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Human Reliability Analysis-Informed Insights on Cask Drops

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ABSTRACT

This report documents human reliability analysis-informed insights on cask drops that may be used as an initial technical basis for activities aimed at reducing the potential for cask drops. The report provides the following:

- Description of the analysis approach used.
- Overview of human reliability analysis (HRA) as applied to dry cask storage operations (DCSOs).
- Overview of human error.
- Description of selected items from the behavioral science technical basis used in analyzing DCSOs.
- Decomposition of DCSOs in a manner that emphasizes human performance contributions.
- Summary of recent concerns related to handling spent fuel casks.
- Set of terms that clarify subtle distinctions related to human performance and cask handling.
- Set of detailed cask-handling scenarios showing various types of human performance vulnerabilities contributing to hypothetical cask drops.
- Collection of insights on how the potential for a cask drop due to human actions may be reduced.

Although performed without the benefit of the context provided by a plant-specific probabilistic risk assessment (PRA), this report builds on previous analyses and subject matter expert interviews to provide an improved understanding of human performance in DCSOs. The study accomplished three goals: (1) investigated what should be included in a qualitative HRA for spent fuel and cask-handling operations to understand the potential for cask drops, (2) demonstrated that the qualitative analysis tasks in the ATHEANA (A Technique for Human Event Analysis) HRA method can be usefully applied to non-control room operations, and (3) began building a technical basis for potential improvements to DCSO procedures and practices to reduce the likelihood of cask drops resulting from unsafe human actions. This analysis was performed after the completion of a preliminary qualitative HRA of spent fuel handling tasks, which is documented in NUREG/CR-7017 (NRC, 2012).

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ABBREVIATIONS

AFR	away from reactor
AIT	augmented inspection team
ALARA	as low as reasonably achievable
ANSI	American National Standards Institute
AOS	annulus overpressure system
ASME	American Society of Mechanical Engineers
ASP	Accident Sequence Precursor
ATHEANA	A Technique for Human Event Analysis
BWR	boiling water reactor
CAD	computer aided design
CFR	code of federal regulations
CLC	cask loading campaign
CoC	Certificate of Compliance
DCSO	dry cask storage operation
DCSS	dry cask storage system
DOE	U.S. Department of Energy
DSC	dry shielded canisters
EFC	error-forcing context
EOC	error of commission
EOO	error of omission
EPRI	Electric Power Research Institute
FHD	forced helium dehydration system
FH	fuel handler
FHP	fuel handling personnel
FSAR	Final Safety Analysis Report
HEP	human error probability
HF	human factors
HFE	human failure event
HI-STORM	Holtec International Storage and Transfer Operation Reinforced Module
HI-TRAC	Holtec International Transfer Cask
HRA	human reliability analysis
HVAC	heating, ventilation and air conditioning
ISFSI	independent spent fuel storage installation
ISLOCA	interfacing systems loss of coolant accident
LPSD	low power and shutdown
MPC	multipurpose canister
NDE	nondestructive examination
NMSS	USNRC Office of Nuclear Material Safety and Safeguards
NPP	nuclear power plant
NRC	Nuclear Regulatory Commission
NUHOMS	Nutech Horizontal Modular System
PRA	probabilistic risk assessment
PSF	performance shaping factor
PWR	pressurized water reactor
QA	quality assurance
RES	USNRC Office of Nuclear Regulatory Research
RVOA	removable valve operating assemblies
SAMGs	severe accident management guidelines

SDP	Significance Determination Process
SF	spent fuel
SFH	spent fuel handling
SFP	spent fuel pool
SFPO	Spent Fuel Project Office (within the NMSS office)
SFST	Division of Spent Fuel Storage and Transportation
SME	subject matter expert
SNL	Sandia National Laboratories
S-R-K	Skill-Rule-Knowledge taxonomy for describing skill acquisition
SSC	structures, systems, and components
THERP	Technique for Human Error Rate Prediction
TN	Transnuclear
TS	technical specification
TVA	Tennessee Valley Authority
UA	unsafe action
USNRC	United States Nuclear Regulatory Commission
VCT	vertical cask transporter
VDS	vacuum drying system

1 INTRODUCTION

The movement and storage of spent fuel assemblies is a growing activity within the nuclear industry. As the spent fuel pools (SFPs) within commercial nuclear power plants (NPPs) reach capacity, the older fuel assemblies are transported and stored within dry casks at an independent spent fuel storage installation (ISFSI) located on site or near the plant where the fuel was first used. This process of cask movement and storage depends on numerous human actions, providing ample opportunity for errors to occur. The extent to which human errors may contribute to a cask drop are the primary concern in this report.

Previous analyses of cask movement operations, as well as reviews of heavy load drops and incidents both within the nuclear power industry and across other industries, have affirmed that load drop frequency highly depends on human performance (NRC, 2003; RIS-05-025 2005; NRC, 2007c). This report identifies human errors that may contribute to a cask drop, and it also describes how human performance vulnerabilities may lead to such human errors. Qualitative human reliability analysis (HRA) activities were used to explore human performance vulnerabilities and to generate illustrative scenarios that involve cask drops. An earlier analysis was performed exploring similar human performance vulnerabilities in relation to cask misloads and additional cask drop scenarios (NRC, 2012). In the present study, in addition to the detailed scenarios, illustrative recommendations and insights are provided to help subject matter experts (SMEs) identify and evaluate potential human performance vulnerabilities specific to a particular cask system used at a specific plant. These illustrative recommendations begin to build a technical basis that SMEs can use to improve procedures and practices in dry cask storage operations (DCSOs). It is important to note that the hypothetical scenarios in this report typically require multiple equipment failures along with one or more unsafe human actions for a cask drop to occur.

1.1 Background

The investigation into human error during DCSOs is essential to better understand what types of accidents are possible in order to better prepare the system to avoid and recover from accidents. Although important in all systems, human errors within complex, high-consequence systems such as NPPs are especially important to avoid or mitigate because of their potential to contribute to incidents or accidents affecting the safety of the public, the environment, and plant personnel. It has been noted that in some NPPs (i.e., boiling water reactors [BWRs] with Mark I or II containments) there is a potential for a heavy load drop to "simultaneously initiate an accident and disable equipment necessary to mitigate the accident" (RIS-05-025, 2005). Ultimately, a severe accident that causes radiological injury to the public and damage to the environment could result. It has also been noted that for heavy load drops, "drop frequency is highly dependent on human performance" (RIS-05-025, 2005). The occurrence of incidents involving heavy loads at NPPs, such as those provided in the following short descriptions, further attests to the importance of this topic:

1. June 10, 2004: At the Sequoyah Nuclear Plant in Tennessee, during the first cask load of a cask loading campaign (CLC), the auxiliary building crane tripped twice while carrying a fully loaded cask. Plant personnel were able to lower the loaded cask to the refueling floor level, avoiding a possible cask drop into the SFP. Upon closer inspection of the crane, more than 20 large cracks were discovered along the welds and base metals. It was

determined that these cracks should have been discovered in prior inspections before the CLC began. This problem led to identifying crane performance degradation issues across the nuclear power industry.

2. October 24, 2004: At the Browns Ferry Nuclear Plant in Alabama, a 289,134 Newton (32.5-ton) overhead crane trolley was dropped while it was being lowered for replacement. One synthetic sling failed, followed almost immediately by another sling failure, and the trolley dropped approximately 1.22 meters (4 feet) to the concrete floor. The load drop damaged the refueling floor (cracked and spalled the concrete) in the defueled Unit 1 reactor building. Root causes included inadequate work practices by contractor support personnel and improper installation and verification of rigging. That is, insufficient sling protection material was provided, the approach for using sling protectors was not disseminated to the rigging crew, and the load was tilted while being lowered (in violation of the procedure) to increase clearance with the new trolley nearby on the refueling floor. The Nuclear Regulatory Commission (NRC) inspection report noted that had this trolley dropped from a higher height in this Mark I BWR it could have damaged the SFP under the refueling floor (Cahill, 2005; RIS-05-025, 2005).

3. April 6, 2004: At Millstone Power Station Unit 3 in Connecticut, during preparations before removing the reactor vessel missile shield and the reactor vessel head, a two-blocking event[1] occurred while the missile shield lifting rig was being raised. The crane operator had moved the crane controls into the neutral position to stop and hold the load. Due to a stuck relay in the hoist controls, the load continued moving upward and impacted fixed equipment. Personnel were able to stop upward movement of the load by removing power to the crane. The missile lifting rig sustained significant damage (Bellamy, 2004; RIS-05-025, 2005).

4. June 2001: At the Turkey Point Nuclear Plant in Florida, a 333,617 Newton (37.5-ton) mobile crane dropped approximately 20.3 centimeters (8 inches) from the turbine building crane when a Kevlar sling failed due to inadequate softener protection at sharp corners against the mobile crane (NRC, 2003; RIS-05-025, 2005).[2]

5. May 2001: At the San Onofre Nuclear Generating Station in California, a 333,617 Newton (37.5-ton) mobile crane dropped approximately 12.2 meters (40 feet) from the Unit 3 turbine building crane when the Kevlar slings failed due to inadequate use of rigging softener material (NRC, 2003; RIS-05-025, 2005).[2]

6. October 6, 1999: At the Comanche Peak Steam Electric Station in Texas, a chain hoist rated to carry a 400,340 Newton (45-ton) load failed while lifting a 373,651 Newton (42-ton) reactor coolant pump (RCP) motor. The failure allowed the lifting chain to move freely through the hoist, and the motor began an accelerating uncontrolled descent approximately

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[1] "Two-blocking" refers to the situation in which the load block near the crane hook makes contact with the upper block near the top of the crane. If the hoist continues to exert force once two-blocking has begun, the wire rope of the crane may fail, resulting in a freefall drop of the load. These two-blocking events are among the most common causes of load drops involving overhead crane failures at NPPs. Inspection, testing, and maintenance affect the likelihood of these events because the events typically involve improper operation of hoist safety interlocks and may involve improper operation of the hoist controls.

[2] Although these load drops occurred in areas of the nuclear plant where damage to irradiated fuel or safe shutdown equipment was not a concern, they demonstrate the potential for a single human error to result in a load drop that causes substantial damage to structures or components (RIS-05-025, 2005).

9.14 meters (30 feet). Riggers riding on the load during the lift were in safety harnesses and managed to jump away from the load as it fell and were unharmed. Fortunately, the rapid drop was arrested 2.44 meters (8 feet) above the RCP base when a chain link snagged in the hoist load block. This fortuitous event prevented the motor from impacting its base and the reactor coolant system piping. Although the reactor fuel had been moved to the SFP, a rapid draining of the refueling cavity could have exposed personnel in containment to high doses of radiation from the exposed core barrel. A root cause analysis found that the chain hoist had been rebuilt and reassembled incorrectly in 1994. During a mechanical inspection of the same hoist in 1996, a cover plate could not be re-installed over the gears because of misalignment. Gear alignment problems were not questioned and corrected; instead, the screw holes for the cover plate were elongated so that the plate could be re-installed. When the hoist was rigged to the polar crane's main hook in October 1999, the hoist would not initially operate in the downward direction. After the hoist was operated in the upward direction, it would operate in the downward direction. No mechanical or electrical inspection of the hoist was performed prior to lifting the RCP motor (Gody and Schwind, 2000; RIS-05-025, 2005).

1.2 Purpose

A number of incidents, whether specifically related to DCSOs or NPP operation in general, have conveyed the need for greater analysis of human performance and the application of HRA to DCSOs. The purpose of this study was to develop HRA-informed insights on cask drops that may be used as an initial technical basis for activities aimed at reducing the potential for cask drops. This report provides the following specific items:

- Description of the analysis approach used during the search for cask drop insights
- Overview of HRA and how its application to moving spent fuel casks differs from NPP control room applications
- Overview of human error in general and as it relates to moving heavy loads in NPPs
- Selected items from the behavioral sciences that form key portions of the technical basis for understanding human performance in DCSOs
- Review of two previous reports documenting DCSO probabilistic risk assessment (PRA) activities involving the same dry cask storage systems (DCSSs) and plant types focused on in this report
- Decomposition of DCSOs that facilitates analysis of human performance contributions
- Detailed descriptions of the basic operations involved in DCSOs for the HI-STORM 100 DCSS at a MARK I BWR, and for the Transnuclear (TN)-40 system at a pressurized water reactor (PWR)
- Summary of recent concerns related to handling spent fuel casks
- Set of terms that clarify subtle distinctions in human performance and cask-handling operations, chiefly new terms describing *human performance vulnerabilities* that are used to explain why unsafe actions may occur in specific contexts

- Numerous detailed cask-handling scenarios showing various types of human performance vulnerabilities contributing to hypothetical cask drops

- Specific, illustrative insights on how the potential for a cask drop involving human actions may be reduced

In completing the activities listed above, the study has accomplished three goals:

- Investigated what should be included in a qualitative HRA for spent fuel and cask-handling operations in order to understand the potential for cask drops

- Demonstrated that the ATHEANA (A Technique for Human Event Analysis) HRA technique can be usefully applied to these non-control room operations

- Began building a technical basis for potential improvements to procedures and practices in spent fuel handling (SFH) operations

The results of this study, particularly the DCSO-specific approach for analyzing human performance, as well as the specific cask drop insights, should enhance the ability of SMEs to analyze potential cask drops in detail and develop techniques for avoiding cask drops for a specific NPP in the future.

1.3 Scope

The analysis documented in this report involved performing typical qualitative HRA tasks such as identifying unsafe actions (UAs),[3] human failure events (HFEs),[4] and relevant influences (e.g., performance shaping factors and other contextual factors) to help develop detailed cask-handling scenarios showing various types of human performance vulnerabilities contributing to hypothetical cask drops. Illustrative insights were also provided on how the potential for a cask drop due to human actions may be reduced. These efforts were accomplished through identifying and reviewing literature relevant to understanding human performance in SFH, interviews with SFH subject matter experts, and selected videos of DCSOs provided to the analysis team. To help a wide range of potential readers understand how the scenarios and recommendations were developed, the report provides overviews of HRA, human error,[5] behavioral science bases of human performance analysis, reviews of previous analyses and recent concerns, a detailed decomposition of operations, and descriptions of terminology customized for analyzing human performance in DCSOs. This analysis was performed after the

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

[4] A *human failure event* is a PRA term for the basic event in the PRA logic models that represents the failure of a plant function, system, or component that is the result of one or more human UAs.

[5] In the PRA community , the term *human error* has often been used to refer to human-caused failures of systems or components. However, in the behavioral sciences, the same term is often used to describe the underlying psychological failures that may cause the human action that fails the equipment. Therefore, in this report (as in the ATHEANA HRA method), “human error” is used only in a very general way, with the terms *unsafe action* and *human failure event* being used to describe more specific aspects of human errors. This distinction will be clarified further in Section B.2.

completion of a preliminary qualitative HRA of spent fuel handling tasks, which is documented in NUREG/CR-7017 (NRC, 2012).

This project addressed two DCSSs and general plant types because they represent the subset of cask-handling operations at U.S. NPPs: (1) the HOLTEC International HI-STORM 100 DCSS as generically used in a Mark I BWR, and (2) the TN-40 DCSS as generically used in a PWR. The HI-STORM 100 DCSS as used in a Mark I BWR involves a highly complex sequence of DCSOs including many manual rigging operations in a plant requiring large vertical and horizontal cask movements relatively close to reactor operations. Thus, it represents the most complex operations with the greatest potential consequences should a cask be dropped during movement. The TN-40 DCSS as used in a PWR involves less complex DCSOs performed in a fuel or auxiliary building outside the reactor containment building. Thus it represents the complexity of operations and potential cask drop consequences typical for most U.S. NPPs. It is important to note that qualitative HRA tasks are typically performed in the context of a plant-specific PRA study. However, this analysis was performed without the benefit of a larger PRA study, and it was not plant-specific. Consequently, this analysis investigated relatively generic HRA issues relevant to SFH. Examples of generically identified HRA issues identified in this report are:

- Possible cask drop scenarios involving human errors
- Plausible human performance vulnerabilities that may contribute to these human errors
- Illustrative approaches for avoiding or mitigating human performance vulnerabilities that may contribute to dropping a spent fuel cask

Note that the recommendations presented in Section 6 for avoiding or mitigating the consequences of human actions that may lead to a cask drop are simply illustrative. It is anticipated that this effort to conceive of ways to mitigate the potential for cask drop events has begun a process that may, following further analysis, improve guidance for conducting and monitoring DCSOs. Of course, a detailed plant- and crew-specific analysis including interviews with plant personnel and on-site observations of DCSO activities would be necessary to generate robust, highly relevant techniques for avoiding or mitigating the consequences of human errors at a given site and for a specific DCSS.

1.4 Report Structure

This report includes the following sections and appendices:

Section 2 briefly describes the analysis approach and introduces the items underlying the technical basis for the approach. Further details concerning the technical basis are provided in Appendix B.

Section 3 discusses DCSOs and DCSSs, reviews two important PRAs involving cask handling, decomposes categories of DCSOs to emphasize human performance contributions, and presents diagrams of basic DCSOs for the two DCSSs analyzed in Sections 5 and 6. Section 3 also introduces new terminology that helps clarify distinctions related to cask drops and other cask movements.

Section 4 describes recent concerns and emerging issues in SFH operations. A discussion of initial actions the NRC has taken to address the recent concerns is also provided.

Section 5 provides illustrative scenarios of possible UAs and HFEs in SFH operations that contribute to cask drops. It defines human performance vulnerabilities and outlines how they can potentially contribute to incidents and accidents. Following the human performance vulnerability descriptions is a brief review of information and previous events relevant to cask drops, followed by the various HFE groups and specific scenarios. The context for each HFE group is established by defining and interpreting the issue analyzed, describing the base case scenario, and describing each specific scenario along with the human performance vulnerabilities contributing to UAs and HFEs.

Section 6 is the most preliminary and speculative section of this report. It contains recommendations and actions for avoiding or mitigating the consequences of UAs and HFEs. In particular, it provides examples of actions that can be taken to avoid or mitigate the human performance vulnerabilities introduced in Section 5.

Section 7 briefly summarizes the results and conclusions of this effort.

Section 8 lists the references for this report.

Appendix A describes in detail DCSOs involving the HI-STORM 100 and TN-40 cask systems. This description formed the nominal operational basis used to develop the scenarios in Section 5. Readers not familiar with DCSOs will benefit from reading Appendix A before reading Sections 5 and 6.

Appendix B provides a detailed discussion of the technical basis underlying the analysis approach including an introduction to human error and HRA, and explains selected items from the behavioral sciences that form key portions of the technical basis for understanding human performance in DCSOs. The behavioral science items informed the process of identifying important contributing factors to UAs and HFEs that were incorporated into cask drop scenarios (Section 5) and generating human performance improvement recommendations (Section 6). Appendix B also introduces new terms that help clarify subtle distinctions related to human performance.

Appendix C defines and discusses in detail the human performance vulnerabilities identified in Section 5.

Appendix D defines terms used in this report, terms used in HRAs to support PRAs for NPP operations, and terms taken from other domains, as well as new terms that aid in understanding human performance and describing potential ways to avoid UAs that could contribute to a cask drop. By clarifying distinctions in human performance and cask-handling operations, the glossary is intended to be a valuable resource for the reader.

2 ANALYSIS APPROACH

The analysis activities performed during this study were chosen to generate insights into how human performance aspects of dry cask storage operations (DCSOs) can plausibly lead to a cask drop and ways to reduce human contributions to cask drops. To achieve this aim, qualitative human reliability analysis (HRA) activities were carried out that allowed the construction of detailed cask-handling scenarios showing various types of human performance vulnerabilities contributing to hypothetical cask drops. These activities also enabled the development of mitigating measures, closely associated with specific scenarios, which might reduce the potential for a cask drop due to human actions. Given that human actions are major determinants of the success or failure of cask movements, the analysis focused on both direct human involvement in cask movement operations and relevant pre-initiator latent error conditions that could "set up" personnel for the unsafe actions (UAs) that become the proximate/ immediate/direct contributors to or causes of a cask drop.

The analysis generally involved an iterative process of gathering information from multiple sources; processing that information to develop credible, hypothetical cask drop scenarios involving UAs and human failure events (HFEs); and inferring potential techniques for avoiding or mitigating the impact of human actions that could contribute to the events described in the scenarios. Specific tasks and the products that resulted are listed below and discussed in greater detail in Sections 2.1 through 2.5.

- Gathered Information: Subject matter experts (SMEs) were interviewed and literature was reviewed to investigate types of spent fuel handling (SFH) and DCSO activities, human performance aspects of SFH, job aids,[6] potential variations from typical SFH activities, and significant incidents that have occurred during SFH and DCSOs. The operations reviewed spanned from fuel movement planning and equipment preparation, to handling of individual fuel assemblies, handling of spent fuel casks, and long-term storage at independent spent fuel storage installations (ISFSIs). While this report focuses on cask drops within a building structure at a nuclear power plant (NPP), an earlier analysis supported by this information-gathering task included scenarios ranging from the misloading of spent fuel into casks to cask drops and cask degradation at ISFSIs. (NRC, 2010)

- Developed Comprehensive Categorization of DCSOs: DCSOs were categorized according to seven phases of operation to facilitate analysis of all planning and preparation activities that can "set up" personnel for an accident in later phases and to provide enough phases for direct, hands-on cask movement and sealing operations to better reflect actual "hand-offs" that may occur between teams of personnel. Concise descriptions of DCSOs for the HI-STORM 100 system at a Mark I boiling water reactor (BWR) and the Transnuclear (TN)-40 system at a pressurized water reactor (PWR), segregated into the seven phases, were also generated to facilitate development and analysis of cask drop scenarios.

- Organized and Developed Human Performance and Cask Movement Terminology and Behavioral Science Items: Terminology related to HRA, human performance, and cask

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[6] 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 (Rossett & Gautier-Downes, 1991).

movement was clarified, customized, and developed to help make important, but often subtle, distinctions in human performance and cask movement activities that may contribute to a cask drop. This included generating terms to describe specific human performance vulnerabilities that help explain why UAs may occur in particular contexts or situations, in a manner easily understood by those who are knowledgeable of DCSOs but who may have limited knowledge of human performance and HRA. As part of organizing and developing the terminology, and in response to feedback from DCSO SMEs, items from the behavioral sciences that form key portions of the technical basis were selected and summarized to benefit readers without expertise in human factors (HFs) and HRA.

- Generated Cask Drop Scenarios Using ATHEANA Tasks: The basic qualitative HRA activities recommended in the ATHEANA (A Technique for Human Event Analysis) HRA method were performed across the seven phases of DCSOs to discover opportunities where cask drops might occur and to develop hypothetical scenarios detailing how and why such events might occur.

- Generated Recommendations for Avoiding or Mitigating HFEs: Illustrative recommendations and examples for avoiding or mitigating the impact of human actions that may lead to a cask drop were developed based on: (1) the specific human performance vulnerabilities described in the scenarios; (2) various human performance insights gleaned from the information gathered; and (3) the authors' accumulated knowledge and experience related to improving human performance.

2.1 Information Gathering

None of the authors of this report have first-hand experience in performing or observing SFH and cask movement activities. Therefore, much information had to be gathered to learn about the nominal performance of SFH and DCSOs as well as observed variations from typical activities, significant incidents that have occurred, and recent/emerging concerns, voiced by SMEs, that could contribute to a cask drop. The interviews with SMEs were invaluable in providing an understanding of the human performance aspects of DCSOs and in guiding the authors to various information sources describing incidents that provided further insights. The entire range of activities from planning fuel movements, assuring the quality of equipment, moving individual fuel assemblies, loading fuel into casks, moving casks, and storing fuel at an ISFSI for the long term were examined. The scope of the information-gathering activity was much broader than simply understanding how cask movements are conducted inside NPP buildings: (1) it was important to probe planning and preparation activities for conditions that could set the stage for subsequent UAs related to cask drops; and (2) an earlier analysis report required the generation of scenarios ranging from fuel misloads to accelerated degradation of fuel and casks at ISFSIs (NRC, 2010).

The sources below provided the foundation for building the content contained in this report:

- interviews with SMEs who have first-hand experience in performing SFH, DCSOs, or overseeing those operations, as well as SMEs with experience in quality assurance (QA) activities for NPP and vendor-supplied equipment used during the conduct of DCSOs,

- an NRC report that reviewed crane operating experience at U.S NPPs from 1968–2002 (NRC, 2003),
- NRC reports describing the proper design and use of heavy lift cranes at NPPs (NRC, 1979; NRC, 1980),
- a pilot dry cask probabilistic risk assessment (PRA) developed by the NRC (NRC, 2007c),
- a bolted storage cask PRA conducted by the Electric Power Research Institute (EPRI, 2004),
- the Final Safety Evaluation Report, Rev. 3, for the Holtec International HI-STORM 100 cask system (Holtec, 2005),
- a short collection of video clips of SFH and DCSOs involving the Holtec HI-STORM 100 system at a particular Mark I BWR,
- a training video involving the TN-40 cask system at a particular PWR,
- various documentation emerging from a literature search and items provided by SMEs, such as inspection reports, 10 Code of Federal Regulations (CFR) Part 21 notifications, NRC memoranda related to resolution of Generic Issue 186 – *Potential Risk and Consequences of Heavy Load Drops in Nuclear Power Plants*, Regulatory Issue Summaries, data from the Nuclear Energy Institute on incidents involving SFH and DCSOs, etc.,
- multiple documents focused on HRA and human performance.

2.2 Development of a Comprehensive Categorization of DCSOs

This project addressed two dry cask storage systems (DCSSs) and general plant types:

(1) the HOLTEC International HI-STORM 100 DCSS as generically used in a Mark I BWR

(2) the TN-40 DCSS as generically used in a PWR

The primary reason for studying these DCSSs and plant types was that information about these systems was made available to us. Two previous analyses were significant sources of information: the EPRI's *Probabilistic Risk Assessment (PRA) of Bolted Storage Casks: Updated Quantification and Analysis Report No. 1009691* (EPRI, 2004) focused on use of the TN DCSS in a PWR setting; and the NRC's *A Pilot Probabilistic Risk Assessment Of a Dry Cask Storage System At a Nuclear Power Plant* (NUREG-1864; NRC, 2007b) focused on use of the HI-STORM 100 DCSS in a Mark I BWR setting. Other sources of information included photographs and a short video of operations gathered during the analysis for NUREG-1864 and interviews with NRC personnel experienced in performing, monitoring, and regulating SFH and DCSOs. A TN-40 DCSS training video developed at a specific NPP site was also made available for review.

In early discussions with SMEs at the NRC, it became apparent that the two DCSSs and plant types mentioned above would be a useful representative subset of environments for cask-handling operations. Analyzing the HI-STORM 100 DCSS typically used in a Mark I BWR was beneficial because it represents a complex sequence of DCSOs involving many manual rigging operations in a plant requiring large vertical and horizontal cask movements relatively close to reactor operations; thus, it represents the most complex operations and largest potential consequences should a cask be dropped during movement. The analysis of the TN-40 DCSS at a PWR represents less complex DCSOs performed in a fuel or auxiliary building outside the reactor containment building; thus, it represents the complexity of operations and potential cask drop consequences typical for most U.S. NPPs.

To develop realistic, credible cask drop scenarios broadly relevant to the U.S. nuclear industry, it was essential to thoroughly understand these two DCSO environments. Previous PRAs and other information sources were reviewed, and a unique categorization scheme for the DCSOs spanning seven phases (defined in Section 3.5) was developed and applied to the two environments. The categorization scheme differed significantly from schemes in previous reports because of the desire to emphasize human performance. In particular, the phases of operation were delineated to facilitate analysis of all planning and preparation activities that could “set up” personnel for a cask drop event and show direct, hands-on cask movement operations that reflect actual “hand-offs” between teams of personnel. These hand-offs may differ among plants due to site-specific practices. Section 3 describes the two DCSO environments, develops the new categorization scheme and applies it to the two environments, and provides new terminology that clearly distinguishes between different types of cask drops and other undesirable cask movements. Appendix A details the activities performed in the seven phases.

2.3 Organization and Development of Human Performance and Cask Movement Terminology and Behavioral Science Items

Early in this study, SMEs in DCSOs expressed a desire to better understand the causes of unsafe human actions that could contribute to events such as cask hang-ups and cask drops. During interviews, questions arose such as “How can you anticipate what unsafe actions (UAs) may occur?”; “Why would any reasonable person do that?”; “Isn’t it impossible to predict why people would carry out that UA?”; “Aren’t some people just error-prone?”; “Is it possible to identify in advance the people who are susceptible to executing UAs?” It was apparent that over the years the SMEs had seen many people make mistakes or violate procedures during DCSOs. Typically, the people were reprimanded, reassigned, or terminated, and often procedures and training were changed. However, after time, it was not unusual to observe different people make similar mistakes or violate procedures in similar ways. The changes made apparently did not have a lasting effect on improving the safety of the system. The SMEs wondered why these situations kept recurring and whether more effective measures could prevent them in the future. Given that DCSO SMEs and others without expertise in the study of human performance often ask such questions and desire to better understand human performance, it was agreed that this report should provide some background material on HRA and behavioral science.

Including key portions of the technical basis for understanding and analyzing human performance (especially UAs) provided an opportunity to organize and further develop terminology relating to HRA and human performance. Section B.1 through B.4, Section 5.1.1,

Appendix C, and Appendix D provide background material and improved terminology, which are then applied to the scenarios and recommendations in Sections 5 and 6. Furthermore, Sections B.1 through B.4 discuss HRA and the differences in its application in NPP control room activities and SFH activities, human error in general and UAs in nuclear industry crane operations, important mechanisms and taxonomies for understanding skill acquisition and UAs, and factors that influence human performance in specific contexts (examples tie these concepts directly to SFH and DCSOs). Section 5.1 and Appendix C describe *human performance vulnerability* terms, and Appendix D defines key terms used in the report and serves as a resource for readers from all technical backgrounds as it clarifies distinctions in human performance, HRA, and cask-handling operations. The background material and terminology will benefit readers without expertise in human factors and HRA in understanding how one may predict: (1) the forms that UAs may take in particular contexts; (2) the reasons why those UAs occur; and (3) the techniques that may be effective in avoiding or mitigating the impact of the UAs.

2.4 Generation of Cask Drop Scenarios Using ATHEANA Tasks

This study produced detailed illustrative cask-handling scenarios showing UAs contributing to hypothetical cask drops (Section 5). The objectives were to (1) identify how and why such UAs may occur and (2) provide an initial basis for illustrative techniques for avoiding or mitigating the effects of human performance vulnerabilities that lead to those UAs in order to prevent a cask drop (Section 6). Fortunately, no spent fuel casks have been dropped at an NPP; thus, all scenarios contain hypothetical elements. However, there have actually been a small number of heavy load drops at U.S. NPPs, and many of the equipment failure and UA contributors included in the scenarios have actually occurred. In addition, the events described in the scenarios were reviewed by a senior structural analysis expert at Sandia National Laboratories (SNL) to ensure they are indeed *possible* with respect to the physics of failure. Some of the scenarios require multiple failures or degradations to occur simultaneously or in a particular sequence for the scenario to be realistic.

To generate cask drop scenarios that enable an understanding of human performance contributions, it was necessary to perform qualitative HRA activities using a method suitable to the SFH domain. However, most HRA methods developed in the past for use in NPPs focused predominantly on human actions in NPP control room settings, with less emphasis on activities outside the control room such as DCSOs or equipment inspection, maintenance, and repair activities. The ATHEANA method was developed with a task, person, and environment-analysis approach, based on the latest behavioral science research circa 2000, which facilitated the discovery of particular situations and contexts that would challenge individuals and crews with particular types of knowledge, skills, experience, attitudes, and working styles in correctly executing goal-directed behavior. Fortunately, while the ATHEANA documentation is tailored to NPP operations, much of the methodology is easily applied to non-control room applications. Therefore, this study includes many qualitative HRA tasks adapted from *Good Practices for Implementing Human Reliability Analyses (HRA)* (NRC, 2005b), NUREG-1624, Rev. 1, *Technical Basis and Implementation Guidelines for A Technique for Human Event Analysis (ATHEANA)* (NRC, 2000) and NUREG-1880, *ATHEANA User's Guide* (NRC, 2007c).

The basic ATHEANA process involves performing the following steps in the general sequence listed (defining the HFEs is usually an iterative process):

- Define and interpret the issue being analyzed.

- Define the resulting scope of the analysis.
- Describe the base case scenarios.
- Define HFEs and UAs of concern.
- Identify potential vulnerabilities.
- Search for deviations from base case scenarios.
- Identify and evaluate complicating factors.
- Evaluate the potential for recovery.
- Resolve issue (including quantification).
- Incorporate into the PRA (if necessary).

In the current study, ATHEANA steps 1–9 were adapted to generate detailed cask drop scenarios that identify and explain the potential impact of human performance vulnerabilities, and to infer techniques for improving human performance. Qualitative HRA tasks are typically performed in the context of a plant-specific PRA study. However, this study was performed without the benefit of a larger PRA study, and it was not plant-specific. Consequently, this analysis investigated somewhat generic HRA issues relevant to SFH and DCSOs.

The starting point for developing scenarios that involved important HFEs for DCSOs was to review scenarios identified in previous PRA-type activities performed on DCSSs, such as the studies by EPRI and NRC (EPRI, 2004; NRC, 2007b). The authors' understanding of nominal DCSOs, recent concerns, and emerging issues grew over time. The scenarios evolved slowly as initial scenarios were formulated and subsequently refined as more insights were obtained. HFE scenario groupings were progressively developed along with the increasing understanding of the potential use or usefulness of job aids, plausible variations in context, potential error mechanisms for cask-handling-specific failures, and other performance shaping factors (PSFs)[7] and vulnerabilities that could influence the likelihood and consequence of particular HFEs.

Knowledge from the behavioral sciences was applied to this deepening understanding of DCSOs to iteratively generate explicit UAs and HFEs and to develop and apply the human performance vulnerability terminology to describe why particular UAs and HFEs might occur in particular scenarios. The starting point for developing the terminology was the list of traditionally applied PSFs summarized in the HRA "good practices" document (NRC, 2005b). From that foundation, other concepts from the human performance literature were adapted and integrated to match the evolving scenario contexts and clarify, customize, and develop improved terminology for describing human performance. Periodic feedback from selected DCSO SMEs during this process was essential for generating credible, clearly described scenarios.

The approach for documenting the scenarios that resulted from this process basically followed the method recommended in ATHEANA. Groups of HFE scenarios were developed that followed the time sequence of DCSOs for the two DCSSs. The context for each HFE scenario group is provided that defines and interprets the issue analyzed, describes the base-case

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[7] *Performance shaping factors* (PSFs) are a set of influences on the performance of an operating crew resulting from the human-related characteristics of the plant, the crew, and the individual personnel (NRC, 2000). PSFs can be thought of as the factors that allow personnel to understand the state of their environment and those factors that influence their response to the state of the environment.

scenario, and describes each specific scenario along with the relevant human performance vulnerabilities contributing to UAs and HFEs.

2.5 Generation of Recommendations for Avoiding or Mitigating Human Failure Events

A major objective of this study was to generate an initial technical basis that DCSO SMEs can refer to when improving DCSO procedures and practices to reduce the likelihood of cask drops. To this end, Section 6 illustrates ways in which the *human performance vulnerabilities* identified in Section 5 may be avoided or mitigated so that *human failure events* involving cask drops may be avoided or mitigated. Section 6 summarizes (1) the overarching engineered design features that appear to distinguish the two DCSSs analyzed with respect to the opportunities for HFEs leading to cask drops; (2) the potential techniques that may be used to avoid or mitigate the human performance vulnerabilities identified in Section 5; and (3) the concept of a safety culture and attributes of an organization with a robust safety culture.

The recommendations that culminate this study were developed based on: (1) the specific human performance vulnerabilities described in the hypothetical cask drop scenarios; (2) various human performance insights gleaned from the information gathered; and (3) the authors' accumulated knowledge and experience related to improving human performance. The material in Section 6 is not complete, nor exhaustive; it is merely illustrative and tied to the types of vulnerabilities described in the scenarios. It is likely that substantial knowledge and experience with a specific cask system and personnel at a specific plant would be needed to appropriately adapt these recommendations into practical guidance for that plant.

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3 DRY CASK STORAGE OPERATIONS (DCSOS) IN THE U.S. AND PREVIOUS ANALYSES

Two important subtleties need to be recognized about dry cask storage operations (DCSOs). First, the specific handling operations depend on the design of the dry cask storage system (DCSS). Some DCSS designs use a directly loaded, bolted-closure storage cask to provide confinement, shielding, and thermal protection. This storage cask can be placed directly on the independent spent fuel storage installation (ISFSI) storage pad; an example of this type of stand-alone bolted cask design is the Transnuclear (TN)-40 metal cask (Figure 3-1). Second, other DCSS designs use the canister as the confinement boundary and use a separate structure to provide shielding and thermal protection. In those types of DCSS designs, the loaded canister must be transferred to the storage structure/container (such as the Holtec HI-STORM 100 storage cask; Figure 3-2) or fixed (a structure like a concrete vault; e.g., the cylindrical, horizontally oriented concrete modules used in the NUHOMS systems).

Figure 3-1 Series of Transnuclear (TN)-40 casks at an independent spent fuel storage installation.

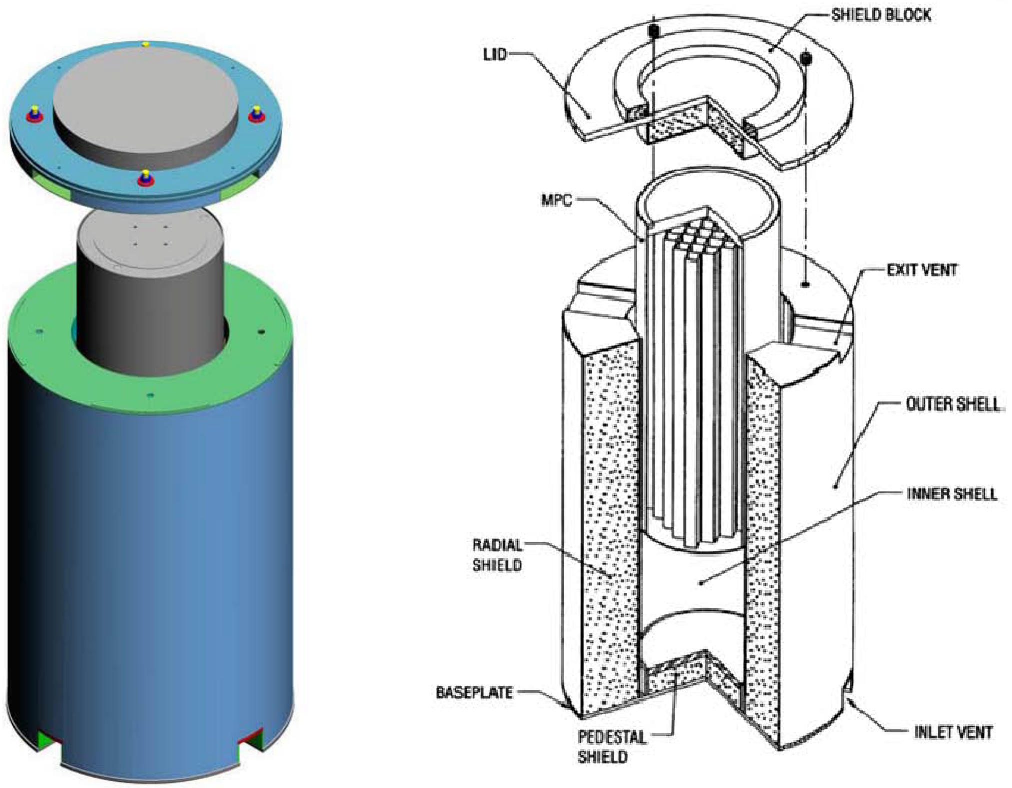

Figure 3-2 Holtec International HI-STORM 100 cask storage system with multipurpose canister (MPC) partially inserted and diagram of features.

Figure 3-3 shows two types of DCSSs widely used in the U.S. Figure 3-3 A depicts the HI-STORM 100 system, consisting of a multipurpose canister (MPC),[8] Holtec International Transfer Cask (HI-TRAC) 100 transfer cask,[9] and storage cask.[10] As discussed later in this report, DCSOs involving the HI-STORM 100 DCSS at a Mark I boiling water reactor (BWR) plant provided the majority of the "generic" operation descriptions used for investigating human performance. Figure 3-3 B provides an overview of the components in the NUHOMS-type storage vault approach. The NUHOMS system uses a dry shielded canister (DSC), which is essentially the same as an MPC. The ISFSI emplacement operations involving the horizontal storage units are not analyzed in this report. However, the HI-STORM and TN-40 cask systems that are analyzed in this report provide many insights that may be generalized to the handling of other casks up to the point when they are connected to a transport vehicle for transport to the ISFSI.

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[8] Materials in a loaded MPC include spent fuel bundles, stainless steel supports, BORAL™ neutron absorber, aluminum heat conduction elements, and helium. The fuel basket which supports the spent fuel is free standing but held in position by basket supports. Upper and lower fuel spacers keep the fuel assemblies vertically positioned in the basket, and each cell wall in the basket is lined with a BORAL™ plate to prevent criticality excursions.

[9] The transfer cask consists of an inner steel shell, lead shield, and outer steel shell; a water jacket provides additional shielding prior to the water-draining processes.

[10] Materials in the storage cask include carbon steels and concrete.

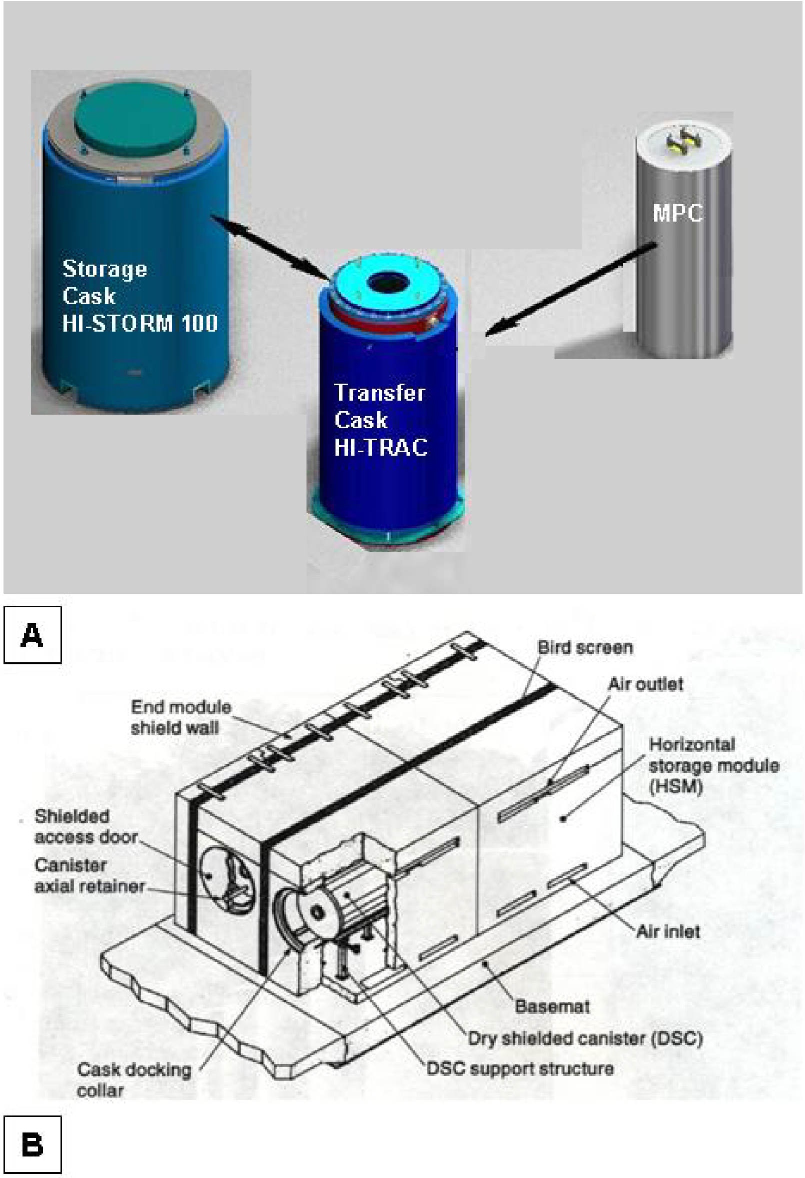

Figure 3-3 Components of the Holtec International HI-STORM 100 cask storage system and components of the NUHOMS-type system.

A shows HI-STORM 100 system components;* B shows NUHOMS-type system components in a horizontal storage vault.†

* Adapted from a figure available at the Holtec International web site: http://www.holtecinternational.com.

† USNRC/NMSS 1994, 1-11.

3.1 Distribution of Operating and Planned Independent Spent Fuel Storage Installations (ISFSIs) in the U.S.

Nuclear power plants (NPPs) in the U.S. were not originally designed to store all of the spent fuel that would be discharged during the life of the plant. The original concept was to transport spent fuel to reprocessing centers to extract and reconfigure useful fissile and fertile materials. Given that the reprocessing approach was not planned and a geologic repository is not available to store spent fuel, licensees have turned to DCSSs as a temporary storage option that enables them to decrease spent fuel inventory in spent fuel pools (SFPs). The NRC determined that all SFP storage capacity at existing NPPs would be expended by 2015 in the absence of removing fuel and storing it in casks. Table 3-1 shows a list of DCSSs in use or planned for the near future for U.S. plants as of 2010 (NRC, 2010). The list is not complete as additional utilities are deciding between storage systems, but does provide a helpful overview which reveals the majority of canister loaded DCSSs fall into the two storage approaches (i.e., HI-STORM and NUHOMS) presented earlier in Figure 3-3.

Table 3-1 Current and expected distribution of cask systems across the U.S.*

Reactor	Dry storage technology	Licensing method[†]	Date Issued
Surry	CASTOR V/21, TN-32, NAC-128, CASTOR X/33, MC-10	Site License	1986
	NUHOMS-HD	General License	2007
H.B. Robinson	NUHOMS-07P	Site License	1986
	NUHOMS-24P	General License	2005
Oconee	NUHOMS-24P	Site License	1990
	NUHOMS-24P	General License	1999
Fort St. Vrain	Foster Wheeler MVDS	Site License	1991
Calvert Cliffs	NUHOMS-24P & 32P	Site License	1992
Palisades	VSC-24, NUHOMS-32PT	General License	1993
Prairie Island	TN-40	Site License	1993
Point Beach	VSC-24, NUHOMS-32PT	General License	1996
Davis-Besse	NUHOMS-24P	General License	1996
Arkansas Nuclear	VSC-24, HI-STORM 100	General License	1996
North Anna	TN-32	Site License	1998
	NUHOMS-HD	General License	2008
Trojan	HI-STORM 100	Site License	1999
Idaho National Lab TMI-2 Fuel Debris	NUHOMS-12T	Site License	1999
Susquehanna	NUHOMS-52B & 61BT	General License	1999
Peach Bottom	TN-68	General License	2000
Hatch	HI-STAR 100, HI-STORM 100	General License	2000
Dresden	HI-STAR 100, HI-STORM 100	General License	2000
Rancho Seco	NUHOMS-24P	Site License	2000
McGuire	TN-32	General License	2001
Big Rock Point	BNG Fuel Solutions W74	General License	2002
James A. Fitzpatrick	HI-STORM 100	General License	2002
Maine Yankee	NAC-UMS	General License	2002
Columbia Generating Station	HI-STORM 100	General License	2002
Oyster Creek	NUHOMS-61BT	General License	2002
Yankee Rowe	NAC-MPC	General License	2002
Duane Arnold	NUHOMS-61BT	General License	2003
Palo Verde	NAC-UMS	General License	2003
San Onofre	NUHOMS-24PT	General License	2003
Diablo Canyon	HI-STORM 100	Site License	2004
Haddam Neck	NAC-MPC	General License	2004
Sequoyah	HI-STORM 100	General License	2004
Idaho Spent Fuel Facility	Concrete Vault	Site License	2004
Humboldt Bay	HI-STORM 100HB	General License	2005
Private Fuel Storage Facility	HI-STORM 100	General License	2006
Browns Ferry	HI-STORM 100S	General License	2005
Joseph M. Farley	NUHOMS-32PT	General License	2005
Millstone	NUHOMS-32PT	General License	2005
Quad Cities	HI-STORM 100S	General License	2005
River Bend	HI-STORM 100S	General License	2005
Fort Calhoun	NUHOMS-32PT	General License	2006
Hope Creek/Salem	HI-STORM 100	General License	2006
Grand Gulf 1	HI-STORM 100S	General License	2006
Catawba	NAC-UMS	General License	2007
Indian Point	HI-STORM 100	General License	2008
St. Lucie	NUHOMS-HD	General License	2008
Vermont Yankee	HI-STORM 100	General License	2008
Limerick	NUHOMS-61BT	General License	2008
Seabrook	NUHOMS-HD-3PTM	General License	2008
Monticello	NUHOMS-61BT	General License	2008
Kewaunee	NUHOMS-39PT	General License	2009

*** From NRC, 2010.**

† Site-specific licenses are granted in accordance with 10 CFR 72; that is, the safety aspects of the ISFSI site are reviewed and, if approved, the NRC issues a specific license for the site. General licenses refer to the storage of spent fuel in certified casks in accordance with 10 CFR 72 Subpart K; that is, if the safety aspects are approved, the NPP licensee is authorized to store spent fuel in NRC-approved dry storage systems at a site licensed to operate a nuclear power reactor.

3.2 Typical DCSO Differences Between Boiling Water Reactors (BWRs) and Pressurized Water Reactors (PWRs)

Two primary differences in plant configurations affect the movement of casks within an NPP. These configurations are associated with the major differences between boiling water reactors (BWRs) with Mark I and II containments as contrasted with pressurized water reactors (PWRs) and BWRs with a Mark III containment. In Mark I and II BWRs, the SFP is typically inside the secondary containment portion of the reactor building immediately adjacent to the reactor vessel. The top surface of the SFP is above the level of the reactor vessel, which places it four or five floors above ground level. Therefore, cask system components that must be placed into the cask pit of the SFP must be vertically transferred (i.e., up to 30.5 meters (100 feet)) above ground level to be lowered into the SFP. This location of the SFP requires heavy cask load movements on the upper floor of the reactor building during full power operation. If a floor were breached during a load drop, safety-related components on lower floors could be adversely impacted. In other words, a load drop that penetrates the floor in certain areas could simultaneously initiate an accident and disable the necessary accident-mitigation equipment (RIS-05-025, 2005).

In PWRs and BWRs with a Mark III containment, the SFP is typically located in the fuel or auxiliary building, which is adjacent to and outside the reactor building that houses the reactor vessel, the primary coolant system, and systems essential for achieving a safe shutdown. The top of the SFP is typically not more than two or three floors above ground level; therefore, the cask system components that must be placed into the cask pit will not have opportunities to drop vertically more than approximately 15.2 meters (50 feet). Other than potential breach of a cask, the primary consequence of concern for a heavy load drop in these plant types is damage to the spent fuel pools (e.g., penetration of the pool). In addition to differences in vertical movement paths and proximity to the operating reactor, the horizontal travel paths for cask components going into and out of the facility are noticeably different in the two major plant configurations. The PWR and Mark III BWR travel paths for cask components are generally more direct, whereas the Mark I and II BWR travel paths may be more complex and involve much greater horizontal movement of heavy loads. ISFSI operations are generally very similar across all NPP configurations; differences arise mainly from the particular storage technology chosen for the site.

Two previous dry cask probabilistic risk assessment (PRA) studies, briefly described in the following sections, provided considerable assistance during the preparation of this report by providing descriptions of spent fuel handling (SFH) activities, initial insight into human failure events (HFEs), and others' perspectives on likelihoods and consequences related to that initial set of HFEs. The first is a pilot dry cask PRA conducted by the Nuclear Regulatory Commission (NRC) (NRC, 2007b). The second is a dry cask PRA conducted by the Electric Power Research Institute (EPRI, 2004).

3.3 NRC Pilot Dry Cask Probabilistic Risk Assessment (PRA) Analysis

To further evaluate public risks from the handling, transfer, and storage of dry casks, the U.S. Nuclear Regulatory Commission (USNRC) Office of Nuclear Regulatory Research (RES) and the Spent Fuel Project Office (SFPO)[11] in the Office of Nuclear Material Safety and Safeguards (NMSS) jointly developed a method for performing a PRA of a DCSS. This method was used to perform a pilot PRA of a specific cask system at a specific BWR site. A request by the SFPO to support its efforts to risk inform NMSS-regulated activities motivated the study. The pilot PRA focused on a welded canister system (i.e., HOLTEC HI-STORM 100) at a specific BWR site (NRC, 2007b). The HI-STORM 100 consists of three major components: an MPC, a transfer cask, and a storage cask (see Figure 3-3). The Mark I-type BWR was chosen for analysis: the Mark I-type represents the general configuration of 69% of the BWR fleet in the U.S., and BWRs compose 33% of the overall U.S. fleet of NPPs. The remainder of NPPs are PWRs. As noted previously, Mark I BWRs are associated with the largest vertical movements (i.e., the farthest potential drop) of loaded canisters alone and loaded canisters emplaced in the transfer casks, and the casks must be moved over or near irradiated fuel and safe-shutdown equipment in the reactor building; therefore, it is logical that this type of plant and cask system would be the focus of the pilot PRA.

The pilot PRA contained a list of initiating events, including dropping the cask inside the containment building during transfer operations and external events (e.g., earthquakes, floods, high winds, lighting strikes, accidental aircraft crashes, and pipeline explosions) occurring during on-site storage. Potential cask failures from mechanical and thermal loads were modeled, and it was assumed that 10-year-old high-burnup fuel would be in a cask at the time of any cask failure/breach. Risk to the public was measured in terms of the individual probabilities of a prompt fatality[12] within 1.6 km (1 mi) and a latent cancer fatality[13] within 16 km (10 mi) of the site. The pilot PRA of a DCSS used the best available point estimates without any uncertainty analyses, and very few sensitivity analyses were performed to evaluate input variables. In situations lacking sufficient information or data, conservative bounding assumptions or estimates were used. Given the paucity of sensitivity analyses and absence of uncertainty analyses, the degree of conservatism in the risk estimates cannot be determined.

The pilot PRA used the following high-level descriptions of three phases of major operations in DCSOs from loading spent fuel into a cask through emplacing it at an ISFSI:

Handling – Activities on the refueling floor and the ground floor, including (1) loading the cask (pre-staged in the SFP cask pit) with fuel; (2) placing the MPC lid in position (i.e., not secured

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[11] Note that at the time this report was published, the SFPO had been reorganized. The new organization charged with developing and implementing the regulatory, licensing, and inspection program for the storage of nuclear reactor spent fuel and the domestic and international transportation of radioactive materials is the Division of Spent Fuel Storage and Transportation (SFST) within NRC/NMSS.

[12] A prompt fatality can be described as any death which occurs as a result of a large acute total body exposure sufficient to cause one or more of three major classes of fatal syndromes: cerebrovascular syndrome—death within 30 to 50 hours from exposure of about 100 Gy (10,000 rads), gastrointestinal syndrome—death within about 9 days from exposures of about 10 Gy (1,000 rads), and hematopoietic (bone marrow death)—death in several weeks from exposures of 2.5 to 8 Gy (250 to 800 rads). Zero probability of a prompt fatality was assumed at doses below a threshold of 150 rem to the red bone marrow and 500 rem to the lungs (NRC, 2007c).

[13] The linear, no-threshold model was used in the pilot study (NRC, 2007c).

with fasteners); (3) moving the transfer cask out of the pool and over to a preparation area; (4) draining, drying, inerting, and sealing the MPC; (5) removing a temporary pool lid from the bottom of the transfer cask and replacing it with a transfer lid; (6) lowering the transfer cask down through the transfer pit opening and mating it to the storage cask; (7) lowering the MPC from the transfer cask into the storage cask (facilitated by long slings supporting the MPC and opening of the transfer lid at the bottom of the transfer cask); and (8) moving the storage cask containing the MPC out of the secondary containment airlock.

Transfer – Activities on the ground floor, beginning with moving the storage cask containing the MPC past the secondary containment boundary, installing the storage cask lid, installing vent shield cross-plates and vent screens over the exposed ends of the convective cooling channels, moving the cask transporter into position over the cask, connecting the cask to the transporter, moving it to the ISFSI storage pad location, and lowering it into position onto the storage pad at the ISFSI.

Storage – Routine monitoring and surveillance of the cask on the ISFSI pad for 20 years or more.[14]

The phases were subdivided into 34 stages that were defined based on factors including height at which the cask is carried, direction in which the cask is moved, rigging of the cask, and type of surface (e.g., concrete, asphalt, gravel) over which the cask is moved (NRC, 2007b). The overarching influence driving the analysis team's selection of these factors was the desire to make meaningful distinctions between conceivable types of cask drops and the potential responses/consequences. The 34 stages used in the pilot PRA are not specifically listed in this report, although Appendix A does provide a broader description of DCSOs of which the 34 stages are a subset.

The critical point conclusions from the study were the following:

(1) No prompt fatalities among the public are expected.

(2) The individual probability of a latent cancer fatality was calculated to be 1.8E-12 during the first year of service.

(3) The individual probability of a latent cancer fatality was calculated to be 3.2E-14 per year during subsequent years of storage.

(4) Cask drops are considered to pose the greatest potential risks to the public, and fuel misloading events are considered to be much less of a concern, but neither type of event poses a risk anywhere near as high as other risks typically encountered during NPP operation.

Several important items deemed to be beyond the scope of the pilot PRA included "subsequent versions of the specific cask system studied in the report, unloading of the cask, offsite transportation, repository storage, uncertainty analysis, worker risk, human reliability, fabrication errors, misloading of spent nuclear fuel, aging effects, and combinations of factors that could impact the probability of MPC failure" (NRC, 2007b). Of particular relevance to the current report was the absence of an HRA; the study explicitly acknowledged the potential importance and benefit of conducting an HRA:

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[14] For risk calculations, the NRC assumed a 20-year period of storage at the ISFSI.

> A human reliability analysis (HRA) of loading spent fuel into the MPC, lifting the transfer cask during the handling phase, and welding the MPC when preparing it for storage, was not incorporated into this pilot PRA.
>
> The frequency of dropping the transfer cask depends on the number of lifts and the probability of dropping the transfer cask given a lift. There are two approaches to estimating the drop probability. The first approach is to perform a reliability analysis of the crane used to lift the transfer cask and an HRA of workers' actions to rig the cask and operate the crane. The second approach is to obtain an empirical estimate based on experience with lifting heavy loads. The study used the second approach.
>
> Although the first approach provides more insight and is possibly more accurate, it is much more complex than the second approach. It must account for both the reliability of the lifting equipment (e.g., crane, yoke) and the reliability of workers to rig the transfer cask and operate the crane. A fault tree analysis of the crane equipment must be based on detailed design and operational information (e.g., lift heights, lift speeds, lift times, movements of the bridge, movements of the trolley). While the fault tree analysis can be performed with standard methods, the HRA requires further evaluation of human performance issues relevant to dry cask storage operations and, possibly, further development of HRA methods. For example, the kinds of actions that could result in dropping the transfer cask, such as the potential for human error in attaching the lift yoke to the trunnions at the subject plant, are not well understood, and not every erroneous action would necessarily cause the transfer cask to fall. (NRC, 2007b).

In addition to describing operations and identifying potential drop scenarios, the pilot PRA made two human-action-related assumptions that are particularly relevant to the current qualitative HRA report. First all crane operators and riggers are qualified according to accepted standards with some plants using professional riggers and second, by other plants use trained plant staff following the guidance contained in NUREG-0612 (1980).

(5) The fabrication of MPC, transfer overpack, and storage overpack was conducted flawlessly (i.e., there were no quality assurance problems).

The pilot PRA authors clearly stated their expectation that NMSS would use both the results of their study and the methodology to develop a basis to determine the need for other PRAs, improvements in data collection and analysis, and additional engineering design analysis, and to identify program areas that may be candidates for increased or decreased staff review or inspection focus. The authors also emphasized that the results may not necessarily apply to other cask systems or sites, but that the method might guide similar PRAs. This current report relied heavily on the pilot PRA's dry cask storage process description to provide insights into DCSOs at BWRs. Given the intentional boundaries of the pilot PRA, no inferences or conclusions about the regulatory implications of the study were drawn.

Within the stated boundaries (i.e., best-estimate point values and lack of a detailed HRA), the pilot study was instructive in developing and applying a methodology for identifying risks to the public and dominant contributors to risk associated with dry cask storage based on statistical and deterministic approaches. The results provided criteria to help focus this current analysis on human actions and HFEs that may be associated with a cask drop involving the Holtec International HI-STORM 100 cask system.

In summary, the NRC's pilot dry cask PRA provided the authors of this report with several important items: (1) a starting point for building SFH process descriptions and HFE scenarios, (2) familiarity with the types of consequences conceivable during SFH activities, and (3) a base of information for generating initial questions for SMEs about SFH activities. It was not the intent of this analysis to delve into many details of consequences. It was primarily important to identify the types of undesirable human events that could happen, particularly involving cask drops, and to explore plausible ways they might occur.

3.4 EPRI PRA of Bolted Storage Casks

While the NRC was conducting its pilot PRA study on the HI-STORM 100 system at a BWR site, the EPRI analyzed a bolted DCSS design at a generic PWR site and further applied generic site conditions based on the northeast U.S. (EPRI, 2004).[15] The bolted cask and PWR were intentionally chosen to complement the NRC's efforts. The EPRI study focused on the radiological risks to the public over the life cycle of a spent fuel cask to obtain insights to optimize risk and resource allocations throughout DCSOs. The authors of the EPRI report also emphasized that they did not conduct a "best-estimate" or a "bounding analysis," but something in between due to the nature of the conservative assumptions. Sensitivity analyses were performed on PRA assumptions, but the report was careful to note that an uncertainty analysis was not performed in a manner that would have necessitated a detailed customization of the PRA to a specific site. Because the authors produced "generic results," they felt that a rigorous uncertainty analysis would not be prudent.

The types of results contained in the EPRI report include (1) the frequency of events that can result in cask confinement failure and (2) radiological risks in terms of cancer fatalities per cask per year to a receptor individual 100 to 300 meters from the cask following a cask-design-basis or beyond-design-basis event. The Transnuclear (TN) bolted cask that can hold 32 or 40 PWR or 68 BWR spent fuel assemblies was used as the baseline cask. The report concluded that the risks from dry storage in a bolted cask are orders of magnitude below other risks found in the nuclear power industry, and it further asserted that the results reveal the ruggedness of the cask to withstand design-basis and beyond-design-basis events.

EPRI's high-level description of the major operations included descriptions of loading spent fuel onto casks and moving those casks into an ISFSI. The report categorized SFH activities into the following three major tasks or cask life cycle phases, which happen to be similar to the NRC's pilot PRA operation headings:

Cask Loading – Activities beginning with placement of the first fuel assembly in the cask or canister and ending with the cask or cask and canister being properly drained, dried, inerted, and sealed.

Cask Transfer – Activities involving placement of the sealed cask system onto a transport vehicle, transport to the ISFSI, and placement in position at the ISFSI.

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[15] The northeast portion of the U.S. (i.e., Maryland and states north and east) includes 17 NPPs (26 nuclear reactor units), all of which are located relatively near large population centers. In addition, a more expansive interpretation of the "north" and "east" portions of the U.S., as overseen by NRC regions I–III encompasses 51 NPPs (83 nuclear reactor units) out of the total U.S. fleet of 65 NPPs (104 nuclear reactor units).

Cask Storage and Monitoring – Activities required during the period of storage at the ISFSI up until the fuel is moved off site (e.g., movement to a central spent fuel repository or fuel reprocessing facility).

One interesting observation in the EPRI report involved the human performance elements of process learning, development of special tools, and codifying such knowledge into effective procedures to guide DCSOs:

> As experience is developed, the procedures and special tools used to coordinate the activities of the plant operation, the transfer crew, the radiation protection team, and the site security team are upgraded. After about 10 to 15 cask loadings, the procedures can reach a significant level of maturity, and a database of the measures from previous loadings, sealings, dry-outs, and testing can be used to verify that each new cask has been properly loaded. (EPRI, 2004)

The EPRI report contains relatively detailed process descriptions for a "generic PWR" plant. EPRI also performed an HRA that helped the current analysis because it provided a list of the types of unsafe actions (UAs) that might be expected during DCSOs involving bolted casks. An initial list of possible UAs was provided based on previous studies, plant observations, review of procedures, and an overarching, deductive master logic diagram. An HRA screening was then carried out, followed by the assignment of preliminary bounds on human error probabilities for human actions considered to contribute to risk.

In conducting their HRA, the authors highlighted an incorrect assumption that some analysts make in applying fault tree analysis to human errors. Fault trees treat basic events as statistically independent, which is not valid for human errors. Human actions contain dependencies when they involve the same operator, the same procedures, or are competing for the same resources in the same time. Therefore, analysts must evaluate possible combinations of human errors, before the quantification effort, to determine if such combinations may be assumed to be independent, and redefine the human errors and/or revise the logic model to correctly represent the dependencies. Dividing human actions into three time categories relative to the initiating event (i.e., pre-initiating, initiating, and post-initiating) helps identify actions that may be credibly assumed to be independent.

The EPRI report was geared toward providing human error probabilities, and a number of methods were used: Technique for Human Error Rate Prediction (THERP), Accident Sequence Evaluation Program Human Reliability Analysis Procedure (ASEP), Cause Based Decision Tree Method (CBDTM), Operator Reliability Experiment (ORE), and Human Cognitive Reliability (HCR). Statistical information on fuel assembly handling and crane events was obtained from the Savannah River Site Human Error Database Development for Non Reactor Nuclear Facilities WSRC-TR-93-581 (Benhardt, Eide et al., 1994). Statistical data from NUREG-0612 (1980), NUREG-1774 (2003) and a Reliability/Safety Assessment for the Oyster Creek Reactor Building Crane (Elrada 1994) also were used to generate EPRI's crane reliability model, but only the WSRC-TR-93-581 report was cited in the human error probability estimates for fuel assembly handling and crane events.

In addition to the human error probability estimates, the EPRI report presented culture and management attention issues that may affect human performance during DCSOs. They organized general observations as follows: commitment, awareness, preparedness, flexibility, fairness, learning, and adherence. These observations are discussed in more detail in Section 6 in the examples and recommendations for avoiding or mitigating HFEs in SFH and DCSOs.

The top six sequences from the EPRI report, composing 89.4% of the estimated radiological risk, included:

(1) Transfer phase: high-temperature fire (57.5%)

(2) Storage phase: heavy loads exceed structural limits (15.3%)

(3) Storage phase: high-temperature and forces (14.8%)

(4) Transfer phase: on-edge drop (1.0%)

(5) Loading phase: seismically induced refueling building failure (0.7%)

(6) Storage phase: cask impacted by a missile (0.1%)

The total radiological risk of DCSOs throughout their life cycle was calculated to be 5.6E-13 per cask per year for the first year and 1.7E-13 for each year thereafter. The transfer phase revealed the highest level of risk, with a cancer risk of 3.38E-13 per cask, most of which was due to a single accident sequence in which a high-temperature fire occurs during cask transfer. This risk was calculated for a receptor individual 300 meters downwind from the cask accident. This transfer phase represented 59% of the total first-year risk.

The loading phase contained the lowest level of risk due to mitigating effects of the building ventilation system, as well as the short duration of the event. The total cancer risk of the loading phase was 6.3E-14 per cask, which encompassed 11% of the total first-year risk.

The radiological risk of the storage phase of the cask life cycle was 1.7E-13 per cask per year. This represented 30% of the total first-year risk. Therefore, the first-year cancer risk per cask was estimated to be 5.6E-13, and the cancer risk in subsequent years was estimated to be 1.7E-13. EPRI emphasized strongly that these calculations were estimates lying somewhere between a bounding estimate and a best estimate.

The overall results of the EPRI report were similar to the NRC's pilot study in that risks to the public did not include early fatalities, and the risk of latent cancer fatalities was very small. However, the phases of operation deemed to contain the largest radiological risks were notably different.

Table 3-2 summarizes radiological risks for both analyses in units of magnitude of risk per cask per year. Figure 3-4 summarizes the percentage of overall risks by phases of operation during the first year and over a 20-year life cycle for both analyses.

The differences between the results appear to be driven by the types of plants and cask systems chosen for study, as well as the analysis approach. Primary drivers for the NRC's results included the choice of a Mark I BWR, the HI-STORM 100 cask system, a point estimate approach without uncertainty analysis, and the lack of an HRA. Primary drivers for EPRI's results included the choice of a PWR, the TN32 cask system, and an approach aiming between best-estimate and bounding cases with some treatment of uncertainty and the inclusion of an HRA. Given the different emphases and approaches of the studies, it is difficult to rank (in ordinal fashion) the many drivers that resulted in divergent analyses.

The authors of this current report suspect that plant type, cask system type, and initiating event category selections will dominate most of the differences in potential consequences between plants engaging in DCSOs, although detailed, plant-specific HRAs will be required, both to determine the full set of potential consequences and to generate defensible likelihood estimates for all identified potential consequences. That is, given the many human actions required throughout the life cycle of DCSOs, further comprehensive qualitative and quantitative HRAs are needed to determine (1) whether or not the risk levels indicated by the NRC and EPRI analyses actually are five orders of magnitude or more below other risks faced by licensees; and (2) whether or not any dominant human factors/human reliability concerns are present within DCSOs that ought to be identified and addressed to ensure that risk levels truly achieve or maintain order-of-magnitude reductions with respect to other licensee risks. The EPRI analysis is a strong step toward using HRA in DCSOs. Of course, more advances are required in HRAs of DCSOs, especially in light of serious recent concerns about the inspection, test, maintenance, up-rating, and operation of large cranes. Recent concerns and emerging issues will be discussed further in Section 4.

Table 3-2 Summary of radiological risks comparing EPRI and NRC results.*

Phase	**First-year risk[+] (cancer risk per cask per year)**		**Subsequent years risk[+] (cancer risk per cask per year)**	
	NRC; HI-STORM-100; BWR	**EPRI; TN32; PWR**	**NRC; HI-STORM-100; BWR**	**EPRI; TN32; PWR**
Cask Loading (NRC: Handling) (EPRI: Loading)	1.8E-12	6.3E-14	N/A	N/A
Cask Transfer (NRC: Transfer) (EPRI: Transfer)	0.0	3.3E-13	N/A	N/A
Cask Storage (NRC: Storage) (EPRI: Storage & Monitoring)	3.2E-14	1.7E-13	3.2E-14	1.7E-13
Total	1.8E-12	5.6E-13	3.2E-14	1.7E-13

*** NRC and EPRI terms for the three main phases of operations are provided in the first column.**

[+] Estimated as risk to the public in terms of annual probability of a latent cancer fatality.

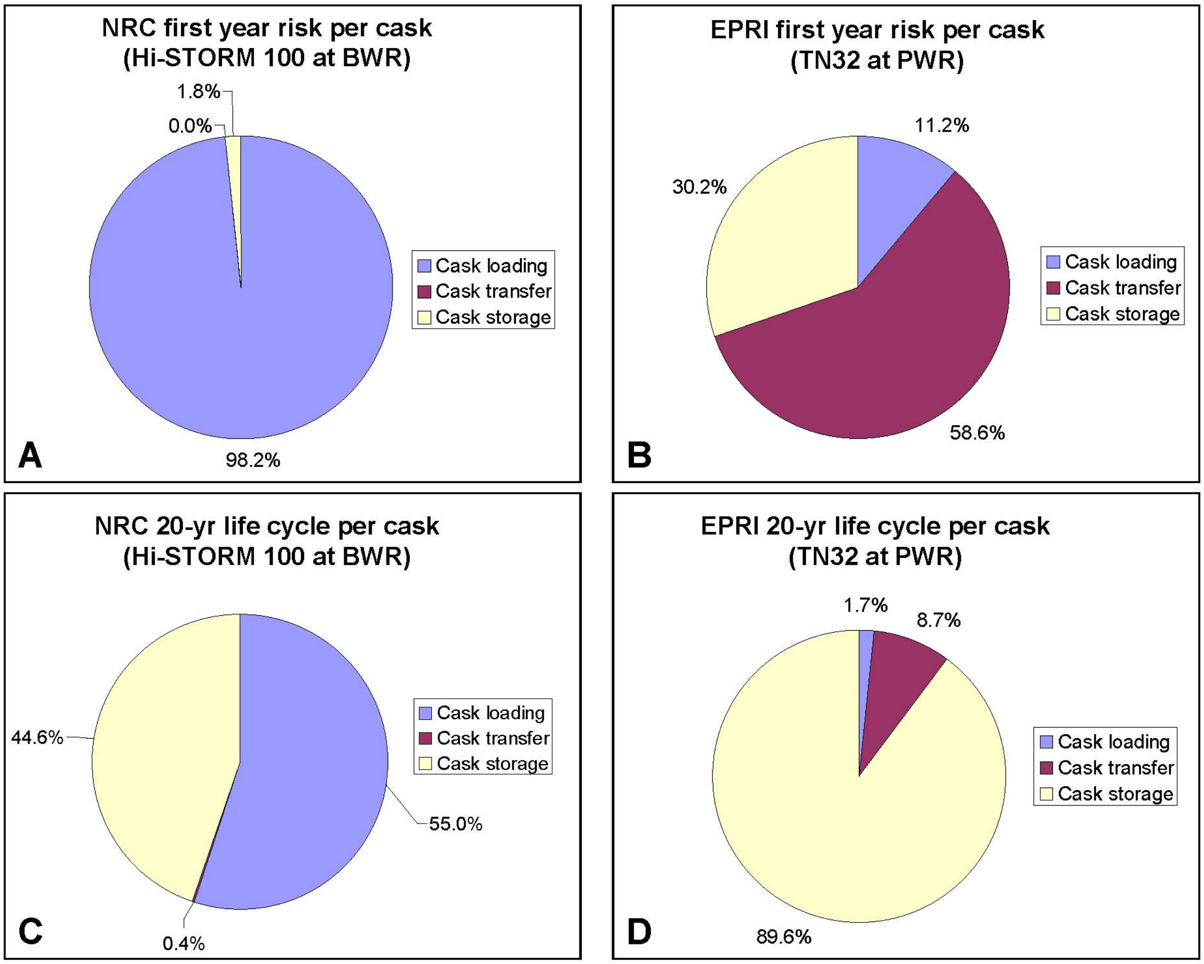

Figure 3-4 Percentage of risk per phase of operation for first-year and 20-year dry cask storage life cycle for NRC (A & C) and EPRI (B & D) analyses.*

* Note the significant differences between the analyses, driven primarily by plant types (i.e., Mark I BWR vs. PWR) and cask systems (i.e., H-STORM 100 vs. TN32), and driven secondarily by analysis approach (i.e., treatment of uncertainty, degree of best-estimate focus, inclusion of HRA, spent fuel load assumptions, etc.).

This section has summarized the approaches and results of both the NRC and EPRI dry cask PRA studies, including the limitations of the HRAs in each analysis. The NRC analysts attempted an HRA but were not pleased with the results; therefore, they used previous statistical data from various heavy load lift situations to estimate the likelihood of a load drop. The NRC analysis also did not include likelihood estimates for misloading fuel into a cask although it presented deterministic analyses to provide some indication of what kind of misload events would threaten the integrity of the cask system. The EPRI analysis included an HRA; however, it did not explain in detail the contexts surrounding UAs. That is, a fuel misload or cask drop may occur with a given likelihood and consequence due to a person or crew not performing an activity properly, but insufficient information was provided to describe how that error, or group of errors, occurred. In simple terms, both studies describe “what” HFEs can happen (the EPRI study identifies many more than the NRC study), yet neither study explains “how” or “why” those events might happen.

For example, the NRC study stated that the likelihood of a heavy load drop from a crane is simply equal to the retrospective number of heavy load drop-related events[16] divided by the number of heavy lifts 54,000[17] (i.e., 5.6×10^{-5}). The NRC study did not attempt to infer how many of these drops would be due to a UA or HFE. In contrast, the EPRI study provided many more specific UAs that may contribute to a cask drop such as "general operator actions in operation" and "failure to activate emergency stop button." UAs identified in the EPRI report were then assigned a human error probability, which may be modified by a performance shaping factor (PSF) derived from a tabulated value in a first-generation HRA method such as THERP (Swain and Guttman 1983) or obtained from expert judgment. The EPRI analysis also stated the assumed level of dependence (complete, high, medium, low, or zero) between some UAs. While the EPRI approach was more helpful in analyzing human performance issues than a single statistical estimate for all cask drops, it did not document "how" these errors might occur. Both studies heavily emphasized quantification; therefore, it is not unusual that they did not detail "how" such errors might occur—this was not their purpose.

It is possible that the SMEs and HRA experts conducting the EPRI analysis did consider details of how specific UAs may occur (including error-forcing contexts [EFCs]), and it is clear from Appendix D of the EPRI report that the analysts were cognizant of many factors that can affect human performance. However, the report does not give the reader an understanding of how specific UAs might occur nor does it give insight into how the occurrence or impact of such errors might be mitigated. This current report begins to fill in the gaps of "how" such errors or HFEs may occur by describing specific, detailed scenarios in which human actions result in consequential failures. For example, the scenarios in this report identify and describe the intentions, actions, interactions, UAs, and error mechanisms that may lead to a particular type of HFE. Additional scenarios, particularly scenarios dealing with misloads, are presented in NUREG/CR-7017 (NRC, 2012). The details of the scenarios in Section 5 impart a greater understanding of how such human failures may occur and allow techniques for identifying and mitigating specific human performance issues to be inferred.

Furthermore, as discussed in Section 4, a number of events related to DCSOs have prompted a need for a more through HRA than was done in either NRC's or EPRI's PRAs. These events and additional human performance concerns explored in Section 5 indicate that risks may be higher than previously reported and possibly growing in magnitude. Ultimately, only detailed, rigorous analyses including more extensive qualitative and quantitative HRA components will provide appropriate insights about actual risks involving DCSOs.

In summary, the NRC report did not include an HRA for SFH and DCSOs in its analysis of activities at a Mark I BWR. Second, while the EPRI report did provide a PRA including an HRA with a quantitative estimate of risk (i.e., somewhere between a best estimate and a bounding estimate) at a PWR, it did not provide extensive details on "how" UAs might occur. Finally, the current report provides scenarios that do supply enough information to begin establishing a technical basis for identifying and mitigating human performance issues.

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[16] These events, reported in NUREG-1774 (2003), were technically load drops or very close to a drop, but none were of the catastrophic type in which a ≥ 266,893 Newton (30-ton) load free falls to the floor or ground.

[17] Statistics estimated from NUREG-1774 (2003).

3.5 Categories of DCSOs Used in This Report

The following general description of fuel handling and cask operations is not specific to any one particular plant, and it represents a somewhat generic perspective. The level of detail is sufficient to build base case scenarios from which contexts for potential UAs and HFEs may be derived. Two slightly different high-level descriptions of the major operations involved in loading spent fuel into casks and moving those casks into an ISFSI were provided in the NRC's draft dry cask PRA (NRC, 2007b) and the EPRI's PRA for bolted storage casks (EPRI 2004), as mentioned in Sections 3.3 and 3.4.

This report modifies the previous high-level categories of the main operations to better categorize major phases in which different types of human performance problems may arise and to slightly increase the detail of high-level comparisons of potential consequences and risks associated with different cask systems. Table 3-3 demonstrates how the DCSO categorization scheme compares to those outlined in the NRC and EPRI reports. The new scheme is divided into seven phases of operation. Three of the seven phases expand on operations that were condensed into two phases in the NRC and EPRI categorization schemes. Two phases are identical to phases used in either or both of the NRC and EPRI reports. Two of the seven phases that involve planning and preparation are completely new (i.e., they were not addressed in the major operation categories in the NRC or EPRI reports). The main function of these categories in this report is to group major SFH and DCSOs in the detailed list of operations in Appendix A.

It is intended that this more comprehensive categorization (i.e., the seven phases) will be used to guide the analysis of human performance in any future site-specific DCSO PRA. There are at least two chief benefits of using the seven phases. First, the planning and preparation phases encourage more comprehensive analysis of operations that can "set up" personnel for an accident in later phases. Second, adding more phases for "direct"[18] cask activities may better reflect actual "hand-offs" that occur among teams of personnel.

Phase 1 — Fuel Load Planning (new; not used in NRC or EPRI report) – This phase involves activities by the appropriate engineering department (e.g., nuclear fuels engineering) to generate a fuel move plan incorporating proper review and approval and subsequent communication to the fuel handlers who will carry out the operation. This activity depends on proper configuration management practices to ensure that an accurate record of the history and specific location of every fuel assembly in the SFP is continually maintained. The fuel movement plan should include *origin information* (serial numbers and alphanumeric locations of assemblies within the SFP) and *destination information* (cask canister locations and serial numbers of assemblies). In addition, the fuel load plan should include the process that fuel handling personnel are to follow during actual loading operations (e.g., three-part communications, independent review of loaded canister before closure).

Phase 2 — Cask Operations Personnel and Equipment Preparation (new; not used in NRC or EPRI report) – This phase involves training and appropriate staffing of personnel for DCSOs, as well as inspecting, testing, maintaining, recertifying, upgrading, etc., all structures, systems, and components required for executing DCSOs. An example of this phase would include assigning

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[18] 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.

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 ensure that no cracks, deformations, or other aberrations threaten crane operations. This activity would be immediately accompanied by thorough inspection, testing, 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 SFP).

Phase 3 — Cask Preparation and Positioning (partially new, but borrows from NRC "handling" phase) – This phase represents the beginning of actual DCSOs as the cask is brought into the plant for loading preparation activities, which culminate with the empty cask/canister system being placed in the cask loading pit of the SFP before fuel loading.

Phase 4 — Cask Loading (not new; borrows from NRC "handling" phase and is identical to EPRI "cask loading" phase; used for consequence grouping) – This phase 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.

Phase 5 — Loaded Cask Transfer Within Structure (partially new, but borrows from NRC "handling" and "transfer" phases, as well as EPRI "cask transfer" phase; used for consequence grouping) – This phase 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.

Phase 6 — Loaded Cask Transfer Outside Structure (partially new, but borrows from NRC "transfer" phase and EPRI "cask transfer" phase; used for consequence grouping) – This phase begins with a loaded cask coupled to the cask transporter and ready for movement to the ISFSI and ends with cask emplacement at the ISFSI.

Phase 7 — Loaded Cask Storage and Monitoring (not new; identical to NRC "storage" phase and the EPRI "cask storage and monitoring" phase; used for consequence grouping) – This phase begins with cask emplacement at the ISFSI and ends when the cask contents (spent fuel) are transferred to an off-site storage or processing location.

Table 3-3 Categorization schemes of major DCSO operations used in the NRC, EPRI, and current reports.

NRC Pilot PRA Structure	EPRI PRA Structure	Current Report Structure
		1. Fuel load planning • Generate fuel move plan • Dependent on previous outages
		2. Cask operations personnel & equipment preparation Training, staffing, inspection, test, maintenance
1. Handling Cask lowered into the pit MPC in storage cask is prepared to move out of secondary containment		3. Cask preparation & positioning • Cask brought into plant • Cask into loading pit
	1. Cask loading • First fuel assembly into cask • Cask drained, dried, inerted & sealed	4. Cask loading • First fuel assembly into cask • Cask drained, dried, inerted & sealed
2. Transfer As MPC in storage cask passes secondary containment Storage cask on ISFSI pad	2. Cask Transfer Placement of cask on transport vehicle Storage cask on ISFSI pad	5. Loaded cask transfer within structure • Move from cask preparation area • Cask coupled to transporter
		6. Loaded cask transfer outside structure • Cask coupled to transporter • Cask emplaced at ISFSI pad
3. Storage Monitoring & surveillance for 20 years or more	3. Cask storage & monitoring Monitoring & surveillance for 20 years or more	7. Loaded cask storage & monitoring Ends when cask contents are moved off site (20+ years)

3.5.1 Basic Operations in DCSOs for the HI-STORM 100 System at a Mark I BWR

Although generally similar across the seven phases described earlier, the DCSSs differ slightly in the steps taken within each phase. Distinction between the steps within the cask systems becomes apparent in phases 3 through 6 in which the specific cask type is loaded with fuel, sealed, and transferred to the ISFSI. More details on the elements of each step are provided in Appendix A.

Figure 3-5 presents the steps within the first two phases in cask loading and fuel handling. These steps are generalized across multiple cask systems and illustrate steps that may be performed at any plant.

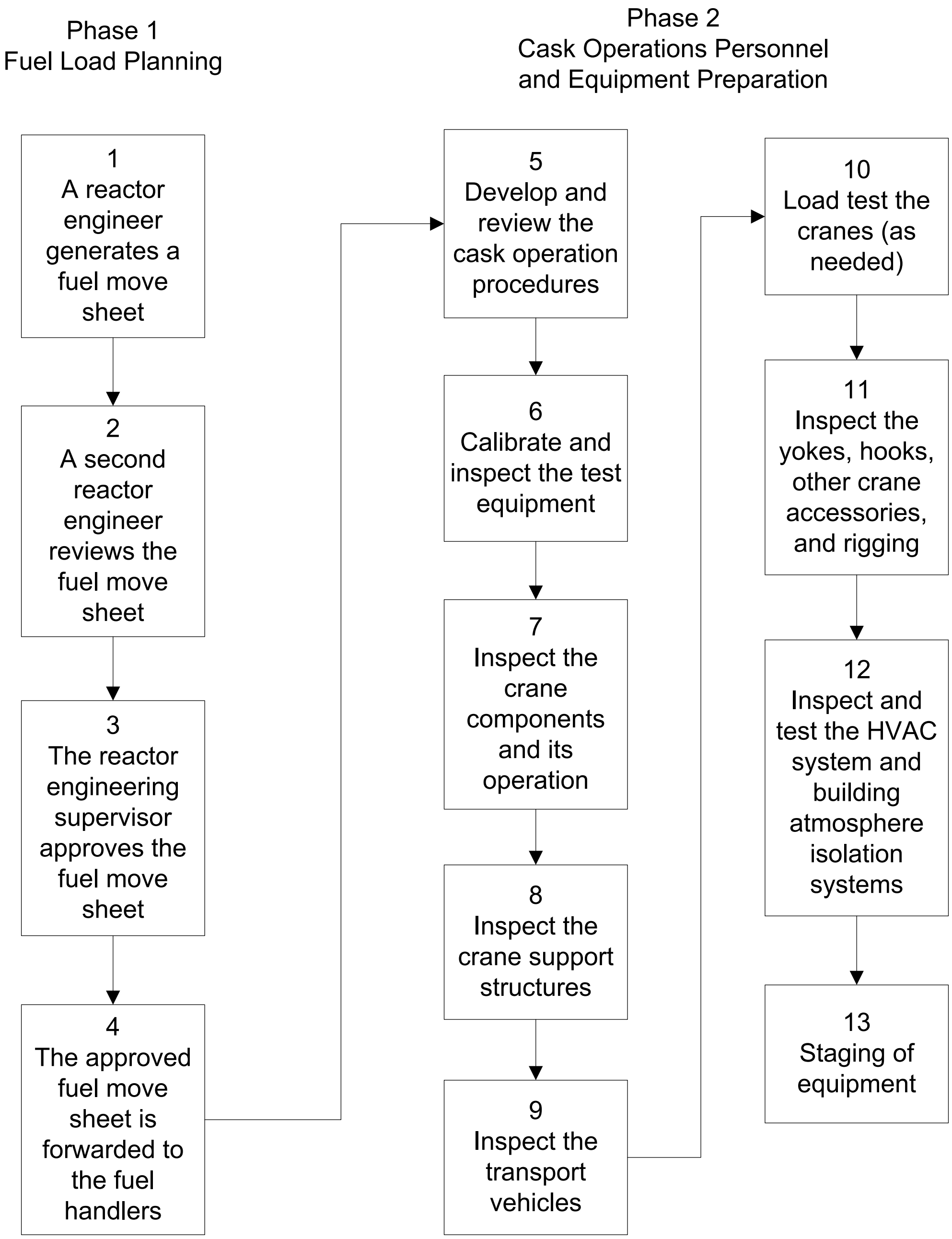

Figure 3-5 Phases 1 and 2 of cask loading and fuel handling.

The steps within the next four phases depend on the design of the DCSS. A primary distinguishing factor among DCSSs involves the number of cask components. For instance, the HI-STORM 100 system contains three components: MPC, transfer cask, and storage cask. Once the MPC is loaded with spent fuel, it is first transported within the transfer cask until it is lowered into the storage cask in which it will stay in while stored at the ISFSI. Figure 3-6 illustrates the steps within phases 3 and 4, and Figure 3-7 presents the steps for phases 5 and 6.

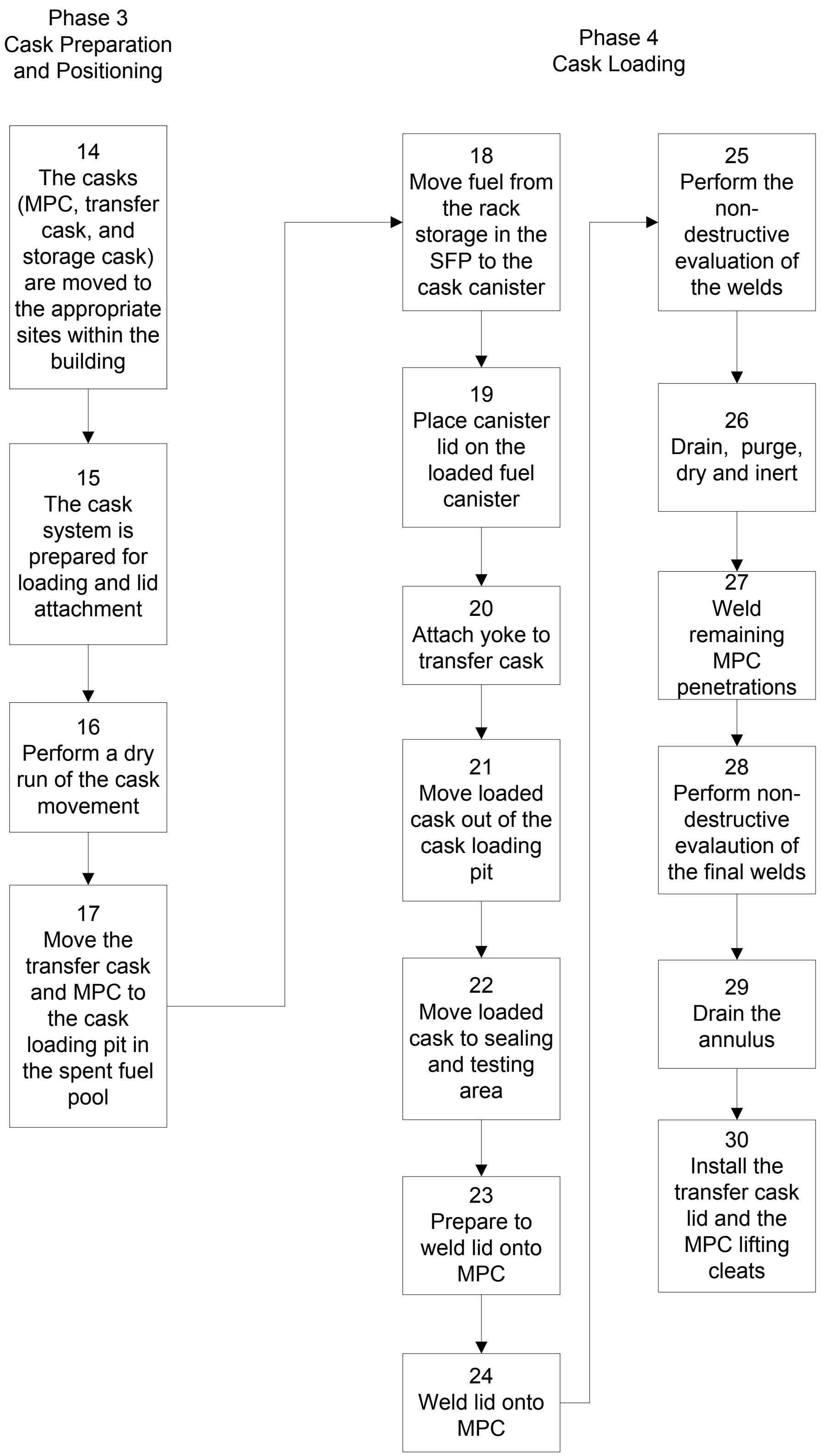

Figure 3-6 Phases 3 and 4 of cask loading and fuel handling for the HI-STORM 100 system at a Mark I BWR.

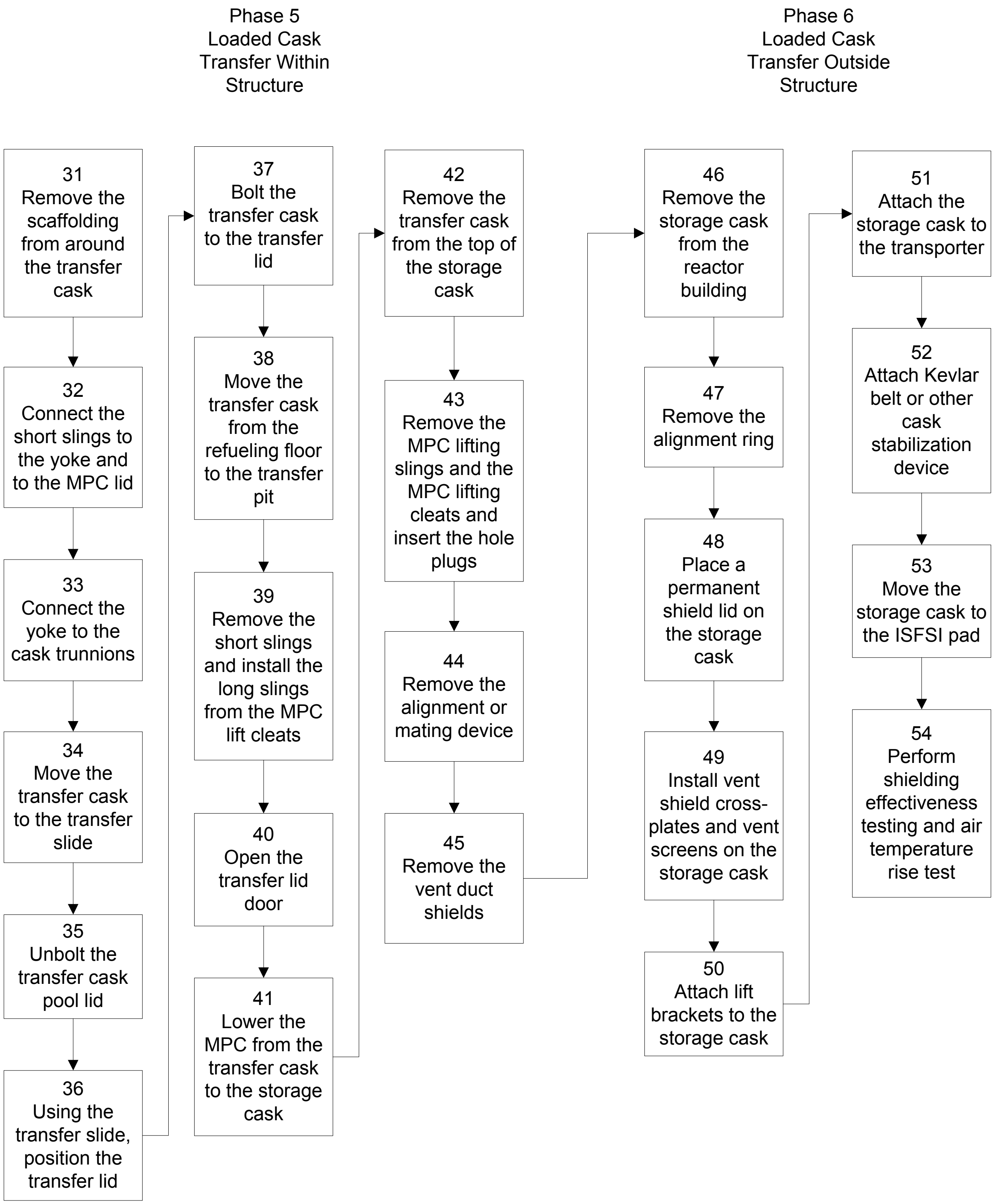

Figure 3-7 Phases 5 and 6 of cask loading and fuel handling for the HI-STORM 100 system at a Mark I BWR.

Similar to phases 1 and 2, phase 7 contains steps that can be generalized across multiple cask systems. The steps illustrate those that may be performed at any plant and focus on ensuring that all ISFSI operations procedures are followed. The steps of Phase 7 are:

1. Ensure monitoring of the following elements:
   a. corrosion of cask components
   b. pressure, temperature, and radiation levels
   c. structural integrity of the pad or horizontally oriented, concrete storage vaults at the ISFSI
2. Ensure that no obstructions to the cask air inlets and outlets required for proper air circulation around the casks are present.
3. Ensure proper calibration of all sensors used during monitoring activities.
4. Ensure the maintenance of the following programs:
   a. QA program
   b. ISFSI security program consistent with the reactor facility security program
   c. training program for personnel assigned to the ISFSI
5. Ensure that potential effluents from casks (should they materialize) are properly handled with structures, systems, and components at the ISFSI and along the travel path to the ISFSI.
6. Maintain detailed records for the fuel loading of each cask provided by the cask supplier for each cask design used
7. Limit the placement of flammable and explosive liquids near the loaded cask during movement.
8. Maintain a process for retrieving spent fuel from a loaded DCSS on the ISFSI and returning it to the SFP.

3.5.2 Basic Operations in DCSOs for the TN-40 System at a PWR

If using a TN-40 system for the DCSOs, the operations are slightly different in phases 3 through 6. The TN-40 system uses a single cask for loading and storing spent fuel, which serves the combined purposes of confinement, shielding, and thermal protection. Therefore, the additional steps inherent in transferring an MPC from a transfer cask to a storage cask are avoided. However, in general, the other steps (e.g., inspecting the cask, loading the spent fuel into the cask within the SFP) may be generalized across storage systems. Figure 3–8, “Phases 3 through 6 of cask loading and fuel handling for the TN-40 system,” displays the key steps within phases 3 through 6 for a TN-40 system.

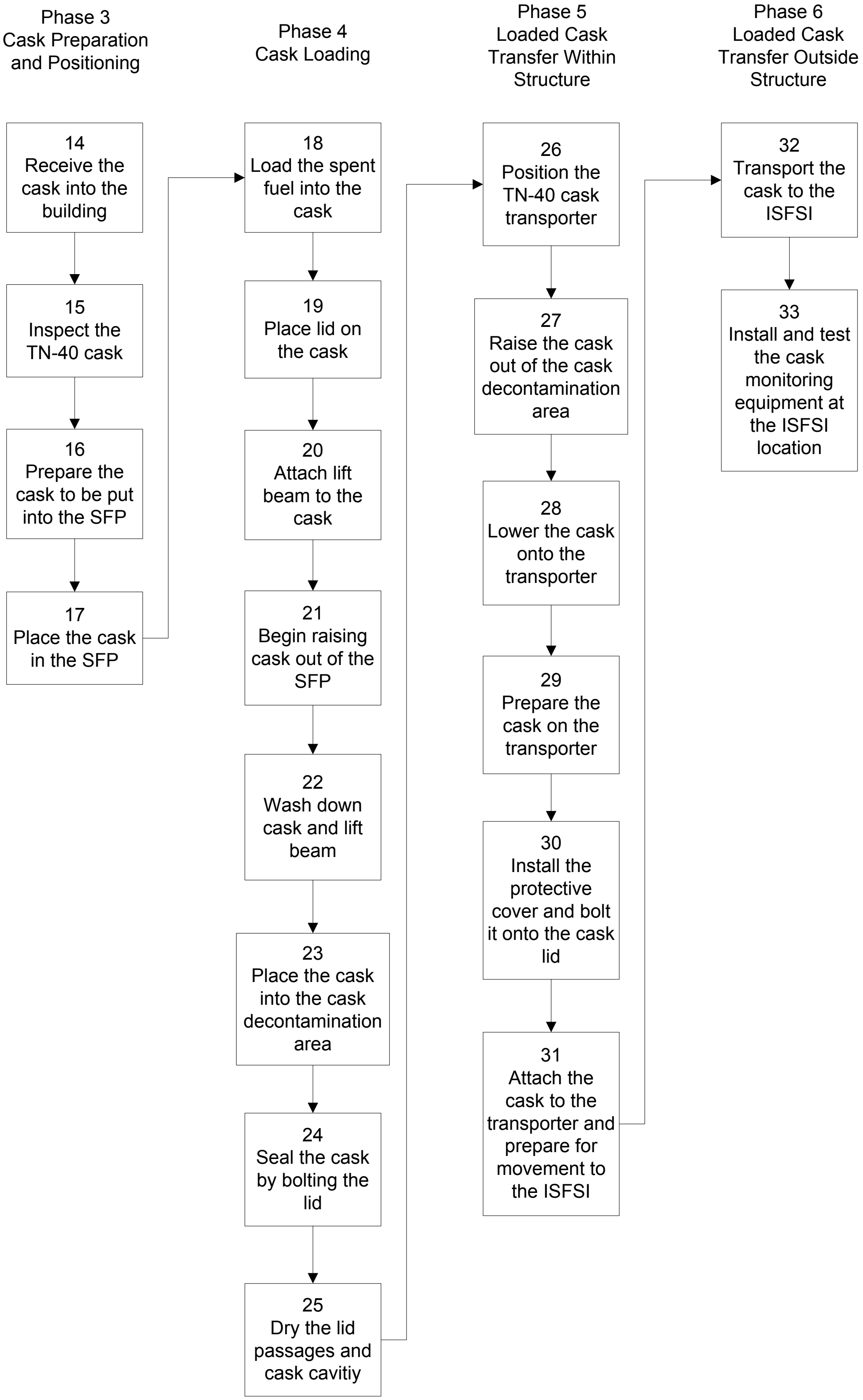

Figure 3-8 **Phases 3 through 6 of cask loading and fuel handling for the TN-40 system.**

3.6 Cask Drop Terminology

As the authors of this report reviewed previous analyses and other documentation referring to cask drops, the terminology used to identify different types of drops appeared to be inconsistent. For example, *cask drop* could be used to identify drop types ranging from a relatively slight uncontrolled vertical movement of the cask, to a 30.5 meter (100-foot) freefall drop of a cask. The term *unplanned descent* was sometimes used to refer to the same wide range of cask drops, and at other times it was used to refer to something less energetic than a freefall drop. In this report, the following specific terminology is used to consistently distinguish between different types of cask drops and other cask movements:

- *Cask drop* or *MPC drop* — In this report a “drop” (i.e., cask drop or MPC drop) refers to a freefall drop.

- *Unplanned descent* — Uncontrolled or inadequately controlled lowering of a cask (or other heavy load), which is not a freefall because acceleration is resisted to some degree by lifting or support equipment.

- *Unintentional lowering* — A controlled lowering of a cask (or other heavy load) by the crane, but at a time not intended; for example, inadvertent lowering of the cask onto the side of the transfer pit opening or edge of the refueling floor above the cask decontamination area. If unintentional lowering occurs such that the center of mass is positioned just beyond the edge of the support surface, a cask tip may occur.

- *Unintentional raising* — A controlled lifting of the load by the crane, but at a time not intended; for example, inadvertent raising of a cask such that a two-block event occurs. Unintentional raising could lead to a two-block event followed by crane cable failure and a cask drop.

- *Cask hang-up* — A situation occurring during raising or lowering such that the cask is immobilized because of a crane-related failure or a cask or crane component impacting/ coupling with an unyielding object; for example, catching a cask trunnion on a rigid object on the wall of the SFP such that damage occurs to the crane and load movement ceases.

4 RECENT CONCERNS IN SPENT FUEL HANDLING (SFH)

This section briefly reviews problems and concerns related to dry cask storage operations (DCSOs) that have occurred primarily within the past few decades, with particular emphasis on those of the last decade. This section also includes emerging issues that may further increase the risk of a spent fuel handling (SFH) accident or incident in the future.

First is a selection of key insights from NUREG-1774, *A Survey of Crane Operating Experience at U.S. Nuclear Power Plants from 1968 through 2002* (NRC, 2003). It was found that the observed probability of a heavy load drop, thus far, appears to be low; however, there is considerable uncertainty because human performance is crucial for safe execution of load movement tasks. Rigging errors, which are highly dependent on human performance, have led to three heavy load drops at nuclear power plants (NPPs). NUREG-1774 also identified that different licensees were applying single-failure-proof crane guidance in different ways and that few plants were analyzing the consequences of a load drop.

Second is a list of concerns involving the design, inspection, maintenance, and use of crane structures, systems, and components (SSCs) related to moving heavy loads—particularly system integrity problems. The most serious concerns surround the uprating of crane capacities with simultaneous discoveries of age-related failure modes, design problems, and deficiencies in inspection procedures that have resulted, in some cases, in an inability to capture signs of age-related failure processes.

Third is a list of emerging issues that may further increase the risk of a SFH accident or incident due to human failure events (HFEs) in the future. The section ends with a brief discussion of actions taken to address concerns that have arisen in recent years in SFH operations.

4.1 Concerns Identified in NUREG-1774

NUREG-1774 was written to respond to candidate generic issue 186, “Potential Risk and Consequences of Heavy Load Drops in Nuclear Power Plants,” to estimate the likelihood and significance of heavy load drops. The survey reviewed crane operating experience from the following sources: actual crane operating experience at U.S. NPPs, licensee event reports, NRC inspection reports, licensee correspondence, and crane vendor reports. Crane operating experience reports issued by the New Mexico Environmental Evaluation Group, the Department of Energy, the Department of the Navy, and the California Division of Occupational Safety and Health (NRC, 2003) were included in the report. Listed below are three key insights from NUREG-1774:

(1) The average rate of drops for very heavy loads (based on retrospective analysis of load drop statistics) was estimated to be 5.6E-5/demand. This estimate could be higher or lower at a particular plant due to varying unsafe action (UA) rates, which appeared to dominate load drop events. Of particular concern, only 8 of 74 plants (11%) indicated that a consequence analysis for heavy load drops had been performed for their plants. During the period from 1993–2002, the number of operating plants increased only 9%

over the period from 1983–1992, yet the number of crane-related injuries during the 1993–2002 period was 100% higher[19] than those from 1983–1992.

(2) Considerable confusion/inconsistency regarding requirements has resulted in varying interpretations of what constitutes a single-failure-proof crane. While the features of dual reeving, redundant limit switches, and redundant brakes have been universally recognized, alleged ambiguity in NUREG-0554 (1979) has led to inconsistent interpretations of the remaining criteria. Therefore, not all declared ”single-failure-proof” cranes are equal.

(3) The three very heavy load drops recorded in NUREG-1774 were all due to rigging failures, not crane failures; thus, they were highly dependent on human performance. Use of a truly single-failure-proof crane could not have prevented any of these drops, although use of single-failure-proof cranes and lifting devices could have prevented other load or hook and block assembly drops that have occurred.

The crane-related events documented in NUREG-1774 can be categorized according to the specific violation or mistake encountered. Table 4-1 relates how many events occurred within each type of violation or mistake category (NRC, 2003). The frequency of events within each category may indicate current trends and provide an ordinal ranking of the types of events. However, caution is warranted in interpreting the frequencies in this manner because the table is based on very limited information. Many of the events listed in Table 4-1 may be strongly influenced by deficiencies in safety culture.

Table 4-1 Relevant previous events related to crane operations.

Types of events	Frequency of events
Violation of procedures	25
Inspection, test, maintenance	16
Rigging mistakes (violation of procedures)	11
Equipment malfunction	7
Violation of defense in depth (violation of procedures)	5
Operational deficiency	3
Procedural deficiency	3
Equipment modifications (violation of procedures)	2
Equipment malfunction due to QA or original installation	2
Material QA	2
Other	9

The review of load handling in the nuclear power industry that occurred as a result of generic issue 186, largely documented in NUREG-1774, highlighted that while the estimated frequency of heavy load drops is low, considerable uncertainty remains when trying to determine the risk of heavy load movements. Operational experience indicates that human performance problems, especially those involving rigging “below-the-hook,” are the principal contributors to load drops (RIS-05-025, 2005). In addition, it was noted that many licensees had not conducted consequence analyses of possible load drops. Section 4.2 describes other sources of human

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[19] The increase in crane-related injuries may be due in part to the increased frequency of lifts during the later time period, as well as higher rates of injury reporting.

performance issues related to the potential for cask drops with a particular emphasis on inspection and quality assurance (QA) processes.

4.2 Concerns Identified in Various Sources

This section contains information on selected events related to cranes and load lifting equipment used to lift heavy casks filled with spent fuel. Major issues noted below include improper engineering analyses, manufacturing defects, improper repair practices, unexpected aging issues with crane components, problems with crane inspection and test processes, and instances of disregard for crane operating procedures and ignoring warnings to derate cranes based on component design or aging effects. These items do not solely attribute problems with cranes to a lack of due diligence on the part of licensees; ambiguous requirements and regulatory guidance are also identified. Table 4-2 lists several significant events related to the potential for heavy load drops and notes the establishment of Generic Issue 186 in 1999 to raise visibility on this potential problem.

Table 4-2 Several significant events related to the potential for heavy load drops.

Date	Source	Primary Equipment Involved	Reported Malfunction	Recommendation
March 1997	Whiting Corp. (10 CFR, Part 21 Notification; accession #: 9703130317)	Auxiliary hoist	Over-stressed auxiliary hoist on type of heavy-lift crane.	Cranes should only be used at or below 40% of the rated capacity; special review and authorization could be made for use with loads as high as 60% of rated capacity.
1999	Generic Issue 186 – “Potential Risk and Consequences of Heavy Load Drops in Nuclear Power Plants”		Inadequate measures to protect against heavy load drops.	Prevent heavy load drops, and ensure that spent fuel, fuel in the core, and equipment needed for safe shutdown and residual heat removal will not be damaged if a load drop occurs.
September 2002	10 CFR, Part 21 Notification; event #: 39190	Crane	No malfunction protection found (e.g., controls to sense and respond to conditions such as excessive electric current, excessive motor temperature, over-speed overload	Provide safety interlocks to prevent injury and/or damage due to component malfunctions.

			and excessive travel). Over speed protection was not provided in the event of a gearbox failure.	
January 2003	Whiting Corp. (10 CFR, Part 21 Notification; event #: 39545)	Hoist unit	Over-stressed internal bolts on a hoist unit.	Cranes should only be used at a 50% reduction in rated hoist capacity.
June 2004	NRC Inspection Report 07200034/2004001 concerning the Tennessee Valley Authority's Sequoyah Nuclear Plant	Crane bridge girder end truck and support	Cracks in crane bridge girder end truck and support. Disagreement between licensee and NRC in deciding what constitutes "inaccessible" for an area that is to be periodically inspected.	Periodic inspections must be performed (even of difficult-to-reach areas).
January 2005	Whiting Corp. (10 CFR, Part 21 Notification; event #: 41318)	Hoist equalizer plates and welds (limited to hoists of some redundant crane trolleys)	Overstressed condition on some hoist equalizer plates and welds.	Visually inspect for cracks in the plates or welds in the assembly adjacent to the rope termination at each end of the equalizer arm that the nut on the rope fitting bears against. Suspicious visual indications of potential cracks may be further examined using magnetic particle testing.

In Table 4-2, the June 2004 event involving several crane-related issues deserves additional explanation. As part of this event, the Tennessee Valley Authority (TVA) halted cask-loading operations at the Sequoyah plant after craftsmen discovered cracks in the crane bridge girder end truck and support. As described in the NRC Inspection Report 07200034/2004001, during the first spent fuel cask loading operation at Sequoyah on June 10, 2004, the auxiliary building crane tripped/stopped twice when it was carrying the fully loaded cask. A broken rail anchor bolt was discovered, as were cracks in welds between the bottom flanges of the crane truck adjacent to the seismic restraint. Additionally, base metal cracks about 30.5 centimeters (12 inches) long were discovered on the web near the concrete wall in a truck corner. Further inspections were immediately performed, and all outside web plates of the four trucks near the concrete walls were found to have similar weld and base metal cracks. More than 20 cracks were identified using visual and magnetic particle examinations. The cracks appeared to have been present for a long time, although their age was not definitively determined. The licensee subsequently repaired the welds and base metal materials, performed functional and load tests on the crane, and resumed cask movement three days later.

The NRC inspection revealed that periodic inspections for the girder structure in the cracked areas were not performed as required by American Society of Mechanical Engineers (ASME) (or American National Standards Institute (ANSI)) B30.2, Overhead and Gantry Crane, Step 2-2.1.3.(c).(1). The previous inspections did not reveal these cracks because the licensee deemed the areas inaccessible. Upon review, the NRC determined that the areas were difficult to access, but not inaccessible. These omissions in inspection were the first indications that the understanding of QA requirements was lacking (Landis, 2004).

In addition, the NRC discovered another inspection process discrepancy when reviewing visual inspection records involving a work order in which specified welds on the auxiliary building 1,112,055 Newton (125-ton) crane were made to verify single-failure-proof conformance with NUREG-0554. The licensee had visually inspected some, but not all, critical welds during the crane upgrade to single-failure-proof status whose failure could result in the drop of a critical load. The welds inspected had been identified as critical welds by the crane vendor and included horizontal welds between the girder top and bottom plates and web plates, and the trolley load girder. However, the crane vendor did not identify the welds in the crane trucks as critical; therefore, they were not inspected. NRC inspectors determined that all the welds in the load path, including the welds in the crane trucks used to carry, transfer, or retain critical loads and prevent load drop, should have been identified as critical welds and consequently inspected. These omissions in visual inspection by the licensee further revealed a lack of understanding of QA requirements designed to ensure crane safety (Landis, 2004).

An additional unresolved item discovered during the inspection involved three apparent problems in the auxiliary building crane seismic qualification calculation. These apparent problems included lack of justification for nearly doubling the allowable structural component stresses, the assumption to use two rails to resist the bridge wheel lateral forces, and the assumption to release wheel loads from the bridge rail longitudinal direction. These problems raise questions about the appropriateness of the assumptions used to uprate the auxiliary building crane and asserting single-failure-proof conformance to NUREG-0554. These discrepancies revealed a lack of understanding of how to perform structural analyses involving heavy lift cranes (Landis, 2004).

The selected issues presented in this section in conjunction with SME interviews and the material from NUREG-1774, helped the authors of this report better understand the engineering and administrative issues surrounding the potential for cask drops (NRC, 2003). These collective insights increased the plausibility of the illustrative cask drop scenarios presented in Section 5.

4.3 Emerging Issues

This section introduces several areas of emerging issues involving DCSOs, identified by SMEs, that appear to warrant additional detailed investigation of potential human performance vulnerabilities. The areas include performance of cask operations by contract personnel, modification of casks to accommodate small cranes, QA issues at cask equipment vendors, installation of new heavy lift cranes, resistance to preparing mitigation for crane malfunction, and the use of stand-alone vertical cask transporter systems. None of these emerging issues are addressed to a significant degree in this current report; however, they did influence the development of particular scenarios in Section 5.

4.3.1 Performance of Cask Operations by Contract Personnel

According to interviews with SMEs at the NRC, licensees are increasingly turning to contractors to execute some or all cask loading campaign (CLC) activities. The SMEs expressed some concern that the use of numerous contractors in conjunction with plant personnel on hybrid teams may present challenges to successful performance of DCSOs. Plant personnel and contractor personnel can be expected to significantly differ in their knowledge and experience with plant structures, systems, components, and cask-system-specific equipment as well as in training and the use of procedures. Additional challenges for hybrid teams involve the division of responsibility for carrying out and monitoring risk-significant DCSO tasks. While the diversity of knowledge and experience among members of these hybrid teams has the potential for producing outstanding DCSOs, methods for integrating and managing these teams will be critical to avoiding human performance vulnerabilities.

SMEs at the NRC noted situations in which licensees had hired contractor teams to carry out major portions of DCSOs and appeared to be delegating too many of their oversight responsibilities to the contractor teams. At times, the NRC has identified the need to highlight excessive delegation by licensees and reiterate that the licensees are ultimately responsible for the conduct and outcomes of the operations. SMEs also noted another potential problem in managing and overseeing hybrid teams—an observation of significantly reduced openness of contract personnel to discuss the operations they are performing or preparing to perform. This affects information exchange during NRC inspections and may signal potential communication barriers between contractor and plant personnel that could impair the execution of DCSOs. One SME mentioned that on two separate occasions a particular plant pieced together CLC teams using personnel from multiple contractors. Both campaigns were considered disasters in terms of cost and schedule. The plant and utility management stated that they would only use a single turnkey contractor with all experienced crews for future CLCs.

The human performance vulnerabilities involving training, communication, independent verification, and team dynamics, described in Section 5 and Appendix C, begin to address the potential impacts of using hybrid teams of plant and contractor personnel. While these discussions represent an initial effort to explore this complex topic, given its importance and the increasing trend of using contractor workforces for CLC activities, additional details of potential human performance vulnerabilities involving hybrid teams should be investigated.

4.3.2 Modifying Casks To Accommodate Small Cranes

In July 2006, after an inspection of dry cask storage campaign preparations and considerable discussion with the utility and the cask vendor Transnuclear Inc., the NRC granted an exemption to the ISFSI licensing requirements in 10 CFR Part 72. The exemption allowed the Fort Calhoun Station (FCS) in Nebraska to use a specialized, lightweight, minimally shielded transfer cask to accommodate the limited lifting capacity of the FCS auxiliary building crane. The single-failure-proof FCS crane had a capacity of 667,233 Newtons (75 tons) instead of the 889,644 Newtons (100 tons) required by the standard NUHOMS DCS transfer cask design. The use of the minimally shielded transfer cask (i.e., reduced lead shielding) led to much higher surface dose rates, which required remotely controlled crane operations and supplemental shielding to reduce radiation doses to personnel. The weight of the lightweight transfer cask was further reduced prior to lifting by draining most of the water from the transfer cask—twice as much as allowed by the NUHOMS Final Safety Analysis Report (FSAR). Specific conditions in the NRC exemption limited loading of only four transfer casks; limited decay heat level per transfer cask to no more than 11 kilowatts; required that the minimum cooling time for fuel to be loaded be 16.2 years; and stipulated new dose limits based on calculations incorporating the configuration of mandatory supplemental shielding (RIS-06-022, 2006).

Although the exemption was granted, there was concern that it could lead to higher dose rates and higher potential fuel temperatures than those allowed by established DCSO requirements. In the Staff Requirements Memorandum (SRM) dated August 31, 2006, the Commission stated that the "exemption issued for Fort Calhoun Station's transfer of spent fuel to dry storage should not be viewed as establishing a precedent that encourages future exemption requests for transferring spent fuel to dry cask storage when a crane does not have sufficient capacity to lift and transfer the approved transfer cask." After this event, the NRC communicated insights, including the following, to all licensees: expect that lead times on the order of five years are needed when planning ISFSI operations at a site; improve CLC planning to avoid exemption requests; allow time and resources to ensure that overhead cranes and crane supports meet licensing basis requirements before starting a CLC; and hold frequent, early discussions with the NRC during the CLC planning process (RIS-06-022, 2006).

According to interviews with SMEs at the NRC, the use of a specialized, lightweight, minimally shielded transfer cask at FCS caused concern at the NRC not only because of the potential for increasing radiation exposures to plant personnel, but also because of questions about whether the increased distance between personnel and the loads being moved could increase the risk of a cask drop event. In addition, while not explicitly mentioned in RIS-06-022, it is likely that there was mounting time pressure on the team carrying out the CLC, given that in September 2006 the FCS began one of the most complex and ambitious outages attempted in the nuclear power industry. From September through December 2006, a team of 650 FCS plant personnel and more than 1,800 contractors replaced the plant's two steam generators, the reactor vessel head, the pressurizer, the low-pressure turbines, and the main output transformer, as well as replacing one-third of the fuel assemblies in the reactor core and performing routine maintenance (Jones, 2007).

Ideally, licensees will follow the NRC's direction to further prepare and modify plant equipment to avoid using lightweight, minimally shielded transfer casks via the exemption process. However, if there is a reasonable possibility for such activities to recur, this is one important area for future investigation of potential human performance vulnerabilities.

4.3.3 Quality Assurance Issues at Cask Equipment Vendors

According to an SME at the NRC, various QA issues have occurred involving casks and other equipment used in DCSOs. For example, a weld removal and nondestructive evaluation activities during cask fabrication were not documented. While not indicative of a structural problem with the cask, this failure revealed a QA process weakness. This type of QA deficiency could increase the likelihood of latent errors in equipment manufacturing and lead to undetected latent error conditions that might contribute to a future undesirable event such as a cask drop. Another example involved an accidental drop of a cask during fabrication many years ago. When checking for damage after the drop, the manufacturer was astonished to find a circumferential crack that completely encircled the cask. The manufacturer was unable to explain how the preceding processes involving multiple inspections failed to detect the large crack (NRC, 2001a; NRC, 2001b).

SMEs provided other examples of QA and configuration management deficiencies related to avoiding undesirable DCSO events, including examples related to fuel tracking and Boral neutron-absorbing material. In the fuel-tracking example, a licensee with identical sister units used a mirror image of one SFP inventory to create a fuel load plan for the SFP at the other unit. Fortunately, the error was identified and corrected before fuel was moved into casks. Additional information indicated that incorrect fuel loads into casks, while not exceeding overall exposure and cooling time limits required by cask certificates of compliance, have actually occurred. In the Boral plate example, nonconforming plates were not properly segregated from "production plates" deemed suitable for use as neutron absorbers inside casks. This event could have resulted in a latent error condition that could have degraded nuclear criticality safety.

This report identifies important human performance problems associated with QA, especially those related to visual inspection. Of course, a future detailed investigation of potential human performance vulnerabilities in QA processes would benefit the development of approaches to reduce latent UAs and latent error conditions that could contribute to a cask drop.

4.3.4 Installation of New Heavy Lift Cranes

When a licensee replaces a reactor or fuel building crane with a newer crane that can safely handle the heavy loads associated with DCSOs (e.g., a single-failure-proof crane rated for 1,334,466 Newton (150-ton) loads), this constitutes a major safety improvement. However, as noted by SMEs at the NRC, replacing a crane involves major modifications to existing structures, systems, and components, which raises the question "could new problems be introduced?" One hypothetical example of a potential problem might include decreased emphasis on crane inspections due to the presence of newer equipment, which hinders detection of a latent error condition resulting from design, manufacturing, installation, or operation errors. Another example might be decreased safety of operational crane use practices due to over-reliance on the capabilities of a "brand new crane." Further investigation of potential human performance vulnerabilities related to the installation of new heavy lift cranes may prove beneficial in avoiding both latent and active UAs that could contribute to a cask drop.

4.3.5 Resistance to Preparing Mitigation for Crane Malfunction

During an interview with an SME at the NRC, it was revealed that some licensees have difficulty believing that their heavy lift crane may hang up or otherwise malfunction during a cask lift. This mindset may impede efforts to plan for and prepare for mitigating such events, and it indicates that there may be an opportunity for licensees to better prepare for hang-ups or various types of uncontrolled descents of casks. Examples of planning activities include preparing active cask-cooling equipment to circulate water from the SFP through the cask for extended periods and preparing impact-limiting devices or additional barriers under cask travel paths. Further investigation into potential human performance vulnerabilities in preparing and executing such mitigation actions may improve the safety of CLCs.

4.3.6 Use of Stand-alone Vertical Cask Transporter Systems

To date, use of the HOLTEC vertical cask transporter (VCT) system to move spent fuel at NPP sites has been limited. During interviews at the NRC, SMEs mentioned possible new human performance issues in using vertical lifting devices to move fuel-filled transfer casks or storage casks. It is noteworthy that the VCT system is designed to be used outside a reactor or fuel building at an ISFSI for storage either above or below ground. This means that lifting and lowering activities involving rigging such as slings will now be increasingly performed outdoors and at some distance from the plant and all of its support equipment. According to SMEs, the first uses of the VCT system involved numerous operational problems. Further investigation of potential human performance vulnerabilities related to using stand-alone VCT systems may benefit the safety of CLCs, particularly if these systems become widely used (e.g., to transfer MPCs into casks before transport to a geologic repository or a fuel reprocessing facility).

4.4 Actions Taken to Address Concerns in Spent Fuel Handling

As a result of the insights gained from investigating Generic Issue 186, the Advisory Committee on Reactor Safeguards (ACRS) concluded during its 505th meeting in September 2003 that heavy load drops in NPPs do not pose a great risk to plant safety, but they do raise concerns about worker safety. The committee further noted that, in response to the NUREG-1774 analysis, "licensees could have reduced the frequency of crane operating events attributable to unsafe actions if they had focused appropriate attention on the crane operating practices described in NUREG-0612" (ACRSR-2050, 2003). The ACRS also concurred with the following NRC staff recommendations (ACRSR-2050, 2003):

1. Evaluate the capability of rigging components and materials to withstand rigging errors.

2. Endorse American Society of Mechanical Engineers (ASME) NOG-1, *Rules for Construction of Overhead and Gantry Cranes*, for Type 1 cranes to clarify the requirements for the construction or upgrade of cranes to the single-failure-proof crane category, which is referred to in NUREG-0612 (1980).

3. Reemphasize the need to follow and enforce NUREG-0612, *Control of Heavy Loads at Nuclear Power Plants,* Phase 1 guidelines, and continue to assess implementation of heavy load controls in safety-significant applications through the Reactor Oversight Process.

4. Evaluate the need to establish standardized calculation methodologies for heavy load drops.

Subsequently, the NRC has been carrying out the above recommendations. As part of that effort, noted in Regulatory Issue Summary (RIS) 2005-25, *Clarification of NRC Guidelines for Control of Heavy Loads*, NRC staff have been "clarifying and reemphasizing existing regulatory guidelines that enhance human performance or compensate for human performance errors" (RIS-05-025, 2005). The NRC has further clarified and emphasized guidelines for the control of heavy loads in its supplement 1 to RIS 2005-25, issued in May 2007 (RIS-05-025, 2007). The NRC's approach for ensuring safety during heavy load movement includes preventing loads from moving over vital areas, conducting analyses verifying that load drop consequences are within acceptable bounds, or using a single-failure-proof handling system. Other general NRC human performance improvement efforts include improving the monitoring of safety culture in the reactor oversight process as described in RIS 2006-13, *Information on the Changes Made to the Reactor Oversight Process to More Fully Address Safety Culture* (RIS-06-013, 2006). These efforts should increase the safety of DCSOs. However, the recent concerns and emerging issues presented in this section suggest the need for further improvements in approaches for achieving and maintaining high levels of human performance to avoid serious events such as a cask drop.

This report analyzes human performance aspects of DCSOs to begin generating a technical basis for further human performance improvements. Section 5 describes in detail human performance vulnerabilities that may impact DCSOs and depicts through several illustrative scenarios how these vulnerabilities may contribute to cask drop HFEs.

5 ILLUSTRATIVE HUMAN FAILURE EVENT (HFE) EXAMPLES WITH HUMAN PERFORMANCE VULNERABILITIES

This section discusses human performance vulnerabilities that may affect cask-handling activities, and it describes cask drop scenarios in which those vulnerabilities have created error-forcing contexts (EFCs). This section identifies how and why unsafe actions (UAs) may occur that could contribute to cask drops, and provides an initial basis for Section 6, which illustrates techniques that may help avoid or mitigate the effects of the human performance vulnerabilities that lead to UAs. Some of the scenarios require multiple failures or degradations to occur simultaneously or in a particular sequence for the scenario to be realistic. The events involving cask drops described in the scenarios were reviewed by a senior structural analysis expert at Sandia National Laboratories (SNL) to ensure they are indeed *possible* with respect to the physics of failure.

5.1 Dropping a Cask

A cask drop, especially of a loaded cask prior to lid sealing, potentially leads to releases of fission products within a plant structure and significant exposures, primarily to plant personnel. Cask drops that cause reactor safety systems to fail might also initiate a severe accident leading to significant fission product exposures to the public; these consequences are not treated in this report because no specific plant design was used, but this possibility was implied in Regulatory Issue Summary 2005-25 in reference to a cask drop in a Mark I boiling water reactor (BWR): “A load drop that penetrates the operating floor in certain areas could simultaneously initiate an accident and disable equipment necessary to mitigate the accident” (RIS-05-025, 2005, p. 4). Also, recent events before and during the analysis performed for this report have revealed problems with crane structures, systems, and components that suggest higher potential likelihoods of occurrence of cask drops than documented in previous analyses. Not only are numerous human actions required for inspection, test, maintenance, and operation of cranes and related components, but also numerous opportunities exist for human failure during rigging operations. Given the potentially high consequences of a cask drop, thorough investigation of cask movement activities is necessary.

There are many opportunities for cask drop events that must be avoided to safely conduct a cask loading campaign (CLC). Emphasis was placed on reviewing past heavy load drop events and related UAs and human failure events (HFEs). Section 5.1.1 discusses some of the factors that can influence human performance during cask movement activities.

5.1.1 Human Performance Vulnerabilities that Could Contribute to Cask Drops

Human performance vulnerabilities are used in this report to refer to a spectrum of performance-shaping factors (PSFs) and plant conditions, including the past history of both latent and active UAs, which may ultimately contribute to HFEs during cask movement activities. The context, emerging from a combination of human performance vulnerabilities, integrates the individual, task, situation, and environment in such a way that the connection between actions and undesirable consequences is apparent. While a positive context can improve human performance, a negative context (i.e., an EFC) can set up personnel to commit UAs and HFEs.

The human performance vulnerabilities discussed in this report are oriented toward EFCs that may lead to HFEs involving cask drops. The following is a summary of some potential human performance vulnerabilities that were derived from process descriptions, review of relevant incidents and accidents related to spent fuel handling (e.g., heavy load drops, crane problems, cask component problems, other incidents during spent fuel handling and dry cask storage operations), and interviews with subject matter experts (SMEs) who have hands-on experience with the processes. An additional motivation for selecting and developing the vulnerabilities was to generate a set of terms that provide human performance distinctions that are readily understood by those who are knowledgeable of dry cask storage operations (DCSOs), but who may have limited knowledge of human factors (HFs) and human reliability analysis (HRA). That is, one goal was to avoid HF/HRA jargon by generating and describing terms useful for a broad audience of people interested in improving human performance in DCSOs. A brief explanation of each vulnerability and an example illustrating its application are presented in Table 5-1; an in-depth discussion of each vulnerability can be found in Appendix C.

Table 5-1 Description of human performance vulnerabilities with examples.

Vulnerability	Description
1. Inadequate procedures	Procedures that are found to be deficient, possibly by discovering that a situation once thought to be unusual or rare is actually more common and deserves to be explicitly addressed in procedures. A deficiency in procedures may also exist when an important situation was not previously considered at all. Other deficiencies in procedures can include omissions in detail that are important for reducing the likelihood of UAs and HFEs. For example, procedures may not explicitly state the maximum height at which to stop lifting the cask from the spent fuel pool (SFP). This may increase the likelihood of a cask drop, for example, due to interactions of cask height and time available to avoid a two-block event caused by equipment failure or a UA.
2. Limited reliance on procedures	In general, many spent fuel operations are skill-based and may not be guided by detailed procedures. However, even if detailed procedures do exist, they may rarely be referenced because skills, informal rules, and heuristics guide task execution. For example, procedures specifying how to move a cask from the SFP to the decontamination/sealing area in great detail may not be regularly referred to, given the perception that the associated crane operation skills are “simple.” This lack of reliance on procedures may lead to latent UAs, and over time could progressively lead to an increased potential for an HFE.
3. Inapplicable procedures	These are procedures, or significant portions of a procedure, that do not apply to a unique or unusual (i.e., off-normal/emergency) situation. This may result from a conscious decision by system designers and managers to avoid changing a procedure to explicitly deal with an unusual situation (because it might confuse or distract personnel dealing with many more commonly encountered situations). To handle the unusual situation, personnel need to know when to deviate from the documented procedures and rely on other factors such as training, knowledge-based problem solving, or engineered-feature response to avoid an HFE. Inapplicable procedures may also result from not considering a particular situation; however, upon discovery of this omission, it may still seem appropriate to avoid explicitly addressing some aspects of the situation in the procedure. The presence of inapplicable procedures may distract and delay personnel if they do not realize the procedures do not apply to current plant conditions.

4. Inadequate training/ experience	Many of the operations performed by the team may be skill-of-the-craft activities that lack a high level of formality both in terms of documented procedures and structured training programs. For example, there may be a lack of training in the immediate responses necessary given indications of a two-block event or a rigging failure in which a crew member is seriously injured and a loaded cask undergoes a freefall drop (e.g., assignment of responsibilities, order of emergency response actions). There may also be a lack of training in critical latent error conditions; for example, training in how to inspect crane support structures or inspect the state of rigging slings for signs of excessive strain loading and/or thermal damage. Inadequate training/experience may be present among: 1. *Individuals*—individuals may not be adequately trained due to omissions or incorrect aspects of training as described above. 2. *Teams*—inadequate training/experience among team members may not necessarily consist of large omissions or incorrect task-relevant training, but their training and experience may not have sufficiently prepared them to work together effectively with multiple people; this vulnerability may be particularly prevalent among hybrid teams consisting of both plant personnel and temporary contractor personnel.
5. Communication difficulties	The working environment of DCSOs is noisy, making verbal communication difficult. Headsets may cause confusion over who is speaking. Hand signals may be misinterpreted or not seen. For example, a spotter at floor level may shout warnings that go unheard by the crane operator; the spotter may also be unable to catch the attention of the crane operator with hand signals.
6. Limited indicators and job aids	Processes are generally controlled by unsystematic visual inspection instead of by positive safety measures such as engineered reference tools or other administrative controls. For example, lifting the cask out of the SFP is primarily guided by visual inspection without the additional safety features of proximity alarms (with auditory, tactile, or visual indicators) or objective reference tools (e.g., a reference scale indicating distance from the cask to the wall). That is, the avoidance of a cask hang-up or impact with items in the SFP may rely on the interpretation of visual cues selected and sampled in a subjective fashion by one or a very small number of people. In addition, for tasks involving numerous steps or for infrequently performed or unusual activities, there may be insufficient job aids to ensure that slips, lapses, and mistakes do not occur (e.g., due to distractions or memory limitations).
7. Visual challenges	Given the immense size of the cask as well as the placement of the workers, the line of sight for tasks may often be blocked or distorted. In addition, the operation of captivating and moving the cask while in the SFP may involve visual distortions from viewing the process through over 6.1 meters (20 feet) of water. Viewing the cask using underwater cameras may greatly reduce distortion from refraction of light; however, the difference in the perspective of the cask shown by the video system and the body positions of the crane operator and spotters may also lead to UAs. Furthermore, in some plants the crane operator is perched high above the cask movement operations and has an unclear view of the travel path and nearby obstructions. Visual challenges are identified as a distinct vulnerability given the prime importance of visually derived information for influencing human behavior.

8. Unchallenging activities	In general, DCSOs are slow-paced and they can be monotonous. Therefore, personnel may become easily distracted. For example, after progressing through several successful loads within a campaign, the crane operator may become distracted while slowly moving the cask and miss a warning from a spotter below of an impending collision.
9. Time pressure	The time pressure felt by the workers during a DCSO may vary considerably. In general, the operations are slow-paced. However, missing scheduled milestones can increase the pressure felt. For example, as a CLC nears completion and a scheduled outage approaches, along with the presence of hundreds of contractors arriving on site, the cask loading crew may rush to finish the last two loads of the campaign. Time pressure can arise from the tension generated by the often conflicting goals of “productivity and safety” (described in Section B.2.1). However, time pressure can also arise from trying to achieve a specific safety goal; for example, pressure to complete rigging operations quickly to reduce radiation exposure to the riggers per the as low as reasonably achievable (ALARA) principle. Note that the safety culture among personnel can significantly affect the degree to which the perception of time pressure leads to rushed task performance.
10. Time-of-day and shift-work challenges	Workers are more likely to commit errors when fatigued, such as when they have performed a double shift or have been unable to sleep sufficiently between shifts. This problem of fatigue may be especially acute when personnel work an occasional night shift; for example, when a day shift worker fills in for a sick colleague one night.
11. Inadequate verification	Inadequate verification results from factors that lead to incorrect checking or overestimation of independence between checks. Key factors include common-mode failures, social shirking, and overcompensation (Sagan, 2004; Brewer, 2009). 1. *Common-mode failures*—these include failures in redundant checks due to inadequate items (e.g., training, tools, equipment). For example, multiple inspectors incorrectly checking for defects will create latent error conditions. 2. *Social shirking /misplaced trust*—a phenomenon in which individuals or groups reduce their reliability in checking by assuming that others will “take up the slack.” The probabilities of error for a checker of another’s work will be much higher than the probability of error for the original performer[20] because the checker usually does not expect to find many errors when evaluating another’s performance (NRC, 1983). Crew members must trust each other to thoroughly review their work and catch any mistakes. A supervisor’s cursory check of an “excellent” subordinate’s work would violate that proper trust. Use of the term “misplaced trust” does not mean the person is “untrustworthy” if they succumb to this behavior—it highlights a subtle yet unsafe behavior that may occur among those who are “trusted.” Also, mixed (hybrid) crews composed of plant personnel

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[20] In cases of skilled performance of tasks, the person performing the task is more likely to detect an error in his/her own performance than a second person who believes that the first person already performed a good check. It is also important to distinguish this phenomenon from a situation in which it *does not apply* (e.g., a teacher reviewing the performance of a student.) A teacher or expert reviewing the work of a student or novice expects to find errors and also learns over time where such errors tend to be clustered given the experience level of the student. The bottom line is that when people do not expect to find errors they are not good at detecting them. It takes special training, crews, and working culture to maintain increased independence between multiple checkers (Brewer, 2009).

	and contractors may not have the same understanding regarding the amount of verification needed or relied upon by others, thereby increasing the occurrence of social shirking. 3. *Overcompensation*—a phenomenon in which the addition of extra items (intended to be redundant) encourages individuals or groups to increase production or engage in riskier behavior. An example would be greatly increasing throughput of newly manufactured crane components at an inspection station after providing additional inspectors. Overcompensation is a distinct action that often compounds the problem of failing to understand and account for dependencies due to social shirking and common mode failures.
12. Quality assurance (QA) problems	Careful verification that all structures, systems, and components (SSC) related to DCSOs meet appropriate conformance requirements may be lacking, which may lead to latent error conditions. QA verification should extend as far back into the manufacturing and procurement stages as possible. For example, a QA problem could allow a control pendant for remotely operating a crane to malfunction when it is unexpectedly dropped during a cask movement. In this case, when a control pendant was purchased, it may have been assumed, but not been suitably verified, that the manufacturer tested it for impacts of this nature. Another QA problem could be failure to detect a material property defect in a load-bearing component.
13. Decision-making bias error	Bias and heuristic errors may mislead personnel and lead to HFEs during DCSOs. Three biases emphasized in this report include: confirmation bias, loss aversion, and overconfidence. 1. *Confirmation bias*—the tendency to seek out evidence that confirms one's current position and to disregard conflicting evidence. *Example:* After several successful cask loads within a campaign, workers will likely require greater evidence (i.e., stronger cues and signals) to suspect that anything is wrong during cask movement. 2. *Loss aversion*—the individual-specific way of mentally accounting for the concept of loss in a given situation provides a strong biasing factor toward information and actions that enable the person to steer away from incurring that loss. *Example:* During movement of a cask, a loud metal-on-metal sound momentarily captures the attention of workers observing the cask movement. The source of the sounds may be movement of the yoke arm on the trunnion; however, the personnel attribute the noise to nearby machinery instead of focusing on the loss-threatening possibility that a cask drop is imminent, so they continue the cask movement. 3. *Overconfidence*—overestimating one's level of knowledge or abilities relative to making a decision or executing a task. *Example:* A crane operator is overconfident in his ability to closely align the cask to the edge of the SFP when raising it to facilitate access for personnel who will decontaminate and partially secure the cask lid. A cask hang-up occurs. The operator's overconfidence was fueled by ample experience in operating the crane and participating in several successful CLCs.

14. Inadequate team coordination	There may be undesirable variability within and between teams involved in DCSOs, especially during predominantly skill-based operations in which there is limited reliance on procedures, new or hybrid teams have been assembled, or responsibilities are handed off between teams (e.g., shift changes or specialized teams for different operations). While team member variability in skills, attitudes, knowledge, and working styles is beneficial in many situations, it can also mask differences in understanding abilities and assumptions guiding others' performance, such that task performance is inadequate for particular situations. Hybrid teams of plant personnel and temporary contractor personnel may be particularly vulnerable to inadequate team coordination. For example, an experienced team member from the plant, overly confident in the ability to perform a task, completes the task quickly and misses a step. Another team member, a temporary contractor who is more slow and methodical by nature, notices the co-worker's rapid task performance and suspects a potential UA. However, coming from a safety culture that discourages challenging others' work performance, the second worker does not attempt to verify the task was performed correctly. As another example, the second worker in the same scenario assumes that the rapid task performance simply demonstrates the first worker's tremendous skill—casting doubt on the possibility of an UA; thus, no verification is performed.
15. Improper or uneven task distribution	The distribution of tasks and responsibilities may not be clearly defined, which may lead to missed opportunities for independent verification. Also, an uneven workload can increase the stress on some employees while allowing others to become bored and easily distracted. For example, consider the crane operator who is tasked with lifting the cask. The crane operator's position within the cab limits the view of the travel path. It may be beneficial for decontamination personnel at ground level to act as spotters responsible for verifying that a clear travel path exists throughout the movement (i.e., being the eyes for the crane operator's hands) instead of resting in place until it is time to decontaminate the cask. This additional assignment of responsibilities to decontamination personnel may keep them more engaged in the CLC activities, reducing boredom and increasing vigilance.
16. Large number of manual operations	As the number of manual operations increases, personnel must exercise increased vigilance in performing them correctly. This caution is especially important when the operations must be completed quickly. For example, imagine that a rigger is pressured to quickly execute all of the manual rigging steps while positioned on top of a loaded cask due to the ALARA principle and to reduce heat stress. In general, as the speed of task execution increases the likelihood of latent or active unsafe actions also increases.
17. Other ergonomic issues	The noise level in the work environment is quite high. In addition to impairing communication, excessive noise levels can exacerbate the effects of fatigue. Other issues may also arise within the work environment such as cramped (or even inaccessible) working spaces (e.g., for inspection), high or low temperatures, high radiation levels (encouraging rapid and/or awkward maneuvers), cumbersome clothing, etc. Of particular concern may be the high temperatures that riggers encounter when positioned on top of a cask. An additional ergonomic issue involves fatigue, distraction, or other impairment due to the onset of illness or upon return to work during recovery or following an illness.

The human performance vulnerabilities listed in Table 5-1 were derived starting from the PSFs discussed in *Good Practices for Implementing HRA* (NRC, 2005b). The "Good Practices" PSFs represent a generic set of factors to consider when performing an HRA emphasizing control room activities. While some of the good practices PSFs consider localized actions outside the control room, they are not tailored to DCSOs. The human performance vulnerabilities identified in this current report effectively encompass applicable areas identified in the good practices PSFs and provide additional distinctions representing a more nuanced account of vulnerabilities in DCSOs.

The good practices PSFs directly applicable to DCSOs are given analogous human performance vulnerabilities in this report. For example, “applicability and suitability of training and experience” maps to the “inadequate training/experience” human performance vulnerability in this report. An example of an extension is the “ergonomic quality of human-system interface” PSF in the good practices that is detailed in three separate human performance vulnerabilities: “limited indicators and job aids,” “visual challenges,” and, in some cases, “large number of manual operations.” Another example of a nuanced extension includes “accessibility and operability of equipment” in the good practices, which is addressed in the three distinct human performance vulnerabilities of “inadequate verification,” “QA problems,” and “other ergonomic issues.” Other aspects of SFH such as “decision-making bias error” are not covered in the good practices. The human performance vulnerabilities in this report therefore address the good practice PSFs and extend them to provide a better account of human activities specific to this domain. The terms used and their explanations were also generated to make human performance distinctions easily understandable to those without an HF or HRA background.

5.1.2 Information Considered When Developing Cask Drop Scenarios

Listed below are additional observations, gathered from SME interviews and other documented sources, that may prove beneficial in understanding relevant contexts for human performance that may contribute to the occurrence of UAs during cask movement. *Italicized* comments are proposed logical extensions of the SME comments. Further discussions with SMEs and plant-specific personnel would be required to substantiate these proposed extensions.

- Crane operations are highly repetitive and monotonous.[21]

- Many maintenance checks are required before use; often there is significant time pressure to get the checks done quickly and get on with the ”real work”; therefore, there may be significant variability on how thoroughly these checks are performed.[22]

- Time pressure during core refueling operations is intense, but time pressure during dry cask operations is generally much less intense. Scheduling delays will occasionally elevate time pressure, especially if they threaten to disrupt the start of a scheduled refueling outage.[23] Plants with a large inventory of fuel in the SFPs can be rushed to load casks to ensure full core pull-out potential as they run up to a refueling outage. Delays from NRC inspections, equipment failures, bad weather, etc., can compress the time schedule.[24] USNRC Office of Nuclear Material Safety and Safeguards (NMSS) personnel were at H.B. Robinson and Riverbend NPPs; both were under time pressure

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[21] From SME interview, August 24, 2005.
[22] Ibid.
[23] Ibid.
[24] From SME interview, September 29, 2005.

during cask operations.[25] More plants may be forced into this time-pressure mode, depending on management at the plants. Some plants invest the resources needed early to unload the pool; others wait and become vulnerable to a time crunch.[26] Even with advance planning, time pressure is always visible among the teams; even if all has gone well with planning, something can ”break” and interfere with the whole process.[27] “I can’t say that plants don’t perform other activities that might interfere with cask operations, but from what I hear, when casks are loading spent fuel, it is likely that other activities would be minimal; important factors might be the availability of personnel, etc.”[28] “Distractions can occur during cask operations: depending on where licensees are in their master schedule, they could be planning for an outage immediately after loading of dry casks—that may be a really big issue for more plants. The plants have detailed plans for refueling outages, for cask loading, I’m not quite as sure, but a crunch between personnel as overlap is occurring between the two operations could be a big problem.”[29] *Note: Intense time pressure during core refueling operations might affect the accuracy of placing off-loaded fuel in the correct alphanumeric grid locations within the SFP. Inaccurate placements would potentially corrupt the fuel loading plans used during CLCs.*[30]

- The cranes used to move the casks have a large 1.112E+6 – 2.224E+6 Newton (125–250 ton) capacity; however, many cranes have had their capacities greatly increased even though no structural changes were made (i.e., decisions have been made to cut into the ”engineering design factors” of the original design).[31] *Note: Some personnel may implicitly assume that the cask-carrying cranes are more robust than they actually are, which leads to load uprate analyses with optimistic performance assumptions for the associated structures, systems, and components. This belief in conservatism in the initial design might encourage a general belief that procedures and equipment are so conservative that bypassing them on occasion is acceptable.*

- Many crane issues are not only mechanical or electrical, but also involve human factors issues of inspection, test, and maintenance. The personnel and management systems are critical to keeping the systems working properly.[32]

- The hooks could fail, although for a single-failure-proof crane, two hooks would have to fail. The yokes could also fail. For example, at the Trojan plant, cracks in the yoke were found during an inspection. Many parts of the hook are difficult to inspect, so it is generally during periodic planned inspections that such defects are found.[33]

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[25] Ibid.
[26] Ibid.
[27] Ibid.
[28] Ibid.
[29] Ibid.
[30] Fuel accountability in the SFP and loading fuel into casks is not a prime focus for this report; however, multiple occurrences of fuel misloads have been observed, and it is possible that this area will be of interest in a future qualitative HRA.
[31] From SME interview, August 24, 2005.
[32] From SME interview, September 29, 2005.
[33] From SME interview, October 20, 2005.

5.1.3 Completeness of Cask Drop Scenarios

The scenarios created to develop HRA-informed insights on cask drops were obtained by combining a relatively limited set of SME information, process descriptions from the Holtec HI-STORM 100 FSAR, a literature review of load drop events (and related events), and the authors' knowledge of how HFEs may result from various failure mechanisms originating in how people perceive, learn, remember, and communicate. The authors did not obtain extensive explanations of cask movement processes or observe operations at a specific site (other than a short edited video of SFH and DCSOs involving the Holtec HI-STORM 100 system at one BWR and a training video involving the TN-40 cask system at one PWR). The authors do not have first-hand experience in carrying out activities related to cask movement (e.g., crane operation).

All of the above-mentioned limitations in the information gathered for the current report translate into limitations of the scenarios themselves to accurately represent the process contexts, individuals, and teams responsible for SFH and DCSOs. Along with these omissions in knowledge of specific process and personnel are unanswered questions; for example:

(1) How many opportunities for cask movement planning and execution actions are generally present during the planning process?

(2) Are personnel involved with cask movement operations adequately checking the actions of team members when they would otherwise be waiting for the next operation (e.g., is a rigger watching another rigger or transfer lid operator to verify proper execution)?

(3) How robust are measures to verify the adequacy of cask movement operations (e.g., captivation of trunnions by yoke, lifting distance of multipurpose container [MPC] with short slings while transfer lid door is being opened, etc.)?

To complete a thorough qualitative HRA and to develop a state-of-the-art quantitative HRA (if desired), the questions above (and many others) would need to be answered by gathering and analyzing additional plant-specific data and information, preferably for both specific PWR and BWR plants. The data and information would ideally be gathered through a combination of expert interviews, observation of actual CLC activities, detailed review of procedures, detailed review of previous cask drop incidents/near misses, and application of a prospective ATHEANA (A Technique for Human Event Analysis)-type HRA. In conjunction with gathering and analyzing detailed plant-specific information from two or a few plants, additional data (e.g., from questionnaires and inspections) should be acquired that indicate general cask movement experience for the population of U.S. nuclear power plants (NPPs) relative to the plant-specific analyses. Thus, a more detailed study of DCSOs would provide plant-specific analyses beneficial for NRC regulation of those particular licensees, as well as insights generalized across the U.S. NPP fleet.

5.2 Summary of HFE Group Descriptions and Scenarios

Listed in Table 5-2 are the HFE group descriptions, a simple list of each scenario within each HFE group, and a numbered list of related human performance vulnerabilities for all scenarios described in Sections 5.4 through 5.7. HFE groups 1, 2, and 3 apply to the HI-STORM 100 system used at BWRs with a Mark I or II containment. HFE group 4 applies to the TN-40 system used in BWRs with a Mark III containment or at PWRs.

The distinction between HFE groups 1 through 3 and HFE group 4 reflects major differences in cask system equipment and potential consequences from a cask drop. As discussed in Section 3.2, BWRs with Mark I or II containments have an SFP inside the secondary containment immediately adjacent to the reactor, which places the top of the SFP above the level of the reactor vessel and four to five floors above ground level. Thus, cask movements take place above reactor safety systems during full power operation, and loaded casks must be vertically lowered up to 30.5 meters (100 feet) down to the ground level. If a dropped cask were to breach the refueling-level floor, it could simultaneously initiate an accident and disable accident-mitigation equipment (RIS-05-025, 2005). In PWRs or BWRs with Mark III containments, the SFP is typically located in the fuel or auxiliary building, outside the reactor building containment. The top of the SFP is within three floors of ground level, which limits cask drop distances to approximately 15.2 meters (50 feet). Other than potential breach of a cask, the primary consequence of concern for a heavy load drop is damage to the SFP. In addition to differences in potential drop heights and proximity to the reactor, the two plant configurations generally have very different horizontal travel paths for cask components entering and leaving the facility. The PWR and Mark III BWR travel paths are generally more direct, whereas the Mark I and II BWR travel paths may be more complex and involve much greater horizontal movement of heavy loads. (For additional discussion of the differences between these systems, see Section 3.2.)

Table 5-2 List of HFE group descriptions, scenario titles, and vulnerabilities.

HFE group & cask system	HFE group description	Scenario description (& associated vulnerabilities)	Human performance vulnerabilities
1 – HI-STORM 100 System at Mark I BWR	Transfer cask movement from SFP to preparation area	1. Failure to align yoke arm leads to yoke arm slipping off trunnion as crane operator lifts transfer cask out of SFP; transfer cask is dropped (1, 4, 6, 7, 11, 13, 15) 2. Crane operator impacts transfer cask into fuel pool wall; transfer cask is dropped (1, 4, 6, 7, 8, 9, 13, 15) 3. Crane operator hangs up transfer cask on structure in SFP, crane is overstressed, cable is broken & transfer cask is dropped (1, 2, 3, 4, 5, 7, 11, 12, 13, 15) 4. Crane operator raises transfer cask too high, cable is broken & transfer cask is dropped (1, 4, 5, 6, 8, 11, 13)	1. Inadequate procedures 2. Limited reliance on procedures 3. Inapplicable procedures 4. Inadequate training/experience 5. Communication difficulties 6. Limited indicators & job aids

2 – HI-STORM 100 System at Mark I BWR	Transfer cask movement from preparation area to transfer pit	1. Crane operator causes transfer cask to hang up on edge of transfer pit; transfer cask is dropped (1, 4, 5, 6, 7, 10, 11, 13) 2. Eye-type yoke arm slips off of trunnion as crane operator lowers transfer cask to transfer pit; transfer cask is dropped (1, 4, 6, 7, 13, 15) 3. Stirrup-type yoke slips off trunnion as crane operator lowers transfer cask to transfer pit; transfer cask is dropped (1, 4, 6, 7, 13, 15)	7. Visual challenges 8. Unchallenging activities 9. Time pressure 10. Time-of-day & shift-work challenges 11. Inadequate verification 12. Quality assurance (QA) problems 13. Decision-making bias error 14. Inadequate team coordination 15. Improper or uneven task distribution 16. Large number of manual operations 17. Other ergonomic issues
3 – HI-STORM 100 System at Mark I BWR	MPC movement from transfer cask down to storage cask	1. Rigging failure due to excessive heat leads to long slings detaching from MPC, causing MPC to drop & impact the interior bottom of the storage cask (1, 4, 6, 12, 13, 16, 17) 2. Rigging failure due to repeated overload leads to long slings detaching from MPC, causing MPC to drop & impact the interior bottom of the storage cask (1, 4, 6, 7, 11, 14) 3. Rigging failure due to a sharp edge leads to long slings detaching from MPC, causing MPC to drop & impact the interior bottom of the storage cask (1, 4, 6, 7, 9, 10, 11, 12, 13, 14, 16, 17) 4. Rigging failure & failure to completely open transfer lid door causes MPC to drop slightly, then jam inside of transfer cask (2, 4, 5, 6, 7, 8, 12)	
4 – TN-40 System at PWR	Cask movement from SFP to preparation area	1. Crane operator impacts SFP wall with cask; cask drops due to defective lifting pin (1, 4, 6, 7, 8, 9, 11, 12, 13, 15, 17) 2. Crane operator hangs up cask on structure in SFP, crane is overstressed, cable is broken & cask is dropped (1, 4, 11, 12, 13, 15) 3. Crane operator raises cask too high, cable breaks, & cask is dropped (1, 6, 8, 12) 4. Crane operator lowers cask onto edge of opening in floor at the SFP level; cask is dropped (1, 4, 7, 11, 12, 17)	

5.3 Scenarios Illustrating Potential HFEs

This section describes the scenarios developed for SFH operations. These scenarios include HFEs that might be modeled in a plant-specific PRA. The scenarios are based on information collected and summarized in previous sections of this report and its appendices. This information is not the "complete" set that would be expected for a full HRA to support a PRA. However, the identified scenarios are sufficient to provide generic insights (i.e., not based on plant-specific information).

Because previous PRA activities formed part of the basis for this analysis (EPRI, 2004; NRC, 2007b), some of the scenarios contain HFEs addressed to some degree in the previous studies, although it is important to note that neither the NRC's dry cask PRA nor the EPRI's PRA of bolted storage casks thoroughly investigated the contexts (i.e., an ATHEANA-like approach) in which failures may occur. Therefore, even for HFEs identified in previous studies, this analysis provides more insight into how those HFEs may occur. A senior structural analysis expert at SNL reviewed these scenarios to ensure that the events involving cask drops are possible events that could occur.

The scenarios are organized within the following categories:

- Scenarios during transfer cask movement from the SFP to the preparation area,
- Scenarios during transfer cask movement from the preparation area down into the transfer pit,
- Scenarios during MPC movement from the transfer cask down to the storage cask.

Within this report, process descriptions, HFEs, UA descriptions, and EFC descriptions are treated somewhat generically. Although specific HFEs were generated, UAs and EFCs were, in general, not explicitly identified during this qualitative HRA in order not to impose excessive structure on these scenarios. In addition, there was no attempt to be exhaustive in the search for possible scenarios; it was deemed sufficient for demonstration purposes to cover a concise selection of examples.

Furthermore, as suggested in the general description of human performance vulnerabilities, many UAs and HFEs may become increasingly likely to occur as a CLC progresses. Therefore, while the scenarios do not specifically reveal this insight (e.g., the cask drop occurs during the fifth of six cask loads), it may be helpful for the reader to keep this in mind when visualizing the potential for a cask drop across a CLC.

Finally, the human performance vulnerabilities identified in each of the scenarios represent only a subset of those that may actually contribute to a cask drop. Virtually all of the vulnerabilities identified in Section 5.1.1 (and more) could conceivably be applied to all scenarios. The discussion of the vulnerabilities following each scenario is intended to be illustrative and not exhaustive because the authors acknowledge that limited information was available to aid in conceiving these scenarios; given the limitations in available information, the authors focused on vulnerabilities believed to be of prime importance in contributing to a cask drop.

5.4 HFE Group 1: Scenarios During Transfer Cask Movement From Spent Fuel Pool to Preparation Area (HI-STORM 100 System at Mark I BWR)

This phase begins with the loaded MPC resting in the transfer cask at the base of the cask pit in the SFP. The MPC lid is about to be placed onto the cask. The phase continues through the removal of the transfer cask from the SFP and placement in the preparation area where the lid is to be firmly affixed to the canister, but ends before the lid is affixed. (For further details about process steps, see Section A.2.2.2 through A.2.2.5.)

5.4.1 Definition and Interpretation of Issue Analyzed

1. *HFE scenarios during movement of the loaded MPC and HI-TRAC transfer cask of a HI-STORM 100 cask system from SFP to cask preparation area* – In this process, the fuel has already been loaded into the MPC. This phase starts at the point when the lid is to be placed onto the MPC. It continues through the removal of the transfer cask with the MPC to the preparation area where the MPC lid is to be firmly affixed to the cask, but ends before the MPC lid is affixed.

2. *Reason for analysis* – These scenarios are analyzed because of the potential for dropping a loaded transfer cask before the cask or canister lid is properly sealed, which leads to damage to the SFP, damage to the primary coolant system and/or damage to safety systems, as well as release of radioactive materials from the cask into the building atmosphere and/or a great increase in radioactivity levels in the building.

3. *Potential consequences* – Dropping a loaded transfer cask outside the SFP may result in severe contamination of the building atmosphere and occupational injuries, and it could simultaneously initiate a reactor accident and disable necessary accident-mitigation equipment. A release of radioactive materials from damaged fuel, coupled with an atmospheric containment breach (e.g., failure to isolate the building, inadvertent opening of a leak path), could also lead to fission products migrating beyond the site exclusion region and posing some hazard to public health and the environment. If a transfer cask drop initiated a severe accident along with damage to accident-mitigation equipment, it would be possible for a significant fission product release from the containment to occur, presenting a greater hazard to public health and the environment.

5.4.2 Base Case Scenario

Initial conditions – The initial conditions for the start of this phase will vary with the specific plant and any plant-specific cask system modifications. A typical situation is defined as:

- The MPC and transfer cask are sitting properly in the loading area of the SFP.
- The fuel elements have been properly loaded into the MPC.
- The yoke is still attached to the crane but has been disconnected from the transfer cask trunnions.

- The MPC lid is connected to the yoke by metal cables.
- The MPC lid is sitting along the side of the cask pit with the crane stationed above it.

5.4.3 Scenario Descriptions

Table 5-3 Scenarios during transfer cask movement from SFP to preparation area.

HFE group & cask system	HFE group description	Scenario description (& associated vulnerabilities)	Human performance vulnerabilities
1 – HI-STORM 100 System at Mark I BWR	Transfer cask movement from SFP to preparation area	1. Failure to align yoke arm leads to yoke arm slipping off trunnion as crane operator lifts transfer cask out of SFP; transfer cask is dropped (1, 4, 6, 7, 11, 13, 15) 2. Crane operator impacts transfer cask into fuel pool wall; transfer cask is dropped (1, 4, 6, 7, 8, 9, 13, 15) 3. Crane operator hangs-up transfer cask on structure in SFP, crane is overstressed, cable is broken, & transfer cask is dropped (1, 2, 3, 4, 5, 7, 11, 12, 13, 15) 4. Crane operator raises transfer cask too high, cable is broken, & transfer cask is dropped (1, 4, 5, 6, 8, 11, 13)	1. Inadequate procedures 2. Limited reliance on procedures 3. Inapplicable procedures 4. Inadequate training/ experience 5. Communication difficulties 6. Limited indicators & job aids 7. Visual challenges 8. Unchallenging activities 9. Time pressure 10. Time-of-day & shift-work challenges 11. Inadequate verification 12. Quality assurance (QA) problems 13. Decision-making bias error 14. Inadequate team coordination 15. Improper or uneven task distribution 16. Large number of manual operations 17. Other ergonomic issues

5.4.3.1 HFE Group 1, Scenario 1: Failure to Align Yoke Arm Leads to Yoke Arm Slipping Off Trunnion as Crane Operator Lifts Transfer Cask Out of SFP; Transfer Cask is Dropped

Operator fails to properly align yoke arms to trunnion; one yoke arm only partially engages – While the operator can see that the yoke arms are closed over the trunnions of the transfer cask, there is not a clear view of the connection to ensure that the trunnions are in far enough to guarantee a safe lift. The indication that there is weight on the crane only indicates that the trunnions are at least partially engaged, which in this case involves only the edge of an arm on the edge of a trunnion.

Maintenance workers fail to notice error – Although three workers are present who potentially could confirm the captivation, only one of these workers is tasked with visually confirming proper captivation of the transfer cask trunnions with the yoke arms. The worker's view is somewhat hampered by distortion of light through the water. The worker judges the yoke arms to be in the proper position, and this assessment appears to be confirmed when the loaded transfer cask rises slightly as the yoke is tensioned. Therefore, the worker begins to prepare for the next task in the process. The other workers also prepare for their respective tasks. A loud metal-on-metal sound momentarily captures the attention of workers observing the cask movement. The source of the sound is relative movement of the yoke arm and the trunnion. Although this noise potentially offers a clue that something is amiss, the workers interpret the sound as being the result of machine noise or other work activities in nearby areas of the building.

Yoke arm slips off trunnion during lift – With the yoke arm only partially engaged, the loaded transfer cask is lifted (initially) by the crane. As the transfer cask bottom reaches the surface of the SFP, the yoke arm slips off the trunnion, followed by a tip of the cask, uncoupling of the other yoke arm with the trunnion, and a cask drop.

Transfer cask drops toward the bottom of the SFP, with transfer cask impacting the bottom of the loading pit – The transfer cask drops into the SFP at an angle due to the sequential loss of coupling with one and then another yoke arm. Due to the particular rotation of the transfer cask in relation to the sides of the cask loading pit, the edge of the transfer cask bottom impacts the floor of the loading pit, and the top of the transfer cask wedges against one wall. Significant structural damage occurs to the bottom of the cask loading pit, yet there is no penetration of the SFP. The impact damages the fuel inside the fuel pins, and several fuel pins are ruptured. Because the MPC lid is still attached by steel cables to the crane yoke, it is completely removed from the MPC during the fall; thus, there is no significant barrier between the fission product gas releases from the depressurization of the fuel pins and the building atmosphere.[34] Radiation alarms activate, and uncertainty over the magnitude of the fuel damage and radionuclide release to the environment delays the start of response and clean-up actions for several hours.

Potential Human Performance Vulnerabilities for Scenario 1:

- *Inadequate procedures* – The procedures did not adequately explain the necessity of continued surveillance of the lift operation or the transfer of responsibility between members of the workforce to afford a clear view of the lifting activity. Furthermore, procedural guidance did not emphasize the number of ways in which the yoke may not properly engage the trunnion (e.g., "Beware: yoke may only partially engage trunnion and still enable lifting," or "Stop cask movement if unusual audible indications are present").

- *Inadequate training/experience* – In addition to the lack of procedural guidance, the training also failed to convey an understanding of the ways that partial engagement of the trunnion may cause an unsafe lifting condition or to teach personnel how to detect these potentially subtle conditions.

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[34] Recall that the fuel pins are highly pressurized. Failure of fuel cladding leads to gap releases that can be transported out of the SFP.

- *Limited indicators and job aids* – There were no control aids to support proper alignment of the yoke arms to the trunnions. Furthermore, the crane control panel indications did not provide positive indication that the yoke arms had engaged the grooves in the trunnion.

- *Visual challenges* – None of the personnel had a clear view of the yoke arm connections. The visual cues were hampered by parallax effects (due to refraction) through the water surface.

- *Inadequate verification* – Crew members would like to trust that if the yoke arms are not completely engaged, someone will see it and stop the activity. However, if no one has an adequate view, or if individuals have inadequate search and/or detection criteria, the crew will be unable to sufficiently monitor performance.

- *Decision-making bias error (confirmation bias, loss aversion)* – Once the workers and the crane operator saw[35] the crane begin to lift the loaded transfer cask out of the pool, they likely inferred that the transfer cask was properly captivated. This inference lowered their expectation that a problem existed; therefore, increasing evidence (i.e., a larger "signal" versus both internal and external "noise") was needed to draw their attention to the fact that the yoke arms were not fully engaged. This interpretation that "all is well" may have even led personnel to completely divert their attention away from monitoring transfer cask movement (e.g., moving on to the next task).

  The worker who heard the loud metal-on-metal sound and quickly attributed it to machine noise or ongoing work activities was implicitly selecting the *non-loss threatening* explanation of the metal-on-metal sound being due to other activities instead of the *loss-threatening*[36] explanation that improper captivation of the transfer cask was signaling an imminent drop.

- *Improper or uneven task distribution* – Team members (maintenance crew, decontamination crew, observers, etc.) who were in between assigned tasks and not focused elsewhere may have been able to help the team determine if the yoke arms were properly engaged (i.e., provide complete or redundant monitoring of performance).

  The human performance vulnerabilities detailed here represent only a subset of the possible instances that may occur in scenarios such as this one. Any of the other human performance vulnerabilities listed in Section 5.1.1 may also apply to specific instances or variations of the scenario above.

5.4.3.2 HFE Group 1, Scenario 2: Crane Operator Impacts Transfer Cask into Fuel Pool Wall; Transfer Cask is Dropped

Crane operator does not lift transfer cask sufficiently to clear pool wall – The crane operator depends on the height indicator on the control panel to determine whether the transfer cask has

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[35] The crane operator and workers may have additional sensory cues indicating that the yoke arms are not properly engaged (e.g., vibrations or noises).

[36] The losses referred to here are the potential losses related to catastrophic cask or plant damage or fission product releases.

been raised to a height sufficient to clear the SFP wall when moved horizontally because the view from the crane cabin does not afford a suitable angle to judge cask height above the pool surface after the bottom of the transfer cask clears the surface.[37]

Maintenance workers fail to notice error – At this point, the workers do not have specifically assigned tasks for monitoring loaded transfer cask movement. They complete the water spray decontamination of the transfer cask surface and prepare to dry the transfer cask surface after it is moved away from the pool. They focus on putting away the equipment used for cask decontamination and radiation monitoring and retrieving the equipment needed for wipe down and drying. They do not expect any problems with the ”simple” movement using the crane.

Operator does not pay sufficient attention to vertical position of transfer cask; transfer cask hits pool wall and tilts over as crane moves; the angle of the transfer cask causes yoke arms to slip off trunnions – The crane operator also does not expect any problems with this move. The operator’s focus primarily alternates between the horizontal position indication on the control panel and on the status of the crane equipment as the transfer cask is being moved toward the decontamination wipe-down area before final positioning in the sealing and testing area. See Figure 5-1.

Transfer cask drops into the SFP; the edge of transfer cask bottom impacts SFP – The transfer cask drops into the SFP. Due to slight rotation during the fall, the edge of the transfer cask bottom impacts the bottom of the cask loading pit, causing significant structural damage. The impact of the transfer cask with the bottom of the SFP leads to fuel pin damage and fission product gas releases into the SFP, which then migrate into the general atmosphere of the SFP building.[38] Radiation alarms activate, and uncertainty over the magnitude of the fuel damage and radionuclide release to the environment delays the beginning of response actions for several hours.

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[37] This scenario assumes that a designated spotter for crane operations has not been assigned or the assigned spotter is temporarily unavailable or distracted during the lift.

[38] Recall that the MPC lid is still attached to the crane yoke by steel cables; therefore, it decouples from the MPC and the transfer cask as it drops away from the yoke.

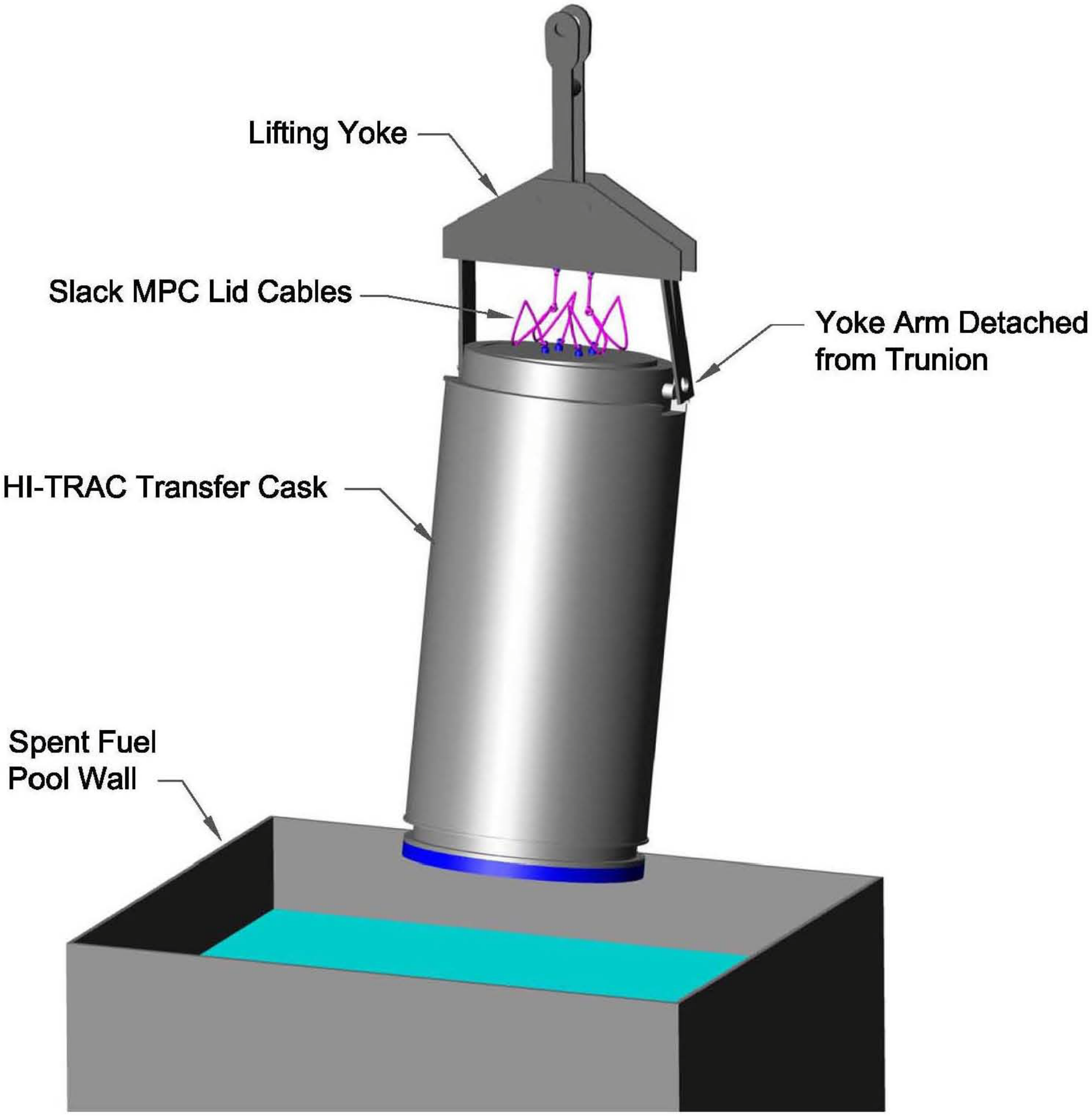

Figure 5-1 Diagram of transfer cask hitting the SFP wall and one yoke arm detaching before the transfer cask drops into the cask loading pit of the SFP.

Potential Human Performance Vulnerabilities for Scenario 2:

- *Inadequate procedures* – The procedure for lifting the transfer cask did not specify exactly (i.e., within inches) how high to lift the transfer cask before moving it horizontally from the cask loading pit to the sealing and testing area. Also, no one other than the crane operator was specifically tasked with monitoring the progress of the transfer cask to ensure proper vertical clearance was attained.

- *Inadequate training/experience* – Incomplete training was provided to the crane operator on systematically ensuring that the transfer cask had reached a proper clearance level before beginning horizontal movement of the transfer cask. Skills training was deficient in specifying, at a minimum, that both the height indicator as well as visual confirmation from other personnel should be obtained before initiating horizontal movement.

- *Limited indicators and job aids* – The control panel offered some indication as to the height of the transfer cask being raised from the SFP; however, there were no engineered height reference tools to verify clearance. Nor were there proximity alarms or other positive indicators to warn the crane operator of an impending collision of the transfer cask with the SFP.

- *Visual challenges* – The crane operator relied almost entirely on the control panel for indication of placement of the transfer cask while raising it from the SFP. The direct visual cues for the transfer cask were relatively useless to the crane operator.

- *Unchallenging activities* – The simplicity of the task led to a level of complacency among the crew.

- *Time pressure* – The crane operator tried to move the transfer cask over to the preparation area as quickly as possible because he was planning to leave work as early as he could to attend his daughter's soccer game. The element of time pressure was evident to one external observer by the frequency with which the crane operator looked at his watch.

- *Decision-making bias error (loss aversion)* – The decontamination workers avoided the thought that the transfer cask movement might not be proceeding well, given their close proximity to the transfer cask. They preferred to believe that the transfer cask could not possibly drop, and they remained attentive to preparing for the subsequent decontamination activity—a task in which they had an assigned role.

- *Improper or uneven task distribution* – Only the crane operator was tasked with (and responsible for) determining the proper height of the transfer cask when raising it from the SFP. The other team members present (e.g., decontamination workers) were not designated as spotters for this task, nor was it common for anyone besides the crane operator to be considered responsible for the success of cask movement.[39]

5.4.3.3 HFE Group 1, Scenario 3: Crane Operator Hangs Up Transfer Cask on Structure in SFP; Crane is Overstressed; Cable is Broken and Transfer Cask is Dropped

Crane operator lowers transfer cask with MPC near the edge of cask loading pit – The crane operator is known to always lower the transfer cask down close to the edge of the cask loading pit because this helps decontamination personnel effectively spray down the transfer cask with water as it is raised from the SFP. In addition, the crane operator has recently been made aware of an incident in which a cask, improperly positioned on a cask stand on the floor of a cask loading pit, tipped over. Therefore, in lowering the transfer cask during this instance, the

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[39] Instead of always placing the responsibility for successful cask movement on the shoulders of the crane operator, it is possible to envision successive hand-offs of primary responsibility throughout a cask movement to those with the best, most direct visual indications of the movement.

operator not only lowers the transfer cask very near the edge of the cask loading pit, but also stops the vertical descent when the transfer cask bottom is only a few feet above the cask stand on the floor of the pit and horizontally moves the transfer cask nearly 30.5 centimeters (1 foot) closer to the edge of the pit. The operator then lowers the transfer cask, now very near the loading pit wall, down onto the cask stand. None of the decontamination workers or other personnel take note of the horizontal movement of the transfer cask near the base of the cask loading pit. Unfortunately, the horizontal movement of the transfer cask while submerged in the loading pit, along with the particular orientation of the transfer cask trunnions, places the crane yoke in a position in which it could collide with a structural element that protrudes from the wall of the cask loading pit above the submerged cask. Once the transfer cask is resting on the floor of the loading pit, the crane operator disengages the yoke arms from the transfer cask trunnions and raises the yoke a few feet until the cables attached to the MPC lid are taut and the MPC lid is approximately 30.5 centimeters (1 foot) above the top of the transfer cask. The operator then horizontally moves the yoke and MPC lid to the other end of the cask loading pit and lowers the MPC lid so that it rests at the base of the loading pit.

Crane operator lifts the transfer cask; yoke hangs up on structure in loading pit – Following the loading of the MPC with fuel, the crane operator lifts the MPC lid, positions it on top of the MPC, and couples the crane yoke arms with the trunnions on the transfer cask. The crane operator then lifts the transfer cask straight up. Because of the orientation of the transfer cask trunnions and the position of the cask near the loading pit wall, the crane yoke is on a collision course with the structure protruding from the loading pit wall. One decontamination worker looks down into the cask loading pit and sees that the crane yoke is about to impact the structure along the loading pit wall. The worker attempts to get the crane operator's attention with a hand signal. Just as the crane operator notices an unusual movement/signal from the decontamination worker, the yoke arm impacts and partially lodges itself into the structure protruding from the wall. The loading on the crane cables and hoist increases dramatically once the hang-up occurs. The transfer cask rotates slightly as the crane strains to continue hoist movement.

Crane operator does not react immediately to transfer cask hang-up – Before the hand signal from the decontamination worker, the crane operator had been distracted during the lift by watching the decontamination workers approach the side of the SFP and contemplating the upcoming movement path of the transfer cask over to the preparation area. Neither the crane operator nor the decontamination workers anticipate any problems during the lift because the lowering operation has been successful, and multiple cask loads during the CLC have already been completed without incident over the past week. When the one decontamination worker notices the impending collision and signals to the crane operator, the worker is able to capture the crane operator's attention just as the yoke arm hits the structure. Immediately after the impact, the crane operator notices a jolt of the crane and begins to see indications that the crane is straining to lift the transfer cask (e.g., vibration, an overcurrent alarm in the crane cab). In these first moments of surprise, the crane operator sits motionless, trying to understand the situation. Once full realization hits that there is a problem, the operator releases the spring-loaded hoist control handle and reaches toward the overcurrent alarm to shut it off. The operator fumbles a bit when reaching for the switch, but manages to shut off the alarm.

Crane control and overcurrent protection switch do not perform within specifications – Even though the crane operator is delayed in noticing and releasing pressure on the crane hoist control handle, two features of the crane should have immediately terminated movement of the hoist. First, the hoist control handle is spring-loaded and should return to a neutral position as soon as manually released. Second, as the hoist strains under the overload condition, the hoist motor draws more electrical current. A safety interlock sensor and switch is supposed to remove power to the hoist within a fraction of a second of onset of an overcurrent state. Unfortunately, the spring in the hoist control handle is slow to return the handle to a neutral position (i.e., causing hoist clutch disengagement) due to the age of the spring and presence of debris around the base of the handle (e.g., rust, dirty oil residues). To make matters worse, the overcurrent protection switch was improperly set such that it requires much higher levels of electrical current to activate than those specified in the component requirements.

Crane hoist overstresses the crane cables due to the hang-up – The crane operator switches off the hoist overcurrent alarm and realizes that the vibration in the cab and noise from the crane hoist have not ceased—in fact, both have increased. The operator then has two disturbing realizations: first, switching off the hoist overcurrent alarm did not remove power to the hoist; it simply turned off the alarm in the crane cab; second, glancing at the hoist control handle, realizes that it is not in the neutral/off position. Following these realizations, the operator's next movement is toward the hoist control handle.

Crane cables break and transfer cask drops to the bottom of the cask loading pit – As the crane operator moves the hoist control handle to the neutral position and then starts moving toward the hoist power-off switch, the crane cables break. The noise of the sequentially snapping cables reminds the crane operator and decontamination workers of loud rifle shots. The transfer cask, along with the crane yoke, MPC lid, and crane block, drops back down into the loading pit such that the transfer cask tips, and the bottom of the transfer cask hits the cask pit stand at an angle. The cask pit stand is severely damaged, and the tipped transfer cask is wedged against two walls of the loading pit. There is no penetration of the SFP. The crane yoke arm, MPC lid, and crane block are arrayed in a complex configuration of equipment on top of and next to the transfer cask. In addition, the position of the transfer cask, crane yoke, and crane block equipment is such that no existing equipment[40] can facilitate easy removal of the transfer cask from the SFP. No personnel are injured by flying debris; however, the violence of the drop, including the crane block, splashes a large volume of SFP water out over the side of the pool and contaminates the decontamination workers with radionuclides from the SFP water.

Small amount of gaseous radionuclides are released to the SFP and then into the building atmosphere – The impact from the fall damages fuel in many fuel assemblies, but only a couple of fuel pins rupture and release gaseous radionuclides. The MPC lid is still partially on top of the MPC, but it is displaced due to the drop, which allows the radioactive gases to migrate up through the SFP and into the building atmosphere. Although the magnitude of the release of radioactive noble gases is not large from a short-term-dose health effects standpoint, radiation alarms in the building are activated, which add to confusion among personnel after the transfer cask drop.

Normal operations are delayed for a few months – The complex orientation of the transfer cask, crane yoke, crane block, and cabling at the bottom of the cask loading pit, along with the need to repair the damaged crane, require specialized engineering expertise to manage and recover from this event over the course of a few months.

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[40] That is, no type of grappling or captivation equipment exists (anywhere throughout the NPP industry) that can readily dislodge the cask from its tipped position and reorient it in an upright position. Typical approaches used in the shipping and construction industries for such events rely on manual arrangement of rigging chains or slings, but this approach is difficult to employ here because of the presence of highly contaminated SFP water and the complex pile of debris.

Potential Human Performance Vulnerabilities for Scenario 3:

- *Inadequate procedures* – The procedures for the transfer cask movement activity in the SFP did not include sufficient detail to better ensure that an unobstructed travel path was always available before and during transfer cask movement. For example, two people were not designated with both the responsibility of verifying a safe travel path and the authority to prevent or stop transfer cask movement. That is, confirmation by a spotter could be required before the crane operator is allowed to move the transfer cask, and the spotter could be given authority to terminate the movement.

- *Limited reliance on procedures* – Detailed written procedures were available for responding to cask hang-ups. However, the crane operator had never encountered a cask hang-up and did not know anyone personally who had, so was not worried about it and did not review the procedures for dealing with such a situation.

- *Inapplicable procedures* – Procedures were in place that addressed a couple of techniques for recovering a transfer cask from the cask loading pit following a cask drop. However, no detailed procedures were developed to recover from a cask drop in the SFP due to a two-block failure. There had been some mention of doing so at the time when the procedures were developed. However, the engineers and manager responsible for developing the procedures determined that too many factors depended on chance to justify the effort of writing up detailed procedures for one or two specific cases that might vary greatly from any event that might actually occur. Therefore, they decided that, given the number of defense-in-depth safety measures protecting against this type of event, it was very unlikely to occur and contained so many uncertainties about specific aspects that it was not beneficial to devote resources to develop a detailed recovery procedure. The procedure that was available did mention a two-block failure resulting in a drop of a transfer cask into the SFP, but it simply stated that “should such an event occur, specialized engineering solutions will be devised as demanded by the state of the damaged equipment.”

- *Inadequate training/experience* – The periodic refresher training for the crane operator was conducted too infrequently and covered the topic of cask hang-up response in insufficient detail to verify that the crane operator had the skills to perform rapid, correct, skill-based responses to various types of cask hang-up events. In addition, available personnel did not have the training and experience required to rapidly respond to a two-block failure and cask drop into the SFP (e.g., resume normal operations within a couple of weeks versus a few months). The reason for the lack of training was closely related to the decision not to develop detailed procedures for this type of situation.

- *Communication difficulties* – The single decontamination worker who noticed the impending collision of the transfer cask with the structural item in the pool attempted and partially succeeded in obtaining the crane operator’s attention. However, the crane operator did not immediately understand that the worker was trying to communicate the hand signal for terminating the transfer cask lift.

- *Visual challenges* – The crane operator’s position high up in the crane cab made it difficult to directly view the location of the transfer cask. A load-height indicator on the control panel helped the operator know when the load was close to the bottom of the cask pit, but direct visual cues of transfer cask position were degraded. In addition, even for personnel close to the SFP surface (i.e., the decontamination workers), it was difficult to determine the position of the transfer cask in the water. Finally, the cask pit portion of the SFP was very well lit; in fact, it was too well lit. So much light was emanating from so many light fixtures that insufficient shadows were cast by important features such as the structural item along the wall on which the crane yoke hung up. The lack of visual contrast highlighting the structural item hampered recognition that the crane yoke was on a collision course. Even the decontamination worker with the best visual perspective of the obstruction was slow to recognize the impending collision.

- *Inadequate verification* – There were inadequate formal procedures for assigning responsibilities to ensure movement of the cask along a safe travel path. In addition, informal behaviors for verifying a safe travel path were migrating away from safe operations. That is, during the previous cask loads in the CLC, at least one decontamination worker maintained a close watch on the transfer cask movement and was able to warn (or at least to attempt to warn) the crane operator of an impending collision. The crane operator was also more attentive to indications from the decontamination workers during the earlier cask loads. By the time of the cask load in which the hang-up and transfer cask drop occurred, both the decontamination workers and crane operator were demonstrating social shirking behavior (i.e., taking a more relaxed, less vigilant attitude toward monitoring the ”simple” cask movements and assuming that someone else would ”take up the slack”).

- *Quality assurance (QA) problems* – The overcurrent protection sensor and switch on the crane hoist motor had not been tested in years; thus, it was not known that the switch would not provide the protection required. In addition, the testing and analysis of the sensor and switch at the time it was designed and produced did not reveal a critical aging- and humidity-related failure mechanism that greatly increased the likelihood of failure for switches over 10 years old. The hoist control handle had been progressively getting ”stickier” in the year leading up to the transfer cask drop; however, it was rare for the handle to stick in place for more than a fraction of a second before returning to the neutral position. Maintenance personnel were not notified of the “sticky” control handle, and periodic inspections of the controls were not performed. The maintenance supervisor had assumed that the crane operators would report any component problems to the maintenance department. The maintenance department did not see a benefit in having a technician periodically inspect the crane for items needing repair.

- *Decision-making bias error (confirmation bias)* – Because the transfer cask had been lowered successfully into the cask loading pit of the SFP, the crane operator and the decontamination personnel believed that it would also be raised successfully. This belief was further reinforced by the many cask loads performed in preceding days without incident. Neither the decontamination personnel nor the crane operator had suspected that the crane yoke arm had passed so close to the structural item in the pool during lowering, or that the horizontal movement near the bottom of the cask loading pit had ”set up” the conditions for a future collision. A confirmation bias error of focusing on previous success made it difficult for personnel to take note of information signaling a collision during transfer cask movement.

- *Decision-making bias error (loss aversion)* – Another decision-making bias error involved loss aversion related to tipping the transfer cask in the cask loading pit. Because the crane operator had received information about how a cask mispositioned on a cask stand had tipped at another NPP, the operator took extra care in placing the transfer cask very close to the wall of the loading pit to avoid the edge of the cask stand. This loss-aversion bias became a bias error as it led directly to the UA of placing the transfer cask too close to the wall of the loading pit so that part of the cask-lifting equipment (i.e., the crane yoke) was now located beneath an obstruction to vertical travel. Interestingly, during the accident investigation of the cask drop it was discovered that this fear of mispositioning the transfer cask on the cask stand was unfounded because the size of the cask stand relative to the size of the bottom of the loading pit essentially prevented a tip from occurring regardless of where the transfer cask was lowered onto the cask stand.

- *Decision-making bias error (overconfidence)* – Finally, the crane operator displayed an overconfidence bias error. Previous successful loads of this CLC and serving as the primary crane operator in a CLC four years ago led to the operator’s high confidence in the ability to move a transfer cask with great precision. Also, increased attention to the possibility of a tip due to mispositioning the transfer cask on the cask stand may have further increased the operator’s confidence and the confirmation bias error. In other words, the overconfidence bias error that blinded the operator to the possibility of a vertical collision with a structure or other equipment in the cask loading pit was magnified by the operator’s satisfaction and belief in the ability to anticipate and avoid a possible transfer cask tip.

- *Improper or uneven task distribution* – Responsibility and authority for assuring and controlling safe movement of the transfer cask were distributed inadequately among multiple personnel (among multiple spotters and the crane operator). In this scenario, at least three other decontamination workers could have been trained and tasked to appropriately verify and guide functions to ensure safe cask movement. The use of multiple personnel with different visual perspectives would likely prevent similar cask hang-up and drop events.

5.4.3.4 HFE Group 1, Scenario 4: Crane Operator Raises Transfer Cask Too High, Cable Breaks and Transfer Cask is Dropped

Crane operator is distracted during lift of transfer cask; fails to stop lift in time – Raising the transfer cask by maintaining pressure on a spring-loaded lever is extremely simple but time consuming. The only subsequent action required of the crane operator is to release the lever at the appropriate time. The crane operator is relatively passive and distracted by internal thoughts during the lift process. This distraction diverts the operator’s attention from the critical task at hand.

Crane operator does not respond to warning from workers – Because the decontamination workers are spraying the transfer cask during the lift, they eventually notice that the transfer cask has risen too high and is still rising. The worker responsible for communicating with the crane operator must get the operator’s attention and announce the situation by communication headset or hand signals. There is quite a bit of noise in the area, and verbal communication is often misunderstood, especially given that multiple individuals communicate on a network and it is sometimes difficult to determine who is speaking, to whom they are speaking, and what they are saying. Hand signals are often clearer, but the operator is distracted in this case and does not promptly see the worker giving the signals.

Transfer cask load tops out, and transfer cask drops due to a two-block failure – The operator does not terminate the lift before the crane cables break from tensile failure; the transfer cask drops.[41]

Potential Human Performance Vulnerabilities for Scenario 4:

- *Inadequate procedures* – Procedural guidance did not detail the specific height at which to stop the lift, nor did it identify cues signaling when to stop the lift to avoid a transfer cask drop due to a two-block event. The available procedural guidance was limited and written in language that was too general (e.g., “do not raise load too high”).

- *Inadequate training/experience* – Training in the use of contextual cues to prompt the crane operator when to halt the lift was lacking. Training overemphasized the transfer cask impacting with objects located within or near the designated travel path and failed to emphasize sufficiently the potential for lifting the transfer cask too high (due to a general disbelief[42] that the transfer cask would ever be lifted high enough to lead to a two-block failure).

- *Communication difficulties* – Although the decontamination workers eventually noticed a problem, because of the noisy environment they were unable to get the crane operator’s attention. The distance between the workers and the crane operator in the crane cab and their reliance on nonverbal communications such as hand signals increased the probability that the crane operator would not see them.

- *Limited indicators and job aids* – There were insufficient indicators and job aids, such as alarms, on the crane control panel to warn the crane operator that the transfer cask was being lifted too high.

- *Unchallenging activities* – The simplicity of the task led to complacency and distraction of the crane operator.

- *Inadequate verification* – Although a junior worker on the team momentarily suspected that something was wrong as the cask continued to rise, there was no sign of concern from an experienced coworker so the suspicion was not confirmed. Therefore, the junior worker focused attention elsewhere on other tasks. In addition, the experienced coworker knew the crane operator well and initially trusted there was a good reason for the action even through the transfer cask was being raised higher than usual.

- *Decision-making bias error (confirmation bias)* – The experienced worker “trusted” the crane operator to have good reasons for lifting the transfer cask higher than usual, and

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[41] While this failure is plausible, even if the crane tops out against the blocks, it does not immediately follow that the cables will break and the transfer cask will fall freely. An upper load limit/interlock, overcurrent, or overload protections on the crane could cause the crane lift motor to shut down and relieve the forces. It is also possible that a partial failure may subject the transfer cask to an “unplanned descent” (in which the cask does not accelerate as fast as in a freefall; however, it descends until it comes to rest on a sufficiently rigid surface). Recall from Section 1 that on April 6, 2004, at Millstone Power Station Unit 3, a two-block event actually occurred (Bellamy, 2004; RIS-05-025, 2005).

[42] It is possible that this disbelief results from knowing there should be a functioning safety interlock preventing the cask from being lifted too high irrespective of the crane operator’s actions.

this trust delayed the worker in noticing the seriousness of the situation by recalling that the crane operator seemed fit for duty when they exchanged greetings earlier.

- *Decision-making bias error (loss aversion)* – The experienced worker also resisted considering that a two-block event and cask drop might be imminent. In the worker's mind it was less loss-threatening to assume that the transfer cask movement was proceeding safely.

5.5 HFE Group 2: Scenarios During Transfer Cask Movement from Preparation Area to Transfer Pit (HI-STORM 100 System at Mark I BWR)

This phase begins with the sealed HI-STORM 100 MPC and transfer cask ready for movement to where the pool lid will be changed out for the transfer lid. A portion of the scaffolding is about to be moved out of the intended path of the transfer cask. The phase continues until the transfer cask is lowered down through the opening into the transfer pit and is resting on top of the storage cask. The phase ends before the short slings are removed and long slings are attached. Further details are included in Sections A.2.3.1 through A.2.3.8.

5.5.1 Definition and Interpretation of Issue Analyzed

- *Human failure event scenarios during transfer cask movement from cask preparation area to transfer pit* – In this process the canister (MPC) has been completely prepared, the lid has been welded in place, and the transfer cask top lid has been bolted on. This phase starts at the point where the scaffolding is to be removed from around the transfer cask. It continues through the removal of the pool lid and attachment of the transfer lid and the movement of the transfer cask over to the transfer pit opening and down into the transfer pit until the loaded transfer cask rests on top of the storage cask. This phase ends prior to the removal of the short slings and attachment of the long slings.

- *Reason for analysis* – These scenarios are analyzed because of the potential for dropping a loaded transfer cask from a large height and potentially damaging the fuel, MPC, and the transfer cask.

- *Potential consequences* – Dropping a loaded transfer cask may result in severe contamination of the building atmosphere and exit of radioactive noble gases beyond the site exclusion region; coupled with an atmospheric containment breach (e.g., failure to isolate the building, inadvertent opening of a leak path), a significant amount of fission products may migrate beyond the site exclusion region and pose some hazard to public health and the environment. In a lesser event, the cask may need to be sent back to the SFP floor level to have the MPC lid cut off and returned to the SFP to be inspected for potential fuel damage.

5.5.2 Base Case Scenario

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

- The transfer cask is sitting properly in the preparation area of the refueling floor.
- The canister (MPC) lid is properly welded to the MPC.
- The MPC drying/inerting process is complete.
- The transfer cask top lid has been bolted to the top of the transfer cask.
- The yoke is still attached to the crane.
- The short slings have not been attached to the yoke or the MPC lift cleats.
- The welding scaffolding is properly configured around the transfer cask.

5.5.3 Scenario Descriptions

Table 5-4 Scenarios during transfer cask movement from preparation area to transfer pit.

HFE group and cask system	HFE group description	Scenario description (associated vulnerabilities)	Vulnerabilities
2 – HI-STORM 100 System at Mark I BWR	Transfer cask movement from preparation area to transfer pit	1. Crane operator causes transfer cask to hang up on edge of transfer pit opening; transfer cask is dropped (1, 4, 5, 6, 7, 10, 11, 3) 2. Eye-type yoke arm slips off trunnion as crane operator lowers transfer cask to transfer pit; transfer cask is dropped (1, 4, 6, 7, 13, 15) 3. Stirrup-type yoke slips off trunnion as crane operator lowers transfer cask to transfer pit; transfer cask is dropped (1, 4, 6, 7, 13, 15)	1. Inadequate procedures 2. Limited reliance on procedures 3. Inapplicable procedures 4. Inadequate training/ experience 5. Communication difficulties 6. Limited indicators and job aids 7. Visual challenges 8. Unchallenging activities 9. Time pressure 10. Time-of-day and shift-work challenges 11. Inadequate verification 12. Quality assurance (QA) problems 13. Decision-making bias error 14. Inadequate team coordination 15. Improper or uneven task distribution 16. Large number of manual operations 17. Other ergonomic issues

5.5.3.1 HFE Group 2, Scenario 1: Crane Operator Causes Transfer Cask to Hang Up on Edge of Transfer Pit; Transfer Cask is Dropped

Crane operator does not properly align transfer cask over transfer pit – The crane operator is positioned high up in the crane cab and has only remote visual cues to help properly align the transfer cask over the transfer pit. The view is partially obstructed by the yoke and the transfer cask itself. Ultimately, the operator depends on the workers on the floor to direct where to position the transfer cask.

Workers positioned around the transfer cask inappropriately signal the crane operator to begin lowering the transfer cask – The workers happen to be viewing the transfer cask from perspectives that do not allow them to completely verify that the transfer cask has an unobstructed descent path down through the transfer pit opening. The omission of positive measures for visually confirming an unobstructed path lead them to inappropriately signal the crane operator to initiate the lowering operation.

Crane operator does not respond to warning from workers – Shortly after the transfer cask begins descending, it becomes apparent to the workers that a collision is imminent. The workers immediately attempt to get the attention of the crane operator. They do not have the convenience of communication headsets, so they must yell or attract the crane operator with hand signals. Verbal communication is masked by high levels of ambient machine noise. Ideally, the crane operator would be looking directly at the workers because they are in the best position to visually monitor cask movement. However, the operator is fatigued and prone to distraction due to an atypical assignment to work on the night shift,[43] which leads the operator to focus attention on maintaining the proper descent rate by closely watching the indicators on the control panel instead of periodically (and frequently) monitoring the spotter(s). In addition, the uncharacteristic fatigue hampers the operator's typical tendency to seek additional information on whether an unobstructed travel path for the transfer cask is being maintained.

Transfer cask tilts in relation to yoke, and both yoke arms slip off the trunnions (one after the other); transfer cask drops – On initial contact with the edge of the transfer pit opening, the transfer cask begins to tilt. As the transfer cask hangs up, the uniform tension on the yoke decreases, and one yoke arm slips off the trunnions. The transfer cask rotates, and the other yoke arm slips off the other trunnion. The transfer cask then drops into the transfer pit and impacts the storage cask positioned at the bottom of the transfer pit. The short slings connected to the MPC do not prevent the drop because they are not designed to hold the full weight of both the MPC and the transfer cask. The presence of the slings simply delays the ultimate freefall drop of the transfer cask and MPC by a fraction of a second.

Potential Human Performance Vulnerabilities for Scenario 1:

- *Inadequate procedures* – The procedural guidance was too general in that it did not ensure complete,[44] continuous, redundant monitoring of the travel path of the transfer cask. For example, the procedure stated, "Move transfer cask horizontally until clear of potential obstructions along the vertical travel path of the transfer cask," but it did not delineate specific clearance requirements such as "transfer cask centerline must be

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[43] Fatigue may occur during the atypical shift, or it may occur during a subsequent shift as a result of insufficient rest between shifts.

[44] The team must continually monitor multiple aspects of the cask movement operation (e.g., travel path obstructions, descent rate, the condition of the crane equipment, coupling of yoke arms with trunnions).

moved to within 30.5 centimeters (1 foot) of the transfer pit centerline as determined using the alignment guides." In addition to the lack of specificity about clearance, the procedures did not direct the crane operator to frequently communicate with spotters to seek independent verification that there were no obstructions in the path of the transfer cask before initiating movement.

- *Inadequate training/experience* – The training omitted crucial elements about safe movement of transfer casks such as crane operation techniques, roles and responsibilities, nonverbal communication techniques, and spotting skills (e.g., correct placement to gain the best viewing angle at different points along the cask travel path). In addition, training did not encourage recognition of fitness-for-duty problems (e.g., the crane operator discounted the effect of fatigue on performance, and other personnel were not trained to look for or recognize signs of fatigue among coworkers).

- *Communication difficulties* – The area was noisy; in addition to the typical machine noise, a couple of spurious alarms sounded during the transfer cask movement. The high-noise environment prevented the crane operator from hearing the workers' shouted commands. Furthermore, because of the lack of radio headsets, the workers on the floor had to rely on nonverbal means to communicate with the crane operator. Given that the operator was not expecting a problem to be identified, hand signals went unnoticed or were misinterpreted.

- *Limited indicators and job aids* – There were insufficient job aids to help positively confirm the position of the transfer cask above the hatch; the crane operator had to rely on direction and secondary feedback from the workers on the floor (i.e., the workers were essentially the "eyes for the crane operator's hands"). Positive measures such as position indicators and proximity/collision alarms were not present.

- *Visual challenges* – Due to the placement of the transfer cask and yoke within the crane operator's field of vision, there was not have a clear view of the travel path and potential obstructions. Furthermore, because of the ad hoc and dynamic self-positioning of the spotters, they were positioned such that they misperceived the point at which the transfer cask would have been properly positioned.[45]

- *Time-of-day and shift-work challenges* – The crane operator suffered from fatigue because of working an atypical shift. This fatigue led to problems with distraction and hampered the operator's task performance and ability to self-monitor performance.

- *Inadequate verification* – The crane operator placed too much trust in the spotter's initial signal to begin lowering the transfer cask through the hatch. Once the lift began, the operator failed to maintain awareness of signals from the spotters. The spotters trusted that the crane operator was continuously paying attention to their signals. However, the excessive trust in the appropriateness of the initial signal allowed/encouraged the operator to divert attention away from the spotters as the transfer cask was lowered.

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[45] Given the lack of accurate feedback provided by a reliable, independent standard, workers were unable to develop the skill required to determine whether or not they had a proper view of transfer cask position. For example, a worker may observe transfer cask positions on many occasions which appear to be acceptable; however, without feedback from an independent sensor such as a measuring stick, optical switch, another person known to have an accurate (e.g., line-of-sight, unrefracted) view, the worker's observational performance will likely not improve and may worsen over time.

- *Decision-making bias error (confirmation bias)* – The typically diligent, yet currently fatigued, crane operator exhibited confirmation bias by readily believing “all is well” upon initiation of transfer cask lowering and subsequently not continuously monitoring the spotters. In this case, this decision-making bias error was closely tied to fatigue, given that it took less physical and cognitive effort for the crane operator to fixate on the current situation and repeatedly execute a simple, well-practiced task (e.g., staring at a height indicator), as opposed to seeking and acting on additional information.

5.5.3.2 HFE Group 2, Scenario 2: Eye-type Yoke Arm Slips Off Trunnion as Crane Operator Lowers Transfer Cask to Transfer Pit; Transfer Cask is Dropped

Crane operator fails to properly align yoke arms to trunnion; one yoke arm only partially engages – This error occurs early in the process, just after the scaffolding is moved. While the crane operator can see that the yoke arms have closed over the trunnions, there is not a clear view that enables confirmation that they are in far enough to ensure a safe lift. The powerful cue that dominates the crane operator’s attention is seeing successful load-bearing of the transfer cask on the crane. In reality, this observation only confirms that the trunnions are *partially* engaged with the yoke arms even though successful load-bearing is almost always associated with full engagement of the yoke arms on the trunnions.[46]

Workers fail to notice the partial engagement of the trunnion – Multiple workers distributed around the transfer cask during movement to and from the transfer slide[47] mating mechanism and to the transfer pit opening fail to detect the misaligned yoke arm. Once they perceive that the yoke arms are in the proper position and their perception is reinforced by the transfer cask rising slightly as the yoke is tensioned, they are less and less likely to question whether or not the trunnions are properly engaged.

Cask captivation becomes progressively less secure during transfer cask movement – While the initial engagement of the yoke arms was sufficient for bearing the load of the transfer cask during the first few phases of the movement, the improperly engaged yoke arms become less secure during the lowering and lifting associated with attachment of the transfer lid. At one point the workers observing the transfer cask movement hear a metal-on-metal sound. This sound results from relative movement of the yoke arm and the trunnion. However, the workers incorrectly attribute this sound to other nearby activities. By the time the transfer cask is lifted, after the transfer lid is attached, one transfer cask trunnion is about to disengage from one yoke arm.

Workers fail to notice the tenuous captivation condition – Having observed the transfer cask being moved twice since the attachment of the yoke, the workers do not anticipate observing any degradation in yoke arm engagement. Furthermore, procedures do not require workers to

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[46] It is conceivable that the following circumstances may lead to partial engagement of a yoke arm with a trunnion: slight misalignment of the yoke arm due to crane operator action, malfunction of a yoke arm (e.g., actuator), undetected trunnion defect, or unanticipated trunnion deformation.

[47] The transfer slide is a major piece of equipment for the Holtec HI-STORM 100 system that consists of an adjustable-height rolling carriage and a pair of channel tracks. The transfer slide supports the transfer step, which is used to position the two lids (i.e., the pool lid and transfer lid) at the same elevation and creates a tight seam between the two lids to eliminate radiation streaming.

re-verify yoke arm engagement after the movement process begins (i.e., the yoke arms are never intentionally disengaged from the trunnions).

Yoke arm slips off trunnion and transfer cask drops – The tenuous captivation condition worsens, and the transfer cask drops down into the transfer pit.

Potential Human Performance Vulnerabilities for Scenario 2:

- *Inadequate procedures* – The procedural guidance was too general in that it did not require complete, continuous, redundant monitoring of the coupling between the yoke arms and the transfer cask trunnions during the cask movement.

- *Inadequate training/experience* – The training omitted crucial elements of task performance such as decision-making bias awareness and guidance requiring investigation of potential problems. The training strongly emphasized the need to efficiently perform operations. This focus implicitly deemphasized the importance of maintaining safety as the highest priority. That is, the training revealed broader deficiencies in the robustness of the plant's safety culture.

- *Limited indicators and job aids* – There were no crane control panel indications or other positive measures that confirmed proper captivation of the trunnions by the yoke arms.

- *Visual challenges* – The crane operator did not have a clear view of yoke arm engagement. Furthermore, due to the vantage points the workers selected, no individual had a clear view of both yoke-arm-to-trunnion interfaces.

- *Decision-making bias error (confirmation bias)* – The tenuous captivation of the trunnions by the yoke arms provided tactile/perceptual feedback (e.g., vibration or other movement) to the crane operator. While potentially perceptible, the feedback remained undetected (i.e., it was effectively screened/filtered out without conscious recognition). After observing the crane successfully lift the transfer cask and the yoke arms support the weight of the transfer cask, the crane operator believed that "all is well"; therefore, signals indicating a problem needed to be stronger, as time passed, to capture the operator's attention.

- *Decision-making bias error (loss aversion)* – Although the workers heard the metal-on-metal sound initiated by the precarious engagement of the yoke arms on the trunnions, they were biased to attribute the noise to some other work activity taking place nearby. This inclination to misattribute the noise was motivated by the desire to minimize the threat (i.e., imminent transfer cask drop) posed by the sound and assume a simple, non-loss-threatening explanation.

- *Improper or uneven task distribution* – Potentially, three[48] maintenance workers could have seen the precarious state of the transfer cask. However, they did not have procedures directing them to continuously monitor the yoke-arm-to-trunnion engagement. Furthermore, given the limited nature of other procedures in DCSOs, it is likely that had there been a procedure requiring continuous monitoring, it would not have

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[48] Three maintenance workers were assumed based on a video of operations provided to the authors. It is not known whether this specific number suitably represents typical DCSOs.

provided clear guidance on when a particular individual had primary responsibility to monitor the yoke-arm-trunnion interface (e.g., based on location and field of view).

5.5.3.3 HFE Group 2, Scenario 3: Stirrup-type Yoke Arm Slips Off of Trunnion as Crane Operator Lowers Transfer Cask to Transfer Pit; Transfer Cask is Dropped

Transfer cask hangs up when being lowered into the transfer pit – The crane operator has successfully moved the transfer cask to the opening of the transfer pit. When lowering the transfer cask into the transfer pit, the operator tries to get the transfer cask as near as possible to the scaffolding to assist the riggers in accessing the top of the transfer cask when they attach the slings. However, in attempting to get the transfer cask near the scaffolding, the operator inadvertently comes too close to the edge of the transfer pit opening. As the transfer cask begins to be lowered into the transfer pit, the bottom edge of the transfer cask catches on the edge of the transfer pit and tilts.

Yoke arm slips off of trunnion when transfer cask tilts – When the transfer cask hangs up on the edge of the transfer pit, the central radial axis of the transfer cask trunnions is perpendicular to the floor edge. This alignment causes the transfer cask to lift out of the stirrup as it tilts. The arrangement of the stirrup-type yoke is not tight against the transfer cask (i.e., there are about 6.4 centimeters (2.5 inches) of clearance between the yoke arm and the transfer cask). Therefore, when the transfer cask tilts and rests on the lower yoke arm, enough movement is possible that the upper yoke stirrup slips off of the trunnion before the lower stirrup binds against the transfer cask.

Crane operator tries to reposition yoke arm to recapture trunnion – After the upper stirrup slips off the trunnion, the transfer cask is perched precariously on the edge of the transfer pit. The lower trunnion is still captivated by the yoke arm. To try and recapture the upper trunnion, the crane operator must raise the crane slightly. However, raising the crane causes the transfer cask to rotate slightly and allows the transfer cask to slip out of the other yoke stirrup.

Transfer cask drops down into the transfer pit – The transfer cask falls through the transfer pit and violently hits the storage cask. The transfer cask is intact, but the MPC is significantly shaken inside the transfer cask, and several fuel assemblies are damaged.

Potential Human Performance Vulnerabilities for Scenario 3:

- *Inadequate procedures* – There was insufficient procedural guidance to direct the operator on how close the transfer cask should be placed to the scaffolding. Furthermore, procedural guidance did not specify appropriate spotters to help the crane operator ensure proper clearance while lowering the transfer cask through the transfer pit opening.

- *Inadequate training/experience* – Along with insufficient procedural guidance, insufficient training was given to the crane operator in positioning the transfer cask near the scaffolding and to personnel surrounding the transfer cask in recognizing proper clearance around the transfer cask.

- *Limited indicators and job aids* – No proximity alarms were positioned on the transfer cask or the surrounding structures that could have warned the crane operator of an impending collision. Furthermore, the surrounding personnel had no position indicators to ensure appropriate clearances were maintained around the transfer cask while the crane operator positioned it for lowering.

- *Visual challenges* – The crane operator did not have a clear view of all angles around the transfer cask to ensure proper clearance once the transfer cask was being lowered. The view was blocked by both the transfer cask and the crane. To ensure proper clearance around the transfer cask, the operator had to rely on other personnel positioned around the transfer cask.

- *Decision-making bias error (overconfidence bias)* – The crane operator had completed several successful loads before this one. In each, the transfer cask had been successfully positioned and lowered with no negative consequences. Previous successes led to the crane operator becoming overconfident in the ability to successfully complete a load. In fact, the operator had a sense of pride in being able to move the transfer cask near the scaffolding to help out the riggers.

- *Improper or uneven task distribution* – The rigging personnel were busy during this time preparing for the rigging operations as well as for the transfer of the MPC into the storage cask. Additional spotters should have been assigned responsibility for helping the crane operator maintain clearance from the scaffolding and edge of the transfer pit.

5.6 HFE Group 3: Scenarios During Multipurpose Cask (MPC) Movement from Transfer Cask Down to Storage Cask (HI-STORM 100 System at Mark I BWR)

This phase begins when the transfer cask, with transfer lid mounted to the bottom, is resting on the storage cask. The crane operator has released the yoke arms from the transfer cask trunnions and has lowered the MPC onto the transfer lid, allowing the short slings to slacken so they can be removed and replaced with the long slings. This phase ends when the bottom of the MPC is resting on the inside bottom of the storage cask and the long slings have been removed from the crane. Further details are included in Sections A.2.3.9 through A.2.3.11.

5.6.1 Definition and Interpretation of Issue Analyzed

- *Human failure event scenarios during lowering of the MPC from the transfer cask to the storage cask* – In this process the MPC is resting against the transfer lid inside the transfer cask, and the transfer cask is resting on top of the storage cask, which is on the floor of the transfer pit. The storage cask is resting on the rail skid on which it will be moved outside of the reactor building using the motorized rail-car tug. This phase starts when the crane operator has just reduced tension on the crane hoist cables so that the short slings become slack and can be removed from the MPC. It continues through attachment and raising of the MPC with the long slings and ends after the MPC has been lowered down into the storage cask and the long slings have been removed.

- *Reason for analysis* – These scenarios are analyzed because of the potential for dropping a loaded MPC cask into the storage cask and damaging the fuel.

- *Potential consequences* – Dropping an MPC into the storage cask could result in a drop of approximately 5.8 meters (19 feet) (NRC, 2007b). This type of violent impact would damage fuel and possibly compromise the integrity of the MPC to retain fission products released from the fuel pins. At a minimum, the MPC would need to be characterized, probably reopened by cutting off the welded MPC lid, and returned to the SFP for unloading and inspection of the damaged fuel. This operation could potentially release fission products to the building environment, as extensive fuel pin/assembly damage would be expected. It is also possible that a leak path could be created as a direct result of the drop (e.g., penetration of the MPC shell), which would release fission products within the building environment (a hazard to plant personnel), and if a pathway were available outside the building environment (e.g., improper operation of HVAC system), the release could become a safety concern[49] for the public. Other potential consequences could involve injury to personnel from flying debris such as rigging items or other damaged pieces of equipment.

5.6.2 Base Case Scenario

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

- The transfer cask is resting on top of the alignment ring/device, which is in turn mounted to the top of the storage cask.

- The crane operator has just shut off the crane to avoid any inadvertent operation during sling rigging activities.

- The MPC inside the transfer cask is resting on the transfer lid, and rigging personnel are moving in to remove the short slings from their attachment point on the lifting yoke.

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[49] The concern may be more a perceived concern than a true public health threat; however, this perceived threat could lead to actual harm to the public if it led to evacuations (e.g., motor vehicle accidents involving injuries or fatalities).

5.6.3 Scenario Descriptions

Table 5-5 Scenarios during MPC movement from transfer cask down to storage cask.

HFE group & cask system	HFE group description	Scenario description (& associated vulnerabilities)	Vulnerabilities
3 – HI-STORM 100 System at Mark I BWR	MPC movement from transfer cask down to storage cask	1.Rigging failure due to excessive heat leads to long slings detaching from MPC, causing MPC to drop & impact the interior bottom of the storage cask (1, 4, 6, 12, 13, 16, 17) 2.Rigging failure due to repeated overload leads to long slings detaching from MPC, causing MPC to drop & impact the interior bottom of the storage cask (1, 4, 6, 7, 11, 14) 3.Rigging failure due to a sharp edge leads to long slings detaching from MPC, causing MPC to drop & impact the interior bottom of the storage cask (1, 4, 6, 7, 9, 10, 11, 12, 13, 14, 16, 17) 4.Rigging failure & failure to completely open transfer lid door causes MPC to drop slightly, then jam inside transfer cask (2, 4, 5, 6, 7, 8, 12)	1. Inadequate procedures 2. Limited reliance on procedures 3. Inapplicable procedures 4. Inadequate training/ experience 5. Communication difficulties 6. Limited indicators & job aids 7. Visual challenges 8. Unchallenging activities 9. Time pressure 10. Time-of-day & shift-work challenges 11. Inadequate verification 12. Quality assurance (QA) problems 13. Decision-making bias error 14. Inadequate team coordination 15. Improper or uneven task distribution 16. Large number of manual operations 17. Other ergonomic issues

5.6.3.1 HFE Group 3, Scenario 1: Rigging Failure Due to Excessive Heat Leads to Long Slings Detaching from MPC, Causing MPC to Drop and Impact the Interior Bottom of the Storage Cask

MPC is lowered part-way into storage cask – The long slings are attached to the MPC and the transfer lid is opened. The ground personnel signal the crane operator to begin lowering the MPC into the storage cask. The MPC has been lowered part-way into the storage cask when the crane faults and the hoist jams.

Maintenance workers attempt to fix crane – As soon as the crew realizes that the crane has stopped moving, the maintenance workers quickly go to work trying to diagnose and fix the problem. The MPC is left suspended as it has been lowered beyond the transfer lid door.

Long slings are damaged due to exposure to high temperatures – While the maintenance crew works on the crane, the long slings are subjected to the high heat of the MPC lid in excess of 300°F. The long slings are not rated to these high temperatures and incur interior damage due to the long exposure. As soon as the maintenance workers are able to fix the crane, they signal to the crane operator to continue lowering the MPC into the storage cask.

Maintenance workers fail to properly check the condition of the slings after the lift – Following the transfer of the MPC into the storage cask, the riggers disconnect the long slings and visually examine their exterior surfaces. The riggers are primarily concerned with detecting weight overload and pay close attention to the stress tabs on the slings; they are not properly trained in how to examine the slings for heat damage. Furthermore, they are not expecting to need to replace the slings this early in the CLC because the long slings had been replaced at the beginning of the campaign. Detecting no damage to the stress tabs, the workers clear the slings for further use.

Long slings snap during the next cask load and MPC is dropped – During the next cask load, the damaged long slings are connected to the MPC, and the riggers signal to the crane operator to begin raising the MPC so that the transfer lid can be opened. Once the transfer lid is opened, the crane operator begins slowly lowering the MPC into the storage cask. During the lowering process, one of the long slings snaps. The second sling is unable to bear the weight of the MPC and snaps almost immediately after the first sling breaks, leaving the crane operator no time to react or try to raise the cask high enough so that the transfer lid can be placed under the MPC. The MPC falls 4.9 meters (16 feet) into the storage cask. The fuel inside the MPC suffers massive damage, but the MPC shell is intact.

Potential Human Performance Vulnerabilities for Scenario 1:

- *Inadequate procedures* – There was limited procedural guidance on how to properly check the slings for wear and for determining when a sling should no longer be used. Guidance on the heat tolerances of the slings was also omitted. Finally, procedures did not provide complete instructions on how to properly maintain the crane components to prevent jamming of the hoist.

- *Inadequate training/experience* – Although the rigging team recognized the need to check the slings for ”wear and tear” following each use, they were not properly trained in how to fully inspect the slings. The rigging personnel were familiar with the stress tabs and relied on these as the sole indicator of fitness for use. They were not trained in how to inspect the slings for heat damage nor were they familiar with the heat tolerances of the slings.

- *Limited indicators and job aids* – Although the slings had stress tabs used by the crew to determine when the slings had been overstressed in bearing weight, the slings did not have an indicator showing when a sling had been exposed to excessive temperatures.

- *Quality assurance (QA) problems* – The crane had not been properly maintained or cleaned to protect against malfunction of the hoist. The maintenance crew did a superficial inspection of the crane components but neglected doing a complete inspection of hoist components because they felt it was unnecessary.

- *Decision-making bias error (confirmation bias)* – The rigging crew was not expecting the long slings to fail so early in their use. The slings had been used only a few times prior to this lift and visually appeared to be in excellent condition. Due to the slings' appearance and short life, the crew was not expecting any nonconformance to requirements when they inspected the slings.

- *Large number of manual operations* – Although the maintenance crew carefully inspected the exterior surfaces of the crane components, the interior components' many surfaces, connections, and mechanisms made it easy to miss some areas. The many interior areas also interfered with the maintenance crew's ability to quickly fix the hoist jam.

- *Other ergonomic issues* – Because the crane was in the middle of a lift when it malfunctioned, the maintenance workers were required to be suspended while working on it. The maintenance crew's efforts in repairing the crane lifting mechanism were significantly slowed and hampered by the uncomfortable working conditions.

5.6.3.2 HFE Group 3, Scenario 2: Rigging Failure Due to Repeated Overload Leads to Long Slings Detaching from MPC, Causing MPC to Drop and Impact the Interior Bottom of the Storage Cask

Contract riggers supply long slings for use in transfer of MPC – Contract riggers are employed to help plant personnel complete the transfer of the MPC into the storage cask. The contract riggers bring along a second set of long slings for use in the MPC loading. Although this set of slings has been used previously, the contract riggers complete a thorough initial inspection and clear them for use. The plant personnel riggers are unaccustomed to this type of sling, but begin using them in the CLC.

Crane operator lifts MPC too high in transfer cask; overstresses long slings – After the long slings are attached to the MPC, the rigging personnel signal to the crane operator to raise the MPC so that the transfer lid can be opened. The crane operator begins raising the MPC. Just before stopping the lifting procedure, a radiation alarm goes off within the plant and distracts the crane operator. While the operator is distracted, the MPC rises too high and makes contact with the top of the transfer cask. The crane operator quickly refocuses attention and arrests the movement of the MPC. Although the contact between the MPC and the ceiling of the transfer cask is quickly recognized and reversed, the long slings are damaged by the extra stress exerted on them.

Rigging personnel fail to properly inspect long slings – After using the long slings in loading the MPC into the storage cask, the plant rigging personnel do not properly check the slings for stress wear by inspecting the stress tabs. The stress tabs are tucked inside the slings, making them impossible to see based solely on a visual inspection. Furthermore, the plant rigging personnel are not trained properly in how to inspect the slings for wear and do not know about the stress tabs. The contract rigging personnel know how to check the slings, but they misunderstand and assume the plant personnel had properly checked the wear on the slings.

Rigging personnel attach long slings to MPC – The rigging personnel attach the long slings to the MPC without checking the status of the stress tabs and signal to the workers below to open the transfer lid. The workers open the transfer lid and signal to the crane operator to begin lowering the MPC into the storage cask.

Crane operator begins lowering the MPC; slings break and MPC is dropped – As the MPC is slowly lowered from the transfer cask into the storage cask, one of the overstressed slings suddenly snaps. The second sling is unable to hold the entire weight of the MPC and breaks quickly after the first sling. The MPC falls 4.6 meters (15 feet) inside the storage cask. The MPC is intact, but several fuel bundles are damaged.

Potential Human Performance Vulnerabilities for Scenario 2:

- *Inadequate procedures* – The procedural guidance was incomplete in instructing the rigging personnel on how to fully inspect the slings for stress and acceptability for use. Procedures were also lacking in specifying explicit guidance on how high to raise the MPC within the transfer cask.

- *Inadequate training/experience* – The plant rigging personnel were not properly trained in how to inspect the slings for stress. Although they did a careful visual inspection of the slings, their lack of experience with this sling type meant they did not know about the stress tabs.

- *Limited indicators and job aids* – Along with the incomplete procedural guidance specifying how high to raise the MPC within the transfer cask, there were no proximity indicators or aids to help determine the proper height for raising the MPC. Instead, the crane operator had to rely on feedback from the riggers looking into the darkened cavity of the transfer cask as well as the feel on the tightened slings. Furthermore, the job aids used to determine the fitness of the slings were poorly designed: the position of the stress tabs made it difficult for the plant riggers to find or even know of their existence.

- *Visual challenges* – It was difficult for the crane operator to know exactly how close the MPC was to the ceiling of the transfer cask because there was no way to view the MPC directly. Instead, the riggers had to use flashlights to peer within the transfer cask and check its status.

- *Inadequate verification* – The contract riggers had prior experience with these long slings, and they incorrectly trusted the plant personnel to accurately check the status of the slings. Furthermore, the plant personnel trusted the contract riggers to perform a thorough inspection and catch any imperfections they might have overlooked.

- *Inadequate team coordination* – The contract riggers brought in to help the plant personnel complete the rigging tasks had different training and experience with the long slings being used. The contract riggers were trained by the vendor on how to check the fitness of the slings. The plant personnel, however, were unfamiliar with this style of long sling and were unaware of the stress tabs. Therefore, the slings were not appropriately checked for fitness before their final use.

5.6.3.3 HFE Group 3, Scenario 3: Rigging Failure Due to a Sharp Edge Leads to Long Slings Detaching from MPC, Causing MPC to Drop and Impact the Interior Bottom of the Storage Cask

Rigging personnel do not notice damage to an inner loop on one of the long slings – A hybrid team consisting of two riggers (a specialized contract rigger[50] and a plant employee trained to perform rigging operations) quickly attaches the slings to the lifting yoke and the MPC lift cleats without noticing a sharp edge on one of the lift cleats. Given the close proximity of the riggers with the top of the MPC, they perform their activities expeditiously to maximize conformance to the ALARA radiation exposure principle.

The CLC has proceeded well for over a week with six successful cask loads completed. However, during the previous cask loadings a repeated event has occurred with one of the long slings because one sling is slightly shorter than the other. Every time the slings are loaded, this particular sling loads first and stretches farther (i.e., greater strain loading) than the remaining sling. The riggers can visually detect the imbalanced loading if they use an engineered reference tool (e.g., level, inclinometer). However, particular riggers are not trained to reliably detect such a subtle load imbalance, and they believe that both slings are the same length.

During this particular cask load, a second event occurs: an MPC lift cleat with a rough and sharp inside edge is used. The rough edge presents a point of very high pressure (i.e., force per unit area) on the loop at the bottom edge of the shorter sling. The slings are manufactured with additional padding material intended to protect against excessive pressure or other wear due to contact with the non-rounded edges of the MPC lift cleats. This added protection, while mechanically beneficial, tends to contribute to riggers overlooking or discounting the potential severity of sharp edges (i.e., the protected material is assumed to compensate or mitigate "minor" component quality issues).

During routine visual inspections of the rigging equipment prior to use, the riggers pay close attention to the general appearance of the slings and the MPC lift cleats. The specialized contract rigger is fairly diligent in inspecting the nearest MPC lift cleat and does not see a need to inspect the other lift cleat and assumes it is under the sole responsibility of the plant rigger. However, the plant-trained rigger is less sensitive to the criticality of carefully inspecting the MPC lift cleat and implicitly assumes that the additional padding material will mitigate rough/sharp edges; furthermore, the plant-trained rigger expects the contract rigger to provide redundant, independent verification of the suitability of the lift cleat for the task.

Rigging personnel signal to the crane operator to start the crane – The rigging personnel carefully unfurl the long slings and attach them to the MPC lift cleats. Each rigger quickly inspects the operations of the other rigger by visually confirming the proper location of slings and additional sling padding. Upon finishing the rigging, a hand signal is made to a nearby team member indicating it is time to start the crane and begin lifting the cask yoke. The team member in radio communication with the crane operator signals the crane operator to start up the crane.

Crane operator starts the crane and then raises the yoke – The crane operator pays careful attention to the signals from the riggers as relayed by the team member on the communication

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[50] The contract rigger is only at the plant for a short time during dry-run activities and the remainder of the CLC because the contractor's work involves traveling from plant to plant across the U.S. to support CLCs involving the Holtec DCSS.

network. The crane operator has minimal ability to directly see the rigger's hand signal and, therefore, primarily depends on radio communications.

Rigging personnel do not recognize any cause for concern about how the long slings are tensioned during this or the previous MPC lifts – The rigging personnel do not take note of slight differences in how the long slings are loaded during the lift.

Crane operator begins to apply tension to the MPC – The crane operator raises the long slings high enough to eliminate the slack, then continues the lift. Significant tension is applied to the MPC as it lifts off of the transfer lid.

Rigging personnel open the transfer lid – Once the MPC is suspended above the transfer lid, the rigging personnel remove the transfer lid locking pins and slide open the horizontal door to open a pathway from the transfer cask to the storage cask. The rigging personnel re-insert the locking pins when the door is open.

Crane operator begins to lower the MPC – The crane operator shifts the hoist into the lowering mode and there is a slight jolt of the lifting cables above the lifting yoke. Immediately there is a tearing sound as fibers of the "slightly shorter" sling abrade the inside of the MPC lift cleat and give way. The rigging personnel simply watch in shock as the sling snaps and violently shoots upward toward the crane operator's cab. Simultaneously, the MPC tips slightly (being still inside the body of the transfer cask) yet abruptly as the remaining sling absorbs the additional load and stretches noticeably. The abrupt rotational impact of the MPC with the transfer cask interior damages some of the fuel pins inside the MPC. The crane operator instinctively hits the stop button when the sling breaks.

A long pause follows the failure of the first sling – Fortunately, the snapped sling does not injure any of the personnel near the operations. Unfortunately, the loading of the remaining highly stretched sling leaves the bottom of the MPC about 30.5 centimeters (1 foot) below the plane of the transfer lid door. There is no way to provide additional support under the MPC. This long pause lasts approximately 20 seconds and is broken by the operation supervisor who orders the crane operator to continue lowering the cask. The only viable option seems to be to get the cask to the base of the storage cask quickly. The personnel standing close to the storage cask on the ground floor of the reactor building run to the opposite side of the storage cask transport vehicle.

The second sling snaps and the MPC drops – The crane operator restarts the lowering operation, and immediately the second sling snaps. The cask falls 5.5 meters (18 feet) and violently impacts the base of the storage cask. Massive damage occurs to the fuel inside the MPC, yet the MPC shell does not fail. The rapid drop of the MPC into the confined space of the storage cask causes compression of air, which slightly slows the MPC. The boundaries of the storage cask also force the MPC to land flat against its bottom surface, which distribute the impact forces relatively evenly across the shell bottom. One of the nearby personnel is severely wounded by parts of a snapped sling.

Potential Human Performance Vulnerabilities for Scenario 3:

- *Inadequate procedures* – There were no clear procedures or training for the crane operator in how to proceed during such an event (e.g., continue the lowering maneuver, initiate a damped free fall by releasing hoist tension via a hoist motor clutch). There were no clear procedures or training for personnel near the sling break point (e.g., "seek cover to avoid 'sling snapback' injuries or fatalities"). Furthermore, there was a lack of procedural guidance or effective training on handling the in-building radionuclide release in the event of such a drop. The safety culture among operations management encouraged a “we must not let this happen” attitude, instead of the more prudent attitude of “we must not let this happen, but just in case it does, we’ll be trained and ready to recover from it.” Procedures for rigging operations were too general and relied excessively on tacit knowledge of skilled rigging behaviors such as sling tensioning, component inspection, and independent verification of rigging tasks.

- *Inadequate training/experience* – A lack of understanding about the potential impact of imbalanced loading of long slings led to incomplete or ineffective training for the hybrid rigging team in detecting or appreciating imbalanced loading conditions. In addition, training was lacking in detection and appreciation of rigging component quality issues. For example, the riggers recognized the importance of additional nylon padding at the sling-cleat interface, yet they overestimated the benefit of such padding in protecting the sling from damage from a wide range of conceivable sharp edges (i.e., riggers did not understand when the edge of the cleat would be sufficiently sharp under the relevant loading conditions, such that the additional sling padding would provide little or no benefit). According to the understanding of the riggers, who had seen various multi-ton loads lifted successively with similar nylon slings and metal connectors with a range of surface roughness and sharp edges, it was difficult to conceive of the point at which the combination of a sharp edge and a very heavy *imbalanced* load would likely lead to sling failure. That is, the feedback provided to the riggers both in training and operational environments was insufficient to teach them how to identify a dangerously sharp edge in relation to a 355,858 Newton (40-ton) MPC load.[51] An additional training problem involved the lack of training in determining whether the slings had been exposed to an overstress condition. The slings had “stress tab” indicators; however, the riggers were neither aware of nor trained in how to use such devices.

  Differences in training and experience between plant personnel and specialized contract riggers led to inconsistent execution and verification of rigging tasks. Furthermore, with regard to plant personnel safety, there was a lack of training for personnel near the sling break point to ensure immediate execution of appropriate tasks (e.g., seek cover to avoid ”sling snapback” injuries or fatalities due to flying debris; provide aid to injured workers while minimizing the spread of radionuclide contamination).

- *Limited indicators and job aids* – The rigging team determined proper sling tensioning and metal edge sharpness solely using skills incorporating visual and tactile cues unaided by engineered reference tools, which increased the variability in task performance. In this scenario, the riggers did not detect the imbalanced sling tension and also failed to detect the rigging component defect (i.e., the sharp edge on the inside of the MPC lift cleat in contact with the over-tensioned sling). Ironically, the slings were equipped with stress tabs indicating whether an overload condition had occurred, but the riggers were not aware the tabs existed.

- *Visual challenges* – Visual inspection of the inner surfaces of the installed MPC lift cleats was severely impaired because of their orientation on the MPC. Therefore, only tactile

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[51] The same type of sling and protective padding could withstand exposure to tremendously sharp edges under less severe loading conditions on multiple occasions. However, an arguably “dull” edge, according to human tactile sensation, combined with a 40-ton load could easily lead to sling failure upon first loading.

inspection could reveal the sharp edge on the inner surface of the lift cleat. This sole reliance on tactile cues removed the redundancy provided by simultaneous visual and tactile inspection typical in most rigging activities.

- *Time pressure* – The riggers perceived significant time pressure while performing their duties within a high-radiation-exposure environment. The riggers were highly motivated to complete their work quickly to reduce radiation exposures[52] per the ALARA principle[53] and due to the high-heat environment created above the MPC.[54] The need for rapid rigging performance highlights the importance of having appropriately trained hybrid teams demonstrate the appropriate skilled behaviors. In this case, time pressure combined with omissions in training and related verification skills contributed to failure to detect the sharp edge on the MPC lift cleat.

- *Time-of-day and shift-work challenges* – The crane operator and one of the riggers typically worked on the day shift; however, they had been called in to work this particular night shift which was being executed to ensure completion of the CLC according to the predetermined time schedule. This atypical performance of a night shift led to increased fatigue and a lowered level of alertness throughout the performance of their tasks. This fatigue also encouraged each of them to finish with their tasks as quickly as reasonably possible so they could take long rest breaks in the nearest employee lounge during their shift.

- *Inadequate verification* – The members of the hybrid rigging team trusted each other to verify each other's work and check the equipment for any damaged or malfunctioning components. In this instance, the contract employee carefully inspected one MCP lift cleat and expected the plant employee to do an equally careful job in inspecting the other cleat. The plant employee, however, was less diligent in the inspections and trusted the contract employee to follow up with checking both cleats and catching any potential misses. Furthermore, the rigging personnel trusted that the plant had very thorough QA processes; therefore, they did not expect to ever encounter nonconforming lift cleats or slings.

- *Quality assurance (QA) problems* – QA activities prior to the CLC did not catch the defects in the lifting equipment (i.e., the rough/sharp edge on the inside surface of one of the lift cleats, the slight length discrepancy in the long sling).

- *Decision-making bias error (confirmation bias)* – This accident happened near the end of a fuel loading campaign. The successful completion of fuel loads before this one misled the riggers into believing that future loads would also progress successfully. Therefore, they were less likely to notice any tearing, excessive wear, or unsafe conditions of the rigging gear (e.g., due to imbalanced sling loading).

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[52] The riggers were motivated to reduce their radiation dose level (both dose rate and cumulative dose), not simply to avoid a potential health hazard, but to avoid exceeding occupational exposure limits that could prevent them from performing similar work in the near future.

[53] The CLC management team prided itself on minimizing occupational radiation doses during the CLC because this measure was a key performance parameter that plant and utility executives used to determine the success of (and apportion financial bonuses to) the CLC management staff.

[54] The surface temperature of the MPC lid was in the range of 149º C (300º F). Given the large mass of the MPC lid, a significant amount of heat was radiated to the air above the transfer cask.

- *Inadequate team coordination* – The rigging team was a hybrid team consisting of plant-trained personnel and contract employees. The team members were trained in two different styles of inspection in which one employee believed each would verify the other's work and the other believed each would use extreme care in executing the task and no verification (or only cursory verification) would be done. Due to this mix of styles, one of the MPC lift cleats was not thoroughly inspected prior to the lift.

- *Large number of manual operations* – In this scenario, a number of equipment items required manual manipulation and careful attention to detail (i.e., inspection, installation, operation, independent verification of others' work) by the rigging team, including slings, sling padding, lift cleats, yoke arm pins, yoke arm pin bolts, ratchet tool, and personnel safety harnesses. The sheer number of human actions required of the rigging team increased the number of potential UAs.

- *Other ergonomic issues* – The hot environment (both thermal and radiological) and the need to assume awkward body positions increased fatigue and the potential for omissions.

5.6.3.4 HFE Group 3, Scenario 4: Rigging Failure and Failure to Completely Open Transfer Lid Door Causes MPC to Drop Slightly, then Jam Inside Transfer Cask

This scenario begins at the point when the MPC is suspended above the closed transfer lid door. The scenario involves the same QA and rigging problems described in scenario 3 above, such that both slings break and the MPC drops as soon as the crane operator begins lowering it. Unique to this scenario is the way the MPC drops and hits the edge of the transfer lid door such that its descent is arrested as it becomes jammed inside the transfer lid and transfer cask.

Two possible versions of this scenario involve differing UAs close in time to the active failure in which the cask is dropped:

Version 1: Rigger fails to completely open transfer lid door before signaling the crane operator to begin lowering the MPC – The rigger slides open the door on the transfer lid. Some resistance is encountered near the end of the travel path, but the rigger still perceives that the lid opens completely. During the previous cask loads of this campaign, the rigger has had difficulties inserting the transfer lid locking pins; therefore, to save time and reduce effort, he does not insert the lid locking pins. The rigger signals the crane operator to lower the MPC, and the crane operator initiates lowering of the MPC.

Version 2: Crane operator begins to lower MPC before transfer lid door is completely open – This error requires the crane operator to perceive that the rigger signals to begin lowering the MPC or to perceive that it is an appropriate time to begin lowering. It is also possible that riggers on the hybrid team miscommunicate, such that a rigger sends a premature signal to the crane operator to begin lowering the MPC. It is also conceivable that the crane operator inadvertently initiates the lowering of the MPC at an unintended time (e.g., intending one action yet executing another, also known as a slip or a lapse, depending on whether the fallibility of either attention or memory mechanisms are the primary culprit).

Irrespective of which version of UAs occurs, the subsequent events take place:

Slings break, and the MPC drops – Momentarily after the crane operator initiates lowering of the MPC, the ”slightly shorter” long sling (i.e., the same sling defect described in the previous scenario) snaps. Within a fraction of a second the remaining sling also snaps and the MPC begins to drop.

Edge of transfer lid door causes bottom of MPC to bind and jam inside the transfer lid – The edge of the transfer lid door protruding under the MPC arrests the MPC’s fall such that the MPC bottom becomes jammed inside the transfer lid. The mechanics of the interaction between the MPC, transfer lid, and transfer cask deform the MPC shell and transfer lid door. It takes a couple of days to devise an effective way to liberate the MPC from the jam. (See Figure 5-2 and Figure 5-3, which contrast a successful MPC lowering operation with the unsuccessful ”MPC jam” event, respectively.)

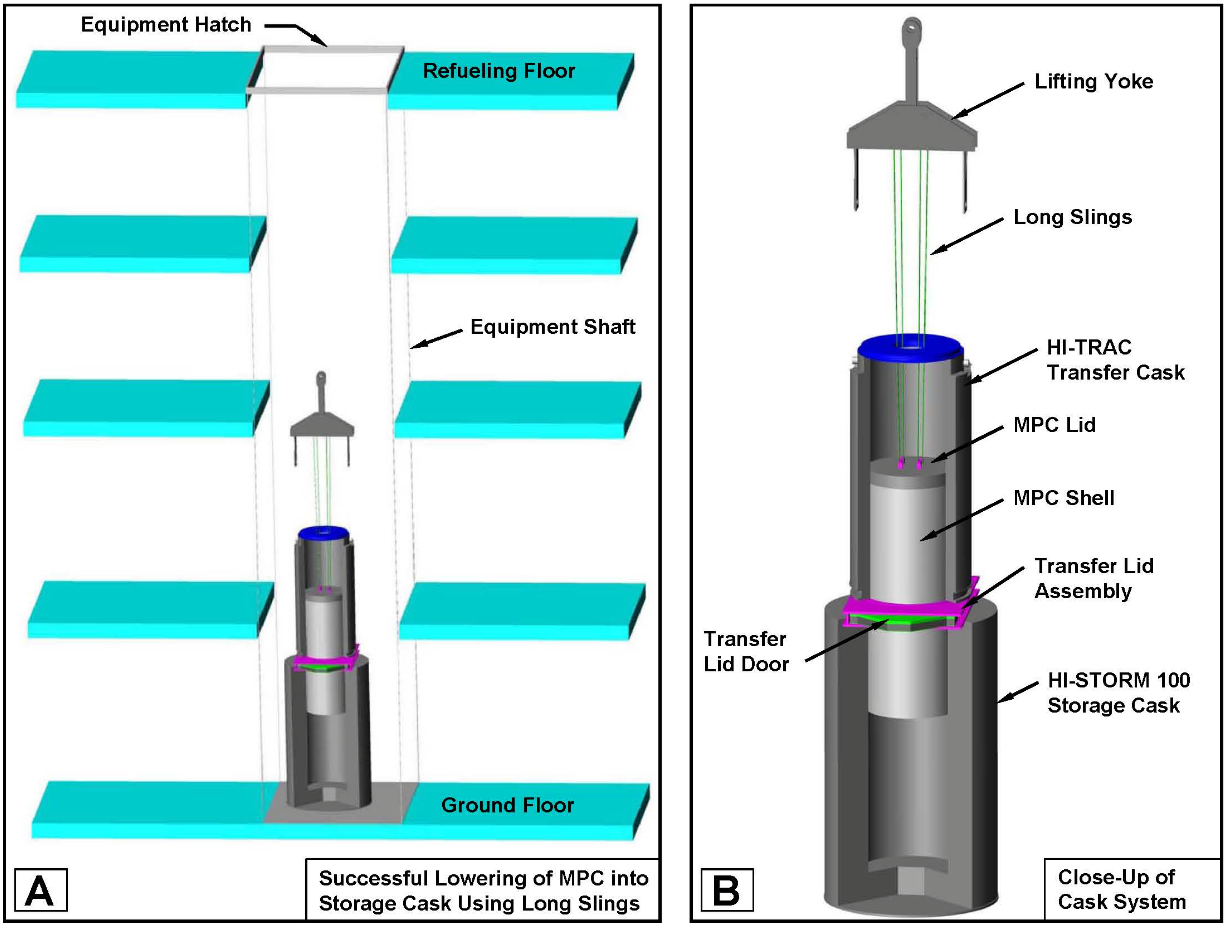

Figure 5-2 Diagram of a successful MPC lowering operation into the storage cask and the arrangement of cask system components in the equipment passageway.

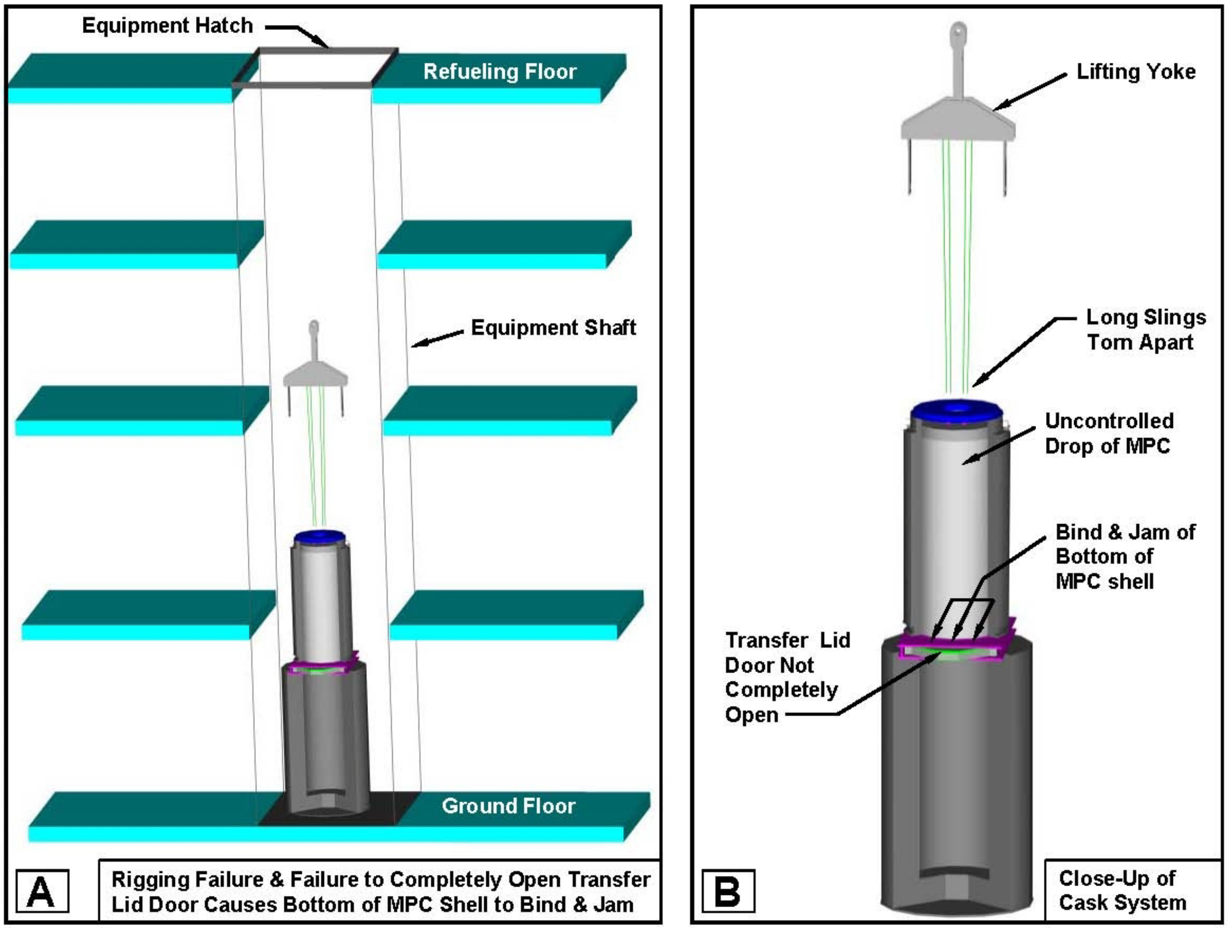

Figure 5-3 **Diagram of an unsuccessful MPC lowering operation (with emphasis on an MPC jam) into the storage cask and the arrangement of cask system components in the equipment passageway.**

Potential Human Performance Vulnerabilities for Scenario 4:

The potential human performance vulnerabilities for this scenario are identical to those in scenario 1 with the following additions:

- *Limited reliance on procedures* – Procedures specified that the locking pins need to be inserted prior to lowering the MPC into the storage cask. Therefore, the rigger did commit a circumvention/violation. However, supervisors and managers fostered a culture that emphasized speed and efficiency; it was common to develop informal rules or workarounds that contradicted procedure steps when it was deemed that formal procedures added unnecessary constraints to carrying out a task.

- *Inadequate training/experience* – The training for these riggers nurtured the virtue of making minor adaptations to procedures to increase operational efficiencies as long as they judged that little or no increase in safety risk was involved. The rigger responsible for opening the transfer lid door decided to forgo inserting the locking pins due to his perception of low safety impact and after experiencing what he perceived to be an "unproductive struggle" inserting the pins during previous cask load operations. This would not normally be deemed an egregious violation of procedures, given the plant safety culture that implicitly rewarded the successful use of informal rules and workarounds.

- *Communication difficulties* – Multiple people communicating on the radio made it difficult to discern who was speaking or to whom they were speaking. In one instance, the crane operator incorrectly believed that the rigger had provided the signal to lower the MPC into the storage cask; in other instances the rigging personnel encountered communication difficulties and signaled the crane operator to lower the MPC at an improper time.

- *Limited indicators and job aids* – There were insufficient positive measures helping the crane operator determine the optimal time to begin lowering the MPC. For example, the operator depended on the judgment of other workers to indicate when the transfer lid had been opened and secured and an unobstructed travel path for the MPC existed.

- *Visual challenges* – The crane operator could not see the state of the transfer lid, and, therefore, relied on indirect visual cues from other personnel to confirm an unobstructed travel path for the MPC. However, the rigger's visibility of the degree to which the sliding door was open within the transfer lid device was also very limited (e.g., it was difficult to visually confirm alignment of locking pin holes). In addition, the crane operator had difficulty in correctly identifying the visually communicated signals from the riggers due to viewing distance, viewing angle, ambient lighting, and visual distractions (e.g., multiple riggers, other simultaneous activities). Thus, the cask was lowered too soon.

- *Unchallenging activities* – The crane operator had successfully performed this operation several times during the previous week and considered it very easy. The operator's level of comfort and familiarity with the task led to a lack of arousal and feeling of boredom, which contributed to a lack of diligence in making sure all was ready before starting to lower the MPC.

- *Quality assurance (QA) problems* – QA activities did not detect problems associated with opening the transfer lid door and inserting/removing the locking pins.

5.7 HFE Group 4: Scenarios During Cask Movement from SFP to the Cask Preparation Area (TN-40 at PWR)

This phase begins when the TN-40 cask is resting on the bottom of the cask loading pit in the SFP and is loaded with fuel. The lid and lid-lifting assembly have been positioned on the cask, and the crane operator has successfully attached the lift beam arms to the trunnions. This phase ends when the TN-40 cask has been placed on the floor in the cask preparation/decontamination area in advance of decontamination and sealing activities. Further details are included in Sections A.3.2.2 through A.3.2.3.

5.7.1 Definition and Interpretation of Issue Analyzed

- *Human failure event scenarios during the movement of the loaded TN-40 cask from the SFP to the decontamination area* – In this process, the TN-40 cask is resting at the bottom of the SFP in the cask loading pit. The cask is fully loaded with fuel, the lid is in position on the cask, and the crane operator has successfully captivated the trunnions with the lift beam arms. The crane operator then lifts the cask partially out of the SFP. With the crane statically suspending the cask partially out of the SFP, workers vacuum out four bolt holes and hand-install four bolts. The crane operator then finishes lifting the cask out of the pool, horizontally moves the cask away from the SFP and over the decontamination area, and lowers the cask down to the floor of the decontamination area.

- *Reason for analysis* – These scenarios are analyzed due to the potential for dropping a loaded TN-40 cask either into the SFP before the four bolts on the lid are hand-secured, or during movement of the cask to the floor of the decontamination area after the four lid bolts have been hand-secured.

- *Potential consequences* – Dropping a loaded TN-40 cask into the SFP as described in one of the scenarios could result in a corner-impact drop after the cask falls approximately 10.5 meters (34.5 feet) before the four lid bolts are hand-secured. This type of violent impact would damage fuel, could spread fuel debris about the SFP (with release of radioactive gases from the damaged fuel), and could severely damage the SFP (i.e., cause a significant loss of radionuclide-contaminated water from the pool).

  Dropping a loaded TN-40 cask with the four hand-tightened bolts on the lid above the decontamination area as described in one of the scenarios could result in a drop of approximately 12.2 meters (40 feet) with a side impact at the middle of the cask. This violent impact would damage fuel and could result in contamination of the building atmosphere with fission products from a small release through the lid seal or a weld seam failure or a large release caused by decoupling of the lid with the cask. If the timing of the fission product releases due to either scenario are coupled with an atmospheric containment breach, a significant amount of fission products might migrate beyond the site exclusion region boundary.[55]

5.7.2 Base Case Scenario

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

- The TN-40 cask is resting at the bottom of the cask loading pit in the SFP.

- The fuel assemblies have been properly loaded into the cask.

- The cask lid has been successfully lowered into position onto the cask.

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[55] The PRA of bolted storage casks conducted by EPRI was used as a basis for inferring potential consequences that might result from these scenarios (EPRI 2004).

- The cask trunnions have been successfully engaged by the lift beam arms.

5.7.3 Scenario Descriptions

Table 5-6 Scenarios during cask movement from the SFP to preparation area.

HFE group & cask system	HFE group description	Scenario description (&associated vulnerabilities)	Vulnerabilities
4 – TN-40 System at PWR	Cask movement from SFP to preparation area	1.Crane operator impacts SFP wall with cask; cask drops due to defective lifting pin (1, 4, 6, 7, 8, 9, 11, 12, 13, 15, 17) 2.Crane operator hangs up cask on structure in SFP, crane is overstressed, cable is broken, & cask is dropped (1, 4, 11, 12, 13, 15) 3.Crane operator raises cask too high, cable breaks, & cask is dropped (1, 6, 8, 12) 4.Crane operator lowers cask onto edge of opening in floor at the SFP level; cask is dropped (1, 4, 7, 11, 12, 17)	1. Inadequate procedures 2. Limited reliance on procedures 3. Inapplicable procedures 4. Inadequate training/experience 5. Communication difficulties 6. Limited indicators & job aids 7. Visual challenges 8. Unchallenging activities 9. Time pressure 10. Time-of-day & shift-work challenges 11. Inadequate verification 12. Quality assurance (QA) problems 13. Decision-making bias error 14. Inadequate team coordination 15. Improper or uneven task distribution 16. Large number of manual operations 17. Other ergonomic issues

5.7.3.1 HFE Group 4, Scenario 1: Crane Operator Impacts SFP Wall with Cask; Cask Drops Due to Defective Lifting Pin

QA inspectors at the crane vendor do not notice a crack in the lifting pin before assembling the lift beam and shipping it to the NPP client – Several years before this CLC, the lifting beam components were inspected by QA personnel at a crane component vendor facility. The QA person in charge of the first inspection of one of the lifting pins was distracted during the inspection and then resumed the inspection at a point beyond the region where a small crack was visible (i.e., a slip). The second inspector performed a cursory job because the first inspector was vastly more experienced and “famous for finding flaws.” These latent UAs during inspection[56] led to the latent error condition of having a defective pin installed into the lift beam. The lift beam incorporated two pins; one pin was defective and the other pin conformed to the design specifications. An additional factor contributing to the first inspector's failure to detect the crack was the recent change in inspection procedures: instead of looking for only one type of defect at a time (e.g., cracks, corrosion, burrs, burnishing, tool marks) and then visually inspecting again for another type of defect, the new procedure specified that all types of defects were to be inspected for at the same time. This procedure change was instituted as a time-saving measure to speed up inspections so a large number of pins could be sent out to various customers within a short period of time.[57]

Crane structure and component inspectors do not identify and monitor growth of the crack in the lift beam lifting pin – QA personnel assigned to inspect incoming crane components upon arrival at the plant do not notice the crack in one of the lifting pins. The crack extends from one end of the pin, mostly concealed by the side plates of the lift beam to which it is mated. Only a small portion of the crack could have been seen by the inspectors. In addition, the inspectors have never seen any significant defect in components from this particular vendor, so they are not expecting to find any defects on any portion of the lift beam. This latent UA during inspection prevents discovery of the latent error condition. Had the QA personnel noticed the crack, they were trained to carefully measure the crack dimensions and determine whether or not the lift beam could be used. Periodic monitoring of crack growth would also be performed. Because the crack is never identified, no measures are taken to address the problem. In the years following installation at the plant, this lift beam with the defective pin has been used in considerable heavy lifting; an entire CLC was completed with the lift beam prior to the current CLC, and five cask loads have been completed successfully in the current CLC.

Personnel tasked with pre-job inspection of crane structures and components do not identify the crack in the lifting pin after the current cask load – Although the crack has grown much larger after many previous heavy lifts, it is still difficult to access and view the region of the pin containing the crack. During pre-job inspections, the lift beam is either suspended several feet above the ground, requiring awkward viewing from a step ladder, or the lift beam is lowered down onto the floor, forcing the inspectors to bend down or crouch in uncomfortable postures. Personnel executing this pre-job inspection are not trained to inspect for only one type of defect at a time; the procedural guidance simply instructs them to look for various defects—no systematic search strategy or visual inspection training is provided. These repeated latent UAs during inspection prevent the latent error condition involving the defective lifting pin from being discovered.

Crane operator raises the cask for decontamination of the top surfaces – The crane operator raises the cask so that the top of the cask is approximately 2.74 meters (9 feet) above the

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[56] It should be noted that failure to detect cracks, even very large cracks, has actually occurred at a cask vendor and appears to occur routinely during aircraft inspection (Wenner, Spencer et al. 2003; Wenner 2008). One SME interviewed during the preparation of this report recalled an event at a cask vendor in which an initial inspection team missed a large circumferential crack circling the entire diameter of a cask. Fortunately, the crack was discovered during a subsequent inspection before the cask was sent to an NPP client.

[57] Lift beam production is not typically a "high-volume business," but difficulties and delays in getting a particular batch of pins forged by the vendor's nuclear-component-qualified steel mill motivated the vendor to speed up the inspection process to fill NPP orders that were months overdue. The original plan was to temporarily allow this change in the QA procedure; however, once changed, the procedure remained static for several years prior to the cask drop described in this scenario.

surface of the water to enable workers to perform initial decontamination of the top of the cask, insert four lid bolts, and drain most of the water out of the cask into the SFP.

Workers focus on preparing for the installation of four hand-tightened bolts – Workers spray down the top of the cask with demineralized water (to decontaminate the surfaces) and then focus on preparing for the installation of four hand-tightened bolts: they ready the vacuum for removing water from the bolt holes and apply Never-Seez (anti-seize product) to the bolt threads.

Crane operator raises the cask slightly – The crane operator lifts the cask approximately 30.5 centimeters (1 foot) higher to allow personnel to easily access the cask lid surface. After vertical movement stops, the bottom of the cask is approximately 10.5 meters (34.5 feet) above the bottom of the cask pit, and the cask trunnions are slightly above the SFP floor level.

Crane operator moves the cask too close to the SFP wall – The crane operator is intent on bringing the cask as close to the wall of the SFP as possible to make it easier for workers to access the top of the cask to install the four hand-tightened bolts and to attach the drain line to the lid. After successfully performing this operation five times during the same CLC, the operator recognizes the value to the workers of bringing the cask as close as possible to the SFP wall.

Maintenance workers fail to notice that the cask is about to hit the SFP wall – The workers present around the cask have various tasks (e.g., monitoring radiation, preparing to install hand-tightened lid bolts, and draining water from the cask). They are all generally trained to maintain awareness of the position of the cask, yet none are solely dedicated to be spotters at this point in the process. The crane operator is using a radio frequency control pendant to operate the crane and is fairly close to the cask movement being controlled. Therefore, nearby workers feel confident that the operator is adequately aware of the cask position at all times.

Crane operator hits the SFP wall with the cask – The crane operator, while relatively near the cask movement being controlled, attempts to bring the cask as close to the SFP wall as possible (within just a few inches). The view of the SFP wall is partially obstructed by the movement of other workers near the edge of the SFP, and the operator inadvertently hits the SFP wall with the cask.

Cask and most of the mass of the lifting beam drop into the SFP, with cask impacting on its edge – Upon impact with the SFP wall, there is a loud metallic buckling/cracking sound due to the failure of the defective lifting pin on the lift beam. This is followed by a rapid shift of the entire load to the other lifting pin, which also breaks apart. The cask and most of the lifting beam (all components below the pin) drop into the SFP. Due to slight rotation during the fall, the edge of the cask bottom hits the bottom of the cask loading pit, causing sufficient structural damage to initiate slow draining of the pool. The impact between the interior of the cask and the bottom of the fuel leads to extensive fuel damage, ejection of the unsecured lid from the top of the cask, and significant fission product releases both into the SFP and into the general atmosphere[58] of the SFP building. In addition, the draining SFP spreads radionuclide-contaminated water throughout the lowest level of the SFP building. (See Figure 5-4.)

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[58] Fuel pins are highly pressurized. Failure of fuel cladding leads to gap releases that can be transported out of the SFP.

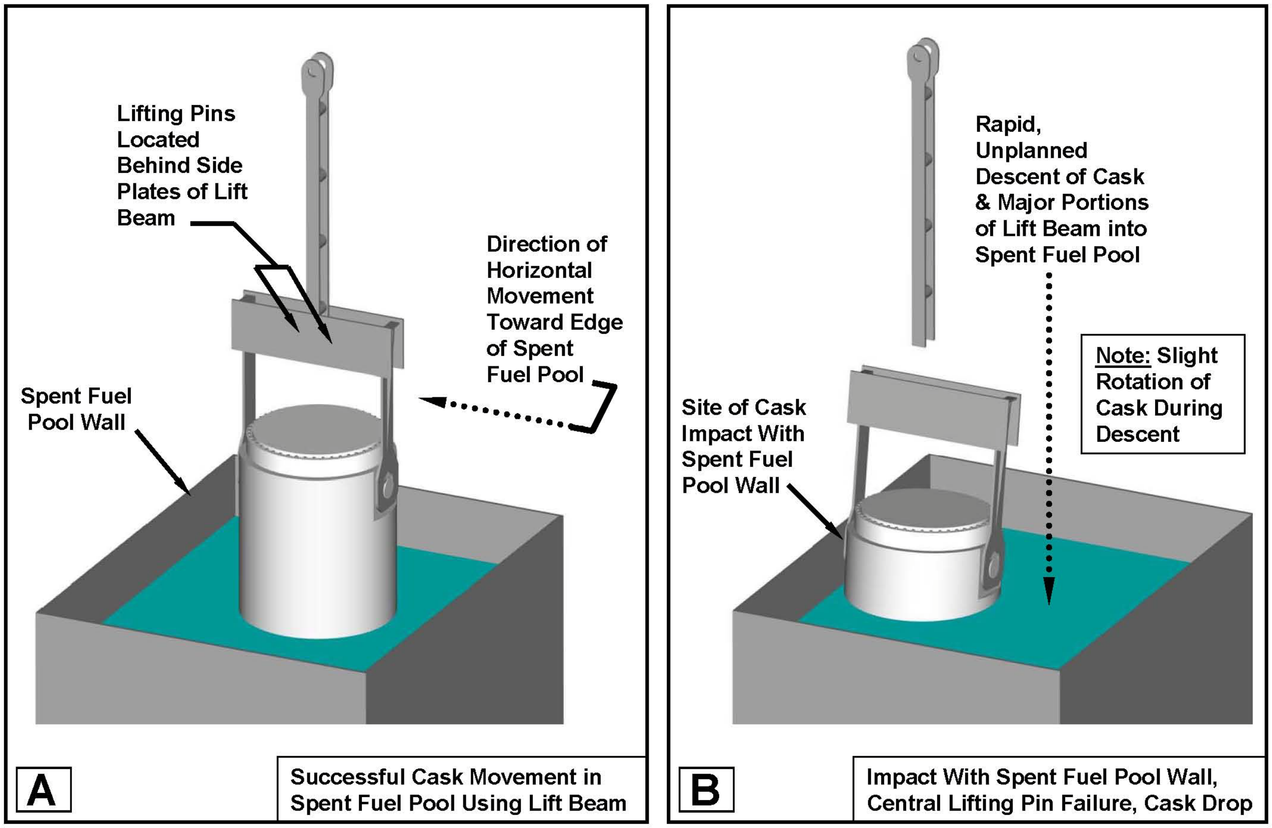

Figure 5-4 Diagram of lifting beam and cask before and after the catastrophic failure of the main lifting pins.

Potential Human Performance Vulnerabilities for Scenario 1:

- *Inadequate procedures* – The procedures and training did not require at least two people to continuously monitor cask movement. This lack of an important requirement was due to the assumption that such redundancy was unnecessary when the crane operator was able to stay close to the load being moved. Furthermore, the procedure-writing process lacked diligent investigation into potential off-normal and emergency cask-handling situations. Procedures both at the crane component vendor and at the plant did not provide sufficient guidance on how to carry out reliable visual inspections based on relevant human performance research. The cask-component vendor once had a good procedure, but it was sacrificed to meet production goals.

- *Inadequate training/experience* – Because procedural guidance was insufficient, crane operator training did not teach the immediate action skills necessary to appropriately respond to this type of off-normal or emergency situation. Similarly, because of the lack of procedural guidance on maintaining two-person monitoring of cask movement, training did not cover continuous, redundant visual monitoring of cask movement. Due to the inadequate procedural guidance for inspectors and insufficient understanding of the potential impact of adequate inspection guidance, training for inspectors did not cover techniques for avoiding systematic visual inspection errors.

- *Limited indicators and job aids* – Insufficient cues were present to warn the crane operator of the cask's position relative to the SFP wall. Positive measures such as horizontal and vertical position indicators and proximity/collision alarms were not present. There were also insufficient job aids or engineering tools to aid the systematic inspection processes at the crane component vendor. That is, no visual inspection search template was available to help a temporarily distracted inspector return to the task without omitting a portion of the search space.

- *Visual challenges* – Although the crane operator was located near the cask being controlled, which typically affords a good view of the cask, at times the view was partially obstructed by personnel conducting or preparing for tasks. Also, during equipment inspections performed multiple times over several years, the location of the lifting pin in the lift beam visually obscured the ends of the pin, including the end with the gradually growing crack.

- *Unchallenging activities* – The simplicity of the task, the slow pace of commanded movements, and the crane operator's close proximity to the load, combined with repeated performance of a well-learned skill, lowered the crane operator's level of arousal/attention and decreased the quality of task performance. The low level of arousal/attention led to decreased vigilance in self-monitoring, which contributed to UAs during crane operation.

- *Time pressure* – The QA organization at the cask-component vendor experienced time pressure due to pin manufacturing delays, which led to a change in procedures in order to speed up activities. The vendor was not aware of visual inspection research showing that the flaw detection rate would likely degrade significantly due to the change. Time pressure also played a part during the cask load. After completion of the CLC, a complex outage involving major system repairs and equipment change-outs was scheduled to take place. Hundreds of contractors and support equipment had already arrived at the plant site and more were streaming in each day. An additional factor exacerbated the perception of time pressure near the end of this CLC: despite the complexity of the upcoming outage, the plant was expected to resume full-power operation quickly because little excess electrical-power-generating capacity was available to the surrounding region due to a severe hurricane season that had damaged transmission systems.

- *Inadequate verification* – Given the floor placement of the crane operator, the maintenance workers believed he had a full and complete view of the travel path of the cask; thus, the tendency toward social shirking was strong. They trusted the crane operator to detect any objects or impediments within the travel path and take appropriate measures to avoid a collision. Also, with respect to latent error conditions involving inadequate verification, previous equipment inspections at the vendor and at the plant included some instances of cursory secondary inspections due to a belief that previous inspections had been effective.

- *Quality assurance (QA) problems* – QA activities at the crane-component vendor and at the plant were not designed and implemented based on knowledge of human performance (i.e., sensitive and reliable visual inspection performance). The procedures, training, and types of feedback available to the inspectors were not sufficient for maintaining short-term vigilance and long-term visual inspection skills. At the vendor, even in the case of one inspection procedure known to be sensitive and reliable (i.e., it called for repeated inspections of the same item for different defects—a method empirically proven to be robust), production pressures were allowed to overrule potential safety concerns. This QA procedure change at the vendor revealed that inspectors and at least one level of management had consciously allowed the safety culture in the QA department to degrade due to an implicit and incorrect belief that either defects would not be present, or if present, would not pose a practical safety concern. The limited feedback they had received led them to believe that even if cracks were found in the lift beam pins, it would not matter because the pins were over-engineered.

- *Decision-making bias error (confirmation bias)* – The inspectors both at the crane-component vendor and at the plant had never seen any significant cracks in lifting pins nor had they ever heard of any large pin failures. They never expected to see any cracks, which made it much harder for them to detect cracks. The particular inspector at the vendor who was “famous for finding flaws” was also occasionally chided for calling attention to “insignificant defects.” None of the inspectors believed that small cracks, even if they were to be found, would lead to a severe event such as a pin failure.

- *Decision-making bias error (overconfidence)* – Although everyone is potentially vulnerable to displaying overconfident behavior, particular individuals may display increasing propensity for such behavior while executing a given task after previously experiencing successes in completing that type of task. In this scenario, the factors that led to complacency and low levels of arousal for the crane operator (i.e., simplicity, slow pace, and close proximity to the cask) also encouraged an overconfident attitude toward task performance. For example, when nearby personnel temporally blocked the crane operator’s view of the cask movement, this visual impairment did not cause worry or increased vigilance/concern because the crane operator was fully convinced that this cask movement would be as successful as all of the previous cask movements.

- *Improper or uneven task distribution* – Although numerous maintenance workers were within close proximity, none were specifically assigned the role of continuously monitoring the clearance between the cask and the SFP wall (i.e., there was no procedural guidance directing the continuous and redundant monitoring of the clearance). Furthermore, given the limited nature of other procedures in the DCSOs, it is likely that had a procedure required continuous and redundant monitoring, it would not have provided clear guidance on when or who (other than the crane operator) was responsible for monitoring the clearance between the cask and the SFP wall and potentially ordering a stop to the cask movement.

- *Other ergonomic issues* – The spatial location of the central lifting pin in the lift beam required inspectors to assume awkward postures for long periods to inspect this potential single point of failure. They often performed cursory visual scans of the lift beam components to shorten the time it took to perform the awkward, uncomfortable activities.

5.7.3.2 HFE Group 4, Scenario 2: Crane Operator Hangs Up Cask on Structure in SFP, Crane is Overstressed, Cable is Broken, and Cask is Dropped

This scenario begins at the point when the cask is loaded and ready to be lifted to the top of the SFP, where the lid will be secured with four hand-tightened bolts, and then the cask will be removed from the SFP.

Crane operator lifts the cask; lift beam hangs up on structure in loading pit – The crane operator lifts the cask approximately 1.52 meters (5 feet) off the bottom of the cask loading pit. At this point, the crane operator halts the lift and proceeds to horizontally move the cask closer to the side of the cask pit so that when the top of the cask is raised above the surface, personnel responsible for installing the four hand-tightened bolts will have easier access to the lid. The crane operator positions the cask within inches of the SFP wall. Unfortunately, the proximity of the cask to the wall, along with the particular orientation of the cask trunnions, places the lifting beam in a position to collide with a structural element that protrudes outward from the wall of the cask loading pit. The crane operator resumes the lift of the cask and is maneuvering the crane using a radio frequency control pendant. The operator is positioned near the surface of the SFP while executing the lift. The lifting beam impacts and partially lodges itself into the structure protruding from the wall. The loading on the crane cables increases dramatically once the hang-up occurs.

Crane operator does not react immediately to cask hang-up – The crane operator is noticing the activity of the decontamination workers and is slightly distracted from monitoring the cask lift. The operator does not anticipate any problems during the lift because multiple cask loads within the CLC have been successfully completed during the past week. The initial impact of the lift beam and the fixed object transmits a significant vibration through the floor, and audible sounds of increasing strain on the crane cables can be heard. The crane operator is surprised and shocked by the unfolding events and delays in releasing the lever controlling the lift.

Crane control overcurrent protection switch does not activate – The height of the lifting beam and cask allows for the cask to be lifted only a few feet above the SFP floor level before onset of a two-block event. Therefore, to avoid spurious shutdown of the crane during cask movement, maintenance personnel are directed to disable the safety interlock that was activated when the hoist position indicated a two-block was imminent. Unfortunately, the maintenance personnel disable not only that interlock, but also the overcurrent protection interlock that activates when the hoist is straining to lift an excessive load.

Crane cable breaks and cask drops to the bottom of the cask loading pit – As the crane operator moves the hoist control lever to the neutral position and then starts moving toward the hoist power-off button, the crane cables break. The cask, along with the lifting beam, drop to the bottom of the cask loading pit. Fortunately, the SFP is not significantly damaged, and the lid, while partially dislodged, remains on top of the cask.

Small amount of gaseous radionuclides are released to the SFP and then into the building atmosphere – The impact from the fall damages multiple fuel assemblies, but only a few fuel pins rupture and release gaseous radionuclides. The partially dislodged cask lid allows the radioactive gases to migrate up through the SFP and into the atmosphere.

Resumption of normal operations is delayed for many weeks – Due to damage to the crane, crane cables, and crane block, it takes several weeks to acquire and install the appropriate equipment and completely recover from this event.

Potential Human Performance Vulnerabilities for Scenario 2:

- *Inadequate procedures* – The procedures for the cask movement activity in the SFP did not specify that more than one person must be designated with the responsibility of verifying a safe travel path and the authority to prevent or stop cask movement. Also, the procedures did not specify a safe horizontal distance that accounted for the structural element protruding from a portion of the wall be maintained between the cask and the wall of the cask loading pit.

- *Inadequate training/experience* – The crane operator’s training was conducted too infrequently and did not address the topic of cask hang-up response in sufficient detail to ensure that the operator had the well-practiced skills to rapidly and correctly respond to various types of cask hang-up events.

- *Inadequate verification* – There were inadequate formal procedures for assigning responsibilities among multiple personnel to ensure movement of the cask along a safe vertical travel path. In addition, the informal behaviors for verifying a safe vertical travel path were migrating away from safe operations (i.e., during the previous cask loads at least one other worker maintained a close watch on the cask movement and may have been able to warn of an impending collision). Finally, the fact that the maintenance team mistakenly disabled two safety interlocks on the crane instead of one could be considered a common mode failure (i.e., a second individual or team could have been assigned to confirm that only the hoist position safety interlock was disabled).

- *Quality assurance (QA) problems* – Before the CLC, the maintenance personnel directed to disable the hoist position safety interlock had mistakenly disabled both the hoist position interlock and the overcurrent protection interlock. This mistake was a latent UA that created a latent error condition that contributed to the overstressing and failure of the crane cables.

- *Decision-making bias error (confirmation bias, overconfidence)* – Because several successful cask loads had been completed during the previous week and because of the operator’s successful performance during another CLC conducted three years earlier, the crane operator was not expecting any difficulties during this cask movement. Confirmation bias and overconfidence from focusing on previous success added to the shock and hesitation in response to the cask hang-up event.

- *Improper or uneven task distribution* – Responsibility and authority for monitoring the safe movement of the cask was inadequately distributed among multiple personnel (i.e., multiple spotters and the crane operator). In this scenario at least two other decontamination workers could have been trained and tasked to provide the appropriate verification and guidance functions to ensure safe cask movement. The use of multiple personnel with different visual perspectives would likely prevent similar cask hang-up and drop events. The crane operator was assumed to have excellent visibility while controlling the lift given being positioned so near to the load being lifted. Therefore, none of the other personnel near the SFP were concerned with visually monitoring the lift.

5.7.3.3 HFE Group 4, Scenario 3: Crane Operator Raises Cask Too High, Cable Breaks, and Cask is Dropped

This scenario begins after the lid has been secured with four hand-tightened bolts and the cask is being raised out of the SFP to be moved to the decontamination/preparation area.

Crane operator is distracted during lift of cask; fails to stop lift in time – The action of raising the cask using the spring-loaded lever is extremely simple, but the lift is slow and takes a considerable amount of time to complete. As the lift is nearing completion, the crane operator is distracted by the activity of several personnel on the refueling floor level.

Cask load tops out, and cask drops due to a two-block failure – The operator does not terminate the lift prior to impact of the two blocks. The operator returns attention to the cask and releases the spring-loaded lever as soon as the loud noise of the two-block impact is heard. There is a delay between the release of the lever and cessation of movement of the hoist. This delay allows for excessive strain on the crane cables, leading to tensile failure and dropping of the cask, lift beam, crane block, and some cabling back into the SFP. An overcurrent protection safety interlock intended to avoid a two-block failure of the crane cables does not function.

Potential Human Performance Vulnerabilities for Scenario 3:

- *Inadequate procedures* – Procedural guidance did not detail the specific height at which to stop raising the cask. The crane operator was expected to visually monitor the lift and cease movement when the cask bottom was above the refueling floor level.

- *Limited indicators and job aids* – There were insufficient indicators and job aids such as an engineered reference for stopping the cask lift and proximity alarms to warn of an impending two-block event.

- *Unchallenging activities* – The simplicity and monotony of this task led to the crane operator's complacency and distraction.

- *Quality assurance (QA) problems* – The overcurrent protection sensor and safety interlock had not been tested in a number of years so there was no awareness that this safety feature would not perform its intended function if a two-block event occurred.

5.7.3.4 HFE Group 4, Scenario 4: Crane Operator Lowers Cask onto Edge of Opening in Floor at the SFP Level; Cask is Dropped

This scenario begins at the point when the cask lid has been secured with four hand-tightened bolts, the cask has been lifted out of the SFP, and the cask is being horizontally transported to the opening in the floor leading down to the decontamination/preparation area.

Crane operator horizontally moves the cask to the opening in the floor at the SFP level – The crane operator horizontally moves the cask, which is vertically positioned approximately 15.2 centimeters (6 inches) above the floor level, toward the opening in the floor that provides a travel path down to the preparation area. The clearance between the bottom of the cask and the floor level is minimal, which reduces the time available for correcting an error in lowering the cask when the cask crosses the floor edge. The cask cannot be raised much higher without use of a different lift beam because the crane hook to which the lift beam is attached is near the upper limit of its travel path.

The doors on the refueling floor level, through which the cask must pass, do not open wide enough to allow the central radial axis of the cask trunnions to be perpendicular to the cask travel path. To clear the doorway, the lift beam and trunnions need to be at an angle much less than 90° to the direction of travel. The crane operator is well aware of this physical constraint, and workers are trained to use the tag lines (ropes) attached to the lift beam to rotate the cask prior to movement through the doors. Once the central radial axis of the lift beam has been rotated and the cask successfully passed through the doorway, neither the procedures nor the training indicate that a change in lift beam orientation should occur before the cask is lowered down to the preparation/decontamination area. (Figure 5-5 and Figure 5-6 depict the cask during movement to the opening in the floor at the SFP level.)

Crane operator loses balance, and crane control pendant is damaged – As the cask crosses over the edge of the opening in the floor at the SFP level, the crane operator shifts body position, anticipating the need to view down two floor levels to the bottom of the preparation area. While shifting weight, the operator loses balance and as a result the control pendant violently impacts[59] against a nearby railing. The control pendant fails such that the horizontal movement of the cask stops, yet cask lowering is initiated. The safety interlock switch on the control pendant fails to stop the crane.

Back-up for the "emergency stop" features of the control pendant are not available – The crane electrical system has a high-voltage circuit breaker located in a fixed position in the refueling building; however, no one is stationed near the circuit breaker as a back-up to provide additional assurance that the crane will stop as needed during "off-normal" and "emergency" conditions.

Cask tilts over as it is lowered at the edge of the opening in the floor at the SFP level – The center of the bottom of the cask is slightly beyond the edge of the opening of the floor when it is lowered onto the edge. The location of the center of mass of the cask in relation to the floor surface leads to significant and increasing tilting of the cask as it is inadvertently lowered. (See Figure 5-5 and Figure 5-6.)

Lift beam arms and trunnion end caps are severely damaged due to cask tilt – The direction of horizontal movement of the cask happens to be in line with the central radial axis of the upper trunnions to which the lift beam arms are attached. This unfortunate orientation of the lift beam means that as the cask tilts on the edge of the opening in the floor, one lift beam arm is subjected to a severe overload condition including a large moment of force at the lift beam arm-trunnion coupling. This overload condition causes simultaneous plastic deformation of both the lift beam arm and the trunnion end cap. See Figure 5-5 and Figure 5-6.

Lift beam arm–trunnion couplings fail, and cask drops down into preparation area – At a critical point during the tipping of the cask at the opening of the floor, the trailing[60] lift beam arm detaches from the trunnion, and the cask swings rapidly, followed by failure of the coupling between the other lift beam arm and its associated trunnion. The cask drops approximately 9.14 meters (30 feet) until the middle of the side of the cask impacts the opening in the floor level immediately above the preparation area. The cask continues falling straight through the floor surface[61] down into the preparation area on the lowest floor level. This cask drop causes

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[59] It is also conceivable that a control pendant could be dropped over the edge of the opening of the floor and subsequently experience a severe impact acceleration upon contact with the floor of the preparation area.

[60] That is, the lift beam arm closest to the edge of the opening in the floor.

[61] Because there is no vertical column/wall underneath the floor area impacted by the cask, the cask will proceed largely unaffected along its path of descent until it comes to rest at the bottom of the structure.

extensive damage to the fuel and results in slight contamination of the building with fission products due to small releases through the lid seal and a weld seam failure.[62]

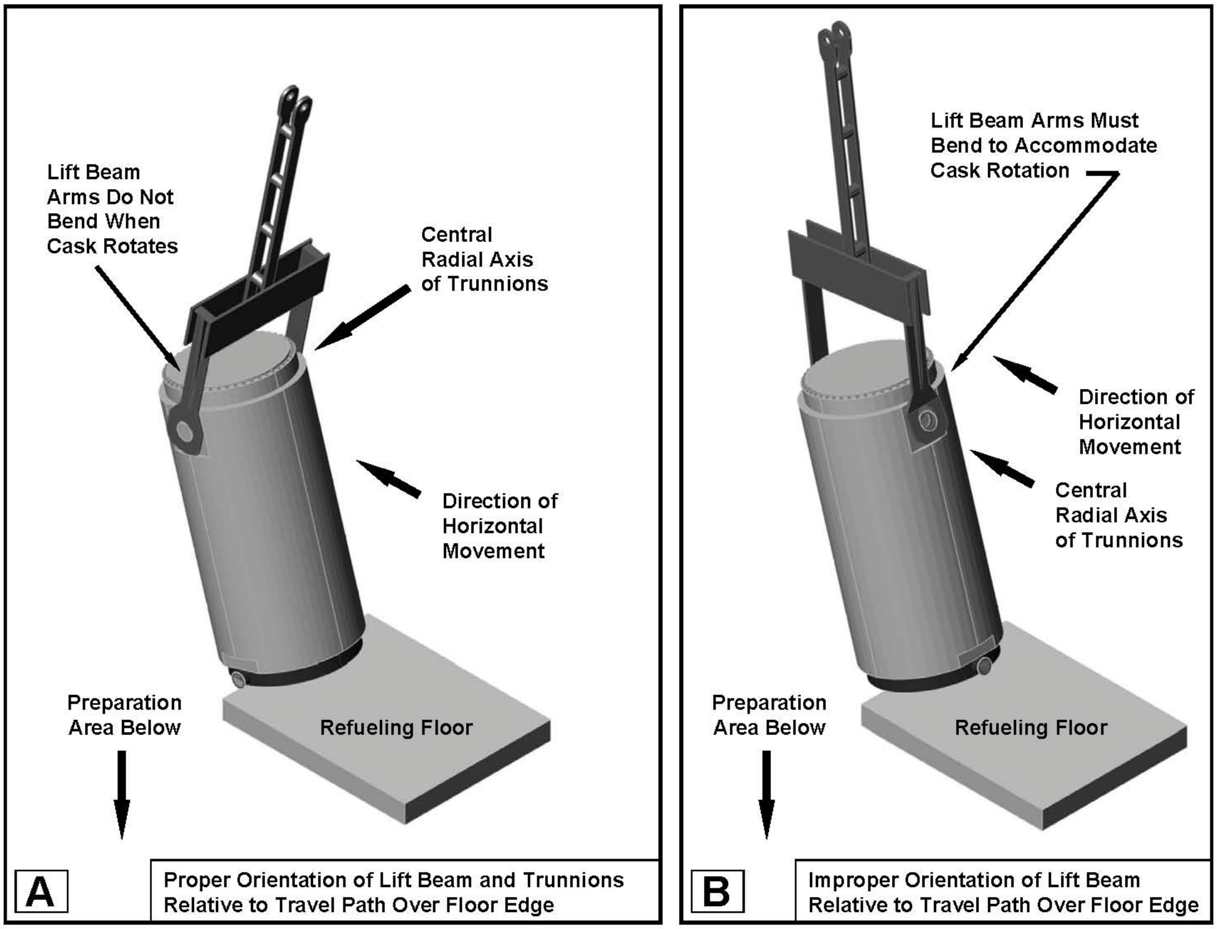

Figure 5-5 Perspective views showing two possible scenarios, given inadvertent lowering of cask onto refueling floor edge.

A shows the cask and lift beam rotation when the central radial axis of the trunnions is parallel to the floor edge and perpendicular to the travel path. In this case, the trunnions are not damaged. B shows the central radial axis of the trunnions perpendicular to the floor edge and parallel to the travel path such that inadvertent lowering damages one trunnion and one lift beam arm.

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[62] Note that a large fission product release could have occurred if the lid decoupled with the cask. In addition, if the timing of the release coincided with an atmospheric containment breach, a significant amount of fission products might have migrated beyond the site exclusion region boundary.

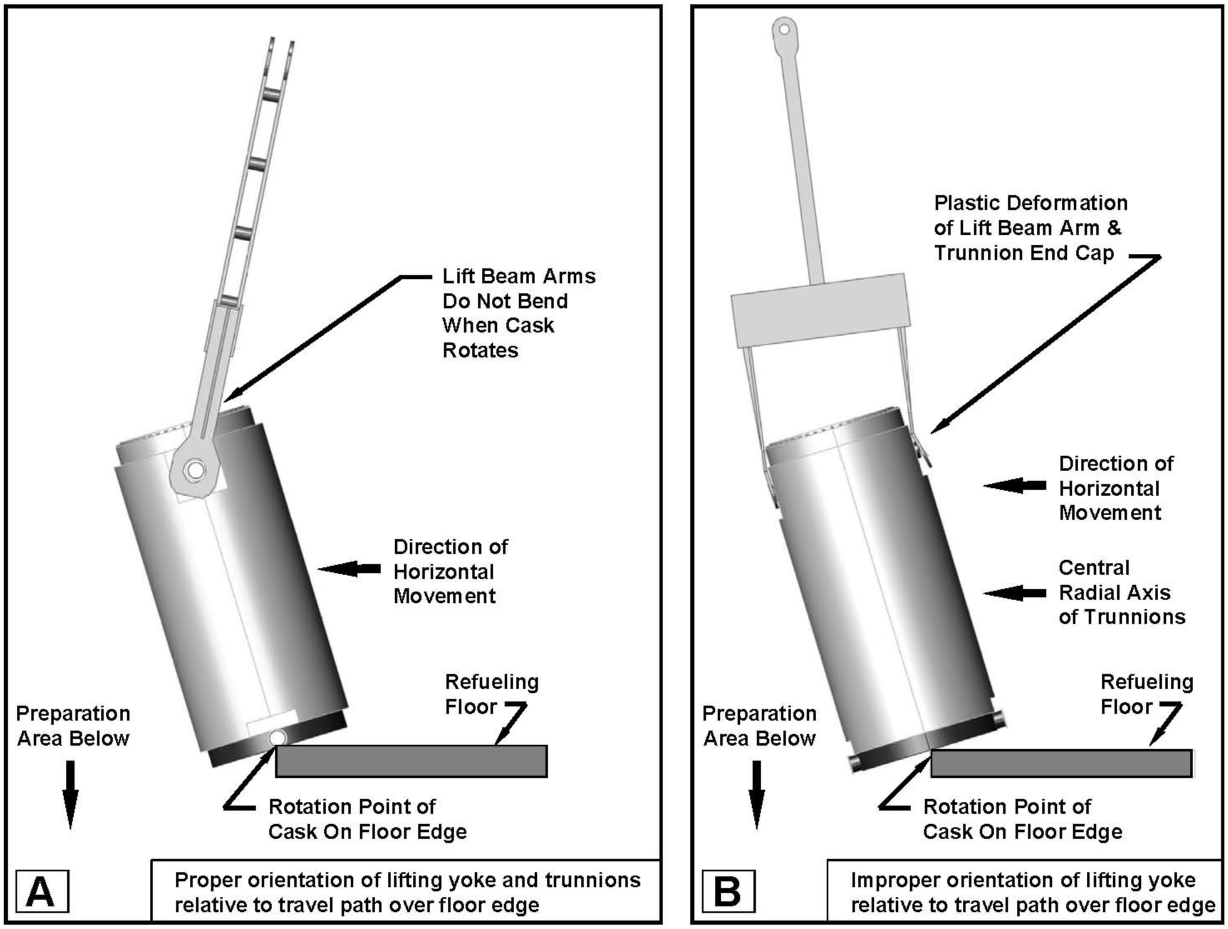

Figure 5-6 Orthographic views of two possible scenarios, given inadvertent lowering of cask onto refueling floor edge.

A shows the cask and lift beam rotation when the central radial axis of the trunnions is parallel to floor edge and perpendicular to the travel path. B shows the cask and lift beam rotation with damage to one trunnion and lift beam arm when the central radial axis of the trunnions is perpendicular to the floor edge and parallel to the travel path.

Potential Human Performance Vulnerabilities for Scenario 4:

- *Inadequate procedures* – Those who developed the procedures did not anticipate the possibility of this type of accident; therefore, they did not include instructions to ensure that the central radial axis of the upper trunnions was perpendicular (or very nearly perpendicular) to the horizontal movement of the cask. In addition, they did not anticipate that the crane control pendant could conceivably fail such that unintended movement would occur (they assumed there was sufficient independence between safety circuits/mechanisms within the control pendant). They did not appreciate the benefit of having a person continuously stationed at the crane's high-voltage circuit breaker to serve as an emergency stop back-up in case the crane control pendant failed or another failure caused unintended movement.

- *Inadequate training/experience* – Training on how to quickly respond to a malfunction of the crane control pendant was limited. In particular, because procedural guidance on how to respond to catastrophic failure of the crane pendant was lacking, training was also deficient with respect to stationing and maintaining communication with additional personnel near the crane's high-voltage circuit breaker. Furthermore, the training did not emphasize maintaining a safe orientation of the trunnions and lift beam during cask movement.

- *Visual challenges* – The crane operator had a limited view of the full travel path of the cask. To view the travel path from the SFP level down to the decontamination/ preparation area, the operator had to lean over a railing. The awkward leaning was a major contributor to the crane operator losing balance.

- *Inadequate verification* – The QA authorities at the crane vendor and the plant site, along with the crane operator, trusted that the crane control pendant would be robust enough to fail "safe" during all expected operating environments.

- *Quality assurance (QA) problems* – The control pendant was susceptible to catastrophic "active" failure when subjected to a mechanical shock that could be produced from the crane operator's hands due to his falling or otherwise being in the path of a person who is falling or trying to regain balance. The testing process at the crane pendant manufacturing plant did not investigate performance in such an environment, and the NPP at which the pendant was being used never conceived that such a test would be necessary. Therefore, this type of shock environment fell outside the design requirements for the pendant.

- *Other ergonomic issues* – The crane operator was required to adjust body position and bend to view the path down through the floor to the preparation area below. The change in body posture, combined with the conditioned desire to maintain positive control over the crane control pendant, led to a loss of balance accompanied by delays in recovery movements. For example, the operator's desire to protect the pendant briefly inhibited him from letting go of the pendant to grasp the railing to regain stability.

6 ILLUSTRATIVE RECOMMENDATIONS AND EXAMPLES FOR AVOIDING OR MITIGATING HFES

This section provides illustrative guidance on how to avoid or mitigate the human performance vulnerabilities identified in Section 5 and thus avoid or mitigate human failure events (HFEs) involving cask drops. It should be emphasized that the material in this section is not complete or exhaustive; it is merely illustrative and tied to the vulnerabilities described in Section 5.

As described in detail in Appendix B, it is common for a significant number of active failures or unsafe actions (UAs) to occur within any complex system. Thus, it is reasonable to assume that multiple UAs will also occur during dry cask storage operations (DCSOs). It may be true in most scenarios that multiple equipment failures and UAs must occur simultaneously or in a particular sequence for a cask drop to occur. The intent of this section is to provide illustrative guidance on ways to reduce UAs and HFEs resulting in latent error conditions and active failures involving cask drops. It is likely that substantial knowledge and experience with a specific cask system and personnel at a specific plant are needed to appropriately adapt these illustrative recommendations into practical guidance for that plant.

6.1 Overall Approach for Avoiding or Mitigating HFEs

This section provides information that forms an initial technical basis for improvements to procedures and practices involving DCSOs to reduce the likelihood of cask drops resulting from unsafe human actions. The first set of information distinguishes the two analyzed dry cask storage systems (DCSSs) in terms of their overarching DCSS engineered design features and opportunities for HFEs leading to cask drops. The second set of information summarizes potential techniques for avoiding or mitigating the human performance vulnerabilities identified in the scenarios in Section 5. The last set of information describes the concept of safety culture and attributes of an organization which are associated with a robust safety culture. The NRC has recognized a strong safety culture as being associated with a decrease in both latent and active UAs. The safety culture subsection also includes specific recommendations generated by an analysis team with first-hand experience observing multiple cask loading campaigns (CLCs) at multiple plants.

6.1.1 Overarching DCSS Design Features

In general, the HOLTEC HI-STORM 100 DCSS involves more movements and more rigging equipment than the TN-40 DCSS. Additional movements and additional rigging allow more occasions for both latent and active UAs. The bolted lid storage cask used in the TN-40 DCSS allows the lid to the container housing the spent fuel to be at least partially secured before the cask is removed from the spent fuel pool (SFP). This feature reduces the opportunity, over the time and distance of cask movement, for a drop of the TN-40 cask to result in significant radionuclide releases that could harm plant personnel. In addition, the geometric differences in the casks and yokes/lifting beams for the two DCSSs, based on two videos of operations at actual plants (i.e., the HI-STORM 100 at one plant and the TN-40 at one plant), further indicate that the TN-40 provides fewer opportunities for a cask drop. For example, the video of the HI-TRAC transfer cask showed cask trunnions without end caps. In contrast, the video of the TN-40 cask showed cask trunnions with end caps, a lift beam with tapered eyes that took ample advantage of the end caps, and recessed trunnions that did not extend beyond the outside diameter of the cask, thus reducing the opportunity for cask hang-ups leading to cask drops. While these particular differences in the yoke/lifting beam interface are significant, relatively minor modifications to the HI-TRAC 100 transfer cask trunnion and yoke arm would eliminate this particular distinction between the two DCSSs.

6.1.2 Techniques for Avoiding or Mitigating the General Human Performance Vulnerabilities that Could Contribute to Cask Drops

Some potential techniques for avoiding or mitigating the human performance vulnerabilities discussed in Section 5 are summarized below. These techniques have been inferred from research in complex systems and discussions with subject matter experts (SMEs). The list is not comprehensive, but it offers suggestions that can be used alone or in combination with one another. Virtually all of the vulnerabilities described in Section 5.1.1 (and more) could conceivably be applied to all the scenarios in Section 5. The avoidance and mitigation techniques generally mirror the vulnerabilities identified in the scenarios. Table 6-1 summarizes each area presented in this section.

Before adopting new processes or equipment intended to improve safety, a thorough review by appropriate system experts and managers is required. Instituting changes such as those suggested in this section may introduce new problems into the system, necessitating further refinement. Therefore, after adopting any new safety procedure, device, or system, a comprehensive evaluation, with periodic follow-on evaluations, should be performed to verify that the intended improvements are being realized.

Table 6-1 Summary of illustrative techniques to avoid or mitigate general human performance vulnerabilities.

Improvement Area	Description
Procedures	*More detailed procedures*—Increase the comprehensiveness and detail of procedures, and include response to low-likelihood events. The procedure will remind the crew of the occasional occurrence of such or similar events and serve as training material for less-experienced personnel. Detailing actions for responding to a particular emergency such as a dropped cask will remind personnel of this possibility and may assist them in adapting the procedures to fit a similar emergency if it ever occurs. Greater detail could include incorporating checklists, specifying roles for personnel, and specifying measureable criteria. *Reliance on procedures*—Require more reliance on procedural direction by instituting checklists to be completed during multi-step operations and by specifying confirmation requirements to be met during inter-crew communications or measurement criteria to be met during cask movement. Develop and maintain a “work-to-procedure” culture in which, if documented procedures deviate significantly from the actions that appear to be needed in an operation, all equipment is placed in a safe configuration and work is stopped until the procedures can be corrected. However, avoid overly prescriptive procedures or a “work-to-procedure” culture that does not allow personnel to respond appropriately to an abnormal situation. Write procedures that give personnel many cues for determining whether the procedure matches the situation encountered and for deciding when it is appropriate to deviate from a portion of a procedure. Procedures should contain many pre-determined “hold” and “exit points” so that if

	a task in the procedure is ambiguous or unworkable, a clear path for achieving a safe, sustainable state of equipment is provided until a solution for successfully completing the operation is generated. Developing detailed procedures, yet avoiding overly prescriptive procedures, requires careful consideration of the potential consequences associated with deviating from portions of the procedure.
Training/ experience	Train employees to value safety first and feel comfortable questioning, without fear of retribution, a situation they feel may be unsafe. In addition to emphasizing safety, train personnel in how to recognize specific unsafe or aberrant situations and how to respond. Continually enhance training by incorporating lessons learned from previous accidents or incidents.
Communication	To help prevent miscommunication or missed communications, have personnel use standardized hand signals and three-way communication. It is also advised that more than one method of communication be used to ensure messages are received.
Indicators and job aids	Implement positive safety measures and job aids that provide feedback pertinent to the situation, or engineered controls to prevent catastrophic failures or collisions.
Visibility	To avoid or mitigate accidents due to poor visibility, train personnel to accurately detect blind spots, and assign multiple crew members to act as spotters. Use of a crane control pendant can allow the crane operator to move around and have the flexibility to find better vantage points.
Adequately engaging activities	Assign personnel extra tasks to engage them during particularly slow or monotonous work. Personnel should also be trained to scan ongoing tasks (under their responsibility as well as under others' responsibility) to see if they can assist in other areas.
Avoiding time pressure	Similar to training personnel to focus on safety, emphasize the need to avoid rushing work processes to ensure a strong safety culture. Organize work processes so they can be completed efficiently.
Time-of-day and shift-work	The effect of fatigue is a primary concern in working atypical shifts or long hours. Train personnel to recognize the signs of fatigue in themselves and others. Encourage personnel to be aware of other signs indicating an employee may not be fit for duty. If work is required during atypical times of day, take other precautions such as scheduling more breaks and ensuring adequate staffing.
Independent verification	To assist in recognizing defects, train personnel in effective search and detection strategies. Train and warn personnel of the social shirking phenomenon and ways to overcome such tendencies. Strategies might include keeping the identity of the checkers anonymous and spacing the checks over appropriate time spans. To help ensure the proper functioning of equipment, check components well before use and near the time of use.
Quality assurance	To ensure the proper function and operability of equipment and components, inspect them regularly. Thoroughly train personnel performing the inspection on how to detect problems.

Avoid decision-making bias errors	To counteract the negative effect of a bias error which leads the decision maker to the wrong conclusion and an inappropriate decision, train the crew on the types of biasing errors that may exist. Establish an organizational culture in which personnel feel safe in reporting unsafe circumstances or safety concerns. Have a diverse team design procedures and training so that a wide array of options and situations are considered and planned for. Ensure personnel are trained on these situations and mentally guided through appropriate responses.
Team coordination	To help a team work together effectively, team members should have appropriate and suitably similar skills, attitudes, knowledge, and working styles for the particular operations. Experts or suitable trainers should be available to probe for and recognize gaps in these attributes relative to the specific operations to be performed. Ensure that hand-offs between teams have been analyzed for gaps in capabilities. Try to avoid assembling a hybrid team of plant personnel and temporary contract personnel shortly before execution of a CLC.
Task distribution among team members	The proper distribution of tasks will help alleviate the stress felt by over-burdened employees and engage personnel tasked with light and easy tasks. Train employees to scan the situation for ways they can contribute if they are working on an insufficiently engaging or low-stress task. Tasks should also be clearly defined so that each worker knows who is ultimately responsible for completing each task. If a task is particularly stressful or complex, assign multiple employees for redundancy and verification.
Reasonable number of manual operations	An employee can easily feel overwhelmed with a large number of manual tasks needing to be completed. Furthermore, it is easy for one of these operations to be inadvertently skipped or missed. Design tasks such that individuals are not responsible for an overwhelmingly large number of operations. Provide job aids to aid employees' memory while they complete tasks so they do not accidently miss steps or subtasks.
Minimize ergonomic issues	To effectively cope with a stressful environment (e.g., due to high temperatures, slippery surfaces, cramped locations) identify the ergonomic stressors within those environments and eliminate or reduce them where possible. If not possible to eliminate the issue, limit exposure time. The employee working in such conditions may need special training or special equipment.

6.1.2.1 Procedures

In this analysis it has been assumed that spent fuel operations are not necessarily highly proceduralized because they depend primarily on skills-of-the-craft, which are not strictly guided by detailed written procedures. In the HFE scenarios, the assumed lack of adequate procedural guidance was a dominant latent error condition that contributed to cask drops. Therefore, opportunities for improving procedures were readily inferred. Potential procedural improvements may include the following:

- Increase the comprehensiveness of procedures for “skill-of-the-craft” and “off normal” and “emergency” situations. Detailed procedures provide a better reference to refresh skilled personnel on infrequently performed tasks and can be a valuable training resource for less skilled personnel. Detailed procedures for responding to low-likelihood, "off normal" and "emergency conditions"[63] will improve performance if a similar event occurs, and they allow management to emphasize the importance of remembering that these events can actually occur.

Examples

- In procedures, address how to handle a situation in which a cask drops, fission products are released, and personnel are seriously injured (e.g., how to limit contamination of the facility and exposures off site, while simultaneously taking actions to address injuries from snapping slings, cables, or other flying debris).
- Provide clear procedures for the crane operator during an event in which the connection between the cask and lifting yoke becomes tenuous (e.g., a sling begins to break). This may involve releasing hoist tension via a clutch or brake to lower the cask in a damped freefall mode.
- Specify how to stabilize and recover a cask dropped into an SFP due to a two-block event in which significant portions of the crane are damaged.

- Provide additional formal checklists to reduce the likelihood of slips or lapses from omissions of process steps or improper understandings of the state of the system (i.e., facilitate easy reference to documented procedures).

  Example

  - Rigging operations comprise many manual activities, including inspection, installation, operation, performance monitoring, etc. Providing a checklist for these activities helps ensure completeness both for individual activities and for actions requiring verification of another's work (e.g., inspection of lift cleats, slings, lifting pins, various fasteners). While the riggers might not complete the checklists because of ALARA radiation or other time-pressure considerations, nearby personnel could direct a verbal call-and-response process to complete the checklists.

- Specify, in detail, individual roles and responsibilities. In particular, codify dynamic transitions of primary responsibility to avoid omissions in performance monitoring.

  Examples

  - Require continuous visual confirmation of the interface of yoke arms and trunnions during cask movement, and clearly specify individuals who have this responsibility (e.g., based on location or field of view, or by name during a task sequence).
  - Explicitly delineate transfers of primary responsibility (e.g., between the crane operator and spotters) for ensuring a clear travel path for a moving cask. In situations in which a crane operator has slightly degraded but adequate visibility for the activities under his/her direct control, assign primary responsibility for the success or failure of those activities to him/her. In contrast, there may be portions of a single cask movement activity (e.g., transitioning from horizontal movement of a cask over a transfer pit to vertical descent down into the transfer pit) in which adequate visibility of the cask travel path transitions abruptly from the crane operator to a nearby spotter. In such a situation, it may become appropriate for the spotter to assume primary responsibility for the activity under direct control of

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[63] It may be impractical to generate detailed procedures for all conceivable off-normal and emergency situations, but it is beneficial to generate detailed procedures for a subset of particularly challenging scenarios to provide valuable reference scenarios from which personnel could adapt as needed.

the crane operator. If a crane operator understands that the spotter is now primarily responsible for the success or failure of the activity, he/she may be more diligent in closely and continuously monitoring communications from the spotter, such that if a problem occurs, cask movement will have been under the control of the spotter to the extent possible.[64]

- Provide sufficient redundancy in controlling power to the crane hoist so that if engineered safety interlocks or personnel fail to perform their desired functions, the last line of defense will be removal of power to the crane by means highly independent from those used for normal crane control operations (e.g., a person near a circuit breaker at the point where electrical power enters the reactor or fuel building).

- Provide additional communication confirmation requirements to ensure that the information received is the information transmitted.

  Example
  - Require three-part communications between crane operators and designated spotters when initiating cask movements. Conversely, to enhance safety, require the crane operator to stop cask movement if any personnel indicate a problem (i.e., require an immediate action upon sign of trouble).

- Provide specific, measurable criteria to reduce variability in interpretation.

  Examples
  - Ensure that procedures state specific heights at which a cask should be raised before horizontal movement rather than general statements such as “raise the cask the minimum level necessary to clear potential obstructions.”
  - Ensure that procedures state the maximum height[65] at which a cask can be raised to minimize the potential for a two-block event.
  - Instead of providing general procedural guidance such as “Translate cask until clear of potential obstructions along the vertical travel path of the cask,” provide specific clearance requirements such as “Cask centerline must be moved to within 30.5 centimeters (1 foot) of the transfer pit opening centerline as determined using the alignment guide.”

- Develop and maintain a “work-to-procedure” culture in which, if documented procedures deviate significantly from action that appears to be needed at the time DCSOs are being performed, all equipment is placed in a safe position and work is stopped until the procedures can be corrected. Of course, a careful balance is necessary to avoid overly prescriptive procedures or a “work-to-procedure” culture that does not allow personnel to respond appropriately to an abnormal situation. Write the procedures so that personnel are given many cues for determining whether the procedure matches the situation they are encountering and for deciding when it is appropriate to deviate from a portion of a procedure. Procedures should include many pre-determined “hold” and “exit points” so that if a task is ambiguous or unworkable, a clear path for achieving a safe, sustainable

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[64] Obviously the spotter is not directly controlling movement of the cask by manipulating the controls in the crane cab; however, because the spotter has explicit, primary responsibility for the success or failure of the activity, the crane operator in the crane cab diligently translates the spotter’s commands into action.

[65] It is recognized that safe vertical positions for casks during movement may be variable depending upon the various tradeoffs involved (e.g., clearance of obstacles, maximizing time to respond to equipment failures). The examples provided simply illustrate specific, measurable criteria.

state of equipment is provided until a solution for successfully completing the operation is generated. Developing detailed procedures yet avoiding overly prescriptive procedures requires sophistication and careful consideration of the potential consequences associated with deviating from portions of the procedure. This improvement in procedures and working culture may also reduce instances in which limited reliance on procedures leads to UAs and HFEs.

6.1.2.2 Training and Experience

Typically, a need for improvements in procedures signals a concurrent need for improvement in training and experience. A lack of specific training and experience was prominent in many of the HFE scenarios presented in Section 5. Potential improvements based on the scenarios include the following:

- Train personnel to maintain safety as the highest priority among the various competing priorities in DCSOs. Although it is important to perform operations efficiently, this should not supersede safety. The goal should be to create a safety-conscious work environment in which an employee feels comfortable questioning a situation and acting on that feeling without fear of retribution for potentially pausing work activities to investigate an anomaly.

  Example
  - The safety culture of the plant should focus on safely performing operations instead of implicitly rewarding the successful use of informal rules and workarounds. Employees should be made aware of the potential dangers in ignoring what may initially appear as insignificant procedural steps. All personnel involved with DCSOs should be able to suspend operations if they believe a serious degradation in safety has occurred or is imminent.[66]

- Train workers to monitor contextual cues and recognize aberrant situations.

  Examples
  - Cover all areas of cask movement, including horizontal and vertical lifting and travel paths, in training so that crane operators or spotters can recognize when a cask is in proper position and free from impact danger or being lifted too high. As a safety precaution, use both a load-height indicator and a spotter to verify location and visually confirm placement and location of the cask.
  - Train spotters to recognize imbalanced loads when sling attachments are used. To underscore the importance, in training, emphasize how the imbalanced loading of slings can lead to a cask drop. Training should cover detecting an imbalance in the load and recognizing rigging-component quality issues (e.g., identifying when an edge is sharp enough to cut through a padded sling attachment).

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[66] An analogous example would be that of a U.S. Navy aircraft carrier executing flight operations. Even the lowest ranking sailor on the deck has the authority (and the solemn responsibility) for signaling a hazardous condition that could endanger flight operations. More than once a junior sailor has stopped flight operations due to the perception of foreign object debris (FOD) that was never confirmed. A sincere sailor is rewarded for such behavior, not punished. The key questions to ask are, “Would a low-seniority DCSO worker be *praised* or *ridiculed* for calling attention to what he/she truly believed was a safety issue? Even if it involved a false alarm?”

  - Train riggers to recognize signs of excessive tensile loading on slings (e.g., position of stress tabs) and other signs of damage to slings (due to overheating, abrasion, etc.)
  - If hybrid teams (i.e., a mixture of plant and temporary contract personnel) perform tasks, ensure that training appropriately bridges or eliminates any critical gaps in knowledge or experience such that personnel have similar understandings of how to execute critical DCSO procedures.

- Increase training on potential incidents/accidents and incorporate “lessons learned” from previous accidents or incidents.

  Examples
  - Maintain awareness of the types of failures that are possible such as non-failsafe modes for a wireless radio frequency control pendant, which may necessitate an independent, redundant method for removing power to the crane hoist.
  - If an incident or accident occurs, it is crucially important to obtain proper insights about human performance. Instead of playing the “blame game,” carefully discover the factors that led to a UA.

- Prepare workers to recognize fitness-for-duty problems. Encourage workers to speak up if they feel uncomfortable with a situation or unfit for a task. As mentioned previously, the safety culture should make an employee feel comfortable and protected in deciding to voice concerns.

  Examples
  - Train workers to recognize signs of human fatigue (e.g., lack of concentration, lethargy, irritability) in themselves or others. If signs of fatigue are present, personnel should feel comfortable discussing, reporting, and resolving the issue (e.g., seeking rest or relief from a critical task). A healthy safety culture is necessary to maintain appropriate behavior regarding fatigue so that good-faith performance is rewarded, not punished. Consider a situation in which an experienced crane operator volunteers for a double shift to help complete a CLC on schedule; however, midway through the second shift he realizes it is imprudent to continue controlling the crane because he is fatigued. The CLC supervisor suspends operations at the request of the crane operator until rested personnel are available to help complete the cask movements. Closely related is the situation in which a worker is coming down with an illness such as a cold or flu. The safety culture should facilitate identification of fitness-for-duty impairments and reschedule or reassign tasks as appropriate.
  - In hybrid operations, train plant personnel to be friendly advocates of appropriate behavior regarding fitness-for-duty problems. Consider a situation in which a temporary contract rigger displays signs of excessive fatigue following rigging operations in a hot, humid environment. Plant personnel should recognize and assist the contract rigger in taking a rest from physically demanding activities as needed to ensure sufficient safety margins to avoid UAs and HFEs.

- Train and prepare employees to respond to an emergency.

  Example
  - Train personnel to execute proper actions in the event of a serious accident. They should be ready to immediately respond and execute appropriate skills (e.g., seek cover to avoid “sling snapback” injuries or fatalities; provide aid to

injured workers while minimizing the spread of radionuclide contamination). Perform this training regularly and before a CLC. Include non-scheduled drills to ensure that skills have been developed.

6.1.2.3 Communication

The information provided during development of the HFE scenarios in Section 5 suggested that environment and equipment issues can readily impair or degrade communication between team members. A reliable and effective communication system is essential for timely and safe completion of DCSOs. Below are suggestions for improving communications:

- Establish and enforce strict protocols for communication using headsets or hand signals.

  Examples
  - When using headsets, use three-part communications in which the speaker issues the instruction, the respondent repeats the instruction, and the speaker confirms that the respondent correctly repeated the instruction. The identity of the speaker and the respondent should be made clear.
  - If relying on hand signals, institute a standard set of signals that are clear and distinct from each other. Instruct every member of the workforce, including contract personnel, in the use of the hand signals. Instruct key personnel such as crane operators to maintain a constant awareness of the signals from spotters. Use common standard hand signals for crane operation whenever possible because these should be well-understood across hybrid teams.

- Ensure redundant communication during cask movements so that two or more independent methods of communication are available between personnel controlling cask movements (e.g., a crane operator and someone stationed by a circuit breaker controlling power to the crane) and spotters responsible for monitoring and verifying the safe travel path for the cask

6.1.2.4 Indicators and Job Aids

In this analysis, many of the HFE scenarios were developed around problems that occur when indicators and job aids are missing or insufficient. Job aids (e.g., books, cards, software, alarms, control panels, various displays) are repositories for information, processes, or perspectives. Job aids are external to the individual; they support the work and activity to be done; and they direct, guide, and enlighten performance (Rossett and Gautier-Downes 1991). Given the great importance of correct cask travel paths and cask placement, position and movement indicators serve an important purpose. Suggestions for improvement of indicators and job aids include the following:

- Implement positive safety measures that deliver objective, reliable, and valid information about the situation.

Examples

- Install indicators (e.g., position indicators, proximity or collision alarms) that inform the crane operator when the cask has reached or exceeded a safe height and warn if the travel path is obstructed.
- Use a centerline alignment gauge or tool to ensure that the centerline of the cask is sufficiently near the centerline of the transfer pit opening prior to lowering. The use of such a gauge or tool, combined with positive measures to warn of an impending collision of the cask with the floor, provides redundant engineering safety features.
- Use engineered reference tools (e.g., levels) to determine the sling tension and balance of the load hoisted by the slings. Avoid general administrative guidance open to subjective interpretation (e.g., avoid nonspecific instructions such as “do not get too close,” “ensure sufficient clearance,” “ensure equal tension,” and “visually verify that the item is level.”)

- Implement positive safety measures that provide engineered controls.

  Examples

  - Provide safety interlocks that stop crane hoist movement when collision or excessive lift height alarms are activated.
  - Provide safety interlocks that prevent or stop crane hoist movement when electrical anomalies in control circuitry occur.

- Implement job aids to guide task performance.

  Examples

  - Provide placards or other helpful written checklists (e.g., laminated cards) that a rigger can directly refer to or that a nearby team member can use to help guide and verify task performance during rigging activities. Do not require personnel to rely on memory for infrequently performed tasks involving more than three to four steps or subtasks. If personnel performing these infrequent or novel multiple-step tasks have not been thoroughly trained at regular intervals on these specific activities, it is unwise to expect them to complete more than four memorized steps correctly without a job aid (Miller 1956; Doumont 2002).
  - Provide a parts template or shadow box for maintainers to captivate, organize, and account for parts and tooling when performing preventive or repair maintenance on cranes, casks, or rigging equipment.

6.1.2.5 Visibility

In general, vision tends to be the primary means of receiving information about interactions with the environment (Orlady and Orlady, 1999), and this certainly appears to apply to DCSOs. Unfortunately, many DCSO activities and tasks do not afford personnel controlling a cask movement a complete field of view around the cask. Thus, HFE scenarios in Section 5 described situations in which communication between multiple individuals involve hand cues that are unseen or critical positioning elements that are not visible. These situations may be avoided or mitigated as suggested below:

- Train personnel to detect blind spots and recognize proper placement of spotters to ensure complete visual coverage.

Examples

  - Train crane operators to recognize the need to rely on spotters, and aid spotters in determining proper positioning to ensure full visibility of the movement of the cask within the SFP and throughout the travel path in the plant. Providing feedback to spotters through an independent sensor (e.g., measuring stick, optical switch, another person with an accurate view) will help them learn how to identify vantage points of proper positioning.
  - Ensure that crane operators and rigging personnel have effective means for visually communicating information when possible. That is, visually communicated hand signals and radio communications may be used as independent methods of indicating the status of cask lifting equipment.

- Enable the crane operator in direct control of cask movements to move into positions offering the best vantage point for obtaining visual feedback. A crane control pendant and proper dynamic positioning of the crane operator may offer better visibility and significant safety benefits over a crane operator in a more static, distant position in a crane control cab. (Of course, a crane operator using a wireless radio frequency control pendant still needs spotters because of visual challenges related to the large size of the cask; the crane operator cannot see all sides of the cask at one time and needs other personnel to ensure adequate visual coverage.)

6.1.2.6 Adequately Engaging Activities

People are often slow or unprepared to react in an emergency after long periods of passive monitoring (Perrow, 1999). Therefore, it is important for them to be engaged in some relevant DCSO activity during slow periods. Many activities completed during a DCSO are unchallenging and appear to lack the optimal stimulation needed to keep the worker engaged with the work and task at hand. It is assumed that there is ample opportunity for diversion and distraction. Suggestions for improving the engagement of personnel in cask movement tasks include:

- Train personnel to use systematic visual scan patterns and methods for reviewing and verifying that other aspects of the CLC that do not require their full attention are proceeding well.

- Assign personnel additional responsibilities for carrying out tasks or verifying the performance of other tasks.

- Create a culture in which personnel are rewarded for taking initiative by assuming additional responsibilities that level their workload throughout a shift.

6.1.2.7 Avoiding Time Pressure

Although time pressure is not always a concern during DCSOs, it can become a significant factor toward the end of the campaign or when scheduling issues arise. And, although time pressure may not be an overarching issue for many personnel in a CLC, it may be an issue for individual tasks in which workers are prompted to hurry because of the ALARA principle, heat stress, or some other environmental factor. Being pressured to increase the speed of work because of time constraints is a latent error condition that can have far-reaching consequences in UAs and HFEs. Some suggestions for avoiding or mitigating time-pressure issues include the following:

- Establish safety policies, reinforced by a strong safety culture, that emphasize that safety is the most important priority during a CLC.

  Examples

  - Urge personnel to proceed only at a pace they are comfortable with in completing tasks and to not fear retribution for slowing or stopping operations due to safety concerns.
  - Have CLC supervisory personnel be on the lookout for signs of work "speeding up." Increased speed in task execution should be investigated to see whether it is simply due to improvements in skills or if it is driven by the perception of time pressure. Note that time pressure may be related in complex ways to task execution. Consider the case in which a CLC team is beginning to rush through tasks on the seventh of seven cask loads because team members feel they know exactly what they are doing and need not be very meticulous. Now consider that one team member feels excessive pressure to speed up task execution to fit into the group mindset of "hurry up and get this last load finished." In this case, multiple personnel may be working too fast to maintain high levels of safety, and one person may be experiencing high levels of stress driven by the perception of time pressure. It may be reasonably inferred that all of these personnel may be more likely to commit UAs and HFEs.

- Establish good organization skills for task execution so that tasks can be completed quickly, and practice these skills often.

  Examples

  - When working in high-radiation environments, workers need to complete their tasks quickly per the ALARA principle. Organizing work activities to include optimal subtask ordering and optimal tool and equipment movement, handling, and retrieval is essential.
  - When working in high-temperature/high-humidity environments, workers need to complete tasks quickly yet methodically to avoid HFEs due to heat stress or slipping on perspiration-soaked items.
  - In situations where environmental factors (e.g., radiation, heat) can induce time pressure, design tasks so that multiple personnel are responsible for suitably small portions of the operation involving the environmental factors. For instance, have one rigger who places and arranges tools and equipment, another rigger who relieves the first rigger and executes a rigging task, followed by a third rigger who relieves the second rigger and gathers up the tools and equipment.

6.1.2.8 Time of Day and Shift Work

Fatigue is one of the primary concerns when personnel work excessive or odd hours or shifts. People are at a greater risk of committing errors when fatigued. Other issues such as rushing may also occur toward the end of the work period or when personnel are working unusual hours. The following are suggestions for avoiding or appropriately dealing with these situations:

- Enable employees to abide by working rules.

Examples

- Ensure properly trained and qualified personnel are available during working periods and within working-hour guidelines (e.g., mandatory rest periods between work periods).
- Instruct personnel in how to verify fitness for duty prior to the performance of critical activities.
- Do not institute payment systems that create a culture in which personnel work nonessential overtime or double shifts simply for financial rewards. This contributes to chronic fatigue among personnel, which simultaneously lowers safety and productivity.

- If CLC operations must be performed during late night or early morning hours, be sure to take adequate precautions.

  Examples

  - Provide extra redundancy in staffing (i.e., have more personnel available to rotate between tasks if needed).
  - If time permits, allow personnel to adapt to night shifts before they must perform operations.
  - Systematically monitor for signs of fatigue during late night and early morning hours.

6.1.2.9 Independent Verification

Human actions contain dependencies when they involve the same operator, the same procedures, or are competing for the same resources in the same time (EPRI 2004). Achieving complete independence between checks of others' work by personnel is a daunting task. As Swain and Guttman noted, "the probabilities of errors for a checker of someone else's work will be much higher than the probabilities of errors for the original performer.[67] This is because the checker usually does not expect[68] to find many errors when he is evaluating someone else's performance—a special case of dependence" (NRC, 1983). Factors leading to incorrect checking or the overestimation of independence between checks results in inadequate verification. The key factors to consider include common-mode failures, social shirking, and overcompensation (Sagan 2004; Brewer 2009). Listed below are methods to help ensure that verification of tasks by multiple personnel occur as independently as practicable:

- Instruct personnel in effective search and detect strategies.

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[67] In cases of skilled performance of tasks, most of the errors that occur will be slips and lapses that are detected by and recovered by the person performing the task.

[68] This may be contrasted with a situation in which a checker does expect to find errors, i.e., a teacher or expert reviewing the work of a student or novice. In this case the expert not only expects errors, but learns over time where such errors tend to be clustered given the experience level of the student. To summarize, when people do not expect to find errors they are not good at detecting them (Brewer, 2009).

Examples

  - Ensure that the checker can effectively and efficiently verify an activity by following a systematic, objective process for searching and detecting abnormalities. Employ engineered reference tools to aid in the verification process where possible (e.g., specific checklist of steps and parts, specific gauges and tooling that provide objective criteria). Have personnel inspect for one type of anomaly or defect at a time instead of expecting them to search for many types of anomalies or defects all at once.
  - Test personnel in their checking performance periodically in a manner that provides accurate, reliable feedback about their performance. Without accurate feedback, verification skills will not be learned properly.[69]

- Provide an appropriate delay in time between the original task performance and verification.

  Examples

  - In a task that may be a source of a latent error condition (e.g., inspection, test, and maintenance of crane or cask equipment) have independent verification personnel perform their inspection after the original team has left the area. This will avoid dependencies related to the presence of the original performers of the task.
  - When it is necessary for the person who originally performed the task to check his/her own work (which is not generally recommended), allow for a time delay between performance of the original task and the checking activity that reduces the opportunity for slips, lapses, and mistakes. During this time delay, it may be helpful to have the person refer to a checklist or other job aid that reminds them of the attributes of successful task completion. The appropriate delay time will vary (e.g., tens of seconds, a few minutes) based on attributes of the task and personnel and should be determined by subject matter experts.

- Provide anonymity (to the extent practicable) between the personnel performing the original task and those verifying task performance.

  Examples

  - In a task that may be a source of a latent error condition (e.g., inspection, test, and maintenance of crane or cask equipment) have independent verification personnel perform their inspection after the original team has left the area and without knowledge of the specific personnel who performed the original task. Anonymity may reduce dependencies related to perceived experience-level differences between the original performer of a task and those conducting verification.

- To avoid common mode failures, have different teams perform tasks on redundant safety features.

  Example

  - If two overcurrent protection interlocks for a crane hoist need to be installed, repaired, or inspected, have different individuals or teams perform these tasks on each overcurrent protection interlock. This separation will avoid dependencies

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[69] This is reminiscent of the old saying "It is not practice that makes perfect, but that perfect practice makes perfect."

related to task performance by specific personnel. The separate teams may then check the performance of the other teams after they have finished with their original tasks—preferably after an appropriate separation in time.

- Be sure to test safety-critical features prior to use in moving casks.

  Examples
  - Actually test the functionality of a critical safety feature (when possible) instead of inspecting or testing an indirect measure of performance. For instance, even if a sling or other piece of lifting equipment visually appears to conform to specifications, load test it prior to use.
  - If a safety interlock has been installed on a crane hoist, periodically test the functionality of the safety interlock to verify performance; such testing is especially important immediately prior to performing a CLC.

- Promote awareness of the functionality and criticality of safety features and cask-handling systems to those in control of those handling systems.

  Example
  - Consider an overcurrent protection interlock designed to avoid spurious operation of a crane hoist due to transient power surges as well as to cease hoist operation when the hoist motor is struggling to draw excessive current. The interlock designers may have made a design-tradeoff decision that introduces significant variability in performance in conditions involving a two-block event. Crane operators should know about the safety interlock's design so they do not place excessive confidence in it performing its safety function if a load must be raised higher than is typical.

- Provide ample time for all verification activities.

  Example
  - Ensure that personnel tasked with verification responsibilities do not encounter significant time pressure when carrying out their duties. If unreasonable time expectations are set for performing inspections or functional tests (possibly because a task scheduler does not understand the activities to be performed), the likelihood of UAs and HFEs increases greatly. Accessing an area for inspection, test, or maintenance is often the most time-consuming portion of the task; therefore, an independent checker will likely require as much time or more time to complete the activity than the original maintenance team.

- Provide awareness of the social shirking/misplaced trust phenomenon in which individuals or groups reduce their reliability in checking by assuming that others will "take up the slack." Generate case studies directly applicable to the potential for cask drops.

  Examples
  - Ensure that less experienced personnel assigned to verify task performance of more experienced personnel realize that they are probably highly susceptible to the social shirking phenomenon because they may not expect to find any defects or anomalies.
  - Explain that "misplaced trust" does not imply that someone is generally "untrustworthy" if they succumb to this behavior—it highlights a subtle yet unsafe behavior among those who are "trusted." Crew members must always be reminded of the proper orientation of the "trust" relationship. In this case, trust

should imply that personnel can “trust” the supervisor or other team members to carefully review their operations to protect them from missing errors that may lead to a cask drop (Brewer, Amico et al. 2006). An improper orientation of trust (misplaced trust) may grow over time (i.e., over multiple cask loading cycles within a campaign) due to repeated successful performances.

- Provide awareness of the overcompensation phenomenon that results when the addition of extra items or personnel, intended to be redundant, encourage individuals or groups to increase production or engage in riskier behavior. Use case study examples such as those mentioned in Section C.11 that directly apply to the potential for cask drops.

  Examples
  - Watch for signs of increasing throughput of crane or rigging components at an inspection station after providing additional inspectors. Ensure that all inspection personnel are aware of the dangers of common-mode failures and social shirking/misplaced trust; if throughput must be increased, do this gradually and with conservative assumptions about the addition of “redundant inspectors.”
  - Do not assign excessive “redundant checking” responsibilities to a worker or supervisor simply because he/she may be willing to accept that responsibility in hopes of using the “successful inspections” to enhance his/her standing during performance review. Human factors limitations in independent verification cannot be hurdled by excessive motivation on the part of eager, but inadequately trained employees.

- Be particularly vigilant about independent verification performed among hybrid teams. Mixed crews of plant personnel and temporary contractors may be especially vulnerable to having different understandings about the amount of verification needed or relied upon by others. This may degrade or eliminate redundant checks. It is essential to carefully review independent verification processes and behaviors when using hybrid crews.

6.1.2.10 Quality Assurance

The HFE scenarios demonstrated that quality assurance (QA) issues may affect various tasks and activities within DCSOs. Careful verification that all DCSS components and related plant structures, systems, and components (SSCs) conform with requirements is essential during all phases of DCSOs. Particularly important to cask drops are lifting-related items such as cask trunnions, lifting yokes, lift beams and associated components, heavy lift cranes and supporting structures, and rigging equipment (e.g., for lifting multipurpose canisters). Examples of QA processes include inspection or testing of crane supports, lift beam support pins, crane control indicators and interlocks, as well as visual and tactile tests of rigging gear. These QA activities are necessary during procurement,[70] prior to first use,[71] following maintenance, and throughout the operational life cycle of SSCs. During QA it is critical to ensure that design requirements are suitable for particular SSCs and that fielded items meet the specified requirements. The suggestions in Section 6.1.2.9 for independent verification also apply to QA. Additional suggestions include the following:

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[70] Rigorous inspections in the procurement process include QA activities executed throughout the equipment fabrication/manufacturing processes.

[71] For example, visual and tactile tests of the rigging equipment prior to first use *should* provide a redundant verification for the equipment procurement process.

- Regularly test equipment.

  Examples

  - Test and inspect wireless radio frequency controlled pendants under normal and harsh environmental conditions (e.g., test after the mechanical shock of being dropped, potentially down multiple floor levels, to ensure that they are properly functioning or that they fail safe in a predictable and reliable manner).
  - Load test heavy lifting equipment prior to (and close in time with) the beginning of a CLC. This will protect against failure modes due to an unexpected failure mechanism which degrade safety-critical equipment.

- Regularly schedule inspections of SSCs, and maintain accurate records of these inspections.

  Example

  - Before the first load of a CLC, inspect all equipment involved in supporting loaded casks. Be vigilant in continuing to perform thorough inspections prior to each cask load in a CLC, not simply the first load. Due to various decision-making bias errors (such as confirmation bias), personnel assigned with QA duties may be tempted either to neglect those duties (i.e., not perform an inspection) or execute them in a cursory fashion after multiple successful cask loads have been completed.

- Train QA personnel to understand critical aspects of successful visual inspection tasks.

  Examples

  - Train personnel to recognize the two groups of challenges for DCSO-related items: (1) small objects and (2) large objects. Relatively small objects (e.g., lift cleats, crane control pendants, trunnions, various fasteners) are items that one person can easily view and manipulate in a designated workspace; they may include job aids and references to specifications. Small objects may be relatively easy to inspect or they may be challenging, possibly requiring use of magnifying glasses, microscopes, or complicated tools. Large objects (e.g., large crane equipment, casks) require inspectors to maneuver on, around, or through them, or manipulate them with heavy equipment multiple times to complete a thorough inspection. Inspecting large objects involves accessibility factors (e.g., the difficulty of inspecting structural supports for a crane) and inspector-specific factors such as mobility (general fitness, flexibility, balance) and visual abilities.
  - Train personnel to use systematic, objective approaches for searching for defects and for deciding when something is a defect that must be addressed (i.e., defect severity). Factors that strongly influence both searching and deciding include instructions, procedures, training, experience, and the culture of the organization in which inspections are performed. Ensure that inspection performance is tested periodically, using objective feedback to minimize variability of performance within and between inspectors. Too often QA personnel are given inadequate feedback to enable them to develop effective inspection skills (e.g., see the description of aircraft inspectors provided in Section C.12).
  - Have QA personnel always use valid, reliable, and objective (as opposed to subjective) references for identifying defects whenever possible.

  - Look for one type of defect or anomaly at a time using a systematic search process instead of having inspectors look for many defect types all at once (e.g., cracks, gouges, burrs, corrosion, tool marks)
  - Provide adequate time to complete inspections, and implement work-rest schedules to maintain inspectors' vigilance over the course of extended QA activities.
  - For summary information and entry points into the extensive literature on visual inspection/signal detection, see Kantowitz and Sorkin (1983), Salvendy (1997), and Wickens and Hollands (2000).

- Train QA personnel to understand the potential consequences of missing a defect.

  Example
  - Inspectors may become less diligent in searching for, detecting, and resolving defects or nonconforming conditions if they do not understand or believe in the potential consequences of damage or failure associated with that defect. A culture that emphasizes that "any defect is a critical defect" (e.g., cosmetic defects are equated with structural defects) may ultimately have the undesired effect of diluting the perception of criticality of all defects.

6.1.2.11 Avoid Decision-Making Bias Errors

There are many biases that may interfere with decision making. The definition of "bias" encompasses a systematic tendency or heuristic that limits a comprehensive application of available knowledge, experience, and related data to decisions or actions (Brewer 2009). Biases, tendencies, or heuristics of human decision making are not inherently bad; they are mental shortcuts people take in recognizing a situation, which normally allow them to quickly select the most plausible choices first, followed by the less plausible choices (Tversky and Kahneman 1974). However, biases or heuristics that tend to work in specific, often "simple," information settings sometimes lead to severe and systematic errors in other settings (e.g., more complex settings) such that they hinder proper interpretation of available information and lead to inappropriate perceptions, decisions, and actions (Tversky and Kahneman 1974; Brewer 2005). A bias error occurs when a systematic tendency or heuristic leads to inappropriate decisions or actions in specific scenarios. While there are dozens[72] of well-researched biases, three decision-making biases are especially prevalent in cask drop scenarios: confirmation bias, loss-aversion bias, and bias due to overconfidence.[73] Techniques that may be used to avoid these biases or lessen their influence include the following:

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[72] The topic of biases is complex and includes many phenomena, for example, the bias process of *overestimation of independence between redundant-type events*, which includes *common mode failures, social shirking, and overcompensation* (Brewer 2008) formed the basis for the Inadequate Verification human performance vulnerability discussed in Appendix C, Section C.11. Another common bias is the anchoring effect, i.e., people are "anchored" to the first option or value they see or the first judgment they make; if you show people a random number between 1 and 100 and then ask them the number of countries on the African continent, their guess will be fewer countries if the random number was small and more countries if the number was large (Tversky and Kahneman 1974).

[73] The overconfidence bias is a wider categorization of various individual specific biases which includes several well-studied bias processes (Hora 2007; Meller and Locke 2007; Brewer 2008).

- Teach crews about the existence and characteristics of cognitive biases that may interfere with decision making (refer to Section 5.1.1 for additional details about confirmation bias, loss aversion, and overconfidence).

  Examples

  - After describing the characteristics of the three cognitive biases, encourage personnel to reflect on and describe instances in which they have committed those bias errors in many different contexts (e.g., during work activities, when driving, performing hobbies).
  - If possible, strengthen performance feedback cues throughout the CLC. For example, after one or two successful cask loads, have additional personnel or additional sensory information available to critical personnel (e.g., crane operators, riggers, spotters) to avoid rote repetition of tasks without adequate processing of new information. Note: This strategy requires sophistication and care to not disrupt the proper functioning of a well-practiced team that is aware of and consciously struggling to avoid bias errors.

- Foster a “reporting” and “learning” culture as described in Section 6.1.3.

  Example

  - Ensure that there is tolerance for a level of “false positives” in which personnel raise safety concerns (possibly halting operations) about a perceived safety problem. This culture will help ensure that if one or more people do avoid the effects of confirmation bias, loss aversion, or overconfidence and detect a safety issue, they will report it in time to avoid an HFE and not be reticent for fear of “crying wolf” when no danger is present. This is related to believing “there are no dumb questions” when it comes to maintaining safety.

- Encourage use of the “premortem strategy” (Klein 1998), also known as the “time portal to failure technique” (Brewer 2005). Ask personnel to imagine that while they are performing a particular cask movement task, something goes wrong and the cask is hung up or dropped. This provides a vantage point from which they can aggressively search for flaws in their plan of action, and it helps remind them that cask drops can happen and that the safety of cask movement operations are the top priority of management when conducting DCSOs.

  Examples

  - During training for horizontal cask movement above the refueling-level floor and over the edge of the floor, then down to the decontamination/preparation area on a lower level, have the crane operator and other personnel imagine that the cask unexpectedly lowers while the cask bottom is above the edge of the refueling-level floor (i.e., recall the conditions of HFE group 4, scenario 4 in Section 5.7.3.4) and the cask drops to the bottom of the decontamination/preparation area. Force the personnel to imagine conditions under which this cask drop may occur and then transform the relevant imagined conditions into safety precautions. For instance, require that the cask be moved horizontally over the edge of a floor surface so that the central radial axis is perpendicular to the direction of travel. This alignment will reduce or eliminate the possibility of binding the crane yoke or lift beam against the cask and trunnion if unexpected lowering occurs.
  - Before conducting rigging operations, have the rigging team imagine that a sling fails and a cask drops. Have the team describe their hypothetical scenario in as

much detail as possible. Review the imagined scenarios for insights into improving safety precautions and emergency response procedures.

- Implement "mental crutches" (Reason 1990) into tasks that demand high memory loads or if there is a concern about decision bias errors. These are essentially job aids tailored to helping a decision maker avoid bias errors.[74]

  Example

  - In the middle of a CLC (e.g., before the fourth of seven cask loads in a CLC), during the pre-job briefing, have the crane operator and designated spotters review and discuss the procedures and the fact that susceptibility to confirmation bias and overconfidence are likely to increase later in the CLC. Then have personnel refer to a checklist that reiterates the key procedures and potential for bias errors immediately prior to carrying out critical rigging operations or cask movements.

- When developing or improving processes and procedures involving a potential for HFEs, assemble a diverse team of experts and have independent reviewers perform multiple reviews of those processes and procedures.

  Example

  - Bias errors by one or more people can be injected into processes and procedures. It may then become necessary for someone not involved in developing the original procedure to carefully review and identify the negative effects of the error. Also, to avoid the emergence of "groupthink" that degrades safety, it is beneficial for a mix of knowledgeable personnel to be involved in developing and reviewing procedures at different times during the development and review cycles. While this is often a resource-intensive process, the diversity of perspectives and scrutiny increases the probability that negative impacts of bias errors will be avoided or compensated.

6.1.2.12 Team Coordination

The teams completing DCSO activities may vary considerably in skills, attitudes, knowledge, working styles, working culture, and other individual characteristics. While team member variability is beneficial in many situations, it can also mask differences in the understanding of abilities, and assumptions guiding others' performance, resulting in inadequate task performance in particular situations. The variability within hybrid teams composed of plant personnel and contract workers can be particularly significant and may introduce unique problems, some of which were detailed in the HFE scenarios. Suggestions for avoiding or mitigating these problems include the following:

- In general, ensure that team members have had adequate and suitably similar skills, attitudes, knowledge, and working styles relative to each of the operations and tasks to be performed. This will require suitable trainers or experts who can anticipate potential gaps in knowledge, skills, attitudes, etc., and provide tailored feedback to the diverse team members so they internalize the desired information and behaviors before they

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[74] Reason (1990) points out that including such aids may open the door to other faults occurring. In the same vein that a worker may become over reliant on a decision-making heuristic, he/she may become overly dependent on these memory aids to the exclusion of proper problem-solving ideas.

conduct loaded cask movements. A key challenge will be in having sufficiently detailed operation descriptions and procedures to reduce variability introduced by different interpretations of skill-of-the-craft activities. Another key challenge may be in correctly identifying the “slow and methodical” personnel and “faster” personnel to facilitate a consistent, task-appropriate pace across all teams.

- Train the teams in the proper independent verification behaviors to ensure redundancy for safety functions.
- Train team members to be vigilant for decision-making biases that could significantly degrade safety-related performance.
- Train senior personnel to encourage junior personnel to immediately report conditions that appear unsafe, without fear of punishment or ridicule even if proven wrong, to establish and maintain a strong culture of safety-focused trust.
- Ensure that all team members, regardless of experience levels, are aware of the phenomena of slips, lapses, mistakes, and circumventions, and that they understand that inadequate team coordination increases the likelihood that these phenomena will result in UAs.

6.1.2.13 Task Distribution Among Team Members

The stress level and workload experienced by the employee affects the timely completion of quality work. Furthermore, work may suffer when no single person is assigned the responsibility for ensuring it is done correctly. Methods for improvement became apparent during construction of the HFE scenarios developed in the previous section. Suggestions include:

- Define tasks and duties so crew members understand who is responsible for what actions. The clear definition of duties helps avoid shirking of responsibilities or over-reliance on others to complete tasks and observe activities.
- Assign team members who are in between tasks to assist in monitoring cask movement. This will improve independent verification and may reduce boredom or distraction during periods of waiting between tasks.
- Avoid having any individual perform particularly boring, monotonous jobs, and provide some minimum level of complexity so that all personnel are either directly performing or actively monitoring cask movement operations.
- Avoid having any individual perform overly complex or challenging jobs. Divide complex tasks among multiple personnel who can provide redundancy and support to complete tasks safely. While regularly assigning complex tasks to a “star performer” may succeed in most cases, if an additional source of stress emerges, that person may commit more slips, lapses, or mistakes that result in latent or active UAs. If significant sources of stress emerge, the star performer may rapidly be pushed over the “stress cliff” (described in detail in Section B.4.3) resulting in an HFE.
- Ensure constant communication between the crane operator and spotters using at least two redundant methods of communication.

6.1.2.14 Reasonable Number of Manual Operations

Some of the activities completed during DCSOs require many manual operations. As the number of manual operations increases, personnel must practice a high level of vigilance in completing each task to avoid an increase in UAs. In addition, various equipment and numerous tools are often necessary. Personnel must observe the condition of the tools and equipment and ensure they are functioning properly. Suggestions for effectively dealing with issues that arise when numerous tasks must be completed include the following:

- Redesign the cask-handling portions of the CLC to reduce the number of manual operations involved, thus reducing the opportunity for UAs and HFEs.
- “Simplify the structure of tasks so as to minimize the load upon vulnerable cognitive processes such as working memory, planning or problem solving” (Reason 1990, p. 236). For example, assign additional personnel to tasks such as rigging or QA inspections that may have previously been performed by one person.
- Provide job aids and indicators to reduce memory loads; reduce the likelihood of slips, lapses, and mistakes; and improve the probability of a rapid recovery from UAs if they occur.

6.1.2.15 Minimize Ergonomic Issues

DCSO environments can be uncomfortable to work in. The HFE scenarios in Section 5 described issues that arise from noise, high temperatures, wet and slippery surfaces, cramped work areas, and areas of relatively high radiation. Suggestions for effectively coping with these work environments include the following:

- Reduce the magnitude of ergonomic stressors where possible. For example, redesign equipment or tooling to reduce or eliminate awkward postures or force requirements during tasks.
- Limit duration of exposure to ergonomic stressors such as hot, humid conditions or high-radiation environments. This may mean having additional personnel perform tasks and frequently handing off responsibility, or having the same personnel take more frequent breaks between subtasks or tasks.
- Provide and enforce the use of personal protective equipment (e.g., hearing protection, appropriate work clothing) when engineering efforts to eliminate ergonomic stressors are not possible or practical.
- If necessary, provide special training or use special selection approaches for personnel who must complete tasks in the presence of significant ergonomic stressors.

6.1.3 Safety Culture

As described in Appendix B, organizations are constantly trying to ensure their long-term success by balancing the often competing priorities of safety and productivity. The nuclear power industry is a high-consequence domain in which safety must be assured to high levels. Therefore, it is important to maintain a strong emphasis on safety to reduce the occurrence of HFEs.

The distinction and importance placed on profitable gains and acceptable safety losses is inherent in an organization’s culture. To promote the safe operation of nuclear power plants

(NPPs), the NRC has urged licensees to improve the safety culture within their organizations by focusing on the nine factors of safety culture listed below (Final Safety Culture Policy Statment, p. 34777-34778):

1. **Leadership Safety Values and Actions** – Leaders demonstrate a commitment to safety in their decisions and behaviors;
2. **Problem Identification and Resolution** – Issues potentially impacting safety are promptly identified, fully evaluated, and promptly addressed and corrected commensurate with their significance;
3. **Personal Accountability** – All individuals take personal responsibility for safety;
4. **Work Processes** – The process of planning and controlling work activities is implemented so that safety is maintained;
5. **Continuous Learning** – Opportunities to learn about ways to ensure safety are sought out and implemented;
6. **Environment for Raising Concerns** – A safety conscious work environment is maintained where personnel feel free to raise safety concerns without fear of retaliation, intimidation, harassment, or discrimination;
7. **Effective Safety Communication** – Communications maintain a focus on safety;
8. **Respectful Work Environment** – Trust and respect permeate the organization; and
9. **Questioning Attitude** – Individuals avoid complacency and continuously challenge existing conditions and activities in order to identify discrepancies that might result in error or inappropriate actions.

These elements may be viewed within Reason's (1997) wider view of four key cultures that lay the groundwork for an effective safety culture.

- Reporting culture
- Just culture
- Flexible culture
- Learning culture

These all interact to foster an informed culture that translates into a safety culture. This environment exists when those who operate and manage the system know the system (including the human, technical, organizational, and environmental factors) and use that knowledge to improve the safety of the system.

A reporting culture exists when personnel are comfortable reporting their errors and near-misses. However, this should not be accompanied by a lax attitude toward error commission. A reporting culture must be mediated with a just culture that makes it clear what constitutes acceptable and unacceptable behavior. Personnel are encouraged to report their errors as well as any safety-relevant information; however, unacceptable behavior (e.g., malicious or negligent behavior) detrimental to safe operations is not tolerated. The key to helping personnel become comfortable with reporting errors and near-misses is to demonstrate tolerance for unintended mistakes. It is not reasonable to expect personnel to report errors in an environment stifled by fear of retribution. A balance must be reached in which personnel are comfortable reporting errors, with knowledge of what exceeds the limits of tolerance. It is unreasonable to punish every error to the same extent, regardless of the intention or consequences. It is equally unreasonable for all actions to be immune from any sanction. Only within a culture that encourages and carries out the reporting of errors can an organization form a complete picture of how the current operational and safety systems are working.

Within the purview of the NRC, the reporting and just cultures described by Reason (1997) ensure an environment that supports the raising of safety concerns. Furthermore, such cultures promote processes that prevent, detect, and mitigate perceptions that people will be retaliated against for raising safety concerns. Within a just culture, accountability for nuclear safety is outlined; lines of authority are established and roles of responsibility defined. A further step is to establish a corrective action program that identifies, evaluates, and acts on issues that affect safety.

In a flexible culture, the reigns of control may transfer from a hierarchical structure during normal operations to a less hierarchical, professional structure during periods of heightened stress or need in which technical experts make the decisions. This flexibility ensures the organization is prepared and can adapt during emergencies. Achieving a robust culture of flexibility depends on nurturing respect throughout the organization for the experience, skills, and knowledge of the workforce. However, even with great knowledge of the system and flexibility embedded in the operations, an organization may not be prepared for everything. “The people in these [high-reliability] organizations know almost everything technical about what they are doing—and fear being lulled into supposing that they have prepared for any contingency. Yet even a minute failure of intelligence, a bit of uncertainty, can trigger disaster” (LaPorte and Consolini 1991, p. 29). Avoiding such disasters becomes a juggling act of being proactive and flexible so that ineffective standard operating procedures are identified and modified, personnel are monitored, and error avoidance is practiced without personnel feeling stifled or distrusted. To help make a flexible culture successful, an effective learning culture should be in place. A successful learning culture examines the effectiveness of the safety information system and *acts* to improve on it. Demonstrating the willingness and ability to implement reforms when needed can be a difficult task.

The combination of these traits and elements as laid out by Reason (1997) and the NRC foster an environment in which an effective safety culture can emerge. Ensuring the continuous success of such a culture requires that policies and training reinforce safety as a priority. A systematic process should be established to evaluate these policies and the associated training for effectiveness and feasibility and make changes when appropriate. Furthermore, as modifications are made, the changes must be clearly communicated to all those affected.

As noted earlier, the authors of this report did not directly observe DCSOs or directly interact with personnel who perform these activities at a plant site; thus, they did not have first-hand experience with the safety culture surrounding a CLC. However, EPRI’s PRA analysis of bolted storage casks provided insights into a positive safety culture. The PRA report included a list of observations (quoted in the bullets below) made during several site visits; the observed qualities appear to aid human performance (EPRI 2004, p. C-8 & D-32, 33) and offer measurable means for reducing the likelihood of UAs:

- Commitment
    - Allocation of significant resources for spent fuel cask loading (crew size with diverse skills, specialized tools and a low-pressure environment).
    - Attention to safety and related issues such as human performance by holding a campaign briefing and stressing concern about complacency after successful cask loadings.

  - High team coordination and cooperation.

- Awareness

  - Constant procedure updating to improve on coordination and timing of each step in the process (e.g., laser beam location, water lancing to speed up vacuum drying, and development of a pre-built scaffolding system).

- Preparedness

  - Procedures are based on Nuclear Energy Institute (NEI) guidelines [such that] the specific cask design, experience of others, dry runs, and actual runs identified and dealt with numerous potential threats to performance during spent fuel loading and transport by including contingency plans in the procedures.
  - The team also maintained all fixtures, couplings, and rigging for a CLC in a portable shed that can be moved off the refueling floor to the other unit.
  - The engineering interface provided alternate fuel elements in case of a problem with the original set.
  - Each equipment element of the process was laid out carefully with an alignment set for easy pick up and movement.

- Flexibility

  - During our observations, the team demonstrated the ability to respond to three unplanned cases (repair to the transporter prior to the 15th cask loading, a potential breach of the secondary containment via a heating ventilation and air conditioning (HVAC) leak identified by the operational staff causing a delay of several hours, and small drops of oil below the crane were investigated and found to be due to some frothing in the open oil bath system). The team was able to restore the schedule after each case.

- Fairness

  - All team members were encouraged to identify problems and discuss them at daily briefings. Any operational errors were quickly corrected and cleaned up by the team, and became opportunities for improvement.
  - The temperature and time on the job was monitored to avoid heat stress for each individual.

- Learning

  - The team was clearly looking for ways to improve their performance on this spent fuel cask design and continually updated the procedures.
  - In practice, they completed the entire cycle during a five-day period using a single shift (including cask inspection, loading, dry-out, and transport to the pad). The time spent was far lower than the cask manufacturer expected for this spent fuel loading and transport operation.
  - The crew learned the importance of decontamination while the cask was wet, which saved hours of decontamination time in the preparation area.

- Adherence

    - The organization was very cautious about exceeding any limitation even though there was a very large margin for each safety concern.

6.2 Recommended Approach for Generating Additional Insights

To improve insights into avoiding or mitigating HFEs involving cask drops, it would be beneficial to carry out additional qualitative HRA activities. These activities would involve gathering and analyzing plant- and cask-system-specific data and information, which would ideally be gathered from expert interviews; observation of actual CLC activities; detailed review of procedures; detailed review of previous misloading, cask drop incidents, and near misses; and application of a prospective ATHEANA-type HRA that generates realistic scenarios based on the increased information. In conjunction with gathering and analyzing extensive plant-specific information, additional data (e.g., from questionnaires, inspections) on fuel load planning, fuel movement, and cask movement experienced across the population of U.S. NPPs should be acquired. This combination of analyses would provide plant-specific analyses beneficial for NRC regulation tailored to those licensees and generalized insights across the NPP fleet that appropriate SMEs could use to improve the NRC's generalized risk-informed regulatory guidance on spent fuel cask-handling activities.

7 CONCLUSIONS

This report documented an application of qualitative human reliability analysis (HRA) tasks that led to insights into the potential for cask drops during the execution of dry cask storage operations (DCSOs). The report described the analysis approach used during the search for insights, an overview of HRA as applied to DCSOs, an overview of human error, a description of the behavioral science technical basis used in analyzing DCSOs, a decomposition of DCSOs that emphasized human performance contributions, a summary of recent concerns related to handling spent fuel casks, a terminology that clarifies subtle distinctions in human performance and cask handling, a set of detailed cask-handling scenarios showing various types of human performance vulnerabilities contributing to hypothetical cask drops, and specific insights on how the potential for a cask drop due to human actions may be reduced. Although performed without the benefit of the context provided by a plant-specific probabilistic risk assessment (PRA), this report built on previous analyses and interviews with subject matter experts to improve understanding of human performance in DCSOs. The study accomplished three goals: (1) investigated what should be included in a qualitative HRA for spent fuel and cask-handling operations to understand the potential for cask drops, (2) demonstrated that the qualitative analysis tasks in the ATHEANA (A Technique for Human Event Analysis) HRA technique can be usefully applied to these operations, and (3) began building a technical basis for potential improvements to procedures and practices involving spent fuel cask-handling operations.

An innovation in terminology unique to this application of qualitative HRA tasks was the development of *human performance vulnerabilities* to explain why unsafe actions (UAs) occurred in specific, hypothetical scenarios. This terminology refers to a spectrum of performance shaping factors and plant conditions, including the history of latent and active UAs, which generate a context that may ultimately contribute to human failure events (HFEs). The potential vulnerabilities were derived from a review of process descriptions, relevant incidents (e.g., heavy load drops, crane problems, cask component problems, other incidents during spent fuel handling and DCSOs), and interviews with SMEs who have hands-on experience with the processes. In addition to examining the direct “hands-on” cask-handling and movement activities for human performance vulnerabilities, various planning, preparation, equipment configuration, and related quality assurance activities were reviewed to provide insights into what can “set up” personnel for HFEs involving cask drops. Analysis of these types of latent conditions, encouraged and facilitated by the ATHEANA HRA technique, is essential given that hypothesized cask drops typically require the occurrence of multiple equipment failures over a span of time, along with one or more unsafe human actions. An additional motivation for selecting/developing the human performance vulnerabilities was to generate a set of terms that provide human performance distinctions that are readily understood by those who are knowledgeable of DCSOs but who may have limited knowledge of human performance and HRA. That is, one goal was to avoid human factors and HRA jargon by generating and describing terms useful for a broad audience of people interested in improving human performance in DCSOs.

Over the course of the analysis it was discovered that the HOLTEC HI-STORM 100 dry cask storage system (DCSS) presents more opportunities for both latent and active UAs than the TN-40 DCSS, simply due to the greater number of movements required and the increased use of rigging operations associated with the HI-STORM 100 system. Furthermore, use of a bolted lid storage cask, as employed by the TN-40 DCSS, allows the opportunity to at least partially secure the lid to the container housing the spent fuel prior to removing the cask from the spent fuel pool. This feature implies that there may be fewer opportunities, over the time and distance of cask movement, for a drop of the TN-40 cask to result in significant radionuclide releases that pose harm to plant personnel. In addition, the specific differences in geometric features of the casks and yokes/lifting beams for the two DCSSs, based on two video recordings of operations at actual plants, further indicate that the TN-40 provides fewer opportunities for a cask drop. Finally, the overall safety benefits of improving human performance aspects of DCSOs may be greatest when used in a Mark I or II boiling water reactor (BWR) because, as described in Section 3.2, a cask drop in these types of plants could initiate a severe reactor accident.

In summary, this report provided human performance insights on how potential cask drops may occur and, in an illustrative sense, how they may be avoided or how the consequences of unsafe actions may be mitigated. Qualitative HRA tasks were performed in a relatively generic manner—they were not part of a larger PRA and were not plant specific. However, the analysis focused on two specific DCSSs and two general types of nuclear power plants. It is anticipated that it will be necessary for a team of plant-specific experts in DCSOs and human performance to establish which of the recommended techniques, or adaptations of the recommended techniques, may be applicable for improving human performance in the context of a specific plant.

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APPENDIX A. DETAILED DESCRIPTION OF DRY CASK STORAGE OPERATIONS

This appendix provides detailed descriptions of activities performed in DCSOs. The first section describes fuel load planning and activities to prepare cask operations personnel and equipment for a CLC which may be generally applied at any NPP. The second and third sections describe two types of cask systems which are typically used at two different types of plants. The first cask system description focuses on operations at a Mark I BWR using the HI-STORM 100 DCSS. The second cask system description focuses on the TN-40 cask system as may be used at a PWR. The fourth section of this appendix describes activities within the last phase of operation, loaded cask storage and monitoring, which generally apply at any NPP and across different DCSSs. Varying levels of detail found in different sections of the DCSO descriptions reflect the degrees of detail in the information made available to the authors of this report.

A.1 Phase 1 — Fuel Load Planning and Phase 2 — Preparation of Personnel and Equipment

This section describes activities within the first two phases of operation out of the seven phases described earlier in Section 3.5 of this report. These activities may be considered illustrative of those that may be performed at any plant.

A.1.1 Phase 1 — Fuel Load Planning

Prepare the fuel load plan–The configuration control responsibility for preparing fuel movement plans generally resides in the appropriate engineering department (e.g., nuclear fuel engineering) at a plant site. Below are the basic steps involved in generating the movement plan:

- A reactor engineer generates a fuel move sheet
- A second reactor engineer reviews it
- The reactor engineering supervisor approves it
- The approved move sheet is forwarded to the fuel handlers

This process involves engineers reviewing the current distribution of fuel assemblies in the SFP (i.e., location, age, burn-up level, etc.) and projecting forward in time to the age of fuel at the time a CLC is scheduled. It is anticipated that the reactor engineer(s) responsible for generating the fuel move sheet select the oldest fuel bundles in the pool for dry cask storage. Given that there is a distribution of assemblies of different ages (all should be at least 5 years old), the “youngest” assemblies should be positioned near the center of the cask or canister with the “oldest” assemblies toward the outside.[75] Care is required to prevent inadvertent loading of insufficiently decayed fuel or combinations of materials which exceed criticality limits Therefore, the reactor engineer(s) are responsible for determining the appropriate, specific placement pattern for assemblies within the canister. The fuel move sheet includes step-by-step instructions for locating the proper assemblies (i.e., alphanumeric grid locations and fuel

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[75] The arrangement of placing the “youngest” assemblies near the center of the canister is done to provide as much radiation shielding as possible.

assembly serial numbers) and configuring them in a vacant portion of the SFP storage racks in a manner identical to the eventual placement in their intended canister.

It is assumed that the second reactor engineer assigned to review the move sheet thoroughly reviews the fuel loading plan and be watchful for any errors (i.e., fuel bundles that do not meet the proper age, burn-up, or canister location criteria). The reactor engineering supervisor approval is assumed to be a largely perfunctory task in which the supervisor may spot check a few assembly assignments and seek some evidence verifying that the required steps of the fuel move sheet process were followed—at a minimum this consists of a verbal confirmation[76] with the engineers who prepared and reviewed the fuel move sheet. Ideally, the supervisory approval check would include a thorough review of the fuel loading plan.

A.1.2 Phase 2 — Cask Operations Personnel and Equipment Preparation

A.1.2.1 Development and review of cask operations procedures – these items are adapted from various references including NRC Inspection Procedures 60854 (NRC, 2008a) and 60856 (NRC, 2008b).

- Ensure that cranes and rigging equipment are properly designed, built, and maintained such that they operate well within safety margins during DCSOs. This includes carrying out periodic crane inspections and tests to ensure that load measurement equipment (e.g., load cells) accurately reflect loading levels.

- Ensure that analyses have been performed and procedures/provisions are in place to mitigate the effects of a heavy load drop in the SFP, a drop during travel inside plant buildings, a drop during travel to and during emplacement at the ISFSI, and the process for retrieving spent fuel from a loaded DCSS in the ISFSI and returning it to the SFP.

- Ensure that all personnel involved in DCSOs have received proper training and certification commensurate to their planned and potential roles during normal, off-normal, and emergency events.

- Ensure that the reactor facility emergency planning program is revised to incorporate provisions for responding to an emergency condition at the ISFSI.

- Ensure that all procedures limit the placement of flammable and explosive liquids near the loaded cask during movement from the fuel building to the ISFSI pad.

- Ensure that proper material storage and handling practices are developed and followed throughout DCSOs per Standard Program and Process (SPP) procedure 4.3. This includes cask systems components and all supporting equipment both inside the plant, at the ISFSI and along cask travel paths.

- Develop classification criteria for determining whether spent fuel is damaged or intact and incorporate into the relevant DCSO procedures.

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[76] Ideally, the supervisory approval check would be include a thorough review of the fuel loading plan.

- Evaluate reactor programs to verify conformance with the conditions of the cask design (e.g., HOLTEC, TN, NUHOMS, etc.), Certificate of Compliance, Final Safety Analysis Report and requirements of 10 CFR Part 72.

- Evaluate site environmental conditions to determine that flooding and high/low temperature extremes will not present problems for storage of spent fuel at the site.

- Establish a safe load path for moving the loaded canister such that it will not be moved over the SFP or safety critical systems (esp. important given that reactor units are often at power during CLCs).

- Establish a process for retrieving spent fuel from a loaded DCSS in the ISFSI and returning it to the SFP.

- Ensure that provisions are established to maintain adequate cask cooling in the event of an extended load hang-up. These provisions will include thermal and structural considerations due to venting and re-flooding as needed to maintain cooling.

- Incorporate into procedures the correct pressure requirements for helium backfill of the canister after drying.

- Incorporate into procedures the requirement for helium leak testing of the canister lid welds. Ensure that acceptable leak rates for passing the test are consistent with the requirements in the technical specifications. Ensure that personnel assigned to perform leak tests are qualified to the appropriate leak test certification requirements.

    - Ensure that procedures have provisions for monitoring hydrogen during cask lid welding.

    - Ensure that personnel performing welding operations on cask are qualified to Section IX of the American Society of Mechanical Engineers (ASME) Code and are certified as either welders and/or welding operators for the welding process to be used (e.g., tungsten arc welding).

    - Ensure that personnel performing weld examinations are appropriately certified for liquid penetrant exams for both normal temperature weld examinations and high temperature weld examinations.

    - Procure and control weld filler material in accordance with quality assurance program and records management program procedures.

    - Ensure that weld procedures are written and qualified in accordance with the requirements in Section IX of the ASME Code.

- Incorporate proper vacuum drying time limits and acceptance criteria into procedures.

- Ensure that the pressure relief valve set point for the canister is set in accordance with manufacturer specifications

- Conduct an extensive pre-operational test program to prepare for the loading of the first cask.

- Ensure that a quality assurance program that satisfies or exceeds reactor facility Part 50 requirements is used for ISFSI activities. The following elements need to be included in the quality assurance program:

    - Procurement controls
    - Control of measuring and test equipment
    - Operating status
    - Quality assurance audits
    - Tracking of problems
    - Identifying corrective actions

- Ensure that radiological controls are established to support cask activities.

- Ensure that potential effluents from casks (should they materialize) will be properly handled by the structures, systems, and components at the ISFSI and along the travel path to the ISFSI

- Ensure that the records management program incorporates the various requirements for creating and maintaining ISFSI records. In addition to maintaining detailed records regarding the fuel loading of each cask, licensees are to maintain the records provided by the cask supplier for each cask design used, and make provisions for transferring these records if a cask is sold, leased, loaned, or otherwise transferred to another user.

- Implement an ISFSI security program consistent with the reactor facility security program including response to events, offsite support, training and certification of security force personnel, lock and key controls, and search requirements. The appropriate safeguards program and security plan must protect against the design basis threat of radiological sabotage in accordance with the requirements of 10 CFR 73.

- Ensure that a training program is established and maintained for personnel assigned to the ISFSI that provides a strong basis for understanding the requirements and safe practices associated with DCSOs.

- Ensure that roadways over which cask will be transported to the ISFSI meet the required compressive strength limits specified by the cask system manufacturer. Also ensure that the effects of weathering, repeated use, and possible interferences from overhead lines or nearby structures have been considered.

- Assess the potential impact of a breakdown of the transport vehicle transporting the cask on reactor site traffic and security activities.

A.1.2.2 Calibration of inspection and test equipment

Examples of equipment requiring calibration include:

- Torque tools
- Radiation monitors
- Radiation alarms
- Pressure gauges
- Nondestructive examination equipment
- Temperature gauges
- Flow meters
- Gas monitors (e.g., hydrogen)
- Load cells used to measure tension loading on crane cabling
- Crane cable travel (e.g., height) indicators
- Crane trolley position indicators

A.1.2.3 Inspection of crane components and operation

NUREG-0554 (1979), Section 2.4 requires cold-proof testing followed by nondestructive examination (NDE) of welds whose failure could result in the drop of a critical load. This method of verifying material properties requires nondestructive examination of critical areas to be performed at an interval of four years or less. Therefore, inspection of critical welds is to have been performed within four years from the time the crane is to be used for a CLC.[77]

NDE should be completed for all Class 1 areas before and after load testing. Welding plans for seismic upgrading must be thoroughly reviewed to ensure adherence to appropriate engineering analysis. NDE time periods should be established to account for latency periods for cracking and lamellar tearing, and a rerating method for upgraded/uprated cranes needs to be established and followed closely. Also, aging of structures, systems, and components must be recognized and negative effects hedged against via an appropriate management/maintenance recommendation.

A.1.2.4 Inspection of crane support structures

Ensure that crane support structures are thoroughly inspected for cracks or other aberrations that might impair or compromise the ability of the structure to safely distribute compression (stress), tension (strain), and shear loads imparted by the crane systems.

A.1.2.5 Inspection of transport vehicles

- Ensure that transport vehicle systems are operational and enable safe locomotion (e.g., no flammable liquid leaks, functional systems operate correctly)

- Ensure that cask support components are operational and prepared for safe movement of cask (e.g., on crawlers–lift unit boom pins in working order; on flatbeds–truck bed is

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[77] It is important to note that NUREG-0554 guidance is not applied in all situations; that is, some cranes that predate NUREG-0554 have not been held to NUREG-0554 requirements. Ideally, engineering analyses are performed such that acceptable (i.e., NUREG-0554 equivalent) consideration occurs for these grand-fathered cranes; however, as discussed in Section 4 of this report there have been many issues regarding cranes and crane monitoring processes.

free from structural anomalies, tires are inflated properly; all rigging equipment used to couple cask to transporter is in proper working order)

A.1.2.6 Inspection of yokes, hooks, other crane accessories and rigging (e.g., slings, mobile cranes, in-house manufactured rigging/support equipment)

- Ensure formal quality assurance for all yokes, hooks, other crane accessories and rigging
- Perform visual checks and NDE evaluations as required
- Ensure proper training of all personnel responsible for rigging and for verifying performance of rigging duties by others

A.1.2.7 Inspection/test of HVAC system and building atmosphere isolation systems

- Ensure that the reactor, auxiliary, or fuel building atmospheric isolation systems will be operational and in use during DCSOs
- Ensure that the reactor, auxiliary, or fuel building atmospheric filtering systems will be operational and in use during DCSOs
- Ensure that emergency/back-up systems, which are required to start/operate under specified conditions, have been tested and are operational during DCSOs.

A.1.2.8 Staging of equipment

- Be sure that cask system components (e.g., MPC, transfer cask, storage cask, fasteners, plugs, and other equipment) are properly received, initially inspected, and stored at the site in advance of the CLC.
- Attach the cask yoke and other lifting accessories to the high-capacity, gantry crane in either the reactor, auxiliary, or fuel building – depending on the specific plant design
- Prepare and position all additional lifting devices and rigging equipment
- Position the transfer slide[78] (if needed)
- Erect scaffolding to safely support welders, welding, and other lid sealing, NDE equipment, and other operational monitoring equipment
- Pre-position all welding and other lid sealing, NDE, and other operational monitoring equipment
- Ensure safe positioning and handling of all flammable and/or hazardous materials (e.g., weld gas cylinders, cleaning/decontamination materials)

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[78] The transfer slide is a major piece of equipment for the Holtec HI-STORM 100 system that consists of an adjustable-height rolling carriage and a pair of channel tracks. The transfer slide supports the transfer step which is used to position the two lids (i.e., the pool lid and transfer lid) at the same elevation and creates a tight seam between the two lids to eliminate radiation streaming.

- Position the storage cask (e.g., Holtec HI-STORM storage cask) in the proper location for receiving the filled and sealed canister and transfer cask system components

- Install vent duct shield inserts[79] (if needed) on the storage cask

- Install the alignment guide or mating device[80] on top of the storage cask (if needed)

- Move all equipment not needed for the CLC or other simultaneous operations away from staging area and travel paths required by DCSO equipment.

A.2 Holtec HI-STORM 100 DCSS at a Mark I BWR

This section describes activities within phases of operation 3–6[81] and is tailored toward operations followed at a Mark I BWR using the HI-STORM 100 DCSS. Details regarding these operations were obtained from various sources, including: the FSAR for the HI-STORM system (Holtec 2005), a video of selected operations, and interviews with SMEs. This operation description formed a significant portion of the context used in developing the HFE scenarios in Section 5.

A.2.1 Phase 3 — Cask Preparation and Positioning

Prior to beginning DCSOs, ensure the following:

- Personnel have been trained and certified per the approved training program.

- A pre-job briefing has been performed for all affected staff (and shift change briefs are prepared as applicable).

- Oversight and command and control responsibilities have been clearly established, including notification requirements.

- Specific radiological hazards are identified and controls implemented.

- All necessary sensors are properly calibrated, positioned, and operational.

- Impact limiters are placed in the cask decontamination or wash-down pit or prepared for attachment to cask system components if required or recommended by regulations, standards, or other approved operating procedures.

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[79] The vent duct shields, used in the Holtec systems, are designed to prevent radiation streaming from the HI-STORM storage cask as the MPC is lowered past the vent openings from the transfer cask into the storage cask.

[80] The alignment guide and the mating device are two components that are used in two different configurations of the Holtec cask system to facilitate the over-under positioning of the transfer cask and the storage cask prior to lowering the MPC into the storage cask.

[81] Out of the seven phases of DCSOs described in Section 3.5 of this report.

A.2.1.1 Bringing the cask into the building

- Move the MPC and transfer cask into the auxiliary, reactor, or fuel building depending on the specific site configuration via cask component transport device (e.g., flatbed vehicle, rail car, crawler).

- Move transfer cask components into the cask decontamination area or wash-down pit[82] using a large overhead gantry crane.

A.2.1.2 Preparation of the cask system for loading and lid attachment

- Visually inspect the MPC upending frame[83] for gouges, cracks, deformation or other indications of damage. Repair or replace damaged components as necessary.

- At the start of CLC, upend an empty transfer cask.[84]

- Position the Holtec International Transfer Cask (HI-TRAC) under the lifting device.

- If necessary, remove the missile shield from the HI-TRAC transfer frame.

- Engage the lift yoke to the lifting trunnions.

- Apply lifting tension to the lift yoke, and verify proper engagement of the lift yoke.

- Slowly rotate the transfer cask to the vertical position, keeping all rigging as close to vertical as practicable.

- Inspect for general condition of the cask system components and main body lift lugs is performed.

- Wash/clean all cask system components as necessary.

- Perform a thorough quality inspection to verify that the cask system meets the criteria for materials, structural integrity, and monitoring systems as stated in the cask FSAR.

- If necessary, remove the HI-TRAC transfer cask top lid by removing the top lid bolts and using the lift sling.

- Store the top lid and bolts in a site-approved location.

- Inspect all cavity locations within the transfer cask for foreign objects.

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[82] The decontamination area or cask wash-down pit is an area designed for the receipt of various types of transport and storage casks. Decontamination is of major importance when storage casks containing or having contained irradiated fuel are brought into the plant or reused from a previous cask loading operation (e.g., the HI-TRAC transfer cask, which may be reused many times during a single CLC). Decontamination is of lesser importance (i.e., with respect to radionuclides) when previously unused DCSS components are brought into the plant.

[83] An upending frame must be used to upend the MPC from the horizontal to the vertical position because the lifting lugs on the MPC are not designed to support large side loads.

[84] The assumption here is that the transfer cask was transported to the plant in a horizontal orientation. It is possible that the transfer and storage casks could have been transferred in a vertical orientation.

- Perform a radiological survey of the inside of the transfer cask to verify that no residual contamination is present from previous use of the cask.[85]

- If necessary, configure the HI-TRAC transfer cask with the pool lid as follows:

- Inspect the seal on the pool lid for cuts, crack, gaps, and general condition; replace the seal if necessary.

- Remove the bottom lid bolts and store them temporarily.

- Raise the empty HI-TRAC and position it on top of the pool lid.

- Inspect the pool lid bolts for general condition. Replace worn or damaged bolts with new bolts.

- Install the pool lid bolts; be sure to comply with bolt torque requirements.

- If necessary, thread the drain connector pipe to the pool lid.

- Install the MPC onto the upending frame; ensure that banding straps are secure around the MPC shell.

- Inspect the upending frame slings in accordance with the sites' lifting equipment inspection procedures.

- Rig the slings around the bar in a choker configuration to the outside of the cleats.

- Attach the MPC upper end slings of the upending frame to the main overhead lifting device.

- Attach the bottom-end slings to a secondary lifting device (or a chain fall attached to the primary lifting device).

- Raise the MPC in the upending frame.[86]

    - Slowly lift the upper end of the upending frame while lowering the bottom end of the upending frame.

    - When the MPC approaches the vertical orientation, tension on the lower slings may be released.

    - Place the MPC in the vertical orientation.

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[85] It is important to remember that during a CLC a single transfer cask and related components will likely be reused many times because only the MPC and HI-STORM storage casks will be dedicated to each individual fuel load and stored at the ISFSI. Therefore, replacement of seals, bolts, and other cask system components should be expected.

[86] Keep the upending frame corner at the bottom of the MPC close to the ground during the upending process.

  - Disconnect the MPC straps and disconnect the rigging.

- Install the MPC into the HI-TRAC transfer cask.

  - Install the four point lift sling to the lift lugs inside the MPC.

  - Raise and place the MPC inside the HI-TRAC.

  - Rotate the MPC so that the alignment marks punched into the top edges of both the MPC and the transfer cask are properly aligned when the MPC is seated.

  - Disconnect the MPC rigging or the MPC lift rig.

- Install the upper fuel spacers in the MPC lid (if required[87]) as follows:

- Position the MPC lid on supports to allow access to the underside.

- Thread the fuel spacers into the holes provided on the underside of the MPC.

- Install threaded plugs in the MPC lid where and when spacers will not be installed.

- Perform an MPC lid and closure ring fit test (at the user's discretion) as follows:

  - Visually inspect the MPC lid rigging.

- Raise the MPC lid such that the drain line[88] can be installed.

- Install the drain line to the underside of the MPC lid.

- Align the MPC lid and lifting yoke so that the drain line will be positioned in the MPC drain location.

- Install the MPC lid.

- Verify that the MPC lid fit and weld prep are in accordance with design drawings.[89]

- Install, align, and fit-up the closure ring.

- Verify that closure ring fit and weld prep are in accordance with the fabrication drawings or the approved design drawings.

- The fit test is now complete; remove the closure ring, vent and drain port cover plates and the MPC lid; disconnect the drain line; store these components in a site-approved storage location.

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[87] Depending upon the specific fuel-type to be stored, fuel spacers may or may not be required.

[88] The drain line is actually a rigid metal pipe, threaded at the end which engages the MPC lid.

[89] The MPC shell is relatively flexible compared to the MPC lid and may create areas of local contact that impede lid insertion into the shell. Grinding of the MPC lid below the minimum diameter on the drawing is permitted to alleviate interference with the MPC shell in areas of localized contact.

- Install lower fuel spacers in the MPC (if necessary) by manually setting the lower fuel spacers into the MPC cells.

- Load any neutron poisons and other internals properly into the cask/canister.

- Fill the annulus[90] with plant demineralized water, and fill the MPC with either SFP water or plant demineralized water (borated as required).

- Install an inflatable seal in the upper end of the annulus between the MPC and the transfer cask to prevent SFP water from contaminating the exterior surface of the MPC. The following steps are used for installing the inflatable seal:[91]

- When filling the annulus with water, stop filling just below the inflatable seal seating surface.

- Manually insert the inflatable annulus seal around the MPC.

- Ensure that the seal is uniformly positioned in the annulus area.

- Inflate the seal.

- Visually inspect the seal to ensure that it is properly seated in the annulus. Deflate, adjust, and inflate the seal as necessary. Replace seal if needed.

- Install the transfer cask top lid bolt plugs and/or apply waterproof tape over any empty bolt holes.[92]

- Fill the MPC with either demineralized water or SFP water to approximately 30.5 centimeters (12 inches) below the top of the MPC shell.[93]

- If necessary due to plant capacity limitations, drain the water from the neutron shield jacket.

- Ensure that any neutron poisons are loaded properly into the cask/canister.

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[90] The annulus is defined as the space between the outer wall of the MPC and the inner wall of the transfer cask.

[91] Do not use sharp tools or instruments to install the inflatable seal; putting some air into the seal aids in the installation process.

[92] Inserting bolt hole plugs or waterproof tape over empty bolt holes reduces the time required for decontamination.

[93] Keeping the water level below the top of the MPC prevents splashing during handling.

A.2.1.3 Dry runs of cask movement

Perform dry runs of cask movement operations according to the plant procedures to ensure that all equipment and personnel are ready for fuel handling to proceed. (The remaining procedures will continue on as if dry run activities were previously performed.)

A.2.1.4 Movement of cask to the cask loading pit in the SFP

- Ensure that the secondary containment is closed.
- Establish slightly negative pressure within the containment.
- If used, fill the annulus overpressure system (AOS) lines and reservoir with demineralized water and close the reservoir valve. Attach the AOS to the transfer cask.
- Verify SFP for proper boron concentration.
- Engage the lift yoke to the transfer cask lifting trunnions and position the transfer cask over the cask loading area (a.k.a., the cask pit, which is an alcove of the SFP) with the MPC fuel basket aligned to the orientation of the spent fuel racks.
- Wet the surfaces of the transfer cask and lift yoke with plant demineralized water while slowly lowering the transfer cask into the SFP.
- When the top of the transfer cask reaches the elevation of the reservoir, open the AOS reservoir valve. Maintain the reservoir water level at approximately 3/4 full the entire time the cask is in the SFP.
- Place the transfer cask on the floor of the cask pit and disengage the lift yoke. Visually verify that the lift yoke is fully disengaged. Remove the lift yoke from the SFP while spraying the crane cables and yoke with plant demineralized water.
- Observe the annulus for signs of air leakage. If leakage is observed (by the steady flow of bubbles emanating from one or more discrete locations) then immediately remove the transfer cask from the SFP and repair or replace the seal.
- Gates between the SFP and the cask pit, above the level of the fuel, are then removed to allow movement of spent fuel assemblies from the SFP into the MPC seated within the transfer cask.

A.2.2 Phase 4 — Cask Loading

A.2.2.1 Fuel movement from rack storage in the SFP to the cask canister

Fuel movement within the SFP – Fuel handlers carry out the instructions on the fuel move sheet to stage the fuel in the SFP in the same configuration as they are to be loaded into the canister. The fuel handlers perform double verification for each of the moves. The fuel handling personnel may be reactor operators, senior reactor operators, or radiation workers with specific training on refueling machine or spent fuel bridge crane operation. The general process for the fuel staging activity is described below:

- The fuel handling personnel (FHP), in this case two people – fuel handler 1 (FH 1) and fuel handler 2 (FH 2) – crawl out to the basket on the refueling bridge crane (many BWRs) or the spent fuel bridge crane (PWRs and some BWRs) carrying their notebook containing the step-by-step fuel move sheets for the cask loading operation.

- The spotter (i.e., observer/verifier) takes up a position at the pool side with binoculars, a copy of the fuel move sheet, and a clipboard for securing the fuel move sheet pages. His duty is to verify that the correct fuel assemblies are moved to the correct positions in both the staging area in the SFP and then into the cask or canister.

- The FHP tapes up the first few sheets of the fuel move plan above the bridge crane console.

- The FHP tests the primary controls on the bridge crane, which include the following:

  (a) Hoist switch (lift/lower switch), spring loaded
  (b) X-axis spring loaded lever (side-to-side movement of bridge/hoist)
  (c) Y-axis spring loaded lever (front-to-back movement of bridge/hoist)
  (d) Weight scale with digital read out (displays tension due to load on the hoist)
  (e) Knob for grapple (rotate to engage or disengage)

- The FHP executes the fuel movement tasks by conducting the following sub-tasks:

Verify the alphanumeric grid location to move to and the serial number of the fuel assembly to pick up with the spotter before executing the move using three-part communications; an example of the three-part communication process is shown below:

- FH 1: Headed to grid location alpha-32 to pick up #100359, over

- Observer/Spotter: I confirm grid location alpha-32 to pick up #100359, over

- FH 1: Roger, out

Move the bridge crane to the grid location specified on the fuel move sheet (note that FH 2 is responsible for the crane movement, and FH 1 is responsible for radio communications with the spotter).

Lower the hoist to the grapple position.

Verify that the correct grid location and serial number is identified via three-part communications with the spotter. An example of this communication is shown below:

- FH 1: Arrived at grid location alpha-32 to pick-up #100359, over

- Observer/Spotter: Roger, I have a visual on #100359 at grid location alpha-32 for pick-up, over

- FH 1: Roger, out

Grapple the assembly.[94]

Lift the assembly; FH 2 monitors the digital weight scale at the early stage of the lift to ensure that the bundle is being raised[95]; FH 2 holds the hoist switch in the raise position as the fuel assembly slowly raises.

Verify the destination for the suspended assembly via three-part communications with the spotter.

Translate the assembly over to the correct grid location for staging.

Lower the fuel assembly into the designated grid location.

Confirm the destination for the assembly via three-part communications with the spotter.

Mark the move on the move sheet with a pen tethered to the fuel move sheet clipboard.

Repeat sub-tasks (a)–(k) for each of the fuel assemblies to form the designated pattern in the SFP. Steps (a)–(j) take approximately 600–720 seconds (10–12 minutes) if all goes smoothly.

Repeat sub-tasks (a)–(k) to move each of the fuel assemblies into the cask or canister.

Have supervisor, nuclear fuel engineer, or other plant personnel provide an independent, final verification of the fuel assemblies as loaded into the cask or canister before beginning canister lid sealing operations.

A.2.2.2 Placement of canister lid over loaded fuel canister with limited fastening to canister

Place Lid on Cask – The crane operator moves the crane to center the lid over the cask. Maintenance workers attach the drain line (a pipe) to the underside of the MPC lid. Operator aligns drain line with the drain location in the MPC and lowers the lid onto the cask.

A single operator is stationed on the crane. The crane is operated in a manual mode, with visual cues being used to initially lift the lid and move it to a position where the maintenance workers can attach the drain line. Approximately three workers are in the vicinity of the pool, and one of them communicates with the crane operator, either through hand signals or a communications headset. Once the lid is in position, the other two workers screw the drain line into the lid (the line is threaded at one end). The crane operator moves the lid over the pool so that the drain line is above the drain location in the cask where it is intended to slide. He uses a combination of the position indicators on the crane, his own visual observation, and direction from the communication worker. The other workers have no specific assignment during this phase of the operation other than to notify the crane operator if some type of misalignment occurs. The crane operator lowers the lid towards the cask, making corrections in the location to get the alignment correct. Once the drain line enters the proper location, he lowers the lid the rest of the way

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[94] Rotating the grapple knob will result in a light illuminating on the crane control panel indicating that the command to grapple was given, not that the grapple successfully occurred.

[95] SMEs interviewed for this project mentioned that the FHP may need to grab and wiggle the hoist cables after grappling a fuel assembly to “break it free” from the grid location and enable lifting.

down. Weight indication on the crane control panel indicates when the lid has stopped moving. Proper seating of the lid is confirmed through observation by the communication worker.[96]

A.2.2.3 Attachment of yoke to transfer cask

Connect Yoke to Cask Trunnions – Crane operator positions yoke at trunnions and engages the trunnions by closing the yoke arms and slightly lifting the yoke.

Once the lid is positioned, the operator spreads the yoke arms. He then continues to lower the yoke and observe, with the help of the communication worker, when the arms are properly aligned with the trunnions. Height indication on the control panel helps to confirm proper height. Once aligned, the operator closes the arms so that the holes in the arms go over the trunnions. The communication worker confirms that this has occurred. The operator then raises the yoke slightly so that the yoke arm engages the grooves in the trunnions, which is confirmed by the communication worker.

A.2.2.4 Movement of loaded cask out of cask loading pit

Lift Cask from Pit – Crane operator raises crane to lift cask from pit. During the lifting process, maintenance workers decontaminate[97] the cask and crane components to remove contaminated water. Radiation is monitored.

The other maintenance workers now position themselves around the cask pit. They have wash-down sprays, and one holds a radiation monitor. The crane operator raises the yoke to lift the cask from the pit. As the cask nears the water surface, the worker with the radiation monitor checks radiation levels, which is the final confirmation that the lid is properly seated. The operator continues to raise the cask unless he is told to stop because of high radiation. As the cask breaks the surface, the workers spray the surface to remove any contamination from the SFP. This continues until the entire cask is out of the water. Using indicators on the crane, the operator stops lifting the cask at the height specified by procedure.

A.2.2.5 Movement of loaded cask to sealing and testing area

- Move Cask Away from Fuel Pool – Once the cask is at sufficient height (i.e., as low as possible with consideration taken for any obstacles in the travel path, e.g., railings and pipes, and to prevent inadvertent contact with the floor), crane operator moves cask away from the fuel pool, hovering it above the refueling floor. Maintenance workers monitor and wipe down the cask.

  The operator moves the cask to a predefined location adjacent to the pool. The position indicators on the crane establish when the crane is in the correct position. The exact location is not essential, so this indication may be sufficient. The cask remains suspended over the floor while the maintenance workers use “mops” to wipe the excess water from cask surfaces.

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[96] Once the MPC lid is installed, the transfer cask/MPC should be removed from the SFP expeditiously to minimize the rise in MPC water temperature.

[97] Decontamination activities include both spraying components with water (typically de-ionized water) and wiping components.

Initial sealing of bolted casks–immediately after the cask is lifted out of and just away from the pool; operators hand insert and hand tighten four bolts to “initially” secure the lid to the cask.

- Move Cask to Preparation Area – Crane operator moves the cask the rest of the way to the preparation area and lowers it to the ground, lowering the yoke sufficiently to take pressure off the trunnions.

  The operator now moves the cask to the preparation area. The position indicators on the crane help establish when the crane is in the correct position, which is confirmed and corrected (if necessary) by visible observation of the crane operator and the workers using alignment aids marked on the floor. The operator lowers the cask to the ground, stopping when the weight indicator on the control panel indicates that the weight is reduced to only the weight of the yoke.

- Move Yoke Away from Cask – Crane operator disengages the yoke arms from the trunnions by opening the arms. Maintenance workers disconnect the yoke straps from the lid. Crane operator moves the yoke away from the cask.

  The crane operator open the yoke arms from the control panel, verifying visually that the arms are clear of the trunnions. Two maintenance workers go to the top of the cask and release the four clasps that connect the yoke to the lid. They are in a position that should allow them to see that the yoke arms have cleared the trunnions. Once they are clear of the cask, the crane operator moves the crane away from the cask. He moves it to a preselected location using the position indicators on the crane, and confirm visually that the yoke is out of the way for the next phase of work on the cask.

- If previously drained, the neutron shield jacket is filled with plant demineralized water or an ethylene glycol solution (25% ethylene glycol solution, as required).

- The dose rates at the MPC lid are measured and verifed that the combined gamma and neutron dose is below expected values. This dose rate measurement at the MPC lid is very important because higher-than-expected dose rates provide the first opportunity to identify that fuel assemblies not meeting the CoC criteria may have been loaded, especially if the higher dose rate assemblies were loaded near the edges of the canister (i.e., furthest from the center of the canister and closest to the dose rate measurement equipment).

- The crane is used to complete the positioning of scaffolding around the transfer cask in the preparation area.

A.2.2.6 Preparations for welding lid onto cask

- Decontaminate the area around the transfer cask top flange and install the temporary shield ring.[98]

- Clean the vent and drain ports to remove any dirt. Install the removable valve operating assemblies (RVOAs).[99]

- Attach the water pump to the drain port and lower the water level to keep moisture away from the weld region.[100]

- Disconnect the water pump.

- Carefully decontaminate the MPC lid top surface and the shell area above the inflatable seal.

- Deflate and remove the inflatable annulus seal.

- Survey the MPC lid top surfaces and the accessible areas of the top 7.6 centimeters (3 inches) of the MPC.

- Install the annulus shield.[101]

- Prepare manual and semi-automated welding equipment for use.

- Position hydrogen monitoring equipment near the lid weld location.

- Ensure that the lid is centered in the MPC shell; it may be necessary to use a hand-operated chain fall to closely control the lift and allow rotation and repositioning by hand. If the chain fall is hung from the crane hook, the crane should be tagged out of service to prevent inadvertent use during this operation.

- If necessary, install MPC lid shims around the MPC lid to make the weld gap uniform.

- Conduct radiation monitoring at regular intervals (continuous monitoring is recommended) to detect evidence of a cask flaw or misloading event.

A.2.2.7 Welded lid fastening operations

- Manually perform tack welds to steady the lid on the MPC.

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[98] If the temporary shield ring is not used, some form of gamma shielding (e.g., lead bricks or blankets) should be placed in the trunnion recess areas of the transfer cask water jacket to eliminate the localized hot spot.

[99] The RVOAs allow the vent and drain ports to be operated like valves and prevent the need to hot tap into the penetrations during unloading operations. The RVOAs are purposely not installed until the cask is removed from the SFP to reduce the amount of decontamination.

[100] Personnel should remain clear of the drain hose any time water is being pumped or purged from the MPC. Assembly crud, suspended in the water, may create a radiation hazard to workers.

[101] The annulus shield is used to prevent objects from being dropped into the annulus and helps reduce dose rates directly above the annulus region. The annulus shield is hand installed and requires no tools.

- Visually inspect the tack welds.
- Mount the semi-automated welding equipment (or welding robot) to the MPC lid.
- Activate and monitor the semi-automated welding equipment (performed by welding personnel).
- Conduct radiation monitoring at regular intervals to detect evidence of a cask flaw or misloading event.

A.2.2.8 Nondestructive evaluation (hydrostatic testing, dye penetrants tests, ultrasonic testing, etc.)

- Perform liquid dye penetrant testing (PT) to test the weld on both the root and final passes.
- Ultrasonic testing (UT) may be performed to test the weld (i.e., the geometry of the lid weld may not permit adequate conditions for ultrasonic testing); if multi-layer UT is not feasible, a multi-layer PT should be performed during the welding operation, including one intermediate examination after approximately every 0.9525 centimeters (3/8 inch) of weld depth.
- Fill the MPC with water to hydrostatically test the weld
- Attach the drain line to the vent port and route the drain line to the SFP or the plant liquid radiation waste system
- Fill the MPC with either SFP water or plant demineralized water until water is observed flowing out of the vent port drain hose.
- Close the drain valve and pressurize the MPC to 861,845 +34,474/-0 Pascals [125 +5/-0 pounds per square inch gauge (psig)]
- Close the inlet valve, and monitor for a minimum of 600 seconds (10 minutes). Any pressure drop is undesirable.
- Following the 10-minute hold period, visually examine the MPC lid-to-shell weld for leakage of water. The acceptance criteria is no observable water leakage.
- Release the MPC internal pressure, disconnect the water fill line and drain line from the vent, and drain port RVOAs, leaving the vent and drain port caps open.
- Perform a second PT on the MPC to verify structural integrity
- Conduct pressure, temperature, and radiation monitoring at regular intervals once cask lid is affixed to enable early detection of undesirable transients

A.2.2.9 Draining, purging, drying and inerting using vacuum drying or forced helium dehydration system (FHD)

- Using a vacuum drying system (VDS) – For MPCs without high burn-up fuel, the vacuum drying system may be connected to the MPC and used to remove all liquid water from the MPC in a stepped evacuation process. A stepped evacuation process is used to preclude the formation of ice in the MPC and vacuum drying system lines.

    - Drain the water from the cask.

        - Attach the drain line to the vent port and route the drain line to the SFP or the plant liquid radwaste system.

        - Attach the water fill line to the drain port and fill the MPC with either SFP water or plant demineralized water until water is observed flowing out of the drain line.

        - Disconnect the water fill and drain lines from the MPC, leaving the vent port valve open to allow for thermal expansion of the MPC water.

        - Attach a regulated helium or nitrogen supply to the vent port.

        - Attach a drain line to the drain port.

        - Verify the correct pressure of the gas supply.

        - Open the gas supply valve, and record the time at the start of MPC draining

        - Start the warming pad[102] if used.

        - Drain the water out of the MPC until water ceases to flow out of the drain line.

        - Shut the gas supply valve, and disconnect the gas supply line from the MPC.

        - Disconnect the drain line from the MPC.

    - Attach the vacuum drying system (VDS) to the vent, and drain port RVOAs.

    - Draw the vacuum to a predetermined level to ensure thorough removal of water from cask–this is performed using a stepped evacuation process; the internal pressure should eventually be reduced below 400 Pascals (3 torr) and held for 1,800 seconds (30 minutes) to ensure that all liquid water is removed.[103]

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[102] An optional warming pad may be placed under the Holtec HI-TRAC transfer cask to replace the heat lost during the evaporation process of MPC drying. This may be used at the user's discretion for older and colder fuel assemblies to reduce vacuum drying times.

[103] The MPC pressure may rise due to the presence of water in the MPC. The dryness test may need to be repeated several times until all the water has been removed. Leaks in the vacuum drying system, damage to the vacuum pump, and improper vacuum gauge calibration may cause repeated failure of the dryness verification test. These conditions should be checked as part of the corrective actions if repeated failure of the dryness verification test is occurring.

- Perform the MPC drying pressure test in accordance with the technical specifications.
- Close the vent and drain port valves.
- Disconnect the VDS from the MPC.
- Stop the warming pad, if used.
- Close the drain port RVOA cap and remove the drain port RVOA.
- Set the helium[104] bottle regulator pressure to the appropriate pressure.
- Purge the helium backfill system to remove oxygen from the lines.
- Attach the helium backfill system to the vent port on the MPC.
- Slowly open the helium supply valve while monitoring the pressure rise in the MPC.
- Carefully backfill the MPC in accordance with technical specifications (TSs).
- Disconnect the helium backfill system from the MPC.
- Close the vent port RVOA and disconnect the vent port RVOA.
- Sample gas to verify that the proper type and quality of fill gas was put into the cask.
- Monitor pressure, temperature, and radiation at regular intervals to enable early detection of undesirable transients.

- Using a forced helium dehydration system (FHD) – This is for high burn-up fuel or as an alternative for MPCs without high burn-up fuel.
  - Circulate helium gas through the MPC to evaporate and remove moisture. The residual moisture is condensed until no additional moisture remains in the MPC.
  - Maintain the temperature of the gas exiting the system demoisturizer below -6.1° C (21° F) for a minimum of 1,800 seconds (30 minutes) to ensure that all liquid water is removed.
  - Once devoid of moisture, backfill the MPC with a predetermined amount of helium gas.
  - If high burn-up fuel has been placed in the MPC, connect a supplemental cooling system (SCS) to the transfer cask annulus prior to helium backfill to circulate coolant to maintain fuel cladding temperatures below required limits.

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[104] Technical Specifications require helium with a minimum purity of 99.995%.

  - Sample gas to verify that the proper type and quality of fill gas was put into the cask.

  - Conduct pressure, temperature, and radiation monitoring at regular intervals once cask lid is affixed to enable early detection of undesirable transients.

A.2.2.10 Welding of remaining cask penetrations

- A port cover and drain cover are welded to the lid

  - Wipe the inside area of the vent and drain port recesses to dry and clean the surfaces.

  - Place the cover plate over the vent port recess.

  - Weld the cover plate.

- Weld the closure ring to the lid and the shell for redundant sealing.

  - Install and align the closure ring.

  - Weld the closure ring to the MPC shell and the MPC lid.

A.2.2.11 Nondestructive evaluation of final welds

- Use dye penetrant testing to test closure ring, port, and drain welds.

- Use ultrasonic testing to test port and drain welds.

A.2.2.12 Draining of annulus

- Remove the annulus shield (if used) and store in approved plant storage location.

- If use of the SCS is not required, attach a drain line to the transfer cask and drain the remaining water from the annulus to the SFP or the plant liquid radwaste system.

A.2.2.13 Installation of the transfer cask lid and MPC lifting cleats

- Install the transfer cask top lid.[105] Inspect the bolts for general condition. Replace worn or damaged bolts with new bolts.

- Install and torque the top lid bolts.

- Inspect the MPC lift cleat bolts for general condition. Replace worn or damaged bolts with new bolts.

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[105] When traversing the MPC with the transfer cask lid using non-single-failure-proof lifting equipment, the lid must be kept less than 2 feet above the top surface of the MPC to protect the MPC lid from a potential lid drop during lid installation.

- Install the MPC lift cleat.
- Drain and remove the temporary shield ring (if used).

A.2.3 Phase 5 — Loaded Cask Transfer Within Structure

A.2.3.1 Remove Scaffolding from Around Transfer Cask

In succession, each scaffolding section is removed from around the cask. For each section, the crane[106] operator moves the yoke/hook in order to attach to the scaffolding. Maintenance workers attach each scaffolding section to the yoke/hook. The operator moves each scaffolding section out of the way. The workers unhook the scaffolding section from the yoke/hook.

A single operator is stationed on the crane. The crane is operated in a manual mode, with visual cues being used to position the crane at each scaffold section so that the maintenance workers can attach the section. Approximately two or three workers are in the vicinity of the scaffolding, and one of them is in communication with the crane operator through hand signals to provide guidance on positioning the crane. Once the crane is in position, the workers attach the yoke/hook to the scaffolding. The crane operator moves the scaffolding to an out-of-the-way location on the refueling floor. He uses a combination of his own visual observation and direction from the communicating worker. The other workers have no specific assignment during this movement. Precise placement of the scaffolding sections away from the cask is not required. Once set down, the workers release the crane from the scaffolding, and the process repeats until all sections are moved.

A.2.3.2 Connect Short Slings to Yoke and to Canister (MPC) Lid

Operator moves the crane to the cask, and workers attach the short slings to the crane yoke and to the lifting loops on the MPC lid.

The operator positions the crane directly above the transfer cask, lowering it so that it is just above the cask. The crane is operated in a manual mode, with visual cues being used to position the crane at each scaffold section so that the maintenance workers can easily reach the yoke from the top of the cask. One of the workers is in communication with the crane operator through hand signals to provide guidance in positioning the crane. Height indication on the control panel helps to confirm proper height. Once the crane is in position, the workers get on top of the cask with tools and the short slings. They remove the support bolts and sleeves that hold the short slings, hold the slings in position, slide the sleeves in so that they engage the slings, slide the bolts back through the hole in the yoke and through the center of the sleeves, put the end plate on the threaded end of the bolt, thread the nut on the bolt, and tighten the nut with a wrench. They then attach the clasps on the end of the slings to the lifting loops on the MPC lid.

A.2.3.3 Connect Yoke to Cask Trunnions

Crane operator positions yoke at trunnions and engages the trunnions by closing the yoke arms and slightly lifting the yoke.

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[106] The crane used may be the main crane (used for lifting the loaded cask), or it may be the auxiliary crane.

Once the slings are attached, the operator spreads the yoke arms. He then continues to lower the crane and observe, with the help of the communication worker, when the arms are properly aligned with the trunnions. Height indication on the control panel helps to confirm proper height. Once aligned, the operator closes the arms so that the holes in the arms go over the trunnions. The communication worker confirms that this has occurred. The operator then raises the yoke slightly so that the yoke arm engages the grooves in the trunnions, which is confirmed by the communication worker.

A.2.3.4 Move Transfer Cask to Transfer Slide

Crane operator raises yoke to lift cask from floor. Operator moves cask above the transfer slide and lowers it on to the slide.

The maintenance workers position themselves around the transfer cask and observe it as the operator lifts the cask off the floor and moves the crane towards the transfer slide. The height indicator on the control panel indicates that the cask has been raised enough to clear the edge of the slide. The operator stops lifting the cask at the height specified by procedure. He movse the crane until the cask is positioned over and close to the slide. The overhead crane is shut down with the transfer cask suspended to prevent inadvertent operation. This is done visually, with assistance from the workers. The transfer slide operator then raises the transfer slide so that it snugly captivates the pool lid attached to the bottom of the transfer cask. The slide has an indented circle that the pool lid of the transfer cask fits in to, which clearly indicates that the cask is properly positioned.

A.2.3.5 Unbolt Transfer Cask Pool Lid

Once the cask is seated on the slide, the workers remove the bolts connecting the pool lid to the transfer cask. Radiation is monitored.

The maintenance workers use wrenches to remove all of the bolts from the pool lid. The bolts are completely removed by one worker and placed in a large bag carried by another worker. Once the pool lid is unbolted, the workers pick up radiation monitors that have a detector at the end of an approximately 3.05 meter (10-foot)-long pole. The receiver/display unit is near the handle, so the worker can see the reading. The transfer slide operator slowly lowers the transfer slide slightly, providing a small space between the suspended cask and the transfer slide so that the workers can check the radiation levels coming from the MPC. Once the workers verify that the radiation levels are acceptable, the operation proceeds to the next step.

A.2.3.6 Use Transfer Slide to Position Transfer Lid

Transfer slide operator moves the transfer lid underneath the cask.

The maintenance workers once again position themselves around the transfer cask and observe it as the transfer slide operator moves the transfer lid into position underneath the cask. The workers help center the cask on the transfer lid and rotate it so that the bolt holes in the cask are properly aligned with the bolt holes in the transfer lid, using hand signals to guide the transfer slide operator’s actions. The operator stops maneuvering the transfer slide when the worker signals that the cask and transfer lid are properly aligned.

A.2.3.7 Bolt Transfer Cask to Transfer Lid

Workers replace the bolts in the lower end of the transfer cask.

The maintenance workers place “washer rings” along the lower flange of the transfer cask, aligning the holes in the rings with the holes in the flange. They then proceed around the cask and place the bolts that were previously removed and placed in a bag back into the flange and though to the threaded holes in the transfer lid. They hand tighten the bolts as they go. Once all the bolts are in, they use a torque wrench to tighten the bolts to a torque level as specified in a the procedure.

A.2.3.8 Move Transfer Cask From Refueling Floor to Transfer Pit

Crane operator lifts the transfer cask from the refueling floor (vertical lift only), moves it over to the transfer pit (horizontal movement only), and lowers it through the transfer pit opening until it is seated on the storage cask in the transfer pit (vertical lower only).

The maintenance workers once again position themselves around the transfer cask and observe it as the operator lifts the cask off the floor (vertical lift) and then moves the crane towards the transfer pit opening (horizontal movement). The height indicator on the control panel is used to indicate that the cask has been raised sufficiently to clear the edge of the transfer slide (attached to the bottom of the transfer cask) and the railings around the transfer pit. The operator lifts the cask to the height specified by procedure to ensure sufficient clearance, but does not lift the cask higher than required. Following the vertical lift, he then horizontally moves the yoke until the cask is positioned over the transfer pit opening. This horizontal movement is coordinated by visual monitoring by the crane operator and by a designated spotter or other designated worker(s). He then lowers the cask through the transfer pit opening into the transfer pit, towards the storage cask. The storage cask is located just below an alignment device that has a series of blocks that delineate the corners of the transfer lid. The workers help to center the cask between the blocks so that the corners properly align with the blocks, using hand signals to guide the crane operator’s actions. The operator stops lowering the cask when the worker signals that the cask is properly seated and the slings are slack, which is confirmed by the height indication on the control panel.

A.2.3.9 Remove the Short Slings and Install the Long Slings

- Remove the short slings from the MPC lift cleats.
- Install the long slings to the MPC lift cleats.

A.2.3.10 Open the Transfer Lid Door

- Slightly raise the MPC.
- Remove the transfer lid door locking pins.
- Open the doors.
- At the user’s discretion, install trim plates to cover the gap above and below the door/drawer. Secure the trim plates using hand clamps or any other method deemed suitable.

A.2.3.11 Lower the MPC from the Transfer Cask to the Storage Cask

A.2.3.12 Disconnect the Slings from the Crane and Lower Down onto the MPC Lid

A.2.3.13 Remove the Transfer Cask from the Top of the Storage Cask

- Remove trim plates (if used).
- Close doors on the transfer slide.
- Remove the transfer cask using crane.[107]

A.2.3.14 Remove the MPC Lifting Slings and MPC Lifting Cleats and Insert Hole Plugs

A.2.3.15 Remove the Alignment or Mating Device

A.2.3.16 Remove the Vent Duct Shields

A.2.4 Phase 6 — Loaded Cask Transfer Outside Structure

A.2.4.1 Remove Storage Cask from Reactor Building

Attach a tug to the skid and use it to pull the skid and the storage cask out of the reactor building. Disconnect the tug from the skid once the storage cask is in the proper position for preparation.

The storage cask is sitting on a skid that rides on a pair of rails. A single operator is stationed in a motorized tug that also rides on the rails. The operator moves the tug towards the skid. A governor limits the speed of the tug to safe levels. Two or three workers stand near the skid and observe the tug. Arms on the tug's hitch slide into position on the skid. No assistance is required to help the operator align the hitch (the rails maintain the proper alignment). The operator stops the tug once the hitch is engaged on the skid, which is confirmed by the workers by hand signal. The workers drop pins through the hitch arms (two on each side) to lock the hitch to the skid. The operator then backs the tug out of the reactor building until he gets to the preparation position for the storage cask. This is done visually, and precise placement is not required.

A.2.4.2 Remove Alignment Ring

Operator moves the crane boom to the storage cask, lifts off the alignment ring, and removes the lid to the ground. Radiation is monitored.

This operation uses a mobile crane. Workers attach lifting straps to the hook on the crane cable. The operator in the crane cab positions the crane boom directly above the storage cask, lowering it so that the lifting straps rest on the top of the alignment ring with some slack. The crane operator uses visual cues to perform this action. At the same time, two workers are lifted in a man hoist to the top of the storage cask. They proceed to bolt the hooks at the four ends of

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[107] Because of radiation streaming, personnel should remain clear (to the maximum extent practicable) of the HI-STORM storage cask annulus when HI-TRAC transfer cask is removed.

the straps to the lifting loops on the alignment ring. They then back the man hoist away from the storage cask. The crane operator then lifts the alignment ring from the top of the storage cask and places it on the ground away from the storage cask. The workers on the mobile crane then use a long-boom radiation monitor to check the radiation levels above the MPC. Other workers on the ground unbolt the straps from the alignment ring.

A.2.4.3 Place Permanent Shield Lid on Storage cask

Operator moves crane boom to permanent shield lid, lifts permanent shield lid above storage cask, and lowers the lid into place. Radiation is also monitored.

The operator moves the crane from the alignment ring to the adjacent permanent shield lid, and the workers bolt the straps to the permanent shield lid. The operator lifts the permanent shield lid and positions it above the storage cask. Using a combination of his own visual observations plus hand signals from the workers on the mobile crane, the operator centers the shield lid over the storage cask and lowers it into place. The lid sits flat only if it is properly centered. The workers once again check the radiation levels above the storage cask and place the shield lid studs into the stud holes in the lid to assure it is aligned with the holes in the cask flange. They then unbolt the straps from the lid, and the operator moves the crane away from the storage cask. The workers tighten the studs.

A.2.4.4 Install Vent Shield Cross-Plates and Vent Screens to Storage Cask

In cask designs with vents, operators mount cross-plates and vent screens to ensure that birds, insects, other animals, or debris do not block air circulation paths through the storage cask. Vent shields also provide radiation protection for the air passageways.

A.2.4.5 Attach Lift Brackets to Storage cask

The lift brackets are attached to the crane boom by the straps. The crane operator moves the brackets to the top of the storage cask, where they are anchored in place.

The maintenance workers on the ground attach the straps on the crane boom to the first of two lift brackets. The crane operator raises the lift bracket a few feet, and a worker puts anti-seize on the threads of the two large bolts that protrude from the bracket. The crane operator then positions the bracket above the storage cask. The two workers on the mobile crane stand on top of the storage cask to line the bolts up with holes on the top of the cask. They use hand signals to direct the crane operator to move and lower the bracket until the bolts slide into the holes. They use a ratchet to tighten the two bolts. They then remove the strap from the bracket and remove the support bolt, end plate, and sleeve from the top of the bracket and place the parts on top of the storage cask. The crane operator then moves the crane boom back to the ground where the second bracket is located, and this process is repeated for the second bracket. The crane boom is then moved away from the storage cask.

A.2.4.6 Attach Storage Cask to Transporter

The storage cask transporter is moved to the location of the storage cask, and the workers attach the lifting bar of the transporter to the lift brackets on the storage cask.

The transport operator drives the transporter to a position lined up with and just short of the point where the lifting bar is aligned with the lift brackets. His visual orientation is such that he can clearly see the proper alignment points, so he does this visually, with no assistance from the workers. Once the transporter is in place, the workers on the mobile crane climb on top of the storage cask. The workers put anti-seize in the holes in the lift brackets and in the lifting arms on the transporter lifting bar. The workers then use hand signals to direct the transporter operator to ease the transporter forward to the proper position. The operator lowers the lifting bar until the lifting arms contact the main body of the brackets, which align all the holes. On each bracket, the workers then slide the sleeve through the holes, the bolt through the center of the sleeve, add the endplate, and tighten the bolt using wrenches. The workers then return to the ground.

A.2.4.7 Attach Kevlar Belt or Other Cask Stabilization Device

The cask is lifted slightly off of the ground by the cask transporter. Once suspended, operators attach a Kevlar belt or other stabilization device to steady the cask during movement.[108]

A.2.4.8 Move Storage Cask to ISFSI Pad[109]

The transport operator drives the storage cask to the ISFSI pad. The workers detach the storage cask from the transport, and the transport leaves the area.

The transport operator raises the lifting bar, lifting the storage cask a short distance off the skid. A gauge on the control panel indicates the proper height. Physical limits of the lifting bar hydraulic system prevent raising the storage cask too high. The operator drives the transporter along a marked path from the skid to a road that leads to the pad. He then follows the road to the pad. The operator is positioned at the controls in a location where he can see the path he needs to follow. The speed of the transporter is limited by the gearing and the maximum engine speed to a very slow pace. The operator maneuvers the transporter to line up with an empty space on the pad (including maneuvering around any storage casks that have already been placed on the pad). The operator positions the transporter on the pad at the proper location and lowers it to the ground. A mobile crane conveys workers to the top of the storage cask, who undo the bolts connecting the lift brackets to the storage cask. The transport operator raises the lift bar so that the brackets clear the storage cask, as indicated by the height gauge on the control panel, and drives the transporter away.

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[108] The cask is primarily suspended via large, bolted pins running through brackets attached to the lid of the storage cask. The additional stabilization device (e.g., a Kevlar belt) helps to decrease large moment loads on the suspension pins resulting from the superimposed motions of the transporter movements along the roadway, other vibrations, etc.

[109] A transport route walkdown is recommended to ensure that the cask transport conditions are met before moving the cask.

A.2.4.9 Emplacement for NUHOMS-type Systems

Once the storage cask is properly positioned on the ISFSI pad, perform shielding effectiveness testing and an air temperature rise test within 5–7 days as follows: [110]

- Measure the inlet air (or screen surface) temperature at the center of each of the four vent screens. Determine the average inlet air (or surface screen) temperature.
- Measure the outlet air (or screen surface) temperature at the center of each of the four vent screens. Determine the average outlet air (or surface screen) temperature.
- Determine the average air temperature rise by subtracting the results of the average inlet screen temperature from the average outlet screen temperature.

A.3 Transnuclear TN-40 at a PWR

This section describes activities within phases of operation 3–6[111] and is tailored toward operations followed at a PWR using the TN-40 DCSS. Details regarding these operations were extracted from a narrated training video of selected operations provided to the analysis team. The terminology and manner of description in this section differs from that used in Section A.2 given the different type of source information provided. This operation description formed a significant portion of the context used in developing the HFE scenarios described previously in Section 5.

A.3.1 Phase 3 — Cask Preparation and Positioning

A.3.1.1 Receiving the cask

- Bring the cask into the auxiliary building on the railcar
    - Transfer the rail car and TN-40 cask into the auxiliary building through the roll-up door
    - The floor plate below the door must be removed before the railcar can be transferred into the building. This is a plant vital area and security personnel must be present at the door. Personnel dosimetry is required when inside the auxiliary building
- Remove the protective coverings
    - When the rail car is secure with the brake set, the protective coverings can be removed from the cask (e.g., coverings over the trunnion recesses)

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[110] The air temperature rise test is to be performed between 5 and 7 days after installation of the HI-STORM 100 lid to allow thermal conditions to stabilize. The purpose of this test is to confirm the initial performance of the HI-STORM 100 ventilation system.

[111] Out of the seven phases of DCSOs described earlier in Section 3.6 of this report.

    - Remove the two hex bolts from the upper tie down strap (that holds the cask securely to the railcar) and lift the strap to the railcar bed
    - Remove the eight hex bolts from the lower trunnion support block caps
    - Remove the lower trunnion support block caps
    - When the cask hold downs and coverings have been removed, the cask is almost ready to be lifted from the railcar

- Upending and lifting the cask from the railcar
    - First follow the Lift Beam Operating Instruction to attach the lift beam to the crane
    - Set the lift beam arms to the release position
    - Engage the lift beam to the upper trunnionsof the TN-40 cask[112]
    - Slowly lift the cask approximately 2.5 centimeters (1 inch)
    - Look for unusual deformations of the lift beam, crane, or trunnions
    - Listen for unusual noises
    - Check that all mechanisms are functioning properly
    - Raise the cask slowly to a full vertical position by rotating it on the lower trunnions
    - The crane must periodically be moved horizontally to ensure that the lift cables stay close to vertical as the cask is lifted
    - Once the cask is near vertical, the cask can be lifted from the lower supports, and the railcar can be removed from the drop area

- Lowering the cask
    - Before lowering the cask, a clean (metallic) mat must first be laid down in the preparation area; the bottom protective cover may be used if approved by Radiation Protection
    - Lower the cask onto the mat
    - Release the lift beam from the cask
    - Raise the lift beam and return it to its storage rack

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[112] The trunnion design of the TN-40 is significantly different from the trunnion design of the Holtec HI-TRAC transfer cask as it has a raised cylindrical end-cap, which improves the degree of captivation between the lifting yoke and the trunnion (i.e., reducing the likelihood of a yoke arm disengaging a trunnion during lifting or other movement).

A.3.1.2 TN-40 Initial Inspection and Preparation

- Remove the Neutron Shield/Lid
    - Remove the over-pressure port flange; using a hex key wrench, loosen the port flange screws ¼-turn counterclockwise following the assigned sequence; then turn the bolts another ¼-turn counterclockwise using the same sequence; finally, remove the bolts completely and store in the bolt storage box
    - Remove the neutron shield
        - Using the hex socket wrench, remove the four bolts that attach the neutron shield to the lid; store the bolts in the bolt storage box
        - Attach blocking to support the overpressure tubing above the neutron shield
        - Attach a lifting sling to the three lifting lugs on the sides of the neutron shield
        - Slowly lift the neutron shield
        - Be careful that the overpressure port flange does not bind
        - Move the neutron shield and overpressure tank assembly to its storage area
        - Lay the assembly down, ensuring that the overpressure flange is sitting freely with no strain on the tubing
    - Remove the cask lid
        - Be sure to number the bolts and bolt holes if needed
        - Using the hex socket wrench, loosen all 48 lid bolts ¼ turn following the assigned sequence in the procedure; give the bolts another ¼ turn using the same sequence; once these two sequences are done the lid bolts can be removed completely and stored in the bolt storage box
        - When all the bolts are removed the lid can be lifted from the cask
        - First perform the lifting device’s visual check as detailed in the procedure
        - Attach the four hoist rings to the proper holes in the lid; the hoist rings should be inserted fully and should hinge toward the center of the lid
        - Torque the hoist rings to 637.2 Joules (470 foot pounds)
        - Attach the bail of the four-legged sling to the crane

        - Make sure the crane is centered over the cask lid
        - Slowly raise the crane hook until the sling cables are slightly taut
        - Make sure all four cables are equally tight; if they are not, adjust the turnbuckles until they are
        - Slowly lift the lid until it is free of the lid recess area
        - Move the lid to the storage area onto the appropriate auxiliary building floor level south of the SFP
    - Inspect the painted surfaces of the cask and note any imperfects that must be repaired; the surface finish must be suitable for decontamination later
    - Inspect the cells in the basket for foreign material; remove any material found and record the location on the report
    - Using the small hook and the crane, place the dummy fuel gauge into each cell; there should be no binding in any of the cells; if there is more than a 111.2 Newton (25-pound) variation, further evaluation is necessary; note the variations and record the scale information on the report
    - Visually inspect the lid bolts and bolt hole threads to ensure that none have any laps, seams, cracks, or damaged threads
    - Check each of the 48 bolt holes by threading one bolt completely into each hole
    - Inspect the lid sealing surface; check for defects in the seal contact surfaces that may prevent a proper seal; wipe the seal areas with a lint free cloth; record the inspection

A.3.1.3 Final Preparation for TN-40 Cask Loading

Once the cask is fully inspected and certified for loading, prepare the cask to be put into the SFP where it will be loaded with spent fuel

- Replace the cask lid seal
    - Carefully remove all the gasket retaining screws using a flat blade screw driver; then remove the gasket
    - Clean the gasket groove with acetone
    - Wipe dry with a clean cloth
    - Visually inspect the groove to make sure it is free of scratches and imperfections
    - Prepare the new gasket for installation

  - Position the gasket in the groove
  - Replace the gasket retaining screws and tighten using a flat-blade screwdriver
  - Lower the lid onto blocking, making sure the lid is not resting on the seals
  - Remove the lifting bail from the crane hook
- Prepare the cask for movement to the SFP
  - Rinse the cask with demineralized water to remove any contaminants that might otherwise enter the SFP
  - Pump the water out of the cask
  - Measure 2.74 meters (9 feet) down from the cask flange and apply grift tape at four locations around the cask to serve as visual markers when the cask is being raised and lowered in the SFP
  - Carefully fill all of the lid and protective cover bolt holes with demineralized water to protect the threads from the effects of the SFP water
  - Inspect the plastic on the top face protective cover for foreign material[113]
  - Install the top face protective cover with tag lines attached to the lifting bails
- Pre-job briefing prior to moving the cask
  - Review the procedure precautions
  - Review the special considerations
- Moving the cask into the SFP
  - Attach the lift beam to the auxiliary building crane
  - Engage the lift beam to the cask upper trunnions
  - Lower the level of the SFP following the procedure
  - Verify that the auxiliary building crane is in the critical position
  - Open the SFP enclosure roof hatches
  - Install the bottom protective cover if it has not already been installed during the cask inspection process

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[113] This cover protects the top of the cask and also has alphanumeric labels to aid in positioning spent fuel assemblies within the cask.

- Attach the cover to the cask by looping the attachment tag lines over the lower cask trunnions and securing them to their attachment points
- The cask is now ready to be raised to the appropriate floor level
- Open the SFP south double doors
- Lower the railing outside the SFP doors
- Mark the area as a safety hazard and keep people clear of the railing
- Remove the railing around the small SFP to allow the cask to pass through
- Move the cask on the safe load path
- When the white permission light is illuminated on the bridge, the trolley is aligned with the hatch centerline
- Replace the hand railing near the SFP doors
- Slowly lower the cask into the SFP while spraying the cask and lift beam with demineralized water to provide a film of clean water on the cask surfaces
- Continue lowering until the grift tape is under water; this is the minimum amount the cask must be lowered; it can be lowered farther if desired
- Pump water from either pool into the cask cavity; the water must be at least 15.2 centimeters (6 inches) from the top of the cask, but the cask may be overfilled if directed by Radiation Protection
- Slowly lower the cask into the pool until water flows over the lip of the cask and enters the cavity; take care to avoid excessive agitation of the water
- Continue lowering the cask until it rests on the bottom of the pool
- Make reference marks for the crane bridge and trolley positions to relocate the center of the cask when replacing the lid
- Release the lift beam from the cask
- Raise the lift beam until it is clear of the cask
- Spray the lift beam with demineralized water as it is removed from the SFP

A.3.2 Phase 4 — Cask Loading

A.3.2.1 Load the spent fuel into the cask

[Refer back to Section A.2.2.1 as it provides a representative process description for loading spent fuel into a cask]

- Verify that the assemblies loaded were the ones intended for loading
- Record the assembly identification numbers and cask locations with an underwater video camera and video tape
- Complete the Cask Inventory Verification form

A.3.2.2 Remove TN-40 Cask from the SFP

Once the cask is loaded it is ready to be removed from the SFP and prepared for sealing

- Lower the level of the SFP using the procedure
- Attach the lid and lid lifting assembly to the shank hook on the bottom of the lift beam
- Slowly raise the crane hook until the sling lines are taut
- Raise the cask lid about 5.1 centimeters (2 inches)
- Using a carpenter's level, make sure the lid is level; if not, adjust the turnbuckles according to the following procedure:
    - Lower the lid back onto the support blocks to relieve the tension on the lifting legs
    - Adjust the turnbuckles as necessary to achieve the proper length and tension
    - If the lid is still not level when lifted, then lower the lid back onto the support blocks and repeat the turnbuckle adjustment
    - Repeat this process until the lid is level
- Attach two to four tag lines to the lid lifting bridle; this allows the lid to be rotated and also facilitates collapsing the bridle when placing the lid onto the cask;
- Attach two tag lines to the lift beam
- Open the SFP south double doors and roof hatches
- Remove the cask top-face protective cover by lifting with the tag lines
- The lid is now ready to set onto the cask
- Verify that the auxiliary building crane is in the critical position

- Transfer the lid to a position directly over the cask cavity lid seating surface; spray the lid with demineralized water as it is lowered into the SFP

- Adjust the lid’s vertical alignment and orientation as needed

- Slowly lower the lid into the cask cavity and on to the alignment pins

- Continue lowering until the lid is fully down; this is indicated by slack in the sling cables

- Using the underwater camera, check that the lid is properly seated

- Collapse the lid lift bridle using the tag lines

- Continue lowering the lift beam until the beam arms are lined up with the trunnions

- Engage the cask

- The cask is now ready to be lifted from the SFP

- Slowly raise the cask and verify that the lift beam is properly engaged on the trunnions

- Continue raising the cask

- Evacuate all nonessential individuals from the SFP

- Survey the lid for radiation streaming as the cask approaches the surface of the water

- Make sure the cask is not more than 2.74 meters (9 feet) out of the water by keeping the grift tape marks at or below the surface of the water

- Wash down the exposed cask and lift beam surfaces with a clean water spray; be careful not to spray water in the lid seal area

- When the top of the cask is accessible, vacuum the water from at least six evenly spaced bolt holes; all bolt holes may be vacuumed if desired

- Apply a light coat of Never Seize to six lid bolts, and install the bolts hand-tight in the vacuumed holes[114]

- Attach one end of a drain hose to the Hansen coupling in the drain port, and route the other end to the pump

- Route the pump through a flow meter/totalizer to quantify the amount of water removed from the cask

- The pump should discharge back into the SFP unless otherwise directed

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[114] Note that this is a significant difference between the TN-40 and Holtec HI-STORM designs. Given that the TN-40 cask uses a bolted lid assembly, fasteners may be used to positively attach the lid to the cask prior to complete removal of the loaded cask from the SFP.

- Dose rates from the hose are monitored by Radiation Protection during the draining of the cask

- Monitor the volume of water being pumped to assist in determining when the draining is finished

- The volume of cask cavity water is estimated at 1,700 gallons

- Raise the cask out of the pool

- Spray the cask surface with clean water

- Perform preliminary decontamination of the cask surface as requested by Radiation Protection, who will survey cask surfaces for dose rates

- Move the cask out of the SFP area, and replace the hand railing near the SFP double doors

- Lower the cask into the cask decontamination area according to the safe load path prescribed

- Close the SFP south double doors and the roof hatches

- Release the lift beam from the cask

- Raise the lift beam until it is clear of the cask, then move it to its storage area

A.3.2.3 Sealing the TN-40 Cask

Now that the cask is in the decontamination area, the cask needs to be sealed.

- Decontaminate the top of the cask

- Torque all bolts to 67.8 Joules (50 foot pounds)

- Torque bolts to 406.7 Joules (300 foot pounds)

- Torque to 813.5 Joules (600 foot pounds)

- Torque to 1,261 Joules (930 foot pounds)

- Repeat the final torquing sequence to ensure that the bolts are at their proper torque

- The cask is now ready for the drying procedure

- Install the vacuum drying system (VDS) to the over pressure port (OP) test connector to dry the area between the inner and outer lid gaskets

- Continue vacuum pumping until gauge G-3 reads approximately 1000 Pascals (10 millibars)

- After the pressure has been held for 600 seconds (10 minutes), close valve V-3, stop the vacuum pump, and then record the time and test pressure in the Cask Loading Report
- For at least 180 seconds (3 minutes) after closing valve V-3, watch gauge G-3, and note the pressure rise; record the final time and pressure in the Cask Loading Report and calculate the pressure rise during the test
- If the observed pressure rise does not exceed 800 Pascals (8 millibars), the lid passages are considered dry
- If the pressure rise test fails, repeat the VDS pumping procedure until the rise is within the 800 Pascals (8 millibar) limit
- As the cask is pumped, the pressure reading should show a steep decrease until it corresponds to the vapor pressure of the residual liquid in the cavity
- At no time should the pressure be allowed to drop below 600 Pascals (6 millibars) as this may cause the remaining water to freeze
- Readings should be taken every 1,800 seconds (30 minutes) for the first four hours and then every hour after that
- Chart the pressure readings and the times on the appropriate chart
- Continue pumping until a pressure of 800 Pascals (8 millibars) is reached
- Isolate the vacuum pump by closing valve V-6
- Turn off the vacuum pump, and record the time in the initial pressure showing of gauge G-2
- The cask cavity is considered dry if the pressure reading on gauge G-2 does not exceed 950 Pascals (9.5 millibars) during a period of 1,800 seconds (30 minutes)
- Record the final time and pressure reading in the Cask Loading Report
- With the vacuum pump running, slowly open valve V-6, allowing the cask pressure to reduce to 1000 Pascals (10 millibars)
- Isolate the vacuum pump by closing valve V-6
- Open valve V-3 until a pressure of 140,000 Pascals (1400 millibars) of helium is reached
- Sign off in the Cask Loading Report
- Now the vent port cover can be installed
- Once the port cover is in place, the residual helium must be removed from the seal area
- Perform a seal leakage check on the overpressure port using the pressure rise method

- Install the mass spectrometer and the baratron gauge to the overpressure port test connector

- After a minimum of 300 seconds (5 minutes), record the observed pressure from the baratron readout

- Calculate the leak rate using American National Standards Institute (ANSI) N 14.5 – 1987, and record the results in the in the Cask Loading Report

- Perform the helium mass spectrometry test

    - Connect a helium mass spectrometer to the overpressure port and expose the outer seals to helium

    - The leak rate should be 1.0E-5 atmospheres per cubic centimeters per second or less

    - Document the leakage on the Cask Loading Report

- The cask is now ready to be loaded on the transporter and moved from the building

A.3.3 Phase 5 — Loaded Cask Transfer Within Structure

A.3.3.1 Position the TN-40 Cask Transporter

- Notify Security that the transporter is ready to move to the auxiliary building

- Move the transporter into position to receive the cask (use the procedure)

- Replace the rollup door limit switch if it was removed

- Remove the upper hoist assembly

- Lift the upper hoist assembly away from the transporter and store on its storage stands

A.3.3.2 Prepare and Position Cask at Transporter

- Check the contamination and radiation levels of all exposed cask surfaces, and decontaminate as required by Radiation Protection Implementation Procedures

- Engage the lift beam to the cask trunnions

- Lift the cask no more than 1.52 meters (5 feet) above the ground and then decontaminate the newly exposed surfaces

- Raise the cask out of the cask decontamination area

- Move the cask over the transporter following the prescribed safe load path

- Determine the maximum surface temperature of the cask
    - While the cask is elevated, rotate it so four temperature profiles can be taken at 90° intervals
    - Each profile should contain one shot of the top half of the cask using the infrared camera and photographic camera and one shot of the bottom half of the cask using the infrared camera and photographic camera
- Position the cask so that it is approximately centered over the transporter
- Lower the cask onto the transporter
- Release the lift beam from the cask
- Contact the Department of Health and notify them that the cask is ready to be moved to the ISFSI pad
- Align the neutron shield and the overpressure tank assembly above the cask lid
- Replace the metallic seal in the overpressure port flange
- Set the neutron shield and the overpressure tank assembly in place on the cask lid
- Perform a seal leakage test on the overpressure system using the pressure rise method
- Perform the helium mass spectrometry test
- Place plastic around the lid and overpressure system to form a dam
- Fill the space between the lid and the dam with helium
- Attach the helium mass spectrometer to the valve plate assembly
- Evacuate the system and check for leaks
- The leak rate should be less than 1.0E-5 atmospheres per cubic centimeters per second or less
- Document the leakage on the form provided for recording this information and then remove the dam
- Backfill the overpressure system with helium to a pressure of 496,425 Pascals (72 pounds per square inch)
- Isolate at the overpressure valve, and remove the test manifold
- Install the protective cover by placing it over the cask lid and aligning the bolt holes
- Torque the bolts in the proper sequence to 108.5 Joules (80 foot pounds)

- Document the torquing on the Cask Loading Report

A.3.3.3 Attach Cask To Transporter and Prepare for Movement to ISFSI

- Replace the upper hoist assembly on the transporter
    - Lift the assembly with the auxiliary building crane
    - Lower the assembly into place on the transporter, making sure the cask links[115] do not catch on the cask trunnions
    - Check that the cask links are in the “out” position
    - Lower the cask hoist so that the cask links can engage the upper cask trunnions
    - Use the control pendant to move the cask links to the “in” position where they should be able to engage the upper trunnions
    - It may be necessary to manually maneuver the links; for safety, handle the cask links from outside only
- Raise the cask by using the raise push button on the control pendant
- Unhook the lower cask restraints from their storage chains and attach to the cask lower trunnions; to fully engage the lower restraints, it may be necessary to place the cup over the trunnion while the jack arms are raised and lowered until the cup falls into place
- The cask is now ready to be moved from the aux building
- First notify Security that the cask transporter is ready to move the cask to the ISFSI
- Remove the west rollup door limit switch
- Connect the tow vehicle to the transporter
- Perform a walk-down of the road leading to the ISFSI to make sure there are no washouts, potholes, or snow buildups that will inhibit safe passage of the transporter to and from the ISFSI
- Two emergency brake operators are required, one on each side of the transporter

A.3.4 Phase 6 — Loaded Cask Transfer Outside Structure

A.3.4.1 Transport the Cask to the ISFSI

- Move the loaded transporter to the selected ISFSI pad location and center the cask on the pad

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[115] The cask links are essentially moveable yoke arms mounted to the upper hoist assembly of the cask transporter.

- Start up the transporter
- Unhook the lower cask restraints from the cask lower trunnions, and store them using the storage chains
- Set the transporter parking brake
- Lower the cask with the lower push button on the control pendant
- Manually clear the cask links from the lifting trunnions
- Use the control pendant to set the cask links to the “out” position
- If necessary, disconnect the tow vehicle
- Raise the transporter using both left and right jack extend push buttons simultaneously
- Release the parking brake when the jacks touch the ground
- Continue raising until the rear wheels are just off the ground
- Set the parking brakes again
- Using the control pendant, unlock the rear turntables,[116] switch them into the load position, and then lock them into position
- Release the parking brakes
- Lower the cask using both jack retract push buttons simultaneously
- Engage the parking brake as soon as the tires touch the ground
- Continue retracting the jacks until they are in the stowed position
- If it was disconnected earlier, reconnect the tow vehicle
- Release the parking brakes and pull the transporter away until it is clear of the cask
- Return the rear turn tables to the travel position using the method just completed
- Shut down the transporter
- Tow transporter to the storage shed

A.3.4.2 Install and Test Cask-Monitoring Equipment at ISFSI

- Install the transmitter stand with lead shielding on the ISFSI pad next to the cask

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[116] The turntables mount each dual-wheel assembly to the transporter.

- Install and fasten the transmitter field cabling conduit and junction box to the transmitter stand
- Install the transmitter and manifold assembly on the stand
- Terminate the field wiring to the transmitter
- Connect the 0.9525 centimeter (3/8-inch) stainless steel tubing between the cask seal monitoring isolation valve and the transmitter valve manifold assembly
- In the rear of the appropriate alarm monitor, terminate the transmitter field wires to the alarm channel calibrated previously
- Install the ground strap from the ground insert to the transmitter stand
- Connect a helium bottle with a low-pressure regulator to the transmitter manifold test fitting
- With the overpressure tank isolation valve closed, open the manifold valve to purge, then pressurize the tubing installed previously to 496,423 Pascals (72 pounds per square inch)
- Close the manifold test valve
- Monitor the digital pressure indicator, and verify that there are no leaks
- Check all fittings if necessary
- Disconnect the helium bottle from the transmitter manifold
- Slowly, open the helium overpressure tank isolation valve
- Perform surveillance procedure
- Calibrate monitoring system on the newly installed loop
- Verify that the digital pressure indicator in the ISFSI alarm monitoring building reads approximately 496,423 Pascals (72 pounds per square inch)
- Check the surface radiation levels following Radiation Protection Implementation Procedures, and record them on the appropriate form and attach this to the Cask Loading Report
- Notify operations that a new cask is located at the ISFSI

A.4 Phase 7 — Loaded Cask Storage and Monitoring

This section describes activities within the last phase of operation.[117] These activities illustrate those that may be performed at any plant using any DCSS.

Adhere to all ISFSI operational procedures. These generally include the following:

- Ensure monitoring for corrosion of cask components
- Ensure monitoring of pressure, temperature, and radiation levels
  - Initial temperature monitoring occurs at 5–7 days to allow temperature levels to reach a steady state following the loading and emplacement process
  - Long-term monitoring begins after the initial monitoring period (i.e., after the first week)
- Ensure monitoring of the structural integrity of the pad or horizontally oriented, concrete storage vaults at the ISFSI
- Ensure that no obstructions required for proper air circulation around the casks are present
- Ensure proper calibration of all sensors used during monitoring activities
- Ensure that a quality assurance (QA) program that satisfies or exceeds reactor facility Part 50 requirements is maintained for ISFSI activities. The following elements need to be included in the QA program:
  - Procurement controls
  - Control of measuring and test equipment
  - Operating status
  - QA audits
  - Tracking of problems
  - Identifying corrective actions
- Be sure to limit the placement of flammable and explosive liquids near the loaded cask during movement from the fuel building to the ISFSI pad.
- Ensure that potential effluents from casks (should they materialize) are properly handled with structures, systems, and components at the ISFSI and along the travel path to the ISFSI. Items that collect liquid effluent wastes (e.g., filters, scrubbers, sumps, and laboratory collection containers) and solid wastes (e.g., anti-contamination clothing and discarded swipe material) must be transferred from the operation systems into the waste stream for volume reduction or solidification, temporary storage, and shipment to a disposal site.
- Maintain detailed records regarding the fuel loading of each cask, records provided by the cask supplier for each cask design used, and be prepared to transfer these records if a cask is sold, leased, loaned, or otherwise transferred to another user.

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[117] Out of the seven phases of DCSOs described in Section 3.5.

- Maintain an ISFSI security program consistent with the reactor facility security program including response to events, offsite support, training and certification of security force personnel, lock and key controls, and search requirements. The appropriate safeguards program and security plan must protect against the design basis threat of radiological sabotage in accordance with the requirements of 10 CFR 73.

- Maintain a training program for personnel assigned to the ISFSI that provides a strong basis for understanding the requirements and safe practices associated with DCSOs.

- Maintain a process for retrieving spent fuel from a loaded DCSS in the ISFSI and returning it to the SFP.

APPENDIX B. TECHNICAL BASIS FOR ANALYSIS APPROACH

This appendix provides background material that helps explain the technical basis that supports the scenarios in Section 5 and recommendations in Section 6. The background material was included based on (1) feedback from dry cask storage operation (DCSO) subject matter experts (SMEs) at the Nuclear Regulatory Commission (NRC) who were not experts in human performance but desired to better understand what factors may lead to human performance decrements in the activities they oversee; and (2) a desire to include background material and terminology that would allow the report to stand alone as a collection of insights for readers who may vary widely in their understanding of human performance, human reliability analysis (HRA), DCSOs, and current perspectives on how to improve human performance. This appendix:

- Summarizes HRA and how its application to moving spent fuel differs from nuclear power plant (NPP) control room applications
- Summarizes the characteristics of human error and specific insights related to moving heavy loads in NPPs
- Explains selected items from the behavioral sciences such as mechanisms and taxonomies for describing skill acquisition, human information processing, and types of human error
- Discusses internal and external factors that influence human performance, often in complex, context-specific ways

This appendix contains terminology, taken from multiple domains, related to HRA and human performance. In some cases, new terms were generated to add precision to concepts that have been ambiguous and confusing in other documents describing HRA and human performance. All key terms are defined in the glossary (Appendix D).

B.1 Human Reliability Analysis (HRA)

B.1.1 Introduction to HRA

Human reliability analysis (HRA) is a structured approach used to identify, assess, and quantify human failure events (HFEs) in support of a probabilistic risk assessment (PRA) study. Traditionally, HRA is performed through two activities: qualitative analysis and quantitative analysis (i.e., assignment of human error probabilities to HFEs). Generating quantitative human error probabilities involves systematic estimation of the probability of an HFE using an HRA quantification method that is based on data, theoretical models, and/or expert judgment.

To support NRC's risk-informed initiatives, the quality of a PRA has been an important issue (see RG-1.200, 2007). As an important element of PRA, HRA also must satisfy certain requirements regarding quality in its analyses. Because qualitative HRA analysis underlies all aspects of HRA (e.g., the identification, definition, modeling, and quantification of HFEs), there has been an increased emphasis on qualitative HRA analysis. In addition, qualitative analysis can help in identifying effective "fixes" to human performance issues associated with risk-significant HFEs.

In HRA, unsafe actions are analyzed relative to other occurrences at the plant. Often a timeline is generated of events and activities preceding and following an initiating event. An *initiating event* is an event that can challenge the safety of the plant. Initiating events include failure of equipment from either internal plant causes (e.g., hardware faults, operator actions) or external causes (e.g., earthquakes or high winds), often called *internal* and *external events*, respectively. Examples of initiating events in SFH operations include:

- a cask hang-up or drop due to an aging-related crane component failure
- a crane operator impacting a cask on the side of a transfer pit opening
- a crane operator failing to terminate a cask lift such that a two-block event occurs
- a crane component failure leading to a two-block event.

Initiating events related to SFH encompass all activities centered on removing fuel from the reactor through sealing it in a storage cask.

In an accident sequence modeled in a PRA, three categories of events are included: 1) initiating events, 2) pre-initiators, and 3) post-initiators. For at-power, NPP PRAs, initiating events are plant upsets that require mitigation by various plant functions that are performed by systems, components, and, sometimes, operator actions. Initiating events for traditional PRAs are usually represented by initiating event frequencies that include both hardware and human-caused plant upsets. Similarly, the mitigating events that occur after the initiating event are post-initiators. A final piece of the overall context described by the accident sequence is pre-initiating events. These events occur before the initiating event and typically represent failed systems and components that were not known to be failed until the accident occurred. An example of a pre-initiator is the failure to correctly restore a system to operation following routine testing or maintenance.

Accident sequences for SFH differ from those modeled in traditional PRAs in that there usually are no mitigating actions that can be taken (and, therefore, no post-initiators to consider). Consequently, the focus of analysis for SFH events is how the initiating event is able to occur. Often, pre-initiating events contribute to the occurrence of initiators in SFH events. So, in the analyses done for this report, the authors found it helpful to build a chronology of events, starting with pre-initiators, in order to better understand the context that can lead to an initiating event.

To deemphasize the punitive aspects of the term *human error*, the unit of human activity captured in HRA corresponding to a basic event in a PRA is called a *human failure event* (HFE). Human actions can be either successful or not. Unsuccessful actions, or failures (as defined by the PRA), are modeled as HFEs. But, successful human actions can be represented in traditional PRAs, too, usually as "up branches" in event tree models. Successful human actions can result in the "recovery" of a failed function, system, or component (due to either hardware or human causes) that was modeled earlier in the accident sequence. However, even "recoveries" as typically defined in PRA, are actually modeled as failures to recover (or non-recovery actions).

When qualitative HRA analysis is performed outside of traditional PRA, as for this analysis of SFH operations, the term *recovery* is a subset in the broader concept of “successful human actions.” In this sense, the word "recovery" may be used to identify the correction of (i.e., recovery from) a preceding UA that occurs close in time with the original UA (e.g., self-checking recovery of an error) or that has been inspected by a co-worker such that the original error is caught and corrected before any harm occurs. In both of these examples, this type of recovery avoids the occurrence of an HFE (which actually represents the initiating event), such as dropping a cask. Without consideration of such opportunities for recovery and the successful execution of recovery actions, it remains difficult for the analyst to evaluate the potential for initiating events for SFH operations.

B.1.2 Qualitative and Quantitative HRA

Broadly speaking, HRA consists of two major activities: qualitative and quantitative analysis.

In q*ualitative HRA,* HFEs are identified and defined from knowledge of expected human activities and which of these activities can affect the significant consequences modeled in PRA. After HFEs are identified and modeled, further information is gathered and evaluated in HRA qualitative analysis in order to support HRA quantification. In particular, the aim of most qualitative HRA is to identify the primary drivers of human performance and reliability. These drivers can be described or expressed in a variety of ways, usually depending on the HRA quantification method that is used. Examples of such descriptions include performance shaping factors (PSFs) and error-forcing context (which includes both plant conditions and PSFs). The results of a qualitative HRA may also be used as the basis for making improvements that reduce opportunities for unsafe acts (UAs) and HFEs.

The ultimate goal of *quantitative HRA* is to produce a probabilistic estimate of the failure likelihood for an HFE. Called the *human error*[118] *probability*, this estimate typically ranges between 1E-5 (0.00001) and 1, with average or nominal values around 1E-2 (0.01) and 1E-3 (0.001), depending on the type of activity. As noted above, the HRA qualitative analysis provides inputs to HRA quantification, usually in the form of PSFs or other descriptions of human performance or reliability drivers. In many first-generation HRA approaches (e.g., Standardized Plant Analysis Risk-Human Reliability Analysis (SPAR-H) method [Gertman, Blackman, et al., 2005]), PSFs are treated as multipliers to increase a nominal human error probability. In a second-generation approach such as ATHEANA (NRC, 2000), an expert judgment elicitation approach is used to arrive at the appropriate human error probability which integrates all influences deemed important for human performance in a particular situation into one or more error-forcing contexts (EFCs).

While there are dozens of HRA quantification methods (NRC, 2006b), the qualitative underpinnings of HRA are similar across methods. There are some notable exceptions in newer HRA approaches, often called second-generation HRA methods (Boring, 2007), which tend to capture more details about cognition and context than their predecessors. Nonetheless, the shared goal of qualitative approaches is to generate insights into the causes of human performance decrements that may ultimately lead to UAs and HFEs. Qualitative approaches to HRA provide taxonomies for understanding the various factors underlying UAs as well as methods for consistently disseminating and documenting these factors (discussed further in Sections B.3 and B.4).

Usually, when qualitative and quantitative HRA are performed together for a PRA, both serve to identify potential improvements to plant or facilities operations. The dominant cut sets, generated after HRA/PRA quantification, are used to identify risk-significant accident sequences and, therefore, HFEs and associated human actions of interest. Then, the understanding of

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[118] The “human error” portion of *human error probability* is deeply ingrained in the culture of PRA communities. To avoid the negative connotations discussed previously it might be better for the PRA community to adapt to using the terms “unsafe action probability” and “human failure event probability.”

human performance and reliability drivers developed in qualitative analysis can help identify effective "fixes" to the human performance portion of the risk-dominant accident sequence.

In this investigation of spent fuel handling, the initiating event of a cask drop is already known to be important. Furthermore, it also is known that human failures play an important role in causing this initiating event. Consequently, the qualitative HRA performed in this study is sufficient by itself in identifying effective "fixes" to the human performance contributions to cask drops.

B.1.3 Retrospective and Prospective HRA

HRA can be applied in two different types of analysis: retrospective and prospective.

A prospective HRA (also called predictive HRA) is the traditional and original way of applying HRA methods and techniques in support of a PRA study. In the traditional HRA/PRA study, HRA is used to model the plant or facility "as-operated" (as opposed to "as designed") while the rest of the PRA models the "as-built" aspects of the plant or facility functions, systems, and components. Consequently, important inputs to HRA/PRA include:

- plant procedures (especially, emergency procedures)
- information about operator training (e.g., content and frequency of training)
- crew staffing and dynamics
- interviews of operators and operator trainers
- simulations of PRA-relevant events
- past operational experience

The above information is supplemented by, usually, PRA-generated information, such as:

- sequence of events in an accident sequence
- timing of events in an accident sequence
- plant functions, systems, and components needed for successful accident mitigation
- failure modes for plant functions, systems, and components
- success criteria (e.g., number of pumps in a system needed to respond for success, time by which certain functions, systems, or components must be working for success)

Using information, such as that above, an HRA analyst must identify and define HFEs, then perform HRA quantification. As part of this analysis, likely drivers of human failure are identified and weighed.

Traditionally, HRA/PRA has been used on existing plants or facilities to assess their vulnerabilities to certain types of accidents. However, HRA/PRA can and has been used in the design of plants or facilities as well, providing useful information in determining the potential benefits of certain design features (e.g., alarms and their placement).

In *retrospective HRAs,* human actions are analyzed for events that have already occurred. For this type of HRA, there have been two different approaches and goals. First, this type of HRA has been used effectively in NRC research programs to better understand human performance and HRA/PRA needs, either to advance the state-of-the-art or to explore a new hazard or issue (e.g., fire PRA, low power and shutdown PRA). For example, the development of NRC's ATHEANA HRA method is strongly based on retrospective analyses of operational events in which operator failures play dominant roles (e.g., NUREG-1624, Rev. 1). Other examples include: NUREG-1921 (for fire HRA/PRA), and NUREG/CR-6093 and NUREG/CR-6265 (for

HRA/PRA in low power and shutdown). In this type of research, HRA is used with the goal of determining the root cause of the event and understanding human performance issues that contributed to the adverse outcome. Such information can be used to develop new HRA/PRA methods or modify existing methods for new applications. In addition, insights may be developed that can be used to improve human performance.

A second goal of retrospective HRA is to support, generally, NRC's risk-informed activities, through retrospective HRA/PRA evaluations. Examples of two NRC risk-informed activities in which HRA/PRA evaluations play a role include the Significance Determination Process (SDP) and the Accident Sequence Precursor (ASP) program. The SDP process evaluates the risk significance of each licensee violation and uses that information to determine enforcement actions (e.g., a Notice of Violation which requires the utility to respond with a plan to correct the violation and ensure it does not happen again, and possibly a fine if the risk significance is high). The ASP program evaluates U.S. NPP operating experience to identify, document, and rank the operating events (precursors) that were most likely to have led to inadequate core cooling and severe core damage, accounting for the likelihood of additional failures. In both the SDP and ASP realms, NRC uses simplified, plant-specific PRA models (called SPAR models) and a simplified HRA method (i.e., SPAR-H) to estimate the risk-significance accident precursors or violations of license requirements.

B.1.4 Differences Between Control Room and Spent Fuel HRA

Most HRA/PRA studies for NPPs have centered on control room, at-power operations and response to emergency conditions. For the most part, SFH operations have not been addressed in HRA/PRAs. Consequently, this report is a first-of-a-kind qualitative HRA for SFH. As such, a full set of lessons learned on HRA for SFH is not readily available. An evaluation of the differences in HRA between control room operations and SFH includes the following:

1. *Procedures.* Whereas control room operations are very procedurally driven, SFH procedures are not as clearly defined because there is more reliance on the skill-of-the-craft of the operators. Control room operations feature extensive emergency operating procedures (EOPs) to provide symptom-driven responses to plant upsets. While SFH has clear emergency protocols, they are not as prescriptive or detailed as EOPs.

2. *Available time.* Control room operations almost exclusively take place during at-power operations, in time windows that are relatively small to respond to a plant upset. SFH cask loading and movement also can take place during plant at-power modes, but it may or may not have a potential to directly affect power production and reactor safety. As discussed in Sections 3.2 and 5.2, the drop of a spent fuel cask in some plant types could simultaneously initiate a reactor accident and disable accident mitigation equipment. In other plant types, a drop would not directly challenge the safety of the reactor core; thus, more time is available to deal with task hazards. However, CLCs (define CLCs) often occur before refueling outages to clear fuel out of the spent fuel pool (SFP); delays in the campaign can lead to time pressure as a planned outage approaches.

3. *Training.* Control room operation personnel are extensively trained and drilled in simulators. Personnel performing SFH activities are trained through transfer of existing skills (e.g., crane operations) and on-the-job training with accompanying pre-job briefings. SFH campaigns come at multiple-year intervals, and it may take several campaigns (e.g., 10–15 cask loads) before procedures are mature and the plant personnel are considered highly

proficient and skilled at the tasks involved (EPRI 2004). Thus, the routine and practiced quality of control room operations may not be present in SFH activities.

4. *Crew dynamics.* A control room crew trains and works closely together in well-defined roles at specific control stations within an optimized work environment at the plant. The control room crew benefits from the redundancy and oversight of the senior reactor operator. In contrast, the SFH crew works across a wider area of the plant encompassed by the cask transport path. SFH personnel may adopt multiple roles throughout the campaign. Noise and the dispersion of personnel across the transport path may severely hinder communication. Many handling activities require difficult physical manipulations that are locally achieved locally rather than centrally coordinated. Many plants feature customized equipment and systems, which can create mismatches in expectations between plant personnel and temporary contractors trained on generic systems or different plant-specific systems.

These differences create unique circumstances that make it important not to group SFH and control room operations under a unified HRA or PRA. These differences also must be considered in light of available HRA methods, most of which were designed for control room operations. The extent to which HRA methods can be generalized from control rooms to spent fuel requires further exploration. For this reason, this report takes a cautious approach to recasting existing HRA methods for the novel application to SFH. The approach is qualitative, because the objective is to identify and classify what appear to be the primary drivers of performance and to begin building a technical basis for improvements that reduce opportunities for UAs and HFEs. Moreover, the approach does not follow a rigid approach to qualitative prospective HRA. The approach is loosely based on the ATHEANA method (NRC, 2000), a second-generation HRA method, without a built-in control room specialization.

B.2 Human Error

B.2.1 Human Error at the Root of Incidents

Humans are remarkably resilient,[119] given the number of opportunities for failure; however, human errors occur with alarming regularity. Human error is perhaps the most significant contributor to the occurrence of incidents and accidents; it is certainly identified as the primary instigator in most accidents (Reason 1990). Human error within complex systems is especially relevant and may be difficult to diagnose because of tightly coupled systems. If latent error conditions[120] align properly, an accident can propagate throughout the system, wreaking havoc along the way. To combat this, complex systems such as NPPs and the nuclear power industry put in place a line of safety systems and catches. These layers of protection, commonly referred to as defense-in-depth,[121] arrest the cavalcade of incidents that might otherwise lead to an accident.

In general, human errors are human actions that lead to failures of systems or components. These errors occur in all industries, but they are especially important to avoid in operations that, if damaged, might expose the community, personnel, and the environment to significant hazards. There is a trade-off between prosperously manufacturing products or providing services and ensuring adequate protection against consequences to persons, property, and the environment, should an accident occur. Issues arise in the cost incurred in providing necessary protection. Although in the long run the goals of (1) ensuring productive manufacturing or provision of services and (2) ensuring a safe production environment should be compatible, in the short run, competition of available resources causes a conflict. As time and money are invested in production, they may not be available for safety, and vice versa (Reason 1990). This trade-off becomes particularly important in very hazardous conditions in which protection should be increased as danger grows. This conflict is represented in Figure B-1.

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[119] In this case “resilient” means tending to recover from or adjust easily to change or slight misfortune in order to achieve a successful outcome. This can be a property of individuals and teams/organizations. A very simple example of resilient behavior would be making a mistake in typing a word in a letter, then immediately recognizing and correcting the error before sending the correspondence. Another example would be correctly interpreting a badly misspelled word in a letter from someone else due to understanding the context and subject matter of the rest of the letter.

[120] Latent error conditions are conditions, often resulting from unsafe actions within a complex organization, which may be present (possibly many years) before combining with local circumstances and active failures to defeat a system’s many layers of safety protections. Latent error conditions “set up” personnel for active unsafe actions and human failure events that may occur at some point in the future. Examples of latent error conditions include: poor design, gaps in supervision, undetected manufacturing defects, undetected aging or corrosion damage, failure to complete reassembly steps during maintenance, etc. See glossary for additional information.

[121] Defense-in-depth may also be defined as employing multiple safety barriers of increasing conservatism (e.g., engineered safety margins, performance monitoring). See the definition of *defense-in-depth* in the glossary.

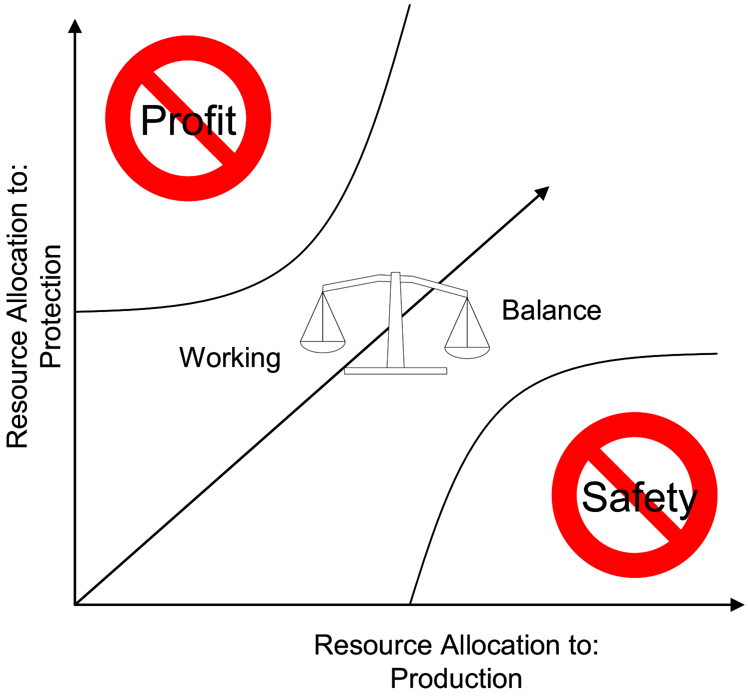

Figure B-1 Trade-off incurred in operating profitably while simultaneously adequately protecting against lurking hazards.*

***Adapted from Reason 1997.**

Accidents at an NPP are likely perceived as more detrimental than in other industries because of concern about the potential risks of radioactive materials (Fischoff, Slovic et al. 1978; Cohen 1990). Although an accident may not lead to radiation exposure that contributes to early fatalities or latent cancers, it will affect the public's confidence and may harm the continued use of the technology (Fischoff, Slovic et al. 1978; Jasanoff 1998; Freudenburg 2001; Cha 2004). Therefore, great care must be taken to protect against NPP accidents. Most areas within NPPs, including SFH, are maintained safely through multiple layers of defense. However, strides can be taken to provide stronger guarantees against failure.

Human error has been found to contribute to 70% (Trager 1985) to 92% (Reason 1990) of incidents and accidents at U.S. NPPs. Statistics are similar in other industries; for instance, 50% to 70% of aviation accidents are attributed to human error (Perrow 1999). Yet, it is important not to draw hasty conclusions from these statistics. The overall percentage of incidents in relation to successful operations remains extremely low, attesting to the overall safety of the industry and the safety and resilience of plant personnel. Human error rates remain low in NPP operations, yet possible human errors are major potential contributors to accidents.

Formally defined, human error is any unwanted action that results in a deviation from expected norms and potentially places people, equipment, or systems at risk of injury or damage. Human error may be an actual incorrect action (an error of commission) or the failure to carry out a required action (an error of omission). Not all human errors escalate to seriously jeopardize safety. Most human errors are inconsequential, and those of potential consequence are often quickly caught and remedied. This ability to recover from most potential errors, both anticipated and unanticipated, highlights the resilient nature of people and the necessity of having them play key roles in controlling high-consequence activities. Plant processes are designed to be single-fault tolerant, meaning a single equipment failure or human error will not trigger an unsafe condition or incident. For example, most processes require verification or double-checking to reduce the likelihood that errors go undetected. Still, no process can be foolproof, especially in complex human-system interactions. Undetected and uncorrected errors have contributed to unsafe conditions at plants and to reportable incidents and accidents.

In the PRA community, *human error* has often been used to refer to human-caused failures of systems or components. However, in the behavioral sciences, *human error* is often used to describe the underlying psychological failures that may cause the human action that fails the equipment. Therefore, in this report (as in the ATHEANA HRA method) *human error* is used in a very general way, and the terms *unsafe action* and *human failure event* are used to describe more specific aspects of human errors (NRC, 2000; NUREG-1880, 2007). *Unsafe actions* are actions inappropriately taken, or not taken when needed, by plant personnel that degrade plant safety.[122] A *human failure event*, modeled as a basic event in the logic models of a PRA, represents the failure of a function, system, or component, and it results from one or more *unsafe actions*. In addition to using the term *unsafe actions*, this report distinguishes between significant differences in the timing and observed impact of unsafe actions by using the terms *active unsafe actions* and *latent unsafe actions*. An *active unsafe action* degrades plant safety and immediately or almost immediately results in an observed failure of a function, system, or component (e.g., raising a heavy load too high resulting in a two-block failure with subsequent damage to a crane or dropping a cask and initiating a loss-of-coolant accident and simultaneously disabling safe shutdown equipment). In contrast, a *latent unsafe action* results in a degraded plant safety condition that does not immediately result in such an observed failure, but it may lead to an observed failure after a period of time (e.g., incorrect inspection, maintenance, or test of a critical crane component). Additional examples of both types of UAs are provided in the next section.

B.2.2 Unsafe Actions in Nuclear Industry Crane Operations

Figure B-2 from NUREG-1774 (2003) illustrates the percentage of reported incidents involving cranes in the U.S. nuclear industry from 1969 to 2002 that included a UA. The percentage increased from under 40% in 1969 to over 80% in 2002, with an average of 73%. This figure might suggest that UAs are increasing; however, a more careful reading is necessary. The figure provides only the percentage of reported events that feature UAs. The figure does not show that the rate of crane incidents is increasing, only that the percentage of those incidents featuring UAs is increasing. The figure does not account for potential increases in crane activities at plants during the same period. As the percentage of crane activities has increased, has the overall incident rate stayed proportionate to the activity level? Further study of NUREG-1774 suggests that incidents featuring UAs have increased over time, not just as a percentage of overall incidents. However, this rising rate may not actually indicate an increase in UAs. The nuclear industry's sensitivity to UAs has increased substantially over the years, suggesting that incidents involving UAs are increasingly likely to be correctly classified as such. Historically, UAs may have been under-reported.

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[122] Another subtle distinction that can be made between "human errors" and "unsafe actions" is that it is possible to have inconsequential human errors that do not degrade plant safety in any significant way.

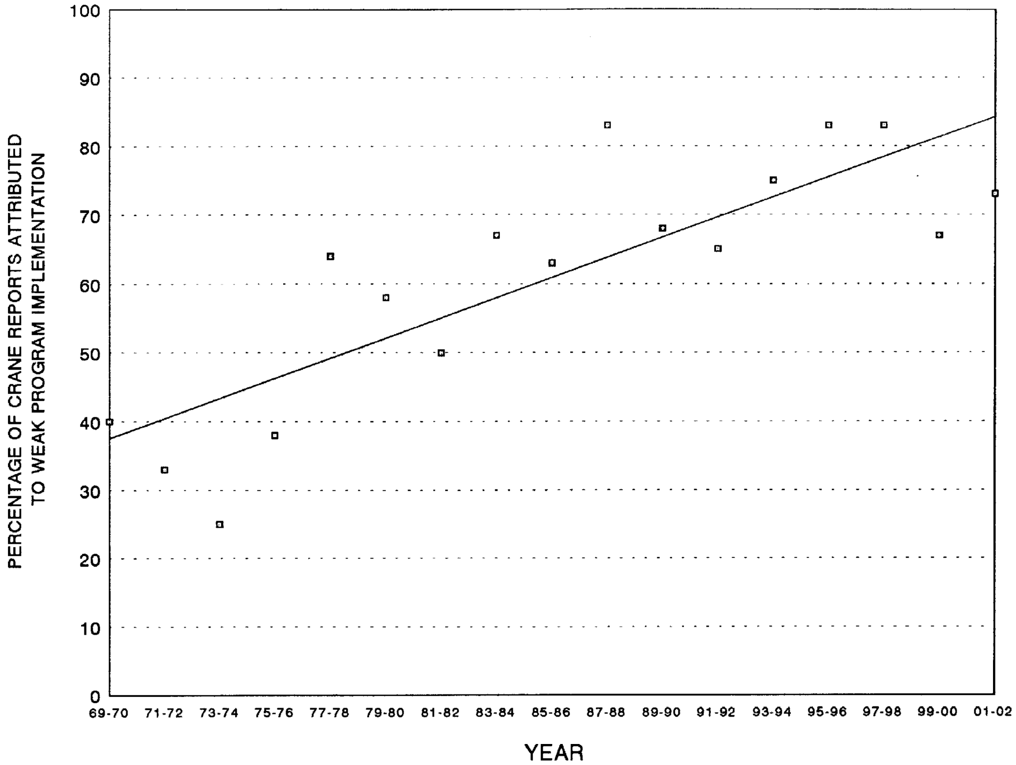

Figure B-2 Percentage of crane operations featuring unsafe actions.*

*** From NUREG-1774 (2003).**

Figure B-2 does not classify the crane activities or the UAs, for which a deeper investigation of NUREG-1774 is necessary. Key insights drawn from reviewing NUREG-1774 as well as other relevant literature are presented in Section 4. This review summarizes recent concerns occurring in DCSOs and emerging issues related to accidents in SFH. However, a short synopsis here helps communicate the importance of human error within this arena, as well as the impact of UAs.

Crane activities referenced in NUREG-1774, involving very heavy loads (over 266,893 Newtons (30 tons)), actually have a lower error rate (around 56% of these incidents featured UAs). This difference may be attributed to more safety-conscious operational processes because of increased awareness of the high consequences of mishandling a very heavy load and less use of “below-the-hook” rigging gear. NUREG-1774 categorized the types of UAs that occurred across all incidents as shown in Table B-1.

Table B-1 Type and rate of unsafe actions for crane activities.*

Attributable to:	Percent (%)
Poor procedures or not following procedures properly	40.9
“Failure to move loads over established safe load path areas”	11.2
“Failure to perform crane surveillance tests prior to use”	9.8
Human errors in the maintenance process	8.8
“Failure to establish the required ventilation prior to load movements”	8.6
Engineering or design issues	7.2

*As categorized by NUREG-1774.

The types of UAs presented for crane operations illustrate the distinction between active UAs and latent UAs. (To reiterate, active UAs have immediate consequences—the effects will immediately or almost immediately result in an observed adverse condition.) A failure to move the loads over the established load path would in many cases readily manifest the consequences of that UA. For example, the load may impact surrounding equipment or structures.

Not every incorrect load path will have immediate consequences, however. Crane operators may consistently follow the incorrect load path with no adverse effect, which reinforces the behavior along with the mindset that the load path is not important in the overall safety process. The crane operator may not realize that the prescribed path may account for situational dynamics beyond the typical case. There may be mobile obstacles that only infrequently obstruct the path. Also, the safe path may avoid safety-critical systems and related structures on lower-floor levels that could be damaged from a freefall cask drop. As a precaution, the prescribed path circumnavigates potential areas of collision or impact, even though the frequency of such an event may be rare. Systematically ignoring the prescribed load path is a form of latent UA. The workaround[123] is not perceived as risk significant, and the very real, yet infrequent, opportunity for collision or drop is ignored or not understood.

As stated previously, latent UAs are actions or inactions that do not immediately result in an observed failure of a function, system, or component, but they degrade safety and may eventually contribute to an observed failure after a period of time. In an analysis of 37 safety significant events at NPPs, it was found that latent UAs were present four times more often than

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[123] *Workarounds* are informal rules or manners of executing tasks which, although they deviate from “as-designed practices and procedures” they reflect the commonly accepted “as-built way to get things done” either because the as-designed process is unworkable or simply because the workaround is more efficient (see also the definition of *informal rules* in the glossary).

active UAs (NUREG/CR-6753 2002). The most common type of latent UAs are related to engineering or design issues or maintenance errors.[124]

A design issue typically results when the system designer has not considered all possible uses, situations, or interfaces of a system. As such, a design issue may go undetected until the system is called into service in a particular way that challenges the design as built. For example, in the crane pendant design, potentially harsh environments and operating conditions of daily use may not have been taken into account. While well designed in other respects, the crane pendant may not stand up well to severe use conditions of the plant (e.g., being dropped).

Latent maintenance UAs tend to occur when a system that has been worked on is not restored to proper working order. Such UAs, when they result in degraded equipment performance, may go undetected in post-maintenance testing but may later result in failure when the system is in use. Maintenance UAs can also contribute to common cause failures whereby a failed component impairs the performance of downstream equipment.

Latent UAs are, of course, not just limited to design and maintenance. Crane operations reveal a significant number of latent UAs as well. For example, crane personnel may fail to inspect or test the rigging gear across multiple CLCs. This latent UA does not cause a potential rigging problem. However, the absence of inspection and/or testing between rigging operations creates a latent error condition that increases the chance that a rigging problem will go undetected and manifest itself as a rigging failure.

B.2.3 Unsafe Action and Failure Defenses

Reason (1990) formulated what has subsequently come to be known as the Swiss Cheese Model of Accidents (Reason, Hollnagel et al. 2006) to explain how latent UAs resulting in latent error conditions can rise to the surface to become active UAs and/or active failures. As depicted in Figure B-3, barriers and defenses are never perfect; gaps or holes of varying sizes and types are always present—these penetrations are latent error conditions on the barriers and defenses. When holes in barriers and defenses align inopportunely, it is possible for the hazard to penetrate these barriers and defenses to become an active UA or failure. A latent error condition such as a cracked crane support structure may escalate to active crane failure if plant personnel fail to inspect it properly before carrying heavy loads. A crane operator's improper or unanalyzed cask load path may serve as an active UA that can escalate into an active failure in the form of the cask colliding with an unanticipated object along the load path.

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[124] According to a review by Reason (1990), the most common latent unsafe actions contributing to system failure is the failure to remove tools or complete a reassembly action following maintenance.

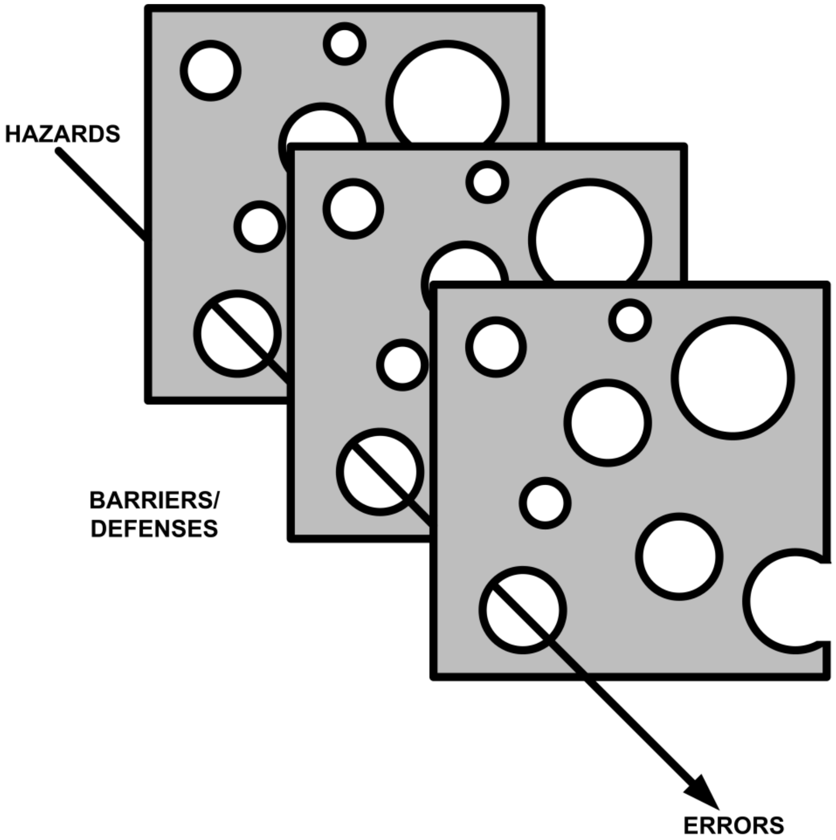

Figure B-3 The Swiss Cheese Model of how latent error conditions can become active errors, unsafe actions, or active failures.*

*** Adapted from Reason 1990.**

Common barriers and defenses in the Swiss Cheese Model range from simple measures such as safety equipment to complex defense-in-depth systems such as redundant or automatic engineered safety systems (Reason 1997). Barriers and defenses may be further thought of as hard and soft. Hard barriers and defenses encompass physical systems such as “automated engineered safety features, physical barriers, alarms and annunciators, interlocks, keys, personal protective equipment, nondestructive testing, designed-in structural weaknesses (for example, fuse pins on aircraft engine pylons) and improved system design” (Reason 1997, p. 8).

Soft defenses (i.e., administrative controls) rely more exclusively on humans minimizing the opportunity for UAs through both regulations and human-system interactions. Regulations may be put in place to ensure the operation of equipment within certain bounds. The opportunity for UAs and failures in human-system interaction may be minimized, for example, through training, procedures, and second checkers. Both hard and soft barriers and defenses ultimately decrease the chance that a particular hazard can escalate to become an active failure or accident.

According to one interpretation, the more barriers and defenses that are put in place, the less likely a latent UA is to result in consequences. It may seem that the key to a fool-proof system is to create a defense-in-depth system that would never allow UA or failure penetration. Practically speaking, barriers and defenses must be kept to a realistic level. They add complexity, time, and cost to operations and, in excess, can impede productive plant operations (recall the balance shown in Figure B-1). Such impediments may have the unintended consequence of encouraging workarounds or overwhelming the operator such that the safety implications of critical activities are not obvious. Moreover, as complexity increases, the opportunity for new, unforeseen latent UAs may actually increase by introducing new vulnerabilities to hazards.

B.2.4 Individual Culpability

Unsafe actions, whether active or latent, should rarely be blamed on the individual linked to those actions. Dekker (2006) points out the tendency to ascribe blame in an incident caused by UAs. Dekker calls this the "Bad Apple" view of human error, in which the specific human at fault is emphasized rather than the UA. In reality, UAs are rarely caused by the peculiarities of a particular person; they are caused by actions made possible and even facilitated by the work environment. Again, the types of UAs that occur in crane incidents help to illustrate this point:

- UAs related to procedures often stem from a poor match between the situation and the procedures. Such procedural errors may represent a case of oversimplification in the procedures, forcing the individual to exercise considerable judgment in how to implement the procedures. Conversely, procedures may be too complex for the situation, overtaxing the individual attempting to follow them. Or, the situation may be complex, requiring the individual to juggle many tasks simultaneously, leading to an increased chance of skipping a step in a procedure.

- As already discussed, a failure to follow the prescribed load path may be the result of well-entrenched workarounds because personnel do not properly understand the safety implications of the load path. The innate capacity of humans to invent more efficient ways to do things can mix with a reinforced emphasis on production and productivity over safety—with negative consequences.

- A failure to perform crane surveillances prior to use is, like load path failures, a product of deemphasized safety and the need or desire to find more efficient ways of performing tasks. Personnel involved in crane operations may not have received adequate training on the necessity of surveillance activities, the plant culture may not emphasize the importance of seemingly redundant steps to ensure safety, time pressures may exist to accelerate crane activities, or staffing levels may be inadequate to ensure proper second checking.

- Individuals not involved in operating the crane typically perform maintenance activities. As such, their mental model of the system may not completely encompass the actual uses of the system. Safety implications may not be clear in all cases. The maintainer is working on as-built systems and may not have full documentation or training requisite for the systems, resulting in some amount of guess work to restore proper system functioning. Manufacturer-specified replacement parts may not be readily available for degraded systems requiring maintenance. Maintenance personnel brought in to repair a broken system may experience time pressure and high stress if operations have been suspended pending completion of the repair.

- A failure to establish required ventilation before a cask movement may be a result of inadequate pre-job briefing, a lack of knowledge about the specific materials being handled, or an incomplete understanding of ventilation requirements and the potential consequences for not meeting those requirements.

- As previously discussed, engineering or design issues typically result from a failure to consider components or systems in the full range of contexts they will be used. That is, the requirements basis used during design was inadequate. Or design limitations may not have been fully considered for systems requalified for new uses. For example, a crane designed to handle specific loads may, over the course of its operational life, be uprated to handle heavier loads. Such heavier loads may fatigue the crane more quickly than originally anticipated, requiring shorter maintenance intervals or new surveillance approaches not anticipated in the original design or equipment procedures. Heavier load carrying may also require changes in operation of the crane; thus, current training for crane operators becomes crucial.

While the individual should be held accountable for his or her actions, such accountability should be viewed in the context of that individual's experience, task expectations, and work environment. Before blaming an individual for a UA, it is necessary to ask, "Were there factors that primed or 'set up' the individual to commit the UA?" These factors may be seen as error-forcing contexts (EFCs), discussed later in this report. Often, UAs are systemic, and it is mere chance which individual commits them. In determining the cause of an actual or hypothetical incident, it is necessary to consider not only the individual's actions in isolation but also the overall context that made the UA possible.[125]

B.2.5 Unsafe Actions and Safety Culture

Section B.2.4 illustrated that a UA is often the product not simply of individual actions but rather of an environment that may have encouraged or "set up" an individual or team to commit a UA. A safe system is one with an appropriate and effective defense-in-depth system in place, one that offsets the ability to perform a UA leading to significant consequences. By planning for UAs and HFEs and assuming they will occur, the system (whether machine or human operator) can be designed to defend itself and continue to operate safely. The system and management can bolster this defense mechanism by ensuring an effective *safety culture* is in place. The NRC defines *safety culture* as: "the core values and behaviors resulting from a collective commitment by leaders and individuals to emphasize safety over competing goals to ensure protection of people and environment" (Final Safety Culture Policy Statement, 2011, p. 34773). With this definition, the commission describes nine traits inherent in a positive safety culture (p. 34777-34778):

1. Leadership Safety Values
2. Problem Identification and Resolution
3. Personal Accountability
4. Work Processes
5. Continuous Learning

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[125] Reason (1997) discusses the importance of developing a reporting culture. Such a culture encourages individuals to report errors by deemphasizing the punitive aspects of errors. Reason draws heavily on lessons learned from NASA's Aviation Safety Reporting System, a voluntary tool for self-reporting errors and near misses. Reason suggests a number of factors that contribute to the success of this system, including indemnity, confidentiality, and ease of reporting. The indemnity cannot be limitless and only extends inasmuch as the error was not intentional or criminal.

6. Environment for Raising Concerns
7. Effective Safety Communication
8. Respectful Work Environment
9. Questioning Attitude

If a robust safety culture is established within an organization, UAs are much less likely to occur. Such organizations are resilient both in avoiding UAs and in recovering from UAs or their precursors in a way that prevents HFEs (e.g., cask drops) from occurring. An organization with a robust safety culture proactively schedules inspections, reports results, and makes modifications as appropriate to maintain and improve the safety of operations. The importance of establishing and maintaining a robust safety culture will be emphasized further in Section 6.

B.3 Mechanisms and Taxonomies Related to Unsafe Actions

This section briefly describes four items from the behavioral sciences that provide a foundation for understanding the origins of UAs and a starting point for understanding how human performance may be improved. The first item is a model showing how the acquisition and application of skills affects human performance. The second item is an early taxonomy of error types corresponding primarily to one portion of the skill acquisition model. The third item is a contemporary, widely used error taxonomy that relates error mechanisms to all portions of the skill acquisition model. The fourth item is a simplified representation of the mechanisms involved in human cognition, which may be applied to both individuals and teams of people engaged in goal-directed behavior. Together these four items provide a useful context for discussing (beginning in Section B.4) numerous factors influencing human performance that may be used to analyze UAs in a specific context using both reductionist and holistic methods (i.e., a convergent approach for revealing practical insights for avoiding UAs).

B.3.1 Rasmussen's Skill Acquisition Model

Rasmussen's skill acquisition model, also known as the Skill/Rule/Knowledge-based (S-R-K) taxonomy, is widely used to understand human performance and UAs (Rasmussen 1979). It is not an error taxonomy but rather a model showing how the acquisition and application of skills affects human performance. It is a foundation upon which taxonomies of UAs have been built. Rasmussen classifies performance along a continuum based on the worker's skill level:

- *Skill-based behavior* — Behavior that requires very little or no conscious control to perform or execute an action once an intention is formed. Skill-based actions involve segments of preprogrammed behavioral sequences interspersed with occasional, momentary, conscious attentional checks to monitor the progress of the sequence. Using system engineering or control theory terminology these are primarily *feed-forward* or *open-loop* behaviors. An experienced driver driving a car in a familiar environment, an experienced crane operator moving familiar loads along familiar load paths, and many rigging tasks are composed primarily of skill-based behaviors. UAs involving skill-based behaviors tend to be the largest numerical contributors to the set of observable errors; however, these errors amount to a very small proportion of the total number of skill-based actions performed. That is, skill-based actions are usually executed correctly.

- *Rule-based behavior* — Behavior based largely on *feed-forward* use of rules and procedures to trigger or select courses of action in familiar work situations once a need for deviating from skill-based execution is detected. The feed-back elements of rule-based behavior include the modification of goals and selection of procedural directions to follow; however, this selection process may involve many rapid choices which are semi-automatic (i.e., made with little conscious effort) based on environmental cues. “Very often, the goal is not even explicitly formulated, but is found implicitly in the situation releasing the stored rules . . . the rule is selected from previous successful experiences” (Rasmussen 1986, p. 102). A common example of rule-based behavior is an experienced driver responding to unexpected interactions with other cars or traffic control signals. The driver consciously detects a problem, selects a rule to follow, and then switches back into skill-based behavior. An example of rule-based behavior in the nuclear power control domain would be an operator reading an instrument displaying the level of coolant in the annulus of a BWR and semiconsciously translating that into being the same as that within the shroud—because that mapping is usually true. In SFH operations, an example of rule-based behavior would be a crane operator moving a cask when suddenly an alarm indicates an overcurrent situation on the crane; the operator releases the lever controlling cask movement, but the alarm continues to sound; the operator then follows the standard procedure by hitting the emergency power shut-off button, which resolves the immediate problem.

- *Knowledge-based behavior* — Behavior that relies on problem solving and uses slow, sequential, effortful, and resource-limited conscious activity to select the appropriate course of action in novel situations. Knowledge-based behavior is initiated after rule-based behavior fails to resolve a problem that was initially identified during execution of skill-based and/or rule-based actions. It is common for individuals to cycle back and forth between rule-based behavior and knowledge-based behavior until an apparent solution to the problem is found (Reason 1990). While errors involving knowledge-based behaviors tend to be the smallest numerical contributors to the set of observable errors, these errors amount to a large proportion of the total number of knowledge-based behaviors executed. In other words, knowledge-based behaviors tend to be required by unusual, unexpected, challenging situations often involving large amounts of uncertainty with respect to achieving a successful outcome. Knowledge-based behavior is prevalent during the learning of a new skill and when something unexpected occurs during execution of an otherwise well-learned skill. Thus, it is understandable that situations demanding knowledge-based behavior, especially when little time is available for action, will often lead to undesirable outcomes.

  For example, knowledge-based behaviors are common among teenagers learning to drive a car. New drivers must constantly move their attention to process feedback from outside the vehicle (e.g., lane markings on the roadway ahead, other traffic on all sides, fixed objects) to inside the vehicle (e.g., the speedometer) while executing steering, acceleration, or braking maneuvers, which accomplish goals of travelling to a desired location. Until skilled behaviors develop, a tremendous amount of consciously controlled mental effort is required to carry out all of these tasks without incurring a negative outcome (e.g., collision, speeding violation). For the highly experienced driver, knowledge-based behavior may only be prevalent when navigating to an unfamiliar location during poor weather conditions (i.e., referring to a paper map and written directions while traveling at night during heavy rain along poorly lit roadways). An example of knowledge-based behavior in the nuclear power control domain would be an operator discovering that three instruments are all displaying values that conflict with his/her understanding of the state of the reactor in different ways (i.e., one reports coolant level too low, another shows coolant level too high, another indicates excessive pressure). The operator will predominantly carry out knowledge-based behavior while seeking additional information and taking actions until he/she believes that a safe operating state has been achieved. In the SFH domain, consider a crane operator who is moving a loaded fuel cask when he/she senses that the load is encountering resistance on its travel path (e.g., a hang-up during lifting). First, the operator will likely execute the rule-based behavior of halting the lift; second, the operator will likely transition into knowledge-based behavior to assess the state of the cask and crane and determine the next course of action (e.g., lower the cask or hold in place).

The S-R-K taxonomy is generally presented in reverse order of skill acquisition: knowledge-based behaviors predominate when we are inexperienced at the task; rule-based behaviors become common when we have adequate knowledge to follow procedures correctly; finally, skill-based behaviors dominate when we are sufficiently experienced and knowledgeable to perform tasks in a highly skilled and automatic manner with little explicit reference to procedures. The reason for the order of skill-rule-knowledge behaviors in the S-R-K taxonomy becomes apparent when considering skilled personnel executing skilled actions who encounter an unexpected situation. A typical sequence involves personnel transitioning from mostly skill-based behaviors interspersed with rule-based behaviors, to mostly rule-based behaviors interspersed with knowledge-based behaviors as undesirable system states fail to be resolved by previous actions. In highly unusual situations, personnel will spend long periods of time in the realm of knowledge-based behaviors. Figure B-4 shows the relationship between the types of behavior, types of situations, and conscious control modes required. The situations may be interpreted as the degree of familiarity, from low (novel problems) to high (routine). The control modes reflect the level of attention required by the task, from high attention (conscious control) to low attention (automatic control with momentary conscious “checks”).

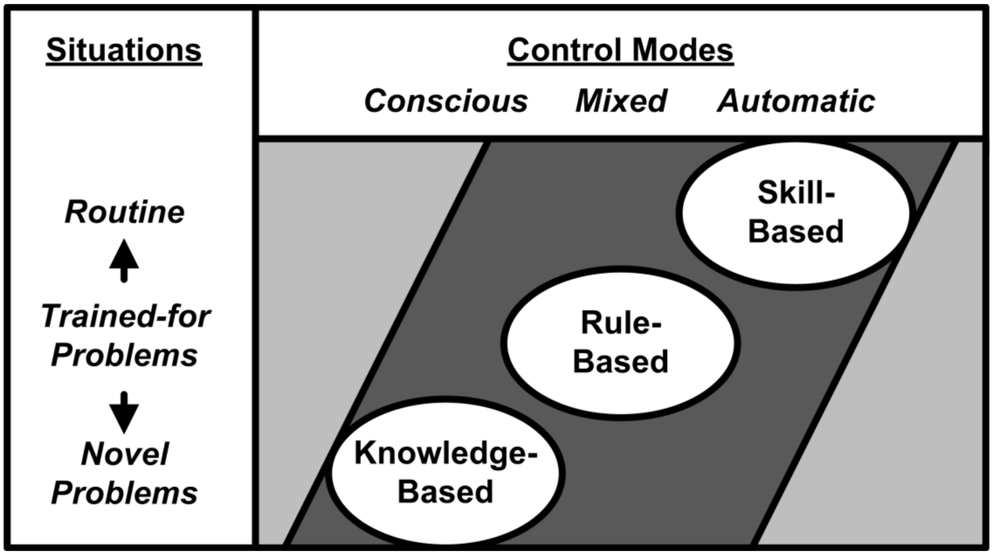

Figure B- 4 Location of the three S-R-K performance levels in relation to control modes and situations.*

***From Reason 1997, p. 69.**

Applying the S-R-K skill acquisition taxonomy proves useful for understanding the cause of an error in the presence of one or more particular PSFs. If upon inspection of an HFE, the analyst determines that the plant worker is using a knowledge-based approach to perform activities, this reveals that the worker is treating the task as a novel problem and expending considerable mental effort in consciously assessing the appropriate course of action. If there is also evidence that the worker was experiencing stress prior to the UA, this insight from the S-R-K taxonomy suggests that the stress was likely the byproduct of the lack of knowledge or novel aspects of the situation rather than the immediate cause of the error. The worker's lack of skill at the task results in increased task load and corresponding elevated disruptive stress, perhaps to the point of distress. The S-R-K taxonomy provides further insights into how such an error might be mitigated. The expectation at the plant is that the worker should act in a rule-based capacity for most operations, but that is not the case in this situation. The solution to this problem is not only training on the particular task but also providing a clear set of rules (i.e., procedures) to assist the worker for this type of situation, especially if it will be encountered infrequently. This combination of training and procedures simplifies the mental task load required of the worker and helps reduce the likelihood of a UA. Use of the S-R-K taxonomy also demonstrates that a cursory analysis of PSFs may not always uncover the fundamental PSFs that most important. For example, the S-R-K taxonomy analysis of an error may suggest that training and procedures might be deficient for a specific task. Observation of the generic PSF of "stress" in this case might be used to simply infer that the worker could not "work well under pressure," thereby masking the subtler effects of training and procedures that were the actual underlying cause of the error. The S-R-K taxonomy serves as a useful foundation for searching for all relevant PSFs and, in conjunction with the error taxonomies discussed below, aids in explaining why particular PSFs may impact performance.

B.3.2 THERP Error Types

Two error taxonomies provide a classification system for understanding distinctions between UAs.[126] Error taxonomies provide a causative model of *why* an error occurred. To this end, contemporary error taxonomies tend to focus on the general cognitive factors that affect performance. Error taxonomies do not provide details on the many factors describing *what* contributed to an error; rather, they provide explanations of why multiple factors affect performance. Error taxonomies help the analyst understand why a particular factor played a role in decreasing human performance. Given that the presence of one or more particular negative performance factors often does not lead to failure, error taxonomies help explain why a factor (or a particular set of factors) manifests a performance decrement on a particular occasion versus no effect on other occasions.

The first error taxonomy presented here accompanied the Technique for Human Error Rate Prediction (THERP) HRA method (NUREG/CR-1278) in 1983. Recalling Rasmussen's skill acquisition taxonomy, THERP primarily emphasized generating human error probabilities[127] for rule-based tasks. THERP presented four error types:

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[126] There is some ambiguity in the term, "error taxonomy." As used here, it refers to a concise classification system for errors. There also exist larger taxonomies such as those used in human performance databases like the Human Event Repository and Analysis (HERA) System (Hallbert, Boring et al., 2006; Hallbert, Whaley et al., 2007) or the Human Factors Information System (HFIS) (NRC, 2006) at the NRC. Such taxonomies are data structures rather than concise classification systems for errors. They are used primarily to capture information about a wide range of events of interest to the NRC.

[127] A human error probability is a measure of the likelihood that plant personnel will fail to initiate the correct, required, or specified action or response in a given situation or perform the wrong action. The human error probability (described in Section B.1.2 Qualitative and Quantitative HRA) is the

- *Errors of omission*—when a person fails to perform a required action
- *Errors of commission*—when a person performs an action that should not be performed[128]
- *Sequence errors*—when a person performs an action in the wrong order
- *Timing errors*—when a person performs an action too slowly or too quickly.

To further illustrate the role of an error taxonomy when coupled with a specific observed factor, consider again the plant worker who is experiencing a high level of stress due to high task load. In most situations, the worker will be able to perform his or her job duties successfully without errors (although perhaps more slowly). On one occasion, this worker commits a sequence error. Without considering the type of error according to the taxonomy, the analyst simply knows that an error occurred in the face of high stress. Upon consideration of the THERP error taxonomy, however, it becomes clear that the high stress and workload made it difficult to maintain the proper sequencing of required activities. This error might have been further compounded by the need to multitask, making it difficult to switch mentally between tasks. Simply understanding that stress was a contributor does not help to prescribe a corrective action to prevent the error from recurring. Guidance on maintaining low stress levels is not always realistic, nor is it tractable or enforceable in a plant context. Understanding the error type allows the analyst to pinpoint how stress contributed to the error. The resulting guidance might therefore aim to minimize opportunities for sequencing errors, such as minimizing the number of allowable simultaneous tasks by increasing staffing for particular tasks.

B.3.3 Reason's Error Taxonomy

A second error taxonomy, which has gained tremendous popularity and widespread application, was created by James Reason (1990). Reason's error taxonomy also consists of four error types and was built in close relation to the skill acquisition model developed by Rasmussen (1979; 1981; 1983). Unlike the THERP error types, which primarily focus on understanding the likelihood of failure for rule-based tasks, Reason's four error types provide a means to understand the mechanisms of failure for knowledge-, rule-, and skill-based tasks. Figure B-5 provides a mapping between Reason's error taxonomy and Rasmussen's skill acquisition taxonomy. The four error types (also called UAs when they degrade plant safety) are described below:

- *Slips — skill-based,* unintended UAs that lead to observable errors due to fallibility of attention processes. These errors are associated with a person's focus of attention, which may be characterized by *inattention* or *overattention*. The most common error form for slips involves inattention (i.e., failing to check the progress of a skill-based action at the appropriate time). The less common form involves overattention, in which a conscious attention check is made at an inappropriate time during a preprogrammed

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probability of the HFE. Often in HRA, PSFs (described in Section B.4 Factors Influencing Human Performance) are used to modify a base human error rate to determine the human error probability.

[128] Errors of commission have become an increasingly important topic in the nuclear industry. Particularly as operations and systems become more automated, the opportunity for human error is reduced. However, there is concern that operators may override automated systems at inappropriate times—an error of commission—when they do not properly understand what actions the automated system is performing. Overriding automated safety systems was a significant contributor to both the Three Mile Island Unit-2 and Chernobyl accidents, but has also been shown to contribute to many less significant events across the industry (NRC, 2000; Nuclear Energy Agency, 2006)

behavioral sequence. An example of an inattention slip would be a distracted crane operator who starts raising a load and then inadvertently fails to stop raising the load before activating a limit switch or two-blocking the crane. Another example is a crane operator walking across the plant floor toward the crane cab ladder to climb into the cab to look for a lost pen. Due to an internal distraction, the cab operator does not turn down the aisle toward the ladder, but proceeds on to the door of a nearby restroom (i.e., inattention at a critical time leads to execution of another preprogrammed, unconscious routine). Another example could involve a worker intending to maintain visual confirmation of a safe load path, who fails to notice that a forklift driver has entered the restricted zone while moving the load (i.e., inattention). An example of the less common type of slip would be a crane operator who intends to raise a load, but while attending to a nuisance alarm on his display panel inadvertently activates the crane control in the direction for lowering[129] (i.e., overattention to stimuli during performance of a typically unconscious/preprogrammed routine).

- *Lapses* — *skill-based,* unintended UAs that lead to errors due to the fallibility of memory. These actions are characterized by an individual forgetting to perform an intended action, often because of an interruption or unanticipated need to modify an action sequence. For example, a worker intends to retrieve a radiation monitor to survey a cask lid, but while walking to the radiation equipment cabinet, he notices a pile of wet rags on the floor. He picks up the rags, deposits them in the proper receptacle, and returns to the cask without retrieving the radiation monitor. Another example of a lapse would be a worker noticing that a torque wrench has not been calibrated before fastening a bolt on a cask lid. Upon noticing the deficiency, he walks over to the calibration table where the calibration gauge should be. Not seeing the gauge, he rummages about to find it and put it in its proper place. Finally, he returns to the cask lid, having forgotten to calibrate the torque wrench. Some lapses involve errors not readily observable to anyone beyond the individual performing the action. An example would be inadvertently forgetting a step in a procedure, but later realizing the omission and correctly executing the procedural sequence (i.e., all that is visible to an outside observer is a delay).

  It should be noted that the distinction between slips and lapses of different varieties is complex because they both involve subtle distinctions between levels of momentary conscious engagement in otherwise automatic behaviors and the interplay and/or switching between the internal resources associated with attention and memory. Slips and lapses are associated with *skill-based* actions, which generally result in errors before there is any conscious awareness of a ”problem” or “error” needing resolution. Mistakes and circumventions/violations, discussed below, involve inappropriate intentions to act that are founded upon various levels of conscious engagement during *rule-based* and *knowledge-based* behaviors.

- *Mistakes* — errors of intention arising from *rule-based* and *knowledge-based* behavior that use the wrong plan, despite whether or not the resulting action was successful. In this case, the person performing the action has the wrong mental model of how to perform the activity. Even if the resulting action is successful, it represents the wrong

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[129] In this example the crane operator had recently lowered the lifting yoke a significant distance; therefore, when momentarily distracted, he or she reverted back to the automatic preprogrammed “lowering” skill behavior. Actions that have been performed recently or actions that are most often performed are strong “attractors” during instances of inattention or overattention. Another way this has been described is by the phrase *strong-but-wrong* action or habit intrusion (Reason 1990).

way of performing that task and is considered an error. If the mistake results in a degraded plant safety condition then the error is an intended[130] UA. The specific form that a mistake will take, particularly when it involves *knowledge-based* actions is very hard to predict. This is because mistakes arise from a complex interaction of cognitive factors such as biases,[131] an inability to consider a large number of relevant factors, and incorrect mental models. An actual example of a mistake involving *rule-based* behavior in the nuclear power control domain occurred at Oyster Creek. An operator read an instrument displaying the level of coolant in the annulus of a BWR, semi-consciously translating that into being the same as that within the shroud (because that is usually true) and taking apparently appropriate actions. Unfortunately, in this case, the annulus and shroud levels were dramatically different due to a previous *skill-based* error in which a pump discharge valve was inappropriately closed. Thirty minutes passed before the core cooling deficiency was identified and eliminated. An example of a mistake involving cask movement would be to intentionally move a cask along an inappropriate load path (i.e., one that moves the load over safety-critical equipment) due to misinterpretation or miscommunication of the instructions describing the safe load path. In this case the crane operator would be doing exactly what he intended to do, but with an incorrect "mental model" of what to do. This intended unsafe[132] action might not be associated with any negative consequences on many occasions, which could reinforce this inappropriate behavior. However, if the cask were to drop due to an equipment failure or HFE, this UA may contribute to large negative consequences.

- *Circumvention*[133]*/ Violation* — an error arising from *rule-based* and *knowledge-based* actions that involves deliberately deviating from rules and practices with the intention of maintaining safe or efficient operations (Reason 1990; NUREG-1624 2000). Circumventions (i.e., workarounds or informal rules) may be routine, in which case they are usually shaped by procedures that are impossible to implement, or they may be an attempt to arrive at shortcuts or efficiencies in an environment that does not enforce

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[130] Intended here simply means that the person executes the action that corresponds with their mental model indicating what should be done in that situation. The person does not intend to do something they understand to be "wrong"; however, the person's mental model of what to do is inappropriate.

[131] The definition of a "bias" encompasses a systematic tendency or heuristic which limits a comprehensive application of available knowledge, experience, and related data to decisions and/or actions (Brewer 2009). Biases, tendencies or heuristics of human decision making are not inherently bad; they are methods of mentally taking shortcuts in recognizing a situation, which normally allow people to quickly select the most plausible choices first, followed by the less plausible choices (NUREG-1880 2007). However, biases or heuristics that tend to work in specific, often "simple" information settings, sometimes lead to severe and systematic errors in other settings (e.g., more complex) such that they hinder proper interpretation of available information and data and lead to inappropriate perceptions, decisions, and actions (Tversky and Kahneman 1974; Brewer 2005). In this report, the term "bias error" is used to describe a systematic tendency or heuristic that leads to inappropriate decisions and/or actions in specific scenarios. Selected bias processes are discussed in detail in Appendix B, Section B.13.

[132] Recall that an unsafe action (UA) is an action inappropriately taken, or not taken when needed by plant personnel that results in a degraded plant safety condition. In this case, the unsafe action removes a level of defense-in-depth which would otherwise limit the safety-related negative consequences of a cask drop.

[133] James Reason (1990), a professor in the United Kingdom, used the term "violation" in his writings; the term "circumvention" is used here as it is not associated strongly with negative/malicious connotations. Furthermore, in the U. S. nuclear and other well-regulated industries the term "violations" has a specific legal connotation related to breaking laws and regulatory rules that are distinct from human performance problems (Forester, Cooper et al. 2008). Although acts of sabotage were one type of violation included in Reason's definition, such malicious behavior is not of interest in this report.

strict compliance with ways of performing actions. Or circumventions may be infrequent, such as when a plant operator must resolve competing goals of completing a task on time or following every step in a procedure. The goal of maintaining production or ensuring plant safety may drive the worker to circumvent required actions in the interest of achieving his or her goal.[134] For example, a worker who has experienced difficulty inserting locking pins into the transfer lid door on five previous cask loads during a single CLC might decide to forgo securing the transfer lid door with the pins during the sixth cask load to expedite lowering of the multipurpose canister (MPC) from the transfer cask to the storage cask. Unfortunately, if the transfer lid door is not opened sufficiently, this circumvention could lead to the cask impacting the door, resulting in either minor damage to components or major damage with radiological consequences (i.e., if a cask were to drop during the operation).

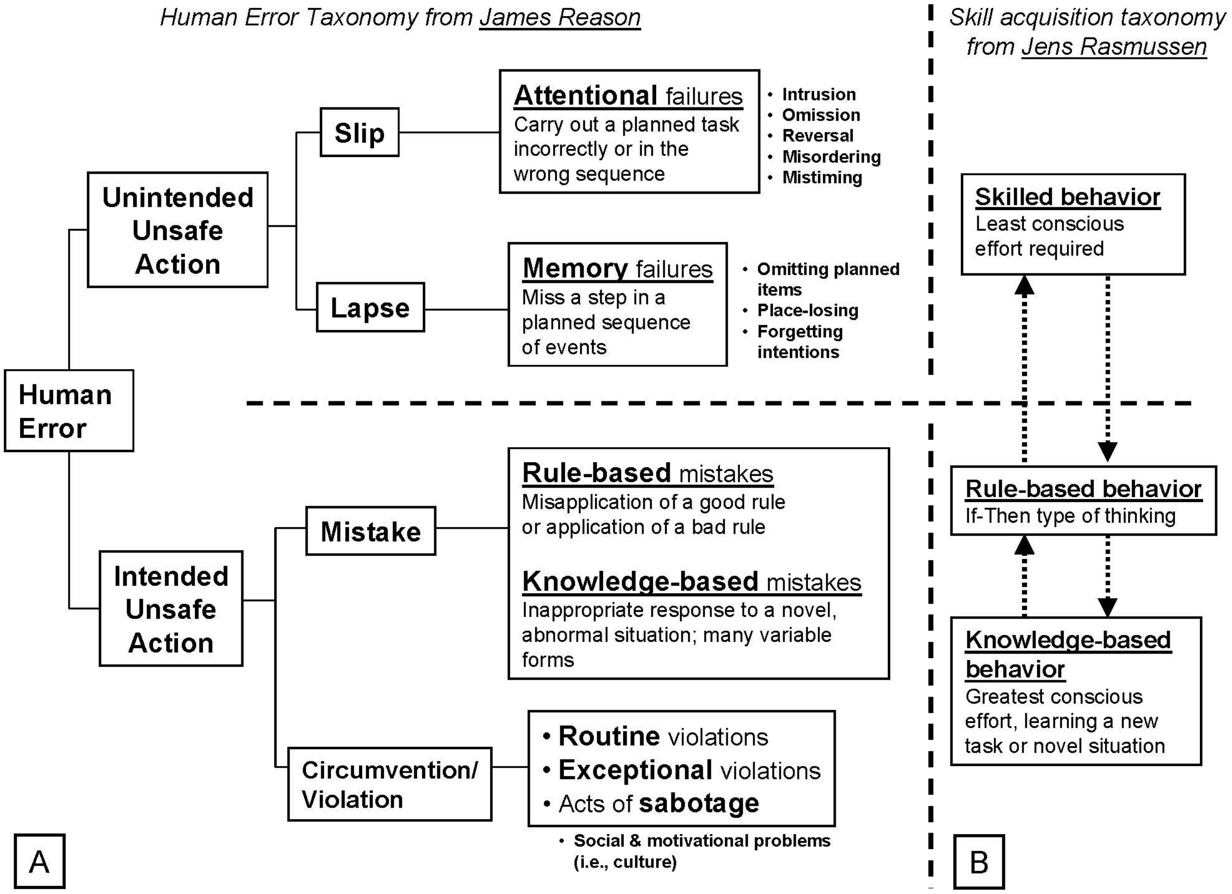

Figure B-5 Human error taxonomy integrated with skill acquisition taxonomy.

A illustrates Reason's taxonomy; B illustrates Rasmussen's taxonomy.*

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[134] Note that Reason (1990) maintains that violations are different from mistakes. For example, research suggests that the frequency of violations is sensitive to age, while the frequency of errors is not. Violations tend to decrease as individuals become older; errors do not. A strong plant safety culture can reduce the occurrence of circumventions/violations.

***Adapted from Reason (1990; 1997) and Rasmussen (1979; 1981; 1986).**

The worker's intentions and mental model—understanding of how to perform an activity—are the key elements in Reason's classification. Slips and lapses occur despite a good understanding of the activity and a proper mental model. They result from fallible aspects of attention and memory during skill-based behaviors. In the case of mistakes, the worker has an incorrect mental model of the activity. In the case of violations, the worker intends to circumvent the prescribed way of performing a task either out of necessity or to increase efficiency. Circumventions/violations rarely involve malevolent intent such as sabotage; in most cases, circumventions represent an attempt to find a better way to perform the task—an informal rule or workaround performed with the aim of keeping the plant operating successfully. In rare cases, circumventions may actually represent cases of heroism, in which a worker puts his or her safety at stake to protect or save the plant. Slips, lapses, mistakes, and circumventions/violations may be either errors of omission or commission.

Reason's taxonomy, by connecting to Rasmussen's skill acquisition taxonomy and incorporating understandings about human attention and memory resources, provides additional insights for avoiding UAs. Again, consider the highly stressed plant worker who has a heavy workload. If an analysis suggests that the worker's error should be classified as a mistake, this implies that the key to preventing the error from occurring again might be through training. The worker's mental model is incorrect—he or she does not properly understand how to perform the activity. This incorrect mental model could lead to incorrect actions, inefficiencies, and ultimately increased stress in the worker. In this case, we see that stress may not have been the root cause of the UA but a contributing factor. The root cause may have been ineffective training leading to improper task execution, which then led to increased stress and further decrements in task execution—a vicious cycle that ultimately results in an HFE.

This section included a model describing how the acquisition and application of skills affects human performance; an early taxonomy of error types corresponding primarily to rule-based behavior; and a widely used error taxonomy that relates error mechanisms to the skill acquisition model. Both error taxonomies build on Rasmussen's framework and yield unique insights about human performance. It is considered a good practice to review all three taxonomies to arrive at a reasonably complete understanding of the causes of a UA.

B.3.4 Simplified Representation of Human Information Processing

An additional behavioral science basis for error types involves a simplified representation of the mechanisms in human cognition that may be applied to individuals and teams engaged in goal-directed behavior. This simple model describes key features of problem-identification and problem-solving behaviors. The model shown in Figure B-6 (NRC, 2000), breaks down human information processing into stages that allow analysts to address types of influences that could interrupt processing during the various stages, and which correlate generally to the classes of behaviors and errors introduced previously. These stages are described below:

(1) *Monitoring & detection* — process by which operators become aware of the occurrence of an event by observing alarms or indications that deviate from their expected values, and by which they continue to monitor the behavior of the plant. Monitoring and detection actions are strongly influenced by the other information processing stages. For instance, if the operators think that a particular type of event is occurring (i.e., their

situation assessment), their search for information will be influenced by their expectations. One particular weakness can be the tendency to search only for confirmatory information, not for evidence that may challenge a situation assessment. This phenomenon of confirmation bias, along with other important bias processes, will be discussed in Section 5.1.1.

(2) *Situation assessment* — active process by which operators create an understanding of what is happening in the plant, in real time, based on current inputs from monitoring and detection activities and their knowledge and experience. The following are associated with situation assessment:

   a. *Situation model*: the operators' explanation, based on experience and training, for what generally is happening in the plant. For example, if the event is believed to be a cask hang-up incident, then what *is* happening and what *will* be happening in the plant in the near future, is based on the operators' knowledge and training for such events. The situation model provides a context for the operators to assess the situation based on current plant information, and it is updated by new information from the situation assessment process.

   b. *Knowledge/mental model*: the knowledge and mental models of the operators are the bases on which the operators create the situation models and awareness; they represent the basic principles and "facts" about NPP behaviors under the ranges of conditions expected.

(3) *Response planning* — stage that represents the operator's selection of appropriate actions to respond to the state of the plant, based on the operators' situation assessment and knowledge, often in conjunction with plant procedural guidance.

(4) *Response implementation*: — stage that represents the operator's actual execution of the intentions formed in the response planning stage, such as directly operating the equipment or directing the actions of other personnel.

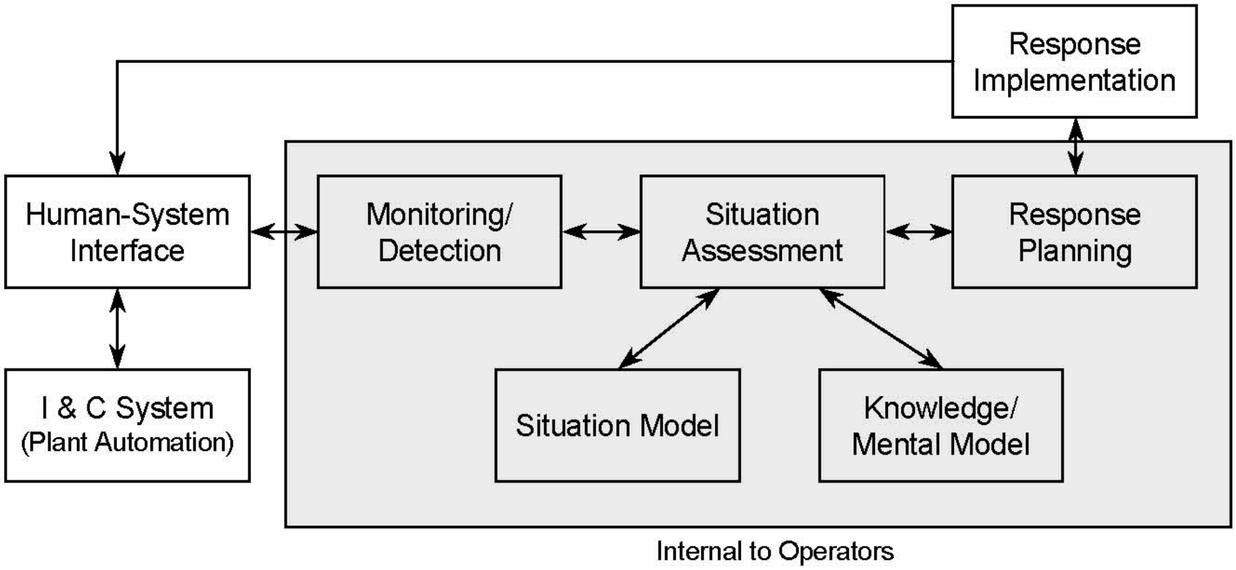

Figure B-6 Major cognitive activities underlying human performance.*

*** From Forester, Cooper et al. 2008.**

Figure B-6 summarizes the stages discussed above. While it presents the processes of a single operator (e.g., a crane operator), it can be applied to teams in which some of the functions are distributed. For example, personnel acting as spotters, along with a crane operator, may monitor, detect, assess the situation, plan the response, and implement the response for some situations, and the crane operator (with little input from the team) may carry out all of the functions for other situations. Carefully considered explicit assignment of these functions across team members can reduce the likelihood of HFEs.

This section has briefly described four items from the behavioral sciences that provide a foundation for understanding the origins of UAs and a starting point for understanding how human performance may be improved. The model showing how the acquisition and application of skills affects human performance; the early taxonomy of error types corresponding to the skill acquisition model; the contemporary error taxonomy that relates error mechanisms to the skill acquisition model; and the representation of the mechanisms involved in human cognition may be applied to both individuals and teams. Together these items provide a context for discussing (beginning in the next section) factors that may inform analysis of UAs using an approach for revealing practical insights into avoiding UAs.

B.4 Factors Influencing Human Performance

B.4.1 Internal and External Performance Shaping Factors (PSFs) and Error-Forcing Contexts (EFCs)

The typical application of HRA methods begins when analysts in a PRA present a particular HFE to HRA analysts for quantification of a human error probability. The HRA experts then perform some level of prospective qualitative analysis on the HFE to develop a scenario or context that can be used to identify the factors that may influence human performance. Once these factors (e.g., PSFs) are identified, their impact in the particular scenario is converted into a numerical probability estimate for committing the HFE. The HRA analysts may focus on only one scenario associated with a particular HFE, or consider several variations of scenarios when quantifying one HFE. In addition, during the qualitative HRA, additional HFEs may be identified, analyzed, and incorporated into the PRA model. Different techniques use different approaches for developing one or more scenario contexts and searching for and categorizing particular PSFs. There is no universally applied technique for developing scenarios or naming, defining, and applying PSFs to the developed scenarios.

The current study‘s framework for articulating scenarios/contexts for HFEs and incorporating PSFs was adapted from the framework that guided the development of the ATHEANA HRA method (NRC, 2000). Selected elements within that framework include PSFs, plant conditions, and EFCs. The approach for analyzing human performance in this study included multiple *human failure event scenarios* (presented in Section 5) that are essentially multiple EFCs applying to specific phases of DCSOs, and *human performance vulnerabilities* (presented in Section 5.1.1 and Appendix C) which compose a spectrum of PSFs and plant conditions that may contribute to HFEs involving a cask drop. This section provides definitions and brief discussion of PSFs, plant conditions, and EFCs. Additional detail regarding these three elements is provided in Sections B.4.2 to B.4.4. Section B.4.5 lists the human performance vulnerabilities used in this analysis and briefly describes how they were selected or developed.

PSFs are a set of influences on the performance of an operating crew resulting from the human-related characteristics of the plant, the crew, and the individual personnel (NRC, 2000). PSFs can be thought of as the items that allow personnel to understand the state of their environment and those items that influence their response to the state of the environment (e.g., procedures, training, time pressure, stress, and human-factors aspects of equipment, as well as organizational considerations such as the safety culture of plant personnel).

PSFs provide a systematic way of cataloging what has or will influence human performance; they serve as a foundation in identifying UAs across most HRA methods. PSFs allow the analyst to attribute contributors to UAs retrospectively and to consider potential contributors prospectively. In addition, in many first-generation HRA methods (e.g., SPAR-H [Gertman, Blackman et al., 2005]), PSFs are treated as multipliers to increase a nominal human error probability. In a second-generation approach such as ATHEANA (NRC, 2000), an expert judgment elicitation approach is used to arrive at the appropriate human error probability which integrates all influences deemed most important for the occurrence of a particular HFE into one or more scenarios referred to as EFCs.

PSFs can be internal or external (see Figure B-7). *Internal PSFs* are human attributes such as skills, abilities, attitudes, and other characteristics, which operate within the individual and are brought to the job by the individual. These intrinsic factors can vary greatly from individual to individual and vary within an individual over time. In practice, internal PSFs tend to be controlled for in the plant by providing common training, minimum experience requirements, standardized procedures, and job briefings to personnel. Managerial influences may also control internal PSFs: if a person consistently performs far below average for the group, the person will usually be retrained, reassigned, or terminated. Those who consistently perform in an exemplary manner will usually be promoted or transferred to a more challenging and responsible position (Peter and Hull 1969; NUREG/CR-1278 1983). *External PSFs* are human-related aspects of situations, tasks, equipment, and organizational culture residing outside the individual that allow personnel to understand the state of their environment and influence human performance (e.g., written procedures to follow). Again, it is important to take individual differences into account. The effects of a particular external PSF can vary greatly depending on the individual,[135] they can vary over time, and they can vary in affecting an individual's performance given different situations or contexts.

Plant conditions compose the actual state of the plant as defined by combinations of its physical properties and equipment conditions, including the measurement of parameters (NRC, 2000). Many plant conditions may be latent error conditions; for example, damaged or weakened crane support structures, improperly manufactured or maintained crane components, improperly calibrated load tension or load height sensors, faulty rigging equipment, malfunctioning safety interlocks (e.g., they fail to function or have history of false alarms), and insufficiently rugged crane control pendants. Other plant conditions include the current state (e.g., magnitude and direction of forces, physical properties) of a crane lifting a loaded cask or an object near a cask travel path that must be avoided. *Plant conditions* should not be confused with external PSFs, as plant conditions represent the actual state of the environment in terms of physical properties and equipment conditions, which are distinct from the information used to communicate those properties and conditions to personnel.

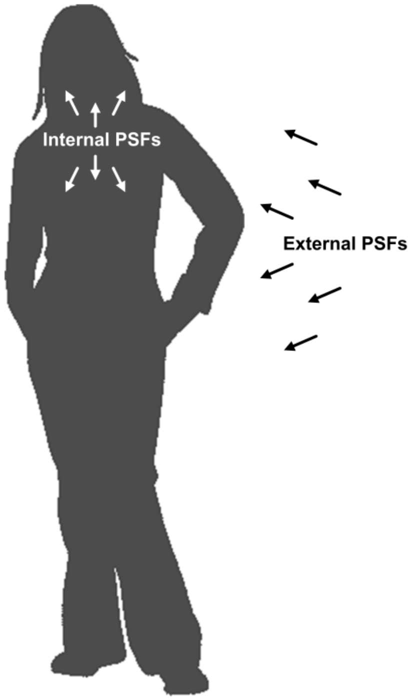

Figure B-7 Individuals bring internal PSFs to the situation, while external PSFs are situational factors that affect the individual.

Error-forcing contexts (EFCs) are situations that arise when particular combinations of PSFs and plant conditions create an environment in which UAs are more likely to occur. The EFC acknowledges that good teams in complex settings do not tend to exhibit random failures; they

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[135] As one example of this variation consider two individuals, one who generally agrees with and reinforces the organizational culture and one who does not agree with or reinforce the prevailing organizational culture.

are typically “set up” for failure by a combination of factors (NUREG-1880, 2007). Analyses of NPP operating events have revealed that EFCs typically involve an unanalyzed (or insufficiently analyzed) plant condition that is beyond normal operator training and procedure-related PSFs. The unanalyzed plant condition(s) and associated PSFs can activate one or more human error mechanisms that lead to a UA. For example, an EFC may lead to refusal to believe evidence that opposes and initial misdiagnosis of a situation (i.e., the *confirmation bias* discussed in Sections 5.1.1 and B.13), or failure to recognize conflicting evidence in the first place, such that a mistake is made that ultimately results in an HFE such as dropping a cask (NRC, 2000). The ATHEANA method systematically searches to discover these EFCs in NPP control operations; however, the search process can be adapted to other domains. The EFC approach to describing human performance avoids a reductionist view of PSFs that may impact performance more or less independently and consistently throughout the progression of an incident or accident. This relatively static view of the influence of PSFs prevailed in typical applications of first-generation HRA methods.[136]

The second-generation HRA methods explicitly encourage HRA analysts to account for complex interactions among various factors that are situation dependent. To further clarify this difference, in ATHEANA, the same PSFs (e.g., training, procedures, individual characteristics), may *reduce* the likelihood of one UA per its corresponding EFC yet *increase* the likelihood of another UA per its corresponding EFC in an analysis in which each UA may lead to the same HFE. For example, in the domain of power operations consider two control-room crews, one that follows a formalized, slow, methodical, rule-based approach to diagnosing plant conditions, then taking actions; and a second crew that tends to display faster, skill-based diagnosis and response actions. The first crew tends to refer closely to written procedures and always holds situation-awareness briefings so that the shift supervisor and operators can arrive at a course of action. For the second crew it is common for the shift supervisor to take control and command rapid responses. Depending on the specific plant conditions facing the operators, either type of crew characteristics may be most effective at avoiding UAs and HFEs.

Applications of first-generation HRA methods typically do not involve a similar level of complexity and realism of action for PSFs given various plant conditions. As in the ATHEANA method, this report adopts the EFC perspective on understanding human performance. Therefore, when specific factors influencing human performance are discussed, it is to be understood that there are often complex interactions among these factors which may change relative to the specific situations and HFEs considered.

B.4.2 Typical PSFs

To date, no standard set of PSFs has been identified. The NRC’s *Good Practices for Human Reliability Analysis* (NRC, 2005b; NRC, 2006b) outlines 15 PSFs that should be considered at a minimum, but these documents clearly state that the 15 PSFs are not all-inclusive. The 15 PSFs identified are:

- Applicability and suitability of training and experience
- Suitability of relevant procedures and administrative controls

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[136] The developers of the first-generation methods may not necessarily encourage this type of simplified analysis process, and particular experts can find ways of interpreting the methods such that additional complexity and realism is considered. However, it is generally true that the guidance provided with these methods does not preclude this simplistic approach for applying PSFs as evidenced by many examples.

- Availability and clarity of instrumentation
- Time available and time required to complete the action
- Complexity of required diagnosis and response (e.g., degree of mental effort or knowledge, ambiguity of information)
- Workload, time pressure, and stress
- Team and crew dynamics
- Available staffing and resources
- Ergonomic quality of human-system interface
- Environment
- Accessibility and operability of equipment
- Need for special tools
- Communication strategy and coordination
- Special fitness needs

Consideration of realistic diversions and deviations due to aleatory factors (e.g., alarms, failed instruments, distracting conversations, failed functional components)

These PSFs are meant as a starting point, which should be tailored to specific applications. Many HRA methods (e.g., THERP [NRC, 1983a] and SPAR-H [Gertman, Blackman et al. 2005]) provide a minimal set of PSFs specific to those methods. Newer approaches deemphasize a rigid or fixed list of PSFs. Methods like ADS-IDAC (Chang and Mosleh, 2007) attempt to cover a broad spectrum of human performance and provide a nuanced list of 50 PSFs; other methods like ATHEANA (NRC, 2000) do not constrain which PSFs are used and make determining relevant PSFs an integral part of the analysis.[137]

B.4.3 Stress as an Example PSF

Individual differences in internal PSFs are illustrated by an individual's stress response to a particular situation. This stress response, often captured by a specific PSF for stress, is in part a byproduct of the individual's level of experience as well as a reflection of his or her optimal arousal levels. Figure B-8 depicts the typical relationship between performance and arousal/perceived stress (Yerkes and Dodson, 1908; Wickens and Hollands, 2000; Brewer, 2008). As can be seen, there is a level of arousal that results in optimal performance for a given situation or context. This is called facilitative stress or *eustress*—the positive manifestation of stress on a person. Eustress is a range, not a single point, where performance may be enhanced by arousal or stress. Below this level of arousal, the person is in a calm state that does not beget high performance. As the level of arousal increases, it crosses the point of optimum performance and starts degrading performance. As performance degrades, it takes the form of disruptive stress or distress. That is, people are aware of performing poorly, which increases disruptive stress and degrades performance further. At a certain point of high arousal,

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[137] HRA methods that decompose human performance into PSFs are often called *reductionist* (analytic or atomistic) methods, while HRA methods that view human performance as indivisible are known as *holistic* methods (Boring and Gertman 2005).

(a “stress cliff”), human performance fails due to the effects of distress in a given situation or context.

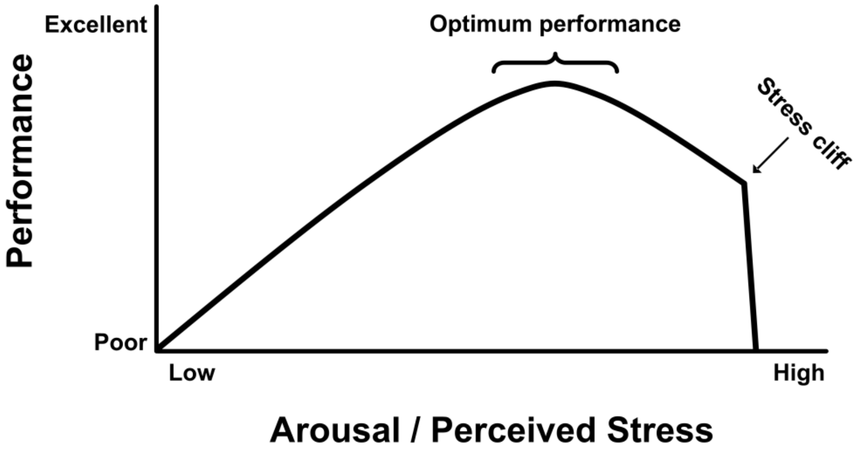

Figure B-8 Performance versus arousal/perceived stress curve.*

*** After Yerkes and Dodson 1908; Wickens and Hollands 2000; and Brewer 2008.**

Swain and Guttman (1983) clarified the effects of stress in terms of task load. The task load represents how much activity the task requires of the person. In other words, task load reflects how busy or involved the person must be to complete the task successfully. For a given situation or context, Swain and Guttmann suggested stress could be usefully categorized into four levels corresponding to four levels of task load, as depicted in Table B-2. As the task load increases, stress goes from a point of low arousal, to a facilitative level of optimum arousal, to a disruptive level of stress, to a point of distress. In common use, the point at which the person’s arousal or engagement in the task becomes disruptive, the term switches from “arousal” to “stress.”[138] The ability of the person to complete the task is influenced by *stressors*—internal or external factors that increase the stress level. Although not specifically addressed by the HRA research literature, stressors may be counteracted by destressors or relaxers, factors that decrease the stress level in a given situation or context.

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[138] Arousal and stress are both explicitly used here as they evoke different connotations in common usage. *Arousal* is often associated with alertness and positive excitement (e.g., awakening from sleep, following a first cup of coffee, response to positive events). *Stress* often carries with it negative connotations related to potential or realized losses.

Table B-2 Four levels of task load and corresponding stress levels.*

Task Level	Very low task load	Optimum task load	Heavy task load	Threat stress
Stress Level	Very low	Optimum	Moderately high	Extremely high
Description	Insufficient arousal to keep alert	Facilitative arousal	Slightly to moderately disruptive stress	Very disruptive stress

*** From NUREG/CR-1278 1983.**

One key to understanding the arousal/stress curve is to consider that each individual naturally falls on a different place in the arousal continuum for particular situations. Some individuals may often require a higher level of arousal to achieve optimal performance, while others often require less arousal. This point can be readily illustrated when considering the levels of arousal or stress brought about by social interactions. Eyesnick (1967) suggested that introversion and extraversion might be explained in terms of social arousal. An extraverted person may typically fall low on the level of arousal triggered by a social interaction. Such a person will therefore tend to seek out greater social contact to raise his or her arousal level to the optimal level. An introverted person may typically fall high on the level of arousal triggered by the same social interaction. Such a person will therefore tend to seek out less social contact to lower his or her arousal level to the optimal level.

The implication of this performance versus arousal/perceived stress curve is obvious for activities in power plants: each worker brings different typical stress levels, which may change in response to events at the plant. A worker's reaction to an adverse situation is subject to individual differences: the adverse situation may cause eustress in one individual and distress in another. Without taking the internal PSF state into account, one risks over-generalizing expected performance. When considering internal or external PSFs, it is essential to acknowledge the high degree of variability in responses to those factors (from individual to individual; for the same individual over time; and for the same individual, given different situations or contexts) and to include this variability as uncertainty in individual or team/crew performance in an HRA.

Beyond individual differences, it is important to consider that PSFs may manifest differently depending on the situation or the co-occurrence of other PSFs. The EFC has one advantage: it is not constrained to a fixed effect of a PSF, but rather considers the PSFs in context. It is rarely possible to look at the effect of a single PSF in isolation. For example, stress is closely related to the amount of time available to complete the task, as well as overall workload and task complexity. Stress, time pressure, and workload may be closely related to one another or interdependent to the degree that it may be difficult to measure their effects separately. Moreover, the effect of a PSF may vary considerably depending on situational or contextual factors. Figure B-9 notionally illustrates the interaction of task complexity as revealed by the predominant type of behavior involved (using an overlay of Rasmussen's skill acquisition taxonomy) on the performance versus arousal/stress relationship (Rasmussen 1983; Wickens and Hollands 2000).

Figure B-9 features two curves—one to capture performance on a simple, well-learned task and one to capture performance on a complex task that requires more actions and/or conscious thought. As can be seen, for the complex task, overall performance decreases. There is a different point of optimum arousal—performance on the complex task peaks at a lower level of arousal than the simple task. Clearly, the nature of the task must be considered when evaluating the effects of stress. Furthermore, different types of stressors tax different types of cognitive or motor skill resources in different ways, which will have corresponding impacts on tasks of varying levels of complexity requiring those resources (Wickens and Hollands 2000). Many HRA methods treat task complexity as a unique PSF; however, it should be noted that task complexity and stress do interact. This example demonstrates that a thorough HRA should attempt to understand the context behind the PSFs and account for significant interactions in addition to potential individual differences. This is the approach that ATHEANA takes with its EFCs, and it has influenced how human performance is understood and described in this report.

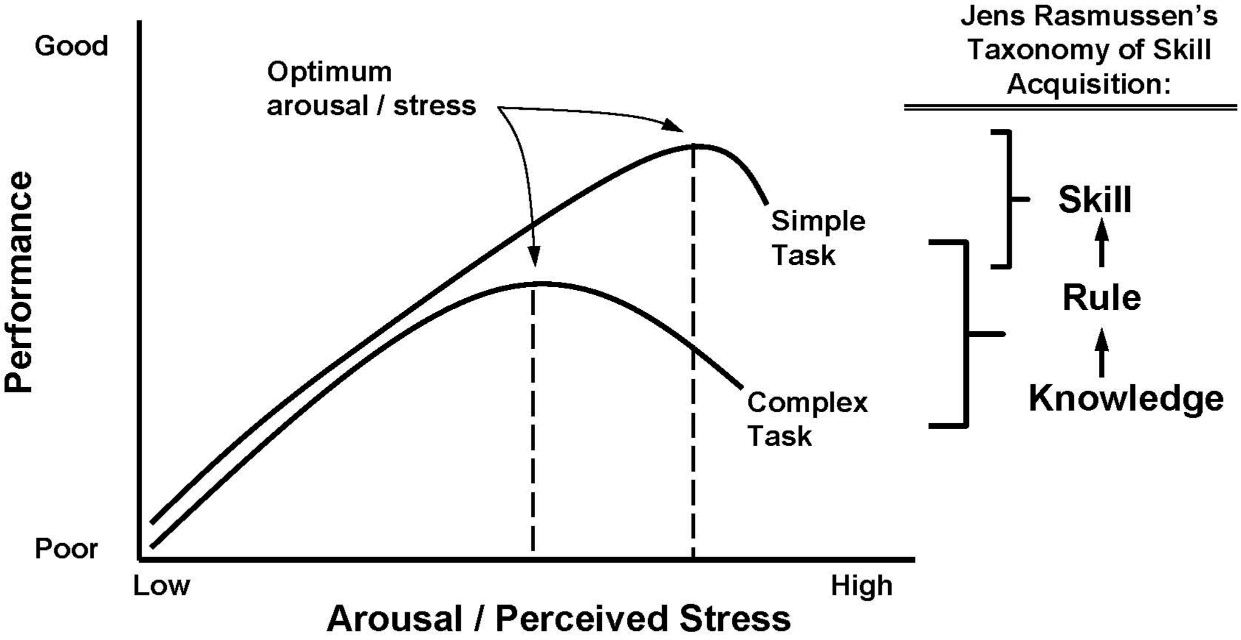

Figure B-9 A performance versus arousal/perceived stress curve for simple and complex tasks* with an overlay of Rasmussen's taxonomy of skill acquisition added.

* Adapted from Wickens and Hollands 2000.

B.4.4 Example of an EFC in DCSOs

As mentioned previously, EFCs are composed of many PSFs and plant conditions that create an environment in which UAs are more likely to occur. In DCSOs, consider the HFE in which a crane operator fails to stop raising a cask, which then results in a two-block failure of the crane cables and a cask drop. One EFC that may be a significant contributor or high-likelihood context for this HFE may include the following:

(1) S*tress*—very low level of arousal/perceived stress during the long, slow lift

(2) *Procedures*—require disabling a vertical height interlock on the crane to allow sufficient clearance due to limited vertical access in the fuel building, tall height of the cask, and long length of the lifting beam on the crane hook

(3) *Inadequate Training* and *experience*—have conditioned the crane operator to (1) use unreliable visual cues for deciding when to halt the lift, (2) expect that the crane hoist overcurrent protection switch would avert any significant damage due to a two-block event, and (3) believe that no problems will be encountered given successful performance of the same task the previous day

(4) *Individual characteristic*—the crane operator tends to be slow and methodical in performing all tasks; while this characteristic is beneficial for most tasks, it is undesirable when immediate actions are required (e.g., shutting off power to the crane hoist at the first sign of onset of the two-block event)

(5) *Communication*—limitations in the ability of other personnel to alert the crane operator of an impending two-block event using nonverbal communication (e.g., hand signals)

(6) *Organizational safety culture*—encourages completing tasks quickly without having to ask questions

(7) *Plant conditions*—inadequately designed, installed, and maintained crane components resulting in little safety margin in excess of the rated load capacity and a random failure of the crane hoist overcurrent protection switch

In a slightly different situation or EFC, any one of these factors may reduce the likelihood for this same two-block HFE. For instance, the crane operator's *training* and *experience* and *individual characteristics* may be such that if he/she has reason to believe that the overcurrent protection switch does not work, his/her behavior may change such that increased arousal and vigilance greatly reduces the likelihood of a two-block failure and a cask drop. Both EFCs, exhibiting different interactions and influences by the same single factors, would be evaluated in determining the overall likelihood of an HFE leading to a cask drop.

B.4.5 Human Performance Vulnerabilities and PSFs

Section 5 discusses *human performance vulnerabilities*. This terminology is used in this report to refer to a spectrum of PSFs and plant conditions, including the past history of both latent and active UAs, which generate a context that may ultimately contribute to HFEs. The potential vulnerabilities were derived from a review of process descriptions and from interviews with SMEs who have hands-on experience with the processes. The context, emerging from a combination of human performance vulnerabilities, integrates the individual, task, situation, and environment in such a way that the connection between actions and undesirable consequences is apparent. While a positive context can improve human performance, a negative context (i.e., an EFC) can set up personnel to commit UAs and HFEs. The human performance vulnerabilities in this report are oriented toward EFCs that may lead to HFEs involving cask drops.

The potential vulnerabilities were derived from a review of process descriptions, review of relevant incidents and accidents related to SFH (e.g., heavy load drops, crane problems, cask component problems, other incidents during SFH and DCSOs) and from interviews with SMEs who have hands-on experience with the processes. An additional motivation for selecting/developing the vulnerabilities was to generate a set of terms that provide human performance distinctions readily understood by those who are knowledgeable of DCSOs, but who may have limited knowledge of human factors (HFs) and HRA. That is, one goal was to avoid HF/HRA jargon by generating and describing terms useful for a broad audience of people interested in improving human performance in DCSOs. The human performance vulnerabilities identified in this report that may negatively impact on cask movement operations are:

- Inadequate procedures
- Limited reliance on procedures
- Inapplicable procedures
- Inadequate training/experience
- Communication difficulties
- Limited indicators and job aids
- Visual challenges
- Unchallenging activities
- Time pressure
- Time-of-day and shift-work challenges
- Inadequate verification
- Quality assurance problems
- Decision-making bias error
- Inadequate team coordination
- Improper or uneven task distribution
- Large number of manual operations
- Other ergonomic issues

These human performance vulnerabilities are described in detail in Section 5.1.1 and Appendix C.

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APPENDIX C. HUMAN PERFORMANCE VULNERABILITIES

Recall from Appendix B that human performance vulnerabilities are used in this report to refer to a spectrum of performance-shaping factors (PSFs) and plant conditions, including the past history of both latent and active unsafe actions (UAs), which may ultimately contribute to human failure events (HFEs) during cask movement activities. The context, emerging from a combination of human performance vulnerabilities, integrates the individual, task, situation, and environment in such a way that the connection between actions and undesirable consequences is apparent. While a positive context can improve human performance, a negative context, i.e., an error-forcing context (EFC), can set up personnel to commit UAs and HFEs.

The human performance vulnerabilities in this report are oriented toward EFCs that may lead to HFEs involving cask drops. The following is a summary of some potential human performance vulnerabilities, derived from process descriptions, review of relevant incidents and accidents (e.g., heavy load drops, crane problems, cask component problems, other incidents during spent fuel handling [SFH] and dry cask storage operations [DCSOs]) related to SFH and from interviews with subject matter experts (SMEs) who have hands-on experience with the processes. An additional motivation for selecting and developing the vulnerabilities was to generate a set of terms that provide human performance distinctions which are readily understood by those knowledgeable of DCSOs, but may have limited knowledge of human factors (HF) and human reliability analysis (HRA). That is, one goal was to avoid HF/HRA jargon by generating and describing terms that were useful for a broad audience of people interested in improving human performance in DCSOs. A brief explanation of each vulnerability and an example illustrating its application are presented in Table 5-1 followed by an in-depth discussion of each of the vulnerabilities.

Table C-1 Description of human performance vulnerabilities with examples.

Vulnerability	Description
1. Inadequate procedures	Procedures that are found to be deficient, possibly by discovering that a situation once thought to be unusual or rare, is actually more common and deserves to be explicitly addressed in procedures. A deficiency in procedures may also exist when an important situation was not previously considered at all. Other deficiencies in procedures can include omissions in detail that are important for reducing the likelihood of UAs and HFEs. For example, procedural guidance may not explicitly state the maximum height at which to stop lifting the cask from the SFP. This in turn may increase the likelihood of a cask drop, for example, due to interactions of cask height and time available to avoid a two-block event caused by equipment failure or a UA.
2. Limited reliance on procedures	In general, many of the spent fuel operations are skill-based and may not be guided by detailed procedures. However, even if detailed procedures do exist, they may rarely be referenced since skills, informal rules and heuristics are used to guide task execution. For example, procedural guidance specifying how to move a cask from the SFP to the decontamination/sealing area in great detail may not be regularly referred to given the perception that the associated crane operation skills are “simple.” This lack of reliance on procedures may lead to latent UAs and, over time, could progressively lead to an increased potential for an HFE.
3. Inapplicable procedures	These are procedures, or significant portions of a procedure, which do not apply to a unique or unusual (i.e., off-normal/emergency) situation. This may result from a

	conscious decision by system designers and managers to avoid changing a procedure to explicitly deal with an unusual situation (as it might confuse or distract personnel dealing with many more commonly encountered situations). That is, to handle the unusual situation personnel need to know when to deviate from the documented procedures and rely on other factors such as training, knowledge-based problem solving or engineered feature response to avoid an HFE. Inapplicable procedures may also result from an omission to consider a particular situation; however, upon discovery of this omission, it may still seem appropriate to avoid explicitly addressing some aspects of the situation in the procedure. The presence of inapplicable procedures may be a source of distraction and delay for personnel if they do not realize that they do not apply to current plant conditions.
4. Inadequate training/experience	Many of the operations performed by the team may be skill-of-the-craft activities that lack a high level of formality both in terms of documented procedures and structured training programs. For example, there may be a lack of training on the immediate responses necessary given indications of a two-block event, or a rigging failure in which a crew member is seriously injured and a loaded cask undergoes a freefall drop (e.g., assignment of responsibilities, order of emergency response actions). There may also be a lack of training with respect to critical latent error conditions, for example, inspecting crane support structures, or inspecting the state of rigging slings for signs of excessive strain loading and/or thermal damage. Inadequate training/experience may be present among: 1. *Individuals*—these are vulnerabilities due to omissions or incorrect aspects of training as described above. 2. *Teams*—inadequate training/experience among team members may not necessarily consist of large omissions or incorrect aspects of task-relevant training, but in training and experience that enables multiple people to effectively work together; this vulnerability may be particularly prevalent among hybrid teams consisting of both plant personnel and temporary contractor personnel.
5. Communication difficulties	The working environment of DCSOs is noisy, making verbal communication difficult. The use of headsets may be complicated by confusion over who is speaking. The use of hand signals may be misinterpreted or not seen. For example, a spotter at floor level may shout warnings that go unheard by the crane operator; the spotter may also be unable to catch the attention of the crane operator with hand signals.
6. Limited indicators and job aids	Processes are generally controlled by unsystematic visual inspection instead of through the use of positive safety measures such as engineered reference tools or other administrative controls. For example, lifting the cask out of the SFP is primarily guided by visual inspection without the additional safety features of proximity alarms (with auditory, tactile, or visual indicators) or objective reference tools (e.g., a reference scale indicating distance from the cask to the wall). That is, the avoidance of a cask hang-up or impact with items in the SFP may rely on the interpretation of visual cues selected and sampled in a subjective fashion by one or a very small number of people. In addition, for tasks involving numerous steps or for infrequently performed or unusual activities there may be insufficient job aids to ensure that slips, lapses, and mistakes do not occur, e.g., due to distractions or memory limitations.
7. Visual challenges	Given the immense size of the cask as well as the placement of the workers, the line of sight for tasks may often be blocked or distorted. In addition, the operation of captivating and moving the cask while in the SFP may involve visual distortions due to viewing the process through over 6.1 meters (20 feet) of water. Viewing the cask using underwater cameras may greatly reduce distortion due to refraction of

	light, however, the difference in the perspective of the cask shown by the video system and the body positions of the crane operator and spotters may also lead to UAs. Furthermore, in some plants the crane operator is perched high above the cask movement operations and has an unclear view of the travel path and nearby obstructions. Visual challenges are identified as a distinct vulnerability given the prime importance of visually derived information for influencing human behavior.
8. Unchallenging activities	In general, DCSOs are slow-paced and can be monotonous. Therefore, personnel may become easily distracted. For example, after progressing through several successful loads within a campaign, the crane operator may become distracted while slowly moving the cask and miss a warning of an impending collision from a spotter below.
9. Time pressure	The time pressure felt by the workers during a DCSO may vary considerably. In general, the operations are slow-paced. However, missing scheduled milestones can increase the pressure felt. For example, as a CLC nears completion and a scheduled outage approaches along with the presence of hundreds of contractors arriving on site, the cask loading crew may rush to finish the last two loads of the campaign. The time pressure described in the scenarios predominantly arises from the tension generated by the often conflicting goals of "productivity and safety" as described in Section B.2.1. However, there is some mention of time pressure related to achieving a specific safety goal, for example, pressure to complete rigging operations quickly to reduce radiation exposure to the riggers per the ALARA principle. Note that the safety culture among personnel can significantly impact the degree to which the perception of time pressure leads to rushed task performance.
10. Time-of-day and shift-work challenges	Workers are more likely to commit errors when fatigued, such as when one has performed a double shift or has been unable to sleep sufficiently between shifts. This problem of fatigue may be especially acute when personnel work an occasional night shift such as when a day shift worker fills in for a sick colleague one night.
11. Inadequate verification	Inadequate verification results from factors leading to incorrect checking and/or the overestimation of independence between checks. Key factors include common-mode failures, social shirking, and overcompensation (Sagan 2004; Brewer 2009). 1. *Common-mode failures*—these include failures in redundant checks due to inadequate items, e.g., training, tools, equipment. For example, multiple inspectors incorrectly checking for defects will create latent error conditions. 2. *Social shirking/misplaced trust*—a phenomenon in which individuals or groups reduce their reliability in checking by assuming that others will "take up the slack." The probabilities of error for a checker of another's work will be much higher than the probability of error for the original performer;[139] this is due to the fact that the checker usually does not expect to find many errors when evaluating another's performance (NRC, 1983a). Also, crew members must trust each other to do a thorough review of their work and catch any mistakes. A cursory check of an

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[139] In cases of skilled performance of tasks, the person performing the task is more likely to detect an error in his/her own performance than a second person who believes that the first person already performed a good check. It is also important to distinguish this phenomenon from a situation in which it *does not apply* (e.g., a teacher reviewing a student's performance). A teacher or expert reviewing the work of a student or novice expects to find errors and also learns over time where such errors tend to be clustered given the experience level of the student. The bottom line is that when people do not expect to find errors, they are not good at detecting them. It takes special training, crews, and working culture to maintain increased independence between multiple checkers (Brewer, 2009).

	“excellent” subordinate’s work by a supervisor would be a violation of that proper trust. Use of the terms “misplaced trust” does not to imply that someone is generally “untrustworthy” if they succumb to this behavior—it is to highlight a subtle, yet unsafe behavior that may occur among those who are “trusted.” Also, mixed, or hybrid, crews composed of plant personnel and contractors may not have the same understanding about the amount of verification needed or relied upon by others thereby increasing the occurrence of social shirking. 3. *Overcompensation*—a phenomenon in which the addition of extra items (intended to be redundant) encourages individuals or groups to increase production or engage in riskier behavior. An example would be greatly increasing throughput of newly manufactured crane components at an inspection station after providing additional inspectors. Overcompensation is a distinct action that often compounds the problem of failing to understand and account for dependencies due to social shirking and common mode failures.
12. Quality assurance (QA) problems	Careful verification that all structures, systems, and components (SSC) related to DCSOs meet appropriate conformance requirements may be lacking, which may lead to latent error conditions. QA verification should extend as far back into the manufacturing and procurement stages as possible. For example, a QA problem could allow for the malfunction of a control pendant for remotely operating a crane when it is unexpectedly dropped during a cask movement. In this case, when a control was purchased, it may be assumed, but not suitably verified, that impacts of this nature were tested by the manufacturer. Another QA problem could be failure to detect a material property defect in a load-bearing component.
13. Decision-making bias error	Bias and heuristic errors may mislead personnel and lead to HFEs during DCSOs. Three biases emphasized in this report include: confirmation bias, loss aversion, and overconfidence. 1. *Confirmation bias*—the tendency to seek out evidence which confirms one’s current position and disregard conflicting evidence. Example: after several successful cask loads within a campaign, workers will likely require greater evidence (i.e., stronger cues and signals) to suspect that anything is wrong during cask movement. 2. *Loss aversion*—the individual specific way of mentally accounting for the concept of loss in a given situation provides a strong biasing factor toward information and actions that enable the person to steer away from incurring that loss. Example: imagine that during movement of a cask a loud, metal-on-metal sound momentarily captures the attention of workers observing the cask movement. The source of the sounds may be movement of the yoke arm on the trunnion; however, the personnel attribute the noise to nearby machinery instead of focusing on the loss-threatening possibility that a cask drop is imminent; so they continue the cask movement. 3. *Overconfidence*—overestimating one’s level of knowledge or abilities relative to making a decision or executing a task. Example: imagine that a crane operator is overconfident in the ability to closely align the cask to the edge of the SFP when raising it to facilitate access for personnel to decontaminate and partially secure the cask lid. A cask hang-up occurs. The operator’s overconfidence was fueled by ample experience in operating the crane and participating in several successful CLCs.
14. Inadequate team coordination	There may be undesirable variability within and between teams involved in DCSOs, especially during operations where actions are predominantly skill-based, there is limited reliance on procedures, new or hybrid-teams have been assembled or there are hand-offs of responsibility between teams (e.g., shift changes or specialized teams for different operations). While team member variability in skills,

	attitudes, knowledge, and working styles is beneficial in many situations, it can also mask differences in understanding the abilities and assumptions guiding other's performance such that task performance is inadequate for particular situations. Hybrid teams consisting of both plant personnel and temporary contractor personnel may be particularly vulnerable to inadequate team coordination. For example, imagine that an experienced team member from the plant, overly confident in the ability to perform a task, completes the task quickly such that a slip occurs and a step is missed. Another member of the team, a temporary contractor who is slower and more methodical by nature, notices the rapid task performance of the co-worker and suspects a potential UA; however, they come from a safety culture that discourages challenging the work performance of others, thus no verification is attempted. As another example, imagine that the second worker in the same scenario assumes that the rapid task performance simply demonstrates the first worker's tremendous skill—casting doubt on the possibility of an UA; thus no verification is performed.
15. Improper or uneven task distribution	The distribution of tasks and responsibilities may not be clearly defined, which may lead to missed opportunities for independent verification. Also, an uneven workload can increase the stress on some employees while allowing others to become bored and easily distracted. For example, consider the crane operator who is tasked with lifting the cask. The position of the crane operator within the cab limits their view of the travel path. It may be beneficial for decontamination personnel at ground level to act as spotters with responsibility of verifying that a clear travel path exists throughout the movement (i.e., being the eyes for the crane operator's hands) instead of resting in place until it is time to decontaminate the cask. This additional assignment of responsibilities to the decontamination personnel may keep them more engaged in the CLC activities, reducing boredom and increasing vigilance.
16. Large number of manual operations	As the number of manual operations increases, personnel must exercise increased vigilance in performing them correctly. This caution is especially important during those times when the operations must be completed quickly. For example, imagine that a rigger is pressured to quickly execute all of the manual rigging steps while positioned on top of a loaded cask due to the ALARA principle and to reduce heat stress. In general, as the speed of task execution increases the likelihood of latent or active UAs also increases.
17. Other ergonomic issues	The noise level in the work environment is quite high, as mentioned in "Communication Difficulties." In addition to impairing communication, excessive noise levels can exacerbate the effects of fatigue. Other issues may also arise within the work environment such as cramped (or even inaccessible) working spaces (e.g., for inspection) and either high or low temperatures in the working area, high radiation levels encouraging rapid and/or awkward, cumbersome clothing, etc. Of particular concern may be the high temperatures encountered by riggers when positioned on top of a cask. An additional ergonomic issue involves fatigue, distraction, or other impairment due to the onset of illness or upon return to work during recovery or following an illness.

The human performance vulnerabilities in Table 5-1 were derived starting from the PSFs discussed in *Good Practices for Implementing HRA* (NRC, 2005b). The "good practices" PSFs represent a generic set of factors to be considered when performing an HRA, with emphasis on control room activities. While some of the good practices PSFs consider localized actions outside the control room, they are not tailored to the domain of DCSOs. The human performance vulnerabilities in this report effectively encompass applicable areas identified in the good practices PSFs, as well as provide additional distinctions which represent a more nuanced account of vulnerabilities in DCSOs.

The good practices PSFs directly applicable to DCSOs have been given analogous human performance vulnerabilities in this report. For example, “applicability and suitability of training and experience” in the good practices is mapped to the “inadequate training/experience” human performance vulnerability in this report. An example of the nuanced extensions is the “ergonomic quality of human-system interface” PSF in the good practices is actually detailed in three separate human performance vulnerabilities: “limited indicators and job aids,” “visual challenges,” and, in some cases, “large number of manual operations.” Another example of a nuanced extension includes “accessibility and operability of equipment” in the “good practices,” which is addressed in the three distinct human performance vulnerabilities of “inadequate verification,” “quality assurance problems,” and “other ergonomic issues.” Other aspects of SFH such as “decision-making bias error” are not covered in the “good practices.” The human performance vulnerabilities in this report therefore address the PSFs from the “good practices” and provide an extension of those PSFs to provide a better account of human activities specific to this domain. The terms used and their explanation were also generated with the intent of making import human performance distinctions easily understandable to those without a HF or HRA background.

C.1 Inadequate Procedures

Inadequate procedures are those which are found to be deficient in providing direction on handling events, symptoms, or other situations. Limitations in procedures represent a latent error condition that may negatively impact performance (i.e., “set up” personnel for subsequent active UAs/HFEs). In power plant operations this specific type of latent error condition has been cited as one of the major PSFs influencing crew performance. A procedural deficiency may be identified by discovering that a situation previously thought to be unusual or rare is actually more common and deserves to be explicitly addressed in procedures. Or the situation may truly be considered rare, but associated with high-potential consequences, thus worthy of being proceduralized. A specific example might include the omission of procedures or related training in handling of a situation in which a cask drops, fission products are released, and personnel are seriously injured (i.e., trying to limit contamination of the facility and exposures off site while simultaneously taking actions to address injuries incurred by snapping slings, cables, or other flying debris). A deficiency may also exist when an important situation was not previously considered at all, but arises due to new insights (e.g., near miss, new analysis, similar event in another industry).

Other procedure deficiencies can include omissions in details important for reducing the likelihood of UAs and HFEs. Procedures may be written generally such that they do not delineate specific, measurable criteria that may be used to avoid incidents or accidents; for example, general guidance such as “ensure sufficient clearance” instead of specific guidance such as “raise the cask 1.22 meters (4 feet).” Another example is unclear guidance on the minimum clearance required between the bottom of the cask and the floor over which it travels. These omissions may increase the likelihood of a cask drop due to interactions of cask height and time available to avoid a two-block event caused by equipment failure, or due to interactions of cask height and avoidance of objects in the cask travel path. In addition, procedures may not specify when primary responsibility should be transferred, although cask movement activities may benefit from frequent transfers of responsibility. For example, a crane operator with slightly degraded but adequate visibility may be assigned primary responsibility for the success or failure of activities under his/her direct control. However, during portions of a single cask movement activity (e.g., transitioning from horizontal movement over a transfer pit opening to vertical descent down into the transfer pit), a nearby spotter may have better visibility. During this portion of the activity, it may be appropriate for the spotter to assume primary responsibility for the activity under direct control of the crane operator. Procedurally codifying these transitions of primary responsibility may reduce the likelihood of undesirable or unsafe distractions from critical tasks at hand due to slips, lapses, and mistakes. As an example, if a crane operator understands that the spotter is now primarily responsible for the success or failure of the activity, he/she may be more diligent in closely and continuously monitoring communications from the spotter so that if a problem occurs, cask movement will have been under the spotter's control to the extent possible.[140]

C.2 Limited Reliance on Procedures

Spent fuel operations are not necessarily highly proceduralized, but depend primarily on skill-based actions which tend to be guided by less-detailed written procedures. Operations that do have detailed procedures and formal checklists may rarely reference them since skills, informal rules, and heuristics are used to guide task execution. For example, procedures specifying how to move a cask from the SFP to the decontamination/sealing area in great detail may not be regularly referred to given the perception that the associated crane operation skills are "simple" and have sufficient "margin." A slight variation of limited reliance on procedures would be to follow them for the first load in a cask loading campaign (CLC), but to then take a more relaxed attitude toward the procedures in subsequent cask loads. One reason for progressive deviation from procedures may be a lack of understanding of why the procedure is important, or an implicit belief that undesirable events are rare and will not happen.

For example, imagine a procedure specifying that a cask raised from the SFP must be raised at least 20.3 centimeters (8 inches) but not more than 61.0 centimeters (2 feet) above the surface of the refueling floor as the cask is transitioned out of the SFP and over the floor surface. Now imagine that for some cask loads in a CLC, the crane operator circumvents the procedure and lifts the cask as high as 91.4 centimeters (3 feet) above the floor level during the transition movement. The crane operator considers the increased lift height beneficial because it increases his comfort level that the cask is actually being raised high enough to clear the edge of the pool—especially given the challenging overhead viewing position. However, consider that the full vertical travel possible at this position in the plant only allows for a 1.22 meter (4-foot) clearance of the bottom of the cask and the refueling floor level before initiating a two-block event. If the crane operator is not fully aware of the total allowable clearance before a two-block failure, or does not believe it is possible to raise the cask too high (i.e., due to a UA or equipment failure), then he may feel comfortable circumventing the procedure on multiple occasions. Appropriate training and a strong safety culture can be used to avoid the human performance vulnerability of limited reliance on procedures.

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[140] Obviously the spotter is not directly controlling movement of the cask by manipulating controls in the crane cab; however, because the spotter has explicit, primary responsibility for the success or failure of the activity, the crane operator in the cab diligently translates the spotter's commands into action.

C.3 Inapplicable Procedures

There may be unique or unusual (i.e., off-normal/emergency) situations in which procedures, or significant portions of a procedure, do not apply. This may result from a conscious decision by system designers and managers to avoid changing a procedure to explicitly cover aspects of a low-likelihood, unusual situation because it might confuse or distract personnel dealing with many more common situations. That is, to handle the unusual situation, personnel must know when to deviate[141] from the documented procedures and rely on other factors such as training, knowledge-based problem solving or engineered feature response to avoid an HFE. Inapplicable procedures may also result from omitting a particular situation; however, upon discovery of the omission, it may still seem appropriate to avoid explicitly addressing some aspects of the situation in the procedure. Inapplicable procedures (or inapplicable portions of a procedure) may distract and delay personnel if they do not realize that the procedures do not apply to current plant conditions.

Below are four examples of inapplicable procedures associated with reactor accident conditions at an NPP and one hypothesized case related to DCSOs:

1. During the analysis of a hypothesized interfacing system's loss of coolant accident (ISLOCA), it was discovered that the procedures did not contain explicit instructions for cross-tying the water supply and pumps between two operating units at the plant site. It was decided that if such an unlikely ISLOCA were ever to occur, depending on the specific conditions, the control room operators and plant personnel would decide how to accomplish this task.
2. During the same analysis of a hypothesized ISLOCA, procedures allowed operators to use the secondary side of the plant to cool down and depressurize the primary side of the plant. To maintain both turbine- and motor-driven feedwater, the written procedures said to stop the cool down at an elevated pressure (and temperature). Because the break was non-isolatable, it would be better for the crew to exceed the written cool-down instructions to maximize the depressurization of the primary system and, therefore, minimize the flow-out of the break location and the make-up requirements. Based on onsite discussions with operations staff, they indicated that they would deviate from the written procedures to achieve this benefit.
3. Severe accident management guidelines (SAMGs) often do not prescribe what specific actions should be taken because of the potential uncertainties about the state of plant conditions. That is, the SAMGs may simply provide the potential advantages and disadvantages of pursing several courses of action. For example, they may state "it may be helpful to ____ to cool down the atmosphere inside the containment; however, this might also cause a steam explosion." SAMGs may provide only limited guidance on possible actions because the authors have recognized that the uncertainties and peculiarities of a given severe accident will require personnel to flexibly apply their knowledge and skills "in the moment" with limited information.
4. As a result of a cask drop into an SFP, it is possible that the cask may end up on its side close to equipment or structures in the SFP so that it is impossible to grasp the cask

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[141] Note that 10 CFR 50.54(x) states that "A licensee may take reasonable action that departs from a license condition or a technical specification (contained in a license issued under this part) in an emergency when this action is immediately needed to protect the public health and safety and no action consistent with license conditions and technical specifications that can provide adequate or equivalent protection is immediately apparent." That is, 10 CFR 50.54 is a directive allowing the plant personnel to go outside of their procedures if necessary to protect public health and safety.

trunnions with equipment available at the plant site. For example, it may not be possible to captivate both trunnions with the existing equipment, or specialized equipment (e.g., the crane yoke or lift beam) may have been irreparably damaged during the accident involving the cask drop. For this type of situation, it is anticipated that the procedures may specify some basic actions such as ensuring sufficient shielding and cooling of fuel, and recovering cask components as soon as possible. However, it is conceivable that procedures may not provide detailed guidance on how to resolve a particular situation involving a two-block failure, other equipment damage, and a uniquely challenging cask orientation. A procedure may simply state, "should such an event occur, specialized engineering solutions will be devised as demanded by the state of the damaged equipment."

C.4 Inadequate Training/Experience

The crew's familiarity and level of training may be limited with respect to cask drop scenarios. Furthermore, many of the tasks may lack detailed procedural guidance, which may lead to difficulties in structuring and conducting formalized training and periodic refresher training that provides effective feedback necessary for developing and maintaining the skills that help mitigate UAs and avoid HFEs. Deficiencies in training and experience are a type of latent error condition and are also considered a major PSF in the analysis of power plant operations. For example, without sufficient training, it is anticipated that crews exposed to the stressful situation of a cask drop may be unable to take appropriate actions. Instead of executing the correct, well-ingrained skills, they may exhibit detrimental fight, flight, or freeze responses.

Determining the items critical for training DCSO personnel may be surprisingly challenging. For example, consider a rigger who must determine the acceptability of the interface between a sling and the edge of a metal object. According to the understanding of the riggers, who will likely have seen various multi-ton loads lifted successfully with similar types of slings and metal edges of different roughness and sharpness, it may be difficult to conceive of the point at which the combination of a sharp edge and a very heavy load will likely lead to sling failure. The feedback provided in training and operational environments (possibly over many years) may be insufficient for teaching the riggers how to identify a dangerously sharp edge in relation to a particular heavy load.[142] The training would ideally enable the riggers to be mindful that materials may be nonconforming due to some latent error condition involving a problem with quality assurance (QA) activities and enable them to reliably answer the important question, "how sharp is too sharp?" In a similar example, riggers would try to determine whether slings used multiple times had been exposed to excessive tensile loading or thermal damage. Additional aspects of inadequate training and experience related to QA activities are described in Section B.12.

Training could also be deficient if they do not address off-normal or emergency situations. For example, consider a situation in which a wireless crane control pendant is dropped, and does not fail safe, during a cask movement. Given that plant personnel assume that a dropped pendant will always fail safe (e.g., a spring-driven movement of a switch to a position which signals the crane to stop moving), training may not include frequent practice with techniques to

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[142] To elaborate on this example, it is likely that the same type of defective sling and protective padding could withstand exposure to tremendously sharp edges under less-severe loading conditions on multiple occasions. However, the arguably "dull" edge, according to human tactile sensation, combined with a 40-ton fully loaded MPC may lead to sling failure upon first loading.

handle the situation (e.g., have personnel stationed near a high-voltage circuit breaker in series with the power supply for the crane, or provide another redundant method of removing power). A related example would be training supported by a strong safety culture such that detailed load movement procedures are followed “to the letter” to provide maximum time to avert a two-block event if a UA or equipment failure leads to unintentional raising of a cask.

Another crucial aspect of DCSO training that often needs to be addressed are hybrid teams consisting of a mixture of plant personnel and specialized contract employees. It is necessary to ensure that training appropriately bridges or eliminates any critical gaps in declarative and tacit knowledge[143] or experience such that personnel have similar understandings of how to execute critical DCSO procedures.

C.5 Communication Difficulties

There are often significant challenges in communication between the team members performing spent fuel operations. The environment contains a great deal of background noise, predominantly machine noise. Although headsets tend to be used by key participants for communication during some parts of the operation, 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/she expects to hear. These kinds of biases can strengthen over the course of a CLC. For example, imagine that during the first six cask loads a particular communication occurs at a particular point in the process (e.g., hearing “Go!”); however, during the seventh load, a different communication occurs at that point in the process (e.g., “No!”) and is misinterpreted.[144]

Hand signals are the predominant method used by members of the team to communicate, but there is no guarantee that the intended recipient will see these signals, identify a change from a repeated signal (or even be looking in the right place). For example, a repetitive crane-lowering hand signal is duplicated by multiple workers, yet abruptly terminated by one worker who observes a problem. There may be difficulty in attracting attention promptly,[145] particularly if the communication must flow serially through multiple people. For example, one spotter’s hand signal may need to be noticed by a second spotter who is in visual or radio contact with the crane operator. Signals may also be interpreted improperly if a standard convention for the meaning of all the signals has not been properly established (e.g., hybrid teams consisting of specialized contractors and plant personnel familiar with different interpretations of the same hand signals, or slight variations in the execution of the signals). Communication difficulties are

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[143] Explicit, figurative, or declarative knowledge (involving semantic memory) is concerned with knowing “facts.” Tacit, operative, or procedural knowledge (involving episodic memory) involves understanding where the “explicit” knowledge comes from or what underlies it. Tacit knowledge also involves the capacity to use, apply, transform, or recognize the relevance of explicit knowledge in novel situations (Brewer, 2005). Tacit knowledge is much harder to develop and communicate to others; in fact, experts may posses a great deal of tacit knowledge of which they are not explicitly aware (Brewer, 2008).

[144] It is acknowledged that it would be very poor communication practice to use the word “Go” as a positive confirmation and “No” as a negative confirmation given the phonetic similarity between these words. This example is simply provided to elucidate this phenomenon of communication difficulties interacting with confirmation bias (discussed in Section B.13) in a memorable way.

[145] Again, this tendency toward inattention or distraction may increase over the duration of the cask loading campaign.

a type of latent error condition that can negatively affect human performance (i.e., “set up” personnel for subsequent active errors/UAs/HFEs).

C.6 Limited Indicators and Job Aids

Compared to the control panel, local indicators, and other job aids common in power plant operations (i.e., the control room), those that exist in spent fuel operations are often quite limited. In general, processes are controlled primarily by visual cues. In power control operations, the prevalence of indicators and job aids can be explained by the need for barriers between the reactor and turbine power phenomena being controlled, as well as the amount and complexity of information that personnel must understand and act upon. In SFH and DCSOs personnel are much closer to the phenomena being controlled (e.g., movement of a cask) and the information being processed is arguably less complex. However, the safety of DCSOs can also benefit greatly from indicators and job aids. Recall from Appendix B that 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 (Rossett and Gautier-Downes, 1991).

Indicators and job aids can help avoid slips and lapses caused by distractions during familiar, skilled activities (e.g., crane operation, rigging) and also avoid mistakes during less frequently performed or novel/unusual activities (e.g., infrequent maintenance or repair for a complex crane component, raising a loaded cask over an obstacle or through a narrow passageway, unique rigging configuration). A job aid may even be considered among positive safety measures. Positive safety measures are design features, safety devices, safety rules, procedures, or other controls that exist solely or principally to provide safety. Positive safety measures are, preferably, engineered controls (e.g., automated safety inter-locks, physical barriers); although they may be administrative procedural controls carried out by personnel using reliable engineered standards of reference such as a radiation monitor, measuring stick, calipers, carpenter’s level, etc. Many job aids fit the definition of an administrative positive safety measures, and some could be engineered control positive safety measures as well (e.g., an alarm coupled with a safety interlock that stops crane hoist movement when excessive lifting is detected).

Another example of an administrative positive safety measure, or job aid, would be use of a measuring device to continuously ensure that the cask bottom is 30.5 centimeters (1 foot) above the floor during horizontal transport. Such controls provide increased repeatability and reliability compared to administrative controls that do not incorporate engineered standards. For example, general administrative guidance such as, “Do not get too close,” “Ensure sufficient clearance,” “Ensure equal tension,” “Visually verify that the item is level” may be expected to be less reliable than those incorporating engineered controls. Other examples of job aids include the use of a specialized kit of parts for particular maintenance tasks, and a parts template or shadow box used to captivate, organize, and account for parts used to complete a task.

Devising and implementing indicators and job aids may be challenging in DCSOs. For example, incorporating administrative positive measures with engineered references into rigging operations can be hampered by the physical scale and energetic state of objects being manipulated (e.g., great length of the slings, high forces to fully tension the slings, large size and momentum of the cask, high temperature and radiation levels near the cask or canister lid) and other environmental challenges (e.g., cramped or inaccessible[146] spaces). In light of such difficulties, decisions may be made to rely on the flexibility, adaptability, and capacity for complex skill execution, which human beings can provide. However, with complex, human-performed skills come opportunities for variations in performance which increase the likelihood of UAs due to slips, lapses, mistakes and circumventions/violations. Of particular concern are mistakes during infrequent or novel tasks requiring more than 3 or 4 steps or subtasks due to memory limitations. If the personnel performing these infrequent or novel multiple-step tasks have not had thorough training at regular intervals on these specific activities, then it would be unwise to expect more than four memorized steps to be completed correctly without a job aid (Miller, 1956; Doumont, 2002).

If accurate feedback on performance is not provided by a reliable, independent standard, personnel may be unable to develop the skill required to determine whether or not they have performed adequately. For example, with respect to determining whether a cask is being moved along a safe travel path, a worker may observe cask positions on many occasions which appear to be acceptable. However, without appropriate feedback relative to potential hazards to safety (e.g., measured distance, optical switch activation, confirmation from another person known to have a clear line-of-sight view), the worker's ability to prevent or mitigate UAs will likely not improve and may even worsen over time. That is, the available feedback may not actually indicate safe operations; the nonoccurrence of a cask hang-up, drop, or collision may simply reinforce the belief among personnel that operations are being carried out safely.

An example contrasting very different degrees of potential variability among indicators and job aids used in rigging operations would be between the short sling to long sling transition for supporting the HOLTEC HI-Storm MPC and the process for leveling the cask lid for the TN-40 cask prior to placing it on top of a loaded cask. In the short sling to long sling transition of the HOLTEC HI-Storm MPC, riggers manually change out the slings and the crane operator will slowly raise the MPC. The riggers observe the lift and make a visual determination that the slings are loaded evenly (i.e., no tilting of the MPC, no slack in a sling)—no special indicators, tools, or other job aids are used. In contrast, leveling the TN-40 cask lid is an iterative process in which the rigger uses a carpenter's level to ensure proper length and tension of the lifting cables. If the cask lid is not level, the crane operator lowers the cask lid onto support blocks, the rigger adjusts turn buckles on the metal lifting cables, the crane operator raises the cask lid several inches, and the rigger again uses the level to verify that the lifting cables are now equally tensioned. Ideally, the MPC rigging would also incorporate positive measures to reduce variability in human performance to better ensure reliable, repeatable, and safe task performance (e.g., sling tension indication devices, MPC lid level indicators). Limited indicators and job aids are latent error conditions that can negatively impact human performance (i.e., "set up" personnel for subsequent active errors/UAs/HFEs).

C.7 Visual Challenges

As mentioned above in the "limited indicators and job aids" vulnerability, visual cues (e.g., direct observation of processes and hand signals) are the primary means of guiding spent fuel operations. Given that the visual modality tends to be the primary means of receiving

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[146] Inaccessibility may consist of a physical inability to reach or manipulate an object or it may involve visual inaccessibility; i.e., an object may be touched or manipulated but not directly observed with the eyes, a.k.a., a "blind" operation. Visual inaccessibility may be overcome using mirrors or cameras as appropriate.

information about our interactions with the environment (Orlady and Orlady, 1999), factors presenting visual challenges deserve special treatment in the list of human performance vulnerabilities. In many cases, properly observing these cues is made difficult by the positioning of people in relation to the activities being observed. Often 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 by the inability to have sufficient resolution to detect the error. In other cases, such as operations within the SFP, additional challenges come from the effect of refraction in the water and reflection from the surface of the water as they can distort the view of operations that require precise positioning.

Crane operations are challenging whether they are conducted in or out of the SFP. The crane operator typically may need to lean out over the crane bridge, and will often only be able to view operations from directly above. Many of the potential errors that could occur are related to vertical position, which is very difficult to determine from directly above the item to be lifted. In addition, even the view from above may be obstructed, either by the yoke or by the load being moved. Thus, personnel close to the cask are often put in the position of being the hands for someone else's eyes, which make the operations susceptible to the communication vulnerabilities discussed previously. These visual considerations can be exacerbated by procedural and training deficiencies (e.g., roles and responsibilities) in identifying who has the authoritative "eyes" for the crane operator at a particular moment in time.

It is recognized that there are plants which operate large cranes using wireless, radio frequency control pendants. This enables the crane operator to be down at the floor level where the cask movement being controlled can be observed from various vantage points as needed. However, even in this case there are visual challenges related to the sheer size of the object being moved relative to the crane operator. That is, the crane operator cannot see all sides of the cask at one time and will likely require assistance from nearby personnel to ensure adequate visual coverage of the cask and any potential obstructions near the cask travel path.

Visual challenges are a type of latent error condition which may impact human performance with respect to active failures that occur close in time and space to the negative consequences of interest (e.g., a cask drop). However, visual challenges can also play a prominent role in latent UAs during quality assurance activities involving structures, systems, and components used in DCSOs that occur long before cask movement activities are conducted. This aspect of visual challenges is addressed in Section C.12 in the discussion of human performance vulnerabilities related to quality assurance.

C.8 Unchallenging Activities

The activities involved in SFH 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. These activities can become boring and monotonous, which may be exacerbated if personnel 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 (as discussed in Section B.4.3). This lack of challenge may lead to increasing complacency as multiple cask loading evolutions within a single campaign occur without incident (e.g., the first five cask loads proceed without incident, however, omissions due to complacency lead to a cask drop during the sixth load).

Unchallenging activities are a type of latent error condition which may negatively impact human performance (i.e., “set up” personnel for UAs/HFEs).

C.9 Time Pressure

Although time pressure during CLCs is generally less than during refueling outages (due to the nonproducing 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 various cask loading operations. The time pressure described in the scenarios predominantly arises from the tension generated by the often conflicting goals of “productivity and safety” as described in Section
B.2.1 Human Error at the Root of Incidents. The tone set by all levels of management regarding the relative goals of ensuring safety versus meeting a predetermined schedule will greatly impact the perception of time pressure among operations personnel (recall Figure B-1). In other words, many of the 13 elements of safety culture can have a significant impact on the presence of time pressure. It is conceivable that time pressure may vary widely between individual cask loads during a CLC. For example, time pressure may be low for the first three of six cask loads, which are performed meticulously and slowly, however, time pressure may increase for subsequent cask loads as the date of a planned outage nears. Time pressure can occur due to various aleatory factors or a host of unanticipated circumstances. For example, during the refueling outage at Diablo Canyon in 2008 (which included the replacement of four steam generators) there was a flu outbreak that sickened and incapacitated many workers at nearly the same time (Michal 2009).

Time pressure may also be increased relative to achieving a specific safety goal such as when rigging personnel are encouraged to complete operations quickly in order to reduce occupational radiation exposures in accordance with the ALARA principle. In this situation it is possible that the execution of actions becomes more skill-based (i.e., involving little or no conscience thought) over the course of a CLC, which may impair the ability to detect certain types of infrequently occurring abnormal conditions. For example, a rigger during the seventh subsequent cask load may skillfully/efficiently perform the change-out from short slings to long slings; however, they may become less likely to detect external damage to the slings.[147] Overall, you may have a mix of people experiencing a wide range of perceived time pressure or stress; some are executing exceedingly slow, monotonous operations and other personnel are executing quick operations (i.e., perceived time pressure may increase with significant attention focused on radiation exposure). Excessive time pressure is a latent error condition which may negatively impact human performance (i.e., “set up” personnel for UAs and HFEs).

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[147] It is conceivable that the opposite phenomenon may be true (i.e., rigging personnel becoming more attentive to the condition of the slings and other rigging gear). Ideally, the authors of this report would have been able to meet crews and observe operations at multiple plants in order to discover the predominant impact (and inter-crew variability) of sequential cask loads with respect to this human performance vulnerability.

C.10 Time-of-Day and Shift-Work Challenges

Slips, lapses, mistakes, and circumventions tend to occur more often when workers are fatigued, especially when that fatigue is encountered during late night or early morning hours.[148] Furthermore, personnel working occasional night shifts may be tempted to rush operations to end shifts early or at least change the focus to non taxing activities (e.g., hurry up with the welding or rigging 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). Multi-shift operations combined with time pressure (e.g., trying to complete seven cask loads as soon as possible) and typical resource constraints may lead to situations in which personnel not habituated to working particular shifts are forced to work those shifts which may result in negative impacts on performance. For example, a crane operator or rigger who consistently provides outstanding performance during the day shift and who is then needed to substitute for a sick colleague on a night shift may encounter unanticipated yet significant decrements in performance (e.g., excessively fatigued, easily distracted, or slightly less coordinated). It should be noted that excessive fatigue due to unaccustomed shift work may occur during the atypical shift or it may occur during a subsequent shift as a result of insufficient rest between the shifts. Personnel returning to work following an illness (e.g., flu) may also encounter atypically high levels of fatigue until they re-adapt to their standard work-rest cycle.

It is important that payment systems do not encourage a culture in which nonessential performance of overtime or double shifts occur simply due to financial rewards. This practice will encourage habitual states of fatigue among personnel that simultaneously lower both safety and productivity. Plant management may need to be particularly vigilant with respect to financial incentives encouraging fatigue among temporary contract personnel. Excessive fatigue related to the time of day and shift work is a latent error condition which may negatively impact human performance (i.e., “set up” personnel for UAs/HFEs). Fatigue is one of three fitness for duty issues focused on in this list of human performance vulnerabilities; another fitness for duty item involves the ability to access[149] structures, systems, and components (SSC), such as crane supports, other crane equipment, and cask equipment during quality assurance and other inspection activities (discussed in Section B.12 and Section B.17). The final fitness for duty issue addressed in this list involves the effects of illness as it relates to fatigue, distraction, or increased workload (as mentioned earlier in this section as well as in Section B.9 and Section B.17).

C.11 Inadequate Verification

Human actions contain dependencies when they involve the same operator, the same procedures, or are competing for the same resources in the same time (EPRI 2004). In addition, achieving complete independence between checks of other’s work by personnel is a daunting task. As noted by Swain & Guttman, “…the probabilities of errors for a checker of someone

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[148] 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-day physiological changes (i.e., circadian rhythms) are well documented in many studies of human performance. See Salvendy (1997) for an introduction and overviews of the circadian rhythm and shift work literature.

[149] In this case, fitness for duty refers to having the agility, flexibility, strength and/or stamina to access the areas and perform the inspection or maintenance activities.

else's work will be much higher than the probabilities of errors for the original performer.[150] This is because the checker usually does not expect[151] to find many errors when he is evaluating someone else's performance—a special case of dependence" (NUREG/CR-1278 1983, p. 2-8 – 2-9). Inadequate verification results from factors leading to incorrect checking or the overestimation of independence between checks. The key factors to consider include common-mode failures, social shirking, and overcompensation (Sagan 2004; Brewer 2009).

- *Common-mode failures*—these include failures in redundant checks due to inadequate items, e.g., training, tools, equipment. For example, multiple inspectors incorrectly checking for defects will not increase levels of safety, they will only create latent error conditions. Similarly, spotters or crane operators relying on inappropriate procedures, indicators or job aids may also jeopardize safety. Critical to proper verification is knowing what to search for and being capable of deciding whether a problem exists once something off-normal is detected (these factors are discussed further in Section B.12). For instance, detection is hampered when access to the area where the problem exists is limited or inaccessible. Recall the event mentioned in Section 4.2 where weld and base metal cracks in crane supports discovered at one plant and had gone unnoticed for a period of time due to the areas for inspection being deemed inaccessible by the licensee. The NRC later deemed the same areas to be accessible for inspection. Another example of a common mode failure would be a worker who consistently over-tightens bolts with a pneumatic tool and then a second worker (the checker) who incorrectly verifies the torque level using a large torque wrench. That is, the use of the torque wrench only verifies that the required torque has either been met or exceeded.

- *Social shirking/misplaced trust*—a phenomenon in which individuals or groups reduce their reliability in checking by assuming that others will "take up the slack." This is due in part to the previously mentioned observation that checkers of another's work, while attempting to perform a thorough check, do not expect to find errors as they believe that the first person already performed a good check. It is also due to improper application of the concept of trust. Trust is an essential component of any team-based activity. Crew members must be able to depend on the correct behaviors of others when performing operations. However, trust can have a negative component as well. An example is where a supervisor "trusts" the experienced crane operators and rigging personnel leading the supervisor to do only a cursory verification of their activities.

    - This type of "misplaced trust" could emerge after careful review of the performance of several instances of an activity without discovering any discrepancies. Use of the terms "misplaced trust" does not imply that someone is generally "untrustworthy" if they succumb to this behavior—it is to highlight a subtle, yet unsafe behavior among those who are "trusted." Crew members must always be reminded of the proper orientation of the "trust" relationship. In this case, trust should imply that the personnel can "trust" the supervisor and other team members to carefully review their conduct of operations to protect them from missing errors that may lead to a cask drop (Brewer, Amico et al. 2006). An

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[150] In cases of skilled performance of tasks, most of the errors that occur will be slips and lapses that are detected by and recovered by the person performing the task.

[151] This may be contrasted with a situation in which a checker does expect to find errors, i.e., a teacher or expert reviewing the work of a student or novice. In this case the expert not only expects errors, but learns over time where such errors tend to be clustered given the experience level of the student. To summarize, when people do not expect to find errors they are not good at detecting them (Brewer 2009).

improper orientation of trust (misplaced trust) may grow over time (i.e., over multiple cask loading cycles within a CLC) due to repeated successful performances. Trust also becomes an issue in searching for nonconforming conditions and deciding whether they constitute a problem in need of correction. A worker trusts another to detect, or "see", a problem; however, the ability to detect an error relies on searching the correct area in the proper manner and being able to correctly decide whether a problem actually exists once something has "caught the eye." The importance of searching and deciding will be discussed further in Section B.12 The phenomenon of "unresponsive bystanders" to a crime witnessed by many people is also an example of social shirking (Darley and Latane 1968; Latane and Nida 1981; Sagan 2004).

- *Overcompensation*—a phenomenon that results when the addition of extra items or personnel, intended to be redundant, encourages individuals or groups to increase production or engage in riskier behavior. An example would be greatly increasing throughput of newly manufactured crane components at an inspection station after providing additional inspectors. Other familiar examples of overcompensation include reckless driving in safer cars, i.e., those with seat belts and airbags versus those without (Crandall and Graham 1984); and the introduction of "baby-proof" safety caps on medicine bottles that are now left outside the medicine cabinet by parents, which lead to increases in child poisoning (Viscusi 1985; Sagan 2004). Overcompensation is a distinct action that often compounds the problem of failing to understand/account for dependencies due to social shirking and common mode failures.

It takes special training, crews, and working culture to maintain increased independence between multiple checkers (Brewer 2009). Mixed or hybrid crews composed of both plant personnel and temporary contractors may be especially vulnerable to having different understandings regarding the amount of verification needed or relied upon by others. This leads to degradation or elimination of redundant checks. Problems involving inadequate verification are latent error conditions that tend to act over a range of timescales. That is, there can be deficient training relative to specific verification activities, there may also be a deficient safety culture in which trust relationships are routinely inadequate with respect to verification, or there can be more immediate time dependence upon factors within a single CLC such as time pressure and fatigue which lead to social shirking/misplaced trust-related cursory inspections of others' work. A deficient safety culture may also reinforce incorrect beliefs that overstate the robustness of verification by multiple personnel such that overcompensation occurs when setting task completion goals.

C.12 Quality Assurance (QA) Problems

Careful verification of all DCSS components and related plant structures, systems and components (SSC) to the appropriate conformance requirements is essential during all phases of DCSOs. Items of particular importance to cask drops include lifting related items such as cask trunnions, lifting yokes, lift beams and associated components, heavy lift cranes and supporting structures, and rigging equipment (e.g., for lifting MPCs). Examples of quality assurance processes include inspection and/or testing of crane supports, lift beam support pins, crane control indicators and interlocks, as well as visual and tactile tests of rigging gear. These activities are necessary during procurement,[152] prior to first use,[153] following maintenance, and throughout the operational life cycle of SSCs. During quality assurance it is critical to ensure that design requirements are suitable for particular SSC and that the fielded items meet the specified requirements. For example, it may be appropriate for QA personnel to ensure that remote control crane pendants are designed and tested to fail safe if subjected to significant shocks during use (i.e., if dropped by the crane operator (potentially multiple floor levels) while moving a cask).

QA activities may also be vulnerable to time dependence within a CLC or across multiple CLCs. For example, crane structure supports may be inspected diligently prior to the first of seven cask loads to be performed within a single campaign. Inspection activities may become less rigorous as multiple successful cask loads are completed even though cracks may be growing and cask drop potential may be increasing. In addition, maintenance of structural integrity during one CLC may bias[154] inspectors such that a cursory inspection is performed prior to a subsequent campaign a few years later.

Visual inspection during QA activities can be susceptible to a number of visual challenges. Two groups of challenges appear to exist for DCSO-related items. The first group involves objects which are relatively small with respect to human inspectors (e.g., lift cleats, crane control pendants, and trunnions) and can easily be viewed and manipulated by one person in a designated workspace. The second group involves objects which are relatively large (e.g., large crane equipment, casks) and require inspectors to maneuver on, around, or over them, or to manipulate them with heavy equipment multiple times to complete a thorough inspection.

Factors that impact visual detection of defects/nonconformance for both large and small objects can be grouped into two areas: searching and deciding. That is, the inspector must search for a defect and when something catches their attention they must decide whether or not they have found a defect. Factors which strongly influence both searching and deciding include instructions, procedures, training, experience and the culture of the organization in which inspections are performed. For example, it is known that defect detection performance is degraded when inspectors use subjective versus objective reference criteria, do not use a systematic visual search pattern, are instructed to look for many types of defects during one visual scan of an item versus repeated scans of an item while searching for only one type of defect, e.g., cracks, gouges, burrs, corrosion, tool marks (Buck and Rizzi 1974; Bloomfield 1975; Wickens and Hollands 2000). The culture aspect is important with respect to whether quick inspections of "typically" problematic areas are encouraged by the organization, or whether there is emphasis on a thorough search all over the item inspected. The level of feedback is also crucial to acquiring and maintaining inspection expertise. For example, in some inspection tasks there may be unclear guidance as to what severity of a defect constitutes a problem and there may not be systematic training programs to ensure consistency in making defect determinations. There are organizations in which the inspectors who are perceived to be the "best" are those who have (1) the most years of experience; and (2) those perceived to have the right balance between identifying major versus minor defects. However, when tested in a controlled environment their actual performance may be quite different from their perceived performance.

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[152] The rigorous inspections in the procurement process include those quality assurance activities executed throughout the fabrication/manufacturing processes for the equipment.

[153] For example visual and tactile tests of the rigging equipment prior to first use *should* provide a redundant verification for the equipment procurement process.

[154] The phenomenon of "confirmation bias" will be discussed in greater detail in Section B.13.

Research at Sandia National Laboratories has recently discovered dramatic levels of omission during aircraft structural inspections among highly experienced, highly motivated maintenance personnel. The experiment involved a number of inspectors who individually inspected an aircraft fuselage for which there were 20 well-characterized, visible cracks. The best inspector found 15 of those cracks. Many inspectors found significantly less than that number. One inspector missed a very large crack because he inadvertently placed a clipboard on the area to be inspected as he entered a portion of the fuselage. When confronted with the results of these experiments, many of the maintenance personnel were shocked and upset to discover their actual level of performance. For many of the inspectors this experiment was the first time they had received objective inspection performance feedback[155] on a well-characterized aircraft (Wenner, Spencer et al. 2003; Wenner 2008). For summary information on the extensive literature concerning visual inspection/signal detection, see references (Kantowitz and Sorkin 1983; Salvendy 1997; Wickens and Hollands 2000). Techniques for improving visual inspection activities, particularly as they apply to QA, are provided in Section 6 of this report.

Inspection problems can also arise when inspectors do not have an appreciation for the level of impact that a particular defect can have on the intended use of an item (i.e., the practical consequences). For example, if inspectors believe the sharp edges or gouges noted as "significant" defects in their procedures will not ultimately result in any performance decrement they may be less likely to identify or call attention to them—particularly if there are production pressures encouraging them to get the components out the door. Factors which are unique to visual inspection of large objects include accessibility (e.g., the difficulty of inspecting structural supports for a crane), and inspector-specific factors such as mobility (e.g., general fitness and flexibility) and visual abilities. QA problems are a subset of latent error conditions.

C.13 Decision-Making Bias Error

There are a number of biases that may interfere with the decision-making processes. Recall from Section B.3.3 that the definition of "bias" encompasses a systematic tendency or heuristic which limits a comprehensive application of available knowledge, experience, and related data to decisions and/or actions (Brewer 2009). Biases, tendencies or heuristics of human decision making are not inherently bad; they are methods of mentally taking shortcuts in recognizing a situation, which normally allow people to quickly select the most plausible choices first, followed by the less plausible choices (NUREG-1880, 2007). However, biases or heuristics that tend to work in specific, often "simple" information settings, sometimes lead to severe and systematic errors in other settings (e.g., more complex) such that they hinder proper interpretation of available information and data and lead to inappropriate perceptions, decisions, and actions (Tversky and Kahneman 1974; Brewer 2005). In this report, the term bias error is generally

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[155] It should be understood that the aircraft maintainers/inspectors that participated in this experiment were among the "best performers" according to the airlines and aircraft maintenance service companies that employed them. This implies that "best" in the eyes of the employing organizations may not have been with respect to being able to identify important defects such as cracks, but in being fast/efficient at carrying out maintenance and inspection tasks. The key question is: "Does the reward system encourage the appropriate behavior for avoiding future accidents?" (e.g., by avoiding latent error conditions); asked differently, "Does the reward system encourage short-cuts and trade-offs which set up the latent error conditions for future accidents?" In the case of these maintainers, the measurement and reward system appeared to have little objective connection to how effective they were with respect to identifying cracks that could threaten the safety of an aircraft.

used to describe a systematic tendency or heuristic that leads to inappropriate decisions and/or actions in specific scenarios.

While there are dozens[156] of well-researched biases, three decision-making biases that are especially prevalent in cask drop scenarios are the confirmation bias, the loss aversion bias, and bias due to overconfidence.[157] A brief discussion of these biases is provided below. The interested reader may refer to Brewer (2005; 2008; 2009) and Arnot (2006) for more extensive discussions of these and many other decision-making biases.

(1) *Confirmation bias*—people tend to seek out evidence which confirms their current position and to disregard evidence that conflicts with their current position (Einhorn and Hogarth 1978). In fact, several studies have specifically shown that preliminary hypotheses based on early, relatively inadequate data interfere with later interpretations of better, more abundant data (Anderson and Jacobson 1965; Greenwald, Pratkanis et al. 1986; Reason 1990). Confirmation bias exists when all seems to be proceeding as planned and the level of evidence required to challenge this belief becomes greater as time progresses. Although workers may be vigilant in observing problems in an activity at the beginning of the procedure, as time progresses (e.g., within a single cask load and/or across multiple cask loads within a single campaign), the crew may increasingly believe "all is well." This belief may lead the crew to relax their vigilance and may even cause them to divert their attention to the next task. Therefore, signals indicating a problem may need to be stronger as time passes in order to capture a crew's attention. For example, consider a situation in which a cask appears to have been properly captivated by the lifting yoke and vertical travel is underway. Personnel observing the cask throughout the course of movement may find it progressively more difficult to detect cues indicating improper engagement of the lifting yoke on the trunnions. That is, as personnel receive feedback that lifting is proceeding successfully, the magnitude of the cue required to draw their attention to the fact that the trunnions are not properly engaged will likely need to be greater (e.g., larger visual discrepancy or louder abnormal audible indication) to overcome the increasing bias that cask movement is proceeding properly. Confirmation bias can be greatly exacerbated by fatigue or increases in perceived stress. Related phenomena include perseveration and attentional/perceptual tunneling or narrowing.

Perseveration arises when high levels of stress cause people to continue executing a given action plan over and over again. This continuation of an unsuccessful routine is repeated even though the very failure of this routine to resolve the problem at hand may be a cause of increasing stress. Attentional/perceptual narrowing is essentially a tunnel vision effect where people become less able to process diverse information or shift the focus of their attention (Swain and Guttman 1983; Hancock and Szalma 2003). One

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[156] The topic of biases is complex and includes many phenomena, for example, the bias process of *overestimation of independence between redundant-type events*, which includes *common mode failures, social shirking, and overcompensation* (Brewer 2008) formed the basis for the Inadequate Verification human performance vulnerability discussed in Section B.11. Another common bias is the anchoring effect, i.e., people are "anchored" to the first option or value they see or the first judgment they make; if you show people a random number between 1 and 100 and then ask them the number of countries on the African continent, their guess will be fewer countries if the random number was small and more countries if the number was large (Tversky and Kahneman 1974).

[157] The overconfidence bias is a wider categorization of various individual specific biases which includes several well-studied bias processes (Hora 2007; Meller and Locke 2007; Brewer 2008).

example from the NPP control room domain which encompasses these various aspects of confirmation bias was the performance of operators during the Three Mile Island Unit 2 accident in which the initial failure appeared to fixate their attention on the one indicator supporting their belief that the water level was too high, thus filtering attention from other more reliable indicators that conflicted with the “high water” interpretation of the situation (Wickens and Hollands 2000).

In DCSOs there is some potential for sufficient stressors to emerge such as general fatigue due to shift work and fatigue due to tedious or difficult operations (e.g., rigging) leading to magnification of confirmation bias errors. There may also be a great potential for confirmation bias and perseveration to emerge if a low likelihood cask drop accident was to occur. For example, if a cask dropped and the consequences included injuries to personnel, extensive equipment damage, and some level of fission product release—would the available personnel be trained and ready to successfully respond in this high stress environment? Or is the attitude at a given plant simply to have a written procedure somewhere to “address the topic,” but the behaviors of personnel to focus only on normal operation in the belief that a cask drop simply will not occur? It should be noted that confirmation bias is related to the safety culture concept, discussed in Sections 2 and 6 of this report.

(2) *Loss Aversion*—in addition to the confirmation bias phenomenon, the manner in which a particular person frames or mentally accounts for the concept of “loss” (Kahneman and Tversky 1979; Bernstein 1998) in a given situation provides a strong biasing factor toward information and actions that enable the person to steer away from incurring that “loss” (Brewer 2005). This bias also includes the widely discussed *dread* factor (Slovic, Fischhoff et al. 1981; Slovic 2000). 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 (Brewer, Amico et al. 2006).

For example, consider a situation in which a cask appears to have been properly captivated by the lifting yoke, however, one yoke arm is actually positioned improperly on the trunnion, and although vertical travel is underway, the cask captivation is unstable/tenuous. Furthermore, consider that a loud, metal-on-metal sound momentarily captures the attention of workers observing the cask movement. The source of the sound may be relative movement of the yoke arm in the trunnion, which could be providing a cue that cask drop is imminent. However, the sound may simply be the result of machine noise or the performance of other work activities in nearby areas of the building. The *non-loss threatening* explanation of the metal-on-metal sound being due to other activities contrasts with the *loss-threatening* explanation of “Oh no, the cask is improperly captivated and a drop is imminent!” The *losses* referred to here are the potential losses related to catastrophic cask or plant damage, injury to personnel and/or fission product releases. Note that this may seem contrary to typical intuition which may suggest that anything “out of the ordinary” would be seen as a signal to pause or stop operations. This may be akin to the observations of Wagenaar and Groenweg, “Accidents do not occur because people gamble and lose, they occur because people do not believe that the accident that is about to occur is at all possible” (Wagenaar and Groeneweg 1987) as cited in (Reason 1997, p. 39).

Another decision-making example that appears to reveal the loss aversion bias error is one mentioned by Swain and Guttman (1983) that involved the control room operator for a refinery. The first indication to the control room operator of a serious fire was that numerous alarms activated and many instruments behaved abnormally. The operator's first response was to run upstairs to the instrumentation technician and demand, "What's wrong with my instruments?" (Swain and Guttman 1983, p. 3-37). By the time the operator returned to the control room, it was too late to take actions to reduce losses due to the fire.

(3) *Overconfidence*—the phenomenon of overconfidence is closely related to individual susceptibility to confirmation bias and individual loss aversion tendencies (i.e., the two biases listed above). However, there are additional factors which can influence the degree to which an individual will tend to exhibit overconfidence including: the law of effect, locus of control, ambiguity aversion, and hindsight bias (Winterfeldt and Edwards 1986; Brewer 2008). The law of effect refers to the degree to which an individual avoids negative stimuli (e.g., pain, discomfort, embarrassment) and seeks to increase positive stimuli, i.e., pleasure (Miller 1962; Kandel, Kupfermann et al. 2000). With respect to DCSOs different people may be willing to exert different levels of effort to avoid an incident involving a cask, while simultaneously exert different levels of effort to ensure that a cask movement operation proceeds quickly (i.e., to earn the praise of a supervisor).

Locus of control involves the degree to which someone perceives that they have control over job performance and work-related rewards such as pay and promotion. People identified as having an internal locus of control believe that such things are largely under their control. Those with an external locus of control believe such things are the result of luck, chance, or whether the boss likes them, i.e., not within their control (Rotter 1966). In the context of DCSOs, locus of control could be manifested as someone's perception of the degree to which task performance is solidly within their control or highly dependent upon others or luck.[158] Having an internal locus of control is beneficial up to a point, indeed it is a necessary condition for assuming appropriate responsibility for task performance; however, an excessive internal locus of control can lead to overconfidence (e.g., not allowing margin to compensate for possible aleatory or epistemic uncertainties that may degrade safety).

The ambiguity aversion bias has been associated with a person's tendency to wager on vague probabilities/beliefs in situations where they feel especially competent, yet wager on chance when they do not. This concept emerged in the study of probability estimation tasks and is closely linked with perceptions of incompetence (Fox and Tversky 1995). An example highlighting this phenomenon would be a crane operator's belief in being able to easily position a cask within 5.1 centimeters (2 inches) of the SFP wall (i.e., with a probability of success of 99.9%) with or without temporary obstructions blocking the movement. The operator's confidence in being able to maneuver the crane is so high that the perception of the odds of success are always much higher compared to the odds of failure, so that it is easy for the operator to discount the likelihood of a negative outcome. That is, over time the operator implicitly believes that the negative outcome could never occur.

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[158] The degree to which people have an internal or external locus of control could be inferred from people's attitudes following a cask load, e.g., "we were lucky, everything went smoothly," versus "everything went great because we had everything under control the entire time—I know I did my job right!"

Another phenomenon relevant to overconfidence is the pervasive hindsight bias in which a person recalls having greater confidence in an outcome's occurrence or lack of occurrence than they had before the resulting events were known (Fischoff 1975). While all people exhibit the hindsight bias, some are more susceptible to succumbing to its influence. An example related to DCSOs would be one crane operator who watches another crane operator make a cask movement mistake that results from temporary obstructions in the second operator's view as people move between the operator and the cask being controlled. In recounting observations made about the move with a co-worker, the first operator comments on knowing something was about to go wrong when a few workers momentarily obstructed the second crane operator's view. In reality, this connection was made after the fact due to hindsight bias, and the first operator mistakenly remembered having foreknowledge of the impending mistake. The primary danger of this bias is that personnel may not learn appropriate lessons from the near misses or accidents of others.[159] They may simply dismiss the learning opportunity by saying (or thinking), "wow, that sure was dumb; I'd never do that!"

In summary, the overconfidence decision-making bias has many subtle aspects which vary by individual and vary within a particular individual over time. It is important in the conduct of DCSOs to have teams of well trained, experienced, and confident personnel. However, many factors (e.g., procedures, training, pre-briefs, methods for capturing and incorporating lessons learned, safety culture) must be managed with sophistication to avoid tipping the balance of performance away from a beneficial level of confidence and toward a regime of excessive risk-taking characterized by overconfidence (a.k.a., false confidence).

C.14 Inadequate Team Coordination

There may be undesirable variability within and between teams involved in DCSOs, especially during operations where actions are predominantly skill-based, there is limited reliance on procedures, new or hybrid teams have been assembled or there are hand-offs of responsibility between teams (e.g., shift changes or specialized teams for different operations). While team member variability in skills, attitudes, knowledge, working styles, and other characteristics is beneficial in many situations, it can also mask differences in understanding the abilities and assumptions guiding other's performance such that task performance is inadequate for particular situations. An opportunity ripe for the influence of inadequate team coordination would be the hand-off of information between teams (e.g., shift changes or specialized teams for different operations). In addition, hybrid teams consisting of both plant personnel and temporary contractor personnel may be particularly vulnerable to inadequate team coordination. For instance, the temporary contract personnel may be highly experienced in general, but they may lack critical items of declarative or tacit knowledge[160] relative to the specific plant, which may not

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[159] "A wise man learns by the mistakes of others, a fool by his own"—Latin proverb. "All men make mistakes, but only wise men learn from their mistakes"—attributed to Winston Churchill.

[160] Recall from Section B.5 that explicit, figurative, or declarative knowledge (involving semantic memory) is concerned with knowing "facts." Tacit, operative, or procedural knowledge (involving episodic memory) involves understanding where the "explicit" knowledge comes from or what underlies it. Tacit knowledge also involves the capacity to use, apply, transform, or recognize the relevance of explicit knowledge in novel situations (Brewer 2005). Tacit knowledge is much harder to articulate and communicate to others; in fact, experts may posses a great deal of tacit knowledge of which they are not explicitly aware (Brewer 2008). The difficulty of explicitly identifying, articulating and communicating tacit knowledge has historically been overcome through knowledge transfer techniques under designations such as guild,

be anticipated or compensated for by the plant personnel. Likewise, the plant personnel may be lacking in declarative or tacit knowledge relative to the equipment and processes familiar to the contractors.

For example, an experienced team member from the plant, overly confident in the ability to perform a task, completes the task quickly such that a slip occurs and a step is missed. Another member of the team, a temporary contractor who is slower and more methodical by nature, notices the rapid task performance of the co-worker and suspects a potential UA; however, they come from a safety culture that discourages challenging the work performance of others, thus no verification is attempted. As another example, imagine that the second worker in the same scenario assumes that the rapid task performance simply demonstrates the first worker's tremendous skill—casting doubt on the possibility of a UA; thus no verification is performed.

Another example of team variability that could lead to inadequate team coordination could include rigging teams. For instance, some teams may be more methodical in carefully inspecting all bolts, slings, and other rigging materials before, during, and after installation than other teams who may be more aggressive in expediting execution of operations. Inexperienced teams may run a greater risk of mistakes and experienced teams may be at higher risk for slips and lapses. Therefore, teams without members having both a range of experience levels and a culture of respectfully challenging/verifying one another's work may be more susceptible to UAs.

In the realm of power reactor operations there are additional examples of inadequate team coordination relative to the specific plant conditions being faced by teams. Consider two control room crews, one which follows a formalized, slow, methodical approach to diagnosing plant conditions then taking actions, and a second crew which tends to display faster, skill-based diagnosis and response actions. The first crew tends to refer closely to written procedures and always holds situation awareness briefings so that the shift supervisor and operators can arrive at a course of action. For the second crew it is common for the shift supervisor to take control and command rapid responses. In a situation where a cask drop occurs in a Mark I BWR that simultaneously initiates an accident and disables the equipment necessary to mitigate the accident, the "fast-acting" crew may do better at avoiding UAs and HFEs. If a similar cask drop only initiates the accident, but does not disable the equipment necessary to mitigate the accident, then the "slow, methodical" crew may perform better. A related set of examples for DCSO crews could include the following: given a cask drop in the SFP at a Mark III BWR or PWR that causes a major penetration in the SFP, a "fast-acting" crew may be better at avoiding UAs or HFEs degrading the ability to cool and provide shielding for the fuel. If a similar cask drop does not impair performance of the SFP to cool and shield the fuel then the "slow, methodical" team may perform better at avoiding UAs or HFEs which lead to ineffective shielding and cooling of the fuel. Thus, depending on the specific plant conditions facing the operators, either type of crew characteristics may be most effective at avoiding UAs and HFEs.

C.15 Improper or Uneven Task Distribution

The distribution of tasks and workload across the members of a team can affect the tempo of the work as well as the stress level of the individual team members. Tasks and duties should be well defined so that crew members understand who is responsible for what actions. The clear

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artisanship, and apprenticeship (Maughan 2006). Modern contemporary techniques of knowledge transfer include mentorship (Denning 2000; Maughan 2006) and shadowing (Swap, Leonard et al. 2001).

definition of duties helps avoid shirking of responsibilities or the over-reliance on others to complete tasks and observe the activities. For example, if decontamination personnel are experiencing "down-time" (e.g., following the cleaning of the outer surface of the cask upon lifting from the SFP), they may be able to serve in an extra capacity elsewhere (e.g., as extra spotters during the cask movement). In this way, the crew members can provide redundant verification for one another and aid in avoiding UAs. The personnel that have shorter job duties could support the personnel doing more complex or time consuming jobs.

Furthermore, if a team member is overloaded with tasks or with a share of the workload, there is the danger that not all tasks will be performed on time or correctly due to the worker's rushed response to the time pressure. In addition, the employee may feel resentful of being loaded with extra duties while other workers appear to have much less to do. This resentment could increase stress to the point at which UAs become more likely. Conversely, if a team member is underutilized, a situation resembling that described for "unchallenging activities" in Section B.8. may exist in which the employee becomes bored. As described earlier, this can create 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.

C.16 Large Number of Manual Operations

Although the pace of DCSOs is generally slow, there are times when a burst of activity is necessary. During these periods, personnel may be required to perform a large number of manual operations. As the number of manual operations increases, personnel must practice a high level of vigilance in completing each of the tasks. In addition, along with the large number of operations, there is often a large number of tools and equipment necessary. The personnel must be observant of the condition of the tools and equipment in these operations and ensure they are functioning properly. With an increase in the number of manual operations (e.g., many manual subtasks for safety critical rigging tasks) comes an increased likelihood of UAs due to slips, lapses, mistakes, and circumventions. Numerous manual operations, such as rigging operations, may also be required under conditions of time pressure caused by to minimize exposure to thermally hot conditions or to minimize radiation exposure per the ALARA principle. The large number of manual operations combined with time pressure will generally increase the likelihood of UAs.

Many crane load drop events that have actually occurred have involved problems with rigging operations. In fact, a primary motivation for developing yokes to move casks was to eliminate rigging activities as they add many manually intensive process steps and a large number of smaller equipment items that must be maintained and used properly. That is, with the rigging operations you have manual removal and installation of multiple slings, fasteners, clips, etc. In addition to frequent interactions with critical equipment and tools, personnel will need to be highly vigilant in identifying any fasteners, load-bearing items, tools, or other equipment that need to be repaired or replaced as these operations are repeated many times during a CLC. Cask system designers (e.g., Holtec International) have been forced to balance a number of competing objectives in order to develop the cask systems, some of these competing objectives include the safe transfer of large amounts of spent fuel (to reduce the number of loading operations), while not overstressing lifting devices and general building structures.

To expand on this point with an example, currently available cranes are not capable of maneuvering a fuel and water laden storage cask of the HI-STORM 100 type in and around the

SFP or in other parts of the plant. Therefore, additional transfer cask and MPC handling using manually assembled rigging equipment is required at various stages of the process (i.e., short slings to support the MPC inside the transfer cask & long slings to facilitate MPC lowering from the transfer cask down to the storage cask). Another potential option would be to make more frequent unloading trips between the SFP and the ISFSI using much smaller spent fuel loads. Of course, this strategy would likely involve longer times for completing the CLC. Holtec International's FSAR for the HI-STORM 100 Cask System, Revision 3 (Holtec 2005) appears to indicate that many of the time intensive operations involved in DCSOs may not change dramatically with the use of much smaller casks. Table B-2 shows a subset of time intensive operations that may or may not change if a much smaller fuel load and cask were used compared to the HI-STORM 100 system.

Table C-2 Subset of time intensive operations that may or may not change if a much smaller fuel load and cask than the HI-STORM 100 systems were used per cask loading sequence.*

Action	Duration (seconds [minutes])	Change with smaller cask? (Yes, No, Maybe)	Estimated duration for 50% smaller cask accomplishing same offload (seconds [minutes])
Loading pre-selected fuel into MPC	61,200 [1,020]	Yes	61,200 [1,020]
Post-loading visual verification of fuel load	4,080 [68]	Maybe	4,800 [80 (i.e., 40x2)]
Install MPC lid and attach yoke	2,700 [45]	No	5,400 [90 (i.e., 45x2)]
Raise HI-TRAC to surface of SFP	1,200 [20]	No	2,400 [40 (i.e., 20x2)]
Decontaminate and survey HI-TRAC	6,180 [103]	No	12,360 [206 (i.e., 103x2)]
Perform NDE on Lid Weld	13,800 [230]	Maybe	24,000 [400 (i.e., 200x2)]
Repeat PT on MPC lid final pass	2,700 [45]	Maybe	3,600 [60 (i.e., 30x2)]
Perform NDE on vent and drain cover plate weld	6,000 [100]	No	12,000 [200 (i.e., 100x2)]
Perform NDE of closure ring welds	11,100 [185]	Maybe	22,200 [370 (i.e., 185x2)]
Draining, purging, drying and inerting activities	21,600 [360]**	Yes	36,000 [600 (i.e., 300x2)]
MPC sling installation, transfer lid mounting & other storage cask mating and loading operations	7,080 [118]	Yes	0
Total for this subset of operations	**137,640 [2,294]**	– – – – – – –	**183,960 [3,066]**

Note: Selected operation durations were taken from Holtec 2005.

* The totals listed only represent estimates for this subset of activities. A detailed task analysis would be needed to accurately assess the differences between large and small casks.

** We approximated six hours; this time period was not specified in the HI-STORM 100 FSAR.

C.17 Other Ergonomic Issues

As discussed in communication difficulties (Section B.5), the work area is extremely noisy, especially due to machine noise, and, at times, additional intermittent noise due to the sounding of various alarms. Although this level of noise may affect communications, it might also affect the work pace and perceived stress levels as personnel are distracted and annoyed by the noise. In addition to the noise in the area, the temperature and humidity of the environment can increase the thermal stress on the personnel as well as change the tempo of the work as the crew endeavor to finish the task as soon as possible. Work within hot or cold environments may provide increased opportunity for mistakes and sweating due to hot, humid environments and may impair vision or lead to loss of footing on slippery surfaces. The presence of relatively high radiation environments can also be an ergonomic issue impacting performance by raising perceived levels of stress and encouraging awkward postures (e.g., to avoid interaction with streaming radiation areas)—this effect may be in addition to vulnerabilities caused by time pressure (as discussed in Section B.9). Some of the DCSOs are performed in cramped locations affecting mobility. For instance, the rigging operations are performed in a relatively cramped space at the top of the transfer cask and underneath the crane hook by personnel who are themselves tethered by personal protective safety equipment.[161] Cramped working spaces can also make it very difficult to perform necessary equipment inspections. Recall the instance cited previously in Section 4.2 regarding the discovery of large cracks in the crane supports. The inaccessibility of these locations limits the ability of the crew and inspectors in performing adequate inspections of the equipment and making safety corrections if needed. In summary, ergonomic issues such as strenuous activities, work in cramped spaces, use of cumbersome work clothes, heat, cold, and noise all increase levels of fatigue, may increase stress, and impair visual inspection. In addition, fatigue, distraction or other impairment due to the onset of illness or upon return to work during recovery or following an illness is an important ergonomic issue. All of these factors can increase the likelihood of UAs and HFEs due to slips, lapses, mistakes, and circumventions as well. Note that fatigue levels are impacted greatly by both ergonomic issues and factors related to working hours as discussed in Section B.10.

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[161] To mitigate fall-related injuries.

APPENDIX D. GLOSSARY OF TERMS

This glossary contains many terms used in conjunction with HRA to support PRAs for NPP operations. It also contains terminology taken from other domains, as well as new terms that aid in understanding human performance vulnerabilities and in describing potential methods for avoiding unsafe actions that could contribute to a cask drop. The glossary is a resource for readers from all technical backgrounds because it clarifies often subtle distinctions related to human performance and cask-handling operations.

Active Unsafe Actions — Actions inappropriately taken, or not taken when needed, by personnel that result in a degraded plant safety condition that immediately or almost immediately results in an observed failure of a function, system, or component. Active unsafe actions (UAs) lead to active failures (see definition below) close in time to when the UA occurs. During an accident or incident investigation active errors are among the local triggering events identified with the immediate/direct/proximate causes of the accident or incident.

Active Failures — Failures that are the result of equipment failures or active unsafe actions that directly impact the safety of the system in which they occur. These failures are called "active" because they occur close in time to their adverse/consequential effects (Reason 1997). During an accident or incident investigation, active failures may result in an initiating event (see definition below) or in failure to mitigate accident conditions. An example of an active failure would be a crane operator failing to stop the raising of a cask which results in a two-block failure of the crane cables and dropping of a cask. Often in complex and/or redundant systems, it takes at least one active failure along with one or more latent error conditions (defined below) to result in a high-consequence event (Reason 1997). For example, on many cranes, it may be necessary for a crane operator to improperly raise a cask too high and a safety interlock to fail for a cask drop to occur.

Aleatory Uncertainty — Random variability in any of the factors that lead to the results. Aleatory uncertainty (1) is (or is modeled as) irreducible, or (2) is observable (i.e., repeated trials yield different results), or (3) exists when repeated trials of an idealized thought experiment will lead to a distribution of outcomes for the variable (this distribution is a measure of the aleatory uncertainties in the variable) (NUREG-1880, 2007). Examples of aleatory uncertainty include the differences in observed tensile strength of seemingly identical crane supports, some observed variations in the motor skill performance of rigging personnel, the set of spurious alarms present at a particular point in time that distracts personnel performing a critical task, and the presence or absence of a particular randomly occurring equipment failure when an unsafe action is executed during a cask lift.

Bias — A systematic tendency or heuristic which limits a comprehensive application of available knowledge, experience, and related data to decisions and/or actions. Biases, tendencies or heuristics of human decision making are not inherently bad; they are methods of mentally taking shortcuts in recognizing a situation, which normally allow people to quickly select the most plausible choices first, followed by the less plausible choices (NUREG-1880, 2007). However, biases or heuristics that tend to work in specific, often "simple," information settings sometimes lead to severe and systematic errors in other (e.g., more complex) settings such that they hinder proper interpretation of available information and data and lead to inappropriate perceptions, decisions, and actions (Tversky and Kahneman 1974; Brewer 2005). In this report, the term "bias error" is generally used to describe a systematic tendency or heuristic that leads to inappropriate decisions and/or actions in specific scenarios.

Cask Drop — In this report a "drop" (i.e., cask drop or multipurpose canister drop) refers to a freefall drop. See also the definitions of unplanned descent and unintentional lowering.

Cask Hang-up — A situation occurring during raising or lowering such that the cask is immobilized due to a crane-related failure or due to a cask or crane component impacting/coupling with an unyielding object. For example, a cask hang-up could involve catching a cask trunnion on a rigid object on the wall of the spent fuel pool such that damage occurs to the crane and the cask ceases to move.

Circumvention/Violation[162] — An error arising from *rule-based* and *knowledge-based* behavior that involves a deliberate, deviation from rules and practices that has the intention of maintaining safe and/or efficient operations (Reason 1990; NUREG-1624 2000). Circumventions may be routine (i.e., workarounds or informal rules), in which case they are usually shaped by procedures which are impossible to implement, or they may be an attempt to arrive at shortcuts or efficiencies in actions coupled with an environment that does not enforce strict compliance to ways of performing actions. Circumventions may also be infrequent, such as when a plant operator must resolve competing goals such as completing a task on time or following every step in a procedure. The particular goal of maintaining production or ensuring safety of the plant may drive the worker to circumvent required actions in the interest of achieving his or her goal.[163] For example, a worker who experienced difficulty inserting locking pins into the transfer lid door on five previous cask loads during a single cask loading campaign decides to forgo securing the transfer lid door with the pins during the sixth cask load in order to expedite lowering of the MPC from the transfer cask to the storage cask. Unfortunately, if the transfer lid door is not opened sufficiently, this circumvention may lead to an impact with the cask and the door resulting in either minor damage to components or major damage with radiological consequences (i.e., if a cask drop were to occur during the operation).

Confirmation Bias — The bias or tendency in which people tend to seek out evidence which confirms their current position and disregard conflicting evidence (Einhorn and Hogarth 1978). In fact, several studies have specifically shown that preliminary hypotheses based on early, relatively inadequate data interfere with later interpretations of better, more abundant data (Anderson and Jacobson 1965; Greenwald, Pratkanis et al. 1986; Reason 1990). Confirmation bias exists when all seems to be proceeding as planned and the level of evidence required to challenge this belief becomes greater as time progresses.

Context — The situation emerging from a combination of performance-shaping factors and plant conditions. A positive context can enhance human performance, while a negative context (see EFC below) may degrade performance.

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[162] James Reason (1990), a professor in the United Kingdom, used the term “violation” in his writings. The term “circumvention” is used here because it is not associated strongly with negative/malicious connotations. Although acts of sabotage were one type of violation included in Reason’s definition, such malicious behavior is not of interest in this report. In addition, in the United States nuclear and other well-regulated industries the term “violations” has a specific legal connotation related to breaking laws and regulatory rules that are distinct from human performance problems (Forester, Cooper et al. 2008)

[163] Note that Reason (1990) maintains that violations are different from mistakes. For example, research suggests that the frequency of violations is sensitive to age, while the frequency of errors is not. Violations tend to decrease as individuals become older; errors do not.

Defense-in-Depth (DID) — (1) The implementation of multiple barriers of increasing conservatism (Powers 2005). (2) A design and operational philosophy with regard to nuclear facilities that calls for multiple layers of protection to prevent and mitigate accidents. It includes the use of controls, multiple physical barriers to prevent release of radiation, redundant and diverse key safety functions, and emergency response measures (U.S. Nuclear Regulatory Commission 2009). (3) A three-level approach consisting of *prevention, protection,* and *mitigation*. Prevention seeks to avoid the operational occurrences that could result in accident precursors, e.g., high reliability components, systems, and operating practices; safety margins in operations, testing, and inspection; regular training; and quality assurance. Protection involves measures that halt or otherwise handle low-probability incidents and transients that cause minor damage and possibly small radioactive releases, e.g., control rods, pressure relief valves, interlocks, continuous monitoring. Mitigation involves systems which act to limit the consequences of an accident to people and the environment, e.g., emergency back up systems, massive containment structures, emergency planning and procedures (Knief 1992).

Epistemic Uncertainty — When the state of knowledge about the effects of specific factors is less than perfect. With epistemic uncertainty, (1) we are dealing with uncertainties in a deterministic variable for which the true value is unknown, or (2) repeated trials of a thought experiment involving the variable will result in a single outcome that is the true value of the variable, or (3) the uncertainty is reducible (at least in principle). Examples of epistemic uncertainty include the average tensile strength for the lot of steel beams used to construct a particular crane support system, the types of decisions and actions a particular crew will make if a cask drop occurs at a particular plant, and the average likelihood that a particular rigger will detect a particular type of surface defect on a particular piece of rigging equipment during a dry run of a cask loading operation.

Error-Forcing Context (EFC) — The situation that arises when particular combinations of performance-shaping factors and plant conditions create an environment in which unsafe actions are more likely to occur. The EFC is important as it acknowledges the observation that good teams in complex settings do not tend to exhibit random failures, they are typically “set up” for failure by a combination of factors (NUREG-1880, 2007). See Sections B.4.1 and B.4.4 for additional discussion of EFC.

Error of Commission (EOC) — A *human failure event* resulting from an overt, unsafe action, that, when taken, leads to a change in plant configuration with the consequence of safety degradation of the plant state. Examples include raising a cask too high (i.e., resulting in a two-blocking event), horizontally moving a cask prior to clearing a vertical obstruction (i.e., resulting in an impact), and moving a cask outside of the safe load path designated for the cask movement.

Error of Omission (EOO) — A *human failure event* resulting from a failure to take a required action, that leads to an unchanged or inappropriately changed plant configuration with the consequence of safety degradation of the plant state. Examples include failing to carefully inspect rigging equipment (which happens to be defective) prior to a cask loading campaign, failing to confirm that a travel path is unobstructed prior to moving a cask along that path, and failing to inspect crane support structures, systems, and components prior to moving casks with that crane.

Heuristic — A way of mentally taking a shortcut in recognizing a situation (i.e., a rule-of-thumb). In general, a heuristic method is used to rapidly generate a solution that is hoped to be close to the best possible answer. Heuristics normally allow people to quickly select the most plausible choices first, followed by the less plausible choices. Since heuristics are approximate solutions based on limited information, heuristics employed during human decision making are often impacted by and may even be solely the result of a bias process. Heuristics may be referred to as rules of thumb, educated guesses, intuitive judgments, common sense, workarounds, informal rules, and even biases. See also the definitions of bias, informal rules, and workarounds in this glossary.

Human Error — Any unwanted action that results in a deviation from expected norms and potentially places people, equipment, or systems at risk of exposure to hazards. In the PRA community, the term “human error” has often been used to refer to human-caused failures of systems or components. However, in the behavioral sciences, the same term is often used to describe the underlying psychological failures that may cause the human action that fails the equipment. Therefore, in this report (as in the ATHEANA HRA method) the term “human error” is only used in a very general way, with the terms *human failure event* and *unsafe action* being used to describe more specific aspects of human errors (NUREG-1624, 2000; NUREG-1880, 2007). In addition, this report distinguishes between significant differences in the timing and characteristics of unsafe actions by using the terms *active unsafe actions* and *latent unsafe actions* (refer to definitions in this glossary).

Human Error Probability (HEP) — A measure of the likelihood that plant personnel will fail to initiate the correct, required, or specified action or response in a given situation or by commission performs the wrong action. The HEP is the probability of the human failure event. In many first-generation HRA quantification techniques, performance-shaping factors are used to modify the base human error rate to determine the HEP.

Human Failure Event (HFE) — A PRA term for 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 component that is the result of one or more unsafe actions (NUREG-1624 2000).

Human Performance Vulnerabilities — The generic term used in this report to refer to a wide spectrum of performance-shaping factors and plant conditions, including the past history of both latent and active unsafe actions, which generate a context that may ultimately contribute to HFEs. The context, emerging from a combination of human performance vulnerabilities, integrates the individual, task, situation, and environment in such a way that the connection between actions and undesirable consequences is apparent. The specific human performance vulnerabilities identified in this report include: inadequate procedures, limited reliance on procedures, inapplicable procedures, inadequate training/experience, communication difficulties, limited indicators and job aids, visual challenges, unchallenging activities, time pressure, time-of-day and shift-work challenges, inadequate verification, quality assurance problems, decision-making bias error (confirmation bias, loss aversion, overconfidence), inadequate team coordination, improper or uneven task distribution, large number of manual operations, and other ergonomic issues. See Section 5.1.1 and Appendix C for detailed discussion of the human performance vulnerabilities.

Human Reliability Analysis (HRA) — A structured approach used to identify, assess, and quantify HFEs in support of a PRA study. HRA applications may be limited to qualitative analysis or they may include both qualitative analysis and quantification, i.e., assignment of human error probabilities (HEPs) to HFEs. Qualitative HRA is necessary for providing a basis for quantification, but it may also be used in isolation for prospectively identifying sources of human errors and unsafe actions or retrospectively analyzing actual events to provide insights into improving human performance. Generating quantitative HEPs involves systematically estimating the probability of HFEs using one or more sets of data, models, or expert judgment. See Section 2.2 for additional discussion of HRA.

Informal Rules — Rules and/or workarounds developed from operational experience, training, discussions among operators, and past practices, that can override or supersede formal rules contained in plant procedures (i.e., “the way we do things around here” (NUREG-1624 2000, p. 7-11 and 10-7). For example, an informal rule may exist among the operating staff such that a certain indicator during vacuum drying or a height indicator on a crane should not be trusted since it often sticks or otherwise reads incorrectly during particular situations. Another example would be acute concern for protecting equipment, that is, if equipment appears to be degrading (e.g., fluctuating performance of building HVAC systems) then personnel will shut it down unless it is deemed essential to the situation at hand (NUREG-1624 2000).

Initiating Event — Events that upset normal operating conditions and require mitigating response(s). These events are categorized as either internal events (i.e., events caused by hardware faults, operator actions, floods, or fires), or external events (such as earthquakes or high winds) (RG-1.200, 2007). Examples of initiating events include a cask drop due to an aging-related crane component failure, a defective crane component failure, or due to a crane operator impacting a cask with the side of an transfer pit opening.

Job Aids — Repositories for information, processes, or perspectives that support the work and activity to be done. They direct, guide, and enlighten performance. They are external to the individual, meaning the individual uses them as tools (e.g., books, cards, software, alarms, control panels, or displays) to help him or her carry out work tasks (Rossett and Gautier-Downes 1991). Job aids can reduce the reliance on memory during task performance which can help in the avoidance of slips and lapses due to distractions during performance of familiar, skilled activities (e.g., crane operation, rigging). Also, of particular concern with respect to memory limitations are infrequent or novel tasks (e.g., repair activities, unusual rigging arrangements) requiring more than 3 or 4 steps or subtasks. If the personnel performing these infrequent or novel multiple-step tasks have not had thorough training at regular intervals on these specific activities, then it would be unwise to expect more than four memorized steps to be completed correctly without a job aid (Miller 1956; Doumont 2002)

Knowledge — In this report, two types of knowledge are of importance. First, explicit, figurative, or declarative knowledge (involving semantic memory) is concerned with knowing “facts.” Second, tacit, operative, or procedural knowledge (involving episodic memory) involves understanding where the “explicit” knowledge comes from or what underlies it. Tacit knowledge also involves the capacity to use, apply, transform, or recognize the relevance of explicit knowledge in novel situations (Brewer 2005). In DCSOs the topic of knowledge arises when trying to discover or anticipate gaps in knowledge between personnel of varying experience levels and among hybrid teams consisting of both plant personnel and specialized contract personnel.

Knowledge-Based Level — Part of the Skill-/Rule-/Knowledge-Based taxonomy accounting for different levels of cognitive engagement in activities (Rasmussen 1981; Rasmussen 1983), this is the cognitive level that comes into play in novel situations for which rules are not available. Operators are required to use conscious analytical processing and stored knowledge to develop a solution to the problem at hand. Knowledge-based tasks require conscious, effortful thought or problem solving, and as such, processing when in this mode tends to be slow, sequential, laborious, and resource-limited. Errors at this level tend to be mistakes that arise from resource limitations, inadequate understanding of the problem, overconfidence, or incomplete or incorrect knowledge.

Lapse — A memory failure in which a step in a planned sequence of events is missed (Reason 1990). Lapses are associated with highly-skilled behaviors that require very little conscious effort. An example of highly skilled behavior would be an experienced crane operator moving familiar loads within a plant over the same travel path used many times before and failing to raise the load sufficiently to clear an obstruction. Another example would be a rigger failing to properly secure a sling due to an internal distraction (e.g., thinking about something else). See Section B.3.3 for additional description of slips.

Latent Error Conditions — Conditions, often resulting from latent unsafe actions (UAs), within a complex organization which may be present (possibly many years) prior to combination with local circumstances and active failures to defeat the system's many layers of safety protections. That is, latent error conditions "set up" personnel for active UAs and HFEs that may occur at some point in the future. Examples of latent error conditions include: poor design, gaps in supervision, undetected manufacturing defects or maintenance failures, awkward automation, deficits in training, excessive time pressure, understaffed operations, unworkable or ambiguous procedures which lead to workarounds and/or highly variable performance of operations, poor communications, and less than adequate tools and equipment. Common latent error conditions involving maintenance may result from latent UAs of failing to complete reassembly steps, and/or failing to remove tools or testing equipment. Latent error conditions arise due to strategic and other top-level decisions made by governments, regulators, manufacturers, designers and organizational managers. The impact of these decisions spreads across the organization, shaping a distinctive culture and creating error-producing factors within the individual workplaces (Reason 1997). Many performance-shaping factors and plant conditions (both defined below) are a subset of the category of latent error conditions.

Latent Unsafe Actions — Actions inappropriately taken, or not taken when needed, by personnel that result in a degraded plant safety condition that do not immediately result in an observed failure of a function, system, or component but they may eventually lead to an observed failure after a period of time. Latent unsafe actions (UAs) can lead to latent error conditions (see definition above) in a complex organization that may become contributing causes for accidents or incidents. During an accident or incident investigation, latent UAs are among the errors occurring well before the onset of recognizable effects of the accident or incident. Latent UAs may involve acute, one-time errors such as failure to include a critical part during reassembly of a repaired item or improper design of a load-bearing component, they may involve failure to test a repaired item, failure to test an item properly, or they may involve chronic errors such as inadequate inspections of components or repeated workarounds to accommodate incorrect or ambiguous procedures.

Loss Aversion — The individual specific bias or heuristic associated with mentally accounting for the concept of loss in a given situation and applying it to decisions and actions. The way a person frames the concept of "loss" (Kahneman and Tversky 1979; Bernstein 1998) in a given situation provides a strong biasing factor toward information and actions that enable the person to steer away from incurring that "loss" (Brewer 2005). This bias also includes the widely discussed *dread* factor (Slovic, Fischhoff et al. 1981; Slovic 2000). In an effort to avoid incurring a "significant loss," 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. For example, consider a situation in which a cask appears to have been properly captivated by the lifting yoke, however, one yoke arm is actually positioned improperly on the trunnion, and although vertical travel is underway, the cask captivation is unstable/tenuous. Furthermore, consider that a loud, metal-on-metal sound momentarily captures the attention of workers observing the cask movement. The source of the sound may be relative movement of the yoke arm in the trunnion, which could be providing a cue that a cask drop is imminent. However, the sound may simply be the result of machine noise or the performance of other work activities in nearby areas of the building. The *non-loss threatening* explanation of the metal-on-metal sound being due to other activities contrasts with the *loss-threatening* explanation of “Oh no, the cask is improperly captivated and a drop is imminent!” The *losses* referred to here are the potential losses related to catastrophic cask or plant damage, injury to personnel and/or fission product releases. Note that this may seem contrary to typical intuition which may suggest that anything “out of the ordinary” would be seen as a signal to stop operations. This may be akin to the observations of Wagenaar and Groenweg, “Accidents do not occur because people gamble and lose, they occur because people do not believe that the accident that is about to occur is at all possible” (Wagenaar and Groeneweg 1987 as cited in Reason 1997, p. 39).

Mistake — Deficiencies or failures in judgment or inference involved in selecting an objective or in determining the means to achieve the objective. The cognitive process associated with mistakes is planning. In this case, the person performing the action has the wrong mental model of how to perform the activity. Even if the resulting action is successful, it represents the wrong way of performing that task and is considered an error. If the mistake results in a degraded plant safety condition then the error is an intended[164] unsafe action. Mistakes involve either rule-based or knowledge-based behavior. Knowledge-based behavior is a slow, serial and consciously demanding type of thinking in which “bounded rationality” is used to make decisions and action plans and execute those action plans based incomplete or inaccurate mental models of a situation (Reason 1990). Knowledge-based behavior is the effortful and slow initial phases of learning just about any activity (recall learning to drive a car). Rule-based behavior is faster and syllogistic; it is based on more complete, less inaccurate, and “historically successful” mental models. Rule-based behavior is “IF-THEN” type of behavior such as “If there is a red light and I want to make a right turn, I must stop completely, then execute the right-turn-from-stop vehicle maneuver.” The specific form that a mistake will take, particularly when it involves *knowledge-based* actions is very hard to predict. This is due to the fact that mistakes arise from a complex interaction of cognitive factors such as biases, an inability to consider a large number of relevant factors, and incorrect mental models. See Section B.3.3 for additional description of mistakes.

Overconfidence — The tendency toward overestimating one’s level of knowledge or abilities relative to making a decision or executing a task. This bias is many subtle aspects and appears closely related to other bias processes. Section C.13 contains a detailed discussion of the concept of overconfidence.

Performance Shaping Factors (PSFs) — A set of influences on the performance of an operating crew resulting from the human-related characteristics of the plant, the crew, and the individual personnel (NUREG-1624 2000). PSFs can be thought of as the items that allow personnel to understand the state of their environment and those items that influence their response to the state of the environment. These characteristics include many factors procedures, training, time pressure, stress, and human-factors aspects of equipment as well as

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[164] Intended here simply means that the person executes the action that corresponds with their mental model indicating what should be done in that situation. The person does not intend to do something they understand to be “wrong;” however, the person’s mental model of what to do is inappropriate.

organizational considerations such as the safety culture of the plant personnel. PSFs may be classified as internal or external. Internal PSFs are human attributes such as skills, abilities, attitudes and other characteristics, which operate within the individual and are brought to the job by the individual. External PSFs are human-related aspects of situations, tasks, equipment and organizational culture residing outside the individual that allow personnel to understand the state of their environment and influence human performance (e.g., written procedures to follow). Note that external PSFs should not be confused with *plant conditions*, as plant conditions represent the actual state of the environment in terms of physical properties and equipment conditions, which are distinct from the information used to communicate those properties and conditions to personnel (see definition of plant conditions below). Sections B.4.1 through B.4.5 contain detailed discussion of PSFs.

Plant Conditions — The actual plant state defined by combinations of its physical properties and equipment conditions, including the measurement of parameters (NUREG-1624 2000). Many plant conditions are latent error conditions. Examples of plant conditions which could impact DCSOs include damaged/weakened crane support structures, improperly manufactured or maintained crane components, faulty rigging equipment, malfunctioning safety interlocks and insufficiently rugged crane control pendants. Other plant conditions include the current state of a crane lifting a loaded cask or an object near a cask travel path that must be avoided. Note that plant conditions should not be confused with *PSFs* (see definition of PSFs above).

Positive Safety Measure — A design feature, safety device, safety rule, procedure or other controls that exist solely or principally to provide safety. Ideally, positive measures consist of engineered controls (e.g., automated safety inter-locks, physical barriers), although they may be administrative controls (i.e., under the direct control/discretion of personnel) using reliable engineered standards of reference (e.g., measuring stick, calibers, carpenter's level). This type of administrative control may be contrasted with administrative controls that do not incorporate engineered standards, but offer only general guidance (e.g., "Do not get too close", "Ensure sufficient clearance").

Post-initiators — A general term referring to active unsafe actions occurring after the initiating event with the ability to challenge the condition of the plant has occurred. For example, actions occurring after a cask drop that exacerbate the consequences of the cask drop would be considered post-initiators.

Pre-initiators — A general term referring to latent unsafe actions and/or latent error conditions present prior to an initiating event. An example of a pre-initiator would be failure to inspect and/or test a crane system prior to its use during a cask loading campaign. Another example would be improper maintenance of a crane component, which greatly reduces the crane's capacity, prior to a cask lift.

Pre-initiator Unsafe Actions — Synonymous with latent unsafe actions.

Probabilistic Risk Assessment (PRA) — A qualitative and quantitative assessment of risk associated with plant operation and maintenance that is measured in terms of frequency of occurrence of risk metrics such as core damage or radioactive material release and its effects on the health of the public. PRA is also referred to as a probabilistic safety assessment (PSA).

Recovery Actions — This is a PRA term with the following meaning: after the occurrence of human failure events (HFEs), or non-human caused failures, these are actions taken by plant personnel that result in an improved plant safety condition. Recovery actions are a subset of the broader concepts of *successful human actions* and *resilient* behavior (see definitions in this glossary). It should also be noted that in qualitative HRA the term “recovery” may be used to identify a recovery from a preceding unsafe action (UA) that occurs close in time with the original UA, e.g., self-checking recovery of an error, or inspection by a co-worker that enables rapid recovery. This type of recovery avoids the occurrence of an HFE such as dropping a cask.

Resilient — Tending to recover from or adjust easily to change or slight misfortune in order to achieve a successful outcome. This can be a property of individuals and teams/organizations. A very simple example of resilient behavior would be making a mistake in typing a word in a letter, then immediately recognizing and correcting the error before sending off the correspondence. Another example would be correctly interpreting a badly misspelled word in a letter due to understanding the context and subject matter of the rest of the letter. See also the definition for recovery actions.

Rule-Based Level — Part of the Skill-/Rule-/Knowledge-Based taxonomy accounting for different levels of cognitive engagement in activities (Rasmussen 1981; Rasmussen 1983), this is the cognitive level at which operators tackle familiar problems via application of memorized or written rules (e.g., IF-THEN), with conscious thinking to verify the correct rule to use and to verify if the resulting solution is appropriate. Errors made when in this mode tend to be mistakes due to application of the wrong rule or incorrect recall of procedures.

Rules — The guidance which personnel follow in carrying out activities. Rules can either be formal or informal in nature. *Formal rules* are specific written instructions and requirements provided to operators and authorized for use by plant management. *Informal rules* include training programs, discussions among operators, experience, and past practices (NUREG-1880, 2007). See definitions of *informal rules* and *workarounds* for additional information.

Safety Culture — That assembly of characteristics and attitudes in organizations and individuals which establishes that, as an overriding priority, nuclear plant safety issues receive the attention warranted by their significance[165] (RIS-06-013 2006). It refers to the necessary full attention to safety matters and the personal dedication and accountability of all individuals engaged in any activity that has a bearing on the safety of nuclear power plants. A strong safety culture is one that has a strong safety emphasis. Safety culture also permeates into a safety conscious work environment, in which employees are encouraged to raise potential safety concerns, which in turn are seriously reviewed and promptly resolved. Safety culture can therefore be seen as the opposite of a work culture that encourages workarounds or emphasizes production over safety.

Skill-Based Level — Part of the Skill-/Rule-/Knowledge-Based taxonomy accounting for different levels of cognitive engagement in activities (Rasmussen 1981; Rasmussen 1983), this is the cognitive level at which human performance is routine, highly-practiced, and carried out in a largely automatic fashion, with occasional conscious checks on progress. At this level, the operator is highly familiar with the environment or task. Errors made when in this mode tend to be slips or lapses.

Slip — An attentional failure in which a planned task is carried out incorrectly or in the wrong sequence (Reason 1990). The cognitive function associated with slips is execution of intended action. These errors are associated with a person’s focus of attention which may be

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[165] This definition is taken directly from the International Atomic Energy Agency’s International Nuclear Safety Advisory Group.

characterized by *inattention* or *overattention*. The most common error form for slips involves inattention, i.e., failing to check the progress of a skill-based action at the appropriate time. The less common form involves overattention, which is when a conscious attentional check is made at an inappropriate time during a preprogrammed behavioral sequence. As with lapses, slips are associated with highly-skilled behaviors that require very little conscious effort. An example of a slip would be a rigger carrying out a well-practiced task who is temporarily distracted by nearly personnel and when resuming the task he or she misses a step due to an implicit belief that he or she was further along in the steps required to complete the task. Slips and lapses are closely related phenomena. See Section B.3.3 for additional description of slips.

Unintentional Lowering — A controlled lowering of a cask (or other heavy load) by the crane, but at a time not intended. For example, inadvertent lowering of the cask onto the side of the transfer pit opening or edge of the refueling floor above the cask decontamination area.

Unintentional Raising — A controlled lifting of the load by the crane, but at a time not intended. For example, inadvertent raising of a cask such that a two-block event occurs.

Unplanned Descent — Uncontrolled or inadequately controlled lowering of a cask (or other heavy load) which is not a freefall drop since its acceleration is resisted to some degree by lifting or support equipment.

Unsafe Actions — Actions inappropriately taken, or not taken when needed, by plant personnel that result in a degraded plant safety condition. See also the definitions for active unsafe actions (UAs) and latent UAs (NUREG-1624 2000).

Violation — See definition for circumvention/violation.

Workarounds — Informal rules or manners of executing tasks which, although they deviate from “as designed practices and procedures” they reflect the commonly accepted “as built way to get things done” either because the as designed process is unworkable or simply because the workaround is more efficient (see also the definition for *informal rules*).