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Adapting Human Reliability Analysis from nuclear power to oil and gas applications

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ABSTRACT: Human Reliability Analysis (HRA), as currently used in risk assessments, largely derives its methods and guidance from application in the nuclear energy domain. While there are many similarities between nuclear energy and other safety critical domains such as oil and gas, there remain clear differences. This paper provides an overview of HRA state of the practice in nuclear energy and then describes areas where refinements to the methods may be necessary to capture the operational context of oil and gas. Many key distinctions important to nuclear energy HRA such as Level 1 vs. Level 2 analysis may prove insignificant for oil and gas applications. On the other hand, existing HRA methods may not be sensitive enough to factors like the extensive use of digital controls in oil and gas. This paper provides an overview of these considerations to assist in the adaptation of existing nuclear-centered HRA methods to the petroleum sector.

1 HUMAN RELIABILITY IN NUCLEAR ENERGY

1.1 *Nuclear energy context*

A nuclear power plant represents a unique environment in which a fission source heats water to produce steam to turn a turbine connected to an electrical generator. It has many commonalities with other electric power generating sources, e.g., it generates steam to power a turbine just like gas and coal fired plants. Unlike gas and coal plants, it produces no carbon emissions during operation. However, the heat source consists of radioactive fuel, which must be carefully contained to prevent potential contamination. Because of the rare but potentially severe consequences of accidental radiation release, there are generally greater safety measures and precautions implemented at a nuclear power plant than at a corresponding fossil power plant. This emphasis on safety has translated into extensive risk analyses associated with nuclear power, with a goal to identify and prevent potential hazards or accidents. Within these risk analyses, there is consideration of opportunities for the human operators at the plant to affect the overall risk.

The earliest renditions of Human Reliability Analysis (HRA) were developed to account for human performance in production systems; however, the field of HRA only later reached maturity in support of Probabilistic Risks Assessment (PRA) for nuclear power plants (Boring, 2012; Boring and Bye, 2008; Forester et al., 2009). In particular, the *Reactor Safety Study*, WASH-1400 (U.S. Nuclear Regulatory Commission, 1975) included significant elements of the Technique for Human Error Prediction (THERP), an HRA approach first developed in the 1960s to address reliability in weapons assembly (Swain et al., 1963). Following the Three Mile Island accident in 1979 (Kemeny et al., 1979), significant refinement work went into both PRA (e.g., U.S. Nuclear Regulatory Commission, 1990) and into THERP (Swain & Guttman, 1983), culminating in an HRA approach that specifically addressed nuclear power plant operations and fully integrated into PRA (Bell and Swain, 1983). It has been estimated that since the advent of the definitive version of THERP in 1983 as NUREG/CR-1278 (Swain and Guttman, 1983) there have been as many as 60 different HRA methods developed (Bell and Holroyd, 2009). These methods have refined and evolved HRA as a field, but with few exceptions, HRA remains closely linked to PRA for nuclear power.

1.2 *Characteristics of nuclear HRA*

Standards and guidance documents, e.g., (ASME, 2013; EPRI, 1992a; IEEE, 1997) outline the basic approach used by HRA to integrate into PRA. In fact, HRA is defined in the PRA standard for nuclear power plant applications (ASME/ANS RA-Sb-2013), published by the American Society of Mechanical Engineers (2013), as:

> a structured approach used to identify potential human failure events and to systematically estimate

the probability of those events using data, models, or expert judgment.

The key to this definition is *Human Failure Events* (HFEs). HFEs are defined in the PRA as those basic events that can be influenced by human activities. Any fault that influences plant performance at the functional, component, or system level is modeled in the PRA. Within this framework, the HFE represents an opportunity where a human error—an action or inaction with unintended consequences—impacts the function, component, or system at the plant. As observed by Boring (2014), the definition of HFE is top-down, starting with possible failures in the plant hardware (i.e., the overarching level of analysis) and looking for places where the human (i.e., a subset of the hardware level) has an impact on those hardware failures.

The HFE is modeled in conventional nuclear plant PRA in event trees (Boring, 2009). In theory, the HFE may be defined without input from an HRA expert. However, the activities that comprise the HFE are typically detailed by the HRA expert in a fault tree. Once the HFE is defined, it is analyzed qualitatively and quantitatively. The qualitative analysis determines the factors that might lead to the failure of the activity. These factors often include context of the plant and Performance Shaping Factors (PSFs). A standardized list of PSFs from NUREG-1792, *Good Practices for Implementing Human Reliability Analysis* (Kolaczkowski et al., 2005) is included in Table 1. This list of PSFs is not meant to be exhaustive but rather to represent the minimum set of PSFs that should be considered in an HRA.

These factors may increase or decrease the error likelihood, which is accounted for in the quantitative phase of HRA. At this phase, the analysis produces the Human Error Probability (HEP) of the HFE and any accompanying uncertainty calculations such as the Error Factor (EF), which is the ratio of the upper (95th percentile) or lower (5th percentile) uncertainty bound to the median HEP.

Table 1. Performance shaping factors from NUREG–1792.

Training and experience
Procedures and administrative controls
Instrumentation
Time available
Complexity
Workload/time pressure/stress
Team/crew dynamics
Available staffing
Human-system interface
Environment
Accessibility/operability of equipment
Need for special tools
Communications
Special fitness needs

There are numerous approaches to quantification in HRA methods. The most common include:

- *Scenario matching methods:* This approach, used by THERP (Swain and Guttman, 1983), entails matching the HFE to the best fitting example scenario in a table and using the HEP associated with that template event as the basis for quantification. Decision tree approaches like the Cause Based Decision Tree (CBDT) (EPRI, 1992b) follow a similar approach except that the events are decomposed across an event tree instead of in tabular form.
- *PSF adjustment methods:* In these methods, exemplified by approaches like the Standardized Plant Analysis Risk-Human Reliability Analysis (SPAR-H) method (Gertman et al., 2005), the PSFs serve as multipliers on nominal error rates. For example, a PSF with a negative influence would serve to increase the HEP over a nominal or default error rate.
- *Expert estimation methods:* In these approaches, subject matter experts including risk analysts will estimate the likelihood of the HFEs. A Technique for Human Error Analysis (ATHEANA) (U.S. Nuclear Regulatory Commission, 2000) uses a structured expert estimation approach to arrive at HEPs. Such approaches often provide anchor values for quantification to assist subject matter experts in producing the relevant HEP, but the specific method used to derive the HEP and the factors that may influence the quantification are largely left to the subject matter experts. Because expert estimation methods typically do not specify how to decompose the factors shaping the quantification but rather look at the HFE as a whole, they are often referred to as holistic approaches (Boring and Gertman, 2005).
- *Simulation based methods:* Although currently uncommon, this emerging approach uses modeled operator behavior through Monte Carlo style permutations to derive frequencies of particular activities, which may be classified as successful or unsuccessful (i.e., erroneous) outcomes (Boring, 2007). The Information-Decision-Action-Crew (IDAC) method (Chang and Mosleh, 2007) is an example of a dynamic HRA method, although it has to date not been fully implemented across a wide range of scenarios (Coyne, 2009; Li, 2013).

Most HRA methods follow a variant on the three steps to quantification outlined in THERP (Swain and Guttman, 1983):

1. *Determine the nominal HEP:* This is the default error rate that would be expected in the absence of any mitigating circumstances.
2. *Calculate the basic HEP:* The nominal HEP is modified to account for any context, plant conditions, or PSFs that might increase or decrease the error rate.
3. *Calculate the conditional HEP:* The basic HEP is modified to account for dependence and recovery. Dependence is the degree to which one error influences subsequent error outcomes. In practice, it may be thought to mean that error begets error—the occurrence of a human error increases the likelihood of subsequent errors. This is treated mathematically, often with a correction factor to increase the HEPs of HFEs in a sequence. Recovery is treated at the modeling level but may also be factored in as a mathematical adjustment to lower the overall HEP when opportunities for correction are possible.

Historically, HRA has most frequently been applied to Level 1 analyses, which are PRAs that model the event evolution up to the point of reactor core melt. Increasingly, there has been an interest in reviewing Level 2 analyses, which consider damage post core melt, and Level 3 analyses, which consider environmental and health impacts (Cooper et al., 2013). Additionally, much of HRA has historically been centered on pre-initiators—the activities leading up to an initiating event like a reactor safety trip. Levels 2 and 3 require more extensive modeling of post-initiators—those activities taken after the initiating event to mitigate or remediate the event.

2 DIFFERENCES IN HUMAN RELIABILITY FOR NUCLEAR ENERGY COMPARED TO OIL AND GAS

2.1 *Oil and gas context*

Oil and gas production occurs at a number of locations, from offshore oil platforms, to onshore oil drilling stations, to shale gas extraction facilities, to refinery facilities. The hazards of such facilities are numerous, and there have been significant high profile accidents resulting in fatalities, facility damage, and environmental pollution (OGP, 2010). A representative list of hazards specific to offshore facilities is published by the Petroleum Safety Authority of Norway (2013a, 2013b) and featured in Table 2. Of those 21 hazards, a dozen are historically associated with major accidents. Most of these relevant hazards can include human errors that contribute to risk and could therefore be modeled as HFEs.

It should be noted that not all hazards are directly related to the activity of drilling or pumping for oil or gas. In the case of offshore oil and gas production, the oil rig structure and associated vessels become equally culpable safety hazards. For example, a helicopter used to transport personnel to and from the offshore structure may, due especially to severe weather conditions at sea, be a hazard to personnel and the structure when landing or taking off. A tanker used to transport crude oil for refining elsewhere may pose a significant environmental threat if it becomes damaged. Even the living quarters, the floating hotels or so-called floatels, may pose risks when unplanned drifting occurs in the open sea. Onshore facilities, which are not typically subject to the same harsh natural environmental forces as offshore facilities, still experience many of the same hazards such as leaks,

Table 2. Hazards commonly associated with oil and gas applications.

Hazards related to major accidents	Hazards unrelated to major accidents
• Non-ignited hydrocarbon leak	• Man over board
• Ignited hydrocarbon leak	• Serious injury
• Well incident/loss of well control	• Serious illness/epidemic
• Fire/explosion in other areas (non-hydrocarbon)	• Blackout
• Ship on collision course	• Non-operational control room (not in use)
• Drifting objects	• Diving accident
• Collision with field related vessel	• Release of H2S
• Structural damage/stability/mooring/positioning failure	• Loss of control of radioactive source (not in use)
• Leakage from subsea systems/pipelines/risers/flowlines/loading buoy/loading hose	• Falling objects
• Damage on subsea systems/pipelines/diving gear caused by fishery equipment	
• Evacuation (precautionary/emergency evacuation)	
• Helicopter accident	

fires, and vehicle transportation accidents. Environmental hazards such as extreme temperatures, oilfield wildfires, or even tornados (Girgin and Krausmann, 2014) have caused accidents onshore. Structurally, the onshore facilities share much in common with their offshore counterparts, and represent large, complex pieces of machinery involved in producing a flammable substance. Whether the ocean or a terrestrial oilfield is the backdrop, oil and gas production represent dangerous undertakings that have substantial hardware and human risks.

2.2 *HRA for oil and gas*

The use of HRA in the petroleum context is much more limited than it has been in the nuclear domain. In part, this stems from the fact that there is no globally accepted requirement for PRA in the petroleum sector. While PRA—or analogous methods like Quantitative Risk Assessment (QRA) or Total Risk Assessment (TRA)—are commonplace in countries such as Norway (Standards Norway, 2010) or the United Kingdom (Health and Safety Executive, 2008), it remains an emerging activity in the U.S. (Cooke et al., 2011).

Even where PRAs exist in oil and gas, they have—like earlier versions of PRAs in the nuclear industry—primarily identified hardware failure risks, often omitting a clear coverage of those HFEs that contributed to overall system risk. For example, the petroleum-centered Barrier and Operations Risk Analysis (BORA) HRA method (Aven et al., 2006) focuses on the breakdown of barriers designed as part of defense in depth to prevent accidents in oil and gas production facilities. These barriers, however, omit many of the HFEs that can precipitate accidents at the facility. PRAs centered on barriers may overlook important precursors to many types of accidents.

A review of three available QRAs for oil and gas installations confirmed only a very general coverage for HRA. The QRAs provided some very limited specific treatment of HFEs, and the overall treatment of HRA is negligible. These QRAs typically defer to overall rates of incidents. For example, the rate of accidental collision of a shipping vessel with an offshore rig is provided as a frequency based on historical data. This rate encompasses all sources of error but fails to delineate the specific root causes or risk contributions attributable to human error. HRA methods are considered estimating methods, and they are advised when actual data are not available for human error rates (Swain and Guttman, 1983). The QRAs present a case where actuarial data are used in place of detailed human performance data. For example, the QRA may draw on historical data to determine the likelihood that a lifeboat fails to drop due to mechanical or human error. Such analyses highlight the historic occurrence of events and provide a data-based frequency estimate of the activity. However, it is not possible to determine in most cases the extent to which human errors contribute to the events, since the data are only presented in aggregate form without causes denoted. While such data may help predict the frequency of events based on previous data, they do not pinpoint the causes of the events. As such, their utility in modeling the causes and in preventing the recurrence of events is severely limited. Estimating methods with detailed HFE modeling are therefore preferable with respect to pinpointing causes of events.

Additionally, the events modeled in the QRAs generally do not consider the opportunity for recovery actions that may correct an escalating event. Recovery actions are an essential component of HRAs; they are also increasingly viewed as one of the unique contributions of resilience in the face of accidents—humans uniquely can recover from mishaps and remedy the situation even for untrained or unexampled events (Boring, 2010). Such recovery actions should not be over-credited in an analysis, but they represent a significant but last-chance effort to save the installation and prevent severe damage, environmental impact, and loss of life.

Interestingly, because new systems require a safety analysis prior to implementation, HRAs are being performed alongside human factors design reviews that are not part of the QRA or PRA (Gould et al., 2012). Such standalone HRAs use task analysis techniques to derive the appropriate HFEs, a process that potentially generates HFEs that are incompatible with the level of analysis used in the PRAs (Boring, 2014). Indeed, one of the emerging challenges with such an approach is the integration of the HRA with the QRA (Van de Merwe, 2015). In the nuclear domain, the HRA is typically built out of the PRA (EPRI, 1992a). Here, the process is reversed, and available guidance from nuclear does not instruct the merger of a standalone HRA with a QRA that does not already have clearly defined HFEs.

3 CROSSWALK OF CONSIDERATIONS

As noted, clearly there are similarities and differences between nuclear and oil and gas installations. In terms of similarity, both are safety-critical industries with high potential consequences to equipment, personnel, and the environment in the event of serious malfunctions. As a result, both are highly regulated facilities requiring highly skilled personnel. Yet, their differences are manifold:

- *Control Center:* While during normal operations, the nuclear power plant is controlled by a crew of licensed reactor operators in the main control room, the control of an oil and gas production facility is much more decentralized. Much of the process must be controlled locally in oil and gas facilities, which are more akin to nuclear power plants during refueling outages than during at power operations. A control center will coordinate these activities, but much of the operation of the facility will be done by field workers. This less centralized control of oil and gas production means that the nature of procedures is different. Nuclear power plant operators follow detailed step-by-step procedures for most activities, whereas field workers rely on broader work orders, which allow greater flexibility to respond to conditions in the field. There tends to be much less detail for required procedures in oil and gas operations. This may shift operations from a more rule-based activity in nuclear to a more skill-based activity in oil and gas (Rasmussen, 1983).
- *Process:* At a coarse level of analysis, the two main activities of a nuclear power plant are controlling nuclear reactivity and generating electricity. In contrast, in oil and gas production, activities may shift from finding a source of petroleum, to extracting it, to transporting it, to refining it for consumer purposes. The oil and gas process involves multiple sites and multiple types of process control. Nuclear operations are largely about maintaining a steady state, while oil and gas production involves changes in the state of the product. As a result, the range of activities is much more diverse as a result for oil and gas applications.
- *Technology:* In the U.S., nuclear power plants originally received an operating license for 40 years. The majority of operating plants in the U.S., and a good number worldwide, have extended their operating license as they've approached that 40-year limit. In other words, many nuclear power plants are not new facilities, and they represent older technology. These plants have upgraded as necessary to maintain safety, but most retain their original analog technologies (Boring et al., 2014). In contrast, oil production occurs across a variety of landscapes. New wells are tapped as old sources are depleted. In some cases, the oil production facilities are refurbished and relocated. In other cases, new rigs are constructed. Because each petroleum source is finite and because advances in technology can translate directly into higher yields, the technology used in oil and gas has significantly leapfrogged technology found in nuclear power production. This newer technology presents new modes of interfacing with control systems, resulting in considerably different concepts of operation for oil and gas than for nuclear applications. This means that the range of contexts and PSFs for oil and gas is potentially much greater than for nuclear HRA.
- *Hazards:* Both nuclear and petroleum applications share the risk of external contamination, either by radionuclides or by oil spill, respectively. Both types of contamination can result in long-term environmental damage; both also have the potential to affect the health of individuals working or living near facilities. The difference in the hazards is really one of magnitude. The level of personal protective equipment required to work in an environment that has been contaminated by radionuclides vs. oil or gas differs considerably. Having said that, due to the severe natural environments often required for oil and gas extraction (e.g., continental shelf), petroleum tends to have higher hazards posed on the facility by the natural environment.

These differences have important implications for using existing HRA methods and approaches originally designed for nuclear power applications to support oil and gas applications. In particular, there seem to be differences in how the PSFs should be treated when generalizing existing HRA methods to oil and gas applications. Gordon (1998) investigated the effects of PSFs in offshore oil industry accidents. While the resulting list of PSFs overlapped considerably with the later *Good Practices* PSFs used for nuclear power (Kolaczkowski et al., 2005), the oil PSFs included organizational, management, and supervision but did not include factors such as instrumentation or the human-system interface. More recent work on reviewing the applicability of PSFs for the nuclear industry suggests several major differences (Rasmussen and Laumann, 2014; Rasmussen et al., 2015), including:

- The heavy reliance on formal written procedures in the nuclear industry is not mirrored in the oil industry. While procedures are certainly used and required in the oil industry, they do not have the same level of detail. Instead, training, skill, and work orders shape the performance of the person carrying out the task. Applying a procedure-related PSF from a nuclear power HRA method to a petroleum context without further guidance would result in significant penalties on performance when the HRA is quantified. Such penalties are unwarranted and would result in unrealistically high HEPs for oil and gas HRAs.

- As discussed, U.S. nuclear power plants (with the exception of new builds) do not typically avail themselves of state-of-the-art digital interfaces. PSFs that address the human-system interface in traditional HRA methods do not adequately address computerized control rooms (Boring and Gertman, 2012; Hickling and Bowie, 2013), and should therefore be updated to reflect the types of control rooms that are standard in the oil industry. The advent of digital displays should also be considered where complexity is modeled as a PSF, since new modes of presenting facility information can significantly increase or decrease information complexity.
- While a high level of safety culture can generally be assumed in nuclear power plants, there appears to be greater variability in petroleum installations. The remoteness of facilities, the distributed nature of activities, and the transient nature of the supporting workforce may contribute to this greater variability in oil and gas. As such, while many HRAs in the nuclear industry do not actually consider safety culture as a major factor in the analysis outcome, safety culture may carry greater risk significance in oil and gas applications.

Furthermore, several important distinctions in HRA within nuclear power actually do not have clear equivalents in oil and gas applications:

- *At power vs. low power and shutdown:* Of course, petroleum facilities do have periods where they are not in operation. However, the distinction in nuclear HRA (e.g., the At-Power vs. Low Power and Shutdown worksheets in SPAR-H) serves to encompass the fact that the plant has shifted from operations featuring centralized control in the control room to distributed activities in the balance of plant. Additionally, the time windows for many of the activities outside full power are greater, as the plant may have greater time margins for safe response in the face of upset conditions. The equivalent condition may exist in oil and gas, e.g., reduced hazards such as no potential of a blowout during shutdown. Conversely, maintenance activities associated with shutdown conditions may actually increase the number of active hazards at the facility, even if the consequences are minimized.
- *Level 1, 2, or 3:* As noted earlier, Level 1 PRA refers to core melt, whereas Level 2 refers to immediate concerns with remediating core melt. In turn, Level 3 covers broader effects such as environmental damage. As Azizi (2014) notes regarding PRA, there is really no equivalent of Level 2 analysis for oil and gas, since there is no equivalent of core melt. Level 1 events are referred to as design-basis accidents, because the system was designed and the risk model accounts for the types of scenarios that could lead to the accident. Level 2 and 3 analyses are referred to as severe accidents, because they go beyond the barriers and mitigation strategies built into the system. In order for these three levels of analysis to be relevant to oil and gas, they must be generalized beyond their specific reference to core melt and placed into a continuum of accident severity. Clearly, oil and gas installations can have severe accidents, but the definitions are not at this time clearly aligned with those in use for nuclear power PRA.

These concepts will need to be reviewed as more experience is gathered with HRA in oil and gas and adapted accordingly to determine if these distinctions maintain their relevance outside nuclear power analysis.

It is worth noting that some of these differences between nuclear power and oil and gas are actually similar to the differences between HRAs for design basis accidents vs. severe accidents (Cooper et al., 2013). As a nuclear power plant is taken out of its normal operational mode, there is shift to a more decentralized operation as distributed personnel respond to the accident. Existing HRA methods and guidance must be adapted as PRAs in the nuclear industry consider more types of accidents, and these changes may mirror changes necessary for generalizing HRA to oil and gas applications.

4 NEXT STEPS

The Norwegian oil industry, through support of the Norwegian Research Council, has sponsored the Petro-HRA project, a four-year research effort to review, adapt, apply, and document HRA for oil and gas applications. The Petro-HRA project consists of several parallel activities to identify best practices in HRA and adapt them to a petroleum context. The purpose of the Petro-HRA project is to bridge existing nuclear-based HRA to the domain of oil and gas, because like nuclear power, oil and gas are a safety critical enterprise in which the consequences of human actions or inactions can be severe in terms of impact to the environment, economy, or individuals. As with nuclear power, although there is a potentially high consequence should something go wrong, the incidence of negative events is quite rare. There are multiple safety barriers put in place to ensure that faults do not occur or that, if they do occur, their effects are quickly minimized. This defence in depth concept of operations permeates both nuclear power and petroleum operations.

Yet, as discussed in this paper, clear differences exist, from the source of the hazards to the nature of the technology and procedures used during operations. The Petro-HRA project seeks to make these differences clear. Moreover, rather than simply highlight differences, the project aims to adapt existing HRAs to a petroleum context. This paper has provided an overview of some of the adaptations that may be desirable or necessary as a result of the differences between nuclear energy and oil and gas. Realizing these differences is but the starting point, and significant research is still needed to develop and validate an adapted HRA approach for oil and gas applications.

5 DISCLAIMER

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