International Journal Of Health, Engineering And Technology (IJHET) *E-ISSN 2829 - 8683*
Volume 5, Number 1, May 2026, *Page. 1073 - 1080*
Email : editorijhess@gmail.com

Integrated Analysis Using FTA, ASPEN HYSYS, And Lopa Of The 2019 HF Alkylation Unit Incident At The Philadelphia Energy Solutions Refinery

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Abstract

The incident at the Hydrofluoric Acid Alkylation Unit of the Philadelphia Energy Solutions Refinery (PES) in 2019 represents a major process safety failure driven by a combination of technical and systemic weaknesses. This study analyzes the root causes, process dynamics, and adequacy of protection layers through an integrated application of Fault Tree Analysis, Aspen HYSYS process simulation, and Layer of Protection Analysis. FTA was used to identify causal relationships between basic events and the top event, while HYSYS simulation provided insight into the thermodynamic conditions of the process fluid prior to the rupture. LOPA evaluated the effectiveness of the existing protection layers. The findings indicate that the rupture of the discharge-line elbow resulted from undetected HF corrosion, improper material selection, weaknesses in the mechanical integrity program, and the absence of an emergency isolation valve. The simulation confirmed vapor-phase dominance, leading to a high-velocity jet release and rapid vapor cloud formation that subsequently ignited. LOPA revealed that most protection layers did not meet the criteria for an independent protection layer *(IPL), with only the Rapid Acid Deinventory (RAD) system proving effective. These results highlight the need to strengthen protection design, implement risk-based inspection, improve material selection, and apply* inherently safer design *principles to prevent similar incidents in high-risk industrial facilities.*

Keywords: ***Aspen HYSYS, Fault Tree Analysis, Hydrofluoric Acid Alkylation, Independent Protection Layer, Industrial Accidents, HF Corrosion, Layer Of Protection Analysis, Mechanical Integrity, Process Risks.***

INTRODUCTION

The oil refining and petrochemical industries are classified as high-risk industries in terms of process accidents because they involve flammable, pressurized, and toxic chemicals that are handled under varying temperature and pressure conditions. Various studies in Indonesia indicate that Occupational Safety and Health (OSH) management in production processes requires quantitative analysis to systematically identify hazard sources and accident-causing factors (Nuryono et al., 2023; Husaini et al., 2023). Fault tree-based analysis methods, such as Fault Tree Analysis (FTA), have been widely used to trace the logical relationships between basic events and top events in the context of OSH, both in manufacturing processes and other industrial services (Saepudin, 2022; Nuryono et al., 2023; Usmar et al., 2025).

On the other hand, risk analysis in modern process industries requires not only an understanding of the causes of accidents, but also the ability to predict process dynamics and the escalation of consequences. In Indonesia, the Layer of Protection Analysis (LOPA) approach is increasingly being applied to chemical process units to assess the adequacy of protective layers against specific hazard scenarios (Putra, 2024; Hamid & Nugroho, 2025). LOPA is positioned as a semi-quantitative method that bridges qualitative analyses such as HAZOP with Quantitative Risk Assessment (QRA), thereby providing an indication of whether the existing combination of protection layers has reduced risk to an acceptable level (Dwiyansah, 2025). The integration of LOPA with other methods, such as FMEA and FTA, is also being continuously developed to improve the accuracy of risk assessment in gas and chemical facilities (Hamid & Nugroho, 2025; Susanti, 2025).

One of the process units with a high hazard level is the Hydrofluoric Acid (HF) Alkylation Unit, which uses HF as a catalyst to produce high-octane alkylate. HF is highly corrosive and toxic, so equipment failure could potentially lead to the release of a mixture of hydrocarbons and HF, which could result in fire, explosion, and widespread toxic effects. A major incident at an HF

alkylation unit occurred at the Philadelphia Energy Solutions (PES) Refinery on June 21, 2019, when an elbow in the pump discharge line corroded and ruptured, releasing a mixture of hydrocarbons and HF. This formed a vapor cloud that subsequently ignited, triggering a series of fires and explosions (CSB, 2022; Uozumi et al., 2023). The final investigation report from the U.S. Chemical Safety and Hazard Investigation Board (CSB) confirmed that the failed elbow contained high levels of nickel and copper residues, making it susceptible to HF corrosion, and that the existing mechanical integrity program did not include adequate inspection points for that component (CSB, 2022).

The CSB's findings indicate that the accident was not caused by a single technical failure, but rather resulted from the interaction of inappropriate material selection, undetected corrosion, weaknesses in the inspection and maintenance program, the absence of an emergency isolation valve on the downstream line, and limitations in the reliability of the HF water mitigation system (CSB, 2022; Uozumi et al., 2023). This aligns with various occupational safety and health (OSH) studies in Indonesia that emphasize that workplace accidents and process accidents are generally a combination of technical, organizational, and behavioral failures, thus requiring an analytical approach capable of systematically mapping the relationships among these factors (Nuryono et al., 2023; Husaini et al., 2023; Islamsyah et al., 2025).

A number of studies over the past five years have demonstrated the benefits of using FTA to identify the root causes of accidents and evaluate the performance of occupational safety programs (Nuryono et al., 2023; Husaini et al., 2023), while LOPA is used to assess the adequacy of protective layers in process units such as boilers and chemical oxidation units (Putra, 2024; Pratyaksa, 2017). However, studies that explicitly integrate FTA, process simulation using software such as Aspen HYSYS, and LOPA in cases of high-risk process accidents, particularly in HF alkylation units, remain limited. Most studies still focus on only one or two methods, such as the integration of HAZOP–LOPA without incorporating more detailed thermodynamic and process dynamics modeling.

Given this gap, this paper was prepared to provide a more comprehensive analysis of the accident at the HF Alkylation Unit at the PES Refinery in 2019 through the integration of several process safety analysis approaches. Fault Tree Analysis (FTA) was used to examine the causal mechanisms from the root cause to the top event, thereby providing a structural overview of the contributions of technical and organizational factors in triggering the incident. Process simulation using Aspen HYSYS was employed to model thermodynamic conditions and fluid behavior before and during the incident, enabling quantitative estimates of pressure, temperature, and potential fluid release. Furthermore, Layer of Protection Analysis (LOPA) was applied to evaluate the adequacy of available protective layers in preventing incident escalation, taking into account the frequency of triggering events and the effectiveness of each protective layer. Through the integration of these three methods, this paper is expected to provide a comprehensive understanding of the root causes, process dynamics, and adequacy of protection in the 2019 PES incident, as well as generate relevant lessons learned for improving process safety at similar facilities.

RESEARCH METHODS

This study employs an integrated process safety analysis approach through the application of Fault Tree Analysis (FTA), process simulation using Aspen HYSYS, and risk assessment based on Layer of Protection Analysis (LOPA). These three approaches were selected because they complement one another: FTA emphasizes understanding the causal relationships between failures, HYSYS models process dynamics and fluid characteristics thermodynamically, while LOPA evaluates the adequacy of protection layers in preventing or limiting accident escalation (Hamid & Nugroho, 2025; Dwiyansah, 2025).

The analysis began with an FTA to identify and describe the causal mechanisms of the critical incident, namely the rupture of an elbow in the discharge line of the HF alkylation unit. This method provides a logical structure that enables the mapping of technical, operational, and management

system factors contributing to the incident, as has been widely applied in industrial and manufacturing safety studies (Nuryono et al., 2023; Husaini et al., 2023). The fault tree was constructed based on chronological information, equipment conditions, and failure mechanism findings reported by the CSB (2022).

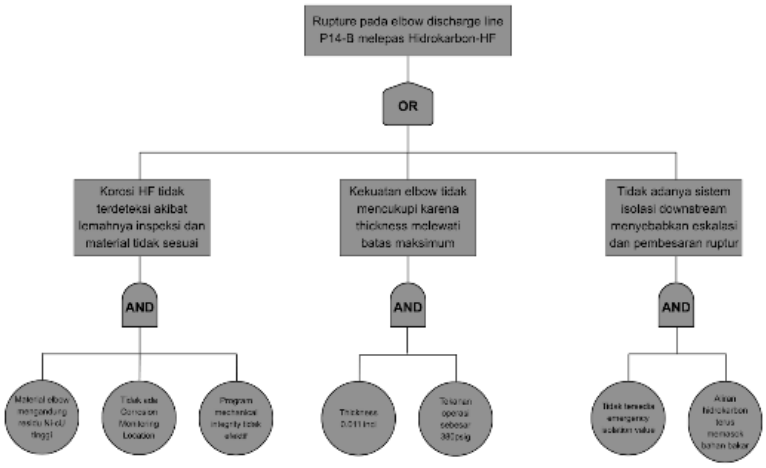
The subsequent process simulation was conducted using Aspen HYSYS to obtain a quantitative understanding of the thermodynamic conditions of the fluids involved in the incident, including composition, pressure, temperature, phase, and potential energy release. This modeling utilized process data from the investigation report, specifically the composition of the hydrocarbon–HF mixture, line operating pressure, and relevant vessel conditions. Process simulation is considered important because it provides a basis for understanding changes in operating conditions during the incident, which cannot be obtained through qualitative analysis alone (Putra, 2024).

Next, LOPA was applied to evaluate the adequacy of existing protective layers, such as the HF detection system, Rapid Acid Deinventory (RAD), water mitigation system, and the presence or absence of emergency isolation valves. LOPA was chosen because it provides a semi-quantitative framework for assessing whether these protective layers have a failure probability consistent with the targeted risk level (Hamid & Nugroho, 2025). This approach allows for the identification of risk gaps arising from the ineffectiveness or absence of protective layers, thereby resulting in a more objective and measurable risk assessment.

As the final step in this research method, the results of the LOPA evaluation were then synthesized to formulate lessons learned, which served as the basis for developing mitigation measures in this study. The synthesis was conducted by integrating findings regarding the adequacy of protective layers, the identification of risk gaps, and technical evidence obtained from investigation reports. Through this approach, the resulting lessons learned serve not only as a summary of the incident but also as an analytical output reflecting the relationship between technical failures, weaknesses in the safety management system, and the effectiveness of risk controls. Thus, the mitigation recommendations formulated in this study have a measurable and accountable methodological foundation, thereby contributing to improved process safety at high-risk industrial facilities.

RESULTS AND DISCUSSION

Results of the Fault Tree Analysis



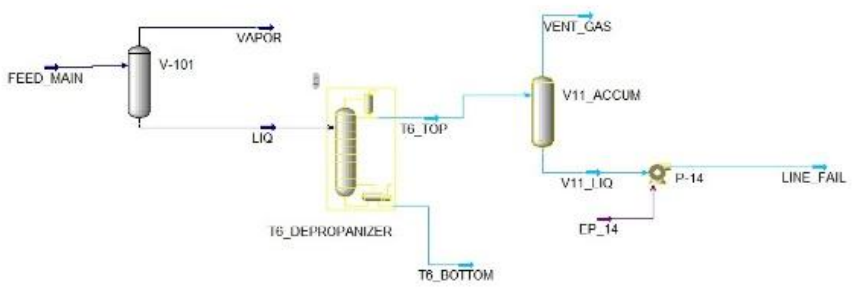
The FTA analysis conducted on the rupture of the P14-B discharge line elbow indicates that the top event resulted from a complex and interrelated set of causal factors. The FTA diagram shows that the rupture was not the result of a single failure, but rather a series of material, operational, and protective design failures that accumulated over a long period prior to the incident.

The FTA results identified three primary failure pathways, each of which contributed significantly to the rupture. The first pathway involved undetected HF corrosion, which occurred due to a combination of the selection of an elbow material with a high Ni Cu residue content, the absence of a corrosion monitoring location (CML), and an ineffective mechanical integrity program. These three basic events are connected via an AND logic gate, indicating that all of them are necessary to allow pipe wall thinning to reach a critical condition. The finding that the elbow experienced thinning to approximately 0.011 inches well below the minimum design limit reinforces the conclusion that corrosion detection failure was the dominant factor.

The second pathway confirms that the mechanical strength of the elbow is no longer sufficient to withstand the operating pressure. A pressure of approximately 380 psig in the discharge line, combined with extreme thinning of the pipe wall, causes internal stresses to far exceed the material's actual strength. These two conditions are also linked via an AND gate, which in the FTA indicates a necessary conjunction that is, failure can only occur if both conditions are met.

The third pathway indicates that the absence of a downstream isolation system contributed to the rapid escalation and enlargement of the rupture. Two key factors the absence of an emergency isolation valve and the continued flow of hydrocarbons supplying fuel exacerbated the release and amplified the initial impact of the leak. Overall, the FTA findings suggest that this incident resulted from multiple failures in material design, inspection, and process protection systems.

Aspen Hysys Analysis Results

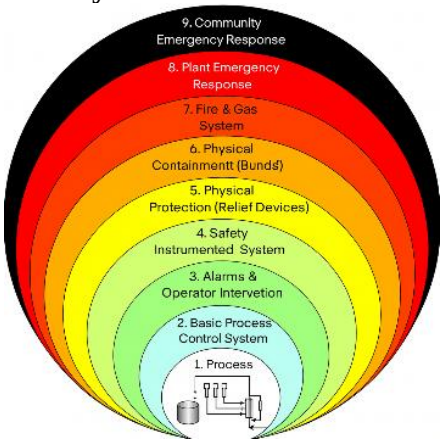


Process simulations using Aspen HYSYS were performed to understand the thermodynamic conditions of the fluid in the process segments relevant to the rupture point. Although the model is simplified, the flowsheet configuration includes a separation unit (V-101), a depropanizer column (T6), an accumulator (V-11), and pump P-14, thereby enabling it to represent the actual fluid path leading to the elbow that failed.

Simulation results show that the fluid entering P-14 and the downstream path is at medium-to-high pressure and is dominated by the vapor phase, which is consistent with the characteristics of the propane–HF mixture under operating conditions. The dominance of the vapor fraction indicates that when the elbow ruptured, the fluid was released as a high-velocity vapor jet. Such a jet possesses significant momentum, enabling rapid dispersion that forms a vapor cloud, which then ignites within a short time exactly as reported in the PES incident timeline

The simulation also shows that the V-11 accumulator plays a key role in pressure stabilization and phase separation before the fluid enters the pump. Thus, the HYSYS results provide a strong qualitative basis for the potential energy of the fluid released during a failure and support the FTA and LOPA analyses.

Summary of the Layer of Protection Analysis



The LOPA results indicate that the layered protection structure implemented in the PES HF Alkylation unit does not possess the reliability required to prevent or limit the escalation of incidents. Of the nine theoretical layers of protection evaluated, only a few provide meaningful mitigation, and only the RAD system can be considered a credible IPL according to CCPS criteria.

The first layer inherently safer design was deemed inadequate because the process continued to use HF as a catalyst even though safer alternatives were available. The BPCS layer functioned prior to the incident but lost its effectiveness immediately after the fire, demonstrating its inability to serve as an IPL in a major fire scenario.

The alarm and operator intervention layers were confirmed to be active, but were unable to alter the course of the incident due to the extremely rapid escalation. The SIS layer was only partially effective, specifically in the RAD system, which successfully reduced the HF inventory; conversely, the water mitigation system failed due to power and communication outages.

Physical barriers such as relief valves and containment systems do not provide significant protection, as evidenced by the BLEVE at V-1 and the failure of the automatic water spray system. Internal emergency response measures functioned partially, but their effectiveness was limited by physical access and the conditions at the incident site. This analysis indicates a significant risk gap, in which the frequency of residual risk remains above the tolerance level for a major HF release scenario.

Discussion

The integration of FTA, HYSYS, and LOPA results provides a holistic view of the mechanisms underlying incidents and the effectiveness of available layers of protection. These three approaches complement one another: FTA identifies the root causes of failure modes, HYSYS provides an understanding of process phenomena, and LOPA assesses the adequacy of protection against residual risk.

The FTA findings emphasize that the primary cause of the incident was undetected HF corrosion, which is consistent with the findings of Nuryono et al. (2023) and Husaini et al. (2023), who state that inspection program failures are a common trigger for process accidents. The absence of CML and weak mechanical integrity indicate that critical risks were not proactively identified. This points to systemic weaknesses in asset integrity management.

The HYSYS simulation supports the FTA's findings by showing that the fluid at the rupture point was in a state that allowed for rapid release and easy ignition. The vapor-dominated phase characteristics explain why the vapor cloud formed in a very short time. These findings are consistent with the theory of high-pressure gas dispersion and the CSB report (2022), which noted that the time between the rupture and ignition was very short.

The LOPA results show that many layers of protection do not meet IPL criteria, primarily due to reliance on the same resources (e.g., electrical power and control systems) that also failed during the incident. This pattern of layered failure is consistent with the findings of Hamid & Nugroho (2025), who emphasize the importance of redundancy and independence in IPL design for high-risk industries.

The failure of the water spray system, loss of control communication, and failure of relief protection on V-1 highlight the need for a review of both passive and active protection designs in the alkylation unit.

Furthermore, the success of the RAD system as the only credible IPL demonstrates that a truly independent system design can slow down the escalation of an emergency, even when conditions are rapidly deteriorating. This shows that investing in the right IPL (e.g., automatic EIVs, fireproofing, power redundancy) provides significant benefits in preventing major accidents.

Overall, this discussion reinforces the understanding that the PES incident was a systemic failure involving design, operations, inspection, and emergency response. The three analytical methods used consistently lead to the same conclusion: that the process safety ecosystem is not robust enough to prevent or limit major failures, and that fundamental improvements are needed through enhanced design, risk-based inspections, and the application of inherently safer technology principles.

Mitigation Efforts as Lessons Learned

Based on the results of the integration of Fault Tree Analysis (FTA), process simulations using Aspen HYSYS, and Layer of Protection Analysis (LOPA), it can be concluded that mitigation efforts for the HF Alkylation unit cannot be focused solely on a single technical aspect, but must encompass comprehensive improvements to the design, inspection, operation, and process protection systems. The 2019 PES incident demonstrated that the multiple failures that occurred were not adequately prevented by the existing process safety systems, necessitating a fundamental shift in the risk management approach.

The primary mitigation measure identified as a key lesson learned is the need to strengthen the mechanical integrity program, specifically addressing HF corrosion mechanisms. FTA results indicate that undetected corrosion was the dominant factor in the rupture, exacerbated by the absence of corrosion monitoring locations (CMLs) on critical elbows. Therefore, the time-based inspection approach needs to be upgraded to a risk-based inspection, with an emphasis on components that have a high potential for degradation due to the HF environment and flow conditions. The inspection program must also be supplemented with the selection of appropriate non-destructive testing methods and inspection intervals determined based on actual risk, rather than solely on the equipment's operational age.

Furthermore, this incident serves as a lesson learned that material selection for HF service cannot rely solely on compliance with nominal specifications. Findings regarding high levels of nickel and copper residues in the failed elbow indicate that metallurgical mismatches can significantly increase the corrosion rate. Relevant mitigation efforts include tightening material selection standards for HF service, including more thorough metallurgical verification from the procurement stage through installation. Thus, the risk of failure due to material mismatch can be minimized early in the equipment's lifecycle.

The next mitigation effort relates to process protection design, specifically the system's ability to limit escalation following an initial failure. The results of the FTA and LOPA consistently indicate that the absence of an emergency isolation valve on the downstream line allows fluid release to proceed unchecked, thereby exacerbating the consequences of the leak. Therefore, the installation of a rapid isolation system that is automatic, fire-resistant, and independent of the main control system is a key lesson learned. Such isolation serves to limit the inventory involved in the incident and provides additional time for other mitigation systems to function effectively.

The LOPA analysis also shows that most existing protection layers do not meet the criteria for an independent protection layer (IPL), primarily due to their reliance on shared resources, such as power and control systems. This results in a significant risk gap in scenarios involving a large-scale HF release. As a mitigation measure, the design of protection layers should focus on enhancing independence and reliability, rather than merely increasing their number. Active protection systems, such as alarms and operator intervention, must be supported by truly independent IPLs, so that they remain functional even in the event of a primary system failure due to fire or explosion

The failure of the water mitigation system during the incident also serves as a lesson learned that active mitigation systems are highly vulnerable to power outages and physical damage during large-scale fires. Therefore, mitigation strategies must be supplemented with enhanced passive protection measures, such as fireproofing, shielding critical equipment, and layout designs that account for the possibility of direct fire exposure. This approach aims to enhance the physical resilience of the facility so that mitigation systems can remain operational during the early stages of an incident.

Conversely, the relative success of the Rapid Acid Deinventory (RAD) system in reducing HF inventory demonstrates that a system designed with a high degree of independence is capable of delivering a significant reduction in risk even as emergency conditions evolve rapidly. The lesson learned from this aspect is the need to optimize RAD functionality by improving actuator reliability, implementing faster activation logic, and conducting periodic testing that simulates actual emergency conditions. Thus, RAD can continue to serve as the primary protective layer in limiting the impact of HF releases

As a long-term mitigation measure, this incident also underscores the importance of applying the principles of inherently safer design to alkylation units. Efforts to reduce HF inventory, simplify process design, and evaluate alternative technologies with lower hazard levels must be part of a strategy to prevent major accidents. In addition, all such technical mitigation efforts must be supported by strengthening the process safety management system, including the integration of FTA and LOPA analysis results into the management of change process, periodic safety audits, and the enhancement of the competencies of the personnel involved.

Overall, the mitigation measures formulated based on lessons learned from the PES incident demonstrate that preventing and mitigating high-risk process accidents requires a systematic and multi-layered approach. By strengthening design, inspection, protection, and safety management in an integrated manner, the risk of similar incidents occurring at the HF Alkylation unit in the future can be reduced to a more acceptable level.

CONCLUSION

Based on the results of the analysis conducted, it can be concluded that the 2019 HF Alkylation Unit incident at the Philadelphia Energy Solutions (PES) Refinery was a high-risk process accident caused by systemic and multi-layered failures. Integration of Fault Tree Analysis (FTA) indicates that the rupture of the elbow in the pump discharge line was not caused by a single technical failure, but rather resulted from a combination of undetected HF corrosion, inappropriate material selection, a weak mechanical integrity program, and the absence of an adequate downstream isolation system. These findings confirm that failures in design and inspection played a dominant role in triggering the peak event.

The results of the process simulation using Aspen HYSYS provide quantitative support for the FTA findings by showing that the fluid at the rupture point is under medium-to-high pressure and is dominated by the vapor phase. These conditions cause the fluid to be released rapidly in the form of a high-energy vapor jet, which subsequently forms a vapor cloud and ignites within a short time. Thus, the process simulation demonstrates that the thermodynamic characteristics and phase of the fluid play a critical role in determining the escalation of the incident's consequences

An evaluation using Layer of Protection Analysis (LOPA) showed that most of the available protection layers in the PES HF Alkylation unit did not meet the criteria for an independent protection layer (IPL), primarily due to their reliance on the same power and control systems. Of all the protection layers evaluated, only the Rapid Acid Deinventory (RAD) system could be categorized as a credible IPL and provided a tangible mitigation contribution. The LOPA results also identified a significant risk gap, where the residual risk remains above the tolerance level for a major HF release scenario.

Overall, this study demonstrates that the integration of FTA, Aspen HYSYS process simulation, and LOPA provides a more comprehensive understanding of the root causes, process

dynamics, and adequacy of protection systems in high-risk process accidents. The research findings underscore the importance of strengthening risk-based mechanical integrity programs, selecting materials suitable for HF environments, and implementing truly independent and reliable layers of protection. By applying the lessons learned and mitigation efforts formulated in this study, it is hoped that the risk of similar incidents at HF Alkylation units and similar industrial facilities can be reduced to a more acceptable level.

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