MARY KAY O'CONNOR PROCESS SAFETY CENTER
TEXAS A&M ENGINEERING EXPERIMENT STATION

22nd Annual International Symposium
October 22-24, 2019 | College Station, Texas

Crosswalk of Human Reliability Methods for Offshore Oil Incidents

Ronald L. Boring*, Jooyoung Park, Thomas A. Ulrich
Human Factors and Reliability Department
Idaho National Laboratory
P.O. Box 1625, MS 3818
Idaho Falls, Idaho 83415, USA
*Presenter E-mail: ronald.boring@inl.gov

Abstract

Human reliability analysis (HRA) has long been employed in nuclear power applications to account for the human contribution to safety. HRA is used qualitatively to identify and model sources of human error and quantitatively to calculate the human error probabilities of particular tasks. The nuclear power emphasis of HRA has helped ensure safe practices and risk-informed decision making in the international nuclear industry. This emphasis has also tended to result in a methodological focus on control room operations that are very specific to nuclear power, thereby potentially limiting the applicability of the methods for other safety critical domains. In recent years, there has been interest to explore HRA in other domains, including aerospace, defense, transportation, mining, and oil and gas. Following several high profile events in the oil and gas industry, notably the Macondo well kick event in the U.S., there has been a move to use HRA to model and reduce risk in future oil drilling and production activities. Organizations like the Bureau of Safety and Environmental Enforcement are adapting the risk framework of the U.S. Nuclear Regulatory Commission for offshore purposes. In this paper, we present recent work to apply HRA methods to the analysis of offshore activities. We present the results of retrospective analyses using three popular HRA methods: SPAR-H, Petro-HRA, and CREAM. With the exception of Petro-HRA, these HRA methods were developed primarily for nuclear power event analysis. We present a comparison of the findings of these methods and a discussion of lessons learned in applying the methods to offshore events. The objective of this paper is to demonstrate the suitability of HRA methods for oil and gas risk analysis but also to identify topics where future research would be warranted to tailor these HRA methods.

Keywords: Risk Assessment, Human Error Assessment, Human Reliability Analysis, Standardized Plant Analysis Risk-Human Reliability

1 Human Reliability Analysis Methods

1.1 General Overview of Quantification Approaches

Human reliability analysis (HRA) methods have historically been developed to account for and mitigate human errors in nuclear power applications. Recently there is increased use of HRA outside the nuclear domain such as to support quantitative risk assessment for oil and gas settings. As HRA is generalized to new areas, it is important that existing HRA methods are validated to a broader range of uses. Where there are shortcomings in existing HRA methods, the methods should be adapted to support these new domains, or new HRA methods should be developed. This validation and evolution of methods ensures that HRA identifies and thereby minimizes risk.

HRA methods serve the twofold purpose to classify the sources of errors qualitatively and to estimate the human error probability (HEP). Qualitative error classification serves as the basis for quantification. Of the roughly 60 HRA methods created, most are centered on quantification [1]. Boring [2] proposed the following ways of classifying HRA quantification methods:

- *Scenario Matching Methods:* This approach, used by the original HRA method, the Technique for Human Error Rate Prediction (THERP) [3], entails matching the human failure event (HFE) to the best fitting example scenario in a lookup table and using the HEP associated with that template event as the basis for quantification. See Table 1(a).
- *Decision-Tree Methods:* Methods like the Cause-Based Decision Tree (CBDT) [4] follow a decision tree (similar to an event tree), which guides the quantification along a number of predefined analysis decision points. See Table 1(b).
- *Performance Shaping Factor (PSF) Adjustment Methods:* In these methods, exemplified by approaches like the Standardized Plant Analysis Risk-HRA (SPAR-H) method [5], 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. A list of PSFs and associated multipliers is provided by the method. See Table 1(c).
- *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) [6] 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 [7]. See Table 1(d).

The wide availability of HRA methods may leave the analyst overwhelmed at which methods to select for which applications. Recent method comparisons exist for nuclear (e.g., [1,8]), and they provide helpful benchmarks in considering the advantages and disadvantages of each method. The National Aeronautics and Space Administration's (NASA's) HRA method guidance [9] serves as another helpful template for downselecting HRA methods. Across multiple selection criteria, NASA selected four primary HRA methods to be used individually or in combination. Table 2 lists the four methods selected by NASA and a summary of their primary strengths and weaknesses in a generalized form (e.g., without consideration of specific NASA domain applications). While this downselection is helpful, it does not necessarily represent optimal methods with respect to offshore oil applications.

Table 1 - Examples of Common HRA Quantification Approaches

(a) Scenario matching lookup table from THERP [3], which provides the HEP and the error factor (EF) for uncertainty.

Table 20-13 Estimated HEPs for selection errors for locally operated valves (from Table 14-1)

Item	Potential Errors	HEP	EF
	Making an error of selection in changing or restoring a locally operated valve when the valve to be manipulated is		
(1)	Clearly and unambiguously labeled, set apart from valves that are similar in all of the following: size and shape, state, and presence of tags*	.001	3
(2)	Clearly and unambiguously labeled, part of a group of two or more valves that are similar in one of the following: size and shape, state, or presence of tags*	.003	3
(3)	Unclearly or ambiguously labeled, set apart from valves that are similar in all of the following: size and shape, state, and presence of tags*	.005	3
(4)	Unclearly or ambiguously labeled, part of a group of two or more valves that are similar in one of the following: size and shape, state, or presence of tags*	.008	3
(5)	Unclearly or ambiguously labeled, part of a group of two or more valves that are similar in all of the following: size and shape, state, and presence of tags*	.01	3

(b) Decision tree from CBDT [4] provides HEPs for the event-tree end states.

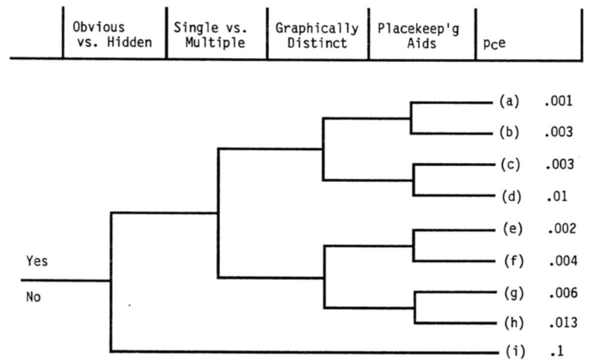

Figure 4-6. Decision tree Representation of P_{ce}, Skip a Step in Procedure

(c) Example PSF multipliers on the nominal HEP (0.001) for diagnosis tasks in SPAR-H [5].

PSFs	PSF Levels	Multiplier for Diagnosis
Available Time	Inadequate time	P(failure) = 1.0
	Barely adequate time (≈2/3 x nominal)	10
	Nominal time	1
	Extra time (between 1 and 2 x nominal and > than 30 min)	0.1
	Expansive time (> 2 x nominal and > 30 min)	0.01
	Insufficient information	1
Stress/ Stressors	Extreme	5
	High	2
	Nominal	1
	Insufficient Information	1
Complexity	Highly complex	5
	Moderately complex	2
	Nominal	1
	Obvious diagnosis	0.1
	Insufficient Information	1

(d) Example anchor HEPs for expert elicitation in ATHEANA [6].

Table 3.8-2. Suggested Set of Initial Calibration Points for the Experts

Circumstance	Probability	Meaning
The operator(s) is "Certain" to fail	1.0	Failure is ensured. All crews/operators would not perform the desired action correctly and on time.
The operator(s) is "Likely" to fail	~ 0.5	5 out of 10 would fail. The level of difficulty is sufficiently high that we should see many failures if all the crews/operators were to experience this scenario.
The operator(s) would "Infrequently" fail	~ 0.1	1 out of 10 would fail. The level of difficulty is moderately high, such that we should see an occasional failure if all of the crews/operators were to experience this scenario.
The operator(s) is "Unlikely" to fail	~ 0.01	1 out of 100 would fail. The level of difficulty is quite low and we should not see any failures if all the crews/operators were to experience this scenario.
The operator(s) is "Extremely Unlikely" to fail	~ 0.001	1 out of 1000 would fail. This desired action is so easy that it is almost inconceivable that any crew/operator would fail to perform the desired action correctly and on time.

Table 2 - The Four HRA Methods Selected for NASA Use

Method	Approach	Strengths	Weaknesses
THERP	Lookup table	Widely used original HRA method. THERP specifies a complete process model for HRA. It has good coverage of errors related to human actions.	Little coverage of cognitive factors. Method may have limited generalizability beyond the nuclear-specific human interactions in the lookup tables.
CREAM[a]	Task types (lookup table) and PSF multipliers	Good coverage of cognitive factors and detailed task decomposition approach for qualitative insights into errors.	Method is complex in practice (e.g., involving many steps for basic quantification) and tends to produce similar HEPs regardless of performance drivers.
NARA[b]	Task types (lookup table) and PSF multipliers	Good use of human factors literature as data source to validate HEPs for task types.	The task types are aligned to nuclear power plant operations, and specialized variants need to be developed for air traffic control and rail domains. The method remains proprietary.
SPAR-H	PSF multipliers	Simplified method that can be used without extensive HRA background. PSFs allow generalizability beyond predefined task types.	Quantification-only approach that assumes HFEs defined in the probabilistic risk assessment (PRA). PSF multipliers are not calibrated to non-nuclear techniques.

a. Cognitive Reliability Error Analysis Method [10]

b. Nuclear Action Reliability Assessment [11]

1.2 HRA Methods for Oil and Gas

Two HRA methods have been developed specifically for oil and gas, and they are briefly noted below.

1.2.1 Barrier and Operational Risk Analysis (BORA)

Despite information suggesting major accident sequences may be attributed to several risk influencing factors classified as technical, human, operational and organizational, the majority of quantitative risk analyses of offshore oil and gas production platforms has been directed at technical safety systems. The Barrier and Operational Risk Analysis (BORA) of hydrocarbon releases (BORA-Release) is a method for carrying out the qualitative and quantitative risk analysis of platform specific hydrocarbon release frequency [12]. In finer detail, the method assesses the effect of risk reducing measures and risk increasing changes within operations. BORA affords the ability to analyze both the effect of safety barriers put in place to impede the release of hydrocarbons as well as how platform specific conditions such as the aforementioned technical, human, operational and organizational factors influence the performance of the barrier. Analysis of hydrocarbon release risk via the BORA method is executed with the use of barrier block diagram/event trees, fault trees, and risk influence diagrams.

The BORA-Release method is made up of eight steps:

1. Development of a basic risk model including release scenarios
2. Modeling for the performance of safety barriers
3. Assignment of industry average probabilities/frequencies and risk quantification based on these probabilities/frequencies
4. Development of risk influence diagrams
5. Scoring of risk influencing factors
6. Weighting of risk influencing factors
7. Adjustment of industry average probabilities/frequencies
8. Recalculation of the risk in order to determine the platform specific risk related to hydrocarbon release.

Many of these steps overlap basic HRA processes found across HRA methods like [3,4,5,6,10,11]. BORA 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, may omit many of the HFEs that can precipitate accidents at the facility. HRAs centered on barriers may overlook important precursors to many types of accidents. Additionally, BORA's emphasis on prevention of accidents may limit some of its application as a risk analytic tool for as-built systems and processes.

1.2.2 Petro-HRA

The Norwegian Research Council and the Norwegian state oil company, Statoil (now called Equinor), recently sponsored development of an HRA method to aid human factors analysts in completing HRAs for oil and gas applications. The approach, named the Petro-HRA method [13], features seven steps that mirror much of what is outlined in the IEEE-1082 HRA guide [14]:

1. Scenario definition
2. Qualitative data collection
3. Task analysis
4. Human error identification
5. Human error modeling
6. Human error quantification
7. Human error reduction.

Quantification in the Petro-HRA method is based on SPAR-H [5], offering some refinement to PSFs and multipliers to make them more oil and gas industry specific. SPAR-H was selected as the basis method because other HRA methods that had been used in the Norwegian oil and gas industry were found to generate unreasonably high HEPs or have low interrater reliability [15]. Because SPAR-H is primarily a quantification approach, additional guidance was developed to aid analysts in completing the qualitative portion of HRA, including translating a task analysis to HFEs when they are not already defined by a PRA. Because HRAs are performed to support the safety evaluation of new technologies in the Norwegian oil industry, specific guidance is provided to improve the system design or operations process to minimize human errors when they are identified.

2 Example Human Reliability Analysis for Well Kick

2.1 Selection of HRA Methods

In this section, we provide a review of the same well blowout event using three different HRA methods: SPAR-H [5], Petro-HRA [13], and CREAM [10]. The selection of these methods is based on the widespread use of SPAR-H and CREAM for non-nuclear applications, including many completed analyses for oil and gas. Petro-HRA, which is a derivative method of SPAR-H tailored to petroleum applications, serves as a useful benchmark. The same HFEs are analyzed using all three methods, and a brief explanation is provided on how the analyses are completed. The explanations of the analyses provide tutorial details, but analysts should ensure they refer back to the source guidance for the methods for a better understanding of how to apply the methods.

2.2 Human Failure Events

SPAR-H and CREAM assume the HFE has been defined in the PRA, while Petro-HRA provides guidance on how to define the HFE. For the present purposes, we have characterized three primary HFEs related to the well kick as depicted in Figure 1. As can be seen in Figure 1, HFE_1 refers to the detection of the well kick, HFE_2 refers to responding to the well kick by actuating the annular of the blowout preventer (BOP), and HFE_3 refers to performing the emergency well disconnect. A brief description of the well-kick related accident is necessary for those who are not familiar with the human activities pertaining to the well-kick event or the Deepwater Horizon accident.

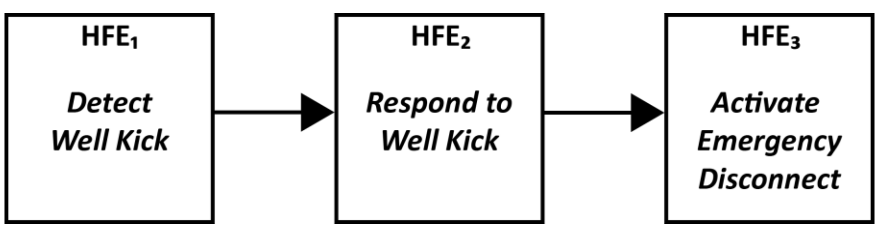

Figure 1 - Example Human Failure Events in Sequence

An excellent and detailed chronological account of the specific events can be found in Chapter 2 of the Transocean Investigation Report titled *Macondo Well Incident* [16]. All event details are not necessary for demonstrating the HRA methods; therefore, here only a brief description is provided for context to the analysis. The event began on April 20, 2010, when an oil and gas blowout incident at the Macondo Oil Well caused an explosion and fire that resulted in 11 fatalities, 17 seriously injured personnel, the sinking of the Deepwater Horizon drilling rig, and the release of millions of gallons of oil into the Gulf of Mexico. The event can be attributed, in part, to a failure to detect the well kick and subsequent blowout or uncontrolled release of oil and gas hydrocarbons from the well. The backpressure drove the hydrocarbons through the drilling apparatus to the rig, in which it was ignited in an explosion that subsequently set fire to the rig. The rig had finished the exploratory drilling phase of operations and was in the process of performing temporary well-abandonment activities to prepare the well for the production phase of operations which another rig was scheduled to perform.

The well-abandonment activities entail plugging the well with cement, ensuring the integrity of the cement plugs via a negative pressure test, and then retracting the drilling apparatus. The negative pressure test circulates chemically treated mud that serves as the primary barrier to prevent the hydrocarbon from traveling through the well and into the drilling apparatus. The negative pressure created by circulating the mud simulates the low pressure sea floor atmosphere in order to verify the cement plug is properly sealing the well. Pressure and flow indications were available to the drilling team, though due to urgency to finish the drilling phase of operations, they went unnoticed until the negative pressure test was performed. A supervising representative from British Petroleum overseeing the drilling operation did raise a concern to the driller; however, any concern was improperly alleviated by more experienced drilling team members stating the odd pressure values were not uncommon and did not merit any significant concerns. Operations resumed, even though the undetected kick had occurred up to an hour prior and was continuing to worsen over time.

The drilling crew closed the upper annular of the blow out preventer (BOP) at 9:34 PM in attempt to arrest the kick. The high pressure and volume of hydrocarbon flow caused the piping within the BOP annular to shift such that a joint between two pipes impeded the closing mechanism and the annular failed to seal the well. Mud began to flow onto the drilling floor, and in response the flow was diverted to the mud-gas separators at 9:45 PM. The volume of flow quickly exceeded the mud-gas separators' capacity, and the blowout alarm sounded at 9:47 PM. Shortly thereafter, at 9:49 PM, the rig lost main power followed quickly by two explosions. At 9:56 PM, an emergency well disconnect was attempted in which the BOP was designed to sever the pipe to eliminate flow to the rig. The bridge team received indication that the disconnect mechanism was activated; however, the pipe was not successfully severed, and flow continued. The order to abandon ship was issued at 10:00 PM.

2.3 A Brief Note on Retrospective HRA

The following HRA walkthroughs are examples of retrospective HRA. Retrospective HRA is an analysis that looks at an event that has already happened. Of course, the probability that the event happened is 1.0, because it actually did occur. The purpose of a retrospective analysis is to determine the likelihood that the event should have happened given its context. In colloquial terms, was the event simply bad luck, or was it the systematic product of circumstances that could have been prevented? In identifying the causes of the event, a retrospective analysis looks at the probability that such an event could occur again, given the same circumstances. Retrospective analyses are crucial for establishing corrective actions and preventing recurrence of similar events.

It should be noted that a retrospective analysis will have greater and more specific insights than would a typical prospective analysis. A prospective analysis, such as an HRA conducted when a system is being designed or built, must rely on the normal course of operations. In other words, the context must be kept general to cover a variety of operating contexts. It is not typical to assume the confluence of multiple poor factors during a prospective analysis. In contrast, a retrospective analysis would feature all known mitigating factors that caused the event to transpire. As such, a retrospective analysis will inherently be more conservative than a prospective analysis. It is assumed that for an extreme event like the Deepwater Horizon accident, the retrospective HEP generated by most HRA methods would be close to 1.0. This represents a much more severe form of the well blowout than would be modelled in a prospective analysis.

2.4 Example Analysis Using SPAR-H

2.4.1 Overview

Here, we demonstrate SPAR-H [5] as a simplified method to help understand how to quantify the three HFEs. A SPAR-H quantification requires several steps:

1. Define the HFE (completed by PRA and a prerequisite for the SPAR-H analysis)
2. Determine the appropriate SPAR-H worksheet
3. Determine the appropriate SPAR-H nominal HEP
4. Evaluate the PSFs
5. Calculate the product of the nominal HEP and the PSF multipliers
6. Apply correction factor for dependence.

These steps are walked through in separate subsections below. The first step—defining the HFEs—was detailed in the previous section.

2.4.2 Determine the Appropriate SPAR-H Worksheet

SPAR-H contains two types of analysis worksheets:

- *At power* (NUREG/CR-6883, Appendix A [5])
- *Low power and shutdown* (NUREG/CR-6883, Appendix B [5]).

The origin of SPAR-H as an HRA method for nuclear power applications is clear here. The basic difference between these two worksheets involves whether the plant is producing electricity (i.e., at power) or in maintenance or refueling mode (i.e., low power and shutdown). It is assumed that there is more opportunity for high consequence events and tighter time windows to take recovery actions during at-power operations. An offshore analogy for at power would be during drilling activities.

For the well kick scenarios, we assume the SPAR-H at-power worksheets are applicable.

2.4.3 Determine the Appropriate SPAR-H Nominal HEP

The SPAR-H worksheets for at-power and low-power-and-shutdown each have two task types that are modeled. The task types determine the nominal or default HEP for the HFE:

- *Diagnosis:* This HFE primarily involves cognitive activities such as monitoring or decision-making. The nominal HEP for diagnosis HFEs is 1E-2 (0.01).
- *Action:* This HFE primarily involves carrying out physical activities such as manipulating equipment. The nominal HEP for action HFEs is 1E-3 (0.001).

Because an HFE may involve a series of activities by the human involved, it is not uncommon for the HFE to be classified as both diagnosis and action. In that case, the *joint HFE* can logically be thought to occur due to diagnosis *or* action errors. Mathematically, this means that the nominal HEPs for diagnosis and action are added together.

In our well kick example, all HFEs involve diagnosis and action components, since they require cognitive monitoring, decision-making, and interaction with equipment.

2.4.4 Evaluate the PSFs

SPAR-H uses nominal HEPs to represent the generic diagnosis and action tasks performed within the HFE. These nominal HEPs are then modified using multipliers corresponding to different levels of influence of the PSFs. SPAR-H makes use of eight PSFs, encompassing:

- Available time to complete the task (which is independent of any time pressure the personnel may experience)
- Internal stress and external stressors
- The complexity of the task and scenario
- The experience and training of the personnel completing the tasks under analysis
- The procedures—either written or oral—to guide the personnel in completing the task
- The ergonomics of the system being used and the human-machine interfaces available to the personnel
- The fitness for duty—including degraded fitness due to fatigue of long-duration events—of the personnel completing the task
- Work processes, including organizational factors, command and control, and communications.

Generally, the SPAR-H PSFs can have three types of effects:

1. *Negative:* A negative effect means that the PSF decreases human reliability and thereby increases the HEP. For example, to denote the negative effect of available time would mean to suggest that there was inadequate time available to complete the task.
2. *Nominal:* A nominal effect means that the default applies. Nominal time, for example, suggests that there's adequate time to complete the task without undue time pressure or extra time.
3. *Positive:* A positive effect means that the PSF increases human reliability and thereby decreases the HEP. A positive effects results in giving credit to the human actions. For example, positive available time means that there is extra time over what is needed to accomplish the task.

In the absence of information to inform the assignment, the analyst would denote "inadequate information," which simply assigns a nominal value.

To assign SPAR-H PSFs, it is useful for the human reliability analyst to consult with an operations specialist to answer the following questions:

- Which personnel are involved in this task?
- What indicators are available for the task?
- What are the timing constraints that could interfere with a successful outcome?
- Do personnel have adequate training and experience on the task?

- What's needed to perform this task successfully?
- What can go wrong?
- What could influence personnel performance in terms of actions or decision-making?

For the three example HFEs, the following PSF effects could be noted:

- For detection of the well kick (HFE_1), the time available will vary from situation to situation, but once a kick occurs, there is a limited window of time before the formation fluid reaches the blowout preventer. As the available time erodes, the ability of the drilling crew to respond decreases proportionately to the decreasing time window. It may be assumed that limited available time to detect will adversely affect the HEP. The clock is ticking, so to speak, which can only operate negatively on the outcome of the event. All other PSFs are assumed to be nominal.
- The detection of a well kick triggers a change: response actions are needed in order to prevent a blowout (HFE_2) and ultimately disconnect the well from the oil rig (HFE_3). This operational shift will generally result in multiple elevated negative PSFs relative to nominal or normal operations. The time window is closing, but there may also be elevated negative stress and complexity, potentially diminished levels of experience for this type of situation, and potentially poor to incomplete procedures. Underlying the situation, negative work processes such as breakdowns in communication, coordination, or command and control may also manifest.

While detection of the well kick (HFE_1) can be seen as a mostly nominal influence of the PSFs, the transition to emergency operations to prevent blowout (HFE_2) and disconnect the well (HFE_3) will likely invoke multiple negative PSFs.

2.4.5 Calculate the Product of the Nominal HEP and the PSF Multipliers

When negative, nominal, or positive effects of PSFs have been determined, these are matched to the appropriate level in the SPAR-H PSF multiplier tables. If there is a negative or positive effect of a PSF, this phase involves determining the degree of that effect, which corresponds to a multiplier. A summary of SPAR-H multiplier assignments for the well kick detection, response, and disconnect HFEs is found in Table 3. For the detection HFE, a single negative PSF—available time—is assumed. For the response HFE, three slightly negative PSFs—available time, stress, and complexity—are assumed. For the disconnect HFE, two negative PSFs—available time and stress—are assumed.

The basic HEP is defined in SPAR-H as the nominal HEP multiplied by the product of all PSF multipliers:

$$\text{Basic HEP} = \text{Nominal HEP} \times \prod \text{PSF Multipliers} \qquad \textit{(Eq. 1)}$$

For HFE_1 related to well kick detection, the PSF is calculated separately for diagnosis and action:

$$HFE_1 \text{ Diagnosis Basic HEP} = 1E\text{-}2 \times 10 \times 1 \times 1 \times 1 \times 1 \times 1 \times 1 \times 1 = 1E\text{-}1 = 0.1 \qquad \textit{(Eq. 2)}$$

$$HFE_1 \text{ Action Basic HEP} = 1E\text{-}3 \times 10 \times 1 \times 1 \times 1 \times 1 \times 1 \times 1 \times 1 = 1E\text{-}2 = 0.01 \qquad \textit{(Eq. 3)}$$

Table 3 - SPAR-H Assignments for Well Kick Detection, Response, and Disconnect

PSFs	PSF Levels	HFE_1: Well Kick Detection		HFE_2: Well Kick Response		HFE_3: Well Disconnect	
		Diagnosis Multiplier	Action Multiplier	Diagnosis Multiplier	Action Multiplier	Diagnosis Multiplier	Action Multiplier
Available time	Inadequate time	HEP = 1.0	HEP = 1.0	HEP = 1.0	HEP = 1.0	HEP = 1.0	HEP = 1.0
	Barely adequate time	10	10	10	10	10	10
	Nominal time	1	1	1	1	1	1
	Extra time	0.1	0.1	0.1	0.1	0.1	0.1
	Expansive time	0.01	0.01	0.1 to 0.01	0.01	0.1 to 0.01	0.01
	Insufficient info	1	1	1	1	1	1
Stress/stressors	Extreme	5	5	5	5	5	5
	High	2	2	2	2	2	2
	Nominal	1	1	1	1	1	1
	Insufficient info	1	1	1	1	1	1
Complexity	Highly complex	5	5	5	5	5	5
	Moderately complex	2	2	2	2	2	2
	Nominal	1	1	1	1	1	1
	Obvious diagnosis	0.1	N/A	0.1	N/A	0.1	N/A
	Insufficient info	1	1	1	1	1	1
Experience/ training	Low	10	3	10	3	10	3
	Nominal	1	1	1	1	1	1
	High	0.5	0.5	0.5	0.5	0.5	0.5
	Insufficient info	1	1	1	1	1	1
Procedures	Not available	50	50	50	50	50	50
	Incomplete	20	20	20	20	20	20
	Available, but poor	5	5	5	5	5	5
	Nominal	1	1	1	1	1	1
	Diagnostic/symptom oriented	0.5	N/A	0.5	N/A	0.5	N/A
	Insufficient info	1	1	1	1	1	1
Ergonomics/ HMI	Missing/ misleading	50	50	50	50	50	50
	Poor	10	10	10	10	10	10
	Nominal	1	1	1	1	1	1
	Good	0.5	0.5	0.5	0.5	0.5	0.5
	Insufficient info	1	1	1	1	1	1
Fitness for duty	Unfit	HEP = 1.0	HEP = 1.0	HEP = 1.0	HEP = 1.0	HEP = 1.0	HEP = 1.0
	Degraded fitness	5	5	5	5	5	5
	Nominal	1	1	1	1	1	1
	Insufficient info	1	1	1	1	1	1
Work processes	Poor	2	5	2	5	2	5
	Nominal	1	1	1	1	1	1
	Good	0.8	0.5	0.8	0.5	0.8	0.5
	Insufficient info	1	1	1	1	1	1

The joint basic HEP is simply the sum of the diagnosis and action basic HEPs:

HFE_1 Joint Basic HEP = Diagnosis Basic HEP + Action Basic HEP

$$= 1E\text{-}1 + 1E\text{-}2 = 1.1E\text{-}1 = 0.11 \qquad \textit{(Eq. 4)}$$

The same general form of the equation applies to HFE_2 related to the response to well kick and HFE_3 related to the well disconnect, but with one exception. Because it is possible to have a resultant HEP greater than 1.0 when there are more than three negative HEPs, SPAR-H prescribes a correction factor:

$$\text{Corrected Basic HEP} = \frac{\text{Nominal HEP} \times \Pi \text{ PSF Multipliers}}{\text{Nominal HEP} \times (\Pi \text{ PSF Multipliers} - 1) + 1} \qquad \textit{(Eq. 5)}$$

Thus, for HFE_2 we first calculate the product of the PSF multipliers, which in this case is identical for the diagnosis and action tasks:

$$\prod \text{PSF Multipliers} = 10 \times 2 \times 2 \times 1 \times 1 \times 1 \times 1 \times 1 = 40 \qquad \textit{(Eq. 6)}$$

This product is then applied in the corrected basic HEP equation for diagnosis and action:

$$HFE_2 \text{ Corrected Diagnosis Basic HEP} = \frac{1E\text{-}2 \times 40}{1E\text{-}2 \times (40 - 1) + 1} = 0.288 \qquad \textit{(Eq. 7)}$$

$$HFE_2 \text{ Corrected Action Basic HEP} = \frac{1E\text{-}3 \times 40}{1E\text{-}3 \times (40 - 1) + 1} = 0.0385 \qquad \textit{(Eq. 8)}$$

The joint basic HEP for HFE_2 is calculated by adding the two basic HEPs:

$$HFE_2 \text{ Joint Basic HEP} = 0.288 + 0.0385 = 0.326 \qquad \textit{(Eq. 9)}$$

HFE_3 is calculated identically to HFE2 but with different multipliers since stress is much higher while the complexity of activating the well disconnect is lower. We first calculate the product of the PSF multipliers, which in this case is identical for the diagnosis and action tasks:

$$\prod \text{PSF Multipliers} = 10 \times 5 \times 1 \times 1 \times 1 \times 1 \times 1 \times 1 = 50 \qquad \textit{(Eq. 10)}$$

HFE3 only has two negative PSFs. Thus, the basic (uncorrected) HEP is calculated:

$$HFE_3 \text{ Diagnosis Basic HEP} = 1E\text{-}2 \times 50 = 5E\text{-}1 = 0.5 \qquad \textit{(Eq. 11)}$$

$$HFE_3 \text{ Action Basic HEP} = 1E\text{-}3 \times 50 = 5E\text{-}2 = 0.05 \qquad \textit{(Eq. 12)}$$

The joint basic HEP for HFE_3 is calculated by adding the two basic HEPs:

$$HFE_3 \text{ Joint Basic HEP} = 0.5 + 0.05 = 0.55 \qquad \textit{(Eq. 13)}$$

There is nearly a threefold increase in the basic HEP between HFE_1 and HFE_2 due to the increased effects of negative PSFs for stress and complexity between well kick detection and response. A further increase in the basic HEP occurs between the HFE_2 and HFE_3 for the well disconnect.

2.4.6 Apply Correction Factor for Dependence

In the final stage of SPAR-H quantification, a correction factor is applied for dependence. Dependence in SPAR-H means that the second or subsequent HFE in sequence may result in greater likelihood of human error. If appropriate, a correction factor is applied to the basic HEP.

For sequences of two or more HFEs, SPAR-H considers four factors that influence dependence:

- Same (s) or different (d) *crew* between the HFEs
- Close (c) or not close (nc) in *time* between the HFEs
- Same (s) or different (d) *location* between the HFEs
- Additional (a) or no additional (na) *cues* (i.e., information available to crew) between the HFEs.

The more the HFEs share crew, time, location, and cues, the more likely there is to be dependence between them. SPAR-H uses a dependency condition table (see Table I-4) to classify dependence along a scale from *Zero*, *Low*, *Moderate*, *High*, to *Complete*.

Table 4 - SPAR-H Dependence Table (from [5])

Condition Number	Crew (same or different)	Time (close in time or not close in time)	Location (same or different)	Cues (additional or no additional)	Dependency	Number of Human Action Failures Rule ☐ - Not Applicable. Why?__________________
1	s	c	s	na	complete	When considering recovery in a series e.g., 2nd, 3rd, or 4th checker If this error is the **3rd error in the sequence**, then the dependency is at least **moderate**. If this error is the **4th error in the sequence**, then the dependency is at least **high.**
2				a	complete	
3			d	na	high	
4				a	high	
5		nc	s	na	high	
6				a	moderate	
7			d	na	moderate	
8				a	low	
9	d	c	s	na	moderate	
10				a	moderate	
11			d	na	moderate	
12				a	moderate	
13		nc	s	na	low	
14				a	low	
15			d	na	low	
16				a	low	
17					zero	

HFE_1 is the first HFE in the sequence and by definition does not have dependence. We assume HFE_2 to have somewhat different crew responding to the well kick. HFE_2 and HFE_3 follow closely in time, have the same location, but also have additional cues. The resultant dependence level as traced (d-c-s-a) in Table 4 is *moderate dependence*.

The conditional HEP is the basic HEP corrected for dependence. SPAR-H features the following equations for levels of the conditional HEP:

- *Zero Dependence:* Conditional HEP = Basic HEP
- *Low Dependence:* Conditional HEP = (1 + 19 × Basic HEP) / 20

- *Moderate Dependence:* Conditional HEP = (1 + 6 × Basic HEP) / 7
- *High Dependence:* Conditional HEP = (1 + Basic HEP) / 2
- *Complete Dependence:* Conditional HEP = 1.0.

For HFE_2 and HFE_3 assuming moderate dependence, we have:

$$HFE_2 \text{ Conditional HEP} = (1 + 6 \times 0.326) / 7 = 0.422 \quad \textit{(Eq. 14)}$$

$$HFE_3 \text{ Conditional HEP} = (1 + 6 \times 0.55) / 7 = 0.614 \quad \textit{(Eq. 15)}$$

Moderate dependence resulted in the HEP for HFE_2 and HFE_3 each increasing by nearly 0.1 in our example.

Using the SPAR-H method, we quantified the HEPs for the three HFEs, arriving at:

$$\text{Detect well kick: } HEP_{HFE1} = 0.11 \quad \textit{(Eq. 16)}$$

$$\text{Respond to well kick: } HEP_{HFE2} = 0.422 \quad \textit{(Eq. 17)}$$

$$\text{Well Disconnect: } HEP_{HFE3} = 0.614. \quad \textit{(Eq. 18)}$$

A final note on SPAR-H is that it only provides the HEP, not a measure of uncertainty. Uncertainty is calculated using the constrained noninformative prior, a method for calculating parameters assuming a single input parameter on a beta distribution. Some PRA software feature the ability to calculate the uncertainty in SPAR-H if required by the analyst.

2.5 Example Analysis Using Petro-HRA

2.5.1 Overview

As noted, the Petro-HRA method [13] is a modified variant of SPAR-H developed specifically for applications in the oil and gas industry. As outlined in the brief introduction in Section 1.2.2, the activities involved with performing the analysis for the Petro-HRA method align closely with SPAR-H. The terminology is slightly different, and some additional guidance specific to the oil and gas industry is included. For example, the SPAR-H method relies on the PRA model to screen and identify HFEs, while the Petro-HRA method does not assume the HFE is defined by the PRA.

2.5.2 Performance Shaping Factor Definitions

Petro-HRA uses the same quantification framework as SPAR-H, but it uses modified PSFs that are tailored to address the context of oil and gas including offshore drilling and refinery operations. The modified PSFs for Petro-HRA include:

1. Time
2. Threat stress (equivalent to stress in SPAR-H)
3. Task complexity
4. Experience/Training
5. Procedures
6. Human-machine interface
7. Attitudes to safety, work and management support

8. Teamwork
9. Physical working environment.

The first six PSFs (i.e., time, threat stress, task complexity, experience/training, procedures, and human-machine interface) are nearly identical to the PSFs in SPAR-H. Petro-HRA has three different PSFs that replace the fitness for duty and work process PSFs from SPAR-H. The PSF entitled "Attitudes to safety, work and management support" reflects organizational aspects of the context surrounding the HFE. The teamwork PSF pertains to the level of coordination and the efficacy of the team to accomplish common and valued goals. The PSF for physical working environment is a more explicit evaluation of the ergonomics surrounding the work environment. In contrast to SPAR-H, physical ergonomics can play a more significant role in the oil and gas industry given the sometimes harsh working environments, and therefore it is defined by its own PSF.

2.5.3 Performance Shaping Factor Levels and Multipliers

A significant difference between SPAR-H and Petro-HRA is the how the levels of the PSF multipliers are treated. In SPAR-H, the levels for the multipliers of each PSF are uniquely defined. Petro-HRA simplifies the multiplier levels, such that each PSF has the same ranking system for impact on performance. The same categorical levels exist across all PSFs, ranging from two levels of negative effect, a nominal effect, and one level of positive effect. However, the assignment of a multiplier value itself has specific criteria and specific numerical values for each PSF. Table 5 provides examples of the multipliers for attitudes to safety, work and management support. Table 6 shows the same multipliers for the time PSF.

Table 5 - Petro-HRA PSF for Attitudes to Safety, Work and Management Support (from [13])

Multipliers	*Levels*	*Level descriptions*
50	Very high negative effect on performance.	In this situation safety is not at all prioritized over other concerns when it is appropriate or there are extremely negative attitudes to work conduct (for example the operators are not monitoring or awake when they should be). There is very low mindfulness about safety. The operators do not experience management support, for example in strong management pressure for production even if safety is clearly in question.
10	Moderate negative effect on performance.	In this situation it is not specified by management that safety should be prioritized when that is appropriate. The operators are uncertain if safety should be prioritized or not, or the operators are uncertain about rules and regulations that are important for performing the task.
1	Nominal effect on performance.	The operators have adequate attitudes to safety and work conduct and there is management support to prioritize safety when that is appropriate. The operator(s) shows mindfulness about safety. Attitudes to safety, work and management support have neither a negative nor a large positive effect on performance.
0.5	Moderate positive effect on performance	The operator(s) has very good attitudes to safety and work conduct and there is explicit management support to prioritize safety when that is appropriate. The operator(s) shows a very high degree of mindfulness about safety.
1	Not applicable.	This PSF is not relevant for this task or scenario.

Table 6 - Petro-HRA PSF for Time (from [13])

Multipliers	*Levels*	*Level descriptions*
HEP=1	Extremely high negative effect on performance.	Operator(s) does not have enough time to successfully complete the task.
50	Very high negative effect on performance.	The available time is the minimum time required to perform the task or close to the minimum time to perform the task. In this situation the operator(s) has very high time pressure or they have to speed up very much to do the task in time.
10	Moderate negative effect on performance	The operator(s) has limited time to perform the task. However, there is more time available than the minimum time required. In this situation the operator(s) has high time pressure, or they have to speed up much to do the task in time.
1	Nominal effect on performance.	There is enough time to do the task. The operator(s) only has a low degree of time pressure, or they do not need to speed up much to do the task. When comparing the available time to the required time the analyst concludes that time would neither have a negative nor a positive effect on performance.
0.5	Moderate positive effect on performance	There is extra time to perform the task. In this situation the operator(s) has considerable extra time to perform the task and there is no time pressure or need to speed up to do the task in time.
1	Not applicable.	This PSF is not relevant for this task or scenario.

2.5.4 Quantification Process

The process of quantifying the HEP for each human failure event is nearly identical to that of SPAR-H, and therefore a detailed explanation will not be repeated. An important distinction between SPAR-H and Petro-HRA is that Petro-HRA only features a single nominal HEP set at 1E-2 (0.01). This nominal HEP is equivalent to the higher nominal HEP associated with cognitive or diagnosis tasks in SPAR-H. Essentially, Petro-HRA does away with the separation of Diagnosis and Action in SPAR-H and assumes all HFEs contain elements of both. In some analyses, this may result in possible conservatism in Petro-HRA compared to SPAR-H.

The completed table for each of the three previously identified HFEs including detect well kick, respond to well kick, and disconnect well is shown in Table 7. The HFE evidence used to assign PSF levels for SPAR-H was also used to populate the PSF multipliers in this table. The assigned values are similar to SPAR-H and follow the same general pattern in which stress was elevated in both HFE_2, recovery from blowout event, and even more so during HFE_3, well disconnect. Complexity was higher in HFE_2 than either of the other HFEs. Unlike SPAR-H, which doesn't have a designated physical working environment PSF, here the physical working environment was significantly deteriorated during HFE_3, in which the fire from the blowout event made it difficult for the crew to reach the control room and activate the emergency disconnect function.

The basic HEPs for the three HFEs are calculated as the product of the nominal HEP and the PSF multipliers:

Detect well kick: $HEP_{HFE1} = 0.01 \times 100 = 1.0$ *(Eq. 19)*

Respond to well kick: $HEP_{HFE2} = 0.01 \times 400 = 4.0 \approx 1.0$ *(Eq. 20)*

Table 7 – Petro-HRA Assignments for Well Kick Detection, Response, and Disconnect

PSFs	PSF Levels	HFE_1: Well Kick Detection Multiplier	HFE_2: Well Kick Response Multiplier	HFE3: Well Disconnect Multiplier
Time	Extremely high negative	HEP=1	HEP=1	HEP=1
	Very high negative	50	50	50
	Moderate negative	10	10	10
	Nominal	1	1	1
	Moderate positive	0.1	0.1	0.1
	Not applicable	1	1	1
Threat Stress	High negative	25	25	25
	Low negative	5	5	5
	Very low negative	2	2	2
	Nominal	1	1	1
	Not applicable	1	1	1
Task Complexity	Very high negative	50	50	50
	Moderate negative	10	10	10
	Very low negative	2	2	2
	Nominal	1	1	1
	Moderate positive	0.1	0.1	0.1
	Not applicable	1	1	1
Experience/Training	Extremely high negative	HEP=1	HEP=1	HEP=1
	Very high negative	50	50	50
	Moderate negative	15	15	15
	Low negative	5	5	5
	Nominal	1	1	1
	Moderate positive	0.1	0.1	0.1
	Not applicable	1	1	1
Procedures	Very high negative	50	50	50
	High negative	25	25	25
	Low negative	5	5	5
	Nominal	1	1	1
	Low positive	0.5	0.5	0.5
	Not applicable	1	1	1
Human-Machine Interface	Extremely high negative	HEP=1	HEP=1	HEP=1
	Very high negative	50	50	50
	Moderate negative	10	10	10
	Nominal	1	1	1
	Low positive	0.5	0.5	0.5
	Not applicable	1	1	1
Attitudes to Safety, Work and Management Support	Very high negative	50	50	50
	Moderate negative	10	10	10
	Nominal	1	1	1
	Low positive	0.5	0.5	0.5
	Not applicable	1	1	1
Teamwork	Very high negative	50	50	50
	Moderate negative	10	10	10
	Very low negative	2	2	2
	Nominal	1	1	1
	Low positive	0.5	0.5	0.5
	Not applicable	1	1	1
Physical working environment	Extremely high negative	HEP=1	HEP=1	HEP=1
	Moderate negative	10	10	10
	Nominal	1	1	1
	Not applicable	1	1	1

Well Disconnect: $HEP_{HFE3} = 0.01 \times 25000 = 250.0 \approx 1.0$ *(Eq. 21)*

Note that the Petro-HRA guidance specifies that an HEP greater than 1.0 should be set as 1.0. This correction has been applied for HFE_2 and HFE_3.

2.5.5 Apply Correction Factor for Dependence

The same calculations and adjustments for dependence performed for the SPAR-H analysis are also performed here for the Petro-HRA method. The reader can refer back to the Section 2.4.6 on SPAR-H dependence for the equations. Note that where the basic HEP is 1.0, there is no change to the overall conditional HEP considering dependence. The results of the calculations are shown below for each HFE:

Detect well kick: Final (Conditional) $HEP_{HFE1} = 1.0$ *(Eq. 22)*

Respond to well kick: Final (Conditional) $HEP_{HFE2} = 1.0$ *(Eq. 23)*

Well Disconnect: Final (Conditional) $HEP_{HFE3} = 1.0$ *(Eq. 24)*

These HEPs are considerably more conservative than the HEPs produced for SPAR-H. As noted in a paper on a similar event analysis [17], whereas SPAR-H was developed for retrospective analyses, Petro-HRA was developed for prospective analyses. This difference may contribute to the conservatism of Petro-HRA.

2.6 Example Analysis Using CREAM

2.6.1 Overview

The Cognitive Reliability and Error Analysis Method (CREAM) method [10] provides a different approach from SPAR-H to quantify the HEP for each HFE. CREAM contains a basic and extended method. The basic method corresponds to an initial screening of the human interactions. The screening or basic method addresses either the task as a whole or major segments of the task. The extended method uses the outcome of the basic method to look at actions or parts of the task where there is a need for further precision and detail. The following sections describe how to use the basic and extended method using the same HFEs examined with the SPAR-H and Petro-HRA methods in the prior sections.

2.6.2 CREAM Basic Method

There are three steps to the CREAM Basic Method:

1. *Describe the task or task segments to be analyzed.* This task is analogous to defining the HFE and any subtasks associated with the HFE.
2. *Assess the Common Performance Conditions (CPCs).* The CPCs are essentially PSFs.
3. *Determine the probable control mode.* The CPCs are used to classify the control mode as either strategic, tactical, opportunistic, or scrambled.

Step 1 was already performed in defining the HFE in Section 2.2 and can be input directly into this analysis.

Table 6 - Summary of the CPC Level Assignments in CREAM

CPC name	CPC Levels		
	HFE$_1$: Well Kick Detection	**HFE$_2$: Well Kick Response**	**HFE3: Well Disconnect**
Adequacy of organization	Very efficient	Very efficient	Very efficient
	Efficient	Efficient	Efficient
	Inefficient	Inefficient	Inefficient
	Deficient	Deficient	Deficient
Working condition	Advantageous	Advantageous	Advantageous
	Compatible	Compatible	Compatible
	Incompatible	Incompatible	Incompatible
Adequacy of MMI and operational support	Supportive	Supportive	Supportive
	Adequate	Adequate	Adequate
	Tolerable	Tolerable	Tolerable
	Inappropriate	Inappropriate	Inappropriate
Availability of procedures / plans	Appropriate	Appropriate	Appropriate
	Acceptable	Acceptable	Acceptable
	Inappropriate	Inappropriate	Inappropriate
Number of simultaneous goals	Fewer than capacity	Fewer than capacity	Fewer than capacity
	Matching current capacity	Matching current capacity	Matching current capacity
	More than capacity	More than capacity	More than capacity
Available time	Adequate	Adequate	Adequate
	Temporarily inadequate	Temporarily inadequate	Temporarily inadequate
	Continuously inadequate	Continuously inadequate	Continuously inadequate
Time of day	Day-time (adjusted)	Day-time (adjusted)	Day-time (adjusted)
	Night-time (unadjusted)	Night-time (unadjusted)	Night-time (unadjusted)
Adequacy of training and experience	Adequate, high experience	Adequate, high experience	Adequate, high experience
	Adequate, limited experience	Adequate, limited experience	Adequate, limited experience
	Inadequate	Inadequate	Inadequate
Crew collaboration quality	Very efficient	Very efficient	Very efficient
	Efficient	Efficient	Efficient
	Inefficient	Inefficient	Inefficient
	Deficient	Deficient	Deficient

For Step 2, Table 8 represents a summary of the level/descriptors on each CPC for the three HFEs. CREAM maps well to the earlier SPAR-H and Petro-HRA examples, but differs on a few items. For example, the working conditions CPC is a factor uniquely considered in CREAM and is not covered as a standalone PSF in other HRA methods like SPAR-H or Petro-HRA. Table 9 shows the selected effects of each CPC for the three HFEs in this analysis. These effects are important for calculation of the HEP.

Table 7 - Summary of the CPC Level Assignments and Their Performance Effects in CREAM

CPC name	HFE$_1$: Detect		HFE$_2$: Respond		HFE$_3$: Disconnect	
	Level / descriptors	**Expected effect on performance reliability**	**Level / descriptors**	**Expected effect on performance reliability**	**Level / descriptors**	**Expected effect on performance reliability**
Adequacy of organization	Inefficient	Reduced	Inefficient	Reduced	Inefficient	Reduced
Working condition	Compatible	Not significant	Compatible	Not significant	Incompatible	Reduced
Adequacy of MMI and operational support	Supportive	Improved	Supportive	Improved	Supportive	Improved
Availability of procedures / plans	Inappropriate	Reduced	Inappropriate	Reduced	Inappropriate	Reduced
Number of simultaneous goals	Fewer than capacity	Not significant	Fewer than capacity	Not significant	Fewer than capacity	Not significant → Reduced
Available time	Adequate	Improved	Adequate	Improved	Adequate	Improved
Time of day	Night time	Reduced	Night time	Reduced	Night time	Reduced
Adequacy of training and experience	Adequate, limited experience	Not significant	Adequate, limited experience	Not significant	Adequate, limited experience	Not significant
Crew collaboration quality	Inefficient	Not significant → Reduced	Inefficient	Not significant → Reduced	Inefficient	Not significant → Reduced

As the last step, the combined CPC score expressed as the triplet [$\sum_{\text{Reduced}}$, $\sum_{\text{Not significant}}$, $\sum_{\text{Improved}}$] is calculated, whereby the total number of instances is summed for the negative, nominal, and positive effects, respectively. For example, in case of HFE$_1$, the triplet is estimated as [4, 3, 2], meaning four negative, three nominal, and two positive effects. The negative and positive effects are used to determine the control mode in Figure 2, whereby the negative (i.e., reduced reliability) number of CPCs is treated as the horizontal axis and the positive (i.e., improved reliability) number of CPCs is treated as the vertical axis. This process classifies the HFE into one of four control modes—scrambled, opportunistic, tactical, or strategic. Table 10 provides the reliability interval for the HEP for each control mode.

The reliability interval for the three HFEs is summarized in Table 11. In all cases, the Basic CREAM analysis produced an opportunistic control mode with in HEP reliability interval of 1.0E-2 < p < 0.5E-0.

Figure 2 – Relationship Between Improved and Reduced Performance and Control Modes in CREAM (adapted from [10])

	7	Strategic	Strategic	Strategic							
	6	Strategic	Strategic	Strategic	Tactical						
	5	Strategic	Strategic	Tactical	Tactical	Tactical					
	4	Strategic	Tactical	Tactical	Tactical	Tactical	Tactical				
Improve	3	Tactical	Tactical	Tactical	Tactical	Tactical	Opportunistic	Opportunistic			
	2	Tactical	Tactical	Tactical	Tactical	Opportunistic	Opportunistic	Opportunistic	Opportunistic		
	1	Tactical	Tactical	Tactical	Opportunistic	Opportunistic	Opportunistic	Opportunistic	Opportunistic	Opportunistic	
	0	Tactical	Tactical	Tactical	Opportunistic	Opportunistic	Opportunistic	Scrambled	Scrambled	Scrambled	Scrambled
		0	1	2	3	4	5	6	7	8	9

Reduce

Table 8 - Control Modes and Probability Intervals (adapted from [10])

Control mode	**Reliability Interval**
Strategic	0.5e-5 < p < 1.0e-2
Tactical	1.0e-3 < p < 1.0e-1
Opportunistic	1.0e-2 < p < 0.5e-0
Scrambled	1.0e-1 < p < 1.0e-0

Table 9 - HEPs Produced by the CREAM Basic Method

HFE	**Triplet** [$\sum$Reduced, $\sum$Not significant, $\sum$Improved]	**Control mode**	**Reliability Interval**
HFE_1	[4, 3, 2]	Opportunistic	1.0e-2 < p < 0.5e-0
HFE_2	[4, 3, 2]	Opportunistic	1.0e-2 < p < 0.5e-0
HFE_3	[6, 1, 2]	Opportunistic	1.0e-2 < p < 0.5e-0

2.6.3 CREAM Extended Method

The Basic CREAM method produces a range of HEPs suitable for screening. In contrast, the Extended CREAM method produces a more specific HEP akin to other HRA methods. There are three steps of the Extended CREAM method:

1. *Build or develop a profile of the cognitive demands of the task.* This step entails classifying each step in the HFE according to its cognitive demands. Cognitive demands encompass observation, interpretation, planning, and execution. These are similar to the Diagnosis vs. Action distinction in SPAR-H, but at a finer level of granularity.
2. *Identify the likely cognitive function failures.* Cognitive demands lead to failures, and CREAM provides a table of possible failure types for each demand.

3. *Determine the specific action failure probability*. In this step, CREAM's equivalent of an HEP is calculated.

For Step 1, Table 12 indicates task steps or activities on each HFE, their basic cognitive activities, and cognitive demands. The cognitive activity consists of fifteen cognitive activity types—coordinate, communicate, compare, diagnose, evaluate, execute, identify, maintain, monitor, observe, plan, record, regulate, scan, and verify. These cognitive activities are matched to each of the four cognitive demands. Multiple demands may be present.

Table 10 - Task Steps or Activities of each HFE and Corresponding Cognitive Demands

HFE	**Task Step or Activity**	**Cognitive Activity**	**Cognitive Demand**			
			Observation	**Interpretation**	**Planning**	**Execution**
HFE_1: Detect Well Kick	Ensure return mud flow is rising	Monitor	✓	✓		
	Ensure BSR does not need be closed and sealed	Observe	✓			
	Ensure annulus are not sealed	Observe	✓			
	Ensure formation fluid does not rise	Monitor	✓	✓		
HFE_2: Respond to Well Kick	Remotely operated vehicle (ROV) intervention	Execute				✓
	Lower marine riser package disconnect	Execute				✓
HFE_3: Well Disconnect	Ensure BOP is unavailable	Observe	✓			
	Decision making for well disconnect	Diagnose		✓	✓	
	Push two buttons for well disconnect	Execute				✓

In Step 2, the analyst identifies the most likely cognitive function failures. The generic CREAM failure types are found in Table 13, while the specific ones identified for the HFEs are found in Table 14.

Table 11 - Generic Cognitive Function Failures (adapted from [10])

Cognitive Function	Potential Cognitive Function Failure	
Observation	O1	Observation of wrong object. A response is given to the wrong stimulus or event.
	O2	Wrong identification made, due to e.g. a mistaken cue or partial identification.
	O3	Observation not made (i.e., omission), overlooking a signal or a measurement.
Interpretation	I1	Faulty diagnosis, either a wrong diagnosis or an incomplete diagnosis.
	I2	Decision error, either not making a decision or making a wrong or incomplete decision.
	I3	Delayed interpretation, i.e., not made in time.
Planning	P1	Priority error, as in selecting the wrong goal (intention)
	P2	Inadequate plan formulated, when the plan is either incomplete or directly wrong.
Execution	E1	Execution of wrong type performed, with regard to force, distance, speed or direction.
	E2	Action performed at wrong time, either too early or too late
	E3	Action on wrong object
	E4	Action performed out of sequence, such as repetitions, jumps, and reversals
	E5	Action missed, not performed (i.e., omission), including the omission of the last actions in a series ("undershoot")

Table 12 - Potential Cognitive Function Failure Modes for the Task Steps for Each HFE

HFE	Task Step or Activity	Potential Cognitive Function Failure Mode	
HFE_1: Detect Well Kick	Ensure return mud flow is rising	O2	Wrong identification made
	Ensure BSR does not need be closed and sealed	O2	Wrong identification made
	Ensure annulus are not sealed	O2	Wrong identification made
	Ensure formation fluid does not rise	O2	Wrong identification made
HFE_2: Respond to Well Kick	ROV intervention	E3	Action on wrong object
	Lower marine riser package disconnect	E3	Action on wrong object
HFE_3: Well Disconnect	Ensure BOP is unavailable	O2	Wrong identification made
	Decision making for well disconnect	I3	Delayed interpretation
	Push two buttons for well disconnect	E3	Action on wrong object

In Step 3, the HEP is calculated. In CREAM terminology, this is called the cognitive failure probability (CFP). A nominal HEP lookup table is provided by CREAM for each function failure mode, as depicted in Table 15. Table 16 provides the nominal HEPs specific to the three HFEs. Table 17 provides the weighting factors for the CPCs. Each task's nominal HEP (i.e., CFP in

CREAM terminology) is multiplied by the sum of the CPC weighting factors, and the largest overall task HEP is retained as the HEP for that HFE. Table 18 shows the CPC weightings for each HFE, and Table 19 summarizes the final result.

Table 15 - Nominal CFP Values and Uncertainty Bounds for Cognitive Function Failures (adapted from [I-10])

Cognitive function	Generic failure type	Lower bound (.05)	Basic CFP value	Upper bound (.95)
Observation	O1	3.0E-4	1.0E-3	3.0E-3
	O2	1.0E-3*	3.0E-3*	9.0E-3*
	O3	1.0E-3*	3.0E-3*	9.0E-3*
Interpretation	I1	9.0E-2	2.0E-1	6.0E-1
	I2	1.0E-3	1.0E-2	1.0E-1
	I3	1.0E-3	1.0E-2	1.0E-1
Planning	P1	1.0E-3	1.0E-2	1.0E-1
	P2	1.0E-3	1.0E-2	1.0E-1
Execution	E1	1.0E-3	3.0E-3	9.0E-3
	E2	1.0E-3	3.0E-3	9.0E-3
	E3	5.0E-5	5.0E-4	5.0E-3
	E4	1.0E-3	3.0E-3	9.0E-3
	E5	2.5E-2	3.0E-2	4.0E-2

*Corrected from erroneous values in the original CREAM documentation [10]

Table 16 - Summary of Basic CFP Value of Each Potential Cognitive Function Failure

HFE	Task Step or Activity	Potential Cognitive Function Failure Mode	Basic CFP Value
HFE_1: Diagnosis of Well Kick	Ensure return mud flow is rising	O2	3.0E-3
	Ensure BSR does not need be closed and sealed	O2	3.0E-3
	Ensure annulus are not sealed	O2	3.0E-3
	Ensure formation fluid does not rise	O2	3.0E-3
HFE_2: Recovery Activities after Well Kick	ROV intervention	E3	5.0E-4
	Lower marine riser package disconnect	E3	5.0E-4
HFE_3: Well Disconnect	Ensure BOP is unavailable	O2	3.0E-3
	Decision making for well disconnect	I3	1.0E-2
	Push two buttons for well disconnect	E3	5.0E-4

Table 17 - Weighting Factors for CPCs (from [I-10])

CPC name	Level / descriptors	Cognitive Function			
		Observation	**Interpretation**	**Planning**	**Execution**
Adequacy of organization	Very efficient	1.0	1.0	0.8	0.8
	Efficient	1.0	1.0	1.0	1.0
	Inefficient	1.0	1.0	1.2	1.2
	Deficient	1.0	1.0	2.0	2.0
Working condition	Advantageous	0.8	0.8	1.0	0.8
	Compatible	1.0	1.0	1.0	1.0
	Incompatible	2.0	2.0	1.0	2.0
Adequacy of MMI and operational support	Supportive	0.5	1.0	1.0	0.5
	Adequate	1.0	1.0	1.0	1.0
	Tolerable	1.0	1.0	1.0	1.0
	Inappropriate	5.0	1.0	1.0	5.0
Availability of procedures / plans	Appropriate	0.8	1.0	0.5	0.8
	Acceptable	1.0	1.0	1.0	1.0
	Inappropriate	2.0	1.0	5.0	2.0
Number of simultaneous goals	Fewer than capacity	1.0	1.0	1.0	1.0
	Matching current capacity	1.0	1.0	1.0	1.0
	More than capacity	2.0	2.0	5.0	2.0
Available time	Adequate	0.5	0.5	0.5	0.5
	Temporarily inadequate	1.0	1.0	1.0	1.0
	Continuously inadequate	5.0	5.0	5.0	5.0
Time of day	Day-time (adjusted)	1.0	1.0	1.0	1.0
	Night-time (unadjusted)	1.2	1.2	1.2	1.2
Adequacy of training and experience	Adequate, high experience	0.8	0.5	0.5	0.8
	Adequate, limited experience	1.0	1.0	1.0	1.0
	Inadequate	2.0	5.0	5.0	2.0
Crew collaboration quality	Very efficient	0.5	0.5	0.5	0.5
	Efficient	1.0	1.0	1.0	1.0
	Inefficient	1.0	1.0	1.0	1.0
	Deficient	2.0	2.0	2.0	5.0

Table 18 - Summary of the CPC Weightings for Task Steps Included in Each HFE

HFE	CPC name	Level / Descriptors	Task Step # 1	Task Step # 2	Task Step # 3	Task Step # 4
HFE_1	Adequacy of organization	Inefficient	1	1	1	1
	Working condition	Compatible	1	1	1	1
	Adequacy of MMI and operational support	Supportive	0.5	0.5	0.5	0.5
	Availability of procedures / plans	Inappropriate	2	2	2	2
	Number of simultaneous goals	Fewer than capacity	1	1	1	1
	Available time	Adequate	0.5	0.5	0.5	0.5
	Time of day	Night time	1.2	1.2	1.2	1.2
	Adequacy of training and experience	Adequate, limited experience	1	1	1	1
	Crew collaboration quality	Inefficient	1	1	1	1
	Total influence of CPCs		9.2	9.2	9.2	9.2
HFE_2	Adequacy of organization	Inefficient	1.2	1.2		
	Working condition	Compatible	1	1		
	Adequacy of MMI and operational support	Supportive	0.5	0.5		
	Availability of procedures / plans	Inappropriate	2	2		
	Number of simultaneous goals	Fewer than capacity	1	1		
	Available time	Adequate	0.5	0.5		
	Time of day	Night time	1.2	1.2		
	Adequacy of training and experience	Adequate, limited experience	1	1		
	Crew collaboration quality	Inefficient	1	1		
	Total influence of CPCs		9.4	9.4		
HFE_3	Adequacy of organization	Inefficient	1	1	1.2	
	Working condition	Incompatible	2	2	2	
	Adequacy of MMI and operational support	Supportive	0.5	1	0.5	
	Availability of procedures / plans	Inappropriate	2	1	2	
	Number of simultaneous goals	Fewer than capacity	1	1	1	
	Available time	Adequate	0.5	0.5	0.5	
	Time of day	Night time	1.2	1.2	1.2	
	Adequacy of training and experience	Adequate, limited experience	1	1	1	
	Crew collaboration quality	Inefficient	1	1	1	
	Total influence of CPCs		10.2	9.7	10.4	

Table 19 - The Adjusted CFP for Each Task Step and the Final CFPs for HFEs

HFE	Task step or activity	Basic CFP Value	Total Influence of CPCs	Adjusted CFP	Final CFP (i.e., HEP)
HFE_1	Ensure return mud flow is getting high.	3.0E-3	9.2	2.76E-2	2.76E-2
	Ensure BSR does not be closed and sealed.	3.0E-3	9.2	2.76E-2	
	Ensure annulus does not sealed.	3.0E-3	9.2	2.76E-2	
	Ensure formation fluid does not rise.	3.0E-3	9.2	2.76E-2	
HFE_2	Remotely operated vehicle (ROV) intervention	5.0E-4	9.4	4.70E-3	4.70E-3
	Lower marine riser package disconnect	5.0E-4	9.4	4.70E-3	
HFE_3	Ensure BOP is unavailable.	3.0E-3	10.2	3.06E-2	9.70E-2
	Decision making for well disconnect.	1.0E-2	9.7	9.70E-2	
	Push two buttons for well disconnect	5.0E-4	10.4	5.20E-3	

3 Method Comparison and Summary

Here, we offer brief insights on the methods, based on the example analysis for the three HFEs. The final HEPs for the three HFEs across the three HRA methods are found in Table 20. As can be seen, Petro-HRA exhibits an overall very conservative tendency across the HFEs. SPAR-H and CREAM exhibit slightly less conservatism but do not offer good inter-method agreement. Generally SPAR-H proved more conservative than Extended CREAM, but the SPAR-H HEPs were comparable to the screening values produced by Basic CREAM. SPAR-H and Petro-HRA proved easier to estimate than CREAM, with fewer steps toward quantification, but CREAM provided greater consideration of factors to consider in the analysis, potentially offering a more nuanced account of the event.

Table 20 - Final HEPs Produced by the HRA Methods for the Three HFEs

HRA Method	HFE_1: Detect	HFE_2: Recovery	HFE_3: Disconnect
SPAR-H	1.10E-1	4.22E-1	6.14E-1
Petro-HRA	1.0	1.0	1.0
CREAM	2.76E-2	4.70E-3	9.70E-2

This article stops short of providing recommendations to use specific HRA methods. The example retrospective analysis is a single snapshot of the methods, and a large-scale benchmark of HRA methods for oil and gas applications has not yet been performed. As part of a benchmark, no comparison has been performed to demonstrate consistency of analysts using these methods for offshore applications, meaning the inter-analyst variability is not well understood. Moreover, the HEPs have not been validated, and it is not possible to say that a particular method has more accurately quantified the event. Still, some recommendations can be extracted from the sample application of the methods:

- For quick analysis, SPAR-H and Basic CREAM provide a succinct and seemingly conservative approach to quantify the HEP.
- There is still limited application of Petro-HRA for retrospective analyses of events that have occurred, and more experience and guidance are warranted.
- Petro-HRA provides the most complete guidance on formulating the HFE compared to SPAR-H and CREAM. If no HFE has been defined in the underlying PRA, the Petro-HRA guidance should be consulted.
- All three HRA methods considered here use some form of PSFs to quantify nominal HEPs. While these PSFs may be slightly different in wording, it is easy to crosswalk the PSFs to account for the main performance drivers in comparable ways.
- Petro-HRA has only a single nominal HEP, SPAR-H has two, and CREAM has multiple. Where consideration of nominal conditions is important, a more nuanced version of the nominal HEPs may be helpful to the analyst such as is found in CREAM.
- The terminology in SPAR-H is the most nuclear specific of the three methods and may require some degree of interpretation and extrapolation to match to petroleum contexts.
- Petro-HRA is well aligned with petroleum tasks, but it proved very conservative, producing HEPs equal to 1.0 for all three HFEs.
- CREAM proves a flexible method that works well in the oil and gas domain.

Thus, the use of particular HRA methods represents tradeoffs. Analysts should be aware of these tradeoffs and ensure that HRAs performed with these methods are credible in their outputs. Likely, no HRA method serves all oil and gas applications equally. Thus, the selection of the particular HRA method must be based on analyst insights into the best method for that analysis. Additionally, there clearly remains research to be done on the use of HRA methods for retrospective analysis in the oil and gas industry. The findings of this comparison point to the need to validate and refine HRA methods for petroleum purposes. Still, there is considerable value in the methods, and they can be readily used to support retrospective analysis with varying degrees of conservatism.

4 Disclaimer

This work was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government, nor any agency thereof, nor any of their employees makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately-owned rights. Idaho National Laboratory is a multi-program laboratory operated by Battelle Energy Alliance LLC, for the United States Department of Energy under Contract DE-AC07-05ID14517.

5 References

1 Bell, B.J., Holroyd, J., Review of human reliability assessment methods, RR679, Health and Safety Executive, Buxton, UK, 2009.

2 Boring, R.L., Adapting human reliability analysis from nuclear power to oil and gas applications, in Podifilini et al. (Eds.), Safety and reliability of complex engineered systems, pp. 2853-2860, Taylor & Francis, 2015.

3 Swain, A.D., Guttmann, H.E., Handbook of human reliability analysis with emphasis on nuclear power plant applications, final report, NUREG/CR-1278, U.S. Nuclear Regulatory Commission, Washington, DC, 1983.

4 Electric Power Research Institute, An approach to the analysis of operator actions in probabilistic risk assessment, TR-100259, Palo Alto, 1992.

5 Gertman, D., Blackman, H., Marble, J., Byers, J., Smith, C., The SPAR-H human reliability analysis method, NUREG/CR-6883, U.S. Nuclear Regulatory Commission, Washington, DC, 2005.

6 U.S. Nuclear Regulatory Commission, Technical basis and implementation guidelines for a technique for human event analysis (ATHEANA), NUREG-1624, Rev. 1, Washington, DC, 2000.

7 Boring, R.L., Gertman, D.I., Atomistic and holistic approaches to human reliability analysis in the U.S. power industry, Safety and Reliability Journal, Vol. 25, No. 2, (2005), pp. 21–37.

8 Forester, J., Kolaczkowski, A., Lois, E., Kelly, D., Evaluation of human reliability analysis methods against good practices, NUREG-1842, U.S. Nuclear Regulatory Commission, Washington, DC, 2006.

9 Chandler, F.T., Chang, Y.H.J., Mosleh, A., Marble, J.L., Boring, R.L., Gertman, D.I., Human reliability analysis methods: Selection guidance for NASA, NASA Office of Safety and Mission Assurance Technical Report, Washington, DC, 2006.

10 Hollnagel, E., Cognitive reliability and error analysis method – CREAM, 1st ed., Elsevier Science, 1998.

11 Kirwan, B., Gibson, H., Kennedy, R., Edmunds, J., Cooksley, G., Umbers, I., Nuclear action reliability Aasessment (NARA): A data-based HRA tool, Safety & Reliability Journal, Vol. 25, No. 2 (2005), pp. 38-45.

12 Aven, T., Sklet, S., Vinnem, J.E., Barrier and operational risk analysis of hydrocarbon releases (BORA-Release), Part I, Method description, Journal of Hazardous Materials, Vol. A137, (2006) pp. 681–691.

13 Bye, A., Laumann, K., Taylor, C., Rasmussen, M., Øie, S., van de Merwe, K., Øien, K., Boring, R., Paltrinieri, N., Wæro, I., Massaiu, S., Gould, K, *The petro-HRA guideline,* The Research Council of Norway, Lysaker, Norway, 2017.

14 Institute for Electrical and Electronics Engineers, Guide for incorporating human reliability analysis into probabilistic risk assessments for nuclear power generating stations and other nuclear facilities, IEEE-Std-1082, New York City, 2017.

15 Gould, K.S., Ringstad, A.J., van de Merwe, K., Human reliability analysis in major accident risk analyses in the Norwegian petroleum industry, Proceedings of the 56th Annual Meeting of the Human Factors and Ergonomics Society, (2012), pp. 2016-2020.

16 Transocean Investigation Report, Macondo well incident, Volume I, June 2011.

17 Boring, R.L., Rasmussen, M., Ulrich, T.A., Blackman, H.S., Retrospective application of human reliability analysis for oil and gas incidents: A case study using the Petro-HRA method, Proceedings of the 61st Annual Meeting of the Human Factors and Ergonomics Society, (2017), pp. 1653-1657.