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A Hazard and Operability Study for Assessing Hazard Risks using Fault Tree Analysis in an Iranian Petrochemical Industry Unit (2016)

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Abstract

Background: Risk assessment is an important tool for reducing casualties and financial damage in the oil and gas industry. This research aimed to identify and evaluate process hazards in the petrochemical industry in 2016.
Material and Methods: In this case study, a team was organized and briefed on the process. Besides, hazard identification was performed using the Hazard and Operability Study. Next, causes were analyzed using the Fault Tree Analysis and occurrence probability of top events. Finally, events and subevents were ranked. The minimum cut sets were determined using Boolean algebra.
Results: A total of 77 events were identified. Accordingly, unacceptable, tolerable, and acceptable risk levels were 41, 31, and 5 events, respectively. Fire was the most unacceptable risk level, with the final events of "human errors in correct gasket installation on the flange surface" and "flange defects" having had the shares of 51.2 and 21.55%, respectively.
Conclusion: The combination of the two HAZOP and FTA techniques is useful in process industries in which incomplete performance of the system and control systems is the most effective factor in the potential occurrence of fire. Human errors and flange defects are the two main factors in this event, so occupational safety and health must be improved in this system. Thus, due to complex interactions between humans, machines, materials, and the environment in systems, such as the petrochemical industry, which lead to uncertainties in safety results of the process, risk assessment is recommended to be performed periodically using different techniques.

Keywords: Safety, Chemical Hazard Release, Chemical Safety, Safety Management.

Introduction

Growth in human populations with the increase in industries have raised risk potentials and accidents. Particular attributes of the oil and gas industry, including its vastness, huge volume of capital, numerous dangers, and high number of employees have attracted the attention of safety experts, which demand their extensive efforts to improve the level of safety in this industry [1, 2].

The presence of hazardous chemicals and operating units under conditions of high temperature and pressure, including reactors and storage tanks in the chemical industry, has raised the possibility of accidents, such as explosions and fires. In this industry, events occur even in industrial units with most up-to-date designs and most experienced employees [3, 4]. The occurrence of several fires and explosions in 2016 in Iranian petrochemical plants, including Shahid Tondgooyan, Maroon, Bandar Imam Khomeini, Mahshahr, and Bouali Sina, showed that inattention to safety considerations could lead to catastrophic human and financial losses within a short time. Thus, there is still a need for comprehensive efforts to prevent similar incidents in the future [5].

Given the incidents in process industries and their damage to humans and the environment, systematic risk assessment, as an effective tool, is widely used to manage safety in process industries [4].

Some methods, such as Hazard and Operability Study (HAZOP) and Fault Tree Analysis (FTA), are specifically used to identify and assess hazards in process industries [3, 6].

In many previous studies, a complex of HAZOP and FTA methods was used to assess safety, health, and environmental hazards and to identify potential hazards in chemical plants. It was also used to identify causes and consequences of possible fault forms under abnormal conditions as most important factors in the occurrence of chlorine leakage in drinking water systems [3, 7-9].

HAZOP is the most well-known and reliable method for qualitatively identifying potential hazards in process industries. This method covers all phases of the life cycle of a plant or equipment, including idea stages, location selection, component design, construction, installation, implementation, operation, decommissioning, and dismantling [3, 7].

Fault tree analysis is a quantitative, logic, and geometric tool for extracting and interpreting root causes in the relationship between component defects, which is used to evaluate the probability of an accident, as a result of the sequence or combination of faults and defects [6, 8, 10]. In this method, all events leading to potential dangers are discovered using Boolean algebra [11].

Given the lack of similar research in the petrochemical industry and the necessity for determining potential hazards through root cause analysis and evaluating the probability of top events, this study was conducted to prepare technical data for safety and health management.

Materials and Methods

The present study is a case study of risk assessment using HAZOP and FTA methods, which was conducted in the Butene-1 unit in the Khorramabad petrochemical industry in 2016 through research project number 1889. In the first step, an expert team was organized and data collection was conducted through direct observation, interviews with HSE unit officials, room control, site experts, and via studying P and ID as well as PFD maps, while the performance of equipment and potential hazards were investigated.

This unit was selected for risk assessment given the presence of catalysts and highly hazardous materials under conditions of high temperature and pressure in the Butene-1 unit. These conditions could lead to catastrophic accidents, such as fire and explosion. The HAZOP method was used to identify potential hazards of the unit.

HAZOP is an effective and systematic method for identifying risks and operational problems in the system and determining their effects. In addition, it is a qualitative study that identifies deviations from the design, which evaluates its causes and consequences [3]. In this method, after formation of a team of experts, familiarizing them with the production process in the unit under investigation, and identification of the nodes, operating parameters (pressure, flow, composition, temperature, and level of liquids) were considered, and their deviations and possible consequences were examined. Next, the Fault Tree Analysis technique was used to determine top events and occurrence probabilities, and to illustrate the path of risk formation [6].

It is worth noting that after choosing the top events, the causes of their occurrence were defined as middle events, with these events analyzed until the final event was determined [6].

After plotting the fault tree, the events were named, and the minimum cut was determined using Boolean algebra [11]. Next, the occurrence probability of the base events was determined based on the company's records and expert opinions. In the absence of the occurrence probability of base events, the occurrence probability of the base events was calculated based on the failure rate per year (λ) according to Eq. (1) and assuming t = 1 (one year) [12] as follows:

Eq. (1). $P=1-e^{-\lambda t}$

Next, probabilistic relationships between input and output events as well as gates were used to calculate the occurrence probability of the main event in the minimum cuts. After calculating the occurrence probability of the top event, the failure rate was calculated per year [12] by defining it in Eq. (2):

Eq. (2). $\lambda = - \ln (1-P)$

One of the major parts of risk assessment is the calculation of risk levels and determination of tolerance of top events. Thus, the risk matrix of the ISO-17776 standard was used to determine the risk level of events. Table 1 shows the risk matrix of this standard [13] as follows:

Table 1. The risk matrix based on the ISO-17776 standard

Repeatability/probability					Consequences				
E	**D**	**C**	**B**	**A**					**Severity ranking**
It happens several times a year in the region.	**It happens several times a year in the company**	**It has not already happened in the company**	**It happens several times a year in the company**	**It rarely happens in the company**	**Reputation**	**Environment**	**Assets**	**Persons**	
					Without impact	Without impact	Without damage	Without damage	0
					Little impact	Minor impact	Minor damage	Mild injury	1
			Gradual improvement		Limited impact	Little impact	Low damage	Low damage	2
					Significant impact	Local impact	Local damage	Major damage	3
		Risk reduction measures			Major national impact	Major impact	Serious damage	A death case	4
Intolerable					Major international impact	Wide-range impact	Severe damage	Multiple deaths	5

In the next step, for events of an unacceptable level, the occurrence probability of their subevents (events occurring immediately in the bottom gate of the top event) was computed. Next, the events were ranked, with the share of each event in the occurrence of the event determined. One of the major outputs of the fault tree analysis is the ranking of the importance of end events. Thus, the end events were ranked using the proposed formula as shown in Eq. (3) [12] as follows:

Eq. (3): $I_A = \sum +U_a / \sum +U_s$

Where the IA, $\sum U_a$, and $\sum U_s$ indicate importance of end event A in creating the main event, the sum of the occurrence probability of minimal cuts in which event A exists, and the occurrence probability of the main event, respectively.

Results

The present study was conducted to assess the risk of hazards using the HAZOP and FTA methods, which were identified through HAZOP implementation in a total of 59 nodes and 123 hazards. The hazards identified using the HAZOP method were used to determine top events using the FTA method. In the present study, a total of 77 risks were investigated using the FTA method. Among them, there were 41 risks with an intolerable level, 31 risks with a tolerable level, and 5 risks with an acceptable level based on the risk matrix of the ISO-17776 standard table 1 [13].

Findings from evaluation of the causes of the identified risks in the HAZOP method showed that 46.84% of the risks were due to "incomplete performance of the system and control systems", 30.38% were related to "system equipment defects", and 22.78% were related to "human errors". Table 2 shows one of the completed HAZOP worksheets.

Table 2. A sample worksheet of a completed hazard and operability study in a petrochemical industry unit

HAZOP worksheet						
Study title: Risk assessment using the HAZOP method in a petrochemical industry unit				**Date:**	**Team members:**	
Examined section (node): re- exit and entry of butane to the drum						
Unit components: flanges, pumps, pipelines						
No.	**Keywords + operational parameters**	**Reason**	**Consequence**	**Available shields**	**Recommended control measures**	**Responsibility for implementation**
1	Lower flow	- Leakage in the flange drum - leakage in the pump - Leakage along the pipeline	Fire	- Installing a detector in different parts of the operational site - Installing banned mobile signage in the site - Firefighting equipment - Audio and video alarms	1- Periodical inspection of flanges and gaskets 2- Choosing the gasket type in accordance with working conditions 3- Proper gasket installation on the flange surface 4- Educating proper gasket installation 5- Periodic inspection and maintenance of pipelines 6- Investigation, control, and prevention of pipeline corrosion 7- Paying attention to pump sealing	Cite man/ HSE unit management

According to the results of the HAZOP study, the corresponding fault tree diagrams were drawn. Due to the large number of fault tree runs and impossibility of introducing all of them in this paper, two of them have been shown in Figs. 1 and 2

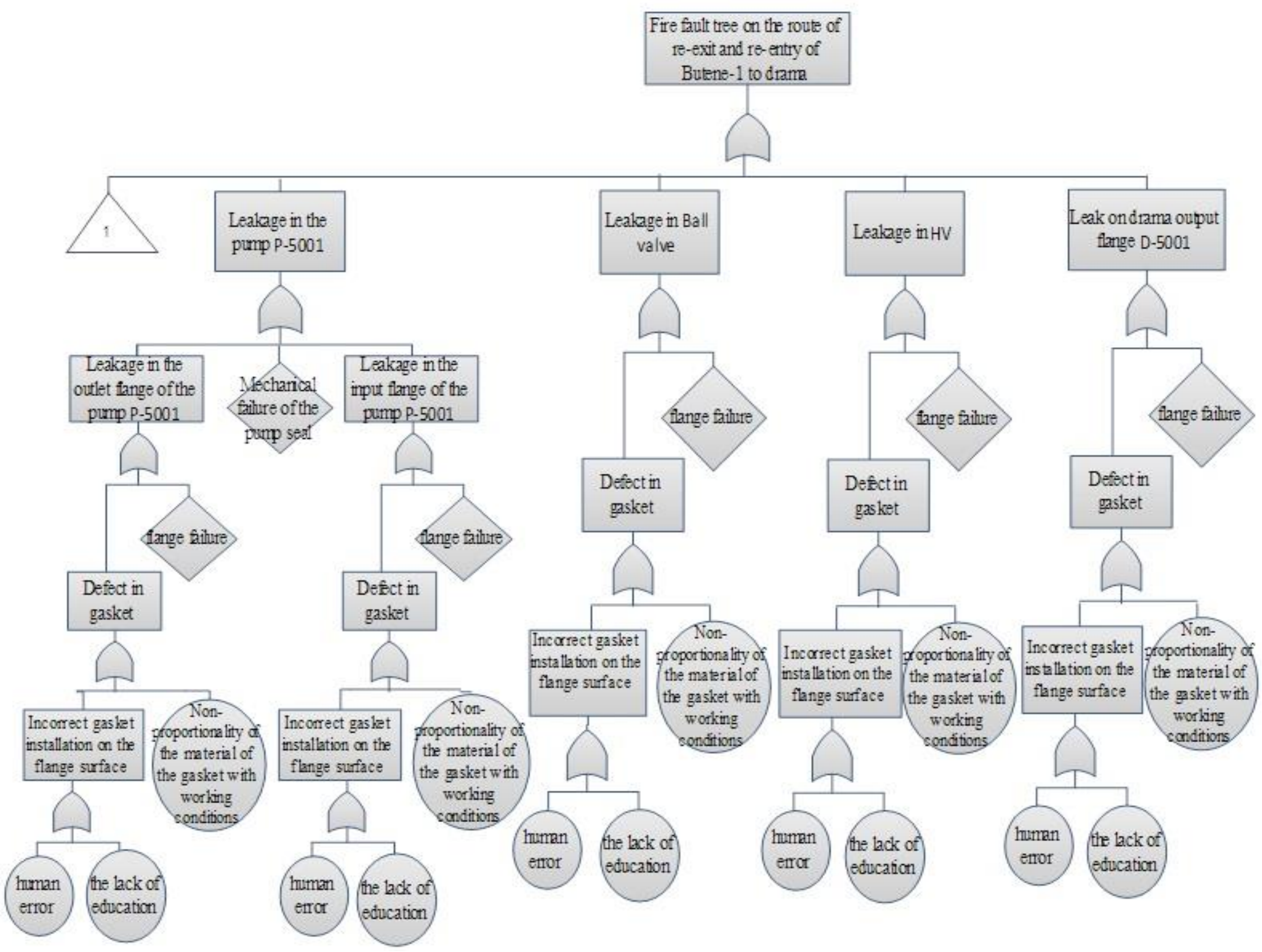

Fig. 1. Fire at the exit and re-entry of Butane-1 to the drum

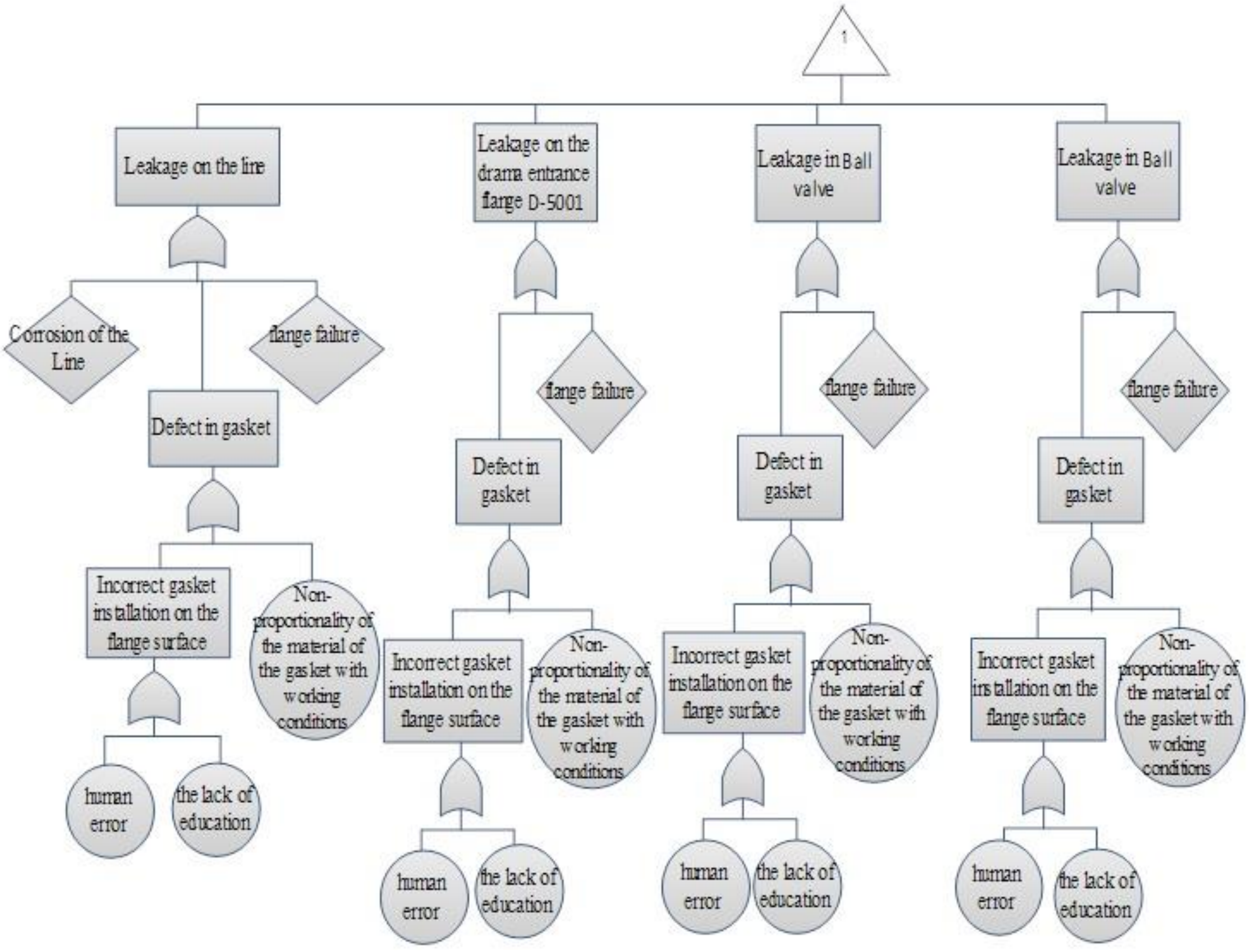

Fig. 2. Fire at the exit and re-entry of Butane -1 to the drum

Table 3. Symbols used to name the events in the Fault Tree Analysis chart

No.	Event	Symbol
1	Leakage in the drum's output flange D-5001	E13
2	Leakage in HV	E8
3	Leakage in ball valves	E6
4	Leakage in pump P-5001	E58
5	Leakage in the drum's entrance flange D-5001	E12
6	Leakage in the line	E9
7	Flange defects	F1
8	Gasket defects	F2
9	Non-proportionality of the gasket material to working conditions	F4
10	Incorrect gasket installation on the flange surface	F5
11	Lack of training	F6
12	Human errors	F7
13	Leakage in the input flange of pump P-5001	E14
14	Leakage in the outlet flange of pump P-5001	E15
15	Mechanical failure of the pump seal	F211
16	Line corrosion	F3

Symbols used to name the events in the FTA charts have been presented in Table 3. Besides, Table 4 presents the failure rate, occurrence probabilities of final events, and minimum cuttings.

Table 4. Failure rates and occurrence probabilities of the final events according to fault tree analysis

No.	Final events	Failure rate	Probability
1	F1	0/0136	0.0136
2	F3	5.4794×10^{-3}	5.4644×10^{-3}
3	F4	0.0109	1.1×10^{-2}
4	F6	5.4794×10^{-3}	5.4644×10^{-3}
5	F7	0.0328	0.0323
6	F211	5.4794×10^{-3}	5.4644×10^{-3}

Table 5. Ranking of subevents according to fault tree analysis in petrochemical industry units

Subevent	Rank (%)
Leakage in pump 5001 (E58)	22.75
Leakage in the line (E9)	11.85
Leakage in the drum's output flange 5001 (E13)	10.9
Leakage in HV (E8)	10.9
Leakage in the ball valve (E6)	10.9
Leakage in the ball valve (E6)	10.9
Leakage in the ball valve (E6)	10.9
Leakage in the drum's input flange	10.9

Eq. (1):

TE= E13+ E8+ E6+ E58+ E6+ E6+ E12+ E9 = 0.5722

λ= 0.849

$$1/\lambda = 1.17$$

According to the data obtained from the FTA method, there were 41 events with an unacceptable risk level, 31 with a tolerable risk level, and 5 with an acceptable risk level. The results of subevent ranking have been presented in Table 5. Besides, the results of ranking the importance of final events have been presented in Table 6. As it was observed, the event of "human errors in correct gasket installation on the flange surface" had the contribution rate of 50.8% to the occurrence of the top event. In the event of fire, the ranking of final events showed that the event of "human errors in correct gasket installation on the flange surface" had the highest share in the occurrence of the top event in all fires, with an average of 51.2%. The next event, having been the most important one in the event of fires, was "flange failure", which averaged 21.55%. After defects in the flange, the event "non-proportionality of the material of the gasket to working conditions "had an average contribution of 17.43%. Next to that, "the lack of education of proper gasket installation on the flange surface" had an average contribution rate of 8.66% in the case of the top event. Compared to the events mentioned above, "line corrosion" had a lower percentage. This event, on average, had a contribution of 0.95% to the incidence of fires. In the paths where the pump seal had mechanical failure, the final event of "mechanical seal failure" could lead to fire with an average contribution rate of 0.81%.

Table 6. Ranking of the importance of final events based on FTA results

Final event	Importance percentage relative to the top event (%)
Human errors in correct gasket installation on the flange surface (F7)	50.8
Flange defects (F1)	21.4
Non-proportionality of gasket materials to working conditions (F4)	17.3
Lack of education about proper gasket installation on the flange surface (F6)	8.6
Line corrosion (F3)	0.95
Mechanical failure of the pump seal (F211)	0.95

The final event was observed in 7 cases (25%) of the fires surveyed, as listed in Table 7.

Table 7. Ranking of the importance of final events in all fires

Final event	Importance percentage relative to the top event (%)
Human errors in correct gasket installation on the flange surface (F7)	51.2
Flange defects (F1)	21.55
Non-proportionality of gasket materials to working conditions (F4)	17.43
Lack of education about proper gasket installation on the flange surface (F6)	8.66
Line corrosion (F3)	0.95
Mechanical failure of the pump seal (F211)	0.81

Discussion

This study was carried out to determine potential hazards, to perform a root cause analysis, and to evaluate probabilities of top events in the Butene-1 unit in the Khorramabad petrochemical industry.

To this end, a total of 59 nodes and 123 hazards were determined by implementing HAZOP.

Besides, a total of 77 risks were examined using the FTA method, in which 41 risks were observed at an intolerable level.

Based on the results, "incomplete performance of the system and control systems", with the contribution rate of 46.84%, was the most effective factor in leading to potential hazards as identified by the HAZOP method. A previous study showed that 30.50% of the risks were caused by "incomplete performance of the system and control systems", having been lower than our results [14]. This difference could have been caused by the diversity in operating procedures, preventive maintenance methods, processes, and environmental characteristics.

The FTA results in the current study showed that human errors in correct gasket installation on the flange surface (F7) was the cause of more than half of the fire-related accidents in the studied unit (Tables 6 and 7). Besides, fault tree analysis showed that "leakage in the pump" was the most effective subevent in leading to the mentioned fires (Table 5).

Based on the FTA results, about 90% of fires were related to three final events that included human errors in correct gasket installation on the flange surface, flange defects, and non-proportionality of gasket materials to working conditions (Table 7).

In the event of fires, "human errors in proper gasket installation on the flange surface" played an important role, which could be attributed to people's carelessness, rushing to work, heavy workloads, and inexperience. Even experienced people could make an error in correct gasket installation because their work experience could make them ignore correct performance of their work [5].

Human factors play a major role in the occurrence of intermediate and major events [5, 15]. Lessons learned from fire accidents at the Bouali Sina Petrochemical Plant showed that human errors having led to leakages through ruptured blind flange gaskets in the pipeline played a key role in the occurrence of these accidents. Thus, it is necessary for safety specialists to acquire extensive skills, expertise, and knowledge in both technical and human aspects. Besides, they are advised to focus on human error control to increase safety of system processes [5].

Other factors that should be considered in process safety management are the operation safety and reliability of technical equipment. The results of this study showed that the most important event in all fires was "flange defects" (21.55%) after human errors (Table 7). As Table 5 shows, the ranking of subevents according to fault tree analysis in the petrochemical industry unit showed that the leakage of technical equipment, especially pumps, was the most common cause of fires (22.75%).

As reported in previous studies, hydrocarbon leakage has been one of the most common incidents in the oil and gas industry [16]. Leakage of hydrocarbon products can lead to great environmental pollution, yet the damage caused by it may not be covered by insurance and environmental protection organizations [17]. According to lessons learned from fire accidents at the Bouali Sina Petrochemical Plant, leakage of hydrocarbon products from a blind flange gasket in the pipeline was the basic event [5]. Therefore, it is necessary that personnel training be included in occupational safety and health management programs. Safety training can enhance the performance of equipment as well as process safety climate and culture [5, 17].

Based on the results of this study, although the HAZOP method is time-consuming, its ability to divide different parts of the process, i.e. operating nodes, increases accuracy of the evaluation and examination of all available equipment. Besides, the results showed that the main disadvantage of the HAZOP method was its failure to determine root causes of the deviations. Therefore, it is necessary to use a complementary method, such as fault tree analysis, to remove this disadvantage

Previous studies show that the fault tree analysis is a reliable method for quantifying findings from qualitative methods, such as HAZOP, given the complexity of the system [3, 9].

According to the findings of this study, the fault tree analysis can be used as a qualitative method to graphically show logical connections between faults and their causes, and to transmit information on intermediate causes affecting the occurrence of the top events [6].

There was no previous study on the extent of equipment failure in the studied unit, having been one of the limitations of this study, which led to some problems in collecting technical information about the equipment. In the end, due to complex interactions between humans, machines, materials, and the environment in systems, such as petrochemical plants, which lead to uncertainties in safety results of the process, risk assessment is recommended to be periodically performed with different techniques.

Finally, the results of this study showed that human factors could play a major role in the occurrence of intermediate and major accidents, being effective in improving occupational safety and health in the system, while the time and cost could be managed.

Therefore, given specific features of the two methods of HAZOP and FTA, they are good supplements for each other in identifying and assessing risks of process industries. Thus, the combining of these two techniques could result in more accurate results.

Conclusion

In this study, the combination of the two techniques of HAZOP and FTA showed that incomplete performance of the system and control systems were the most effective factors in the occurrence of potential fire hazards and quantitatively showed that human errors along with flange defects were two main factors in the occurrence of all fires. To prevent accidents, careful monitoring of the work performed during repairs and training courses for staff are effective in identifying events leading to various incidents, including leaks. Thus, regular and periodic inspection of equipment, ensuring their proper functioning, and timely replacement of gaskets are effective in accident prevention.

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