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REVIEWARTICLE

BP Texas Refinery Incident Causes: A Literature Review

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ABSTRACT

The likelihood of incident occurring in oil and gas industries is high due to the inherent risks associated to high temperature, high pressure, hydrocarbon, and etc. One of the prominent incidents that have taken place is the Texas refinery explosion. The purpose of this review was to investigate the causes of the BP Texas refinery incident. There are three sources of references for the reviewed articles: Web of Science, Scopus, and Science Direct. The search results were filtered according to six selection criteria, and after reading the abstracts and full texts, ten articles were included in this review. These studies and reports were reviewed to understand modeling and simulation of the incident process and to identify the root causes of the incident. The review highlights the main factors that led to the incident including: lack of management of change (MOC), maintenance, preliminary hazard analysis, lack of effective safety barriers, and human errors in some sectors. It is recommended that lessons learned from the incident be shared to relevant parties to improve the process safety and further studies on safety barriers and their failure instead of simulation of the incident dynamics.

KEYWORDS: *Texas Refinery, Explosion, Incident, Process Safety, Hazard Analysis*

INTRODUCTION

Texas refinery:

Due to the value of oil as the main source of energy in the world and its limitation to some countries and economic value, the refineries have been built around the world to get crude oil [1]. These refineries are naturally unsafe and dangerous because they work with combustible, crude oil, toxic, volatile materials, and compounds and from 1985 to 2001, petrochemicals and refineries have been ranked second in main events in the European Union [2]. The major incidents in these refineries are explosions, vapor cloud explosions (VCE), boiling liquid expanding vapor explosions (BLEVES), emission of dangerous materials, etc. [3].

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Because of the high consequence incidents, to reveal casual factors, improve safety performance, prevent re-occurrence, these incidents should be investigated following incidents. As defined by the center for chemical process safety, incident investigation is a systematic approach for determining the causes of an incident, and developing recommendations that address the causes to help prevent or mitigate future incidents. The department of energy (DOE) divides the process of incident investigation into three main parts: 1. Data and facts collection, 2. Evidence analysis, 3. Writing reports and judgments. On the other hand, three main objectives of the incident investigation method are: 1. organize collected information, 2. Description of the incident and the hypothesis created by the experts, 3. Provide corrective action [4-5-6-7].

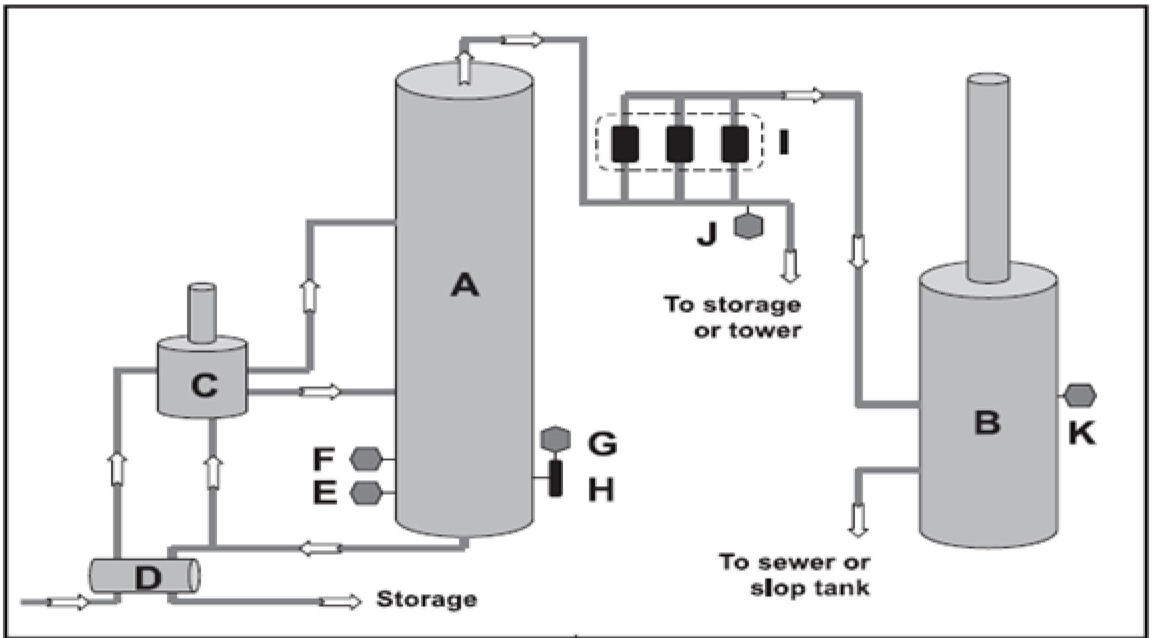
One of the main incidents in the oil industry is the Texas refinery incident in 2005. The Texas refinery is the most complex oil refinery, which includes oil refining and exploration, located in the south-east of Houston and its area is 1200 hectares and has 4 chemical units, 30 process units, 29 units of oil purification with a ranked ability of 460,000 barrels per day (bpd) and has the capability of producing about 11 million (gallons) gasoline per day as well as jet fuels and diesel fuels. The number of permanent staff was 1600 people, during the incident, 1600 permanent employees and 800 additional contractors for turnaround work [8-9]. In an explosion at the refinery, 15 people were killed and 180 wounded. The estimated financial loss for rebuilding from 2005 to 2006 was 1.5 billion [10-11].

Description of the incident:

The distillation tower (raffinate splitter section) in the isomerization unit was restarted during a maintenance operation that lasted for a month and the power was cut off. This restarting process was contrary to the BP restart instructions, so the operating employers continued pumping flammable hydrocarbons into the distillation tower. The hydrocarbon introduced lasted for almost three hours without any discharge from the tower. The HC accumulated inside the column and led to raise the level up to 17 feet inside the tower. Due to the lack of critical alarms and control tools, this problem was not noticed by the involved team. The hydrocarbons filled up in the tower, formed a sufficient hydrostatic pressure in the overhead piping, and added to the existing pressure of the tower. Consequently, the pressure at the bottom increased rapidly from 21psi to 64psi. For this reason, three pressure relief valves were opened and flammable hydrocarbons discharged to blow-down through a header collection tubes to blow-down drum (that was not attached to the flare) and stack attached to it. It is worth to know that the blow-down was not connected to the flare. Blow-down drum was fully filled and the excess HC released to the ground through a stack connected to the top of the blow-down. Unfortunately, the flammable hydrocarbons were exploded probably due to the spark potential of a moving trailer near the discharged area [9-10-12].

Process units:

The incident occurred when a section of the ISOM unit of the refinery was re-launched after a one-month maintenance period. The ISOM unit, which was built in the refinery in the mid-1980s to provide higher octane components for unleaded gasoline, has four parts: an ultrafiner desulfurizer, a penex reactor, vapor recovery/liquid recycle unit, and a raffinate splitter. Isomerisation is a refining process that causes the essential changes in atoms in the molecule without adding or removing anything from the original material. In the BP Texas City refinery, the ISOM unit transformed straight-chain normal pentane and hexane to higher octane branched-chain Isopentane and Isohexane for gasoline mixing and chemical feedstocks [12]. The schematic diagram of the *Raffinate* section of the ISOM has been illustrated in Figure 1.



A	Raffinate splitter tower	G	Level transmitter
B	Blowdown drum	H	Sight glass
C	Reboiler furnace	I	Safety relief valves
D	Heat exchanger	J	Pressure transmitter
E	High-level alarm	K	Blowdown drum alarm
F	Redundant high-level alarm		

Fig 1. The schematic diagram of the Raffinate splitter section adapted from[13].

Raffinate splitter section:

On the incident day, the startup of the ISOM raffinate splitter section was begun. The raffinate splitter section took raffinate from the aromatics recovery unit (ARU) and came apart it to light and heavy components. About 40% of the raffinate was recovered as light raffinate, mostly pentane and hexane. The remaining raffinate feed was retrieved as heavy raffinate, which was practiced as a chemicals feedstock, JP-4 jet fuel, or blended into unleaded gasoline [12].

The tower was a vertical distillation column with an internal diameter of 12.5 ft (3.8 m) and a height of 170 ft (52 m) with a volume of almost complete liquid of 154.800 gallons (586,100 liters). The tower had 70 distillation trays, which separated the light from heavy raffinate [12]. The liquid raffinate feed was transferred inside the tower (near the middle). The feed rate was controlled by an automatic flow control valve. A heat exchanger preheated the feed using raffinate product and again this feed was preheated in reboiler furnace using refinery fuel gas. Heavy raffinate pumping was carried out from the bottom of the tower, and after heating in the reboiler furnace, it was returned to the bottom of the tray. As a side stream, the heavy raffinate outcome was also taken off at the discharge of the circulation pump and transferred to storage. A level control valve that, when placed in "automatic," adjusted to maintain a steady level in the tower, handled the flow of side stream. There was a level transmitter in the splitter tower that showed the tower liquid level for the control room operator. The liquid surface of the tower is 170 feet was measured by the transmitter in a 5-foot (1.5-m) span within the bottom 9 feet (2.7 m). In addition, there were two alarms in the splitter tower that showed the level of the liquid, one of them, was sounded when the transmitter readings got to 72% (2.3 m). The second alarms acted as redundant, and when the level reached 78% ((2.4 m)), it sounded. There was a low-level alarm as redundancy in the tower. There were two heat exchangers in which the raffinate side stream passed through it. One of them exchanged the heat of a heavy raffinate by feeding the cold inlet and one used the water to exchange the heat of the raffinate before being sent to storage or mixing tanks. Before the light raffinate vapors condensed by the air-cooled fin fan condensers, they moved the top and down a 148-foot (45-m) long section of the pipe and then deposited into a reflux drum. Then liquid from the reflux drum (this Liquid called "reflux") pumped back up into the raffinate splitter tower on top of the top tray (Tray 1) [12].

During normal steady-state operation, the reflux drum was kept thoroughly full and worked as a "flooded" drum. There are also high and low-level alarms, and a safety valve in the reflux drum at a pressure of 70 psig (483 kPa). A bypass line, which discharged into the raffinate splitter disposal header collection system, lets the release of non-condensable gas (e.g. nitrogen) and wipe out the system. While startup, uncondensed vapors that built up in the drum were normally vented through a control valve to the refinery's 3-pound purge and vent gas system. This control valve was not used during the March 23, 2005, startup because of breakdown [12].

Safety Relief Valves:

To protect the raffinate splitter tower from overpressure, three similar safety relief valves were placed in the overhead vapor line 148 feet (45 m) below the top of the tower. The outlet of the relief valves was channeled to a disposal header collection system that discharged into a blow-down drum equipped by a vent stack [12].

The set pressures on these relief valves were 40, 41, and 42 psig (276, 283, and 290 kPa), respectively. An 8-inch NPS20 (8.625-inch, 21.9 cm outer diameter) line, fitted with a hand-operated chain valve, bypassed the safety relief valves and was used to discharge non-condensable gases and for system purging. The safety valves were designed to open and discharge mainly vapor into the raffinate splitter disposal header collection system when their set pressures were exceeded [12].

Disposal header collection systems:

The disposal header collection system accepted liquid and/or vapor hydrocarbons from venting relief and blow-down valves from equipment in the ISOM unit and discharged them to the blow-down drum. The header collection system included a 14-inch NPS (35.6 cm outer diameter) lifted pipe about 885 feet (270 m) long from the raffinate splitter tower. Other sections of the ISOM unit also released from two additional collection headers into the blow-down drum. The schematic diagram of the disposal header collection has been shown in Figure 2.

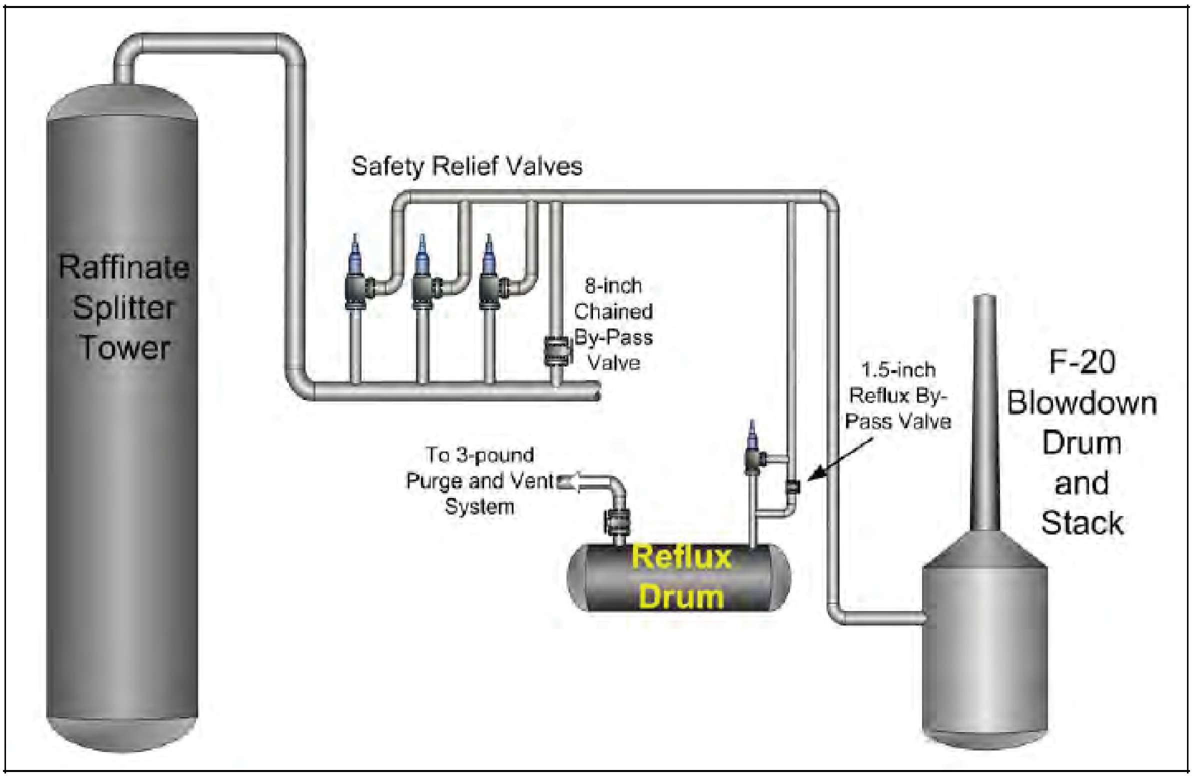


Fig 2. The schematic diagram of the disposal header collection systems adapted from[12].

Blow-down drum and stack:

The blow-down drum and stack were designed to receive blended liquid and/or vapor hydrocarbons from venting relief and blow-down valves during unit upsets or following a unit shutdown. In normal operation, light hydrocarbon vapors release from liquids, get up through a series of baffles and spread out the top of the stack into the atmosphere. Any liquids or heavy hydrocarbon vapors discharged into the drum either fall or condense and then fall to the bottom of the drum. The liquid would then be released from the base of the blow-down drum into the ISOM unit sewer system because a 6-inch NPS (6.625 inches; 15.24 cm outer diameter) manual block valve was chained open. This method of discharging to the sewer was unsafe; industry safety guidelines recommend against discharging flammable liquids that evaporate quickly into a sewer [12]. The schematic diagram of the blow-down drum section has been shown in Figure 3.

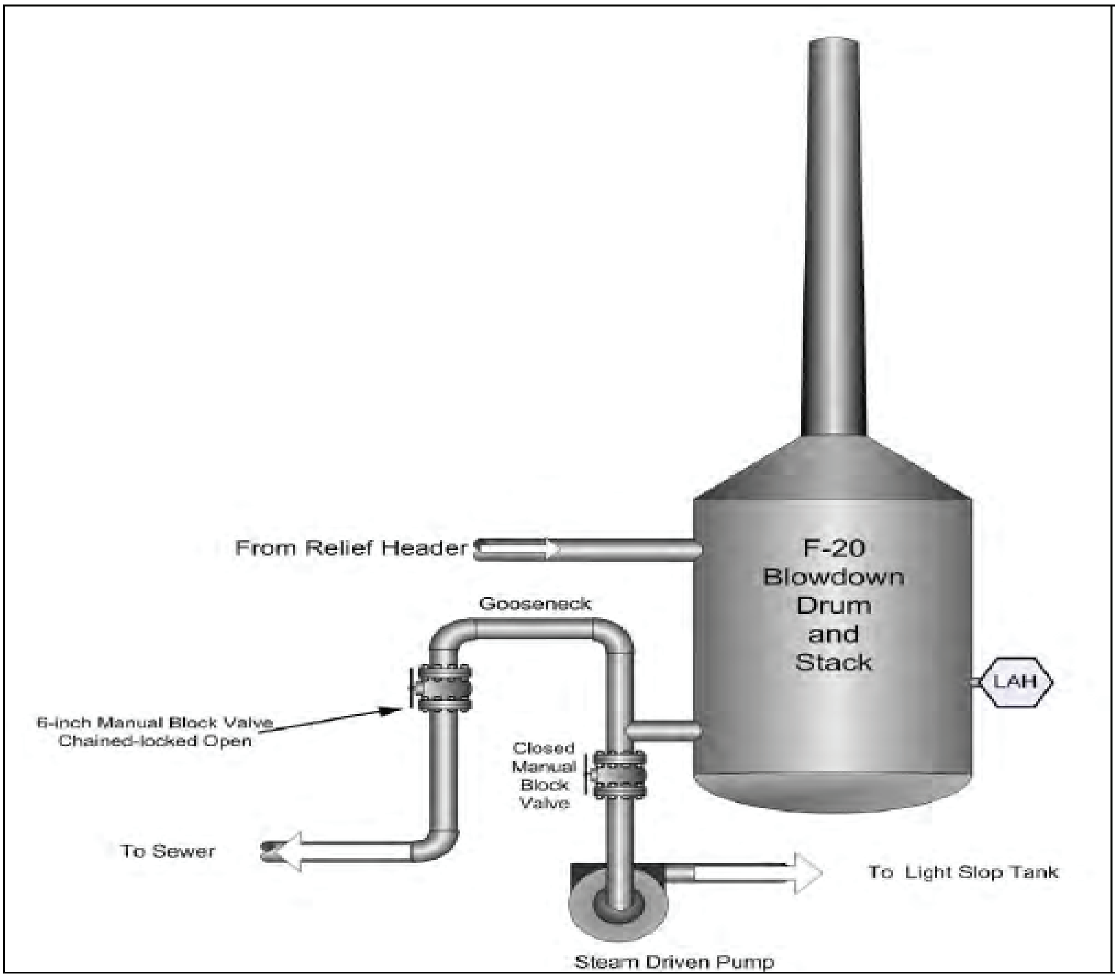


Fig 3. the schematic diagram of the blow-down drum section adapted from [12].

The blow-down system, set up in the refinery in the 1950s, was a vertical drum with an inside diameter of 10 feet (3 m) and is 27 feet (8 m) tall. The drum was fitted with a 34-inch (86 cm) diameter stack that released to the atmosphere at a height of 119 feet (36 m) off the ground. The approximate liquid full volume of the blow-down drum and stack was 22,800 gallons (86,200 L). The drum had seven internal baffles; the disposal collection header systems from the ISOM unit released into the drum under the lowest baffle [12].

A liquid level, usually water, was retained in the bottom of the blow-down drum. The height of this level was controlled by a "gooseneck" seal leg piped to a closed drain. A level sight glass was available to monitor the water level and a high level alarm was set to activate when the liquid level in the drum was close to flowing over the top of the gooseneck seal leg. A second manual block valve was located in a branch line of the blow-down drum discharge pipe (Figure 3). Following this valve, which was normally closed, was a manual steam-driven pump and a light slop tank [12].

Various incidents have taken place today and are being investigated. A main focus of existing investigation approaches is understanding why incidents happen, and on how to offer feedback to decision makers about the causes of adverse events [4]. Studies of the Texas incident provide useful information about key factors. CSB [14] and Mogford [15] are main reports that described and analyzed the incident. Among the studies, MacKenzie et al. identified some important human factors that contributed to the incident, such as inadequate training, operator fatigue, communication deficiencies, and so on [16].

Jennifer et al. investigated the effects of the incident after BP Bake report that highlighted the safety of chemical processes and extended it to other industries[17]. Kalantarnia et al. provided a predictive model that uses the BP Texas refinery incident for consequence assessment as a valuable tool to conjecture the effects of loss of containment incidents [8]. Mark's et al. study showed the importance of trailer siting and safety distance in the incident that proximity to the critical facilities led to an increase in consequences and fatalities [18].

Although there have been numerous studies and reports on the BP Texas refinery incident, each scientific article investigates a specific aspect of the incident and have not comprehensively investigated the various causes and a review study has not been done. The main goal of this review was to investigate the causes of the BP Texas refinery incident according to studies that have been performed. We present a more extensive vision of the incident so that highlight the important causes. We also briefly described some recommendations that can prevent the reoccurrence same incidents.

METHODS AND MATERIALS

The current study was conducted to review published studies on the BP Texas refinery incident and investigated important causes of this explosion. First, the published studies were extracted with a regular search in databases, and by reviewing some of the inclusion criteria, the final articles were extracted, and the results and findings of these articles were reviewed

Search strategy:

This section discusses the methods which were used for selecting articles and criteria of these articles for entering the study. The database sources that used were the Web of Science (WOS), Scopus, and Science Direct databases. The search was done in the "title, abstract and keyword" field, of Scopus and science direct databases, and "Topic" of Web of Science database. The general search strategy included key terms such as "Texas AND accident", "Texas AND incident", "Texas AND explosion", "Texas AND event". After completing the search in the databases, the total number of identified articles was 83.

Eligibility criteria:

To be eligible for inclusion, the studies were required to comply with the following criteria:

1) The articles were implied the BP Texas refinery explosion,
2) The articles were published in a refereed journal,
3) The articles were only a research type,
4) The articles were limited to those published from 2005 to 2019,
5) The articles were written in English language,
6) The articles were available online and in the form of full-text.

Review process:

Reference management (Endnote X9) were used for ordering and evaluating the titles and as well as for recognizing any duplicate entries. After duplicate articles were removed, the number of remainders articles were reviewed for title, abstract and keywords and some articles included. Any article that it's abstract was not available or when it was not clear, the full-text of article had been reviewed completely (in the third step).

RESULTS

This article describes the findings from studies that aimed to review and investigate the important causes of BP Texas refinery incident. After duplicate articles were removed, the number of remainders articles reached to 59. The remainders articles were reviewed for title, abstract and keywords and 15 articles included. After full-text articles were reviewed nine selected studies were included. The summary of Texas refinery incident related studies is detailed in Table 1.

Table 1. summary of studies and their details

Study	Location	Object	Method	Result(s)
Ramos et al. (2017)	Brazil	Investigating the potential impact of human error on safety and operations	Phoenix methodology	The oil industry could benefit from having a tailored Phoenix HRA methodology
Isimite et al. (2016)	United Kingdom	Extend the application of the lessons learnt from the incident by offering an approach to HAZOP	A dynamic model of the sequence of events	The resulting simulation model is used as the framework for a dynamic HAZOP study
Saleh et al. (2014)	United State	Identify a fundamental failure mechanism(safety–diagnosability) principle	Examine the accident pathogens and analyze the sequence of events	Defense-in-depth be augmented with safety–diagnosability principle
Manca et al. (2012)	Italy	Modeling the chain of events	Commercial dynamic process simulator (UNISIM)	A homogeneous equilibrium model (HEM) cannot explain the blowdown drum filling and release, and further studies are necessary
Manca et al. (2011)	Italy	These phenomena and provide some simulation results	Commercial dynamic process simulator (UNISIM)	The HEM model does not provide satisfactory results
Kalantarnia et al. (2010)	Canada	To demonstrate testing and validation of one such approach, dynamic risk assessment or predictive model	Dynamic risk assessment (integrates Bayesian failure updating mechanism with the consequence assessment)	Dynamic risk assessment has the ability to learn from near misses, incident, past accidents and predict event occurrence likelihood
Kaszniak et al. (2008)	United State	General information on trailer siting issues	Survey of adequacy of risk analysis methods in API RP 752 and safety distance in trailers	PHA and MOC have important role in occurrence
MacKenzie et al. 2007	United State	Found several pre-existing latent conditions and safety system deficiencies	Investigating documents, interviews and electronic data from the computerized control system	Some deficiencies include: lack of effective communication
Khan et al. (2007)	Canada	Demonstrate the usefulness of QRA as a process safety decision-making tool	Different modeling approaches (consider three likely incident scenarios)	If had QRA been conducted during the MOC severe consequences (personnel trailers) would then not have occurred

DISCUSSION

Models of incident evolution:

Reports have been given so far on the incident, although there are some contradictions in the full description of the incident. The articles which studied have used some simulation models of the incident. In Manca et al. [11] study the UNISIM modeling technique is used to model the incident regarding the distillation tower unit and its interactions, but due to the complexity of the distillation column operation on the incident, this method cannot replicate the sequence of events, therefore the dynamics of the downstream events of the safety valves are not disclosed, and critical information such as the type of safety valves and process conditions for the input and output of safety valves are lost [19-20].

On the other hand, in previous reports, partial evaporation of the feed that resulted in the formation of a vapor cap, like a liquid plug, and led to the top of the feed tray to the column head has been mentioned cause of overflow in the distillation tower. Manca et al. showed that the cause of flood and overflow in the distillation column after 1 pm is that the steam phase was broken due to the presence of 30 sieve trays above the feed tray to the bubbles and liquid swelled due to the dispersion of those bubble in the liquid holdup. The presence of tray holes smaller than 8 mm leads to a plug and subsequently overflows. So the partial evaporation hypothesis of the steam is rejected [11-19].

Among the studies that have been done, Manca et al. have been used the UNISIM modeling method, which mentioned the presence of trays was the cause of the distillation tower overflow. On the other hand, the homogeneous equilibrium model (HEM) cannot describe the dynamics of a sub cooled liquid flow or pressure at the bottom of the blow-down drum pipe. Nevertheless, this model helped to show that a nonlinear pressure drop across 270 meters of pipe causes partial evaporation of the fluid released in the relief valves with a significant reduction in both temperature and density. Because of the insufficiency of the HEM method, it is suggested that the alternative model, the separate phases model (SPM), based on a non-homogeneous, two-phase mixture (unlike HEM), be used. Another contradiction that can be seen is the presence of a flare on blow-down drum. One study conducted by Khan et al. [9] and also based on a report's results [21] emphasized and pointed the importance of the presence of flare which in case of flare existence the liquids and hydrocarbon vapors was not discharged outside the blow-down drum and vapor cloud was not created, but the study of Manca et al. [11] was done later pointed, the safety of the blow-down drum on another view. In other words, the geyser like release it was not due to inherent safety and the presence of flare in the blow-down, but because of the size of the blow-down drum, that if had been large enough it would have taken all the liquid hydrocarbons from the isomerization unit [11].

Kalantarnia et al. used the dynamic risk model approach based on the concept of dynamic risk assessment. This method showed that if the dynamic risk assessment was carried out on the refinery, the incident would be prevented. Although this approach is heavily dependent on incident information and data accuracy and needs a strong safety culture during the process stages to monitor and record incidents [8-11]. Also, improving human factors, the reporting system is important in addition to the safety culture [22]. In spite of this, in addition to some deficiencies for some models, it is recommended instead of modeling the accident dynamics to investigate the failures in the barriers that led to the incident to improve process safety [10].

Lessons from incident:

A description of several point that referred to in literature in other words, their role is highlighted in studies and reports is given as follows:

Human factors:

Although measures have been taken to improve safety in the oil industry, there are still severe events that are often due to human error or human failure events (HFE). HFEs are principally human errors that have an adverse consequence on system safety and are the unit of analysis in human reliability analysis (HRA) [23]. One of the studies about the Texas refinery incident suggested that the relationship between safety–diagnosability principle and the HRA be investigated. Another study after this, through HRA and Phoenix, (which is an HRA method), examines human failures that finding indicates a large number of factors and latent errors, affect the decisions and actions of operators in the aromatics, isomerization, and naptha desulfurization units (AU2 / ISOM / NDU series [2-12-13]. These defects create a suitable work environment for human error. Some pre-existing latent conditions and safety system deficiencies are lack of effective communication during unit startup, poor computerized control board display, malfunctioning instrumentation, insufficient staffing during start up, operator fatigue, and inadequate training [16]. It is worth mentioning that one of the significant causes of the happening of human error that, in turn, is responsible for work related accidents in developed countries, is inadequate training and experience [24]. It is suggested that training also was an important factor for prevention of the incident.

The absence of supervising staff to confirm the correct procedure of doing work and absent in pre-startup and startup procedures had not been followed properly, and preventive intervention was not performed [9]. Therefore, it can be concluded that ‘organization process’, ‘inadequate supervision’ and ‘skill-based errors’ were the main human factors and latent conditions. This finding is consistent with the findings of other studies [25-26-27-28]. Among these factors the skill-based error, happen amongst highly skilled members when task performance is being directed by automatic habit routines [29-30] and the only way to prevent this error is to pay attention to the surrounding circumstances [31].

Preliminary hazard analysis:

Process decisions and activities require the use of a process safety management system (PSM). Such a system should plan, do, check, and act the program's essential management functions to be effective. Equally important to the effectiveness of a PSM system are the commitment and leadership showed by company management. The procedural measures, such as work permits and hot permit to work, to control the potential sources of combustion, including vehicles in restricted areas and vehicles on adjacent roads, when events such as startup and shutdown are scheduled [9].

Preliminary hazard analysis (PHA) [17] is an effective method to identify and evaluate hazards in a system [32]. One of the key points raised in this incident was the poor implementation of the PHA, since, one of the management elements that should be considered following the PSM standard is to conduct a Process PHA. To be According to occupational safety and health administration (OSHA), PHA is "a complete and systematic approach to identifying, assessing, and controlling the risks of chemical processes." The results of one Texas refinery incident report recommend that PHA risk analysis be applied to industries. The hazard and operability study (HAZOP), which is one of the PHA tools, is a high-performance method for systematically identifying and assessing the safety risks involved in the process and, like other PHA tools, identify unacceptable risks [10]. Although Herbert study [33] confirmed this, the Baybutt [34] showed HAZOP study is not without its faults.

The main 1993 PHA method for the ISOM unit identified the measuring instrument on raffinate splitter as protection against tower overfilling (and reaffirmed in 1998 and 2003). However, raffinate splitter devices were not on the list of essential tools. The ISOM unit was particularly feeble in the fire and explosion hazards.

The disadvantages associated with poorly performing PHA in the refinery are as follows:

- The consequences of the high-pressure levels in the raffinate splitter tower and the higher level in the blow-down drum and stack were not sufficiently identified. The excessive filling of the tower caused a high pressure in the safety valves and liquid overflow in the blow-down drum and stack.
- High heat-up rates or blocked outlets are not known as a potential high-pressure cause.
- Blow-down drum measurement was not evaluated for inhibiting the potential release of ISOM [12].

Also in investigating Pennzoil refinery explosion in Rouseville, pennsylvania, environmental protection agency (EPA) suggested that the company use PHA method to assess the hazards of siting equipment and work regions [35].

Management of changes:

Management of changes (MOC) in organizations, subject to main accident hazards, is one of the key elements of a safety management system [34-36]. On September 21, 2005, OSHA issued 18 egregious willful violations to the Texas BP refinery, which was unsuccessful enough to evaluate the safety and health effects of a catastrophic explosion for 18 temporary trains near the ISOM unit, with reference to PSM management of change requirements [18].

During the March explosion, the trailer was occupied by contractor personnel in November last year. The MOC was never approved by the ISOM unit administrator. After the March 2005 disaster, the refinery revealed that most mobile office trailers were not using the MOC process, and therefore no PHA or position evaluations were carried out. They also found that although the MOC process was used for a trailer or group of trailers, site analysis of the PHA site was either not performed, or not properly completed [18].

The MOC program intended to allow changes to be made by the executive director after the PHA was completed, and all items of safety measures were considered. However, this did not always happen. For example, placing a double-wide trailer next to the ISOM unit is not allowed. Management of the change processes (MOC) did not take into account the significant release of hydrocarbons in the stack. Otherwise, the trailers would not have been located where they were placed, and the consequences of this incident would have been far fewer severe [9-18]. So we can conclude that MOC deficiencies in the Texas refinery is more apparent in trailer siting. The conventional management of change procedures typically consider only the technical and technology related changes, and it has been proposed that the organizational changes are important as well [37-38].

Quantitative risk analysis:

Quantitative risk analysis (QRA) is widely used in various industries as a tool for evaluate the risk of fire incidents in storage tanks [39-40], gas pipeline [41], ship being involved in ship collisions [42], improving safety, as part of the design, licensing, or operation of applied processes [43]. An important part of the system safety is identifying the potential risks associated with a process and assessing the probability of occurrence and its consequences. This approach determines the probability and consequences of a negative impact event. QRA originated in the nuclear industry and is now widely used in process industries with desired results. Kalantarnia et al. demonstrated the utility of the quantitative risk assessment (QRA) in modeling the events of the BP refinery in Texas on March 23, 2005. QRA (in the analysis of specific results) has identified important lessons such as facility mapping and hazard classification considerations [2-8-9]. On the other hand, the investigation of the incident demonstrates that the role of QRA in the trailer sitting in vicinity of refinery is striking. If the QRA was implemented during the management of change (MOC) decision making trailer probably would not be close to process units [9]. Domenico study showed the use of the simulator in relationship with the QRA also permitted testing the risk in new operating conditions in order to delimit safe regions for the plant [44]. These finding confirmed with previous studies [45-46].

Defense-in-depth and safety–diagnosability:

It should be taken into account that the high liquid level and the base temperature contributed to the high pressure in the raffinate splitter. The presence of water, nitrogen, or inadequate feed is key factors contributing to the rapid increase in fluid pressure and transport. Stopping feed, increasing off take or decreasing heat input earlier would prevent incidents [9].

The deficits of the refinery design consisted of mechanical defects and old technology. Most tower tools did not work on the day of the incident. The second high-level alarm did not sound, the sight glass was not clean and did not provide visual information, and the correct level transmitter was incorrectly calibrated and just determined liquid levels over a 5 ft. length of the 170 ft. tall tower. As a consequence, operators' observing ability to liquid levels was reduced, and understanding of the hazardous situation developing is decreased. If the safety–diagnosability principle is used correctly, in such cases, the operator's awareness of the situation increases, and after the initiating event, the opportunity is likely to be that the incident is likely to be prevented or the severity and consequences are reduced [13].

Incidents usually be caused by the absence or gap of defenses or violation of safety constraints [47-48-49]. Defense-in-depth in safety management means having more than one protective tool (such as multiple barriers, inherent safety features, engineered safety features, etc.) to achieve a safety goal so that even if one of the protective tools fails. The defense-in-depth strategy depends on the identification of the set of relevant initiating events against which barriers are needed. In the Texas incident, defense-in-depth was prominent, which if applied, would improve safety–diagnosability principle. In other words, defense-in-depth is complemented by the safety–diagnosability principle [13-50]. Also, one of the barriers that could reduce the severity of the incident was the evacuation alarms that people adjacent to the release site (i.e. trailers) were not notified before starting up or discharging hydrocarbons from the stack because of failure to sound the evacuation alarm [9]. Overall, the findings demonstrate that this factor could have prevented or reduced the consequences of the incident. Bakolas et al. [51] also confirmed this.

The summary of the lessons that can be learned from the incident is shown in Figure 1. Admittedly, some of the causes of the incident may be overlooked. Further studies are needed to reveal all of these causes. It is recommended that different methods, such as root cause analysis (RCA), STAMP, and etc. be used to investigate incidents, especially the BP Texas refinery incidents. Among these methods, STAMP is recommended because of its higher reliability than other methods such as Accimap [52].

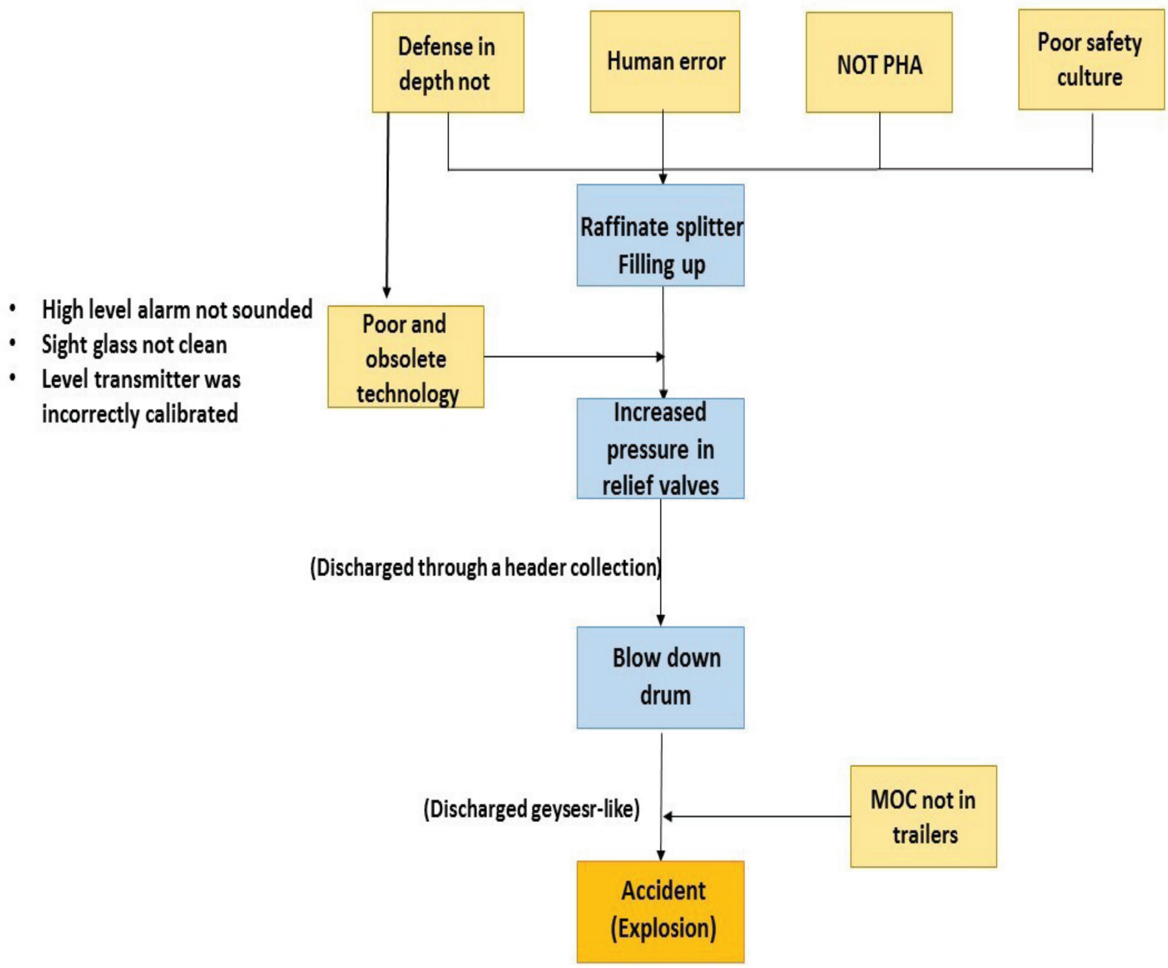


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Fig 4. Schematic diagram of incident causes and Lessons from the BP Texas incident.

Human factors, deficiency in defense in depth, preliminary hazard analysis [17], poor safety culture and management of change (MOC) are root and contributory causes of the incident.

CONCLUSION

This study has presented to explain the causes of the incident at the texas refinery and survey deficiencies and root causes, which together led to this catastrophe. A discussion and comparison of the studies revealed that the modeling of accident dynamics does not help to improve the process safety, and instead, it is suggested that it focus on barriers and their failures. The factors that led to the incident occurring at the texas refinery include defects in moc processes, inappropriate preliminary hazard analysis [17], poor maintenance, human factors, inadequate supervision, and defective barriers. It can be said that the most important factor was the defect in safety barriers. If the obstacles were activated properly, the incident did not occur. Also, if the trailer sitting was appropriate and the management of change procedure was well done, the severity of the incident would be reduced. It is recommended that more attention be paid to these factors in industries, especially in the oil and gas industry, and further studies on such incidents need to be undertaken to take advantage of lessons learned to improve process safety and incident prevention.

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