

Human Reliability in the Petroleum Industry: A Case Study of the Petro-HRA Method

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ABSTRACT: This paper presents an overview of the Petro-HRA method, which was developed to analyse the human contribution to major accident risk in the petroleum industry. The paper describes a recent case study of a loss of position event that was analysed using Petro-HRA. The case study demonstrates how the Petro-HRA method enabled an in-depth investigation of the scenario, and how it revealed issues with timing, human-machine interfaces and procedures that could set the operator up to fail, and that were otherwise not evident from the Quantitative Risk Assessment model of the scenario.

1 INTRODUCTION

1.1 HRA in the Petroleum Industry

Quantitative Risk Assessment (QRA) is a formal method used in the petroleum industry for calculating individual, environmental, employee and public risk levels from operation of petroleum installations. The results of the QRA are used for comparison with regulatory risk criteria to determine whether the risk from operation of those installations is acceptable. The human contribution to risk is represented in the QRA as Human Failure Events (HFEs). These typically describe the potential failure of a human operator action or intervention as part of a safety barrier.

Human Reliability Analysis (HRA) is a powerful method for investigating these human actions to understand the factors that drive human performance and to quantify these for inclusion in the QRA. Organizations are increasingly using HRA to ensure that the human contribution to risk, as described in the QRA, represents the installation *as it is actually operated* and not as it was designed. In addition to supporting a robust and systematic analysis of the HFEs, the HRA results can be used to develop and justify the implementation of error reduction measures for safety critical tasks.

1.2 The Petro-HRA Project

Until recently, analysis of the human contribution to major accident risk in the petroleum industry has been relatively limited. This is partly because most currently used HRA methods were developed for the commercial nuclear industry, and thus were not di-

rectly translatable to operator activities on a petroleum installation. In 2012 a joint industry project was established in Norway to adapt the SPAR-H (Standardized Plant Analysis Risk-Human Reliability Analysis) method by Gertman et al. (2005) to a petroleum context. SPAR-H was chosen for adaptation based on an analysis by Gould et al. (2012), which evaluated a number of different methods for analyzing human reliability for post-initiator petroleum events, and concluded that SPAR-H was the most promising method for analysing these events.

The Petro-HRA project was funded by the Research Council of Norway's PETROMAKS program, and was carried out by the following research and industry partners: Institute for Energy Technology (IFE), Sintef, Idaho National Laboratory, Norwegian University of Science and Technology (NTNU), DNV-GL and Statoil.

The main goal of the Petro-HRA project was to evaluate the SPAR-H method against the HRA requirements and needs for the petroleum industry, and to adapt SPAR-H to make it more suitable for application in such a context. The project also aimed to more fully describe the qualitative analysis and error reduction aspects of the HRA, as these are often overlooked in other HRA method descriptions.

1.3 The Steps in a Petro-HRA

The Petro-HRA method comprises seven steps, covering both the qualitative and quantitative analysis requirements for a complete HRA method. Although the steps are described linearly in Figure 1 and in the following sections of this paper, it is important to note

that HRA is rarely a linear process. There is often iteration within and between steps throughout the whole process (shown by the dotted lines in Figure 1), and the HRA analyst will often have to revisit and repeat some steps to ensure a robust and comprehensive analysis.

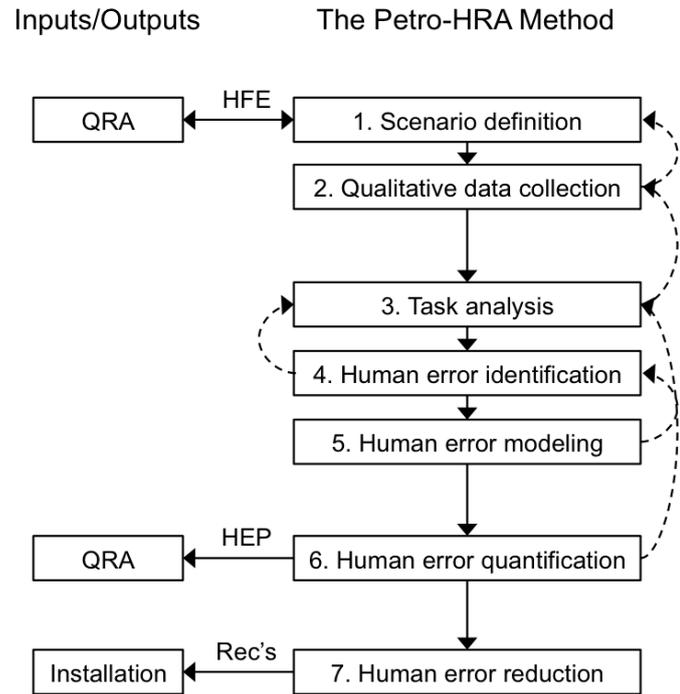


Figure 1. The Petro-HRA Method

The seven steps in the Petro-HRA method are briefly described as follows:

- 1 *Scenario definition*: define the scenario that is to be analysed, and the scope and boundaries of the analysis. This is an essential step as it significantly shapes the subsequent qualitative and quantitative analyses.
- 2 *Qualitative data collection*: collect specific and focused data to enable a detailed task description, which includes information about factors that may affect human performance and the outcome of the scenario. This is usually done via scenario walk-talk-through, observation, interview and documentation review.
- 3 *Task analysis*: describe the actions that are performed for the tasks in the scenario. This is a systematic way of organizing information about the tasks to help the analyst understand how the scenario is likely to unfold.
- 4 *Human error identification*: identify and describe potential errors related to the tasks, the consequences of each error, recovery opportunities and Performance Shaping Factors (PSFs) that may have an impact on error probability.
- 5 *Human error modeling*: model the tasks to logically describe how the HFE can occur in this scenario, and to clarify the links between the errors. The model logic can then be used to calculate the

Human Error Probability (HEP) for the HFE (in Step 6).

- 6 *Human error quantification*: quantify each chosen task or event based on a nominal value and an evaluated set of PSFs.
- 7 *Human error reduction*: an optional step; the aim is to develop risk-informed recommendations for improvements to either prevent the occurrence of human error or mitigate the consequences.

1.4 The Petro-HRA Guideline

The main deliverable from the Petro-HRA project is a guideline describing how to apply the method. Petro-HRA is considered a “complete” method in that the guideline includes a detailed description of how to perform the qualitative analyses that underpin the HEP quantification. Most HRA method descriptions assume a degree of qualitative analysis without providing guidance on how to do this. Previous studies by Forester et al. (2013), Liao et al. (2014) and Taylor (2015) have shown that this can lead to uncertainty about how to perform qualitative analysis and how to link this to the quantification step. The Petro-HRA guideline aims to eliminate this uncertainty by providing detailed guidance and examples of how the qualitative analysis not only links to the quantification, but also how the overall Petro-HRA integrates with the QRA.

At the time of writing this paper, the Petro-HRA guideline is undergoing final editing. It is expected to be published in September 2016.

2 CASE STUDY: ANALYSIS OF A LOSS OF POSITION EVENT USING PETRO-HRA

2.1 About the Case Study

A case study was carried out in 2015 in which the Petro-HRA method was used to analyse a loss of position event scenario (in this case, a drive-off scenario) on a semi-submersible drilling rig in shallow waters (320m or less) on the Norwegian Continental Shelf. The aim of the case study was to test the robustness and completeness of the Petro-HRA method by applying it to a real-world major accident event scenario.

2.2 The Analysis Scenario and Context

The case study addresses a drive-off scenario of a semi-submersible drilling unit (see Figure 2). The first step in the Petro-HRA of this scenario was to fully describe the drive-off scenario itself. It is important to develop as complete a scenario description as possible in the early stages of the Petro-HRA as this sets the scope and context for the subsequent analyses that are carried out. The following description was developed based on information about the

scenario that was provided over the course of several initial meetings with representatives from the rig operating organization.

In order to avoid potential damage during a drive-off, the rig should maintain position above the wellhead where the drilling operations are conducted. Positioning is maintained without a mooring system through the autonomous action of a set of thrusters controlled by the Dynamic Positioning (DP) system. Operations in shallow waters admit low tolerance in terms of rig position due to potentially higher riser angles (Chen et al., 2008). In Norwegian waters, operations in 320-meters-deep waters or less (internationally the limit is about 600m) are classified as shallow water operations.

Input for the DP system is provided by the position reference system (Differential Global Positioning System (DGPS), and Hydroacoustic Position Reference (HPR)), environmental sensors, gyrocompass, radar and inclinometer (Chen et al., 2008). A Dynamic Positioning Operator (DPO) located in the Marine Control Room (MCR) is responsible for constant monitoring of DP panels and screens and carrying out emergency procedures if needed (Giddings, 2013).

In this case study it is assumed that some (undefined) failure in the DP system initiates 6 out of the 8 platform thrusters to accelerate up to full thrust in one direction, leading to a “fast drive-off” scenario. In order to establish whether the rig is located in the safe-operation area, specific offset position limits are drawn (Figure 2). Such limits are defined taking into account riser angle, position data and environmental variables. The riser has relatively low capacity of inclination, despite the upper and lower flex joints, and it can reach a maximum angle of 12 degrees. Exceeding this physical limit may result into damages to wellhead, Blowout Preventer (BOP – sealing the well) or Lower Marine Riser Package (LMRP – connecting riser and BOP) (Chen et al., 2008). For this reason, a conservative maximum angle of 8 degrees is considered in the limit calculation.

If the rig moves to an offset position, specific alarms will sound and indicate that the DPO should stop the thrusters and initiate the manual Emergency Disconnect Sequence (EDS) to disconnect the riser from the BOP. If the manual EDS ultimately fails, the automatic EDS activates at the ultimate position limit allowing for safe disconnection (Chen et al., 2008).

Stopping the thrusters is considered a critical step; in shallow waters, if the thrusters have not been stopped the EDS might not disconnect safely because the riser angle will be too steep. This is true even for automatic activation of the EDS.

Operations in shallow waters imply shorter available time for detection and position recovery, for both systems and operators. For this reason, automatic EDS must always be enabled in shallow waters.

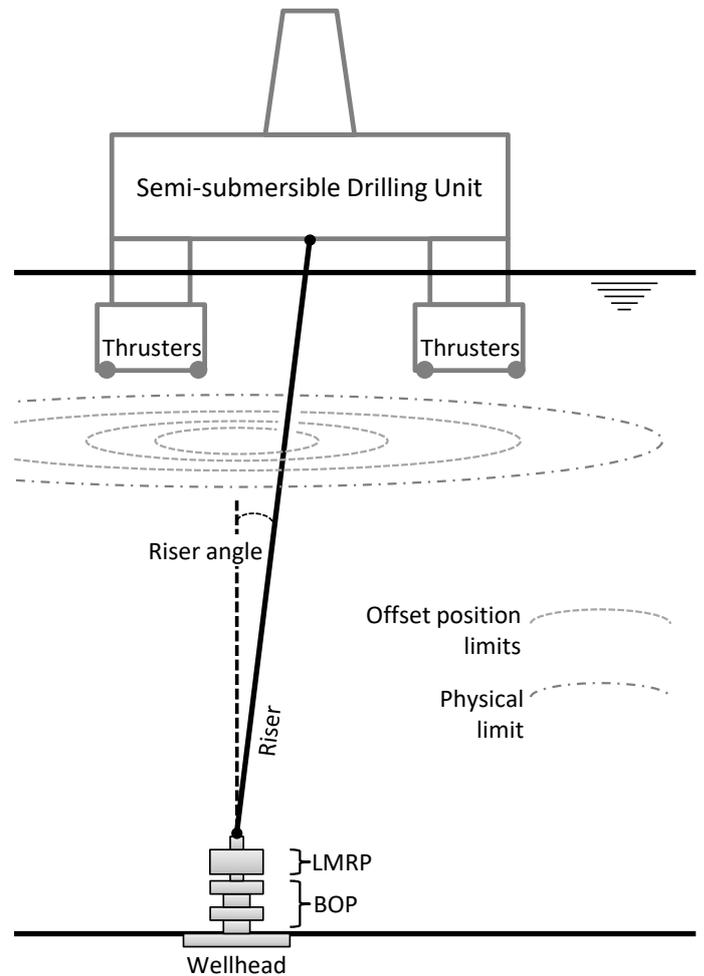


Figure 2. Dynamic positioning during drilling operations (adapted from Paltrinieri et al., 2016)

2.3 Workshop with Operators

The main data collection activity for the case study was a two-day workshop with DPOs who had in-depth technical knowledge and operational experience from the drilling rig in question. The goal of the workshop was for the analysts to confirm their understanding of how DPOs would detect and respond to a drive-off event. In particular, the workshop aimed to verify the scenario description and hierarchical task analysis (HTA) that had been prepared based on initial telephone meetings with organization representatives and a review of documentation provided by the operating organization prior to the workshop. The analysts also aimed to establish a timeline for the scenario and collect information about PSFs that could positively or negatively affect task performance.

Initially, the DPO response to a drive-off scenario appeared to be quite straightforward; as soon as the DPO detects a loss of position (e.g. by hearing the high force thruster alarm or position alarm), the DPO should stop the thrusters and manually initiate the EDS. However, the scenario talk-through during the workshop revealed that there were some critical factors that make a successful scenario outcome more unlikely, as described in the following subsections.

2.4 Timeline Analysis

An important part of Petro-HRA is to consider the effect of time on task performance and human error probability by assessing the difference, or margin, between what is referred to as *available time* and *required time* (see Figure 3).

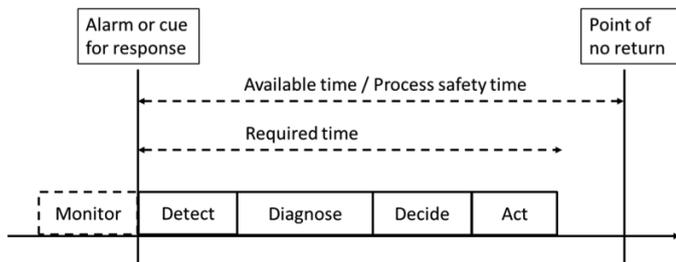


Figure 3. The relationship between operator actions, time required and available time

In most loss of position scenarios, such as drift-off and DP drive-off, time is a highly critical factor (Chen et al., 2008). After the occurrence of a drive-off there is limited time to safely disconnect the rig from the well before damage to the well and subsea equipment can no longer be prevented. In this case study, successful disconnection relies on the DPO pushing the emergency thruster stop and initiating the EDS within a certain amount of available time determined by external factors such as thruster force, water depths and the mechanical disconnect sequence. Relative to the available time there is also the time required by the DPO to successfully perform the actions necessary to reach the decision of disconnecting from the well.

While available time was calculated based on relatively accurate and obtainable (physical) parameters, required time relied on obtaining human performance data. It was not possible during this case study to collect data from simulators or observations, so a timeline analysis was conducted based on input from the DPOs about the duration of the actions identified in the initial task analysis. Findings were documented using a timeline diagram indicating the start and finish of each main task step, accounting for simultaneous activities within the task. A timeline table was made to capture additional details about individual actions, as well as assumptions made and the need for further clarifications.

Overall, the analysis suggested that the DPO has *very limited time available* to respond in this fast drive-off scenario, making time the most influential performance driver on the overall HEP for the HFE.

One of the most challenging aspects of obtaining data on required time is to account for effects from the subjectivity (i.e. biases) inherent in the interviewees' input. For example, operators may be overly optimistic about their own performance, rely on experience from a single or few previous events, and not sufficiently account for influence from other contex-

tual factors such as disturbances from others. A timeline analysis can help control such factors by combining interview techniques such as triangulation and brainstorming guidewords, with the structure provided by the task analysis.

2.5 Task Analysis of the DPO Workshop Findings

Following the workshop, a more detailed analysis of the information collected during the workshop was performed. This included the development of a tabular task analysis (TTA), as well as human error identification and modeling. The identified human errors were then quantified, but because the Petro-HRA method was still under development at the time, the quantification was not used for impact assessment or error reduction and integration in the QRA, and therefore is not reported in this paper. The analysts did develop human error reduction measures based on the findings from the qualitative analysis.

Task analysis is, in many ways, a cornerstone technique for qualitative analysis and HRA. It is typically used to describe the tasks that are performed by the operator during the scenario, the time required, roles and responsibilities, procedures and equipment used, etc. It is also a useful technique for pulling together all of the information known about the scenario at that time, including assumptions and uncertainties about the scenario. The task analysis is generally used as the basis for subsequent human error identification, evaluation of PSFs and the development of improvement measures for human error reduction. The TTA format, in particular, can be an invaluable tool for documenting the link between the different qualitative analysis techniques.

A basic cognitive behavioural model (i.e., detect, diagnose, decide, act) was used in this case study to structure the task analysis. An ongoing point of discussion regarding task analysis is how far to decompose the task steps, and this issue also came up during the case study. Unfortunately, there is no hard and fast rule that can be applied here, because the appropriate level of decomposition will vary from HRA to HRA, depending on many factors such as the complexity of the task being modeled, the amount of information available about the task steps, the goal of the analysis, etc. There is a risk that if the task analysis is decomposed to too low a level, the analyst will get lost in the detail and the analysis risks becoming unmanageable. Conversely, an insufficient level of detail might result in human error traps or important PSFs going undetected by the analyst.

The approach that was used during the case study was to decompose the task steps to a level that matched the PSF descriptions from the Petro-HRA method. In this case, that meant decomposing the tasks to two levels below the top goal. This provided a sufficient level of detail for human error identification and PSF evaluation.

2.6 Human Error Identification

The Systematic Human Error Reduction and Prediction Approach (SHERPA; Embrey, 1986) error taxonomy was used to identify possible human errors. Rather than strictly applying the SHERPA method, the taxonomy was instead used as a prompt to identify possible errors, based on the information provided to the analysts thus far.

For each task step and sub-step in the TTA, the analysts considered what errors could occur and documented these in the appropriate column in the TTA. The likely consequences of the error were also identified, along with possible opportunities to recover from the error, and these were also documented in the TTA. Errors that were considered to have insignificant consequences, and/or that had high recovery potential were not analysed any further. This enabled the analysts to focus on the errors that were more likely to cause problems during a drive-off scenario, as shown in Figure 4.

2.7 Human Error Modeling

The QRA for this drilling unit identified and assessed a series of consequences related to a generic loss of position scenario. “Failure to prevent damage to wellhead” was deemed as the most critical consequence for this case study. This was used as the top event of the fault tree diagram used to model the identified human contributions to risk (Figure 4).

A failure to prevent damage to wellhead may be caused by either: (a) failure to stop the movement of rig, or (b) failure to disconnect from wellhead. In fact, disconnecting while the rig is moving or stopping the rig in a position out of the physical limit (see Figure 2), while being connected, would damage the wellhead.

Failure to stop movement of the rig may be caused by one of the following basic events (BEs):

- *BE1 Failure to stop drive-off in time:* the DPO may fail to hear the first alarms sounding (thruster force alarm), not realize that the thrusters should be stopped first, take too long to decide or take too long to press the emergency stop buttons for all the active thrusters.
- *BE2 Failure to identify drive-off:* the DPO may not detect all the alarms sounding, including the last one sounding (position alarm), or fail to diagnose the drive-off.
- *BE3 Failure to fully stop drive-off:* the DPO may stop the wrong thrusters (this scenario assumed a maximum of 6 out of 8 thrusters are used).

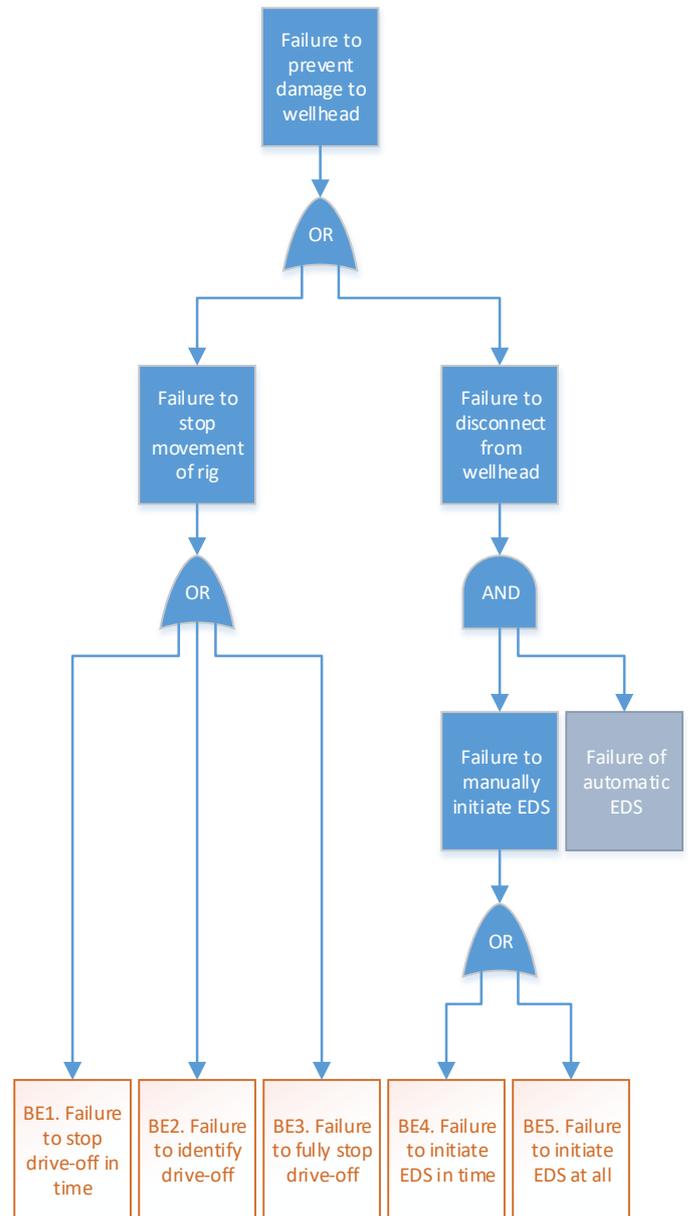


Figure 4. Human error modelling fault tree

A failure to disconnect from the wellhead is possible only if both the manual and the automatic EDSs fail. This case study focused on the former, where a DPO is involved. Failure to manually initiate EDS may be caused by one of the following BEs:

- *BE4 Failure to initiate EDS in time:* the DPO may not detect the first alarms sounding, take too long to decide, or take too long to press the EDS buttons.
- *BE5 Failure to initiate EDS at all:* the DPO may not detect all the alarms sounding, fail to diagnose the drive-off, decide not to initiate the EDS, or fail to press the EDS button.

The benefit of developing a human error model was that it allowed the analysts to check their understanding of the failures that could occur that would lead to the top event, to check the logic of how the different failures fit together and influenced one another, and to ensure that all of the errors identified in the TTA were represented in the fault tree.

2.8 Human Error Reduction

One of the main motivations behind the HRA was to identify risk-informed solutions for how to improve reliability and safety in a drive-off situation. To achieve this goal an error reduction analysis (ERA) was performed to develop a set of error reduction measures (ERMs) and/ or error reduction strategies (ERSs). ERMs are risk reducing measures targeted at specific operator actions, while ERSs address human performance on a more general level, for example across several accident scenarios.

ERMs and ERSs were developed by combining the insight obtained through the various qualitative analyses performed as part of the HRA. It is important that the final recommendations effectively target the factors actually influencing the error probability, and that this can be demonstrated. Three main findings were helpful in guiding this process. First, the task analysis revealed that the task itself was relatively straightforward and not particularly complex. At the same time the timeline analysis showed that the DPO had very limited amount of available time to perform the required actions. Furthermore, while the HEI indicated that few errors were likely to cause subsequent unsafe actions; several errors could create critical delays in completing the task. As such, the greatest concern was not necessarily *incorrect*, but rather *delayed* actions. Most ERSs and ERMs therefore aimed at reducing the time required for the DPO to execute the task.

A critical step in the sequence of actions was timely pushing of the emergency stop buttons for the six out of eight active thrusters in this particular scenario. This required the DPO to lift up the protection lids and push each individual button, one at the time. Although a simple operation, an effective ERM would be to install one single push-button deactivating all running thrusters simultaneously. This would not only reduce the time spent on performing the action; it would also avoid the potential error of not stopping all thrusters, or stopping the incorrect ones.

The most significant challenge related to error reduction was accounting for uncertainties associated with the data collected about some of the time estimates. For example, in some cases it was difficult to determine how soon alarms and other cues about the drive-off would be presented to the DPO, and if they would be sufficiently obvious. For the sake of validity, such uncertainties were managed by defining and documenting a set of assumptions about the scenario. But more importantly, what could be regarded as key uncertainties were embedded as part of several ERSs. For example, it was recommended to use simulators for training on early detection of drive-offs, while at the same time use the opportunity to verify assumptions made in the analysis.

A thorough ERA presents the stakeholder with a decision basis for how to select and prioritize

measures with the most significant effect on the risk level. Although not part of this case study, by documenting implementation of ERMs and ERSs, the HRA could later be updated to demonstrate reduction in quantified HEP values and overall risk levels.

3 DISCUSSION OF RESULTS

Overall, the HRA concluded that a successful outcome in this particular scenario is unlikely, due to the very short amount of time available for the DPO to respond to the event. As noted earlier, the scenario in this case study assumes initiation of 6 out of 8 thrusters to full thrust in a short amount of time (i.e. a “fast” drive-off), and so this scenario could be considered somewhat extreme. Although loss of position events are not infrequent, operating experience shows that disconnection from the well is often successful. In fact, one of the operators that attended the workshop had experienced a loss of position event the week before the workshop, and had successfully disconnected the rig from the wellhead in time. Regardless, the Petro-HRA provided valuable insights into how operators would respond in a fast drive-off and the other factors present that could hinder a successful outcome in this event.

3.1 Summary of Findings from the Case Study

The main findings from the Petro-HRA analysis of this fast drive-off scenario were as follows:

- *The DPO does not have sufficient time available to successfully intervene in this scenario.* This factor is considered to have the highest influence on the probability of a failure outcome in this scenario.
- *No formal procedure exists for how to safely disconnect from the well in case of a drive-off.* As a result, the DPOs that attended the workshop had some different opinions and understanding about how to respond in this scenario and in which order tasks should be carried out.
- *There are uncertainties regarding how quickly the DPO is presented with cues triggering him/her to further diagnose the situation as a drive-off.* Therefore, it was difficult to make an exact estimate of exactly how much time the DPO would have between detecting that something had gone wrong and performing the correct action to intervene.
- *The HMI design for emergency stop of the thrusters does not support the DPO in quickly turning the drive-off into a drift-off (which would have less severe consequences).* As a result, the DPO must spend some critical seconds on stopping each individual thruster, and there is an increased risk of making a mistake and failing to stop one or more of the active thrusters.

- *There is insufficient training and experience available on how to successfully manage drive-off events.* While the task itself is relatively simple, the lack of time available makes it necessary to ensure that the DPOs maintain adequate knowledge and skills to respond quickly to this scenario. These should be maintained through regular training and simulation of these types of scenario.
- *The effects of teamwork on task performance are uncertain.* There was some speculation during the workshop regarding whether and how the second DPO on duty could provide support during the scenario. However, there was no clear, documented protocol for this.

The case study confirmed that human performance in drive-off scenarios is critical to ensure that the rig disconnects safely from the well, without any damage to equipment or the environment. In particular, a successful outcome relies fully on the DPO being able to manually stop all running thrusters within a short timescale. Failure to stop all of the thrusters in time can result in the rig continuing to move out of position, which can make the riser angle too steep and result in damage to the wellhead and BOP.

The results from the case study indicated that there is a high degree of uncertainty associated with the outcome of some task steps in this scenario. In particular, it was not certain how quickly the DPOs are likely to detect and diagnose that a drive-off is occurring. The DPOs have a very limited amount of time within which they must act, and any delayed action will contribute to the DPOs being unable to stop the thrusters in time.

3.2 *Added Value of Performing a Petro-HRA*

It is clear from the case study that the Petro-HRA approach provided a more detailed, systematic analysis of the scenario and revealed a number of hidden deficiencies that could be improved to support human performance in the case of future drive-off events.

The human actions in this scenario had been represented in a somewhat simplistic manner in the QRA (i.e. two events in an event tree – “close BOP” and “disconnect riser”), which did not reveal much detail about how the DPOs would respond in a drive-off scenario, nor how realistic the estimated HEP was. The two steps in the QRA event tree do not accurately reflect how the DPO would respond in a drive-off scenario. “Close BOP” and “disconnect riser” both refer to disconnecting from the wellhead, which would actually be performed automatically as part of the EDS. The DPO does not manually initiate these two actions separately; rather, the DPO presses a single EDS button, which and the system automatically closes the BOP and disconnects the riser.

In addition, the Petro-HRA identified that the DPO should also stop the thrusters before initiating EDS.

Failure to do so could result in damage to the wellhead as the rig continues to move forwards, even if the EDS is initiated. It was also important to identify this additional step because it is another task that the DPO must carry out within the very short timescale of this scenario, and therefore it creates an additional time pressure burden for the DPO. As noted previously, the poor design of the HMI for the emergency thruster stop buttons can actually create a delay of critical seconds as well as increasing the risk of making a mistake, which could result in failure of the scenario.

The Petro-HRA analysis also highlighted issues about the lack of a formally documented appropriate response, lack of regular training to maintain the necessary knowledge and skills to quickly react to a drive-off situation, and uncertainties about how and when team members should support the DPO in such an event. Inevitably, this resulted in some inconsistencies between DPOs about exactly how they would respond in a drive-off scenario, which increases the likelihood of something going wrong.

Disconnecting from the well is not a decision that is made lightly; it has significant impacts in terms of potential loss of equipment into the well and/or damage to equipment during disconnection, loss of production during downtime and the cost of getting connected to the well again, if reconnection is possible. However, the Petro-HRA also identified a strong safety culture and good management support for DPOs in this scenario. The DPOs reported a strong message from management that “it is better to disconnect one time too many, than one too little” which reinforced the feeling that they had trust and support from the management, and that their decisions about how to respond would be respected during the aftermath of an incident. This positive aspect of safety culture and management support should be reinforced to support and maintain operator reliability in such scenarios.

3.3 *Limitations of the Petro-HRA Method in this Case Study*

As noted earlier, at the time of conducting the case study, the Petro-HRA method was still under development and so, although the analysts did perform some quantification, this was not used for impact assessment or error reduction and integration in the QRA. As a result, the findings and risk-reducing measures were not prioritized according to their contribution to the overall risk level of this scenario. However, the qualitative results did specify which factors appeared to have the most influence on operator performance; in this case, the extremely short time available between the initiating event and the required operator action.

Despite the slightly reduced scope of the Petro-HRA for this case study, the qualitative analysis that

was performed gave much greater insight and a more realistic view of a drive-off scenario, and yielded practical improvement measures that can be implemented to improve operator reliability today.

4 CONCLUSIONS

In this paper, we present an overview of the Petro-HRA method and described a recent case study of a loss of position event scenario that was analysed using this method. The case study findings demonstrate how Petro-HRA that enables in-depth investigation of major accident scenarios. The case study revealed issues with timing, the HMI, training and procedures that could set the operator up to fail, and that were otherwise not evident from how the scenario was represented in the QRA. The Petro-HRA also identified good practices with respect to safety culture and management support that should be maintained in the future.

The paper demonstrates that Petro-HRA enables more structured and systematic “as operated” analysis of HFEs, and describes how this is useful both for representation in the QRA and for organizational learning and continuous improvement. The paper also demonstrates the value of qualitative analysis for the development of specific, targeted improvement measures which can enhance the robustness of human intervention as part of a safety barrier system, and reduce the human contribution to risk in major accident scenarios.

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