HUMAN RELIABILITY ANALYSIS OF AN OIL REFINERY OPERATION USING THE PHOENIX HRA METHODOLOGY: A HYDROGEN GENERATION UNIT CASE STUDY

Marilia A. Ramos[1], Enrique L. Droguett[2], Ali Mosleh[3]

[1] Chemical Engineering Department, Federal University of Pernambuco, Recife, Brazil. marilia.aramos@gmail.com
[2] Mechanical Engineering Department, University of Chile, Santiago, Chile. elopezdroguett@ing.uchile.cl
[3] B. John Garrick Institute for the Risk Sciences, UCLA, Los Angeles, United States. mosleh@ucla.edu

Methodologies for risk analysis within the oil industry tend to neglect the potential effects of human error. Oil refineries frequently face incidents during their operation, which can lead to a broad range of objectionable consequences. These may concern unplanned stops, production delays, and operators' injuries; yet, more serious situations such as loss of life and substantial financial costs are also among the potential consequences. Deeper analysis of such accidents shows that they often involve human error at some point. Quantitative Risk Analysis (QRA) of petroleum refinery installations has mostly focused on technical barriers to avoid these incidents. It has thus neglected the relevance of human error and its prevention. Through Human Reliability Analysis (HRA), Human Failure Events (HFE) can be identified, modeled, and quantified in the context of accident scenarios. 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 accidents. Among the more advanced HRA methods is the Phoenix methodology. Phoenix 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. It utilizes a Crew Response Tree (CRT) to provide a structure for capturing the context associated with the HFE. It parallels event trees of a typical probabilistic risk analysis (PRA). Phoenix 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). Phoenix has, thus, three layers: the top layer being the CRT, the mid layer being the human performance model with the CFMs, modeled as fault trees, and the bottom layer being the PIFs, modeled and connected to the CFMs through BBNs. In order to demonstrate how a modified version of Phoenix can be used to analyze possible Human Failure Events within a refinery operation, we have developed a potential scenario involving a Hydrogen Generation Unit, which produces hydrogen through steam reforming to provide to hydrotreating reactions. The scenario consists of a leak of process gas into the reformer furnace that could lead to an explosion, and was built based on Qualitative Risk Analysis of the system. We first establish potential interactions between the operators and the process in order to build the crew response tree. Following that, we identify the Crew Failure Modes, and analyze and described the PIFs for each CFM. Through this application we highlight the importance of identifying and investigating the potential impact of human error in the Petroleum industry.

I. INTRODUCTION

Petroleum refining installations and processes, as well as petrochemical plants, pose safety concerns inherent to their characteristics - working with flammable and toxic fluids. Even though the oil industry is always advancing in process safety, small and big accidents still occur. 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[1]. In the United States the number of accidents in petroleum refineries is also significant. Between 1992 and 2007 the United States had 36 fatality/catastrophe (FAT/CAT) incidents related to hydrocarbon release in the refining industry, according to the Occupational Safety and Health Administration (OSHA) - more than the combined total of the next three highest industries over the same period. Even though the approximately 150 petroleum refineries operating in the U.S make up only roughly one percent of all the facilities covered by Environmental Protection Agency (EPA) Risk Management Program between 2000 and 2010, they experienced more recordable accidents than any other industry – 234 accidents. During 2012, the Chemical Safety Board (CSB) tracked 125 significant process safety incidents at US petroleum refineries[2].

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 petrochemical industries have human failure as a primary cause[3]. Although the human contribution to major incidents is widely accepted, few major hazard sites proactively seeks out potential human performance issues[4]. 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.

Among the more advanced HRA methods is the Phoenix methodology. Phoenix 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, the methodology makes use of a human response model that relates the observable crew failures modes (CFM) to the Performance Influencing Factors (PIFs). The detailed Qualitative and Quantitative Framework of the Phoenix Methodology can be seen in the work of Ekanem and Mosleh (Refs. 5, 6, 8) and Ekanem (Ref 7).

In order to demonstrate how Phoenix can be used to analyze possible Human Failure Events within a refinery operation, this paper presents an application to a potential scenario involving a Hydrogen Generation Unit, which produces hydrogen through steam reforming to provide to hydrotreating reactions.

An overview of Phoenix methodology is presented in Section 2. Section 3 presents details of the Hydrogen Generation Unit process as well as the scenario developed, with its possible human failure events and the use of Phoenix to analyze it. Section 4 provides concluding thoughts.

II. PHOENIX METHODOLOGY

This section presents a very brief overview of Phoenix Methodology, focusing on the qualitative aspects regarding CFMs and PIFs. For further details on the methodology, including the definitions of the CFMs and PIFs, the reader is referred to Refs 5, 6, 7, 8.

Phoenix analysis framework has three main layers, illustrated at Figure 1.

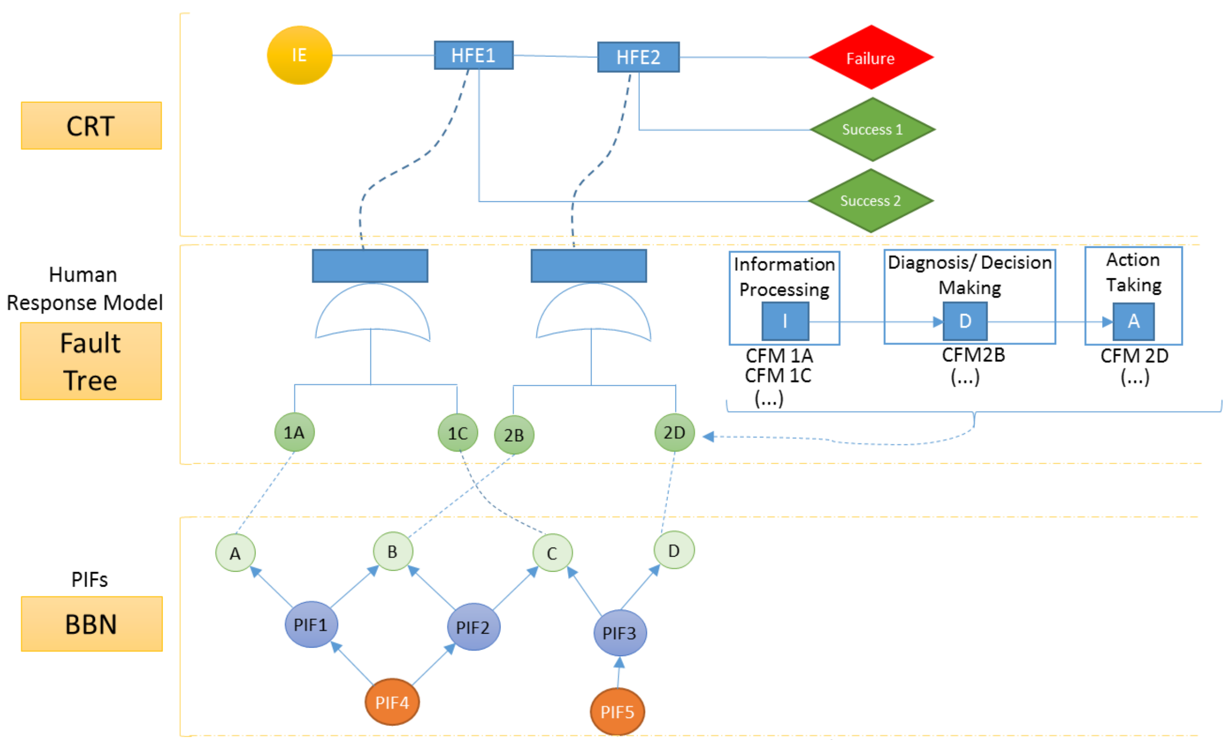

Fig. 1. Phoenix Methodology layers[6]

The top layer is the "crew response tree" (CRT), which is modeled through an event tree. It 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 mid layer is the human performance model, modeled through fault tree. It makes use of a team-centered version of the Information, Decision and Action (IDA) cognitive model[9] to define the Crew Failure Modes. The bottom layer is composed by the PIFs - context factors (including plant factors) that affect human performance. At this layer the PIFs are linked to the CFMs through a CFM – PIF model, using a Bayesian Belief Network (BBN). The path through this integrated model gives the details of how the entire story needs to be narrated and read[6]. The CFMs and PIFs are presented in the following sub-sections.

I.A. Crew Failure Modes

The crew failures modes (CFMs) are connected to the human response model - IDA, a crew centered version of the Information, Decision and Action cognitive model, originally developed to model nuclear power plant operator response in emergency situations. IDA is a three-stage model and these stages serve as the basis for linking failure mechanisms to the possible human failures. For details on the IDA model see Refs 9, 10. The IDA phases are as follows[7, 10]:

I - Information pre-processing: This phase refers to the highly automatic process of processing incoming information. It includes information filtering, comprehension and retrieval;

D - Diagnosis/ Decision making: In this phase the crew uses the perceived information and the cues from the previous stage, along with stored memories, knowledge and experience to understand and develop a mental model of the situation. In addition, the crew engages in decision-making strategies to plan the appropriate course of action;

A - Action: In this final phase the crew executes the decision made through the D process.

The CFMs are therefore used to specify the possible forms of failure in each of the Information, Decision and Action 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. In order to avoid double counting crew failure scenarios during the estimation of human error probabilities (HEPs), the CFMs are defined as being mutually exclusive or orthogonal[7]. Table 1 below presents the set of Phoenix CFMs. Phoenix defines each CFM based on the particular IDA phase in which it occurs.

TABLE I. Phoenix's set of CFMs[8]

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				

I.B. Performance Influencing Factors

PIFs are the contextual factors that affect human performance by enhancing or degrading it. Under different situations, they are used to simplify the contexts and causes affecting human performance. 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 main groups to cover emotional, cognitive and physical aspects, and 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[7].

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. Level 1 PIFs, which are also the main or Primary PIF groups, have a direct impact on human performance (CFMs). Level 2 PIFs either directly affect or form parts of (make up) the level 1 PIFs and the same applies to the Level 3 PIFs[7]. Human System Interface, for example, is composed by HSI input and HSI output, both 2nd level PIFS. Resources is composed by Workplace Adequacy and Tools, both 2nd level PIFs. Tools is affected by two 3rd level PIFs: Tool Availability and Tool Adequacy. The full set of Phoenix's PIFs can be seen in Ref. 8.

Next section presents how Phoenix CFMs and PIFs can be used to analyze a scenario within a refinery unit.

III. CASE STUDY: HYDROGEN GENERATION UNIT

Hydrogen production is mainly obtained through hydrocarbons reforming, especially natural gas reforming. Indeed, 95% of the hydrogen produced in the United States is made by natural gas reforming in large central plants.[11]

At a petroleum refinery, the Hydrogen Generation Unit (HGU) produces hydrogen to be provided mainly to Hydrotreater Units, which demand a large amount of hydrogen for its reactions.

A HGU normally comprises the following sections: Desulphurization, Reforming, CO conversion, Purification by PSA unit, Steam generation and Process condensate treatment. The process is briefly described below.

The HGU feed is, in general, Natural Gas, Natpha or a mix of both. The feed is mixed with hydrogen and goes through Sulphur removal at the desulphurization section. After desulphurization the product goes to the reforming section, where the hydrogen is produced. The hydrogen is then purified at the PSA unit. The reforming reactions produce CO, which is converted to CO_2 at the CO conversion section. The HGU can also produce steam to be used at this unit or other refinery units, at the steam generation section.

Figure 3 illustrates the reforming section of the HGU unit analyzed at this case study.

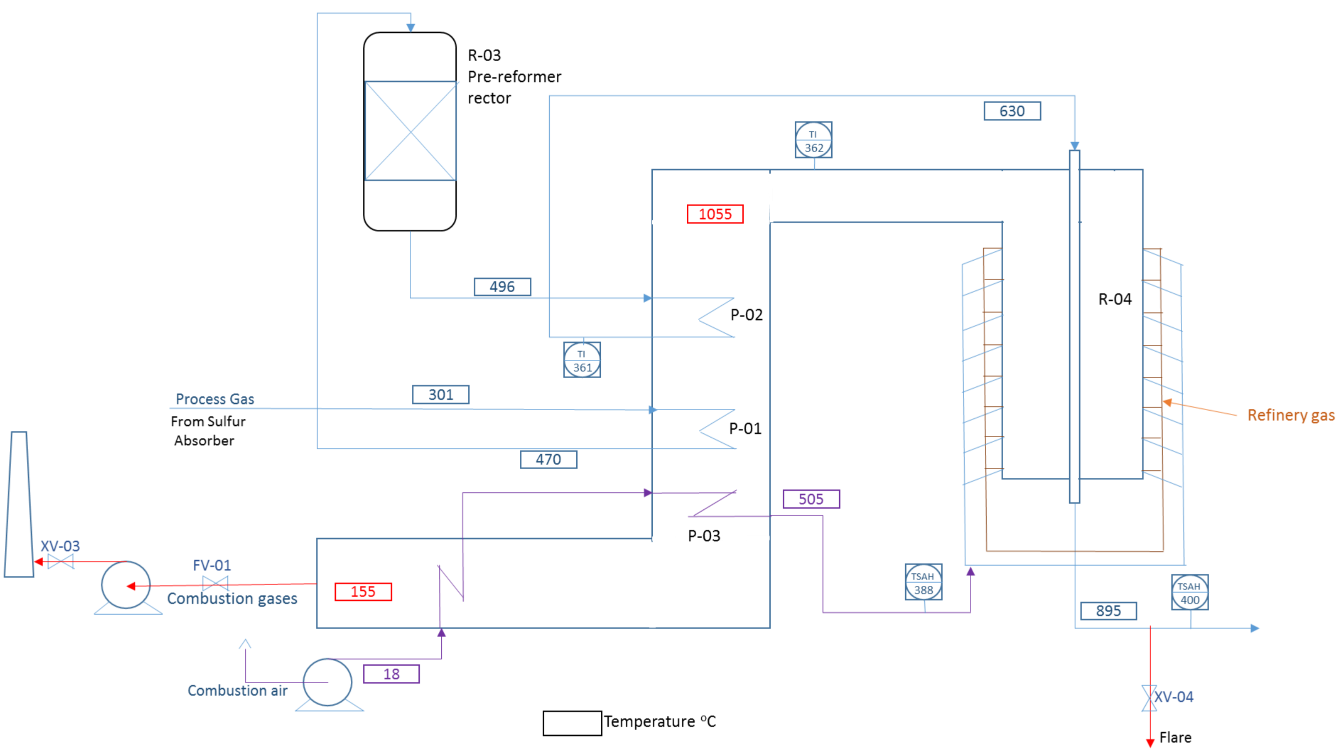

Fig. 3. Reforming Section of the Hydrogen Generation Unit

This unit makes use of a pre-reformer reactor (R-03). Because this unit can use Naphta as feed, the installation of an adiabatic pre-reformer upstream of a tubular reformer (R-04) is suitable. This design is common at naphtha based plants and plant operating on fuel gases with higher concentrations of higher hydrocarbons. The pre-reformer reactions convert the higher hydrocarbons (equation 1 below), and the inlet temperature in the reformer can be increased, which reduces the size of the tubular reformer[12].

The reformer reactor (R-04) uses a furnace to provide heat of reaction, since the steam reforming reactions are overall endothermic. Therefore, the steam reformer is not simply a catalyst reactor; it is a combination of catalyst reactor and heat exchanger. The steam reformer consists of two main sections: furnace or radiant section and convection section.

Equations 1, 2 and 3 describes the reforming reactions. The reactions (1) and (2) are endothermic while reaction (3) is exothermic.

$$C_nH_m + nH_2O \rightarrow nCO + (n+m/2)H_2 \text{ -Heat} \quad (1)$$
$$CH_4 + H_2O \rightleftarrows CO + 3H_2 \text{ - Heat} \quad (2)$$
$$CO + H_2O \rightleftarrows CO_2 + H_2 + \text{Heat} \quad (3)$$

All higher hydrocarbons are completely converted by reaction (1) at the pre-reformer R-03, while reactions (2) and (3) will be almost equilibrated. The flow leaving the pre-reformer reactor doesn't have higher hydrocarbons anymore, and it can be heated up without risk of carbon formation due to thermal cracking.

Reaction (2) takes place mainly at the tubular reformer, R-03. Some of the CO produced is also converted in CO_2 at the reformer, according to reaction (3), although most of it actually happens at the CO conversion section. The reaction (2) is strongly endothermic and the heat of reaction is supplied indirectly by firing, at the radiant section of the reformer.

The process gas enters the tubular reformer through the top of the vertical tubes and flows downwards. The flue gas collector passes the flue gas from the radiant chamber to the flue gas waste heat recovery section where the sensible heat of the flue gas is used to preheat the feed through heat exchangers P-01 and P-02 and the combustion air through P-03 and P-04. The flue gas leaving the waste heat recovery section is then sent to the stack through C-01.

III.A. HRA Scenario

The scenario analyzed consists of a leak of process gas inside the radiation chambers of the reformer, due to a leak at the reactor tubes. This scenario was chosen based on the Qualitative Risk Analysis of this Hydrogen Generation Unit. Among all the scenarios listed in the HAZOP, this one presented the more severe consequence - risk of explosion.

The Hazop extract for this scenario is as Table 2.

TABLE II. HAZOP table for the scenario analyzed

Guideword	Cause	Consequence	Safeguard
Contamination	-Leak on reformer tubes	-Increase of combustion gases temperature -Risk of explosion	-TSAH 400 -TI 362 -TI 361 -TI 388

A small hole on the reformer tubes would leak process gas into the radiation chamber of the reformer. The content of the process gas, especially the hydrogen, may react with the oxygen still present at the combustion gases, which is a very exothermic reaction. The heat produced would increase the temperature of the combustion gases, which, in turn, would heat even more the feed going through the heat exchangers P-01 and P-02 and the combustion air going through P-03. The temperature indicators TI-362, TI-361 and TI-388 would therefore indicate higher temperatures than normal process temperatures, which would be visible to the operator, and the associated High Temperature Alarms (HTA) would sound. The exit temperature of the process gas, indicated by TSAH-400, would also be higher than normal.

According to automatic control of this unit, TSAH-400 actually activates the trip of the reformer. The trip consists of shutting off all air combustion and refinery gas to the burners, stop the feed to the reforming section and depressurizing the furnace and the reformer, and opening XV-04 to send process gas from the reformer to the flare.

The scenario established in this paper considers the failure of the automatic trip of the reformer. The operator would have then to understand the cues and trip the reformer manually. It also considers that the HTA of TI-361/362/388 will function.

In case the operator does not trip the reformer, the heat generated by the exothermic reactions could increase the temperature above the design temperature of the reformer tubes. This would lead to a catastrophic rupture of the tubes, and a high amount of process gas would rapidly leak into the radiation chamber, which would cause an explosion.

Figure 4 illustrates the event tree of the scenario, considering the failure of the automatic trip IS-1.

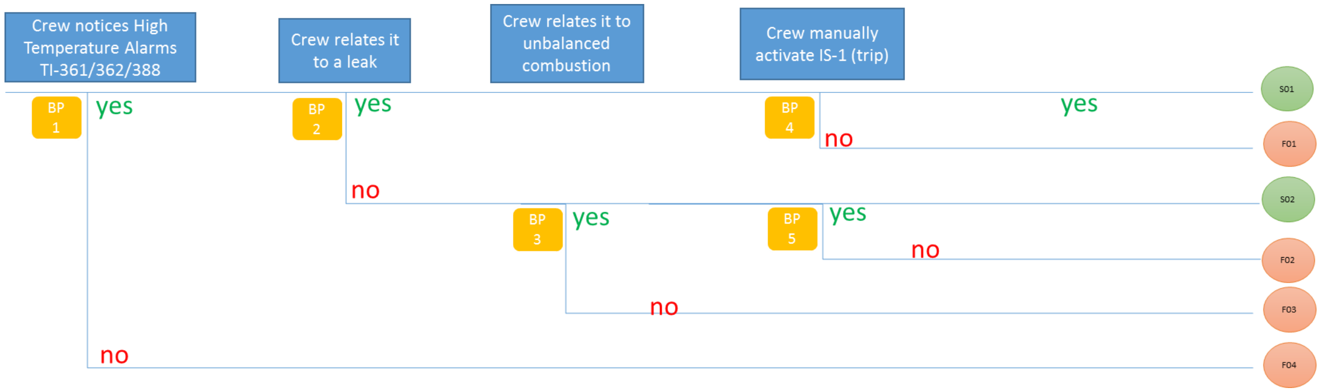

Fig. 4. Event tree of the scenario

The possible outcomes for the scenario are:

S01: Crew notices HTA, relates it to the right cause and trips the reformer
F01: Risk of explosion: crew notices HTA, relates it to the right cause but fails to trip the reformer
S02: Crew notices HTA, relates it to unbalanced combustion, trips the reformer
F02: Risk of explosion: crew notices HTA, relates it to unbalanced combustion but fails to trip the reformer
F03: Risk of explosion: crew notices HTA, can't find the cause and therefore doesn't trip the reformer
F04: Risk of explosion: crew does not notice HTA

Each branch point BP at the event tree is related to one or more Crew Failure Modes. The possible factors leading to each CFM are analyzed as one of Phoenix's PIFs, and the PIFs and CFMs are modeled through BBNs, composing the 3rd layer of Phoenix. The identification of the CFM and PIFs of the Branch Point 1 is described below.

Branch Point 1 is related to noticing the High Temperature Alarms. In Phoenix methodology, the fault in noticing and responding to the alarms is described by the CFM "Key Alarm Not Responded to". The definition of this CFM is "This is a case where the crew intentionally or unintentionally fails to respond to a key alarm. A key alarm is one for which response is expected to be immediate and the crew is adequately trained. It includes failure to detect, notice or understand the alarm. (…) A key alarm is typically expected to initiate an immediate response which may include working through a procedure. This CFM also includes not perceiving, dismissing and misperceiving the key alarm."[7]

The Fault Tree from Phoenix leading to this CFM is illustrated at Figure 5. The Fault Tree is pruned in order to show the relevant parts for this CFM, and the whole fault tree can be seen in Ref. 7. The relevant parts of the fault tree are indicated using red lines and the CFMs have red circles underneath them.

The main reasons for the operators not to notice the alarms are summarized at Table 3 below, with the corresponding PIF from Phoenix. Note that these are the main PIFs for this specific CFM, and other PIFs may be identified as having smaller influence at this CFM. The identification of these PIFs was made through discussion with analysts and engineers and through visitations of the control room of this refinery and observation of its operation.

TABLE III. Main PIFs for BP1 CFM

Possible reasons for the operators not to notice the alarms	**Phoenix corresponding PIFs**
Too many alarms at the environment at the same time	Passive Information Load
Inadequate panel interface	HSI Output
Operator not attentive/tired	Attention
Operators working also on another unit	Extra work load
Not defined who should be paying attention to the alarms	Role awareness, Leadership, Team Training
Too much ambient noise	Workplace Adequacy
Operator absent at the moment	Morale/Motivation/Attitude (commitment)

Figure 6 represents the BBN model of this CFM and its PIFs.

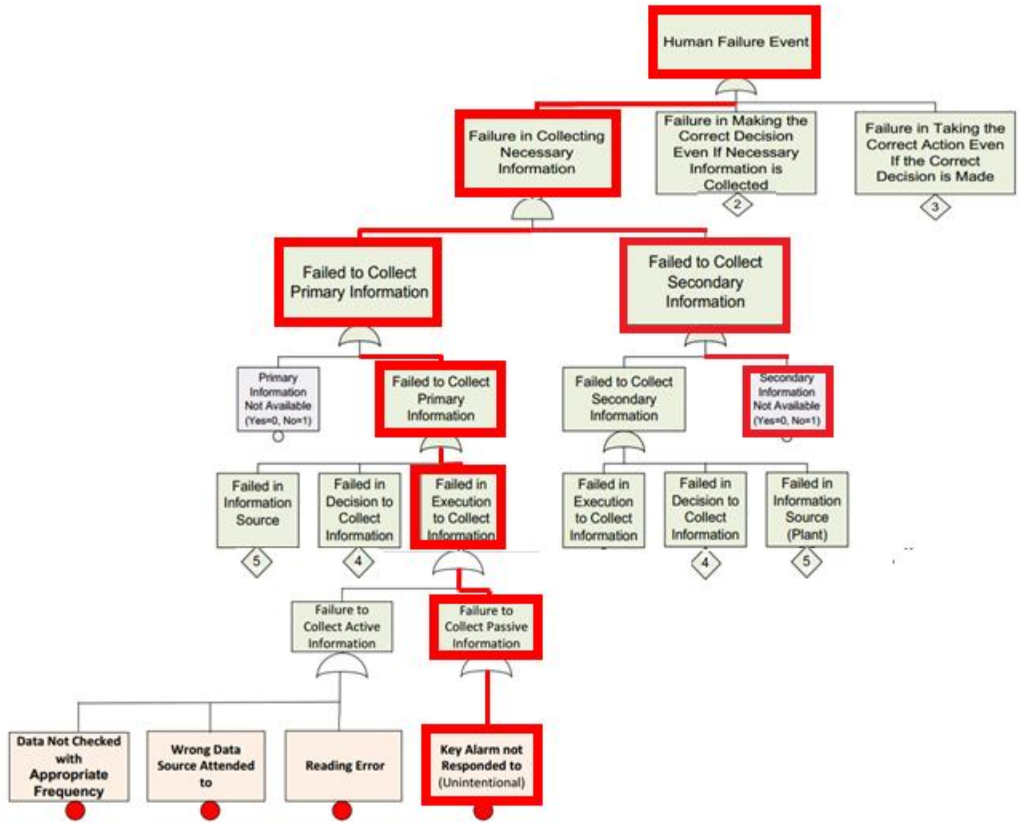

Fig. 5. Fault Tree for BP1

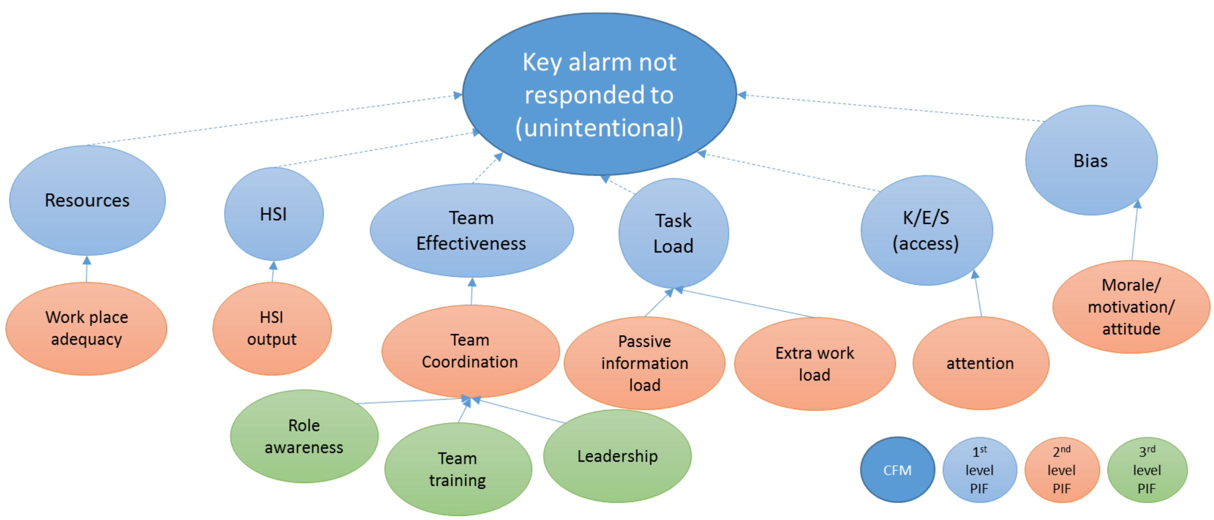

Fig. 6. CFM-PIF BBN for Branch Point 1

The analysis of the other Branch Points would follow this same path: identification of the CFM(s) related and the PIFs influencing each CFM. The BBNs, the fault trees and the event tree together would then form the three layers of Phoenix.

The next step of the analysis would then be the quantitative analysis, with determination of the Human Error Probability (HEP). After analyzing the relevant CFMs and PIFs, the levels of each PIFs is assessed by the HRA analyst and then inputted into the model for each PIF. Phoenix provides tables for assessing the level of each PIF. Then the temporal ordering of the relevant CFMs is determined, and the conditional probabilities of the CFMs is estimated through the BBN. The final step in the analysis process involves the incorporation of the conditional probabilities of the relevant CFMs into the logic equation of the CFM cut-sets (formed by the relevant CFMs) in order to obtain the estimated HEP for the HFE of interest. Details on the quantitative analysis can be seen in Refs 5 and 7.

Phoenix provides the BBN model parameters, which combines data from different sources since there is no single source that would be able to provide all the information required, most of these sources being from NPPs. The ideal process of applying Phoenix to a refinery scenario would be using data from refineries to populate the BBN. However, as the availability of the required type of data for analysis is one of the major issues in the field of HRA[7], this could be difficult to achieve.

IV. CONCLUSIONS

The use of Phoenix to analyze Crew Failure Modes and PIFs at the Petroleum industry is a systematic way of identifying and investigating the potential impact of human error in this industry. This paper demonstrates how to implement the qualitative steps of Phoenix at a potential and critical scenario at a refinery. The quantitative analysis can be applied to this scenario in the future, and risk-based decisions can be taken to prevent its possible consequences, especially when integrating the HRA performed with a Quantitative Risk Analysis.

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