REVISITING PAST REFINERY ACCIDENTS FROM A HUMAN RELIABILITY ANALYSIS PERSPECTIVE

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RESUMO – *Despite the Oil Industry efforts in improving safety, it still presents a high rate of serious accidents, many involving human error. Human Failure Events (HFE) can be identified, modeled, and quantified through Human Reliability Analysis (HRA). The Oil Industry commonly analyzes process safety focusing on technical barriers, and therefore it could benefit from human reliability assessment. Phoenix methodology is an HRA method that uses a human response model that relates the Crew Failures Modes (CFM) to context factors - Performance Influencing Factors (PIFs). Based on Phoenix CFMs and PIFs, two refinery accidents were analyzed: the BP Texas City (2005) and the Chevron Richmond (2012). 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. This article provides insights on value of investigating the potential impact of human error in the Petroleum Industry accidents.*

1. INTRODUCTION

Petrochemical installations and processes pose safety concerns inherent to their characteristics - working with flammable and toxic fluids. Statistical analysis of 489 major accidents from 1985 to 2001 in the European Union reported to the European Major Accident Reporting System (MARS) exposes that petrochemical installations presented the second biggest number of accidents (17% of the total number of accidents), behind general chemicals (32%). Moreover, 70% of the major accidents took place when the plants were in normal operation status (Nivolianitou et al., 2006). In the United States the number of accidents in petroleum refineries is also significant. During 2012 alone, the Chemical Safety Board (CSB) tracked 125 significant process safety incidents at US petroleum refineries (CSB, 2014).

Deeper analysis of many of these accidents can reveal that they involve human error at some point, and that some of them could have been avoided. Indeed, statistics show that majority of accidents (over 80%) in the chemical and petro-chemical industries have human failure as a primary cause (Kariuki & Lowe, 2007). Through Human Reliability Analysis (HRA), human contribution to risk both qualitatively and quantitatively can be assessed. HRA aims to identify, model and quantify human failure events (HFE) in the context of various 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 highly advanced HRA methods have largely been developed and applied in support of nuclear power control room operations and in context of quantitative risk analysis (QRA). In the petroleum industry, QRA is one of the main tools for risk management. Laumann et al. (2014) points that QRAs differ on the extent to which they incorporate human and organizational factors, and that a reason for this might be a lack of research on how to apply HRA in the petroleum industry. Another reason pointed by Boring (2015) is that there is no globally accepted requirement for QRA in the petroleum sector. In fact QRAs applied in oil and gas industry have primarily identified hardware failure risks, neglecting those human failure events that contribute to overall system risk.

In Brazil, risk analysis studies for petrochemical plants normally follow CETESB standards (CETESB, 2014), which determines rules for QRA. It starts by a QRA of the process, followed by the estimation of consequences and frequency and final Individual and Social Risk. It does not prescribe that a human factors analysis or HRA should be performed. This is the case despite the fact that the benefits of conducting HRA within a QRA include the identification and analysis of factors that may influence the operator´s behavior and the potential human errors that can lead to major accidents.

Among the more advanced HRA methods is the Phoenix methodology. It is a model-based method that incorporates strong elements of current HRA good practices, leverages lessons learned from empirical studies, and also takes advantage of the best features of existing and emerging HRA methods. 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).

Based on Phoenix CFMs and PIFs, two refinery accidents are analyzed in this paper to illustrate the value of analyzing human behavior within the Petroleum industry. The first event concerned BP Texas City Refinery (2005) and the second one took place at Chevron Refinery at Richmond, California (2012). By making use of these accidents, this article highlights the value of investigating the potential impact of human error in the Petroleum Industry accidents. 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.

This paper is organized as follows. Section 2 presents an overview of Phoenix methodology. Section 3 presents the analysis of BP Texas City and Chevron Richmond refineries accidents using Phoenix's CFMs and PSFs, followed by the conclusions at Section 4.

2. PHOENIX METHODOLOGY

Phoenix methodology was developed as an attempt to address the issues of the previous HRA methodologies. The improvements it brings in comparison to other HRA methodologies can be seen in Ekanem et al. (2016). For the details about the methodology the reader can refer to Ekanem (2013) and for an overview of the qualitative framework, Ekanem & Mosleh (2014,a) and Ekanem et al. (2016). The quantitative framework is also presented in Ekanem & Mosleh (2014,b). The qualitative framework of the methodology is briefly described in this session.

Phoenix analysis has three main layers. The top layer is the "crew response tree" (CRT), represented by an event tree; the mid layer is the human performance model - using fault trees, and the bottom layer consists of the PIFs, which are the context factors (including plant factors) that affect human performance, modeled through Bayesian Belief Networks (BBN). The CRT provides a structure for capturing the context associated with the HFE and can be connected to a typical probabilistic risk analysis (PRA) event tree model. The PIFs are linked to the Crew Failure Modes of the human response model through a CFM – PIF model, using a BBN. The three layers - CRT, Fault Trees and BBN - are combined together to form the integrated model illustrated in Figure 1. The path through this integrated model gives the details of how the entire story needs to be narrated and read (Ekanen & Mosleh, 2014).

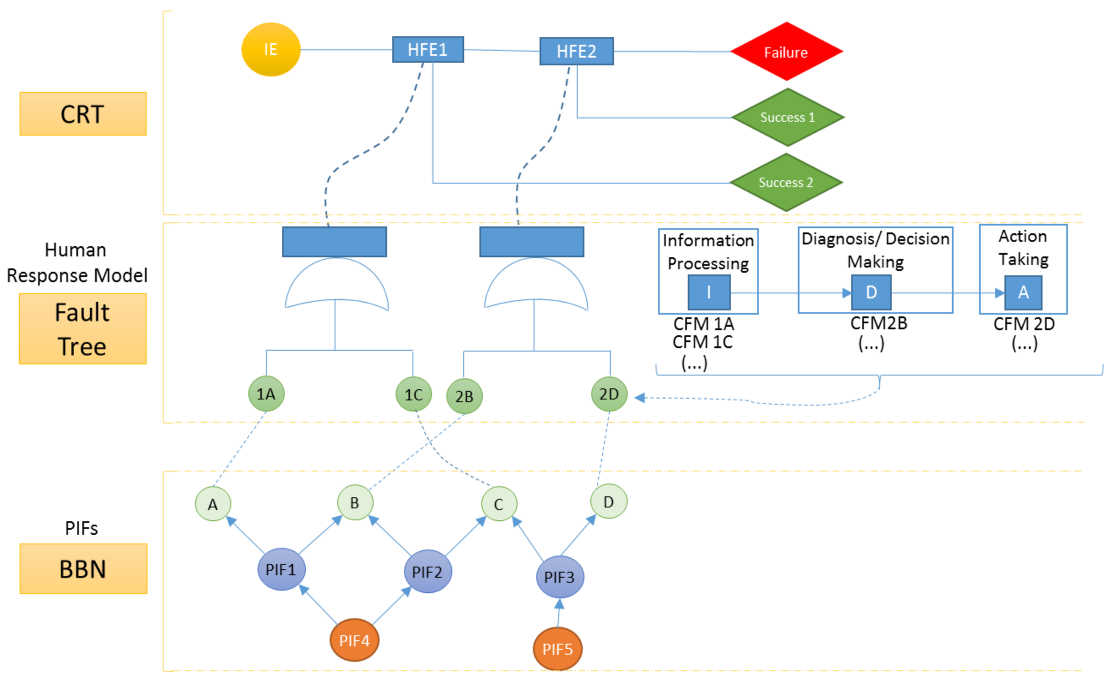

Figure 1: Phoenix Layers

The Crew Failures Modes (CFMs) are connected to the human response model - IDA (Mosleh, Chang; 2007), a crew centered version of the Information, Decision and Action cognitive model. IDA is a three-stage model which serve as the basis for linking failure mechanisms to the possible human failures.

The CFMs are therefore used to specify the possible forms of failure in each of the IDA phase. Moreover, they are the generic functional modes of failure of the crew in its interactions with the plant/system and represent the manifestation of the crew failure mechanisms and proximate causes of failure (Ekanem et al, 2016). The set of CFMs used in Phoenix can be seen in Ekanem et al. (2016). It includes, for example, "Key Alarm not Responded to" in the "I" phase, "Plant/System State Misdiagnosed", "Procedure Step Omitted" in the "D" phase, and "Incorrect Timing of Action" in the "A" phase. The "I" phase comprises 9 CFMs, the "D" phase 7 CFMs , and the "A" phase 3 CFMs.

The CFMs are connected to the PIFs in the third layer of the model, through BBNs. PIFs are the contextual factors that affect human performance by enhancing or degrading it. When an abnormal event occurs in the plant, the crew starts the process of trying to solve the problem by responding cognitively, emotionally and physically. The PIFs in Phoenix have been organized into nine primary groups to cover emotional, cognitive and physical aspects. These groups are also individually considered as PIFs themselves. The groups (also known as the "primary or level 1 PIFs") are Knowledge/Abilities and Bias 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 (Ekanem, 2013). The PIFs are classified into levels within the groups, hence forming a hierarchical structure which can be fully expanded for use in qualitative analysis and collapsed for use in quantitative analysis. The PIFs are connected to the CFMs through a BBN - the CFMs are directly affected by the Level 1 PIFs. The latter are affected by the Level 2 PIFs, which are affected, on their turn, by the Level 3 PIFs. The Level 1 PIF Procedures, for example, is affected by Level 2 PIFs Procedure Quality and Procedure Availability. The full set of PIFs used in Phoenix can be seen in Ekanem etc all. (2016).

Next section presents the analysis of two past refinery accidents using Phoenix's CFMs and PIFs.

3. ANALYSIS OF HUMAN ERROR IN PAST OIL REFINERY ACCIDENTS

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). These accidents were analyzed through a timeline of the accidents constructed in order to highlight the operators' actions. These were identified as one of Phoenix CFMs and the PIFs related to each CFM were identified, with the support of the accidents' reports. For a definition of each of the CFMs and PIFs pointed in this section the reader can refer to Ekanem (2013).

3.1 BP Texas City Refinery Accident (2005)

The BP Texas City Refinery accident took place in March 23, 2005. At 1:20 p.m. a vapor cloud ignited, and an explosion and fire killed 15 people and injured another 180, alarmed the community, and resulted in financial losses exceeding US $1.5 billion. During the startup of an isomerization (ISOM) unit the raffinate splitter tower was overfilled and liquid was sent to a blowdown stack that was not equipped with a flare. This resulted in a flammable liquid geyser flowing out of the stack, which led to an explosion and fire, reaching a near office trailer where the fatalities occurred. A shelter-in-place order was issued that required 43,000 people to remain indoors.

The CSB report (CSB, 2007) highlights problems with BP's safety culture, lack of maintenance of equipment, regulatory weaknesses, and human failures during the accident, showing that this accident, one of the worst industrial accidents in recent U.S. history, could have been avoided. The main events of the accident are shown in Figure 2.

The numbers 1-4 in Figure 2 indicates the main human events in the timeline, related to a crew failure mode, which can be described as follows:

<u>Event 1</u> – During the startup the operators fill the tower above the level indicated in the procedure. The startup procedure called for the level in the tower to be established at a 50% transmitter reading, but it was filled until 99% of the transmitter reading.

<u>Event 2</u> – The operator resumes startup with the control valve closed. The procedures indicated that this valve should be open to control the level at the tower, but the operator received conflicted instructions.

Event 3 – The crew did not know the source of the high pressure and opens valve to vent gases to blowdown unit. However, the high pressure was due to the high level of liquid, which was compressing 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. Therefore, opening this valve caused the rise of the temperature of the feed entering the tower which led to a high pressure over the emergency valves, that opened and sent the liquid to the blowdown drum.

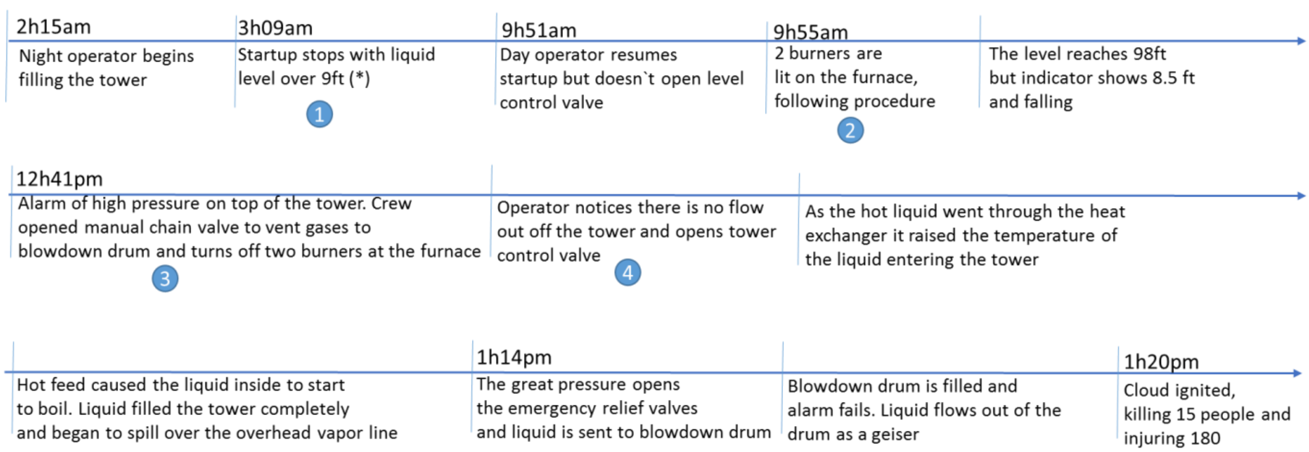

Figure 2 – Timeline of BP Texas City Accident in March 23, 2005

In the following, Event 1 will be described and detailed in terms of CFM and PIFs. The PIFs are supported by excerpts from the corresponding CSB report. The PIFs identified listed below are the dominant ones, and other PIFs could be relevant to the events.

EVENT 1 - Initial tower overfilling
CFM: D4 - Procedure Step Omitted (Intentional).

In this event, the crew had all the information needed, but made a decision not to follow the startup procedure, which indicated that the level should be established at a 50% transmitter reading. It implies that the crew decided to rely on their knowledge instead of following the procedure step by step. The factors influencing the crew decision are explained below, with the support from 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 (...)." (CSB, 2007).

2. Safety Culture

"Management had also allowed operators to make procedural changes without performing proper Management of Change hazard analysis, thereby encouraging operators to make unplanned (and potentially unsafe) deviations during startup. All of these managerial actions (or inactions) sent a strong message to operations personnel: the procedures were not strict instructions but were outdated documents to be used as guidance." (CSB, 2007).

3.2 Chevron Richmond Refinery Accident (2012)

This accident took place on August 6, 2012. It consisted of the catastrophic pipe failure of one of the sidecuts of the distillation tower in the Crude Unit. The pipe, a 52-inch long, 8-inch diameter carbon steel piping, ruptured and released flammable, hydrocarbon process fluid, which partially vaporized into a large vapor cloud that engulfed 19 Chevron employees and ignited. All of the employees escaped, narrowly avoiding serious injury. The ignition of the flammable portion of the vapor cloud and subsequent continued burning of the hydrocarbon process fluid resulted in a large plume of particulates and vapor traveling across the Richmond, California area. Approximately 15,000 people from the surrounding area sought medical treatment due to the release (CSB, 2015)

The main events during the accident can be seen at Figure 3. Items 1 and 2 in Figure 3 indicates the main human events in the timelines related to a crew failure mode:

Event 1 – The head operator misdiagnoses the state of the plant, believing that the leak was not big enough to shut down the unit. He did not realize how corroded was the pipeline.

Event 2 – The crew decided to pinpoint the leak by removing the isolation of the pipeline, since this sidecut was not isolated by valves. This actually made the leak worse, since the pipeline walls were already too thin due to corrosion.

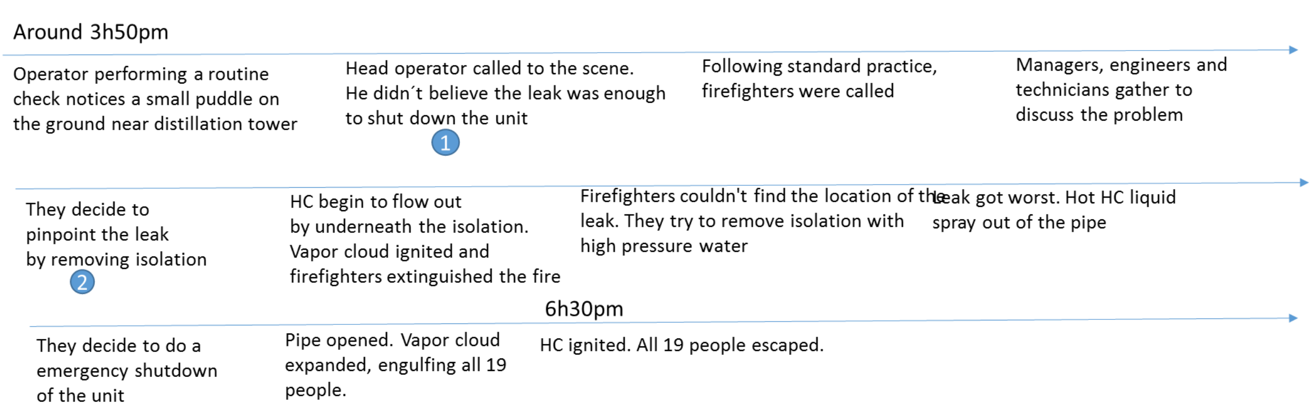

Figure 3 - Timeline of the Chevron Richmond accident at August 2, 2012

In the following, Event 1 will be described and detailed in terms of CFM and PIFs

EVENT 1 - Head operator does not believe the leak was big enough to shut down the unit.

CFM: D1 - 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. The head operator should therefore diagnose the pipeline state to decide if that was enough to shut down the unit. He misdiagnosed the state and underestimated the leak.

Main PIFs

1. Procedure Quality

"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, the new leak response protocol would require unit shutdown." (CSB, 2015)

2. Safety Culture

According to CSB (2015), Chevron Richmond Refinery didn't have a strong safety culture, presenting a "decision making that encourages continued operation of a unit despite hazardous leaks."

3. 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, the facility and the society in general (Ekanem, 2013). 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.

The construction of the timeline of these two accidents, highlighting the operators' actions, allowed to identify the Human Failure Events that contributed to final outcome. The BP accident, considered the worst industrial disaster in recent U.S. history, involved 4 main HFEs, and Chevron accident involved 2 main HFEs. It demonstrates that to fully understand these accidents and its causes a HRA can not be neglected.

4. CONCLUDING THOUGHTS

The study of two significant accidents in the 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 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 had influence the identified errors. The analysis shows that the 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 some light on the necessity of looking beyond the mechanical and chemical factors in safety analyses within the Oil/Gas sector,and the importance of modeling and analyzing human reliability.

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