DYNAMICIZING THE SPAR-H METHOD:
A SIMPLIFIED APPROACH TO COMPUTATION-BASED HUMAN RELIABILITY ANALYSIS

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In this paper, we discuss the adaptation of the Standardized Plant Analysis Risk-Human (SPAR-H) human reliability analysis (HRA) method to dynamic risk modeling. SPAR-H was developed as a worksheet-based method in which human reliability analysts assign the appropriate level of influence for performance shaping factors (PSFs). These PSFs then serve as multipliers to calculate the human error probability. In the adaptation presented here, PSFs are auto-calculated based on plant parameters and scenario context. Auto-calculation enables the dynamicized version of SPAR-H to be coupled to thermo-hydraulic code to estimate event outcomes. The approach demonstrates the value of adapting existing static HRA methods for dynamic modeling.

I. BACKGROUND

The U.S. Department of Energy's Light Water Reactor Sustainability (LWRS) program partners with industry and utilities to deliver research and practical technologies to help extend the life of the current U.S. operating fleet of commercial nuclear power plants (NPPs). Within LWRS, the Risk-Informed Safety Margin Characterization (RISMC) pathway systematically characterizes ways to maintain and optimize the safety and reliability of NPPs. Research includes development of new codes and frameworks to support the intersection of probabilistic risk assessment (PRA) and plant operating parameters as can be characterized through thermo-hydraulic modeling. For example, the Risk Analysis Virtual Environment (RAVEN) code[1] serves as a software tool to couple dynamic PRA models with Reactor Excursion and Leak Analysis (RELAP)[2] thermo-hydraulic modeling.

Because NPPs are not fully automated, accounting for the human operation of the plant is essential to achieve high-fidelity simulation. For example, the timeliness and reliability of operator response can determine the ultimate success or failure of various plant processes, which can affect safety outcomes. For this reason, dynamic human reliability analysis (HRA) has been integrated into the RISMC program of research. In order to create accurate models of plant performance, it is essential to include operator simulation.

The Human Unimodel of Nuclear Technology to Enhance Reliability (HUNTER; see Fig. 1)[3] serves as a framework for gathering HRA methods and models to interface dynamically with RAVEN. Many dynamic HRA approaches exist in various stages of implementation,[4] and the development of the HUNTER framework is decidedly not to create a new dynamic HRA method. The complexity of a completely rendered dynamic HRA model, which requires modeling human cognition and decision making, can verge on the intricacies of artificial intelligence. These approaches may require long-term research efforts to reach fruition. The HUNTER framework is designed to be scalable to incorporate rich dynamic models of HRA like The Information-Decision-Action-Crew (IDAC) method.[5] However, in an effort to meet immediate modeling needs, the HUNTER framework necessarily considers simplified approaches to dynamic HRA. In fact, the term *unimodel*—the *U* in HUNTER—refers to a simplified model of cognition or decision making. HUNTER uses simplified approaches to dynamic HRA as a stepping stone to richer modeling. The goal is to realize dynamic operator models in terms of timing and reliability quantification that can augment dynamic PRA approaches.

Because there is an emphasis not just on the temporal evolution of modeled scenarios, which are synonymous with the term *dynamic*, the HUNTER framework is considered computation-based HRA (CoBHRA). CoBHRA considers timing and other dimensions in modeling the operator. More importantly, it uses computational models linked through RAVEN to derive its quantification. For the sake of simplicity, the term *dynamic* is maintained throughout this paper.

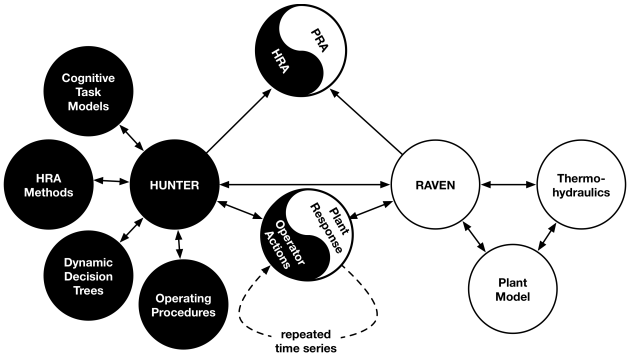

Fig. 1. The HUNTER HRA framework.

II. ADAPTING SPAR-H

II.A. The Standard SPAR-H Process

The HUNTER team set out to find a streamlined or simplified approach to CoBHRA. As a first approximation, HUNTER incorporates a dynamicized version of a static HRA method. The Standardized Plant Analysis Risk-Human Reliability Analysis (SPAR-H) method[6] is a worksheet-based HRA method that uses nominal human error probabilities (HEPs) for cognition (a.k.a., Diagnosis) and execution (a.k.a., Action) tasks. These nominal HEPs are modified by multipliers corresponding to levels of eight performance shaping factors (PSFs) as defined briefly in Table 1.

It is worth mentioning that the SPAR-H PSFs are not completely independent from one another.[7] A high workload situation, for example, will affect both Stress and Complexity. Procedures cannot compensate for poor Training or Experience nor a poor Human-Machine Interface (HMI). A poor HMI will greatly increase the Complexity and likely decrease the Time Available to complete the task. The interrelatedness of PSFs is not a unique challenge to SPAR-H, but it requires analyst expertise and finesse to avoid double-counting effects.

In a conventional analysis, using the SPAR-H worksheets, a human reliability analyst will complete the analysis of a particular event or scenario in order to calculate the HEP. Typically, the PRA will provide a predefined human failure event (HFE). In fact, SPAR-H as published in NUREG-6883[6] is a support tool for the SPAR models, which are plant models used by the U.S. Nuclear Regulatory Commission to review plant risk. For the HFE, the determination is first made by the analyst if the human activity is predominantly Diagnosis or Action (or a combination of both). Then the eight PSFs are evaluated to determine their level of influence on the outcome of the HFE. The SPAR-H multipliers associated with the level of influence may either increase or decrease the HEP. If a PSF has no effect, its multiplier is set to 1, meaning it will not change from the nominal HEP when multiplied. The HEP is simply the product of the nominal HEP and all applicable PSF multipliers. Correction factors are applied when there are multiple PSFs that increase the HEP, to ensure the HEP is truncated at a maximum of 1.0. The HEP may also be adjusted for dependence between HFEs when there is a sequence of human activities.

TABLE I. SPAR-H PSFS and Definitions

PSF	**Brief Definition**	**Multiplier Range**[1]
Available Time	Amount of time that an operator or crew has to diagnose and act upon an abnormal event.	0.01 – ∞
Stress/Stressors	Level of undesirable conditions and circumstances that psychologically impede the operator from easily completing a task.	1 – 5
Complexity	How difficult the task is to perform in the given context.	0.1 – 5
Experience/Training	Years of experience of the individual or crew, whether or not the operator/crew has been trained on the type of accident, the amount of time passed since training, and the experience and training with specific systems.	0.5 – 10
Procedures	Existence, quality, and use of formal operating procedures for the tasks under consideration.	0.5 – 50
Ergonomics/HMI[2]	Equipment, displays and controls; layout, quality and quantity of information available from instrumentation; and the interaction of the operator/crew with the equipment to carry out tasks.	0.5 – 50
Fitness for Duty	Whether or not the individual performing the task is physically and mentally fit to perform the task at the time.	1 – ∞
Work Processes	Aspects of doing work, including inter-organizational, safety culture, work planning, communication, and management support and policies.	0.8 – 2

[1] Multipliers are from the At-Power worksheet in SPAR-H. Multipliers differ between Diagnosis and Action. The infinity multiplier (∞) effectively sets HEP = 1.0.

[2] HMI refers to human-machine interface.

II.B. Dynamic SPAR-H

The nature of a dynamic HRA approach is that the analysis can dynamically change as the context in a scenario does. In a traditional HRA approach the contextual impacts on a scenario are evaluated and attributed by a human reliability analyst. While it would be possible to have an analyst do this dynamically through a scenario, it is likely to be a very resource demanding task. This is particularly true if the HRA is matched with a simulated scenario that runs thousands of times. To avoid this problem, dynamicizing SPAR-H entails finding ways to remove the manual assessment by the analyst. The HUNTER team has developed two approaches for dynamicizing SPAR-H:

- *Surrogate distribution model:* In the absence of prior information to determine the proclivity of the PSF multiplier, a distribution of possible outcomes for each of the PSFs can serve to model the range and frequency of HEPs. SPAR-H PSF multipliers have been computed based on distributions of assignments made by HRA experts across a variety of events.[8,9]
- *Deterministic model:* In this approach, the PSF multiplier is auto-calculated based on available information, particularly plant parameters. Similar work on auto-calculating PSFs was done within the IDAC method.[10,11] A primary difference in the approaches is that here we focus on adapting an existing, simplified HRA method for dynamic modeling. In contrast, IDAC is a standalone dynamic HRA method. In our SPAR-H modeling, for example, we have used plant parameters to calculate a measure of task complexity that is calibrated to the range of multipliers in SPAR-H.[12,13] This approach can, of course, be made stochastic by introducing variability into the calculation process to reflect individual differences in operator performance or even variability in assignments by human reliability analysts.

This paper focuses on the deterministic model of auto-calculated SPAR-H PSFs. The goal of developing such a model may be seen as creating either a *virtual operator* or a *virtual analyst*.[14] While a complete implementation of HUNTER would approximate a virtual operator, the simplified nature of SPAR-H is more akin to modeling a virtual analyst. A major limitation of this research is that SPAR-H does not consider decision-making at a level where it could be prescriptive of operator actions. The SPAR-H analyst speculates on what the operator is presumed to have done or will do, but the method does not detail the operator's cognitive mechanisms at such a level that breaks free of subjectivity by the analyst. A virtual operator model would feature decision-making algorithms that could guide courses of action and also establish the likelihood of different outcome paths and event sequences. For example, in A Technique for Human Event Analysis (ATHEANA),[15,16] a detailed static HRA method, there are techniques to anticipate the types of decisions operators will take. Such an approach, if modeled dynamically, would reflect an operator model of decision-making. In contrast, SPAR-H is mainly concerned with how PSFs overall influence outcomes but not with the mechanisms that lead to those outcomes step-by-step. A dynamicized ATHEANA model that automated decision-making could be a virtual operator model. Because SPAR-H is simplified, it requires greater infilling of details by the analyst. A dynamicized SPAR-H model is a virtual analyst model, meaning the event cannot drive itself and must be guided by analyst or modeler inputs.

As noted, the HUNTER framework serves to couple different HRA approaches. We have substituted a more complete list of task types for the two nominal task types (i.e., Diagnosis and Action) in SPAR-H. The Goals, Operators, Methods-Selection rules (GOMS) task analysis approach[17] was adapted for dynamic HRA to become GOMS-HRA.[18] The GOMS-HRA task types can readily be mapped to operating procedures,[19] provide more nuanced nominal HEPs corresponding to a wider variety of task types,[18] and provide empirically derived timing data for modeling required time for task completion.[20] The use of GOMS-HRA for task types is not strictly necessary for a dynamic adaptation of SPAR-H but helps align SPAR-H more closely with the subtask-level modeling typical in dynamic HRA rather than the HFE-level modeling typical in static HRA.[21]

II.B. Implications of Internal and External PSFs for Auto-Calculation

Already in the first HRA method, the Technique for Human Error Rate Prediction (THERP),[22] there was discussion of *internal vs. external PSFs*. In THERP, Swain and Guttmann made the following distinction (p. 2-5):

> The external PSFs include the entire work environment, especially the equipment design and the written procedures or oral instructions. The internal PSFs represent the individual characteristics of the person—his skills, motivations, and the expectations that influence his performance.

In slightly different parlance, external PSFs are those things in the environment that act upon the individual to influence performance, while internal PSFs are those things the individual brings to the situation. Environmental and task considerations may be considered external, while psychological considerations may be considered internal.

A third class of PSFs is found in *stress*, in which external stressors cause internal psychological and physiological stress. In other words, stress bridges external and internal considerations. Swain and Guttman[22] suggest that when there is a match between the external PSFs like situational and task characteristics and internal PSFs, this can serve to optimize performance through good or facilitative stress. In contrast, when there is a mismatch between external and internal PSFs, this can serve to decrease performance by inducing negative or disruptive stress. In other words, external PSFs serve as task demands for the mental states brought to bear by the individuals.

The overlap of external and internal PSFs around stress is reflected in SPAR-H by designating a PSF as *Stress/Stressors*—corresponding to internal stress and external stressors.

While the classification of internal vs. external PSFs is helpful for analysts in their understanding of a scenario, this distinction is rarely used in the implementation of HRA methods. HRA methods do not typically classify PSFs according to an internal-external taxonomy that affects the manner in which the analysis is performed. Perhaps the main legacy of this duplicity in THERP is to remind analysts to apply psychological as well as situational and plant insights when performing an HRA. In other words, HRA requires an understanding of the process and system—the external PSFs—as well as the psychology—the internal PSFs—of those interfacing with that process and the system. The distinction between internal and external PSFs becomes meaningful in dynamic HRA.

SPAR-H does not classify PSFs as internal or external, although it would be possible to do so as depicted in Table 2. Doing so does not, however, have any bearing on the analysis except inasmuch as the analyst uses knowledge about particular factors to select the appropriate level of the PSF influence. There is no separate analysis path prescribed for internal or external PSFs. In fact, SPAR-H provides separate considerations for each PSF, irrespective of the internal or external nature of that PSF.

When dynamicizing PSFs, such as the SPAR-H approach discussed in this paper, distinguishing between internal or external PSFs becomes a crucial consideration. The reason for this is that the way of auto-calculating the influence of PSFs is quite different for internal vs. external PSFs. An external PSF is one that should be readily derivable from objective and observable parameters of the process or system. An internal PSF requires a psychological model of the operator and can likely not be readily deduced or inferred from these process or system parameters. Additionally, internal PSFs may vary due to individual differences, more so than is the case with external PSFs. Thus, there is greater modeling uncertainty associated with internal PSFs.

TABLE II. Internal and External PSFs in SPAR-H

PSF	External	Internal
Available Time	✓	
Stress/Stressors	✓	✓
Complexity	✓	
Experience/Training		✓
Procedures	✓	
Ergonomics/HMI	✓	
Fitness for Duty	✓	✓
Work Processes	✓	✓

SPAR-H has broad definitions of PSFs that may span both internal and external considerations. In our classification, three PSFs can be considered both external and internal:

- *Stress/Stressors*—As already noted, this PSF straddles both internal and external elements. Stress is the internal manifestation of external stressors imposed on the individual. The psychological response of stress to the same stressors may vary considerably across individuals.
- *Fitness for Duty*—In most cases, fitness for duty is a condition brought to work by the individual. However, there are cases when fitness may be degraded as a result of the work environment. Extreme environmental conditions such as high heat can predictably degrade the physical abilities of individuals. Likewise, long work shifts such as might be present during an emergency without adequate relief personnel would result in extreme fatigue.
- *Work Processes*—Much of this is internal to the individual, but it may be imposed on the individual by the culture or work culture. Thus, culture becomes internalized in the individual, even when it is strongly rooted in external expectations and requirements.

Additional PSFs might under some interpretations be both internal and external. For example, if time pressure is considered as a dimension of the Available Time PSF, this would clearly be an internal facet of the PSF. Task complexity is clearly external, but aspects of cognitive complexity such as the amount of mental effort expended might be considered internal.[23] Such definitions stretch the originally intended meanings of the SPAR-H PSFs, and we have retained definitions as formally defined in SPAR-H.[6]

Below are each of the external PSFs in SPAR-H and a brief discussion of considerations for auto-calculation:

- *Available Time*—SPAR-H discusses available time in terms of the ratio of required time to available time. The difference between the total available time and the required time is the time margin, which is used by the analyst to select the appropriate PSF level. The available time, which can be calculated using thermo-hydraulic software, is simply the time until the system becomes unavailable, meaning the time until the system fails. Calculating the required time by the operators has been a challenging task, which has entailed methods from walkthroughs to subjective time estimation. To address the potential subjectivity and uncertainty in estimating how long it will take operators to complete tasks, the HUNTER team used empirical data from simulator studies to arrive at time distributions for individual task types modeled in GOMS-HRA.[20] These provide a credible basis of estimate for required time and thereby enable auto-calculation of the Available Time PSF.
- *Complexity*—SPAR-H considers task complexity, which may be seen contextually as the product of how much is being done. Plant parameters—particularly when many values deviate from the desired state—are a good indication of how much needs to be done to bring the plant into alignment. Using a regression equation of plant parameters, the HUNTER team has been able to create an auto-calculation of Complexity that outputs values normalized to the SPAR-H multipliers.[12,13]
- *Procedures*—In contemporary practice, operating procedures in main control rooms are the product of decades of development and vetting. While this history does not preclude issues, quality symptom-oriented procedures are one of the hallmarks of NPP operations. Thus, the quality of procedures may generally be assumed to be a constant, positive value. Exceptions arise for beyond-design-basis events that are simply not within the scope of the procedures or for situations in which faulty or misleading instrumentation may drive operators to use the wrong procedures. The amount of time spent on a procedure—particularly looping back through the procedure—becomes an indicator of problems. Additional cues for modeling procedures dynamically are the number of active procedures, whereby a large number of concurrent procedures may suggest difficulty completing all tasks. The HUNTER team has begun using text mining of operating procedures in combination with the GOMS-HRA approach.[24] By mapping procedure steps to operator actions,[19] it is possible to gauge the number of tasks required as well as their overall complexity and error proneness.
- *Ergonomics/HMI*—SPAR-H primarily emphasizes the quality of the human-machine interface, including availability of required information to complete particular tasks. Assuming a fully functional and adequate HMI, this PSF would not be something that would change dynamically throughout a scenario.[a] In the event of failed instrumentation, however, this PSF becomes an important consideration and should be modeled to increase the HEP in the face of degraded instrumentation at the plant. Some aspects of HMI design—like the quality of visual alarm placement, the intuitiveness of menu design, and other usability considerations—may prove difficult to derive and quantify automatically. Regarding the first part of the PSF, *Ergonomics*—the physical interaction with the system—does bring with it some internal PSF considerations such as the adequacy of strength to crank a large valve wheel. Where Ergonomics as a function of individual physiological limitations becomes a limiting function to the completion of the task, we believe this effect may be best modeled under the Fitness for Duty PSF.

Beyond these PSF-specific insights, we also provide three overarching considerations when modeling external PSFs:

- *PSF dynamics.* As noted in Boring,[25] there are three types of PSF modifications. When PSFs remain constant across the events in the scenario, that represents a *static condition*. When PSFs evolve across events in a scenario, that represents a *dynamic progression.* Finally, a sudden change in the scenario may cause sudden changes in the PSFs, which is referred to as a *dynamic initiator*. Some external PSFs like Complexity may be seen as a direct and dynamic function of plant parameters. Other PSFs like Ergonomics/HMI may remain largely invariant across scenarios and may essentially be a static condition. Such PSFs, whether external or internal, may be better served by setting them once during a scenario run rather than building a dynamic model. Where little change is expected, a priori setting of the PSF in the overall HRA framework may be sufficient.
- *PSF validation.* It is possible to build a multiple regression model that links plant parameters to PSF multipliers without consideration of psychological plausibility. However, the engineering of PSFs should always be grounded in the natural laws of psychology. The first approximation of PSFs should be informed by an understanding of psychological relationships and experience with human performance. First-order models may then be refined

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[a] While the HMI itself might not change, the multiplier produced by the PSF could, e.g., if the HMI is no longer providing the relevant information for the operator to diagnose what is going on in the face of the evolving scenario.

and calibrated, but they should always be validated for reasonableness as a psychological approximation of operator performance.

- *PSF calibration.* One unique aspect of dynamicizing an existing static HRA method is that the values the dynamic model produces must align to the static values. In the case of SPAR-H, the multipliers calculated dynamically should fall within the range of values that an expert analyst would produce. This is not to say that the dynamic model must produce the step function common to SPAR-H multipliers, but the values should anchor to those values. To ensure that calibration is generalizable beyond a specific scenario, the model should be tested against a range of scenarios and accompanying parameters.

Internal PSFs are, by definition, not easily observed, because they constitute mental phenomena that may not overtly manifest. In fact, internal PSFs may often only be measured indirectly, according to their effects on other measurable phenomena. Because many indirect PSFs are not clearly mapped to other measurables,[26] there remains considerable research before these PSFs may be operationalized as dynamic models. An additional challenge is for internal PSFs occurs when the effects of mental phenomena lag in terms of performance effects, or linger past any definitive cause.[27] For example, stress may build over time—not manifesting deleterious effects on performance until a certain threshold level is crossed. Stress may also not dissipate immediately when the cause of stress disappears.

Because it is not possible simply to map plant parameters to arrive at the dynamic level of internal PSFs, the HUNTER team has developed several strategies for modeling internal PSFs:

- *Nominal bias.* Many mental phenomena and psychological traits are enduring despite changing contexts. As such, internal PSFs may prove somewhat less variant over time and scenarios than their external counterparts. One way to address this is to anchor internal PSFs toward either an a prior assignment or toward the nominal level. In our modeling, internal PSFs are biased to nominal values, only changing when there are clear indications to shift the PSF state. For example, good experience and training is assumed in SPAR-H as the norm for operators at nuclear power plants. A nominal level assumption for the Experience/Training PSF is warranted in most circumstances, and this level would not tend to change without a dynamic initiator that forced operators out of their competence.
- *Characteristics profiling.* While it may not be straightforward to map the flow of scenario changes to the internal aspects of the Work Processes PSFs, there may be certain characteristics that define poor work processes. These characteristics essentially become parameters specifically configured for mapping internal PSFs. The parameters may not be linked to plant parameters, meaning the modeler must define how these evolve over time or over different contexts. Certain decision points in the procedures may invoke consideration of the characteristics—and the model may actually flag the modeler to provide manual input. Alternately, once certain contexts (e.g., certain types of procedures) are understood and modeled, it becomes possible to form a profile for those contexts, and future matches to those contexts may result in a particular reconfiguration for the internal PSF.
- *Trigger points.* This concept is related to the previous discussion of characteristics profiling. Trigger points simply result when certain contexts (i.e., certain groupings of internal parameters) are met, resulting in a change to the PSF level. The PSF level may not adjust on a continuous scale but rather have abrupt changes to match trigger points. For example, entering certain scenarios like a plant trip may trigger elevated Stress. This elevated Stress may not be a direct function of any specific plant parameters but rather an emergent property of the status of the plant.

Internal and external PSFs are synonymous with PSFs that respectively cannot or can be auto-calculated in a simplified model. To be realized as a continuous function, internal PSFs may require an operator model to match the plant model. This operator model would have internal parameters that could be mapped to performance levels in PSFs. Building an operator model represents a significant undertaking that exceeds the scope of a simplified dynamic model. Absent a cognitive model to drive internal PSF calculations, the HUNTER team has adopted the shorthand approach outlined above, in which specific cues trigger pre-defined PSF levels. This approach is analogous to template matching. While the dynamicized version of SPAR-H presented here is capable of auto-calculating several of the external PSFs, the approach uses lookup tables to map specific contexts to the levels of internal PSFs. Of course, mapping PSFs to exampled experiences may not deviate considerably from the process expert human analysts employ in SPAR-H.

III. SUMMARY

The HUNTER team has successfully adapted SPAR-H from a static HRA method to a dynamic approach. This approach provides a proof of concept of the opportunity to reuse static HRA methods in dynamic models. Further, this approach demonstrates the value of simplified dynamic HRA. There remain clear limitations to this example that highlight the importance of continued development of detailed dynamic HRA approaches like

IDAC.[5] Nonetheless, the approach shows promise, especially with respect to modeling external PSFs. The approach highlights the value of developing a virtual analyst capable of producing HEPs automatically. However, an ideal of dynamic HRA is the development of a virtual operator. A virtual operator will require not only a thermo-hydraulic plant model but also a psychological human model. The interface between internal operator parameters and external plant parameters will result in truly dynamic HRA. The dynamicized SPAR-H approach in HUNTER is indeed computation-based, but there remains more research to be done before it is truly model based across the spectrum of internal and external phenomena.

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