Human Reliability Assessment of Blowdown in a Gas Leakage Scenario on Offshore Production Platforms: Methodological and Practical Experiences

Sondre Øie[a], Koen van de Merwe[a], Sandra Hogenboom[a], Karin Laumann[b], and Kristian Gould[c]

[a] DNV GL, Høvik, Norway
[b]NTNU, Trondheim, Norway
[c]Statoil, Oslo, Norway

Abstract: This paper aims to share insights gained through the use of a Human Reliability Assessment (HRA) in Quantitative Risk Analysis (QRA) of offshore gas leakage accident scenarios. HRA was applied to one of the basic events in the QRA event tree, 'failure to manually activate blowdown'. Based on a case study, the chosen approach to HRA is presented along with examples of how it was applied in practice. Using available guidelines, a set of well-established methods was selected for task analysis, human error identification (HEI), -modelling, and -reduction. A nuclear-specific HRA, the Standardized Plant Analysis Risk-Human Reliability Analysis (SPAR-H) technique, was chosen for quantification of Human Error Probability (HEP). Some challenges were identified, for which methodological adaptations and improvements are suggested. This especially concerns the accuracy of HEI, the detail level and petroleum relevance of Performance Shaping Factor (PSF), as well as integration of HRA results in the QRA model with respects to the function of time. Overall, the method was found to be successful in analyzing human errors and identifying risk reducing measures when directly applied to a petroleum context. This opens for a new type of risk informed decision-making not previously made available by traditional QRA practices.

Keywords: Human Reliability Assessment, Quantitative Risk Analysis, Major Accidents, Offshore.

1. INTRODUCTION

This paper aims to share insights about the practical application of a Human Reliability Assessment (HRA) as part of Quantitative Risk Analysis (QRA) for offshore major accident scenarios. It draws on experience from QRAs of hydrocarbon (gas) leakage on offshore production platforms. For this purpose, post-initiating HRAs performed as part of QRAs for two platforms on the Norwegian Continental Shelf (NCS) are used as a case study. Due to the similarity in applied methods, platforms types, and accident scenarios, the two HRAs will be referred to as one. The objective of the HRAs was 1) to render a description of human contribution to the installations' total risk level, and 2) to identify how to reduce that risk. In addition, the authors draw on knowledge gained through participating in a Norwegian research and development project named "Petro-HRA". The objective of Petro-HRA is to adapt and validate HRA methods and practice from the nuclear industry to accommodate specific needs of the offshore petroleum industry [1].

2. HRA IN THE OFFSHORE PETROLUM INDUSTRY

Over the last 20 years, the offshore petroleum industry has attained a step change in occupational safety on an international basis, with an improvement by a factor of 10. Unfortunately, the same improvement has not been evident for process safety. From 2009 to 2012, the drilling rigs West Atlas, Deepwater Horizon, and KS Endeavor all experienced catastrophic blowouts, while the Kolskaya sank after capsizing during transit [2]. On the NCS, which is the context of this case study, there have not been catastrophic events since Alexander Kielland in 1980. That being said, incidents with major accident potential have not decreased since 1996 [3]. Serious incidents continue to occur, several which under slightly different circumstances could have had devastating outcomes (e.g. Snorre A in 2004, [4] and Gullfaks C in 2010 [5]). As investigations of recent accidents have pointed out, the systems, tools and indicators suitable for managing occupational safety do not necessarily apply to managing process safety [6]. This combined with the continuing of accidents and serious incidents calls for the industry to explore new ways of managing major accident risk.

QRA is one of the key tools for managing major accident risk on the NCS. QRA has primarily a technical scope and is used to provide risk-informed decision basis about relevant design issues. Although a powerful tool, it is not common practice to systematically assess the contribution of human performance to risk in QRA in the petroleum industry [7]. The nuclear industry however, has used human reliability assessments (HRA) as means to integrate contribution of human performance in probability risk/safety assessments (PRA/PSA) ever since the Three Mile Island accident in 1979. Human reliability can be defined as the probability that a person will correctly perform some system-required activity during a given time period (assuming time is a limiting factor) without performing any extraneous activity that can degrade the system [8]. HRA is understood as an assessment of the impact of human errors on systems safety and, if warranted, the specification of ways to reduce human error impact and/or frequency [9].

There is little evidence of HRA being systematically practiced in the offshore petroleum industry, and the concept is relatively new to both operators and regulatory agencies. Early attempts and some sporadic examples from the British and Norwegian sector can be found in the literature [9,10,11]. However, it was not until recently that HRA has received significant attention among companies on the NCS [12]. A number of HRAs have been performed, indicating promising adaptations of nuclear HRA methods for offshore petroleum, such as well control during drilling operations [13,14]. Encouraged by this experience, a consortium of industry and research partners formed the “Petro-HRA” project with an aim adapt and validate nuclear HRA techniques for use in the petroleum industry [1]. The presented case study explains how HRA can be applied to accommodate the needs of stakeholders and risk-owners on the NCS. Experiences are used to exemplify both benefits and improvement areas.

3. A HRA CASE STUDY OF BLOWDOWN IN A GAS LEAKAGE SCENARIO

Experience from the NCS with applying various HRA techniques suggests that the Standardized Plan Analysis Risk-HRA (SPAR-H) is an efficient and potentially fit-for-purpose method for quantifying human error probabilities [12]. Quantification of human error enables the results of the HRA to be integrated in QRA. However, prior to quantification, the analyst needs considerable knowledge about the accident scenario, tasks involved, potential human errors, possibilities for recovery, and more. For this purpose SPAR-H does not recommend any specific techniques and the choice of approach is up to the analyst [13]. The sub-sections in this chapter describe the HRA approach used in this paper’s case study. It combines a set of well-established methods found suitable for HRAs according to available guidelines and textbooks [9,14,15].

Data required for the assessment was collected through document reviews, offshore visits, and workshops with technical experts and operational personnel. Documents reviewed included previous QRAs, Human Factors analyses, Cause & Effects matrices, emergency shutdown (ESD) hierarchies, emergency procedures, P&IDs, and operating manuals and philosophies. The purpose of the document review was to obtain an understanding of the control room’s role in emergency situations; gather data about the control room operators’ (CRO) tasks and work context; provide input for the offshore visit, and give input to the initial analyses drafts. The purpose of the offshore visit was to interview CROs and field operators; take photos of the control room and field instruments/equipment; observe control room (normal) operations hands-on; and to identify potential human errors. Finally, a workshop onshore was used to supplement, verify and further analyze the data based on the participants’ operational and technical expertise. As such, this data gathering process provided the required foundation for the analysts to conduct the HRA.

3.1. Step 1: Defining Human Failure Events

One of the initial steps in a QRA is to perform a hazard identification (HAZID) and select which hazardous events shall be subject for further analyses. A HAZID meeting was used to identify which major accident scenarios involved human failure events (HFE) relevant for the HRA. Relevance here was limited to HFEs associated with Type C actions, meaning normal responses of CRO to accident initiators [15]. From this meeting it was concluded that "hydrocarbon leakage" represented a major accident scenario in which the operators(s) contributes directly to the platforms risk level. 'Failure to activate blowdown' was identified as the HFE to be analyzed and included as a basic event in the QRA event tree (see Figure 1). This conclusion was further confirmed through a review of technical documentation about the platform's safety systems and previous QRA event tree models for the platform. Last, a representative scenario was described in text format, including assumptions for the analysis.

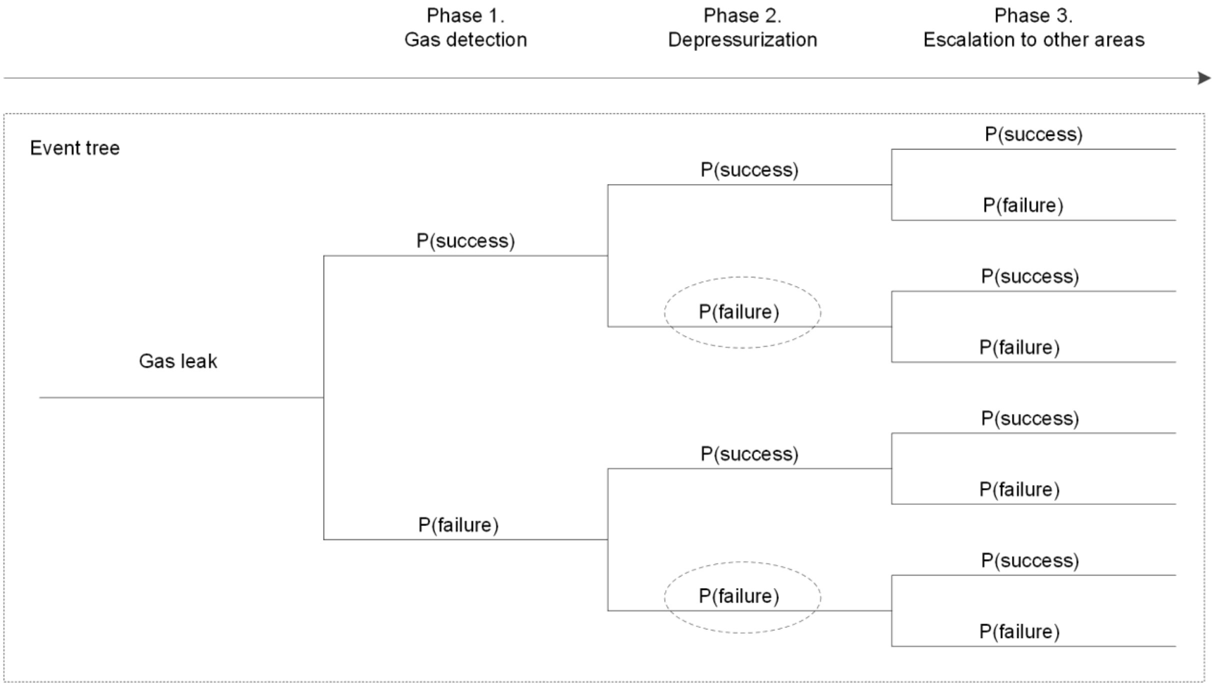


Figure 1. Simplified QRA Event Tree (Ellipses Indicate the HFEs)

Case study: Hydrocarbon (here: gas) leakages, with potential of explosions and fire, are one of the most critical major accident scenarios for offshore production platforms. Such scenarios involve high risk for escalation, loss of multiple lives, extensive damage to assets, as well as impact on the environment and company reputation. Consequently, gas leakage is considered one of the most important defined situations of hazards and accidents (DSHA) to be included in a QRA.

In case of an unignited leakage (leakage size from 0.5 kg/s and more), when two or more detectors sense gas, this is considered a 'confirmed leakage' by the safety system logic. The detection system automatically initiates the ESD sequence to bring the plant into a safe state. This includes ignition source control to avoid explosion and fire; closing of process- and emergency shutdown valves to isolate pipe segments and stop flow of hydrocarbons; and activation of deluge and fire water to reduce explosion pressures in case of ignition. Not a part of this automatic sequence is the activation of the blowdown system, which is performed manually by CROs. The platforms analyzed in our case study had limited flare capacity in relation to the amount of gas present in the processing system. As such, blowdown was not performed automatically, but required a segment-by-segment approach initiated by the CRO. Blowdown depressurizes leaking and/or affected pipe segments by routing the gas away from ignition sources on the platform and up to the flare. In addition, depressurization reduces explosion pressures in case of ignition and pipes being exposed to fire loads. As such, manual activation of blowdown plays a critical role in both reducing the probability of explosion and fire, as well as mitigating the consequences if hydrocarbons ignite.

3.2. Step 2: Hierarchical Task Analysis

Based on the scenario description, a hierarchical task analysis (HTA) was performed to obtain a structured and detailed description of physical and cognitive actions required by operators to successfully activate blowdown. The variables analyzed were plan for execution; personnel involved; information requirements; time required for task; communication requirements; and performance shaping factors (PSFs) influencing the task. The HTA structure followed a simple behavioral model suitable for Type C actions [15]. Main- and sub-tasks were identified for detection, diagnosis, decision, and actions required for responding to an initiating event (see Figure 2). The HTA process was iterative and made using procedures, site visits and workshops with operating personnel as input.

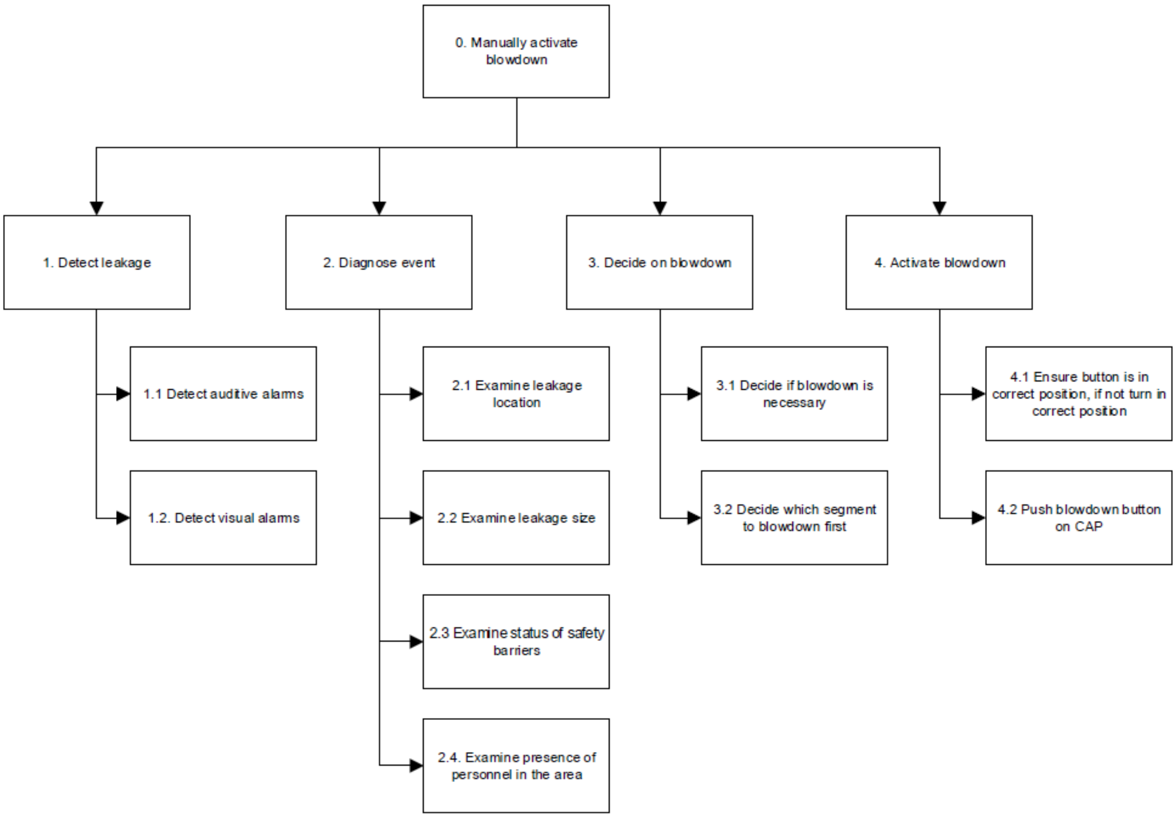


Figure 2. HTA From the Case Study (Simplified Version)

Case study: When gas detection is confirmed, the CRO in the Central Control Room (CCR) detects various alarms and diagnose the situation based on information obtained through different Human Machine Interfaces (HMIs). The CCR included visual display units (VDUs) for the production process, utility systems, and Fire & Gas, in addition to alarm lists, CCTV and some other screens (e.g. maritime watch). Upon gas detection, alarms are depicted on the process production screen and the affected area and detectors are highlighted on the Fire & Gas screens. In addition, a hardwired Critical Action Panel (CAP) will indicate the presence of gas in a specific segment through an alarm light and will produce a clearly audible alarm sound. One of the two platforms also had a Large Screen Display (LSD) with dedicated screen sections for alarms and Fire & Gas.

Based on the information provided from the various information sources (VDUs, CAP, CCTV and LSD), the CRO will attempt to determine the location, size and direction of leakage; which segment and valve or pipe is leaking; and the volume and movement of the gas cloud (e.g. towards ignition sources). In addition, they also continuously monitor the status of other safety barriers (e.g. successful initiation of ESD, the status of firewater pumps). Depending on the outcome of their diagnosis the CROs decides whether depressurization is necessary and which segment to blowdown. If yes, blowdown of affected segment(s) is activated in the preferred sequence by using push buttons on the CAP.

3.3. Step 3: Human Error Identification

The Systematic Human Error Reduction and Prediction Approach (SHERPA) [16] was used to identify human errors of concern associated with the actions described in the HTA. Besides predicting credible human errors, SHERPA identifies possible consequences of error, chances of recovery from error, probability of error to occur, and level of error criticality. Added to the original approach, a 3 by 3 criticality matrix (Figure 3) was developed to help identify human errors with a potential of leading the plant to a less safe state (so called 'unsafe actions'). In this matrix, probability was assigned using the ordinal probability scale as described in SHERPA: 'Low' if the error has not occurred previously; 'medium' if the error has occurred on previous occasions; and 'high' if the error has occurred on frequent occasions. SHERPA rates criticality based on the severity of the error's consequence (and regardless of probability) by using the categories 'low', 'medium', and 'high', or simply 'critical' or 'not critical'. However, available SHERPA guidance material offers little information about what type of consequence and which level of severity determines criticality [9,17]. The following consequence severity levels were therefore developed: 'Low' – error has no effect event sequence; 'medium' – error has indirect on event sequence; 'high' – error has direct effect on task or event sequence. Following the criticality matrix, red errors were considered highly critical and therefore devoted the most attention in explaining how unsafe actions could result in the HFE. Yellow errors were considered of medium criticality but nevertheless considered relevant for further assessments (e.g. error modelling and reduction). Green errors were assigned low criticality and ignored unless the understanding of either red or yellow errors called for other task steps to be re-visited. The SHERPA was performed partly in discussion with CROs offshore and in workshops, and partly by the HRA analysts as a desk-top exercise.

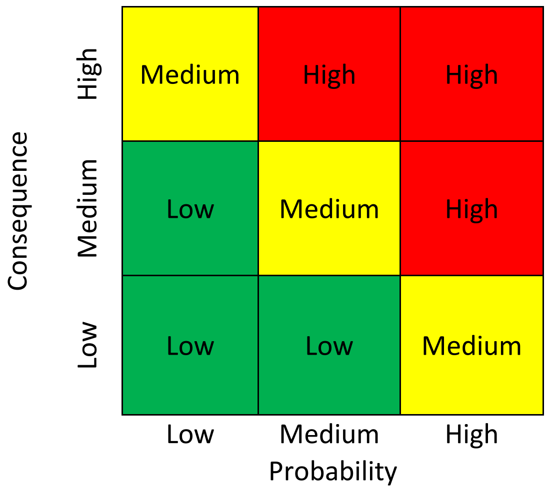


Figure 3. Criticality Matrix

Case study: Activation of the blowdown system depends on how the CRO detects, diagnoses, decides, and acts on the gas leakage. The following discussion highlights some of the considerations concerning human errors associated with the scenario. Detection errors include the CRO failing to hear an alarm, or miss an important alarm due to an alarm flood. Potential of recovery is high during subsequent tasks, and the consequence is most likely limited to a delay in confirming the gas leak. The diagnosis phase is far more prone to errors, and may include the CRO identifying the wrong location of the leakage, or omitting to check other areas and/or for signs of escalation. Combined, this affects the CRO awareness about gas proximity to potential ignition sources, which in turn affects the decision of when to activate blowdown on which segment. Decision errors, such as omitting to share specific critical information about the event, will hamper decision making and can lead to the decision not to depressurize or to depressurize the incorrect segment first. Both errors are critical as the first leaves the entire platform pressurized and the second will leave the affected segment pressurized for an unnecessarily long time. Finally, action errors occur when the CRO inadvertently selects the incorrect segment on the CAP or omits to push the activation button. For example, choosing the incorrect segment will lead to a delayed activation of depressurization and leave the affected (i.e. leaking) segment unnecessarily pressurized until flare capacity is regained.

3.4. Step 4: Human Error Modelling

Effect of human errors on the system was modelled using Fault Tree Analysis (FTA) [9]. Following a top-down logic, the fault tree was used to determine which intermediate and basic events must occur alone or together in order for the Top Event to happen (i.e. the HFE 'Failure to activate blowdown'). The fault tree was developed as a stand-alone analysis by working deductively backwards in the event sequence from the Top Event to a suitable basic event detail level. Relationships between the events were depicted using AND- and OR- logic gates, allowing the combinations of events that can lead to the Top Event, so called cut-sets, to be identified. Final adjustments were made by comparing the basic events with the human errors identified in the SHERPA. As a rule of thumb, there should be a high degree of coherence between the unsafe actions identified in the SHERPA and the basic events identified in the fault tree. The FTA was performed by the HRA analyst as a desk-top exercise using previous analysis (HTA, SHERPA) and collected data as basis. Technical failures were excluded from the fault tree and assumed to be functioning (see Figure 4).

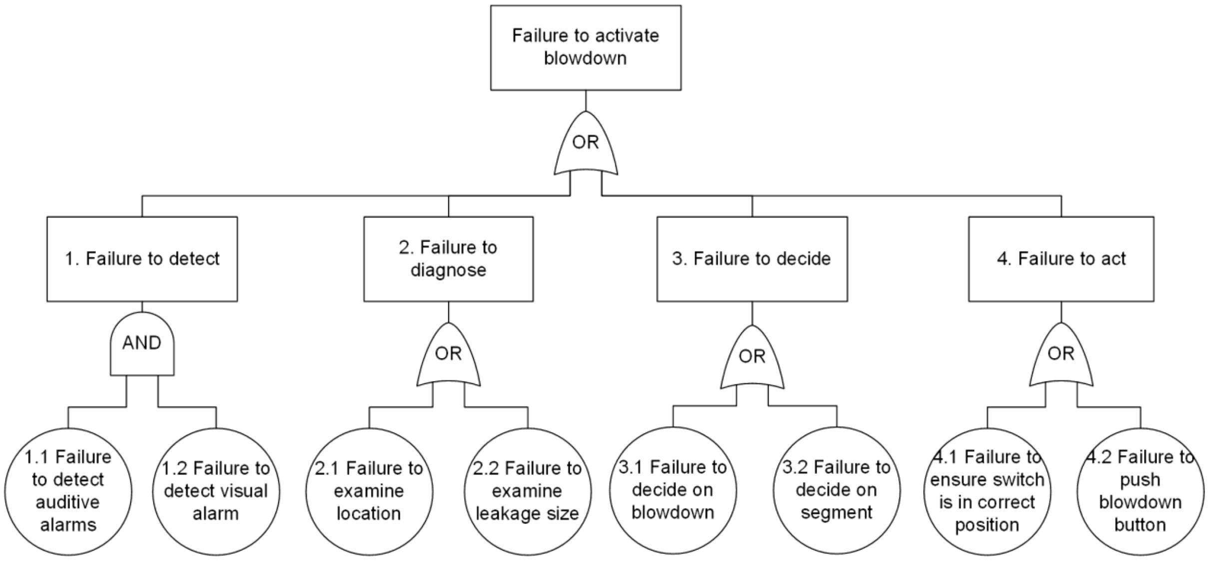


Figure 4. Fault Tree Analysis (Simplified Version)

***Case study**:* The HTA describes all tasks the CROs perform in response to the gas leakage scenario in detail. Potential errors and their consequences were subsequently identified in the HEI analysis. The fault tree only incorporates events that are most relevant and credible. For example, the CROs monitor the state of the safety barriers (task 2.3, see Figure 2) and they check if there are relevant personnel in the affect gas leakage area (task 2.4). Although these tasks are part of their routine, they are not included in the fault tree as a failure on these tasks does not directly affect the likelihood of failure of the HFE (assuming no technical failures occur). As such, the HTA and the HEI provided input to the modelling, but only the basic events in the fault tree were quantified.

3.5. Step 5: Human Error Quantification

The contribution of human performance on the total risk level was estimated by incorporating a human error probability (HEP) for the HFE in the QRA event tree. This required HEP estimates for each of the basic events identified in the FTA, so that the Top Event failure probability could be calculated. For this purpose the SPAR-H method was applied following recommendations in available guidance [13,18]. SPAR-H assumes two different nominal HEP values depending on whether the task is an action or diagnosis (0.01 and 0.001 respectively). For each task the nominal HEP is adjusted according to positive or negative influence from a set of correlated Performance Shaping Factors (PSF). SPAR-H uses eight PSFs: Available time; stress/stressors; complexity; experience/training; procedures; ergonomics/HMI; fitness for duty, and; work processes. The PSFs have levels for determining influence on task performance (good, nominal, poor etc.). Each level has a value with which the nominal HEP is multiplied. If the number of PSFs with negative influence exceeds 3, an adjustment factor is applied. For tasks involving both action and diagnosis HEP is calculated separately for both and then added together. Dependency between HFEs was not accounted for as the analysis consisted of only one HFE: “failure to activate blowdown”. HEP estimates were calculated as a desk-top exercise by HRA analysts using previously gathered data as basis for the PSF assessment.

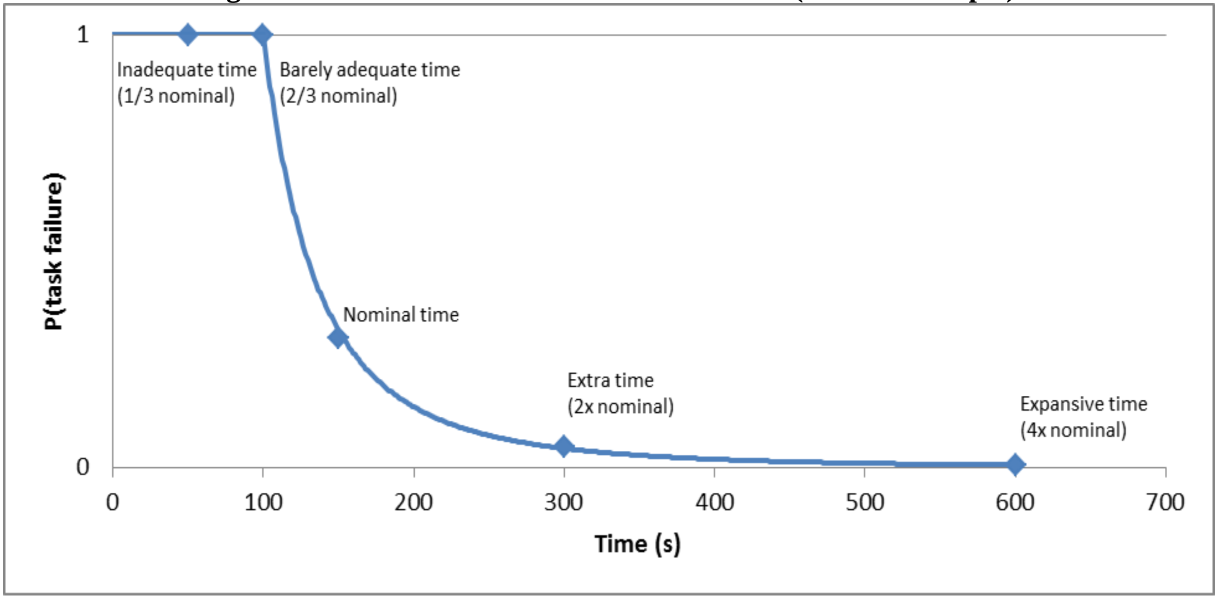
Case study: For each of the basic events in the FTA, a HEP was calculated with SPAR-H. Once all the data has been gathered and the analyses have been performed (HTA, HEI and FTA), the assessment of the PSFs is relatively straightforward. A number of shortcomings with directly applying SPAR-H to the petroleum context have been reported elsewhere [19,20]. More specifically, these are related to the definitions of the PSFs, the validity of the PSFs and their multipliers, and the relevance of the PSFs for the petroleum industry. For the case study, it was calculated that the decision phase (event 3.1 and 3.2, see Table 1) of the scenario was the most error prone with a number of contributing PSFs (stress, complexity and ergonomics/ HMI). The HEPs for the other basic events were calculated to be very low with the stress/ stressor PSF being the most significant contributor to the HEP.

Table 1. SPAR-H HEP Calculation Sheet for Basic Event 3.2 in the FTA (Fictive Example)

PSFs	PSF levels	Multiplier	Notes
Available time	Nominal	1	-
Stress/stressors	Extreme	5	The danger associated with a gas leakage is considered a very strong stressor.
Complexity	Moderately complex	2	There are many steps involved in this task, making this task difficult.
Experience/training	Nominal	1	-
Procedures	Nominal	1	-
Ergonomics/HMI	Poor	10	The HMI does not support the CRO in his decision making.
Fitness for duty	Nominal	1	-
Work processes	Nominal	1	-

After calculating the individual HEP estimates for the basic events in the fault tree, the overall HEP was calculated. The HEP for the available time PSF was set at “nominal” as a default. In our case study, it was estimated that the operators require about 2:30 minutes to activate blowdown. For the control room operators, the activation of the blowdown sequence was based on the idea "the sooner the better". That is, a longer lasting release of gas will generate a higher ignition probabilities, increased explosion pressures and longer lasting fires. Therefore, there was no requirement for the operators to activate blowdown within a specific time-frame. To understand the impact of available time on the overall HEP, a range of HEPs were calculated keeping all PSFs constant except for the available time PSF. This provided a time-probability curve for the discrete PSF values across which a power curve was fitted (see Figure 5). The purpose of this activity was to facilitate the integration of the HEPs in the event tree. The event tree in our case study includes three discrete branches to represent various stages of the scenario progression: 1) early confirmed gas detection (after 3 minutes); 2) late confirmed gas detection (after 6 minutes), and; 3) no confirmed gas detection. The detection time, and therefore the activation of safety systems has consequences for when an operator is able to activate blowdown. For example, if the operator has double the time available than required, the HEP is lower compared to when barely adequate time is available. As such, this curve provided the QRA team with a flexible solution to find representative HEP values for the three detection branches.

Figure 5. HEP as a Function of Available Time (Fictive Example)



3.6. Step 6: Human Error Reduction

How error reduction is carried out depends to a high degree on the problem definition and objective of the HRA, as well as what types of methods are included [9,14].

Case study: Recommendations about error reduction measures were made for unsafe actions/basic events identified in the SHERPA and FTA, meaning the errors and associated tasks contributing to the HFE. Each of the various analyses contributed to developing suggested measures, 1) the HTA strengthened recommendations concerning time aspects, task sequences, roles and responsibilities; 2) the SHERPA and FTA identified specific error mechanisms and error traps for which measures could be implemented, and 3) evaluations of PSF influence ensured that contextual factors were considered both for specific errors, but also on a higher level across several tasks. Recommendations where further prioritized based according to HEP estimates from SPAR-H. Combined, this allowed for a risk-based approach to error management.

4. LESSONS LEARNED

This chapter highlights the main challenges and benefits encountered with the presented HRA approach as it was applied to the case study.

4.1. Re-visiting the Probability, Consequence and Criticality Dimensions in SHERPA

For a post-initiating HRA to be successful, the method must be capable of identifying human errors that significantly contribute to the total risk level and provide recommendations to reduce their potential. SHERPA is an exhaustive and systematic approach to human error identification (HEI) and provided the analyst with confidence that all potential errors have been considered for each task step in the HTA. While this process can be tedious and time consuming for larger tasks, it proved manageable for the task in question. The taxonomy of credible error modes were easily matched to tasks and error descriptions were made to aid understanding in later reviews of the analysis.

The criticality matrix (Figure 3) was both efficient and flexible for aiding HEI. For the purpose of this HRA, the SHERPA method could however benefit from including more specific descriptions of consequence, probability and criticality. This could help increase the accuracy of the SHERPA and simplify later analysis, such as the FTA. What makes an error critical, and so determines if it represents an unsafe action, depends partly on the error's consequence. There is no clear definition of what is meant by 'consequence' in available SHERPA guidance, other than "…consequences associated with the error" [17]. This explanation is comparable to what is referred to as 'failure effects' in Failure Mode Effect and Criticality Analysis (FMECA). FMECAs commonly distinguish between local and global failure effects, respectively referring to effects on the component and system level. Distinguishing between different error effect types could be helpful in performing post-initiating HRAs, especially for capturing human-machine interactions. The effects could in addition be described as immediate or delayed. This would help the analyst to understand the dynamics of the scenario and add more realism to the analysis. Examples of such 'effect' categories could be:

1. Immediate / delayed effect of error on *task sequence*; e.g. CRO unaware of need to…
2. Immediate / delayed effect of error on *system functions*; e.g. segment not depressurized…
3. Immediate / delayed effect of error on *event sequence*; e.g. size of gas leakage increases…

This HRA mainly considered consequence in terms of errors effect on event sequence. Retrospectively, for the operational goal in this case's scenario – activation of blowdown – error effects on task sequence would probably dominate the analysis. A majority of the task steps are cognitive actions, such as detection, diagnosis and decision making. Only the final tasks involve activation of system functions, in which effects of errors on system and event sequence will be most relevant. While the immediate outcome of cognitive actions can seem harmless, they may prove to be critical through their influence on performance of subsequent tasks.

Assessment of the suggested error effect categories should be accompanied by descriptions of criticality levels to assist identification of unsafe actions. A simple solution could be to use the same three levels as applied in this case study, i.e. no, indirect and direct effect (on task, system, or event). However, providing more sophisticated or complex solutions is beyond the scope of this paper. Further work on this topic is encouraged in which the guidance provided from Energy Institute [14] should be reviewed.

The probability ranking in SHERPA implies that the tasks are carried out relatively frequently, and that operating personnel have gained experience about the occurrence of various errors. For rare scenarios, such as larger gas leakages, this is not the case. Historical data from incident reports or simulator training could have been used, but was unfortunately not available. As such, when predicting probability based on input from the CROs, their opinion is more a qualified estimate than based on actual experience. This worked quite well for identification purposes, but was not considered optimal for risk evaluation. After quantifying HEPs for basic events later in the process, this also revealed that discrepancies between the probabilities assigned in the SHERPA and the HEPs calculated using SPAR-H. For example, errors assumed to have medium probability in SHERPA could have lower HEP than errors assumed to have low probability. In summary, experiences suggest that probability assessments as part of error identification can be considered superfluous. Instead more efforts could be focused on assessing error consequence (i.e. effects) and their criticality. This would provide the analyst with valuable help in later building the human error model (e.g. fault tree) and prioritizing error reduction measures together with HEP estimates from SPAR-H.

4.2 Detail Level and Relevance of PSF Descriptions

Thorough evaluation of PSF influence on human performance is possibly the HRAs most important contribution to the QRA. Together with error identification and modelling, understanding how PSFs drives human performance forms the decision basis for how human reliability can be increased.

Some of the more complex issues were related to the level of detail in task decomposition required by SPAR-H. One of the aims of this HRA was to target specific human errors with the most significant contribution to the event outcome. SHERPA and FTA were included to enable identification of human errors at a relatively detailed task level, a process found both successful and useful. HEP levels were then used to prioritize error reducing measures, according to which PSF contributed the most. When it comes to HEP calculations, SPAR-H does not give specific guidance regarding task level decomposition or how different sub-tasks can be aggregated to facilitate analysis. Assuming consistency of task decomposition within the same HRA, SPAR-H guidance states that the choice of detail level is not thought to result in large changes in the effects of HEPs on the overall risk estimate [13]. Nevertheless, both the PSF descriptions and task examples in SPAR-H are relatively high level, indicating that SPAR-H was not originally developed to calculate HEPs for detailed tasks.

As experience showed, the discrepancy between PSF descriptions and task detail levels did create some occasional challenges when calculating HEPs. For example, the influence of PSFs such as training and stress can easily be evaluated to influence all or most tasks in the scenario. Oppositely, in some cases it proved difficult to link specific aspects of PSFs to detailed tasks. In order to practically overcome this issue, the analysts agreed on a set of good practices. Using the same information as basis, two analysts individually evaluated the PSFs and calculated the HEPs. Afterwards their results were compared and noticeable differences were examined in further detail to achieve consensus between raters. Furthermore, to better differentiate between which out of e.g. two correlating PSFs were dominating, the principle of "performance driving" PSFs was practiced [18]. For example, a gas leakage is perceived as a dangerous situation by the CROs and is likely to cause stress throughout the event. However, its influence on operator performance may vary considerably depending on the type of task. By being consistent this helped to avoid double-counting PSF influence. For a more in-depth discussion regarding similar issues, see Van de Merwe et al. [20].

4.3 The Importance of Human Error Modelling

The main reason for modelling human errors using FTA was to quantify the HFE probability by aggregating HEP values assigned to basic events. However, the FTA also proved effective in complementing the SHERPAs shortcomings, both when it came to illustrating combined effects (i.e. consequences) of human errors as well as identifying unsafe actions. The SHERPA produces a large number of credible errors and it is easy to lose overview of the consequences (i.e. error effects). Losing track of which errors are most critical also makes it difficult to develop and prioritize error reducing measures. Going backwards from the Top Event, deductively determining contributive events, the FTA reduced the amount of data from the SHERPA, which in turn facilitated an even more focused HEI and error reduction process. By comparing basic events in the FTA with human errors identified in the SHERPA, this worked to cross check whether all credible errors had been accounted for in the fault tree. Hence, our experience indicates that the quality, efficiency and impact of HRA rely to a high extent on accurate human error modelling. FTA is a well-established technique and was selected based on recognized guidance on practical application of HRA [9,14,15]. While it worked well for the presented HRAs, this may not have been the case if the task and scenario was different. The importance of error modelling suggests that the industry could benefit from HFE/scenario specific guidance for selecting and performing different methods. This guidance should clearly account for the methods' benefits and limitations, and facilitate a good, common practice among HRA analysts in the petroleum industry.

4.4 Integration of HRA Results in QRA

One of the main objectives for performing the HRAs was to better estimate the contribution of human performance on major accident risk. This was achieved by integrating quantitative HRA outcomes (HEPs) in the QRA event tree. Although this seems relatively straightforward, the HEPs produced by SPAR-H are single-point estimates based on the time required to execute a task. However, the QRA event tree required estimates for a range of time-dependent steps in order to calculate a number of "what if" scenarios. As few requirements were in place for the time the operators had available for activating blowdown (i.e. "the sooner the better"), some adaptations were necessary to the original HEP calculation method before the HEPs could be correctly integrated in the event tree.

Our solution was to perform an assessment of the available time PSF for all its multiplier values, while keeping the other PSFs constant. Combined with an interpolation of the outcomes using a power curve, this exercise gave a continuous HEP estimation across categories for the available time PSF. This curve could then be used by the QRA analysts to estimate HEPs for times other than the ones assessed in the HRA for this scenario. Even though this solution worked well for this case study, future work should focus on obtaining time available to operators based on limits set by ignition probabilities, explosion pressure limits and escalation probabilities. This way, an upper time limit can be set for operators to activate blowdown based on physical and chemical properties inherent to gas leakages. In conjunction with the time required to activate blowdown this enables an adequate assessment of the time available PSF at an HFE level.

4.5. Task Analysis as Means for Revealing Optimistic Time Estimates

Besides providing the foundation for further analysis (e.g. SHERPA, FTA), the HTA served several other useful purposes. As mentioned in the previous sub-chapter, an important aspect of most HRAs is the consideration of time. For QRAs not including HRAs it is common practice to assess risk assuming both quick and delayed activation of ESD and blowdown after release of hydrocarbons (gas). Although assumptions may vary, one minute is often used for quick activation and three minutes for delayed activation. Conservative assessments may only operate with an assumption of five minutes. Through on-site observations and interviews with CROs the HTA allowed time to be systematically recorded for each task. Even when accounting for parallel tasks, this exercise suggested that the entire task had a significantly longer time span than previously assumed. Time until activation has a potentially high impact on the total risk level through its effect on gas leakage size, ignition probability, and explosion pressures. Consequently, this was considered an important finding and the original time estimates in the QRA were updated to reflect a more realistic scenario. Furthermore, risk reducing measures could be suggested, such as preferred sequence and inclusion of tasks based on their criticality and necessity.

5. CONCLUSIONS

Based on the lessons learned from this case study it is evident that HRA provides valuable insights about how to manage risks associated with human contribution. Some methodological challenges appeared, with the most significant being related to accuracy of HEI, relevance and description level of PSF, and accounting for the function of time as part of integrating HFE probabilities in the QRA. Experiences still suggest that the combined set of analyses was effective in achieving the HRAs objective as-is. This opens for a new type of risk informed decision-making not previously made available by traditional QRA practices. The petroleum industry now has the benefit of building on over three decades worth of experience from the nuclear domain. With the frequency of major accidents and serious incidents not being significantly reduced, HRA can prove to be a valuable tool for improving process safety. This is also the purpose behind the Petro-HRA project [1], into which the findings from this case study will be used as input.

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