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# Assessment of Layers of Protection in Oil and Gas Industries

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**ABSTRACT:** Using the Piper Alpha tragedy as a case study, this study examines how the Swiss Cheese Model is used to evaluate protection layers in the oil and gas sector. James Reason created the Swiss Cheese Model, which views organizational defenses as several levels of defense with innate weaknesses or "holes." When these flaws line up, disastrous results may result. Technical safeguards, operational processes, management systems, and emergency response mechanisms are among the layers of protection in the Piper Alpha incident that are thoroughly evaluated by the study using this model. Key flaws in each tier are identified by the analysis, including poor emergency preparedness, insufficient communication, and technical system failures. It shows how these gaps lined up and caused the catastrophe to worsen. The research provides recommendations for closing these vulnerabilities and preventing their alignment in future incidents. Suggested improvements include enhancing technical safeguards, improving communication and operational procedures, fostering a stronger safety culture, and bolstering emergency response systems. The findings emphasize the importance of maintaining robust, independent layers of defense to mitigate risks and prevent similar disasters in high-risk industries.

**KEYWORD:** Model of Swiss cheese, layers of defense, safety of gas and oil, risk control, The Piper Alpha catastrophe

## I. INDRODUCTION

Sequel to the hazardous nature of the oil and gas industry which involves pressurized and combustible substances multiple layers of protection techniques (LOPA) are necessary to minimize hazards. In order to reduce accidents and guarantee safety, these layers which comprise engineering controls, administrative controls, and personal protective equipment are essential (Pisu et al., 2024; Garrigou et al., 2020; National Institute for Occupational Safety and Health, 2024). However, poor maintenance, device malfunctions, and human mistake can all reduce its efficacy. Given the intricacy of the systems, a thorough assessment is necessary to determine how well these layers perform, which is what this study attempts to accomplish while also pointing up possible areas for improvement.

Inadequate risk mitigation because of potentially ineffective protection layers, difficulties assessing protective measures in the context of complex systems and processes, and the necessity of identifying common failure factors like human error and equipment malfunction are some of the major concerns with the safety measures used in the oil and gas industry that are addressed in this study. Understanding these weaknesses will enable the study to make empirical suggestions for improving safety protocols, which will ultimately lower incident rates and safeguard both the environment and employees.



By analyzing existing protection layers, evaluating their efficacy in preventing accidents and managing risks, identifying factors that contribute to their failure, and offering empirical recommendations for improvement, this study seeks to assess the evaluation of layers of protection in the oil and gas industry. In the end, fewer occurrences, smaller financial losses, and a decreased risk of injury to workers and the environment will result from the study's ability to improve protection tactics, decrease accidents, and educate industry practitioners, safety regulators, and legislators.

### Overview of oil and gas industry

Key stakeholders in production, consumption, and reserves control the worldwide oil and gas industry. The United States (22.1%), Russia (17.1%), and Iran (6.1%) are the major producers of natural gas, while the United States (18.6%), Saudi Arabia (12.4%), and Russia (10.8%) are the top producers of oil. The United States (19.7%), China (14.2%), and India (5.6%) are the biggest users of oil, while the United States (26.3%), China (14.1%), and Russia (8.5%) are the major consumers of natural gas. Venezuela (17.5%), Saudi Arabia (16.2%), and Canada (10.2%) have the largest oil reserves, while Russia (24.4%), Iran (16.2%), and Qatar (13.4%) hold the largest natural gas reserves. Major oil and gas companies include ExxonMobil, Royal Dutch Shell, Chevron, BP, and Saudi Aramco (Williams, 2025).

As the main source of energy for a variety of applications, the oil and gas sector is a crucial one that propels the world economy. Each of the three primary industry segments upstream, midstream, and downstream plays a vital part. The upstream sector, focused on exploration and production, relies significantly on technology and has been altered by digitalization, with AI, machine learning, and automation boosting exploration accuracy, reducing downtime, and saving costs (Okeke, 2024;). By anticipating equipment breakdowns, these advances also increase safety. Meanwhile, real-time monitoring and decision-making are made possible by digital twins and data analytics, which streamline operations and increase profitability.

With the US emerging as a major global oil producer, largely due to the abundant Permian Basin, the oil and gas upstream industry has used technologies like hydraulic fracturing and horizontal drilling to tap unconventional deposits (Hanson et al., 2025). However, the industry is under increasing pressure to meet climate goals, which include integrating renewable energy sources like solar and wind power and lowering greenhouse gas emissions through investments in carbon capture, utilization, and storage (CCUS) technology (Bose et al., 2024). In order to maintain competitiveness in a changing energy landscape and balance economic viability with environmental sustainability, the industry must innovate and shift to greener technologies, investigating strategies like methane capture and low-carbon hydrogen, in light of stricter emissions standards and net zero targets by 2050 (Saxena et al., 2024).

With the midstream sector developing liquefied natural gas (LNG) infrastructure to meet the increasing demand for cleaner energy and the upstream sector concentrating on low carbon solutions, the oil and gas industry is changing through partnerships and technological advancements, establishing North America as a major player in the global energy market and assisting the sector's transition to a more sustainable future. Oil and gas transportation depends on the midstream sector's pipeline infrastructure, but new pipeline building is hampered by environmental and indigenous rights concerns, as evidenced by the Keystone XL pipeline's cancellation (Emanuel et al., 2021).

Despite these obstacles, the industry is adjusting to new technology, changing consumer needs, and the drive for decarbonization (Abo-Khalil, 2024). Businesses are looking into ways to incorporate renewable energy sources and create low-carbon infrastructure, such as the production and distribution of hydrogen (Chipangamate & Nwaila, 2024). The industry must strike a balance between present and future demands as it negotiates complicated regulatory environments and tackles social and environmental issues. This presents both opportunities and difficulties for sustainable growth and development..

### Downstream Sector

The downstream sector, which involves the marketing, processing, and refinement of petroleum products, has made significant use of oration fuels (Olujobi et al., 2022). Long-term issues facing the industry as the globe recovers include the move to electric vehicles (EVs), which is being fueled by environmental consciousness, technological developments, and policies that encourage them, and stricter environmental laws that are forcing the sector to adopt cleaner technologies and sustainability. In order to increase productivity and lower emissions, the industry is also seeing advancements in refining technology, such as carbon capture and storage (Udendhran et al., 2025).

Driven by market dynamics, regulatory demands, and climate goals, oil firms are expanding into renewable energy sources including wind, solar (Khaleel et al., 2025; Olabi et al., 2023), and biofuels in response to these problems. For example, Shell plans to invest in renewable energy and hydrogen production in order to achieve net-zero emissions by 2050. Long-term viability and competitiveness are thought to depend on investments in hydrogen and renewable energy. The industry's future trajectory will be shaped by its emphasis on renewable energy and technical innovation as it adjusts to these changes and aligns with global environmental aspirations (Olabi et al., 2023).

### Environmental and Geopolitical Considerations

Geopolitical issues, such as OPEC+ production decisions, U.S. shale output, and the continuous transition to a low-carbon energy future, have a big impact on the oil and gas sector (Marangoz, 2025). Europe was forced to diversify its energy sources and accelerate the use of renewable energy after the Russia-Ukraine conflict in 2022 significantly disrupted global energy markets. Oil and gas companies are under pressure to reduce methane emissions, invest in renewable energy sources, and increase energy efficiency as environmental concerns grow and the IEA emphasizes the urgency of switching to low-carbon energy to meet Paris Agreement targets and mitigate climate change (Zhang et al., 2023).

### Environmental Impact and Sustainability

With the International Energy Agency stressing the need for businesses to lower carbon footprints and switch to low-carbon energy, the oil and gas sector is under severe examination for its effects on the environment (Zhou et al., 2025). Many businesses, including ExxonMobil, are responding by investing in carbon capture, utilization, and storage (CCUS) technologies. However, some contend that this may not be enough in the absence of a more comprehensive transition to renewable energy sources. Investor expectations are pushing for more accountability and transparency in environmental reporting, and the US and EU are enforcing stricter management practices, which is further regulatory pressure on the industry to lower methane emissions (Jaiswal et al., 2022).

## II. CURRENT EVENTS

In view of the nature of the materials handled and the procedures involved, the oil and gas business is subject to serious risks, such as fires, explosions, poisonous gas leaks, and environmental damage. According to, hydrogen sulfide ( $H_2S$ ) is an extremely harmful gas that can result in respiratory failure or even death in a matter of minutes. Another significant concern associated with high-pressure systems used in drilling and refining operations is the possibility of catastrophic oil leaks and environmental harm. As demonstrated by the Exxon Valdez and Deepwater Horizon catastrophes, environmental risks like oil spills as shown in figure 1, and leaks can harm ecosystems and local economies for a long time (Mohamadzadeh & Omidvar, 2023).

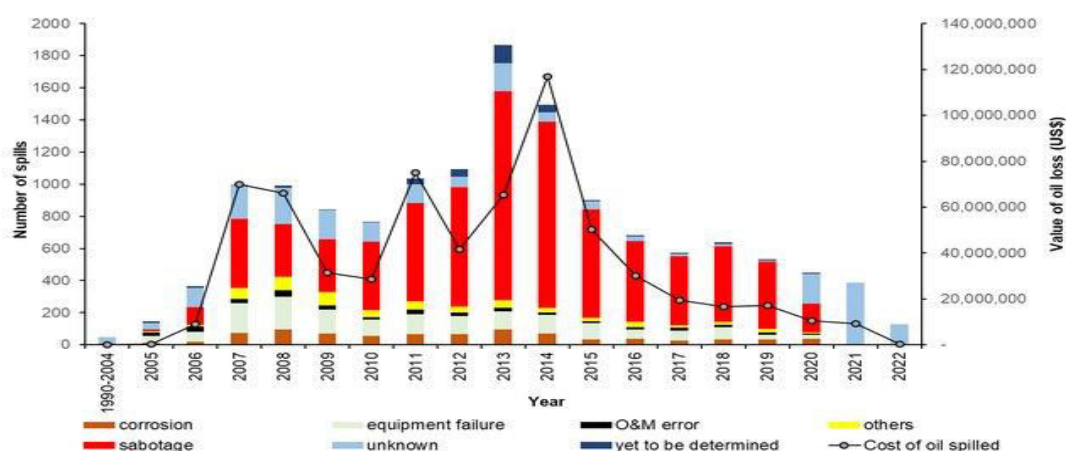


Figure 1. Chart showing the trend of oil spillage from 1990 to 2022, including causes and cost (Compiled from NOSDRA data, assessed 2022)  
Source: Ekeu-wei & Ekeu-wei, 2024)

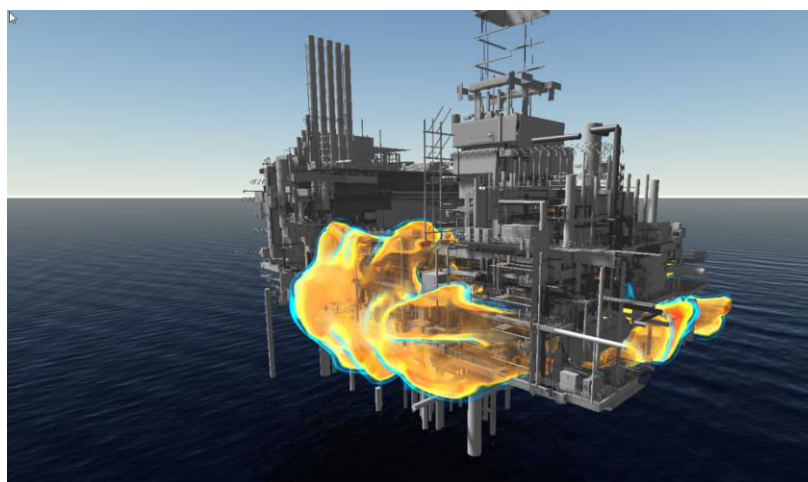
The risk profile is complicated by the human aspect, as risks are exacerbated by human error, exhaustion, and insufficient training. Risk assessments, safety exercises, and emergency response plans are among the strict safety management systems (SMS) that the industry uses to reduce hazards. Notwithstanding these safeguards, risks are still present in the industry, necessitating ongoing attention to detail and strict adherence to regulations (Bai & Jin, 2016). Although recent developments like automation and technical improvements have improved safety capabilities, preserving a strong safety culture is essential for safeguarding employees, communities, and the environment from future calamities (Huser & Kvernfold, 2001).

### The Oil and Gas Industry's Failures

According to Mohamadzadeh & Omidvar, (2023) in the oil and gas business, equipment failures and human mistake are the main causes of catastrophic accidents. These incidents are frequently brought on by inadequate safety checks, corrosion, and poor maintenance, especially in aged infrastructure. The 2010 Deepwater Horizon accident, which claimed the lives of 11 workers and resulted in a significant oil spill, emphasizes the importance of both human and equipment aspects in maintaining safety. Investigations showed that risk assessments and warning indications were disregarded. Equipment failures can be made worse by human error, which includes weariness, poor training, and disregard for safety procedures. To reduce these risks, it is crucial to have strong safety systems, ongoing training, and maintenance enhancements (Mohamadzadeh & Omidvar, (2023).

### Famous Mishaps in the Oil and Gas Sector

In the view of Reid, (2020) a number of significant accidents have occurred in the oil and gas industry, such as the 1988 Piper Alpha disaster, which killed 167 workers due to a combination of mechanical failure, poor safety procedures, and inadequate communication; the 1989 Exxon Valdez oil spill, which destroyed the local environment and resulted in significant regulatory changes, including the Oil Pollution Act of 1990, due to human error and inadequate safety measures; and the 2010 Deepwater Horizon disaster, which claimed 11 lives and was the largest marine oil spill in US history due to equipment failure and poor decision-making (Reid, 2020). These incidents highlight the significance of strict safety procedures, equipment maintenance, and trained personnel in preventing disasters as shown in figure 2 below.



**Figure 2. Piper Alpha Disaster Model**  
Source: Powell, (2022)

### Layers of Protection

In high-risk sectors like oil and gas, the Layers of Protection (LoP) strategy is an essential safety measure that uses several separate safety barriers to stop or lessen dangerous incidents. Physical barriers, safety systems, and procedural controls are only a few of the layers that this method builds to handle multiple aspects of risk management, acknowledging that no single safety measure is infallible. While safety systems like fire and gas detection systems and control systems detect and react to abnormal conditions, physical barriers like pressure vessels and containment dikes provide containment or isolation of hazardous materials (Hosseinnia Davatgar et al., 2021)

For LoP to be effective, it must be properly designed, implemented, and maintained; this calls for ongoing monitoring and a smooth integration into operational procedures. But obstacles including complexity, resource limitations, and integration problems can affect efficacy. Recent developments have improved LoP capabilities, enhancing safety procedures and lowering human error. Examples of these developments include automation and technical breakthroughs. Safety is also maintained via procedural controls, such as emergency response plans and standard operating procedures (Hosseinnia Davatgar et al., 2021).

### The Piper Alpha Disaster's Background

One of the deadliest incidents in the history of offshore oil and gas activities was the Piper Alpha accident, which happened on July 6, 1988, and claimed 167 lives. A normal maintenance procedure that went horribly wrong because of human error and poor communication, such as restarting a pump with a safety valve removed, resulted in a huge gas leak and explosion. The disaster was made worse by the platform's design and changes, which included gas processing, which added complications and dangers (Macleod & Richardson, 2018). Additionally, the absence of a thorough risk assessment and sufficient safety measures, such as firewalls and automatic deluge systems, made matters worse (Reid, 2020).

With the control room destroyed and communication systems down, the emergency reaction was disorganized and ineffectual, leaving the crew without guidance. Many workers were forced to leap into the North Sea, where many perished from hypothermia or drowning as a result of the platform's poor firefighting and evacuation protocols and the inaccessibility of lifeboats due to the extreme heat and smoke (Macleod & Richardson, 2018). The creation of the safety case regime was one of the 106 recommendations made by the Cullen Inquiry, which was headed by Lord Cullen and found many shortcomings in safety protocols, management techniques, and regulatory supervision (Reid, 2020).

Safety rules and best practices have been impacted by the Piper Alpha tragedy, which has had a long-lasting effect on the global oil and gas sector. The accident continues to be a crucial case in the study of risk management, safety engineering, and organizational behavior, and other nations have followed the safety case regime that was first implemented in the UK. The incident emphasizes the necessity for businesses to learn from near-misses and put in place efficient communication and risk management procedures, underscoring the significance of a strong safety culture and ongoing enhancement of safety management systems (Reid, 2020; Macleod & Richardson, 2018).

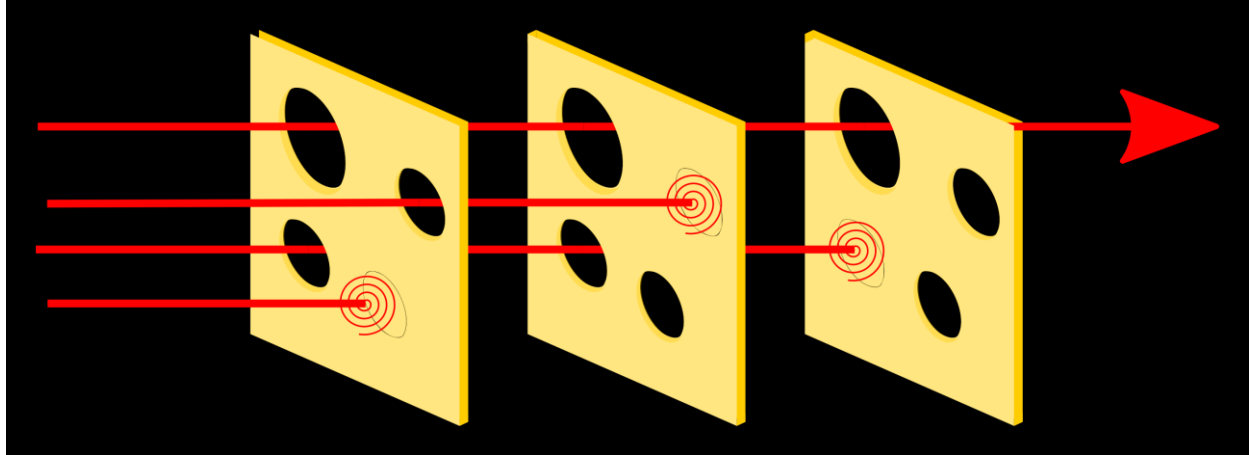
### Model of Swiss Cheese

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Safety rules and best practices have been impacted by the Piper Alpha tragedy, which has had a long-lasting effect on the global oil and gas sector (Vernaz et al., 2020). The accident continues to be a crucial case in the study of risk management, safety engineering, and organizational behavior, and other nations have followed the safety case regime that was first implemented in the UK. The incident emphasizes the necessity for businesses to learn from near-misses and put in place efficient communication and risk management procedures, underscoring the significance of a strong safety culture and ongoing enhancement of safety management systems using the Swiz Cheese model as shown in figure 3 below.





**Figure 3. Model of Swiss Cheese**  
Source: Okrona, (2025)

### **III. MATERIAL AND METHOD**

#### **Research Materials**

Literature about the Bhopal tragedy, and conference proceedings. These original sources offered insightful information about the disaster's causes, effects, and repercussions.

Secondary sources included institutional repositories, internet resources (arXiv, PLOS ONE, and DOAJ), and academic databases (Google Scholar, PubMed, Scopus, and Web of Science). Research articles, case studies, and professional opinions from chemical engineering, safety, and environmental studies were among the other materials used in this study. For information on material qualities and uses, material databases such as MatWeb and ASM Materials Information were also reviewed. Together, these various resources made it possible to comprehend the Bhopal tragedy in its entirety.

#### **Research Method**

This study uses a thorough methodology to examine how the Swiss Cheese Model might be applied to the analysis of protective layers and enhancement of safety protocols in the oil and gas sector. The study uses a wide range of sources, such as industry reports and data on safety performance, safety management system documentation, pertinent literature on safety management and risk analysis, and in-depth case studies of previous accidents like the Piper Alpha disaster. Furthermore, the analysis is informed by industry-specific standards and regulations from organizations such as ISO and API, Swiss Cheese Model frameworks and tools, risk assessment software, and expert comments and interviews with researchers and industry people.

The Swiss Cheese Model, which views organizational defenses as several layers with innate flaws or "holes" that could come together to produce disastrous results, is the main tool used in this study. By using this model, the study seeks to pinpoint each protective layer's vulnerabilities, examine any gaps, and suggest ways to strengthen safety protocols in order to avert serious mishaps. In order to improve overall safety and lower the likelihood of events like the Piper Alpha tragedy, the research specifically aims to comprehend how flaws in each layer align to contribute to system failure and design focused solutions to seal these holes or prevent their alignment.

#### **Applying the Swiss Cheese Model to the Oil and Gas Industry**

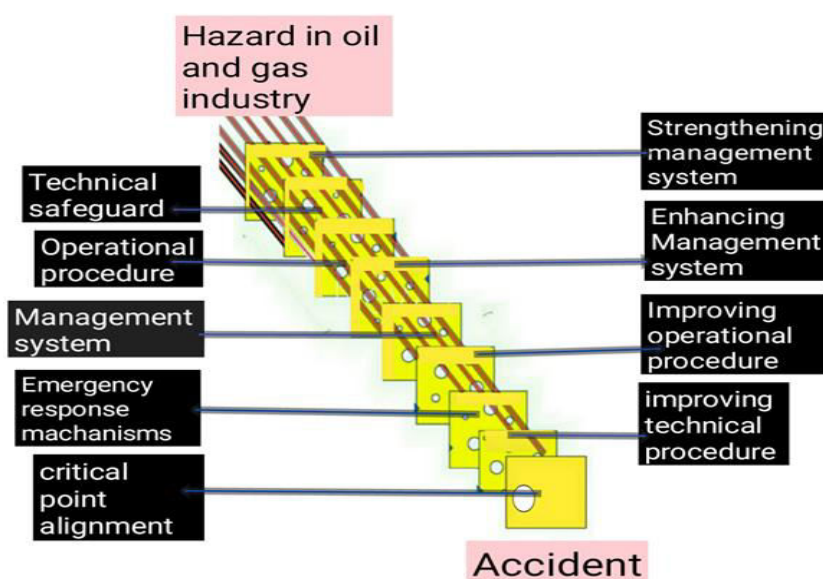
In high-risk sectors like oil and gas, where numerous safety barriers are necessary to avert catastrophes, the Swiss Cheese Model is especially pertinent. Engineering controls like fail-safe equipment and emergency shutdown systems, procedural safeguards like maintenance procedures and operational checks, organizational systems like communication channels and decision-making frameworks, and cultural factors like safety culture and risk perception are just a few of the layers of protection in offshore operations that will be evaluated in this study using the model. The research

attempts to offer insights for enhancing the resilience of safety barriers and reducing the possibility of alignment that could result in accidents by assessing these layers' failure in the context of the Piper Alpha tragedy.

A useful framework for comprehending the intricacies of safety management in high-risk sectors such as oil and gas is the Swiss Cheese Model. The model offers a helpful lens for evaluating the efficacy of the many safety barriers that are essential to averting catastrophes in these industries. The Swiss Cheese Model will be used in this study to evaluate the different levels of security that are commonly present in offshore operations. Engineering controls, such as emergency shutdown systems and fail-safe equipment, are part of these layers and are intended to stop accidents before they start.

The study will look at organizational structures, cultural elements, and procedural protections in addition to engineering controls that support safety in offshore operations. This covers risk perception, safety culture, communication channels, operational checks, maintenance procedures, and decision-making frameworks. The research attempts to offer insights for enhancing the resilience of safety barriers and reducing the possibility of alignment that could result in accidents by assessing these layers' failure in the context of the Piper Alpha tragedy. The results of the study will advance knowledge on how to develop and put into place efficient safety management systems in high-risk sectors such as the oil and gas industry.

#### IV. RESULTS



**Figure 4. Modeled layer of protection for oil and gas industry**

Figure 4 shows the oil and gas industry's modeled layer of protection. A complex interaction of failures across several layers of protection, including technical safeguards, operational procedures, management systems, and emergency response mechanisms, is shown when the Swiss Cheese Model is applied to the Piper Alpha accident. Significant "holes" in each layer are identified by the analysis, including the manual operation of the fire suppression system, poor managerial decision-making, delayed evacuation protocols, and inadequate communication regarding maintenance efforts. These flaws coincided in a way that made it possible for the situation to worsen without any meaningful action being taken, which ultimately had disastrous results.

The study emphasizes how crucial it is to comprehend how flaws in every line of defense might come together to produce a perfect storm of failures. In the instance of Piper Alpha, the risk was increased by the delayed activation of the fire suppression system and the platform's continuing operation after the condensate pump under maintenance failed and there was no communication regarding its condition. The investigation also identifies contributing elements that hastened the alignment of holes, including environmental conditions, insufficient training, and a weak safety culture.



Several important suggestions might be made in light of the findings to prevent holes from aligning in upcoming oil and gas activities. These include bolstering technical protections with automation and redundancy, enhancing emergency response systems with thorough training and better evacuation infrastructure, strengthening management systems with proactive shutdown policies and a safety-first culture, and improving operational procedures with improved communication protocols and frequent safety drills. The oil and gas sector may lessen the possibility that such catastrophes will happen again by putting these suggestions into practice.

## **V. CONCLUSION**

The study highlights how important it is to understand how weaknesses in each line of defense could combine to create a perfect storm of failures. In the case of Piper Alpha, the risk was elevated by the platform's continued operation following the failure of the condensate pump undergoing repair and the delayed activation of the fire suppression system, as well as the lack of communication regarding the pump's condition. The report also finds factors like poor safety culture, inadequate training, and environmental variables that accelerated the development of holes.

## **VI. RECOMMENDATIONS**

Suggestions Recommendations for averting tragedies such as Piper Alpha include automating vital safety systems and adding redundancy to safety systems, establishing transparent communication procedures and holding frequent safety exercises, taking a cautious approach to shutdowns and encouraging a safety-first mentality, offering thorough emergency training, and improving evacuation infrastructure. These actions will ultimately strengthen the layers of protection in oil and gas operations

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