REVISITING PAST REFINERY ACCIDENTS FROM A HUMAN RELIABILITY ANALYSIS PERSPECTIVE: THE BP TEXAS CITY AND THE CHEVRON RICHMOND ACCIDENTS

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Despite the oil industry's efforts in improving safety, it still presents a high rate of serious accidents, many involving human failure events (HFE), which can be identified, modelled, and quantified through human reliability analysis (HRA). The oil industry commonly analyzes process safety by focusing on technical barriers, and thus it could benefit from HRA. Phoenix methodology is an HRA method that uses a human response model and relates the crew failures modes (CFM) to performance influencing factors (PIFs). Based on Phoenix CFMs and PIFs, two refinery accidents, the BP Texas City (2005) and the Chevron Richmond (2012), are analyzed in this paper. The analysis consists of the construction of the accident timeline; identification of the HFEs and assigning them to appropriate CFMs; and, finally analysis of the PIFs. The analysis helped better understand how the operators responded to an abnormal condition of the process, and why they took the actions they did, investigating the contribution of human error to the accidents. The assessment of the role human error played in these accidents is a major contribution to the understanding of why they happened, and a key information to avoid the same happening again in the future. Moreover, the features and limitations of the application of Phoenix HRA, which was developed based mainly on nuclear power plant operations, to Oil Refinery operation scenarios, are discussed and evaluated. This article provides insights on value of investigating the potential impact of human error in the Petroleum Industry accidents.

Keywords: risk analysis, human reliability, human failure, oil and gas industry

INTRODUCTION

Petroleum refining installations and petrochemical plants pose safety concerns that are inherent to their characteristics—working with flammable and toxic fluids. From 1985 to 2001 petrochemical plants presented the second biggest number of major accidents in the European Union, making up 17 % of the total number reported to the European Major Accident Reporting System. Moreover, 40 % of these accidents have causes attributed to human factor.[1]

In the United States the refining industry presented more fatality/catastrophe (FAT/CAT) than any other industry between 1992 and 2007. During 2012 alone there were 125 significant process safety incidents in U.S. petroleum refineries.[2]

Kariuki and Lowe[3] state that over 80 % of accidents in the chemical and petrochemical industries have human failure as a primary cause. The high rate of human failure in this industry can also be seen in specific regions, such as the Greek petrochemical industry, in which human factor was the most common single case of reported accidents from 1997 to 2003,[4] or Australia, where an analysis of 2000 cases of accidents from the first Australian Incident monitoring study revealed that human error was attributed in 83 % of these cases.[5]

Through human reliability analysis (HRA), human contribution to risk can be assessed qualitatively and quantitatively. Indeed, HRA aims at identifying, modelling, and quantifying human failure events (HFE) that may happen in different accident scenarios. Such analyses form the basis for prioritizing and developing effective safeguards to prevent or reduce the likelihood of human-caused accidents.

To date most credible and advanced HRA methods have been developed and applied in support of nuclear power plants control room operations. In the petroleum industry, quantitative risk analysis (QRA) is one of the main tools for risk management. However, QRAs applied in oil and gas industry have primarily identified hardware failure risks, neglecting those HFEs that contribute to overall system risk.

Presently, a variety of HRA methods exist. Moreover, new methods are still in development. The so-called first-generation HRA methods were the first formalized methods developed to aid risk assessors to predict and quantify the likelihood of human error. They include technique for human error rate prediction, THERP,[6] and human error assessment and reduction technique, HEART.[7] In the 1990s, efforts were made to improve the application of first-generation HRA methods, which led to the so-called second-generation methods, such as standardized plant analysis risk human reliability analysis, SPAR-H,[9] cognitive reliability and

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error analysis method, CREAM,[8] and information, decision and action in crew context, IDAC.[10,11,12] Among the more advanced HRA methods is the Phoenix methodology.[11] It is a model-based method that assimilates strong elements of current HRA good practices and adopts lessons learned from empirical studies. Moreover, this specific methodology makes use of a human response model that relates the observable crew failures modes (CFM) to "context factors" commonly known as performance influencing factors (PIFs).

In this paper, two major past oil refinery accidents are analyzed based on Phoenix CFMs and PIFs. The first event concerned BP Texas City Refinery (2005) and the second one took place at Chevron Refinery at Richmond, California (2012). This article highlights the role human error played in these two accidents, the value of applying HRA to investigate the impact of human error in the Petroleum Industry accidents, and the strengths and limitations of using Phoenix to do so. The analysis consisted of the construction of the accident timeline, identification of the HFEs and assigning them to appropriate CFMs, and analysis of the PIFs.

The rest of this article is organized as follows. First we briefly describe the Phoenix methodology and its qualitative aspects. We will then provide an analysis of human errors in BP Texas City and Chevron Richmond Refineries accidents. This analysis is comprised, for each accident, of a description of the accident, its timeline with identification of HFEs, the classification of the HFEs based on Phoenix CFMs, and the identification of the PIFs affecting the identified CFMs with support of investigation reports' extracts. This is followed by a subsection with a discussion on our findings and on the use of Phoenix for performing HRA on oil refineries accidental scenarios. Finally, some concluding thoughts are presented in the last section.

PHOENIX METHODOLOGY

The development of Phoenix methodology came as an attempt to address key issues of the previous HRA methodologies. Ekanem et al.[11] summarize how these issues have resulted in discrepancies, deficient traceability, and reproducibility in the qualitative and quantitative aspects of HRA. Moreover, these issues have led to variability in the results when different HRA methods are applied, and when different HRA analysts apply the same method.

Mosleh and Chang[13] have listed high-level requirements in the development of new HRA methods that would overcome the abovementioned problems. They argue that, to ensure robustness of the predictions and reproducibility of the results, a model-based method is necessary.

A model-based HRA framework was introduced in Mosleh et al.[14] and Hendrickson et al.[15] with an application example in Shen et al.[16] This model-based HRA was further developed in Mosleh et al.[17] and Oxstrand et al.[18] Ekanem[19] improved several aspects of this method by developing the model-based methodology called Phoenix. The improvements it brings in comparison to other HRA methodologies can be seen in Ekanem et al.[11] The qualitative framework of the methodology is briefly described in this section. For further details about the methodology the interested reader is referred to Ekanem;[19] an overview of the Phoenix qualitative framework is given in Ekanem and Mosleh[20] and Ekanem et al.[11] and the quantitative framework is summarized in Ekanem and Mosleh.[21]

Phoenix has three main layers (Figure 1). The top layer is the Crew Response Tree (CRT), represented by an event tree; the middle layer is the human performance model, using fault trees, and the bottom layer consists of the PIFs, modelled through Bayesian Belief Networks (BBN). The PIFs are the contextual factors that affect human performance, i.e. they influence the operators' decisions and actions. The BBN then presents the paths of influence of the PIFs on the CFMs that are relevant to the HFEs. The three layers—CRT, Fault Trees, and BBN—are combined to form the integrated model.[20]

CRT is the first modelling tool for the qualitative analysis process. It is a forward branching tree of crew cognitive activities and actions, and acts as a crew-centric illustration of the crew-plant scenarios. Its role is to ensure a systematic coverage of the interactions between the crew and the plant that is consistent with the scope of the analysis being conducted, thereby providing traceability for the analysis. In the CRT, each sequence of events indicates a graphical representation of one of the possible crew responses across the entire accident sequence. This characteristic helps in increasing consistency and reducing variability in the HRA task analysis.[14] Ekanem et al.[11] provide

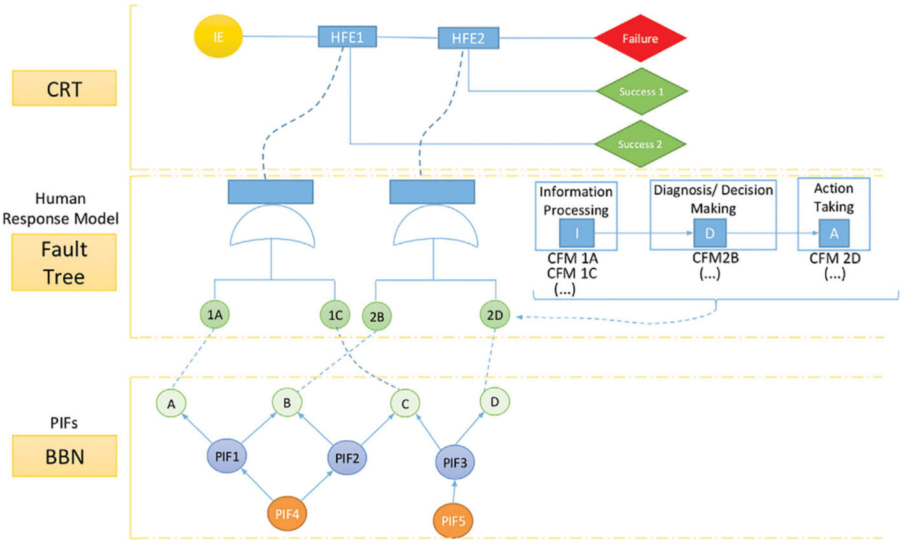


Figure 1. Phoenix's Integrated Model.[19]

a flowchart in order to aid the analyst to construct the CRTs, with questions to illustrate how to aid branches to the CRT.

However, the CRT branches and sequences do not cover the human failure mechanisms or their causes.[18] Instead, the human failure mechanisms are modelled in Phoenix's second layer, through Fault Trees, making use of the information, decision, and action (IDA) human response model.[10] According to IDA, an error can be performed because the operators failed in the information-gathering stage (I), or, given correct information, they failed in situation assessment, problem solving, and decision making (D), or, given a correct decision, they failed in action execution. These errors—crew failure modes—are then the possible forms of failure in each of the IDA phase.[11] Phoenix's set of CFMs can be seen in Table 1. The full description of each of the CFMs can be seen in Ekanem.[19]

Finally, the CFMs are connected to the PIFs in the third layer of the model through BBNs. As argued by Hollnagel,[8] the fact that the quality of human performance depends on the conditions under which the tasks or activities are carried out (PIFs) can be considered a consensus in HRA approaches. Hence, although human error is the main object of study of HRA, it should not be viewed as the product of individual shortcomings.[22] When an abnormal event occurs, the crew starts the process of trying to solve the problem by responding cognitively, emotionally, and physically. Thus, the PIFs in Phoenix have been organized into eight primary groups to cover emotional, cognitive, and physical aspects. These groups are also individually considered as PIFs themselves (Table 2). The groups (also known as the "primary or level 1 PIFs") are knowledge/abilities and biases that map to cognitive response, stress that maps to emotional response, while procedures, resources, team effectiveness, human system interface (HSI), Task Load, and Time Constraint all map to physical world.[19] The PIFs are organized in a hierarchical structure, which can be fully expanded for use in qualitative analysis and collapsed for use in quantitative analysis. In the CFM-PIFs BBN framework, the CFMs are directly affected by the Level 1 PIFs; the latter are affected by the Level 2 PIFs, which are affected in turn by the Level 3 PIFs. The description of each PIF can be seen in Ekanem.[19] The next section presents the analysis of two past refinery accidents using Phoenix's CFMs and PIFs.

ANALYSIS OF HUMAN ERRORS IN PAST OIL REFINERIES ACCIDENTS THROUGH PHOENIX

This section presents the analysis of two of the biggest recent accidents in oil refineries: the BP Texas City Refinery accident (2005) and the Chevron Richmond Refinery accident (2012). The conditions in which the BP Texas City accident took place and its tragic consequences led to papers on different aspects, such as trailer sitting issues,[23] application of process design life cycle for a safer design,[24] and organizational factors and safety culture.[25] In addition, a number of papers have focused on risk.[26–28] Different aspects of the Chevron Richmond refinery accident have also been addressed, such as the corporate social responsibility,[29] and an application of system theoretic accidental analysis.[30]

The present paper focuses on the human actions that contributed to these accidents to answer the question "how and why did the operators fail?" This question has not been addressed in previous studies on these accidents in a systematic approach. The assessment of the role human error played in these accidents is a major contribution to the understanding of why they happened, and key information to avoid them happening again in the future.

The accidents were analyzed through a timeline constructed to highlight the operators' actions—these were identified as one of Phoenix CFMs. The conditions that influenced the operators' decisions and actions were identified as one of Phoenix's PIFs. The use of Phoenix's set of CFMs and PIFs will make it possible to evaluate the suitability of these sets to represent oil refineries operations. The Phoenix version presented in Ekanem et al.[11] was developed for use in nuclear power plant (NPP) probabilistic risk assessments. Phoenix's set of CFMs and PIFs have roots in studies on NPP operations and on previous HRA methodologies, which were also mainly developed for NPP operations.

The PIFs identification is justified with excerpts of investigations reports to support these findings with traceable documentation. For a definition of each of the CFMs and PIFs pointed in this section the reader can refer to Ekanem.[19] The next two subsections describe each accident and present its timeline and the identification of the CFMs and PIFs, followed by a subsection with discussion on the CFMs and PIFs and the applicability of Phoenix HRA Methodology.

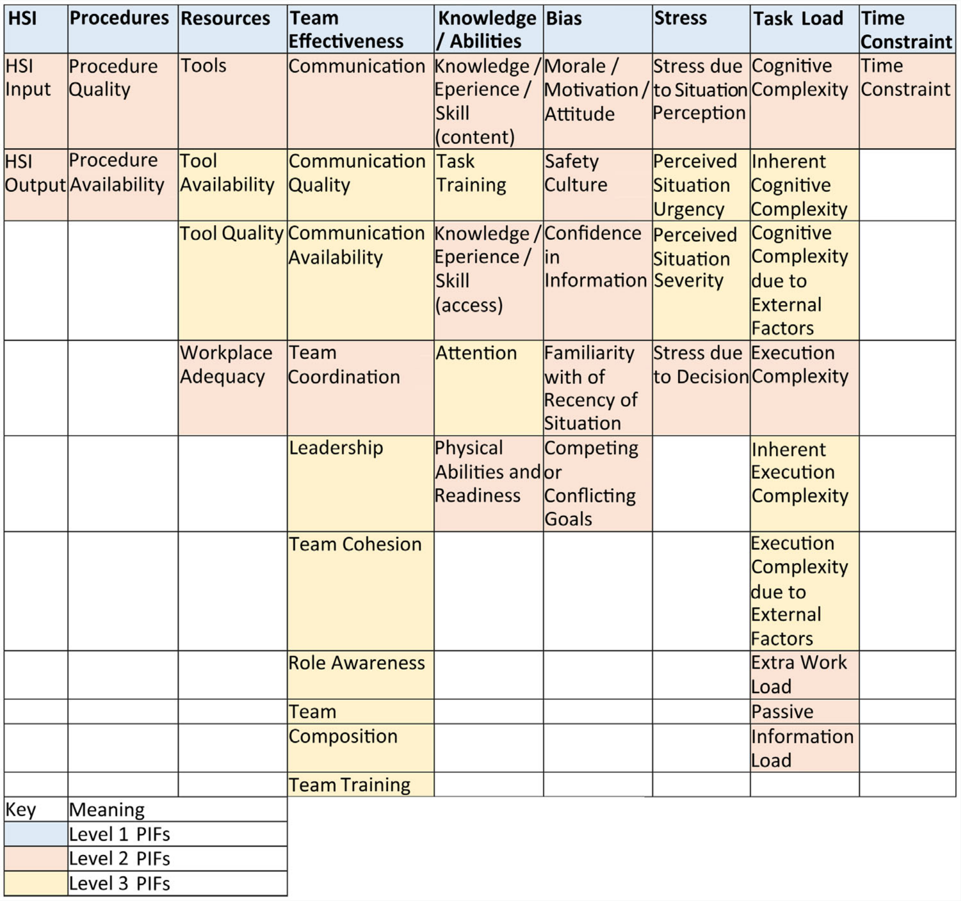
BP Texas City Refinery Accident (2005)

The accident in the BP Texas City Refinery on March 23, 2005, is one of the worst industrial disasters in recent U.S. history. During the startup of the isomerization unit (ISOM), the raffinate tower was overfilled. The flammable liquid was led to a blowdown system that was not equipped with a flare, resulting in a flammable liquid geyser, followed by an explosion and fire. As a result, 15 persons were killed and 180 were injured, and 43 000 people had to remain indoors after a shelter-in-place was issued. The financial losses exceeded $1.5 billion.[31]

Table 1. Phoenix set of Crew Failure Modes (Ekanem et al.[11])

ID	Crew Failure Modes in "I" Phase	ID	Crew Failure Modes in "D" Phase	ID	Crew Failure Modes in "A" Phase
I1	Key Alarm Not Responded To (intentional & unintentional)	**D1**	Plant/System State Misdiagnosed	**A1**	Incorrect Timing of Action
I2	Data Not Obtained (Intentional)	**D2**	Procedure Misinterpreted	**A2**	Incorrect Operation on Component/Object
I3	Data Discounted	**D3**	Failure to Adapt Procedures to the Situation	**A3**	Action on Wrong Component/Object
I4	Decision to Stop Gathering Data	**D4**	Procedure Step Omitted (Intentional)		
I5	Data Incorrectly Processed	**D5**	Inappropriate Transfer to a Different Procedure		
I6	Reading Error	**D6**	Decision to Delay Action		
I7	Information Miscommunicated	**D7**	Inappropriate Strategy Chosen		
I8	Wrong Data Source Attended To				
I9	Data Not Checked with Appropriate Frequency				

Table 2. Phoenix set of PIFs (Ekanem et al.[11])



HSI	Procedures	Resources	Team Effectiveness	Knowledge / Abilities	Bias	Stress	Task Load	Time Constraint
HSI Input	Procedure Quality	Tools	Communication	Knowledge / Eperience / Skill (content)	Morale / Motivation / Attitude	Stress due to Situation Perception	Cognitive Complexity	Time Constraint
HSI Output	Procedure Availability	Tool Availability	Communication Quality	Task Training	Safety Culture	Perceived Situation Urgency	Inherent Cognitive Complexity	
		Tool Quality	Communication Availability	Knowledge / Eperience / Skill (access)	Confidence in Information	Perceived Situation Severity	Cognitive Complexity due to External Factors	
		Workplace Adequacy	Team Coordination	Attention	Familiarity with of Recency of Situation	Stress due to Decision	Execution Complexity	
			Leadership	Physical Abilities and Readiness	Competing or Conflicting Goals		Inherent Execution Complexity	
			Team Cohesion				Execution Complexity due to External Factors	
			Role Awareness				Extra Work Load	
			Team Composition				Passive Information Load	
			Team Training					

Key	Meaning
🟦	Level 1 PIFs
🟧	Level 2 PIFs
🟨	Level 3 PIFs

The causes of the accident were a combination of multiple failures at different levels: instrumental, organizational, and operational. Although the instrumental and equipment failures played an important role in this accident, if the operators' answers to the plant abnormal situation would have been adequate, the accident could have been avoided. The more detailed investigation of the BP Texas City accident is the Chemical Safety Board Final Investigation Report;[31] hence, the description of the accident to follow is based on that report.

The isomerization process aims to alter the fundamental arrangement of atoms in a molecule. The ISOM unit comprised four sections: a desulphurizer, a reactor, a vapour recovery/liquid recycle unit, and a raffinate splitter. The accident happened in the raffinate section (Figure 2), which produced light and heavy components by separating the raffinate, which is a non-aromatic, primarily straight-chain hydrocarbon mixture prevenient from the Aromatics Recovery Unit (ARU).

The raffinate splitter section was shut down for maintenance and the raffinate splitter tower was drained, purged, and steamed-out to remove hydrocarbons. One month later, on March 23, 2005, the startup of the section took place and was conducted by the Night Lead Operator. The splitter tower was equipped with a level transmitter and associated alarms. The level transmitter measured the tower's liquid level in a 1.5 m span from the bottom 2.7 m of the 52 m tall tower. When the transmitter reading reached 72 % of the bottom (2.3 m) the primary alarm should sound, and when the reading reached 78 % (2.4 m), the redundant high-level alarm should sound. During the startup, the level reached 99 % on the transmitter, thus being beyond the set point of both alarms. However, only the first one sounded.

Although it was mentioned on the startup procedures that, during the startup, the level should be established at a 50 % transmitter reading, it was not unusual for the operators to fill the bottom of the tower until 99 %. They would do this to avoid the liquid level of the tower dropping, which had happened in past startups, and thus avoid damaging any equipment. After filling the tower, the operators stopped the startup, by closing the tower feed and shutting off the bottom pumps. Even though startup procedures instructed to put the tower level control valve on "automatic" and set as 50 % after a level was reached in the tower, it continued in the "closed" position.

The Night Lead Operator, who had initiated the startup, left the refinery one hour before his shift ended. After briefly describing to the Night Board Operator and to his supervisor the actions he had taken during his shift, he added to the control room logbook "ISOM: Brought in some raff to unit, to pack raff with," which only meant he started filling the tower with no further details. In this sense, the Day Board Operator started his shift with an inappropriate level of information on the state of the unit. The Day Supervisor (Supervisor A), who was ISOM-experienced,

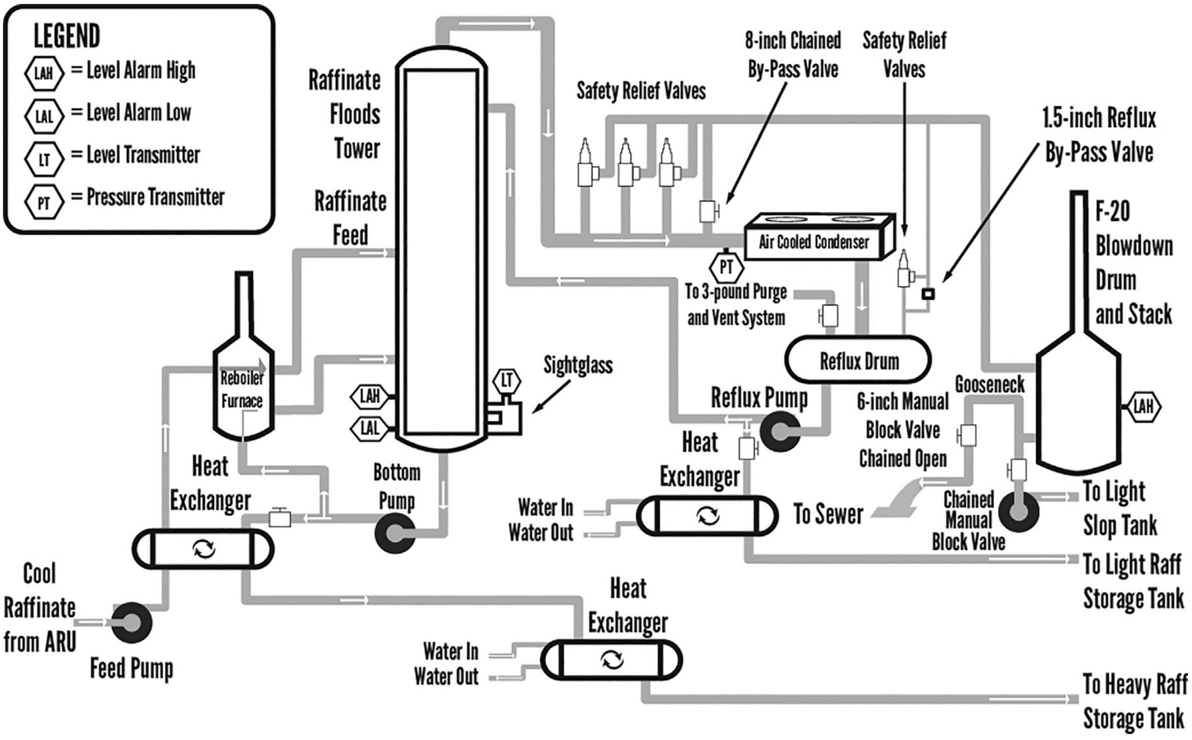


Figure 2. Raffinate Section of BP Texas City Refinery Isomerization Section.[31]

arrived for his shift over an hour late, and did not conduct shift turnover with any night shift personnel.

When the startup resumed, a written procedure was not available for the Day Board Operator to comprehend the exact stage of the startup. Yet, he restarted raffinate circulation and added feed into the already high liquid level of the tower.

The tower instrumentation was showing a liquid level below the maximum range of the transmitter, although it was higher than that. The tower was equipped with a level sight glass; however, for years it was covered with buildup of dark residue, being thus unreadable.

At 10:47 a.m. Day Supervisor A, due to a family emergency, left the plant to the responsibility of the second Day Supervisor, who was not ISOM-experienced. Moreover, the latter was in charge of supervising the final stages of the ARU (Aromatics Recovery Unit) startup. After Supervisor A left, no ISOM technical expert was assigned to this section startup, contradicting BP's safety procedures.

Around 11 a.m. it could been read at the transmitter that the liquid tower level was at 93 % (2.64 m) from the bottom of the tower; however, the actual level in the tower was 20 m. At 12:41 p.m. the increase in the liquid level started to compress the remaining nitrogen in the tower, leading its pressure to rise to 227.5 kPa (gauge). However, the crew assumed that this was a consequence of an overheat of the tower bottoms because it had happened in previous startups. The outside operations crew then opened the 20-cm NPS chain-operated valve, to send product to the blowdown drum, which reduced the pressure in the tower. Moreover, at the time of the pressure rise the Day Board Operator and the Day Lead Operator discussed the need to remove heavy raffinate from the tower, and opened the level control valve.

Opening the valve made the total amount of material in the tower begin decreasing. However, it also heated the feed of the tower, exchanging heat from the hot bottom of the column with the feed through the heat exchanger. With a hotter feed the whole content of the column heated, and the liquid level at the top of the column continued to rise. The column was then overfilled and the content spilled into the overhead vapour line, followed by the column relief valves and condenser. Moreover, heating from the furnace created a temperature profile in the raffinate splitter column (Figure 3).

By the time of the accident, most of the column was heating at a fast pace and just a cold layer of liquid remained at the top. The entire column then approached the boiling point of the liquid, and the vapour bubbles, which initially were rising and condensing after contact with the liquid, began to accumulate. This caused an increase in volume from vaporization. Consequently, the liquid in the column top began to overflow into the vapour line.

The safety relief valves opened as a result of the increase of the hydrostatic head in the line and the tower pressure, and let liquid raffinate into the raffinate splitter disposal header collection system. The crew was concerned by the high pressure, and noticed that the blowdown drum's high-level alarm had not sounded. However, they still thought that the cause of the overpressure was lack of reflux or a buildup of noncondensible gases.

Given the events abovementioned, the crew fully opened the level control valve to heavy raffinate storage and shut off the fuel gas to the furnace from the satellite control room. Thus, the amount of material decreased, the pressure to dropped and the safety relief valves closed, after approximately 196 500 litres of flammable liquid flowed into the collection header–and discharged into the blowdown drum. The blowdown system filled, leading flammable liquid to discharge to the atmosphere from its stack as a geyser and falling to the ground (Figure 4).

The liquid ignited, and the flame rapidly spread through the vapour cloud, compressing the gas ahead of it to create a blast pressure wave. The burned area was estimated to be approximately 18 581 m^2.

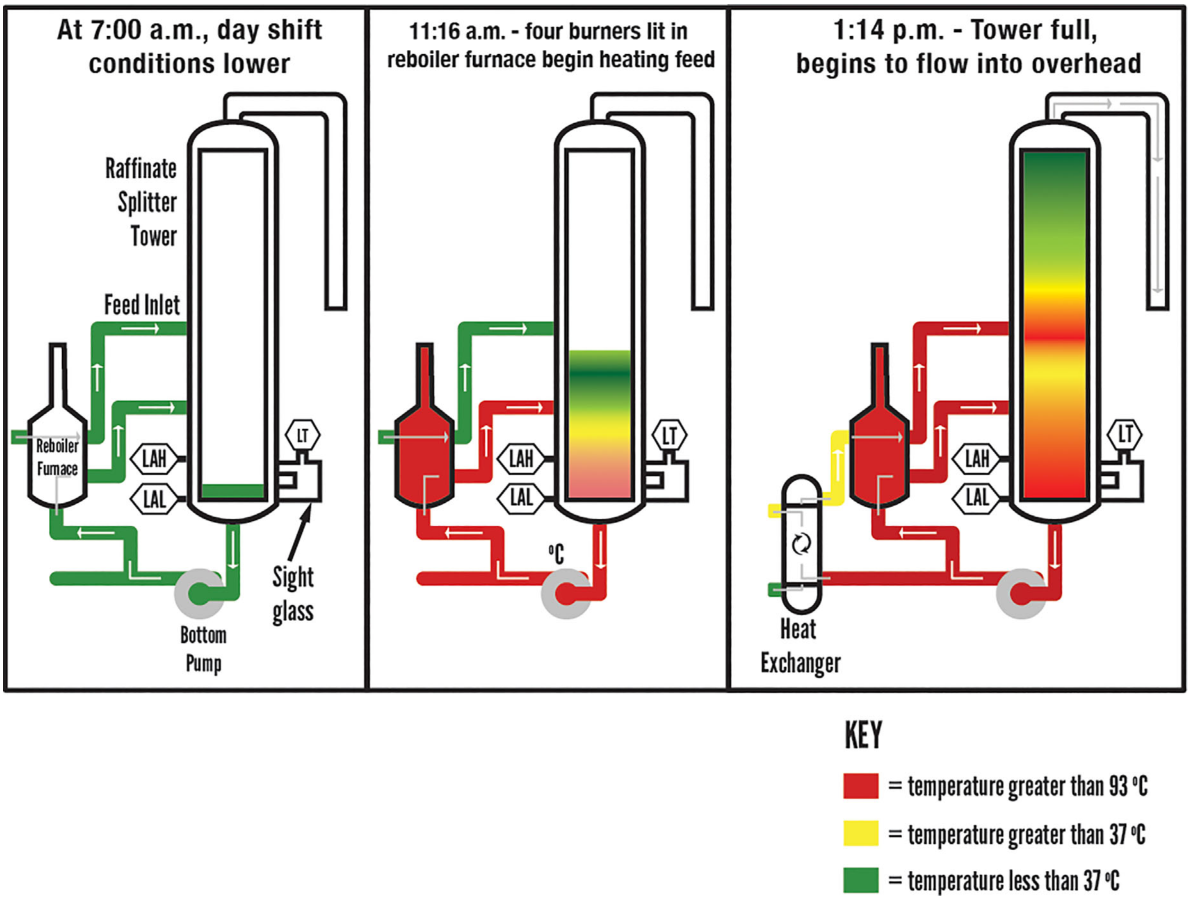


Figure 3. Temperature profile in the tower.[31]

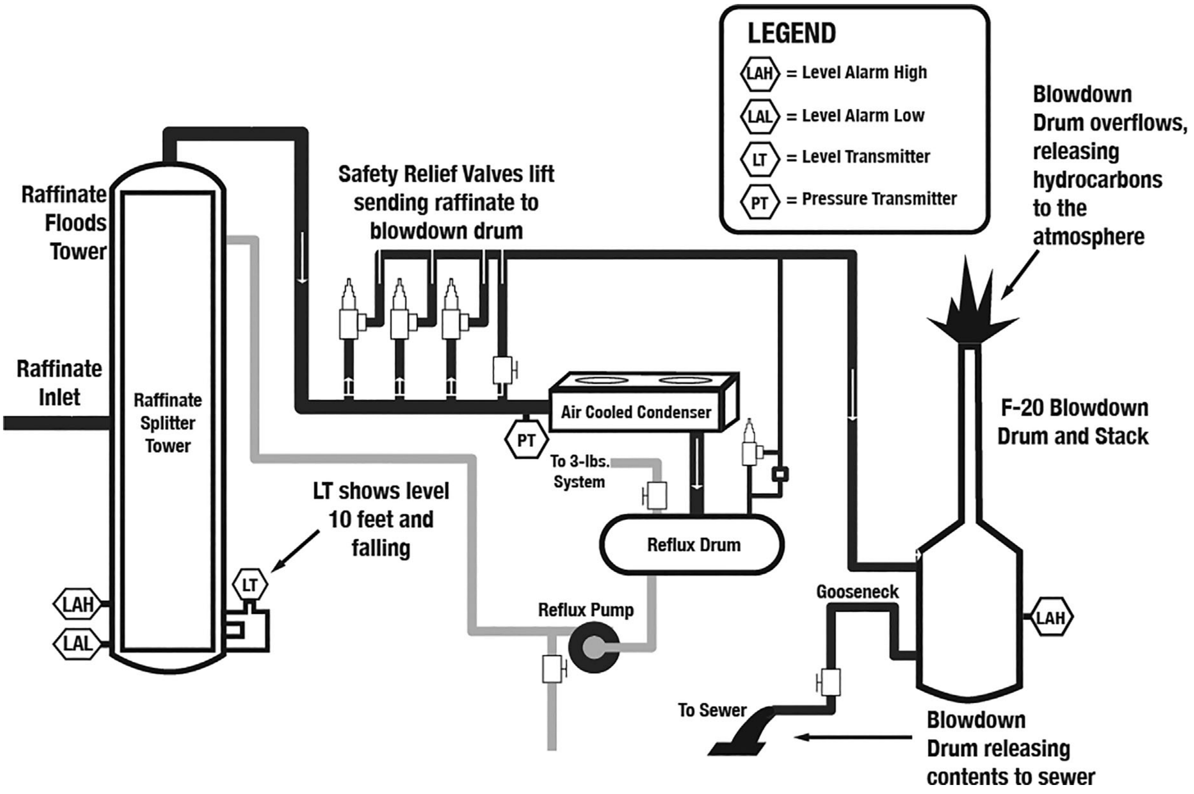


Figure 4. Tower is overfilled and sends hydrocarbons to blowdown drum, which overflows.[31]

The consequences of the explosion were extremely significant, ranging from small to fatal injuries. Indeed, it killed 15 contract employees who were working in or near the trailers that were placed in the surroundings of the ISOM unit, and injured a total of 180 workers in the refinery; out of these, 66 had serious injuries and had to be away from work, adapt to a restricted work activity, and/or had to go through medical treatment.

Based on the description above it is possible to build a timeline of the accident, focusing on the operators' actions and their interaction with the plant, in order to identify the Human Failure Events. The timeline of the accident (Figure 5), highlighting the operators' actions, shows four HFE that can be seen as major contributors to the accident (numbers 1–4):

Event 1: During the startup, the operators fill the tower above the level indicated in the procedure, 50 % of the transmitter reading. It was filled up to 99 % of the transmitter reading.

Event 2: The operator resumes startup with the level control valve closed. The procedures indicated that this valve should be open.

Event 3: The crew misdiagnoses the source of the high pressure and opens the valve to vent gases to the blowdown unit. However, the high pressure was due to the high level of liquid, which was compressing the remaining gases on top of the tower.

Event 4: Operators open the control valve with the liquid already too hot. The liquid from the bottom of the tower exchanged heat with the feed of the tower. This caused the rise of the temperature of the feed entering the tower, which led to a high pressure over the emergency valves, which opened and let liquid into the blowdown drum.

In the following, the HFEs will be described and detailed in terms of Phoenix's CFM and PIFs.

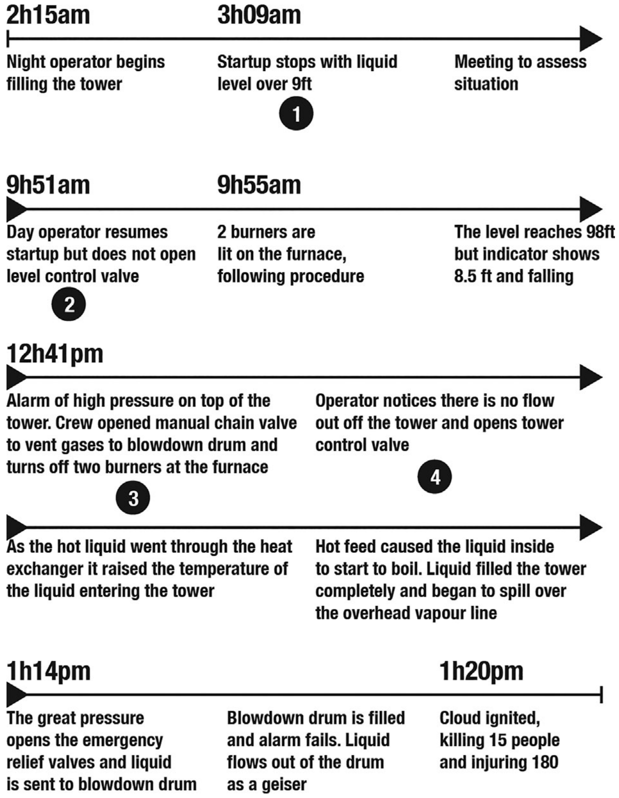


Figure 5. Timeline of BP Texas City Accident on March 23, 2005.

Event 1: Initial tower overfilling

CFM: Procedure Step Omitted (Intentional)

In this event, the crew had all the information needed, but decided not to follow the startup procedure, which indicated that the level should be put at a 50 % transmitter reading. It implies that the crew decided to rely on their knowledge instead of following the procedure. Phoenix's CFM that better relates to it is "procedure step omitted." The factors influencing the crew decision are explained below, with support from the CSB report.

Main PIFs

1. Procedure Quality

"Management did not ensure that the startup procedure was regularly updated, even though the startup process had evolved and changed over time with modifications to the unit's equipment, design, and purpose. The procedure did not address critical events the unit experienced during previous startups (...)."[31]

Event 2: Startup resumed with control valve closed

CFM: Procedure Step Omitted (Intentional)

Even though the startup procedures called for the level control valve to be put on "automatic" and set as 50 %, the operators resumed the startup with this valve closed, and maintained it this way along most time of the startup. Phoenix's CFM that better relates to it is "procedure step omitted."

Main PIFs

1. Communication Quality

"Two critical miscommunications occurred among operations personnel on March 23, 2005, that led to the delay in sending liquid raffinate to storage: 1) the instructions for routing raffinate products to storage tanks were not communicated from Texas City management and supervisors to operators; and 2) the condition of the unit—specifically, the degree to which the unit was filled with liquid raffinate—was not clearly communicated from night shift to day shift."[31]

2. Tool Quality

"Even though the tower level control valve was not at 50 percent in 'automatic' mode, as required by the startup procedure, the Day Board Operator said he believed the condition was safe as long as he kept the level within the reading range (span) of the transmitter. (. . .) The level sight glass, used to visually verify the tower level, had been reported by operators as unreadable because of a buildup of dark residue; the sight glass had been nonfunctional for several years. Knowing the condition of the sight glass, the Day Board Operator did not ask the outside crew to visually confirm the level. (. . .) The Day Board Operator continued the liquid flow to the splitter tower, but was unaware that the actual tower level continued to rise."[31]

3. Human System Interface Output

"The computerized control system screen that provided the reading of how much liquid raffinate was entering the unit was on a different screen from the one showing how much raffinate product was leaving the unit."[31]

4. Extra Work Load

"One board operator was in charge of monitoring and controlling the NDU (Naphta Desulphurization Unit), AU2 (Aromatics Units #2), and ISOM units, which under normal conditions, would take about 10.5 hours of a 12-hour shift to run, if all units would be running at a steady state (normal), according to a BP assessment. On the morning of the incident, however, the Board Operator was also responsible for managing the startup of the ISOM raffinate section. A startup is an abnormal unit condition that requires significantly more manual control of a process, as well as critical thinking and decision-making that goes beyond normal unit operation."[31]

Event 3: Crew responds to high pressure alarm by opening valve

CFM: Plant/system state misdiagnosed

The tower's pressure rose because of the increase in the liquid level compressing the remaining nitrogen in the raffinate system. The crew, however, thought that the high pressure was a result of the tower bottoms overheating, which had not been unusual in previous startups. They misdiagnosed the incoming information about the plant.

Main PIFs

1. Physical abilities and readiness and extra work load

"On the day of the incident, the Day Board Operator was likely fatigued, experiencing both acute sleep loss and cumulative sleep debt. He had worked 12-hour shifts for 29 consecutive days and generally slept five to six hours per 24-hour period, although he reported feeling most rested with seven hours of sleep per night. The Night Lead Operator, who filled the tower from the satellite control room, worked 33 consecutive days, from February 18–March 23, 2005. The Day Lead Operator—who was training two new operators, dealing with contractors, and working to get a replacement part to finish the ISOM turnaround work—had been on duty for 37 consecutive days, from February 14 until March 23, 2005. Finally, another experienced outside operator, who was helping the Day Lead Operator, worked 31 consecutive days, February 21-March 23, 2005. These individuals were working 12-hour shifts. (...) Evidence suggests that the operators' fatigue degraded their judgment and problem-solving skills, hindering their ability to determine that the tower was overfilling. In the hours preceding the incident, the tower experienced multiple pressure spikes. In each instance, operators focused on reducing pressure: they tried to relieve pressure, but did not effectively question *why* the pressure spikes were occurring. They were fixated on the symptom of the problem, not the underlying cause and, therefore, did not diagnose the real problem (tower overfill). The absent ISOM-experienced Supervisor A called into the unit slightly after 1 p.m. to check on the progress of the startup, but focused on the symptom of the problem and suggested opening a bypass valve to the blowdown drum to relieve pressure. Tower overfill or feed-routing concerns were not discussed during this troubleshooting communication. Focused attention on an item or action to the exclusion of other critical information—often referred to as cognitive fixation or cognitive tunnel vision—is a typical performance effect of fatigue."[31,32]

2. Familiarity with or recency of situation

"The operations crew, however, believed the high pressure to be a result of the tower bottoms overheating, which was not unusual in previous startups."[31]

Event 4: Operator responds to lack of flow off the tower by opening the control valve

CFM: Inappropriate strategy chosen

The Day Board Operator was worried about the lack of heavy raffinate flow out of the tower. After a discussion with the Day Lead Operator, he opened the splitter level control, which led to a temperature profile in the tower, as showed in Figure 3. The consequence was the complete filling of the column, and its contents being spilled over into the overhead vapour line, leading to the column relief valves and condenser.

Main PIFs

1. Tool Quality, Tool Availability

"The tower level instrumentation consisted of a displacer type level transmitter, a level sight glass, and two redundant level switches (high and low level), both of which failed to trigger alarms on the day of the incident. The tower level transmitter provided faulty readings and the level sight glass was dirty and non-operational."[31]

In addition to the PIFs above, the PIFs Morale/Motivation/Attitude can be seen as an important one for this accident affecting all HFEs. There were some indications of the operators' lack of commitment such as the fact that the Night Lead Operator left the refinery around an hour before his scheduled shift end time; in addition, the ISOM-experienced Day Supervisor, Supervisor A, arrived for his shift almost over 1 h late. Team Composition also affected all crews' decisions and actions, since the Day Supervisor A was the only ISOM-experienced one, and, once he left the refinery, no technically-trained employees were allocated to support and supervise the Board Operator. Moreover, Task Training likely affected all HFEs. Operator training did not adequately cover the risks of unit startup, such as tower overfill scenarios.

Safety Culture also influenced all HFEs during the accident: "the disaster at Texas City had organizational causes, which extended beyond the ISOM unit, embedded in the BP refinery's history and culture."[31]

The four HFEs involved in the BP Texas City accident make it clear that human error was not only present during this accident, but also played an important role. The use of Phoenix's CFMs and PIFs to represent the HFEs and its contextual factors is discussed in the subsection "Discussion," following the next subsection, which analyzes the CFMs and PIFs involved in the Chevron Richmond refinery accident.

Chevron Richmond Refinery Accident (2012)

This accident took place on August 6, 2012. A catastrophic rupture of the 4th sidecut of the distillation tower in the Crude Unit (Figure 6), a 132-cm long, 20-cm diameter carbon steel pipe, released flammable hydrocarbon process fluid. The line operated at a temperature near 337 °C and had an operating pressure of approximately 379 kPa (gauge) at the rupture location. The hydrocarbon fluid partially vaporized into a large vapour cloud that surrounded 19 Chevron employees and ignited. All the employees escaped. The ignition of the cloud and subsequent burning of the hydrocarbon process fluid caused a large plume of particulates and vapour to travel across the Richmond, California area. Almost 15 000 people from the adjacent area had to look for medical treatment due to the release.[33]

The technical cause of the accident was sulphidation corrosion of the piping. However, a deeper analysis of the accident reveals that human error played an important role. In the 4th sidecut of the column, light gas oil exits the column to be further refined and processed. This sidecut was not isolated by valves; thus, if a leak occurred in this pipe, an operator could not actually block this section to repair it while the unit was operating.

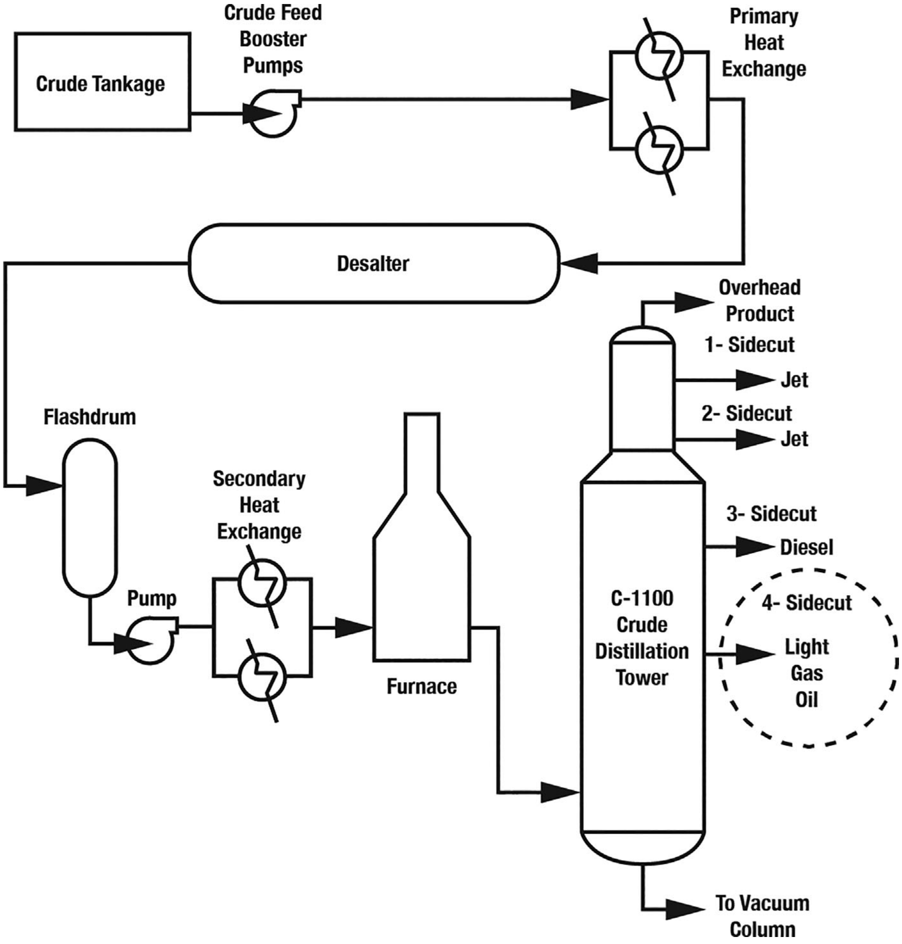


Figure 6. Chevron Richmond refinery Crude Unit atmospheric column and upstream process equipment.[33]

Once a leak is identified in such circumstances, operators would have two choices; they could either repair the leak while the unit was operating or they could decide to shut down the unit to fix/replace the leak. The report of the Chevron Richmond Refinery accident shows that the pipe walls were already too damaged by sulphidation corrosion; hence, the repair could not be easily done. Indeed, anything could increase the leak, making the situation worse, which is what happened during the accident. The accident is briefly described below, and a detailed description can be seen in CSB.[33]

On the day of the accident, an outside operator found a puddle of hydrocarbon on the refinery concrete pad, and identified the leaking pipe as a portion of the 4-sidecut piping of the Crude Column. The visual analysis of the piping led the operator to determine that the line could not be isolated from the process. The supervisor and the shift team leader then arrived at the location, but could not identify the precise source of the leak. The conclusion was that it was not a major leak, thus not requiring a shutdown.

Additional personnel presented themselves at the scene to support the leak analysis, and Chevron inspectors provided information on inspection history of the 4-sidecut line. They informed the group that its pipe walls were thinning due to sulphidation corrosion, but data collected two months prior specified that the wall was thick enough to last until the next turnaround in 2016. Due to this information the group believed that the cause of the leak should be a localized mechanism, such as abrasion on the line from a pipe support near the dripping location.

To be able to decide between repairing the leak online and shutting down the unit, they tried to remove the insulation initially using a pike pole. However, the force of the pulling caused the piping to move, and the group determined this approach to remove the insulation was too dangerous.

Much of the aluminum sheathing surrounding the insulation was removed by then, and a hydrocarbon cloud emerged from the pipe. A portion of the hydrocarbon autognited once exposed to oxygen. The fire was put out by the hose team. The location of the leak was still covered by underlying insulation. The Chevron Fire Department then attempted to knock the insulation off the pipe by straight streaming the fire hoses on the insulation. They successfully knocked off the insulation up to the location where the aluminum sheathing had been removed; however, at this point the leak had aggravated and hydrocarbon was then spraying from the pipe.

The operations managers present ordered the shutdown of the unit. This, however, required hours to complete. A vapour cloud quickly began to accumulate, engulfing 19 firefighters and operators. 2 min after the vapour cloud formation, the light gas oil ignited. Just before the ignition 18 employees safely escaped. One firefighter, who was wearing full body firefighting protective equipment, could escape through the flames without physical injury.

The leak resulted in a large plume of vapour, and the ignition and burning of the hydrocarbon process fluid created a large black cloud of smoke. This situation resulted in a Community Warning System (CWS) Level 3 alert, and a shelter-in-place advisory (SIP) was issued at 6:38 p.m. for Richmond, San Pablo, and North Richmond. In following weeks, nearby medical facilities received over 15 000 members of the public seeking treatment for breathing problems, chest pain, shortness of breath, sore throat, and headaches.

The main events during the accident can be seen in Figure 7, where Items 1 and 2 indicate the main human events in the timelines are related to a crew failure mode. Note this timeline focuses on the operators' actions and their interaction with the plant.

Event 1: The head operator misdiagnoses the state of the plant, believing that the leak is not big enough to shut down the unit. The strategy chosen is to remove the insulation by using a pike pole. This actually made the leak worse, since the pipeline walls were already too thin due to corrosion.

Event 2: Hydrocarbon flows out underneath the insulation and autoignites. The team decides to continue to remove the insulation, by straight streaming the fire hoses.

In the following, the events will be described and detailed in terms of CFM and PIFs. Note that some excerpts from the CSB investigation report relate to more than one PIF.

Event 1: Team do not believe the leak is big enough to shut down the unit. They decide to use a pike pole to remove insulation.

CFM: Plant/system state misdiagnosed

This CFM applies to a situation where the crew makes a wrong assessment of the plant condition. Chevron inspectors knew that this sidecut had thinned over the years due to corrosion, but they did not realize how thin it was, and there was no shutoff valve between the pipe and the distillation tower, thus no way to isolate the leak. Therefore, the head operator should have diagnosed the pipeline state to decide if that was enough to shut down the unit. He misdiagnosed the state and underestimated the leak.

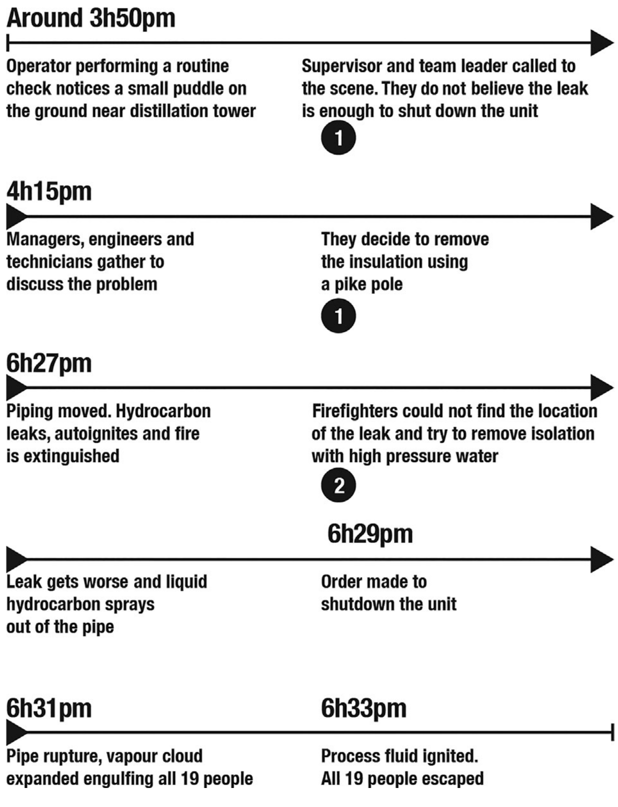


Figure 7. Timeline of the Chevron Richmond accident on August 2, 2012.

Main PIFs

1. Procedure availability

"At the time of the incident, Chevron did not have procedures to direct when a unit should be shut down. Since the incident, Chevron has developed a leak response protocol that should be used to guide decisions in future leak incidents. If a similar leak were to occur in a Chevron refinery (nowadays), the new leak response protocol would require unit shutdown."[33]

2. Stress due to decision

This PIF refers to the tension/pressure on the crew caused by the awareness of the responsibility that comes along with that particular decision and their perception of the impact/consequences of the decision on themselves, on the facility and on the society in general.[19] In this case, the operator would have to be very certain that the leak was enough to shut down the unit, because of the consequence of this to the process, causing a stress that contributed to his misdiagnose of the situation.

3. Team Composition

"(...) Chevron had no formal system to ensure the right people were gathering all important information before deciding on leak mitigation strategies. Such an evaluation could have led to the conclusion that the cause of the leak was general thinning due to sulphidation corrosion, and clamping the pipe—a mitigation strategy being considered—was not a viable solution because the pipe likely did not have the structural integrity to support a clamp. This realization likely would have resulted in deciding to immediately shut down the unit."[33]

4. Role Awareness, Team Training

"The CSB learned that some personnel participating in the insulation removal process while the 4-sidecut line was leaking were uncomfortable with the safety of this activity because of potential exposure to the flammable process fluid. Some individuals even recommended that the Crude Unit should be shut down, but they left the final decision to the management personnel present."[33]

5. Team Cohesion

"Stop Work Authority has been used successfully at the Chevron Richmond Refinery in unsafe work situations (e.g. skipping a step in a procedure, working in unsafe weather conditions, wearing improper personal protective equipment (PPE), employing improper safety precautions when working at heights). The difficulty arises when faced with a process safety situation—a leak, vibration, process upset—especially where shutdowns are being considered. Under these circumstances, there are significant limitations to a Stop Work Authority initiative, the most familiar being the reliance on the individual employee to assert a dissenting viewpoint in an atmosphere where a group of individuals may not agree. Groups of employees working together to solve a problem can be hindered by the group think mindset: Without conflict, or without enough conflict, a phenomenon called group think can result. This occurs when group members do not express their personal opinions but rather willingly submit to what the group as a whole thinks. Group think can lead to bad decisions and inappropriate actions."[33]

6. Communication Quality

"(...) many personnel responding to the leaking 4-sidecut pipe were not properly informed through information disseminated in the Incident Command structure of the operating temperature of the line. Interviews show that some firefighters believed the line was operating at a temperature of about 54 °C rather than the actual temperature, which approached 338 °C. (...) This inattention to the temperature hazard likely resulted in the miscommunication and misunderstanding of the actual operating temperature of the piping. (...) CSB interviews indicate that had the responders been aware of the actual operating temperature, some likely would have raised concerns about the safety of removing insulation from the hot, leaking piping and concerns regarding the responders' close proximity to the leak to their supervisors."[33]

Event 2: Team decides to continue to remove the insulation, by straight streaming the fire hoses, even after flash fire

CFM: Inappropriate strategy chosen

In this moment of the incident, the crew could, once again, decide for the shutdown of the unit. However, they decided to continue to remove the insulation, i.e. they decided on a wrong strategy. This CFM applies to a situation, where the crew decides to take a different course of action from the expected "normal" one, when the expected or normal course of action is the guaranteed success path. The crew's decision to choose an alternate path may be a result of their failure to consider all options.

Main PIFs

1. Cognitive complexity due to external factors

To identify that the unit required a shutdown was a complex task, because "underlying insulation still obscured the location of the leak."[33] Thus, they could not recognize the size of the damage.

2. Stress due to situation perception, time constraint

At that point of the accident, after a flash fire occurred, the team could realize the situation urgency and severity. As an employee stated to CSB, the operations management present said "This is an emergency. We need it done right now."[33] Note that this also relates to the crew's perception of the available time to complete the task (Time Constraint PIF).

3. Procedure availability

As in Event 1, the lack of procedures to instruct when a unit should be shut down influenced the crew's decision at this point.

Moreover, Safety Culture is a PIF that affected both events in this accident, indicated not only by the lack of procedures, but also by "decision making that encourages continued operation of a unit despite hazardous leaks."[33]

The following subsection discusses the CFMs and PIFs involved in the BP Texas City and Chevron Richmond refineries accidents.

DISCUSSION

The construction of the timeline of the two subject accidents, highlighting the operators' actions, allowed to identify the HFE that contributed to the final outcome. The BP accident, considered the worst industrial disaster in recent U.S. history, involved 4 main HFEs, while the Chevron accident involved 2 main HFEs. The analysis demonstrates that to fully understand these accidents and their causes, a Human Reliability Analysis cannot be neglected.

It can be seen that had the operators taken a different path of decisions, the accidents could have been avoided. On the Chevron Richmond refinery accident, CSB clearly states that "the piping rupture and subsequent hydrocarbon release occurred two hours after the original leak was identified. (...) had Chevron decided to shut down the unit once staff knew the line could not be isolated, the pipe rupture and the endangerment of the community and Chevron personnel could have been avoided."[33] Moreover, it can be noted that all relevant CFMs identified in these accidents are particularly related to the "Situation Assessment and Decision" phase of the human response model IDA, i.e. the operators failed to have a correct situation assessment and/or failed in taking the correct decisions about them. The predominance of these CFMs in the accidents is not surprising because one of the characteristics of an oil refinery operation is the large amount of (inter-related) process variables involved. This can make it more challenging to identify the source of variation in a process condition, such as a temperature rise, or the consequence an action can have on the process, such as the rise of a temperature because of a valve opening. In the BP accident, for example, the rise of the pressure in the top of the tower could indeed be caused by a different reason than it was in reality. In addition, the opening of the level control valve led to the increase of the temperature in the tower, because the tower level was interconnected to the temperature of the feed, since there was a heat exchanger between the bottom and feed of the tower. The assessment of the causes of a plant abnormal condition and the consequence of the operator's action in an oil refinery operation demands good procedures, well-functioning equipment and instruments, a well-trained and effective team, and strong safety culture. All of these were lacking in the BP accident, and some (such as good procedures and team effectiveness) were issues in the Chevron accident.

The CFMs and PIFs identified can be connected through a BBN, in Phoenix's third layer, which can afterwards connect to fault trees and then to the Crew Response Tree, completing all layers of the analysis. With the three layers connected, one can see which paths the operators could have taken and why, then constructing a full narrative of the operators' actions during the accidents.

It should be noted that Events 1 and 2 of the BP accident were here represented by the CFM "Procedure Step Omitted," which was the most relevant from the Phoenix CFM list. However, during the accident, the crew was not following a procedure when they decided to omit a step; instead, they decided not to follow the procedure at all, and rely on their own knowledge.

In the Chevron Richmond accident, a lack of procedure indicating if a unit should be shut down when facing abnormal conditions was a strong influencing factor. However, the factor that was extremely important for the operators' decision was the lack of awareness on how thin the pipe was. Although the crew was informed that the 4-sidecut pipe walls were thinning due to sulphidation corrosion, data collected recently indicated that the walls were thick enough to last until the next turnaround in 2016. The reality was, however, that the pipe was thinner than they knew. The misinformation on this thickness was due to a communication breakdown when reviewing the results of the inspection in 2011. This factor is not relatable to any of Phoenix's PIFs, although of great importance to understand the operators' decisions. Hence, although Phoenix is a good strong HRA methodology, its CFMs and PIFs fall short in describing some failure modes and contextual factors that can happen in an oil refinery operation. The cause for it is that Phoenix, as the majority of HRA methodologies currently used, was developed in a NPP operation context. The authors believe that, given the relevance of human error in oil refineries accidents, an HRA methodology tailored for this type of operation is necessary to reflect all the idiosyncrasies of this industry. The development of an HRA methodology for this industry, with specific CFMs and PIFs, is the issue of ongoing research by the authors and is the subject of a forthcoming paper. Given the findings of this paper, however, we anticipate that in such HRA methodology, Events 1 and 2 of the BP accident would be described by a CFM "Procedure not Followed," while the lack of awareness about the pipe thinning walls in the Chevron accident would be represented by PIF "Knowledge of Plant Conditions."

CONCLUDING THOUGHTS

The study of two significant accidents in the oil refining industry focusing on the crew failure modes and performance influencing factors illustrates a systematic way for identifying and investigating the potential impact of human error on safety and operations in the Petroleum Industry. This paper contributes to the analysis of these accidents by identifying the human failures that led to the accident and the context factors that influenced the identified errors. The analysis shows that human factor is strongly present in the two accidents, and that the events could have even been avoided if the operators had acted differently. The paper therefore sheds new light on the necessity of looking beyond the mechanical and process factors in safety analyses within the oil and gas sector, and the importance of performing human reliability. This paper also demonstrates that the oil industry could benefit from having a tailored Phoenix HRA methodology that would reflect better its operators' actions and contextual factors. Such extended methodology is the subject of a forthcoming paper by the authors.

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ACRONYMS

ARU	aromatics recovery unit
BBN	Bayesian belief network
CFM	crew failure mode
CRT	crew response tree
CSB	chemical safety board
FAT/CAT	fatality/catastrophe
HFE	human failure event
HRA	human reliability analysis
IDA	information – decision – action
ISOM	isomerization unit
NPP	nuclear power plant
PIF	performance influencing factor
QRA	quantitative risk analysis

REFERENCES

[1] Z. Nivolianitou, M. Konstadinidou, C. Michalis, *J. Hazard. Mater*. **2006**, *137*, 1.

[2] CSB - U.S. Chemical Safety Board, *Regulatory Report – Chevron Richmond Refinery Pipe Rupture and Fire*, Report No. 2012-03-I-CA, U.S. Chemical Safety and Hazard Investigation Board, Richmond **2014**.

[3] S. Kariuki, K. Lowe, *Reliab. Eng. Syst. Safe*. **2007**, *92*, 1764.

[4] M. Konstatinidou, Z. Nivolianitou, N. Markatos, C. Kiranoudis, *J. Hazard. Mater*. **2003**, *135*, 1.

[5] M. Ziarani, A. Mazloumi, M. Jahangiri, Z. Kazemi, M. Ziaei, P. Mohadessy, *International Journal of Occupational Hygiene (IJOH)* **2016**, *8*, 1.

[6] A. Swain, H. Guttman, *Handbook of Human Reliability Analysis with Emphasis on Nuclear Power Plant Applications (THERP)*, NUREG/CR-1278, U.S. Nuclear Regulatory Commission, Washington **1983**, https://www.nrc.gov/docs/ML0712/ ML071210299.pdf.

[7] J. Williams, "HEART – A Proposed Method for Achieving High Reliability in Process Operation by means of Human Factors Engineering Technology," *Symposium on the Achievement of Reliability in Operating Plant*, Safety and Reliability Society, Southport, 16 September **1985**.

[8] E. Hollnagel, *Cognitive Reliability and Error Analysis Method (CREAM)*, 1st edition, Elsevier Science, Amsterdam **1998**.

[9] D. Gertman, H. Blackman, J. Marble, J. Byers, C. Smith, *The SPAR-H Human Reliability Analysis Method*, NUREG/CR-6883, U.S. Nuclear Regulatory Commission, Washington **2005**.

[10] Y. Change, A. Mosleh, *Reliab. Eng. Syst. Safe*. **2006**, *92*, 997.

[11] N. Ekanem, A. Mosleh, S. Shen, *Reliab. Eng. Syst. Safe*. **2016**, *145*, 301.

[12] J. Bell, J. Holroyd, *Review of human reliability assessment methods*, RR679, Health and Safety Laboratory, Buxton **2009**, accessed on 4 August **2017**, http://www.hse.gov.uk/research/rrpdf/rr679.pdf.

[13] A. Mosleh, J. Chang, *Reliab. Eng. Syst. Safe*. **2004**, *83*, 241.

[14] A. Mosleh, J. Forester, R. Boring, S. Hendrickson, A. Whaley, S.-H. Shen, D. Kelly, J. Chang, V. Dang, J. Oxstrand, E. Lois, "A model-based human reliability analysis framework," *International conference on probabilistic safety assessment and management PSAM 10*, International Association for Probabilistic Safety Assessment and Management, Washington, 7–11 June **2010**.

[15] S. Hendrickson, A. Whaley, R. Boring, S.-H. Shen, A. Mosleh, J. Oxstrand, J. Forester, D. Kelly, "A Mid-Layer Model for Human Reliability Analysis: Understanding the Cognitive Causes of Human Failure Events," *International conference on probabilistic safety assessment and management PSAM 10*, International Association for Probabilistic Safety Assessment and Management, Washington, 7–11 June **2010**.

[16] S.-H. Shen, A. Mosleh, D. Kelly, R. Boring, "Example Application of Model-Based HRA Approach," *International conference on probabilistic safety assessment and management PSAM 10*, International Association for Probabilistic Safety Assessment and Management, Washington, 7–11 June **2010**.

[17] A. Mosleh, S.-H. Shen, D. Kelly, J. Oxstrand, K. Groth, "A model-based human reliability analysis methodology," *International conference on probabilistic safety assessment and management PSAM 11*, International Association for Probabilistic Safety Assessment and Management, Helsinki, 25–29 June **2012**.

[18] J. Oxstrand, D. Kelly, S.-H. Shen, A. Mosleh, K. Groth, "Model-based approach to HRA: Qualitative Analysis Methodology," *International conference on probabilistic safety assessment and management PSAM 11*, International Association for Probabilistic Safety Assessment and Management, Helsinki, 25–29 June **2012**.

[19] N. Ekanem, *A Model-Based Human Reliability Analysis Methodology (Phoenix Method)*, PhD thesis, University of Maryland, College Park **2013**.

[20] N. Ekanem, A. Mosleh, "Phoenix – A Model-Based Human Reliability Analysis Methodology: Qualitative Analysis Overview," *International conference on probabilistic safety assessment and management PSAM 12*, International Association for Probabilistic Safety Assessment and Management, Honolulu, 22–27 June **2014**.

[21] N. Ekanem, A. Mosleh, "Phoenix – A Model-Based Human Reliability Analysis Methodology: Quantitative Analysis Procedure and Database," *International conference on probabilistic safety assessment and management PSAM 12*, International Association for Probabilistic Safety Assessment and Management, Honolulu, 22–27 June **2014**.

[22] R. Boring, "Fifty years of THERP and Human Reliability Analysis," *International conference on probabilistic safety assessment and management PSAM 11*, International Association for Probabilistic Safety Assessment and Management, Helsinki, 25–29 June **2012**.

[23] M. Kaszniak, D. Holmstrom, *J. Hazard. Mater*. **2008**, *159*, 105.

[24] K. Kidam, N. Hussin, O. Hassan, A. Ahmad, A. Johari, M. Hurme, *Process Saf. Environ*. **2014**, *92*, 412.

[25] M. Kaszkniak, "Examining Organizational and Safety Culture Causes of the BP Texas City Refinery Explosion," *2007 AIChE Spring Meeting & Global Congress on Process Safety*, American Institute of Chemical Engineers, Houston, 22–27 April **2007**.

[26] D. Manca, S. Bambilla, *J. Loss. Prevent. Proc*. **2012**, *25*, 950.

[27] F. Khan, P. Amyotte, *J. Loss. Prevent. Proc*. **2007**, *20*, 387.

[28] M. Kalantarnia, F. Khan, K. Hawboldt, *Process Saf. Environ*. **2010**, *88*, 191.

[29] A. Kahn, *Corporate Social Responsibility and its Effects on Corporate-Community Relationships: A Case Study of Chevron's Richmond Refinery Fire in 2012*, MSc dissertation, University of San Francisco, San Francisco **2013**.

[30] P. Thammongkol, *The System Theoretic Accidental Analysis of a Crude Unit refinery Fire Incident*, MSc Dissertation, Massachusetts Institute of Technology, Boston **2003**.

[31] CSB - U.S. Chemical Safety Board, *Investigation Report – Refinery Explosion and Fire*, Report No. 2005-04-I-TX, U.S. Chemical Safety and Hazard Investigation Board, Texas City **2007**, p. 54–55, 72, 79, 83, 89–92, 106, 143.

[32] M. Rosekind, K. Gregory, D. Miller, E. CO, J. Lebacqz, *Analysis of crew fatigue factors in AIA Guantanamo Bay aviation accident, appendix E Aircraft Accident Report: Uncontrolled Collision with Terrain*, NTSB/AAR-94/04, National Transportation Safety Board, Washington **1993**.

[33] CSB - U.S. Chemical Safety Board, *Final Investigation Report - Chevron Richmond Refinery Pipe Rupture and Fire*, Report No. 2012-03-I-CA, U.S. Chemical Safety and Hazard Investigation Board, Richmond 2015, p. 12, 13, 23, 80, 91, 93, 100.

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