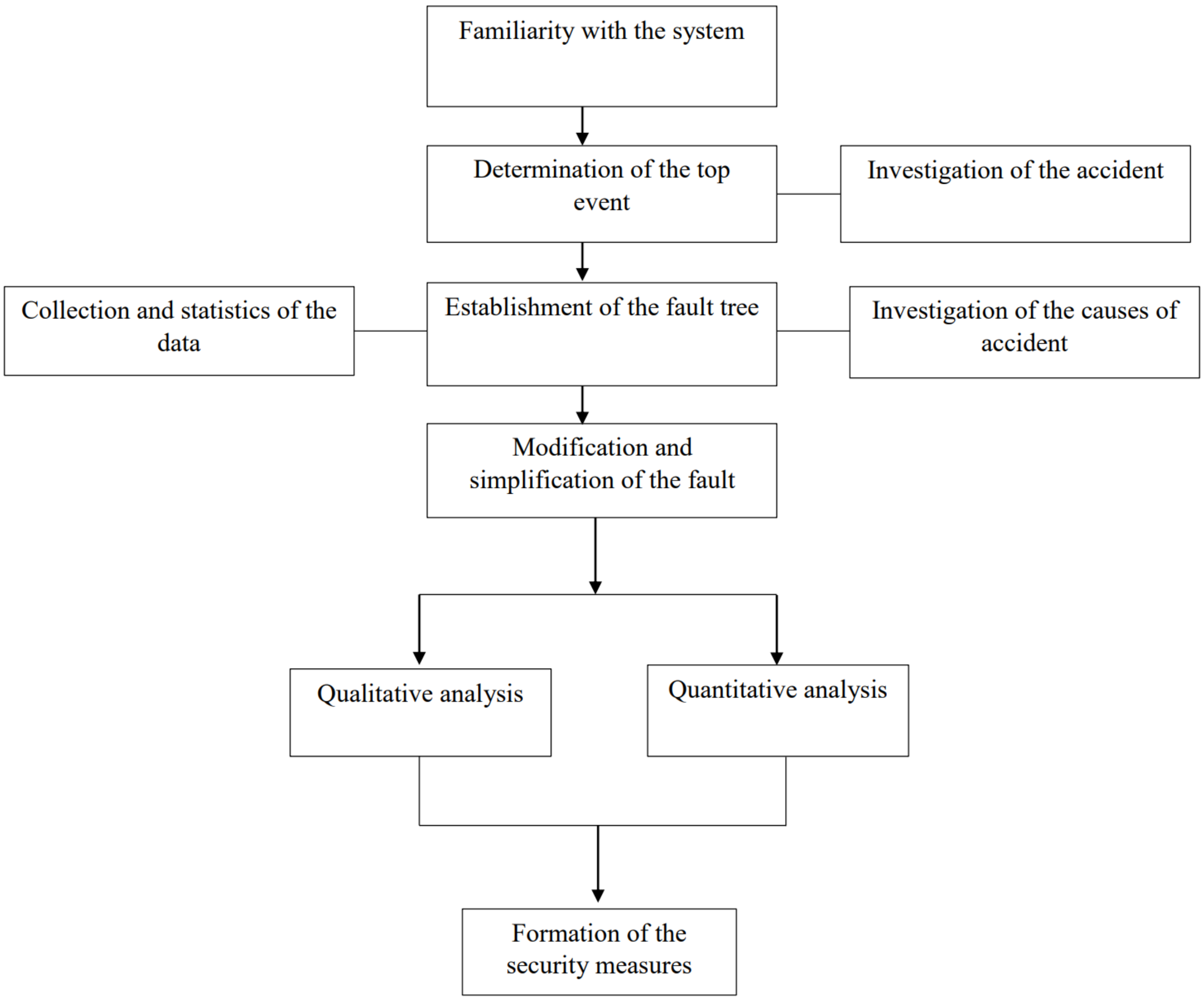

Figure 2. Fault Tree Analysis Process (Vesely, Goldberg, Roberts, & Haasl, 1981)

2.1. Structure of Fault Tree Analysis

The analysis begins with the identification of the top event (TE), which represents the undesired outcome or system failure that the analysis aims to prevent. This could be anything from a catastrophic failure in an aircraft to a minor malfunction in a manufacturing process. Basic events are the root causes that can lead to the top event. These are typically individual failures or faults in components, systems, or processes. The identification of basic events often involves brainstorming sessions, expert consultations, and historical data analysis (Hamza & Hacene, 2019).

The relationships between the top event and basic events are depicted using logic gates. The logic gates connect all the events in the fault tree, which essentially are: AND gate, where both of the basic events have to occur for the top event to occur, and OR gate, where one of the basic events has to occur for the top event to occur. Fig. 2 shows different kinds of gates.

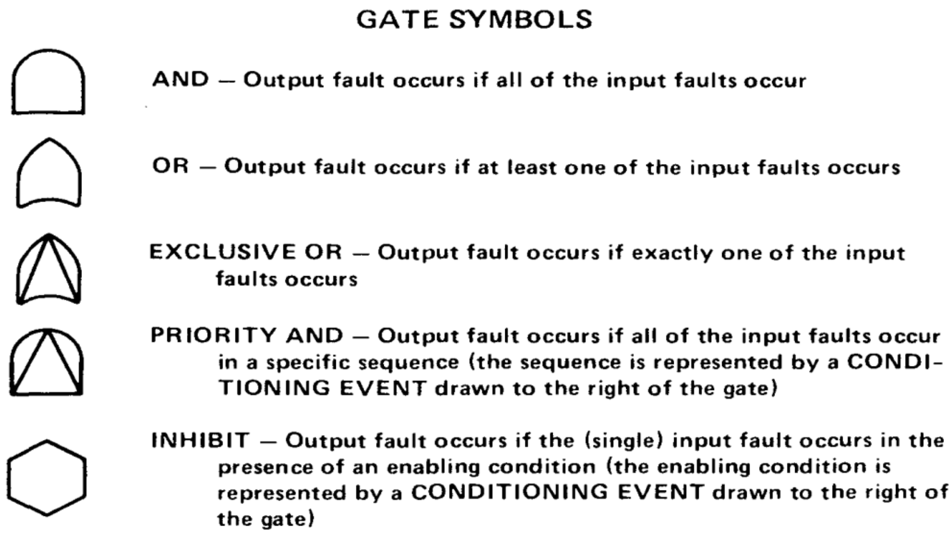

Figure 3. Gate symbols used in Fault Tree (Vesely, Goldberg, Roberts, & Haasl, 1981)

An AND gate is a basic logic gate that outputs true (or "1") only when all of its inputs are true (or "1"). If any input is false (or "0"), the output will also be false (Table 1). An OR gate is a basic logic gate that outputs true (or "1") if at least one of its inputs is true (or "1"). If all inputs are false (or "0"), the output will be false (Table 2).

Table 1. Truth Table of AND Gate (Provided by authors)

Input A	Input B	Output Y
0	0	0
0	1	0
1	0	0
1	1	1

Table 2. Truth Table of OR Gate (Provided by authors)

Input A	Input B	Output Y
0	0	0
0	1	1
1	0	1
1	1	1

2.2 Qualitative and Quantitative Analysis

Qualitative analysis of fault trees plays a crucial role in identifying potential factors that could lead to equipment failures. Central to this analysis are the concepts of cut sets and minimum cut sets. A cut set is defined as a collection of events that, when combined, lead to the occurrence of a top event, which ultimately results in system failure. The minimum cut set, on the other hand, represents the smallest subset of these events necessary to trigger the top event. This concept is fundamental in reliability statistics and serves as a indispensable tool in understanding system risks. By identifying the minimum cut set, analysts can gauge the likelihood of faults and assess the overall risk associated with the system. (Bai, 2023) believes that finding the minimum cut set can enhance the understanding of the possibility of fault occurrence and the associated risks of the system. When any event in the cut set is removed randomly, the cut set in which the top failure event no longer occurs is the minimum cut set, and everything in a minimum cut set can be considered equivalent to the top failure event.

To determine the minimum cut set, two primary methods are employed: the ascending method and the descending method (He & Xu, 2021). The ascending method begins with the bottom events and works its way up through the fault tree, utilizing set operations such as union and intersection to simplify calculations. This approach allows for an efficient reduction in operational complexity. Conversely, the descending method, often implemented through algorithms like those by (Vesely, Goldberg, Roberts, & Haasl, 1981), starts from the top event and moves downward. This method systematically replaces inputs at each logic gate, ultimately generating a comprehensive list of cut sets. By comparing these cut sets, analysts can identify those that are most critical for understanding potential failures.

Quantitative analysis complements qualitative methods by focusing on the failure rates or probabilities associated with individual system components. This analysis aims to calculate the likelihood of top events occurring and to derive important reliability metrics. The results provide valuable insights into system reliability, helping analysts prioritize which components require closer scrutiny or improvement. Together, qualitative and quantitative analyses form a robust framework for fault tree analysis, enabling organizations to proactively manage risks and enhance the reliability of their systems. (Bai, 2023) described how the results of quantitative analysis give the analyst an indication of the reliability of the system and help determine which parts of the system are more critical.

3. Accident Overview

3.1. Substance and Installation

The accident was caused by adding an incompatible substance, specifically potassium hydroxide, to XL10 and TD 6/12. During this process, the foamy composition resulting from the reaction of the substances was expelled from the container, and a cloud of colorless and odorless hydrogen vapors filled the low bay area (Fig 3). The company used potassium to adjust the pH of the product, determining the necessary amount based on samples sent to the quality control unit. However, on the day of the incident, the barrels of potassium hydroxide from the first shift were left in place because of their similar color, as all the barrels were blue. This led to a mistake in the operator's diagnosis, resulting in the addition of potassium hydroxide to the mixture instead of XL 10. The combination of the three substances—potassium, TD 6/12, and XL 10—is very unstable. Based on this, a test was conducted by CSB, whose results can be seen in (Fig 4).

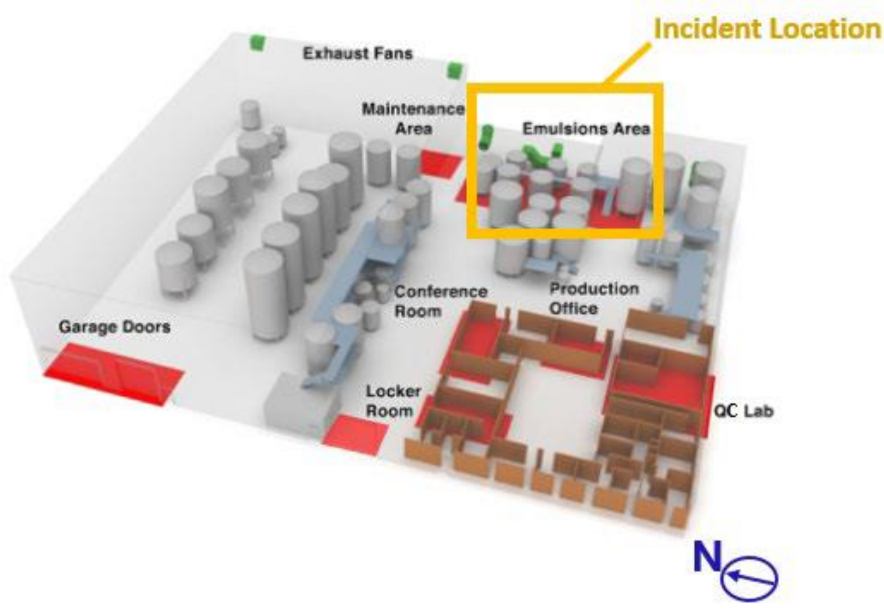

Figure 4. Map of the accident scene (CSB investigation team., 2021)

The AB Specialty operation took place inside a production building. The production building was divided into two adjoining areas known as the “High Bay” and the “Low Bay,” reflecting their structural heights. These bays were subdivided into different production areas, including the “emulsions area,” where the incident occurred (Fig. 3), and were equipped with reactors, tanks, storage vessels, and other equipment for the manufacture of various silicone products.

At the time of the incident, AB Specialty was manufacturing an emulsion known commercially as (Andisil EM 652), a waterproofing agent, in the Low Bay emulsions area. AB Specialty had been producing EM 652 since 2013 as needed. Because AB Specialty manufactured other emulsions and did not produce the same emulsion products continuously, AB Specialty used different tanks to perform the EM 652 batch process based on equipment availability. The EM 652 batches were made in tanks that were loosely sealed with a hatch-type lid (Fig 5). During production, workers often opened these tank lids to perform visual inspections, among other tasks.

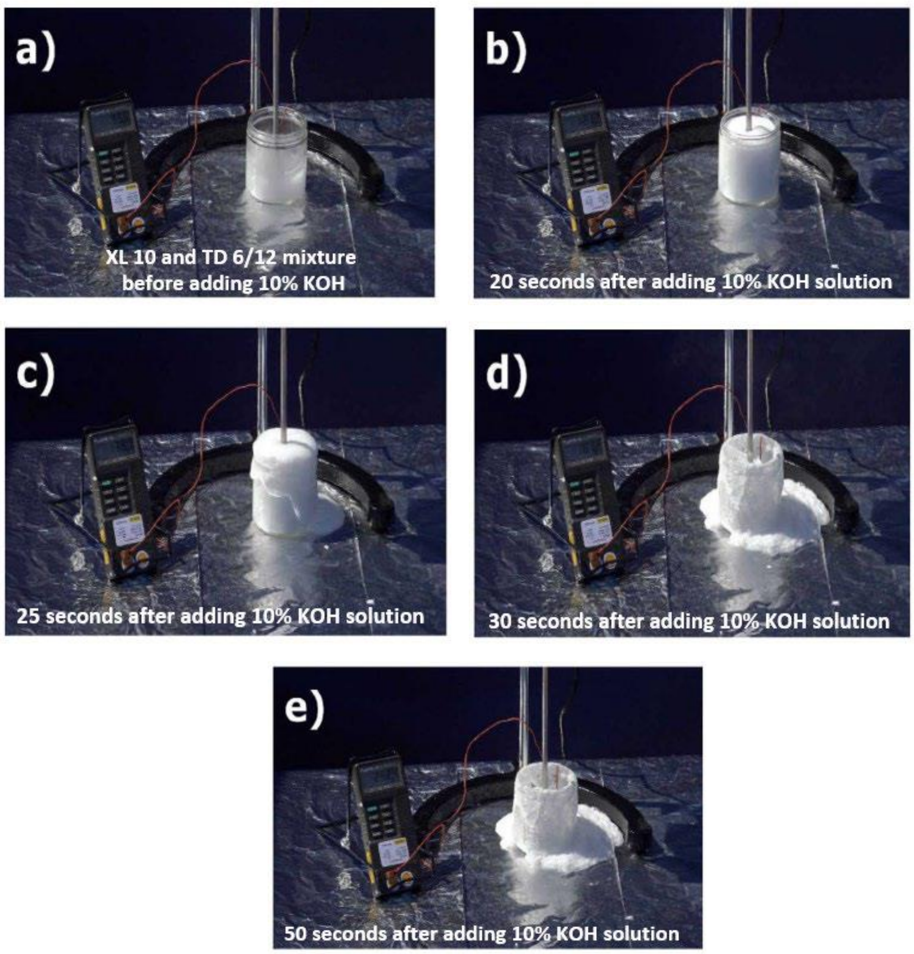

Figure 5. Photographs of the chemical reactivity test of XL 10, TD 6/12 blend, and 10% KOH solution. (CSB investigation team., 2021)

Figure 6. Exemplar AB Specialty batch tank with agitator and lid (CSB investigation team., 2021)

3.2. Process and Consequence

On May 3, 2019, a catastrophic incident at AB Specialty Silicones in Waukegan, Illinois, highlighted the critical importance of safety in chemical manufacturing. A violent explosion occurred when an operator mistakenly introduced an incompatible chemical into a batch process during the production of a silicone product known as EM 652. The operator added potassium hydroxide (KOH) to a mixture containing two other chemicals, XL 10 and TD 6/12 Blend. This error triggered an exothermic reaction that generated hydrogen gas rapidly, leading to a massive explosion that claimed the lives of four employees and obliterated the production facility. First responders arrived to find a scene of devastation, with the building reduced to rubble and emergency personnel facing significant challenges in managing the situation. Tragically, four employees lost their lives, and several others were injured, leaving the community grappling with grief and loss.

In response to the incident, the U.S. Chemical Safety and Hazard Investigation Board (CSB) launched an inquiry that revealed critical safety deficiencies within AB Specialty's operations. Key findings included:

1. Improper Storage and Handling of Incompatible Materials: The facility lacked adequate protocols to prevent the storage of incompatible chemicals in close proximity.

2. Lack of Effective Hazard Analysis Programs: Comprehensive hazard analyses were not conducted, failing to identify potential risks associated with chemical reactions.

3. Inadequate Design of Batch Equipment and Ventilation Systems: The mixing equipment design did not account for pressure buildup from gas generation, and ventilation systems were insufficient.

4. Absence of Gas Detection and Alarm Systems: There were no systems in place to detect hydrogen gas or alert employees to its presence.

5. Insufficient Emergency Preparedness Measures: Emergency response protocols were inadequate, leading to confusion and delays during the crisis.

6. Weak Safety Culture: A culture prioritizing production over safety contributed to neglecting essential safety practices.

The explosion at AB Specialty Silicones was a wake-up call for the entire chemical industry. It emphasized the severe consequences of neglecting safety protocols and recognizing the inherent risks associated with chemical reactions. The loss of life and destruction will resonate within the community for years to come, serving as a poignant reminder of the importance of vigilance, proper training, and adherence to safety standards in preventing future catastrophes. As companies reflect on this incident, they must take proactive measures to safeguard their employees and communities from similar disasters in the future.

4. Fault Tree Analysis of AB Specialty Silicone

Figure 7. Fault Tree Diagram for AB Specialty Explosion (Provided by authors)

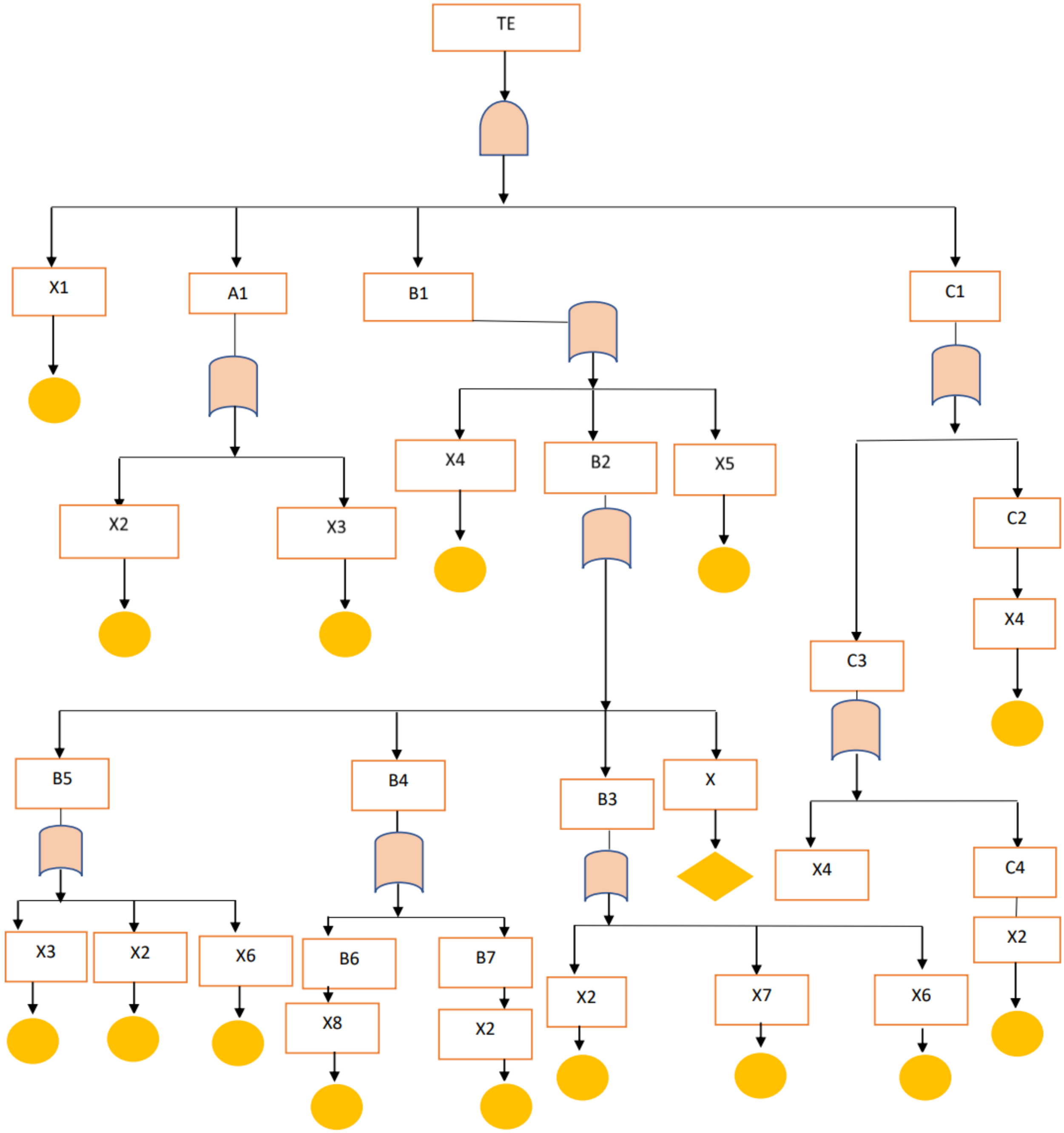

Table 3. Symbols and Meanings of AB Specialty Fault Tree (Provided by authors)

code	Basic event
• TE	• Building explosion
• X1	• Ignition source
• A1	• ERP
• B1	• Hydrogen gas
• C1	• Improper ventilation
• X2	• Lack of management procedures
• X3	• Lack of training system
• X4	• Improper container design
• X5	• Lack of gas detection system
• X6	• Weakness of process safety culture
• X7	• Weakness in PSMS
• X8	• There were no procedures for storing chemicals
• B2	• Incorrect chemical reaction
• B3	• Lack of hazard identification
• B4	• Operator error
• B5	• Housekeeping
• B6	• Placement of KOH and XL10 drums together
• B7	• The color similarity of the drums
• C2	• Batch tank ventilation issue
• C3	• Low bay ventilation issue
• C4	• Weakness in technical inspection
• X	• Use of materials with lower risk

The top event of the fault tree has four different causes. Some of them have only developed to one stage, while others have progressed to several stages and have multiple reasons. It should be noted that, as shown in Fig 6, some of the root causes have repeated more frequently, indicating a higher priority for addressing them. In this regard, a qualitative evaluation has also been conducted, as presented in Table 4. Many of the root causes of the events were fundamental, but there are also undeveloped events in this analysis that require further investigation.

Table 4. Minimal Cut Sets of the Previous Fault Tree Diagram (Provided by authors)

	EVENTS	TYPE
1	X1, X2	Basic
2	X1, X3, X4	Basic
3	X1, X7, X2, X4	Basic
4	X1, X6, X2, X4	Basic
5	X1, X8, X2, X8	Basic
6	X1, X, X2, X4	Basic
7	X1, X, X3, X4	Undeveloped / Basic
8	X1, X7, X3, X4	Basic
9	X1, X6, X3, X4	Basic
10	X1, X8, X3, X4	Basic

In the qualitative evaluation, more than 30 minimal cut sets were identified, with some of the most important listed in Table 4 based on the repeatability of basic events.

5. Conclusion and Recommendations

After the occurrence of a large number of accidents in industries, we are still witnessing accidents, many of which continue to occur due to weaknesses in learning from past incidents (Labib, 2015). In the history of industries like Bhopal, we have seen similar incidents. Therefore, in this research, we aimed to discover the root causes by selecting one of the recent industrial accidents and analyzing it using the FTA method, which is very effective in identifying the root causes of accidents (jafarian & Rezvani, 2012). By identifying these causes, we can work to prevent future accidents.

As a result of the above research, the root causes of the AB Specialty incident were identified. We found that some causes, such as defects in organizational procedures, were among the most significant root causes of this incident. Other contributing factors included insufficient training and inadequate ventilation systems. Therefore, all companies with processes similar to AB Specialty can benefit from the results of this research. Based on this research, companies should focus on the following aspects to prevent accidents:

- Ensuring drums of materials are stored in different colors to avoid confusion
- Developing and refining clear, specific organizational procedures
- Providing regular training for workers to enhance their awareness of workplace hazards
- Establishing a suitable and sufficient ventilation system
- Implementing gas detection sensors, optimizing their placement, and ensuring regular maintenance
- Redesigning containers to enhance safety and minimize risks
- Learning lessons from past near misses to improve future safety measures

A major challenge in FTA studies is obtaining accurate data for quantitative analysis, Consequently, many studies, including (Hu, 2016), rely on qualitative analysis to complement FTA studies. Thus, we conducted qualitative analysis to identify and highlight the causes of this incident.

Future research could focus on expanding this study by incorporating quantitative risk assessment using FTA to evaluate probabilities and improve predictive accuracy, Future studies could also explore the relationship between organizational safety culture and incident prevention to design targeted intervention, and exploring how IoT and AI technologies can predict and prevent chemical hazards in real-time.

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