Qualitative Human Reliability Analysis for Spent Fuel Handling

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Human reliability analysis (HRA) methods have been developed primarily to provide information for use in probabilistic risk assessments (PRAs) that analyze nuclear power plant (NPP) operations. Given the original emphasis of these methods, it is understandable that many HRAs have not ventured far from NPP control room applications. Despite this historical focus on the control room, there has been growing interest and discussion regarding the application of HRA methods to other NPP activities such as spent fuel handling (SFH) or operations in different types of facilities. One recently developed HRA method, 'A Technique for Human Event Analysis' (ATHEANA) has been proposed as a promising candidate for diverse applications due to its particular approach for systematically uncovering the dynamic, contextual conditions influencing human performance. This paper describes one successful test of this proposition by presenting portions of a recently completed project in which a scoping study was performed to accomplish the following goals: (1) investigate what should be included in a qualitative HRA for spent fuel and cask handling operations; and (2) demonstrate that the ATHEANA HRA technique can be usefully applied to these operations.

The preliminary, scoping qualitative HRA examined, in a generic manner, how human performance of SFH and dry cask storage operations (DCSOs) can plausibly lead to radiological consequences that impact the public and the environment. The study involved the performance of typical, qualitative HRA tasks such as collecting relevant information and the preliminary identification of human failure events or unsafe actions, relevant influences (e.g., performance shaping factors, other contextual factors), event scenario development and categorization of human failure event (HFE) scenario groupings. Information from relevant literature sources was augmented with subject matter expert interviews and analysis of an edited video of selected operations. Elements of NUREG-1792, Good Practices for Implementing Human Reliability Analyses (HRA) and NUREG-1624, Rev. 1, Technical Basis and Implementation Guidelines for A Technique for Human Event Analysis (ATHEANA) formed critical parts of the technical basis for the preliminary analysis. Misloading of spent fuel into a cask and dropping of a loaded cask were the two human failure event groupings of primary interest, although all human performance aspects of DCSOs were considered to some extent.

Of important note is that HRA is typically performed in the context of a plant-specific PRA study. This analysis was performed without the benefit of the context provided by a larger PRA study, nor was it plant specific, and so it investigated only generic HRA issues relevant to SFH. However, the improved understanding of human performance issues provided by the study will likely enhance the ability to carry out a detailed qualitative HRA for a specificNPP at some point in the future. Furthermore, support was obtained regarding the potential for applying ATHEANA beyond NPP settings. This paper provides a description of the process followed during the analysis, a description of the HFE scenario groupings, discussion regarding general human performance vulnerabilities, and a detailed examination of one HFE scenario developed in the study.

I. INTRODUCTION[a]

Human reliability analysis (HRA) methods have been developed primarily to provide information for use in probabilistic risk assessments (PRAs) that analyze nuclear power plant (NPP) operations with particular emphasis on decision making in the control room. Despite this historical focus on the control room, there has been growing interest and discussion regarding the application of HRA methods to other NPP activities such as spent fuel handling (SFH) or operations in different types of facilities. One recently developed HRA method, 'A Technique for Human Event Analysis' (ATHEANA) has been proposed as a promising candidate for diverse applications due to its particular approach for systematically uncovering the dynamic, contextual conditions influencing human performance. This paper describes one successful test of this proposition by presenting portions of a recently completed project in which a scoping study was performed to accomplish the following goals: (1) investigate what should be included in a qualitative HRA for spent fuel and cask handling

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operations; and (2) demonstrate that the ATHEANA HRA technique can be usefully applied to these operations. This analysis was performed without the benefit of the context provided by a larger PRA study, nor was it plant specific, and so it investigated only generic HRA issues relevant to SFH. However, the improved understanding of human performance issues provided by the study will likely enhance the ability to carry out a detailed qualitative HRA for a specific NPP at some point in the future. Furthermore, support was obtained regarding the potential for applying ATHEANA beyond NPP control room settings. This paper provides a description of the process followed during the analysis, a description of the human failure event scenario groupings, discussion regarding general human performance vulnerabilities, and a detailed examination of one HFE scenario developed in the study.

II. DESCRIPTION OF THE ANALYSIS PROCESS

The human performance analysis approach used in the work reported here was a qualitative, scoping level analysis conducted using elements of NUREG-1792 *Good Practices for Implementing Human Reliability Analyses (HRA)* [1] and NUREG-1624, Rev. 1, *Technical Basis and Implementation Guidelines for A Technique for Human Event Analysis (ATHEANA)* [2]. However, given the preliminary nature of this analysis, process descriptions, HFEs[b], unsafe actions[c] (UAs), and error forcing context[d] (EFC) descriptions were treated in a somewhat generic manner. In fact, although specific HFEs were generated, UAs, and EFCs were, in general, not explicitly identified during this qualitative HRA in order not to impose an excessive amount of structure on these preliminary scenarios. The resulting presentation of various scenarios and human performance considerations developed in the scoping analysis, while intentionally unconstrained to a specific HRA technique, were intended to serve as a good starting point for a more focused or plant specific state-of-the-art HRA analysis, including information gathering and HRA quantification activities.

Specific tasks that were conducted in support of this effort included:

- Identification and review of the literature on SFH and DCSOs (i.e., normal operations and incidents) ranging from handling and storage of individual rods to handling and storage of spent fuel casks. Examples of the items reviewed include: analysis materials provided by the U.S. Nuclear Regulatory Commission and the Electric Power Research Institute (EPRI); the Final Safety Evaluation Report, Rev. 3, for the Holtec International HISTORM 100 cask system [3]; and NUREG-1774 *A Survey of Crane Operating Experience at U.S. Nuclear Power Plants from 1968 through 2002* [4].
- Interviews with subject matter experts (SMEs) to investigate the details of SFH and DCSO activities including: human performance aspects, job aids[e], potential variations from 'typical' activities, and significant near misses and/or accidents that have occurred during these activities;
- Performance of an initial, scoping, qualitative, ATHEANA-type HRA of SFH and DCSO activities to discover opportunities where misloads and drops may occur, and to detail both how and why such events might occur given current understandings of human performance

The basic approach used in performing the scoping qualitative HRA was to separate the SFH and DCSO activities into HFE scenario groupings and then examine/explore the potential use or usefulness of job aids, plausible variations in context, potential error mechanisms for fuel handling-specific failures, and other performance shaping factors (PSFs) and vulnerabilities that may influence the likelihood and consequence of particular HFEs. The specific structure of the approach included the identification of a number of scenarios in which similar groups of human failure events may occur. Each HFE scenario grouping included a definition and interpretation of the issue being analyzed including a summary statement of the issue, the reason for the analysis, and the potential consequences should the issue materialize. In order to capture PSFs and vulnerabilities, without imposing an excessive degree of structure on the scenarios (i.e., to avoid undue bias toward a particular HRA method; however details beneficial for an ATHEANA application were generated), these items were grouped into 'general' human performance vulnerabilities – broadly applicable to an entire HFE group, and 'specific' human performance vulnerabilities associated with individual scenarios. The next two sections of this paper provide a description of the HFE scenario

[b] 'Human failure events' are events that would be modeled as basic events in the logic models of a PRA, and that represent the failure of a function, system, or components that is the result of one or more *unsafe actions*.

[c] 'Unsafe actions' are actions inappropriately taken, or not taken when needed, by plant personnel that result in a degraded plant safety condition.

[d] 'Error-forcing contexts' are situations that arise when particular combinations of *performance shaping factors* and *plant conditions* create an environment in which unsafe actions are more likely to occur.

[e] Job aids are repositories for information, processes, or perspectives; they are external to the individual; they support the work and activity to be done; they direct, guide, and enlighten performance (e.g., books, cards, software, alarms, control panels, various displays) [5].

groupings, and then give an example of a scenario excerpted from one of the groupings, respectively.

III. HUMAN FAILURE EVENT SCENARIO GROUPINGS

A general description of fuel handling and cask operations was subdivided into categories of operations to facilitate logical grouping of HFEs and associated human performance vulnerabilities identified during the analysis. The categories that were developed represented a departure from previous groupings of operations as proposed in analysis materials provided by the USNRC and EPRI. The development of the following categories of operations was motivated by an attempt to effectively capture a wide range of human performance problems that may contribute to a misload and/or cask drop and to facilitate high-level comparisons of potential consequences[f] and risks associated with different cask systems. The SFH and DCSO categorization scheme used in the analysis was divided into the following seven phases of operation:

1. Fuel Load Planning –This phase of operation involves activities by the appropriate engineering department (e.g., nuclear fuels engineering) to generate a fuel move plan, incorporating proper review and approval with subsequent transmission to the fuel handlers who will carry out the operation. This activity depends upon proper configuration management practices such that an accurate record of the history and specific location of every fuel assembly in the spent fuel pool (SFP) is maintained. The fuel movement plan should include the *origin information*–serial numbers and alphanumeric locations of assemblies within the SFP, and the *destination information*–cask canister locations and serial numbers of assemblies. In addition, the fuel load plan should include the process to be followed by fuel handling personnel during actual loading operations (e.g., 3-part communications, independent review of loaded canister before closure, etc.).

2. Cask Operations Personnel and Equipment Preparation –This phase of operation involves training and appropriate staffing of personnel for DCSOs as well as inspection, test, maintenance, recertification, upgrading, etc., of all structures, systems, and components that are required for executing DCSOs. An example of this phase would include assigning trained personnel or enabling proper training of personnel who then conduct detailed structural inspections of auxiliary or refueling building crane supports and interfacing building structures to insure that no cracks, deformations, or other aberrations threaten crane operations. This activity would be immediately accompanied with thorough inspection, test, and maintenance of crane systems and components before any critical heavy lifts are attempted (e.g., lifting a fuel-loaded and water-filled cask from the spent fuel pool).

3. Cask Preparation and Positioning –This phase of operation represents the beginning of actual DCSOs as the cask is brought into the plant for loading preparation activities which culminate with the placement of the empty cask/canister system into the cask loading pit of the SFP in advance of fuel loading.

4. Cask Loading (esp. useful for consequence grouping)– This phase of operation begins with placement of the first fuel assembly in the cask or canister and ends with the cask or cask and canister being properly drained, dried, inerted, and sealed.

5. Loaded Cask Transfer Within Structure (esp. useful for consequence grouping)–This phase of operation begins with preparations to transfer the loaded, sealed cask from the reactor, auxiliary, or fuel building and ends with the cask coupled to the cask transporter.

6. Loaded Cask Transfer Outside Structure (esp. useful for consequence grouping)–This phase of operation begins with a loaded cask, coupled to the cask transporter and ready for movement to the independent spent fuel storage installation (ISFSI) and ends with cask emplacement at the ISFSI.

7. Loaded Cask Storage and Monitoring (esp. useful for consequence grouping)–This phase of operation begins with cask emplacement at the ISFSI and ends when the cask contents (i.e., the spent fuel) are transferred to an off-site storage and/or processing location.

There are at least two major benefits of using the seven phases presented above. First, the inclusion of planning and preparation phases encourages more comprehensive analysis of the context of operations and events that can 'set-up' personnel for an accident in later phases[g]. Therefore, a prospective analysis team may be more inclined to search for such 'latent' UAs when incorporating conceivable/credible HFEs into their analysis models. Second, the number of phases for

[f] Consequences were of particular interest in the preliminary scoping effort, although likelihood determination and risks (i.e., the product of consequences and likelihoods) were estimated to some degree in other analyses, the focus here was how a set of undesirable human actions might occur.

[g] On numerous occasions, HFEs (or near misses) that have actually occurred in nuclear power plants were preceded in time by UAs that were not anticipated during prospective human performance analyses and were often (at least initially) overlooked by post-incident/accident investigation teams [2].

'direct[h]' cask activities is generally expected to mirror the high-level 'hand-offs' that occur between teams of personnel. It is hoped that this categorization of operations (i.e., the seven phases) will be used to guide the analysis of human performance in any future, site-specific DCSO PRA.

The seven phases of operation were used to group detailed descriptions of SFH and DCSO and to help guide the search process for potential HFEs and related human performance vulnerabilities. Seven grouping categories were then developed to separate logical, mid-level regions of conceivable/credible HFE scenarios that link to the taxonomy of operations. The HFE scenario descriptions were organized by the following seven HFE scenario grouping categories:

1. Scenarios before and during fuel loading
2. Scenarios during cask movement from spent fuel pool to preparation area
3. Scenarios during multipurpose canister (MPC) and transfer cask sealing operations
4. Scenarios during cask movement from preparation area to transfer pit
5. Scenarios during MPC movement from transfer cask down to storage cask
6. Scenarios during storage cask movement from transfer pit to ISFSI pad
7. Scenarios during monitoring and storage at the ISFSI

It should be recalled that HFEs are defined as events that would be modeled as basic events in the logic models of a PRA, therefore the categories above do not always map to the phases of operation in a one-to-one fashion. For example, the first category (i.e., *scenarios before and during fuel loading*) includes all of the planning and preparation operations, but also includes fuel loading since it is likely that this would be the first PRA-modeled operation[i] available for a HFE. The 2nd and 3rd HFE scenario grouping categories represent a subdivision of the 4th phase of operation, and the 4th and 5th scenario grouping categories represent a subdivision of the 5th phase of operation. The increasing detail for the HFE scenario groupings for those two phases of operation allows for a better logical separation of conceivable /credible HFEs. Furthermore, the specific terminology (e.g., MPC, transfer pit, etc.) used in this particular HFE grouping strategy is intentionally biased toward the Holtec International HISTORM 100 cask system and a boiling water reactor plant design (this was a result of the specific information sources made available to the analysts). PRAs focused on different cask systems and/or plant designs would be expected to have slightly different HFE scenario grouping categories, while the cask operation categories would remain the same.

IV. GENERAL HUMAN PERFORMANCE VULNERABILITIES

A mixture of inductive and deductive approaches were used to generate a listing of both general human performance vulnerabilities (applying to one or more scenarios in an HFE scenario grouping category) and specific human performance vulnerabilities unique to each scenario. To provide an indication of the types of vulnerabilities investigated, a small sample of general human performance vulnerabilities selected across several HFE scenario grouping categories is presented below:

Unchallenging Activities – The activities involved in spent fuel handling are, in general, quite simple in nature. In addition, the speed of the movements is quite slow, so each action takes a long time to complete. Basically, this is mostly boring work, and some individuals in the process have a significant amount of downtime between actions. There is ample opportunity for diversion and distraction, and an air of informality and complacency can easily exist within and amongst the team members. From a psychological perspective, there is potentially insufficient dynamic activity to generate an optimum stress/arousal level for performance. This lack of challenge, combined with high experience levels of personnel (i.e., they have performed these operations without incident many times) may lead to a progressive disregard for step-by-step procedures. Over time, a migration from strict adherence to step-by-step procedures, to occasional violations of procedures, to routine violations of procedures, may result in 'informal rules' that personnel accept as normal at some point in time.

Limited Indicators and Job Aids – Compared to the control panel and local indicators and other job aids that are common in the power plant operations, those that exist in spent fuel operations are quite limited. In general, processes are controlled primarily by visual cues.

Visual Challenges – As mentioned above, visual cues are the primary means of performing spent fuel operations. In many cases, properly observing these cues is made difficult by the positioning of people in relation to the

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[h] In this instance 'direct' refers to hands-on activities that involve moving fuel, sealing casks, moving casks, etc. in contrast to 'indirect' activities involving planning, preparation, administration, etc. This 'direct' labor versus 'indirect' labor is common terminology in product manufacturing settings.

[i] Given typical PRA practice, this could be considered the first operation in which a HFE is anticipated to potentially result a radiological incident or accident even though one or more UAs during previous operations may also contribute to the 'consequential' event.

activities being observed. Operations within the spent fuel pool can be particularly challenging, as the effect of refraction in the water and reflection from the surface of the water can distort the view of operations that require precise positioning. Observing signs of damage to individual fuel pins within a cask or canister may be severely hampered by structural elements.

Crane operations have challenges whether they are in the water or not. The crane operator may need to lean out over the crane bridge as the view of an operation is essentially only from directly above. Many of the potential errors that could occur are related to vertical position, which cannot be determined from above. In addition, even the view from above may be obstructed, either by the yoke or by the load being moved. Thus, the operator is often put in the position of being the hands for someone else's eyes, which make the operations vulnerable to the communication vulnerabilities discussed below.

Finally, in many cases the action being viewed, by its very nature and location, must be viewed from a distance. In such cases, small deviations that could possibly lead to significant problems can be missed simply because of the inability to have sufficient resolution to detect the error.

Communication Difficulties – There are significant challenges in communication between the team members performing spent fuel operations. The environment contains a significant amount of background noise, predominantly machine noise. Although headsets are used by key participants for communication, they do not eliminate the potential for misunderstanding. Garbled communication (due to system interference or background noise) is clearly possible, and in some cases it may not even be possible to clearly determine who is speaking. A belief that a particular individual is speaking, even if they are not, can bias the listener into hearing what he expects to hear.

Time pressure – Although time pressure during cask loading campaigns (CLCs) is generally less than during refueling outages (due to the non-producing status of the plant during an outage), missing scheduled milestones can lead to increased expenses and increased uncertainty with regard to time schedules for upcoming outages. SMEs have stated that time pressure can quickly emerge, even during fuel assembly movement operations. This ability for time pressure to emerge may be exacerbated by the perception of low consequence for errors during this process. All personnel perceive the dropping of a very large cask from a crane to create high consequence outcomes; therefore those operations are much less susceptible to time pressure. Handling of individual fuel assemblies may not carry with it the same need for slow, step-by-step execution. The tone set by all levels of management regarding the relative goods of ensuring safety versus meeting a predetermined schedule will greatly impact the perception of time pressure among operations personnel.

Other Ergonomic Issues – Additional stressors include the cramped working space on the refueling crane bridge and those related to clothing (i.e., the suits required when working above the spent fuel pool).

Configuration control – Configuration control processes are not always designed to avoid specific human performance problems that may arise due to design peculiarities at a specific site. Such processes are driven by the accumulation of knowledge and experience by those who administer/manage the system, but thorough documentation of such knowledge and experience, which influences the assumptions and error checking processes used during activities, may not be present. These omissions can lead to problems (e.g., improperly prepared fuel movement plans) when a hand-off of configuration control activities to new personnel occurs.

Trust – Trust is an essential component of any team-based activity. Crew members must be able to depend upon the correct behaviors of others when performing operations. However, trust can have a negative component as well. An example is provided in one scenario where a supervisor 'trusts' his experienced FHP and spotter leading to a cursory verification of fuel assembly loading. Crew members must always be reminded of the proper orientation of the 'trust' relationship. In this case, trust should imply that the FHP and spotter can 'trust' the supervisor to carefully review the fuel load to protect them from missing errors that will be sealed inside the cask and may present hazards to others years later.

V. EXAMPLE OF A HUMAN FAILURE EVENT SCENARIO

The work that is briefly described in this paper included a number of preliminary scenarios developed for SFH and DCSOs. These preliminary scenarios included human failure events that might be modeled in a plant-specific PRA, although they were generated from a non-plant specific information base that was notably impoverished relative to a "complete" set that would be expected for a full HRA/PRA analysis. Since previous analyses were reviewed during the performance of this preliminary effort, some of the scenarios contain human failure events that were addressed to some degree in those previous studies. However, it is important to note that none of the previous analyses provided a thorough investigation of the contexts (i.e., an ATHEANA-like approach) in which failures may occur. Therefore, even for HFEs identified in previous studies, this analysis provided more insight and enables more understanding of how those HFEs may actually occur. In addition, there was no attempt to be exhaustive in the search for possible scenarios, but rather it was deemed sufficient for scoping and demonstration purposes to cover a broad spectrum of scenario examples.

The example HFE scenario given in this section is taken from the 3rd HFE scenario grouping category (i.e., *Scenarios during multipurpose canister (MPC) and transfer cask sealing operations*). The introductory, context-setting material for this scenario grouping category (containing five scenario descriptions) is provided first and is followed by the first scenario description titled: *Failure to identify a fuel misload event.*

The phase of operation related to this HFE scenario grouping category begins with the loaded transfer cask resting in the proper position in the preparation area for closure operations with the scaffolding properly arrayed around the outside of the transfer cask. It continues through sealing, purging, drying, and inerting operations. This phase ends when both the MPC and transfer cask are ready to be transported to where the MPC will be inserted into the storage cask.

1. Definition and interpretation of issue being analyzed

a. *Human failure event scenarios during MPC and transfer cask sealing operations* – In this process the MPC is loaded, with the MPC lid placed on top and the MPC is resting inside the transfer cask at the preparation area. All of the closure and preparation activities are performed such that the MPC becomes ready for emplacement in the shielded storage cask.
b. *Reason for analysis* – These scenarios are being analyzed due to the potential for identifying a fuel misload event, a human initiated fire event, and most importantly, for the potential to leave a leak path, or a 'soon to be present' leak path condition from the inside of the MPC to the outside of the MPC.
c. *Potential consequences* – Storing misloaded fuel may result in a degradation of fuel assemblies such that fission products migrate to the general environment within the MPC; a human initiated fire during closure operations may create a condition that leads to fuel damage and a release of fission products to the reactor, auxiliary, or fuel building environment; and the establishment of a leak path could allow for fission product migration to the storage cask or module at the ISFSI, which may then migrate away from the ISFSI and pose a threat to the public and the environment.

2. Base case scenario

Initial conditions – The initial conditions for the start of this phase of operation will vary with the specific plant and cask system being used. A typical situation is defined:

- The loaded MPC in the transfer cask is positioned properly in the preparation area with scaffolding also properly positioned around the cask.
- The MPC lid has been placed into position, but is merely resting, unsecured on the MPC shell.
- Personnel are decontaminating the area around the top flange of the transfer cask and getting ready to install the temporary shield ring or other form of gamma radiation shielding to prevent radiation streaming from the trunnion recess areas of the transfer cask water jacket.

3. General Human Performance Vulnerability Concerns

Provided below is a brief summary of some potential human performance vulnerabilities that may impact MPC and transfer cask sealing operations:

Decision making biases based on perception of loss – The manner in which a person frames the concept of 'loss' in a given situation provides a strong biasing factor toward all actions that enable the person to steer away from incurring that 'loss' [6]. People often tend toward the discovery of a *simple, non-loss threatening* alternative explanation to a situation, instead of attending to a *complex, loss-threatening* explanation to a situation. For example, the situation in which a radiation protection (RP) person detects high radiation levels after a re-decontamination of the lid enables him to choose the *non-loss threatening* explanation of "I just swiped too close to a normally 'hot' area" as opposed to the *loss-threatening* explanation of "Oh, no, we've got misloaded fuel in here and need to spend considerable time and effort to get the cask back in the pool and thoroughly investigate. Not only that, but we better move quickly." The *losses* referred to here are the loss of time, lost of respect for those who 'messed up and got us into this situation', and potential loss related to damaging fuel that then leads to a fission product release. Another example of this *loss avoidance* behavior is that of personnel draining, purging, drying, and backfilling who choose the *simple, non-loss threatening* explanation of a 'welding delay' leading to excessive temperatures (the specifics of this example are elaborated on in scenario 1 in this section).

Interestingly, at the point in the future when the fuel misload condition described in scenario 1 is eventually discovered, the incident investigators will probably be astounded that multiple personnel disregarded signs of a fuel misload, as the potential consequences of fuel damage, fission product release, etc. are much higher than any 'mere inconvenience' of getting the fuel back in the pool and carefully tending to a potential problem. Of course, for the personnel conducting the tasks 'in the moment' (e.g., under some level of time pressure, not wanting to disrupt major operations and schedules, not wanting to tarnish the team's reputation, etc.) the mental accounting of 'loss' may allow them to filter out and explain away signals that point to a misload event. Personnel 'in the moment' may be thinking that they don't want to be forced to deal with a misload event and they also can't really imagine that the many barriers against a misload event would somehow be circumvented[j]. Readers wanting to learn more about the interesting, important, and complex topic of loss avoidance and how people may conceptualize or perceive real/potential losses are encouraged to review references 6–8.

Limited Nature of Procedures – The cask sealing operations may be relatively well proceduralized, but they still depend primarily on skills learned and additional training experiences. In these activities, procedures specify basic tasks in the process, but a number of skill-based sub-tasks are performed at the discretion of particular individuals and teams. Examples of specific, potential procedural oversights in SFH and DCSOs may include: CLC preparations not accounting for potential rapid relocation of fire ignition sources to flammable material storage areas due to rapid air movement by the HVAC system. This may lead to improper designation of 'safe' areas for flammable items and stationing of fire fighting personnel during 'ignition prone' operations (e.g., welding, grinding, or cutting torch operations). Second, a lack of explicit procedures specifying that both members of a cask closure team must inspect all bolt holes for the presence of water. Procedures reviewed during the analysis only specified that all bolt holes needed to be visually inspected; therefore an opportunity for quality assurance redundancy may be missed.

Time of day and shift work – Many of the scenarios reveal an all too common pattern that emerges in shift work situations. Slips, lapses, mistakes, and violations tend to occur more often when workers are fatigued, especially when that fatigue is encountered during late night or early morning hours[k]. Furthermore, personnel working occasional night shifts may be tempted to rush operations in order to end shifts early or at least change the focus to non taxing activities (e.g., hurry up with the welding that demands significant mental and physical effort, and then leisurely finish the balance of the shift with minimal effort tasks of tear-down and clean up activities).

Pace of Operations – Some of the activities involved in cask sealing, drying, purging, backfilling operations are, in general, quite simple in nature. In addition, the speed of many of the movements is quite slow, so each action takes a long time to complete. Basically, this can be boring work, and some individuals in the process have a significant amount of downtime between actions. There is ample opportunity for diversion and distraction, and an air of informality and complacency can easily exist within and amongst the team members. From a psychological perspective, there may be insufficient dynamic activity to generate an optimum stress/arousal level for performance.

Visual Challenges – As mentioned above, visual cues are the primary means of performing cask closure operations such as cleaning, grinding, tack welding, and even liquid dye penetrant testing and hydrostatic testing. Maintaining visual vigilance for long periods is difficult work[l]. Ultrasonic testing is often not suited for the major lid and closure ring welds, therefore, visual and tactile cues are critical. Another specific visual challenge exposed in the example scenario below comes from the use of a non-auto darkening welding helmet which reduces the ability of the welder to rapidly detect ignition of flammable material following a hydrogen ignition during lid closure operations.

Other Ergonomic Issues – Additional stressors include the cramped working space around the transfer cask and heat stress due to ambient temperatures and those related to clothing (i.e., the contamination control suits and additional clothing for protection from welding slag).

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[j] It should be noted that the authors of this paper are not trying to imply that such a fuel misload event scenario is somehow highly likely; such scenarios are simply designed to plausibly argue how an occurrence deemed 'highly unlikely' using certain analysis techniques, may actually happen when human beings play crucial roles in the process. It should also be noted that one of the authors of this report has devised a framework which may provide assistance in detecting and mitigating parts of an operation that are vulnerable to undesirable actions based on the mental accounting of real or potential 'loss' in addition to many other associated perceptual/decision making biases (e.g., confirmation bias, etc.) [6].

[k] It is possible that not all individuals are affected this way as a function of late night or early morning activities, but the general stereotype has proven to be very strong, and despite some directed efforts, there has not been a reliable way to identify/select people who are especially suited to night shifts or early morning shifts (i.e., within subject variability is not well-understood). Day-to-night physiological changes (i.e., circadian rhythms) are well documented in a many studies of human performance. See reference [9] for an introduction and overviews of the circadian rhythm and shift work literature.

[l] Unpublished research at Sandia National Laboratories has recently discovered dramatic levels of omission during aircraft structural inspections among highly experienced, highly motivated maintenance personnel. When confronted with the results of these experiments, many of the maintenance personnel are shocked to discover their actual level of performance. For discussion on human signal detection and for entry points into the extensive literature on this topic, see references [9–11].

A number of actual events involving incomplete or incorrect procedures during sealing operations and also of actual hydrogen ignition events during lid sealing have occurred as documented in the NEI database on Spent Fuel Handling events. Summaries of those events were made available to the authors via a CD from the NRC. Specific events are not listed here as they were generally events of minor consequence. The point made here is that slips, lapses, mistakes, and violations have occurred during these types of operations.

4. Example of a Scenario Description within the 3rd HFE Scenario Group

This section provides a high-level overview of the five scenarios that were developed for the 3rd HFE scenario group titled: *Scenarios during multipurpose canister (MPC) and transfer cask sealing operations*. Table 1 briefly lists the five potential human failure event scenarios and associated human performance vulnerabilities identified in the 3rd HFE scenario group. It is important to note that not every one of the listed vulnerabilities apply to each of the scenarios. The first scenario description within the 3rd HFE scenario group, which is the example included in this paper, is titled: *failure to identify a fuel misload event.*

Table 1. Scenarios during MPC and transfer cask sealing operations.

HFE Group	HFE Group Description	Scenario	Vulnerabilities
3	MPC and transfer cask sealing operations.	1. Failure to identify a fuel misload event 2. Human initiated fire event–welded cask 3. Failure leaves leak path existing at the end of sealing and preparation activities–welded cask 4. Failure leads to impending leak path due to undetected problem during sealing and preparation activities–welded cask 5. Failure leads to impending leak path due to undetected problem during sealing and preparation activities–bolted cask	• Biases based on perception of loss • Limited nature of procedures • Time of day & shift work • Pace of operations • Visual challenges • Perceived time pressure • Omission in hazard analysis • Improper training • Overconfidence • Lapse • Other ergonomic issues (welder's helmet)

5. Description of the example scenario: Failure to identify a fuel misload event

The example below begins with a description of the sequential operations performed in the scenario, and finishes with a list of potential human vulnerabilities specific to the scenario.

Preparation worker does not decontaminate lid properly – The preparation worker (i.e., the individual responsible for decontamination of the MPC lid surface and top flange area) does not completely wipe down and decontaminate the MPC lid and top flange area. The specific area that is not wiped down completely is near where the shield ring is installed to absorb gamma radiation near the trunnion recess areas of the transfer cask. The omission occurs as the preparation worker is trying to work around other personnel preparing to move the shield ring into position.

Radiation protection worker detects high radiation levels – After the shield ring is installed, the radiation protection (RP) worker detects an unusually high level of radiation emitting from the area that was not properly decontaminated above the trunnion recess area. The preparation worker who is standing next to the RP workers recalls that he forgot to wipe down that area and mentions that fact to the RP worker. The preparation worker then wipes down the area. The RP workers makes another pass with the radiation monitor and finds a lower, but still unusually high level of radiation. He readily dismisses the radiation level to moving the probe too close to the trunnion recess side of the shield ring.

Welding equipment delay – A problem with the automated welding equipment causes a delay that postpones closure operations for more than an hour.

Excessive temperatures during draining and purging are attributed to delay – Unusually high MPC internal temperatures noted during the draining and purging processes are attributed to the delays in getting the cask sealed. Even some indications of localized water boiling in the cask are not investigated thoroughly. That is, personnel are expecting the cask to heat up due to fuel decay heat when the MPC is filled with non-circulating, non-cooled water. The personnel are encouraged to keep moving and get the vacuum process under way as that will remove a large amount of heat from the MPC.

Lack of evidence of excessive cooling in the vacuum lines is positively received by personnel – Typically, a gradual step process is used when lowering MPC pressure using the vacuum drying system, this is often necessary to prevent ice from forming in parts of the system. With the present 'warm' cask, evidence of icing never occurs and the preparation personnel just continue with a rapid evacuation process and subsequent helium backfill.

Early pressurization with helium is not noticed – The personnel backfilling the cask with helium did not carefully estimate how much gas should be required to pressurize the MPC (e.g., from past experience, or from rough phenomenological calculations); therefore, they did not notice that it required a significantly smaller volume of helium to reach required pressures in the cask. Welding of remaining cask penetrations was completed quickly after the backfill and an increased MPC internal pressure was not discovered.

Potential Human Performance Vulnerabilities for which may facilitate the human actions that lead to the realization of the scenario 1 human failure event includes the following:

- Lack of detailed procedures without appropriate thresholds for alarm
- Equipment calibration errors
- Perceived time pressure
- The ease of finding a *simple, non-loss threatening* alternate explanation to a situation, instead of attending to a *complex, loss-threatening* explanation to a situation. Examples: the RP person detecting and explaining away high radiation levels after the re-decontamination of the lid; the draining, purging, drying, and backfilling personnel who choose the *simple, non-loss threatening* explanation of a 'welding delay' leading to excessive temperatures.

VI. CONCLUSIONS

ATHEANA has been proposed as a promising candidate for diverse applications due to its particular approach for systematically uncovering the dynamic, contextual conditions influencing human performance. This paper described one successful test of this proposition by presenting portions of a recently completed project in which a scoping study was performed to accomplish the following goals: (1) investigate what should be included in a qualitative HRA for spent fuel and cask handling operations; and (2) demonstrate that the ATHEANA HRA technique can be usefully applied to these operations. This paper provided a description of the process followed during the analysis, a description of the HFE scenario groupings, discussion regarding general human performance vulnerabilities, and a detailed examination of one HFE scenario developed in the study. Although the preliminary analysis was generic and performed without the benefit of the context provided by a larger PRA study, it is argued that the improved understanding of human performance issues provided by the study will likely enhance the ability to carry out a detailed qualitative SFH and DCSO HRA for a specific NPP at some point in the future. Furthermore, support was obtained regarding the potential for applying ATHEANA beyond NPP control room settings.

REFERENCES

[1] NUREG-1792, "Good Practices for Implementing Human Reliability Analysis," U.S. Nuclear Regulatory Commission, Washington, DC, April 2005.

[2] NUREG-1624, Rev. 1, "Technical Basis and Implementation Guidelines for A Technique for Human Event Analysis (ATHEANA)," U.S. Nuclear Regulatory Commission, May 2000.

[3] Holtec International, "Holtec International Final Safety Analysis Report for the HI-STORM 100 Cask System, Revision 3, Report no. HI-2002444," Holtec International, Marlton, NJ, 2005.

[4] NUREG-1774, "A Survey of Crane Operating Experience at U.S. Nuclear Power Plants from 1968 through 2002," U.S. Nuclear Regulatory Commission: Washington, DC., 2003.

[5] Rossett, A. and J. Gautier-Downes, "A Handbook of Job Aids," Pfeiffer & Company, San Diego, CA., 1991.

[6] Brewer, J. D., "Risk Perception & Strategic Decision Making: General Insights, a New Framework, and Specific Application to Electricity Generation Using Nuclear Energy, SAND2005-5730," Sandia National Laboratories, Albuquerque, NM., 2005.

[7] Kahneman, D. and A. Tversky, "Prospect Theory: An analysis of decision under risk," *Econometrica*, 47(2): 263-291., 1979.

[8] Kahneman, D. and A. Tversky, "Choices, Values, and Frames," *American Psychologist*, 39(4): 341-350., 1984.

[9] Salvendy, G. ed., *Handbook of Human Factors and Ergonomics*, John Wiley & Sons, New York, NY., 1997.

[10] Wickens, C. D. and J. G. Hollands, "Engineering Psychology and Human Performance, 3rd edition," Prentice Hall, Upper Saddle River, NJ., 2000.

[11] Kantowitz, B. H. and R. D. Sorkin, "Human Factors: Understanding People-System Relationships," John Wiley & Sons, New York, NY., 1983.