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A Multi-Methods Approach to HRA and Human Performance Modeling: A Field Assessment

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Abstract: During a review of the Advanced Test Reactor (ATR) safety basis at the Idaho National Laboratory, human factors analysts identified ergonomic and human reliability risks involving manual fuel handling in the ATR canal. An initial human reliability scoping study identified risks involving the inadvertent exposure of a fuel element to the air during manual fuel movement and inspection. There were clear indications that these risks increased the probability of human error and possible severe physical outcomes to the operator. In response to this concern, a detailed study was conducted to determine the probability of the inadvertent exposure of a fuel element. This study refined the previous HRA scoping analysis by determining the probability of the human failure event. The HRA analysis employed the SPAR-H method and was supplemented by information gained from a detailed analysis of the fuel inspection and transfer tasks. This latter analysis included ergonomics, work cycles, task duration, and workload imposed by tool and workplace characteristics, personal protective clothing, and operational practices that have the potential to increase physical and mental workload. Part of this analysis consisted of NASA-TLX analyses, combined with operational sequence analysis, computational human performance analysis and 3D graphical modeling to determine task failures and precursors to such failures that have safety implications. The application of multiple analysis techniques in support of HRA methods in this project helped to produce sufficient information to indicate that the postulated fuel exposure accident was less than credible.

Keywords: HRA, Human Factors Method, Computational Human Performance Modeling, Ergonomics

1. INTRODUCTION

The Advanced Test Reactor (ATR) at the Idaho National Laboratory is primarily used to perform tests on materials to be used in other, larger-scale and prototype reactors. The ATR canal has facilities to conduct underwater operations such as experiment examination or removal and also to temporarily store completed experiments and used fuel.

In reviewing the ATR safety basis, a number of concerns were identified involving the handling of fuel elements in the canal. The primary concern involved the inadvertent manual withdrawal of a fuel element from the water during the process of moving the fuel. Specifically, it was postulated that if the operator were to fall off the parapet onto the floor, such a fall could lead to the fuel being elevated high enough to surface out of the canal water. An abnormal radiological event like the accidental raising of an irradiated ATR fuel element out of the water such that it remains out of water long enough to melt the fuel element is of key importance because the canal is outside the confinement boundary. This means there would be a significant potential for exposure consequences to collocated workers and also off-site individuals.

In response to this postulated event, a preliminary human reliability analysis (HRA) was conducted to determine if the probability of having a fuel handling incident was lower than 1.0E-5 (less than 1 in 100,000) and if not, if there were physical and administrative barriers that could be implemented to achieve <1.0E-5.
During on-site observations of the fuel handling task for the purpose of the HRA, several ergonomic issues were identified and it was noted in particular that manual handling of fuel by operators involved awkward body postures and tool angles that clearly increased the probability of an accident induced either by the work conditions or by human error. Such unwanted outcomes could lead to a safety and health event, equipment damage, and/or fuel assembly damage.

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As a result of these additional human factors concerns, the preliminary study was subsequently extended to a dual HRA and human factors investigation. This consisted of a study to analyze the physical and cognitive human factors issues that may affect human reliability and human performance. In particular, the HRA part of the study aimed to estimate the probability of inadvertently raising an irradiated ATR fuel element out of the canal long enough to melt and to determine what physical and administrative measures could be implemented to preclude such an event from occurring. To help support risk-informed decision-making, we chose to use workload assessment methods to inform HRA. To provide the information needed by the HRA, the analysts determined that a task analysis and a detailed study of the operational procedures and stressors associated with work practices should be conducted.

2. METHODOLOGY

The primary objective of the study was to determine the probability associated with the inadvertent exposure of a fuel element to the air during fuel movement and inspection. A number of objectives were formulated to support the HRA part of the study. This included a field observation of the canal operator's task which focused on the identification and recording of stressors that affected the operator performing the fuel handling. It was initially assumed that the stressors would include ergonomics, work cycles, task duration, workload imposed by tool and workplace characteristics, personal protective clothing, operational practices that have the potential to increase physical and mental workload. In a 2005 field study of human reliability in nuclear power plant control rooms, Carvalho [1] pointed out that "ergonomics has been trying to demonstrate that the cognitive flexibility, local and contingent knowledge developed by the operators can be an effective way to reduce and correct errors." This supported our decision to perform an assessment of the ergonomic and associated workload characteristics of the task. The ergonomic focus is also of interest to HRA in general because, while there have been some ex-control room studies, the majority of HRA performed focused on control room activities and additional ex-control room studies are needed to add to the existing data. The two parts of the study were subsequently performed on site in parallel.

Due to practical and safety constraints, it was not possible for the human factors team to perform a detailed ergonomic assessment and analysis of the canal operators' task. For example, safety requirements prevented analysts from approaching operators at the canal for close observation, nor was it possible to interrupt the task at certain stages for interrogation of the operators. It was found however that, because the task was governed by a strict procedure and operators followed a familiar work pattern, it would be possible to model the entire process computationally as a task network.

However, during initial observations a number of additional operational and environmental conditions were identified that influenced the development of an accurate task network. These included the psychophysical constraints imposed upon operators by the canal layout and various objects in the environment, the configuration of tools, the exact sequence of the operating procedure, and the varying levels of visual, cognitive and physical strain experienced by the operators during a fuel handling sequence. To ensure that these conditions were properly understood and factored into the study, it was further decided to perform five additional analyses that would all contribute to information needed for the HRA. These methods are summarized below.

2.1 Ergonomic Assessment

As pointed out earlier, it was not possible to intervene in the task of the canal operator. It was therefore decided to conduct a detailed naturalistic observation of the operators in their natural work environment. This was necessary because the situation made laboratory research impractical, cost prohibitive and it would have affected the operators' behavior. A video recording of the entire task was made with the consent of the participants and management. Because the observation was conducted in the actual work environment, it helped to support the ecological validity of the study.

It should be noted that, although performance shaping factors such as heat, physical workload and ergonomic layout could contribute to variations in tool manipulation and misplacement, they were not contributors to fuel element exposure.

2.2 NASA-TLX Analysis

The NASA-TLX method is a multi-dimensional subjective rating process that derives an overall workload score based on a weighted average of ratings on six subscales that include Mental Demands, Physical Demands, Temporal Demands, Own Performance, Effort and Frustration. The analysis allows analysts to perform subjective workload assessments on operators working with various human-machine systems. In this study the main purpose was to find correlations between the NASA-TLX workload scores and the performance shaping factor (PSF) levels obtained from the SPAR-H analysis.

Three ATR canal operators and two trainees completed the self-report immediately after completion of the task. This was followed by a debriefing session by human factors analysts.

2.3 Operational Sequence Analysis

This is a powerful task analysis technique that combines events, information, actions, decisions, and data to capture the sequence of operator tasks, in relation to other concrete or abstract entities. The resulting graphic, called an Operational Sequence Diagram, provides a visual representation of the relationships between tasks and contextual triggers that is easier to understand than textual reports or conventional flow diagrams. The evolution and sequence of activities performed by the various actors are shown on a vertical timeline and the interaction between entities is shown as arrows from one to the other.

2.4 Task Network Modeling (TNM)

Task Network Modeling is a computational task analysis technique that is applied to available task information to determine if a task might be susceptible to high risk, uncertainty or human performance problems. The technique employs discrete-event simulation software for a range of human factors analyses, including prediction of operator performance, workload estimates and procedural simulations. Models developed with this system can represent tasks, operator characteristics, PSFs and the human's response to them, as well as other events in the task environment. Typically, such models produce results by averaging over many runs with random distribution of delays, event probabilities and failures. The technique allowed the analysts to perform a detail task analysis and to simulate and determine task failures and precursors to such failures that have safety implications. While it would have been possible to develop a conventional hierarchical task analysis from the observations, this would not have revealed the critical information obtained through TNM. In performing the TNM we selected Alion Science and Technology's Integrated Performance Modeling Environment (IPME) system that produces a prediction of performance (Dahn & Laughery [2]; Fowles-Winkler [3]; Keller [4]). Part of the basis for this system is Wickens' [5] multiple resource theory and the task resource demand concept of McCraken and Aldrich [6] that is implemented in the VACP (visual, auditory, cognitive, psychomotor) model. The VACP method uses task ratings and a method for estimating operator workload as a function of the interaction between the four channels (Sarno & Wickens [7]). This enables the analyst to pinpoint periods of high workload and investigate modifications to the system that might mitigate the level of workload for the operator. Because of the flexibility offered by the system, we decided to use this technique to analyze the physical as well as cognitive aspects of the fuel handling task.

In the development and analysis of the task models, each task was defined to a sufficient level to allow realistic physical and mental workload variables to be calculated. In IPME each task is assigned three sets of parameters:

- The operator who is assigned to perform the task.
- Task mean time and standard deviation based on a normal or gamma distribution curve.
- VACP workload values (assigned by selecting the most appropriate task type from the tables embedded in the IPME system).

Additionally, as part of input values, expert estimation was determined from the canal workers and supervisors for a number of potential errors, as shown in Findings and Results below.

2.5 Two- and Three-Dimensional Models

Two and three-dimensional models of the task environment were developed to analyze the basic physical features of the work environment. This included the typical work zones, the approximate locations where the operators perform the tasks, and measurements and approximate positions of tools when various stages of a task are performed. 3-D manikins were added to mimic the postures of the operators when performing tasks that were judged to be hazardous. The models were compared to and validated against video and still pictures of the real work environment.

Figure 1 shows the inspection fixture used by workers to examine individual fuel elements.

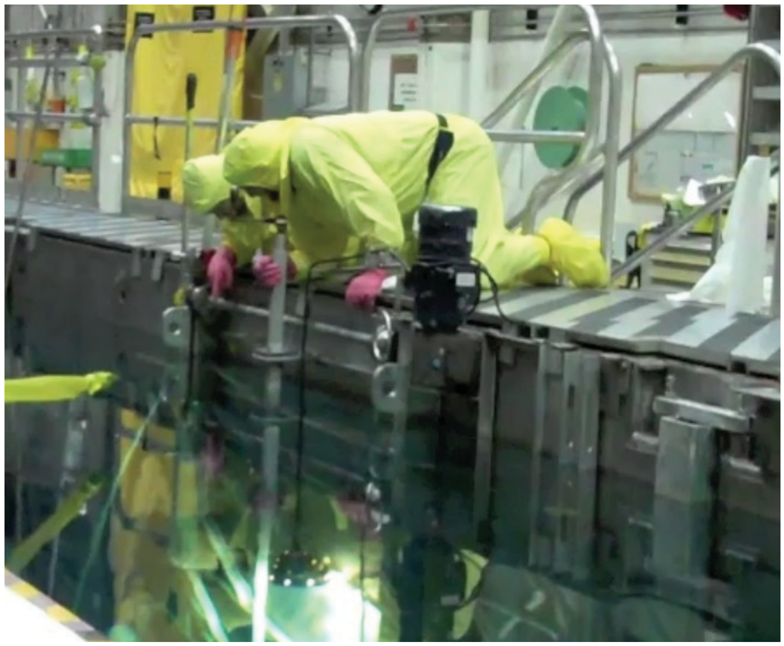

Figure 1: Use of inspection fixture to inspect fuel element under water

Figure 2 illustrates the 3D software-determined position of the two-man crew when using the positive latching tool. Upon inspection, the authors determined that there were no ergonomic issues with the latching tool, but the fuel inspection fixture presented some severe ergonomic challenges, as can clearly be seen from these images.

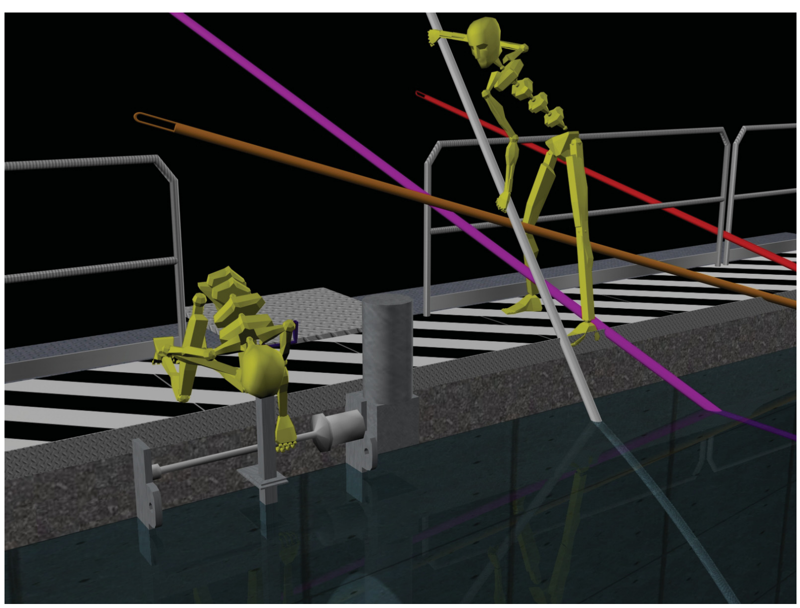

Figure 2: Operators at the inspection fixture and positive latching tool in various positions

3. FINDINGS AND RESULTS

3.1 Workload analysis results

Estimation of the severity of HEPs was based upon the judgement of experienced operators. The results of this *expert estimation* was used as part of the IPME model development and presented in Table 1 below:

Table 1: Human Error Probabilities

Item	Parameter	Probability
1	Debris found	<0.1
2	Tool dropped	< 0.01
3	Failed to lock pin	< 0.001
4	Fuel damaged	<0.001
5	Fuel element dropped (due to failure to lock pin)	< 0.0001
6	Slip/fall	<0.0001

Table 1 reveals that tool dropping or discovery of debris is relatively commonplace and are assessed as E-2 and E-1, respectively. However, slipping and falling is much less likely, estimated at E-4. As determined in subsequent analyses, slipping and falling is much more important in terms of raising fuel above water levels than is failure to engage the locking pin.

These inputs were then incorporated with results obtained from the workload analysis. Different tasks and configurations were run in the simulation. An example of a task posing a hazard to an individual operator is presented in Figure 3 – this is the IPME simulation output:

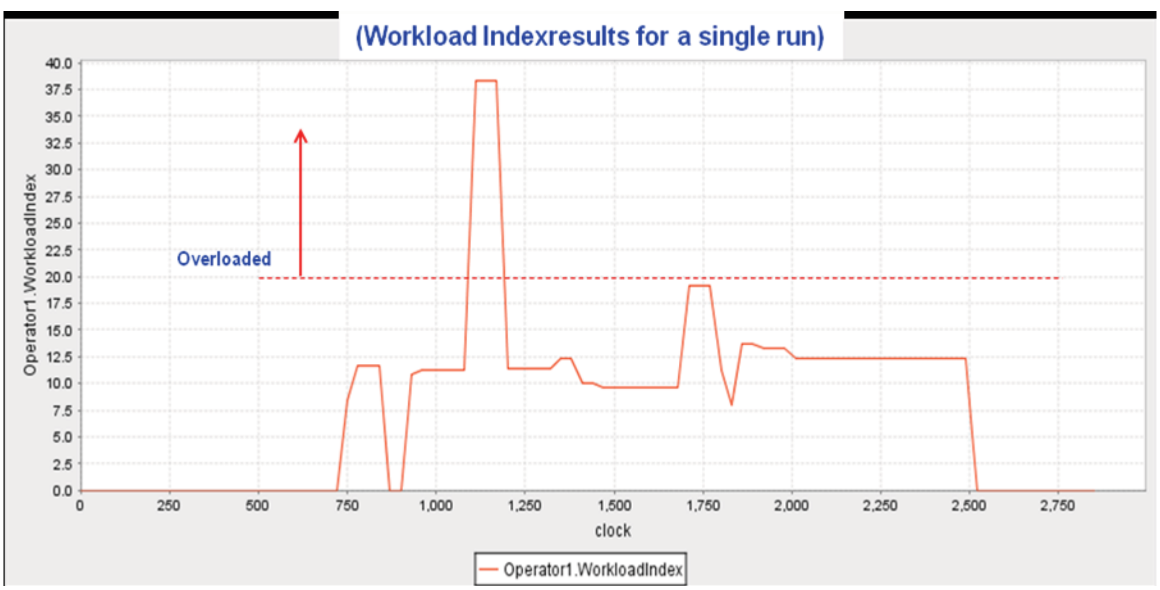

Figure 3: Workload Index Results for Fuel Handling Task

The overload peak shown in the graph is associated with specific task sequences shown in canal fuel handling with varying levels of VACP channel loading:

- Inspect plate 19 for damage –hazardous body position.
- Rotate inspection fixture –physically intensive, requires the most effort of all tasks.

- Inspect fuel element through bottom end box - visually intensive, with decision-making, coupled with hazardous body position

3.2 Application of SPAR-H

The SPAR-H human reliability analysis (NUREG/CR-6883 [9]) was used to qualitatively and quantitatively characterize human system performance associated with canal material handling. As part of that analysis the following performance shaping factors were assessed and used to modify base failure rates for errors of omission and commission: time available, stress, complexity, training, procedures, ergonomics, fitness for duty, and work processes. In general, the following assumptions were followed:

- The tasks performed are largely part of a manual process involving skill of the craft.
- A two person rule is in effect (that is, the "buddy system" that requires one person performing the task and one person assisting for safety).
- A Canal Supervisor and Radiological Control Technician are present during fuel moving operations.
- Procedures are available and used.

The authors verified these practices during observations of fuel moving operations. The use of specially designed tools was noted and interview and video data were collected regarding the entire work process. The canal operators used call-backs during fuel element identification and movement and followed proper procedures to wipe down and sleeve tools during and after work execution. A radiological control technician and canal supervisor were observed to be present during all work performed as prescribed by procedures.

Originally, there was only one failure of interest, namely the human error probability (HEP) for exposure of the fuel element. The one failure mode identified for exposing the fuel to the air was HEP1- Falling backward with fuel element lifting tool attached to fuel element.

A barrier analysis was performed for this HEP and it was found that the guardrail on the parapet effectively makes HEP 1 difficult to achieve. The length of the lifting pole and latching hook tool would require the operator to fall over backwards in order to expose the element to the air, with the guard rail in place and this would be extremely unlikely to occur. Further, the operator must fail to let go of the fuel tool while falling. Canal operator training, attention to safety and use of a 2-man rule also limits HEP1 even further so that operator falling backward, and holding on to the lifting tool at an angle sufficient to expose a fuel element is less than credible (<1.0 E-5).

Beyond this initial analysis, HRA was used to highlight a number of other failure modes and consequences that were of interest to fuel handling operations management. Each one of the potential failures presented below was evaluated for its potential impact upon safety and mission success:

- HEP2 - Falling forward into canal while turning the crank used for mechanical fuel inspection.
- HEP3 - Slipping or falling forward (into the canal) or back related to awkwardness of the workplace environment, i.e., ergonomics, the unique lifting tools being used, parapet design, or fatigue.
- HEP 4 - Tools being dropped in canal with repercussion.
- HEP 5 - Inappropriate relocation of fissile material (fuel) leading to hotter than anticipated areas within the fuel storage racks (possible mislocating, or misplacements due to lighting conditions, fatigue, failure to verify transfer or grid map sheets, etc.) including attempts to double load fuel elements into a single test storage cell.
- HEP6 - Attempts to move more than one fuel element at once leading to exposure etc.
- HEP7 - Scaling debris from fuel element nicks the element rendering it unusable.
- HEP 8 - Failure to use the positive latching tool properly resulting in dropped stack fuel or operator lifting without resistance and slipping and falling into canal.

- HEP 9 - Multiple fuel elements outside of approved storage area or conditions in violation of procedure.

From this list of failures, the second HEP of concern, HEP 2 (falling into the canal while leaning over the fuel canal and performing a fuel element inspection), was analyzed to be on the order of E-3. This failure mode also included an operator slip *into* the canal, HEP-1, which was limited to falls outside of the canal with the element attached). The exertion of turning a crank handle while leaning over the canal could give rise to the operator falling in, however, the second operator would have to fail to prevent the operator slipping. Figure 4 (PSF analyses for HEP 2 subtasks) clearly indicates that, although heat stress may be elevated due to performing operations while wearing personal protective equipment, ergonomics is the real cause for concern. Four subtasks were modeled (HEPs 1 – 4 shown in the graph), operator one falling in and the second operator failing to intervene, and operator one snagging the fuel tool and failing to let go and interrupt the fall. Operator two is only arms length away from operator one during the fuel inspection, and not actively involved in fuel handling (the "buddy system"). Stress was assigned a slightly higher rate to indicate the physiological state while falling and also an element of heat stress.

Values on the Y axis are multipliers used to adjust SPAR-H base failure rates.

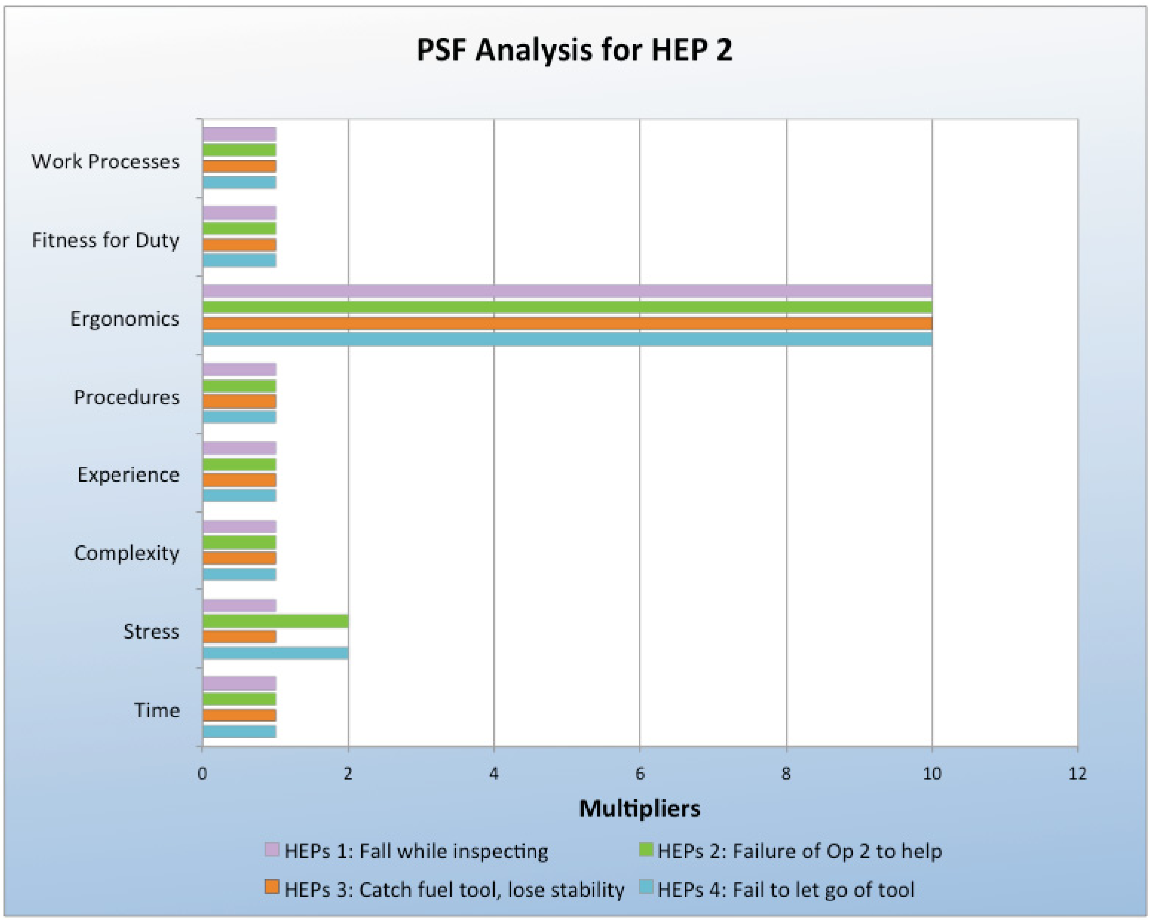

Figure 4: PSF analysis for Operator Falling Into Canal During Fuel Inspection for HEP 2

In performing the HRA, work processes were evaluated to be positive; canal operators stressed safety during pre-job briefings, during task execution and all stated that they were comfortable with stopping work should they be fatigued or anything appear unsafe. They stated that this was part of their training. Additionally, callbacks and verifications were followed.

HRA assessment of these HEPs was further aided by the use of 3D modeling, task analysis, computational performance modeling, naturalistic observations of work, and video recording and debrief. The combination of multi-methods yielded a more complete characterization than possible from any one method alone.

3.3 NASA-TLX results

The results from this workload self-assessment method confirmed the observations, interviews, and workplace ergonomic measurements, especially with regard to the physical demand of the fuel inspection task. In a 2007 study by Laux and Plott [8], it was demonstrated for the first time that PSF levels in SPAR-H correlate with workload as it is assessed by VACP and NASA-TLX. However, the nature of the relationship is not immediately obvious because of conceptual differences in the approaches to assessing workloads and deriving SPAR-H error probabilities. The NASA-TLX for the ATR study did suggest periods where workload was high in terms of physical demand (which correspond to SPAR PSF assessment for sub-optimal ergonomics and moderately high stress). In some instances operators also experienced high mental workload during inspection for debris on fuel elements. This information was captured in SPAR-H, but assigned to the ergonomics and stressors PSF categories where this information was used in conjunction with negative PSF loadings to reach a final value. Overall TLX findings correlated conceptually with the VACP and SPAR-H results and thus supported a conclusion that workload dimensions may contribute to the HEP. No direct link was made between the findings as in [8], but this could be the focus of future research.

4. CONCLUSION

The combined IPME computational human performance simulation in conjunction with 3D modeling, task analysis, and ergonomic analysis made it possible to make recommendations for improvement of various physical aspects of the task. For example, the fuel inspection task is visually intensive due to the fact that the fuel element is under water and can only be viewed from a distance of approximately 12 ft. Any method that would decrease the visual strain would not only decrease the time needed for a thorough inspection, but would also improve the reliability of the inspection. The model has highlighted the physical effort required to remove a fuel element from the storage grid at the far side of the canal. Any method that would decrease the physical strain would not only decrease the time needed for fuel transfer, but would also improve safety

The parallel investigation of the original postulated human failure event that had prompted this study was also concluded successfully. In fact, human performance modeling provided substantial empirical information that aided the analysis of the human error. The human reliability analysis concluded that the event for exposure of a fuel element during inspection and manual transfer operations was less than credible, with a probability of less than 1.0E-05.

This project demonstrated that discrete event simulation, combination with traditional HRA and ergonomic analysis can be a very effective method to perform task analyses and to examine process safety through the identification and analysis of human task failures as well as environmental factors that are most likely to occur and the points in the process most vulnerable to severe consequences.

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