Human Error Contribution to Nuclear Materials-Handling Events

By

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ABSTRACT

This thesis analyzes a sample of 15 fuel-handling events from the past ten years at commercial nuclear reactors with significant human error contributions in order to detail the contribution of human error to fuel-handling activities, emphasizing how latent conditions can directly contribute to events. In particular, procedural inaccuracies often create conditions that lead to the development of errors related to maintenance work practices. This would be of significant concern for a pre-closure safety assessment for a geologic repository for spent nuclear fuel and high-level radioactive waste, where many fuel-handling work activities would be performed. Specific emphasis is placed on fuel movement activities and control of ventilation systems, which could significantly impact worker and public health and safety in the case of a fuel-handling accident.

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Contents

Acronyms

ABGTS	Auxiliary Building Gas Treatment System
CIV	Containment Isolation Valve
CREACS	Control Room Emergency Air Conditioning System
DOE	U.S. Department of Energy
DSC	Dry Shielded Canister
HFIS	Human Factors Information System
HLW	High-Level Radioactive Waste
HVAC	Heating, Ventilation, and Air Conditioning
INEEL	Idaho National Engineering and Environmental Laboratory
ISFSI	Independent Spent Fuel Storage Installation
LCO	Limiting Condition for Operation
LER	Licensee Event Report
NRC	U.S. Nuclear Regulatory Commission
OOS	Operations Out of Service
PACU	Post-Accident Cleanup Unit
PRF	Penetration Room Filtration
RCCA	Rod Control Cluster Assembly
RCU	Refrigeration Condensing Unit
SBGTS	Standby Gas Treatment System
SFP	Spent Fuel Pool
SNF	Spent Nuclear Fuel
TS	Technical Specification

1. Introduction and Background

Administrative controls can have a significant effect on human reliability. In a study of commercial nuclear power plants performed by Idaho National Engineering and Environmental Laboratory (INEEL), 37 operating events in which human error was a factor were analyzed qualitatively and categorized as shown in Table 1 [1].

Table 1: INEEL Human Error Report (Gertman, et al.) Summary by Category

Error Category Descriptions	Percentage of Operating Events
Operations	54%
Design and Design Change Work Practices	81%
Maintenance Practices and Maintenance Work Controls	76%
Procedures and Procedure Development	38%
Corrective Action Program	41%
Management and Supervision	30%

Operations errors included resource allocation, operator knowledge or training, operator actions, and communications, while design and work design change work practice errors included design deficiencies, design change testing, and inadequate engineering evaluation, with maintenance practice and maintenance work control errors considering issues in work package development, inadequate maintenance practices, inadequate technical knowledge, and inadequate post-maintenance testing, while corrective action program errors included failure to respond to industry notices, failure to follow industry practices, and failure to correct known deficiencies, and errors resulting from management and supervision included issues such as inadequate supervision, organizational structure, and inadequate knowledge of plant operations. Procedures and procedure development included no specific sub-classifications. 81% of the total errors were latent errors, which are errors that are committed prior to the event initiator and are not recognized until the event occurs [1]. Latent errors were noted as causing the greatest increase in plant risk [1]. Many of these errors could have been mitigated by the placement of and adherence to correctly documented procedures and appropriately implemented administrative controls, since latent errors can accumulate over time and, if correctly identified, can be resolved before an event occurs.

Human errors in nuclear materials-handling (cask, canister, and fuel assembly handling) are likely to affect safety operations of the potential geologic repository for spent nuclear fuel (SNF) and high-level radioactive waste (HLW), such as the proposed geologic repository at Yucca Mountain which is designed to potentially accommodate up to 119,000 metric tons of heavy metal. Such a repository would involve pre-closure operations including receiving spent nuclear fuel and high-level radioactive waste in shipping casks, unloading and packaging of SNF and HLW into suitable waste packages for long-term underground storage, transporting waste packages from the surface to the underground facility and emplacing waste packages in underground drifts [19]. It is necessary for the U.S. Department of Energy (DOE) to perform an assessment of safety before permanent closure for such a repository in order to demonstrate compliance with performance objectives to limit doses to workers and the public within acceptable risk levels. The preclosure safety analysis must consider potential hazards to demonstrate that repository can be operated within specified exposure limits and safety standards in the preclosure period [18]. This is performed through an identification of hazards and initiating events, including any site specific hazards, as well as determination of their associated probabilities of occurrence and consequences. This leads to identification of event sequences and determination of the effectiveness of safety features and availability of safety systems, developing risk significance categorizations of structures, systems and components related to safety, allowing a consequence analysis that can demonstrates the repository's ability to satisfy regulatory acceptance criteria [18]. Examination of how both active and latent human errors occur and how they can be prevented will provide insight into preclosure safety analysis at such a repository.

Through examination of past nuclear materials-handling issues, this report gives insight into: (1) what materials-handling issues have occurred in the past and why, (2) what are the potential consequences, and (3) the implications for a repository. By examining licensee event reports (LERs), which are required from the licensee whenever off-normal events occur, this report qualitatively analyzes past materials-handling events at commercial nuclear power plants in which human error contributed to overall risk, and identifies administrative controls (e.g., procedures) that could reduce the risk due to human errors.

2. Methodology

Licensee event reports cite control issues that can be analyzed qualitatively according to event types and safety significance. An LER is required each time an event meets reporting requirements according to U.S. Nuclear Regulatory Commission (NRC) regulations. By classifying events into error categories following Gertman, et al. methodology, an investigation of the most effective administrative controls to reduce risk due to human errors in materials-handling events can be performed. Categories were chosen to divide errors into areas pertaining to different employee groups, including operators, maintenance staff, and management, before classifying the error into sub-classifications that more specifically define the error type. This combination of categories and sub-classifications allows for a general overview of the type of work activity in which the errors occurred. The Human Factors Information System (HFIS) database, created by the NRC as a source of information on human performance issues, was used to select events for analysis. The HFIS database attempts to describe overall performance at individual plants, and is not all-inclusive. For this reason, the HFIS database can be utilized to describe overall human performance concerning fuel-handling activities, reporting typical fuel-handling incidents.

The HFIS database identified sixteen events concerning fuel-handling issues since January 1, 1996 at commercial nuclear power plants in the U.S. in which human performance errors contributed. Fifteen of these events were broken down into error sub-classifications and analyzed qualitatively from information provided by the corresponding LER. One event LER was unable to be procured. The time span of January 1, 1996 to present was decided to give a time span recent enough that events are all relevant considering evolution of nuclear industry regulations and typical management procedures over time.

Individual errors that contribute to events are broken down into four over-arching classifications and nine total sub-classifications. These classifications were used to categorize and assess the common varieties of events in fuel-handling resultant from human errors. The initial categories are operations errors, maintenance practices, procedures, and management errors. Operations errors include those that directly involved operations personnel. In the context of events studied, these were broken down into two sub-classifications, (1) inadequate knowledge or training, where the operators erred due to a deficiency in knowledge of a specific system or activity that contributed to the event, and (2) communications errors, in which an error occurred as a result of ineffective or misleading communications between operations personnel and other department personnel. Maintenance errors include all errors stemming from work occurring on the plant floor, including refueling, inspections, or other work practices that are not wholly controlled by operations personnel. This was developed into the three sub-classifications of (1) work package development – dealing with preparations for work activities, including effectiveness of pre-job briefings – (2) inadequate maintenance and maintenance practices – occurring when a work activity was performed incorrectly or ineffectively, or otherwise failed to achieve the work task – and (3) inadequate technical knowledge – grouping errors due to work personnel lacking knowledge or technical skills related to the equipment or system or which work is being performed. The procedures category contains only a single classification, inaccurate procedures and procedure development, concerning incomplete and unclear procedures or procedures that are otherwise in need of revision. Management and supervision errors include those issues occurred due to inadequate supervision, management, or organizational concerns. Management errors are also divided into three sub-classifications, including (1) inadequate supervision, for errors that occurred because inadequate supervision led to a failure to meet established work activity requirements, (2) inadequate knowledge of systems and plant operations, for errors that occurred due to inadequate knowledge of plant systems and operations on the part of plant management to effectively administrate work practices, and (3) organizational structure, for errors that occurred due to the organizational structure of the plant causing inefficient or improperly developed work activities.

Gertman, et al, from which these present classifications were adapted, considered additional categories and classifications, but these are unnecessary for consideration of fuel-handling events, which mainly concern the spent fuel pool (SFP), ventilation system, and refueling operations, and were not affected as frequently by operations or design and design change work practices [1]. LERs do not cite sufficient information to analyze errors involving plant corrective action programs. The classifications that are considered here are sufficient for developing an understanding of likely issues to contribute to a pre-closure safety analysis for a large-scale long-term repository for spent nuclear fuel and high-level radioactive waste.

3. Event Analysis Results

The events selected for review included fuel-handling issues in commercial nuclear reactors in the U.S. from the past ten years in which human errors were a significant contributor. Due to this specific subset of operating experience, no serious significant system losses were examined, with most event reports resulting from Technical Specification (TS) violations. TS are criteria under which plants are required to operate, regulating most every aspect of plant operations including, among others, reactivity control systems, refueling operations, containment systems. Technical Specifications are developed by the NRC to effectively govern plant operations and safety [17]. While failure to meet established TS requirements alone may not be significant risk issues, these violations can be significant risk-contributors and indicate breaches in nuclear fuel-handling safety important for consideration.

Table 3-1: Error Summary by Human Error Categories

Category Description [Count / % of Total Errors (40)]	# of Latent Errors	# of Active Errors
Operations [5 / 11.9%]		
Inadequate Knowledge or Training	2	1
Communications		2
Maintenance Practices and Work Control [24 / 57.1%]		
Work Package Development, QA and Use	8	2
Inadequate Maintenance or Maintenance Practices	4	7
Inadequate Technical Knowledge	4	
Procedures [9 / 21.4%]		
Inadequate Procedures and Procedure Development	9	
Management and Supervision [4 / 9.5%]		
Inadequate Supervision	1	
Inadequate Knowledge of Systems and Plant Operations	1	
Organizational Structure	2	
Subtotals	31	12

Tables 3-1 and 3-2 give error summaries by human error categories. Maintenance Practices and Work Control is clearly the dominant human error classification for these fuel-handling events, containing 55% of classified errors and occurring in 14 of the 15 events studied. The 15 events analyzed in this thesis are presented and described below. A summary is given for each event as well as insights from the LER. This is followed by a listing of human performance issues for each event, classified as either "active" errors – "human errors that influenced the initiation, mitigation, or progression of the event" [1] – or "latent" errors – "errors committed prior to the event whose effects are not discovered until the event occurs" [1] – and are itemized into specific error subcategories. Table 3-3 summarizes the errors by category and by event.

Table 3-2: Error Category Presence in Events

Error Category Description	% of Events
Operations	33.3
Maintenance Practices and Work Control	93.3
Procedures	53.3
Management and Supervision	20.0

3-1: Arkansas Nuclear Unit 2 Event, November 16, 2000 (LER 2000-003-00)

On November 16, 2000, with Unit 2 core reload in progress during a scheduled refueling outage, refueling machine underload indications were received and the core reload was suspended. Investigation revealed that the weight of the dummy fuel assembly used to calibrate the refueling machine was approximately 104 pounds heavier than the value used for calibration. The refueling machine was recalibrated with the revised dummy fuel assembly weight and core reload was resumed. The calibration was incorrect due to an incorrect dummy fuel assembly weight approximation, originally assigned the conservative value of 2387 pounds in 1992, then determined as 1904 pounds in February

1994 but determined in the course of investigation into this event as 2008 pounds. The most likely reason for the discrepancy is that a load cell with a large span was used [2].

Human Performance Issues

Description	Error Type	Error Subcategory
Underdeveloped refueling machine calibration procedures	Latent	Procedures and procedure development
Personnel incorrectly calibrated refueling machine	Active	Inadequate maintenance or maintenance practices

3-2: D.C. Cook Unit 1 Event, November 19, 2001 (LER 2001-005-01)

On November 19, 2001, the Rod Control Cluster Assembly (RCCA) tool was mistakenly moved over the Spent Fuel Pool (SFP) fuel racks. The potential impact energy of the RCCA tool is greater than the limit of 24,240 in-lbs detailed by technical specifications. The surveillance requirement to determine potential impact energy as within this limit before moving each load over the fuel racks also was not performed. The spent fuel crane operator mistakenly moved the load over the spent fuel pool racks, failing to reinstate the hoist height interlock before moving the crane. The SFP area supervisor noticed this action immediately and alerted the crane operator to stop and lower the load to below the hoist interlock and reinstate the interlock [3].

Human Performance Issues

Description	Error Type	Error Subcategory
Crane operator moved load over SFP racks without reinstating hoist height interlock	Active	Inadequate maintenance or maintenance practices
Failure to perform peer check prior to RCCA tool movement	Latent	Inadequate maintenance or maintenance practices
Failure to calculate potential impact energy	Latent	Inadequate maintenance or maintenance practices

3-3: D.C. Cook Unit 2 Event, July 20, 2000 (LER 2000-011-00)

On June 28, 1999, the SFP exhaust ventilation system was determined to be in a degraded condition, requiring the placement of the SFP exhaust ventilation system in the charcoal filter mode of operation prior to movement of fuel within or over the SFP as a compensatory condition to maintain the system in an operable status. On July 19, 2000, the system was placed in charcoal filter mode as fuel top nozzle inspections began. A pre-job brief was conducted including those involved in fuel inspections, and the refueling supervisor contacted the control room to ensure operation of SFP exhaust ventilation system prior to starting inspections. The SFP exhaust ventilation system was removed from the charcoal filter mode of operation when fuel inspections were stopped for the day. On July 20, 2000, the SFP exhaust ventilation system was place in charcoal filter mode while fuel inspections continued. Auxiliary building crane and main hoist inspections were also begun, with no pre-job brief conducted. The crane clearance which maintains the main load block was de-energized and removed for crane inspections. The refueling supervisor contacted the work control center to ensure that the crane clearance would be restored prior to removing the SFP ventilation system from the charcoal filter mode of operation. Work control personnel misinterpreted this and notified control room personnel that fuel inspections were complete, resulting in the crane clearance being rehung and the SFP exhaust ventilation system being removed from the charcoal filter mode of operation. The ventilation system was removed from the charcoal filter mode of operation for approximately 1-1/2 hours with fuel movement still in progress. Removing the charcoal filters from operation resulted in the system being inoperable since the compensatory actions were no longer in place. Upon discovery of this condition, control room personnel suspended all operations involving movement of fuel and cranes within the SFP area [4].

Human Performance Issues

Description	Error Type	Error Subcategory
Inadequate/miscommunication between control room and inspections personnel	Active	Communications
No pre-job brief conducted for auxiliary building crane inspections	Latent	Work package development, QA and use
Control room personnel not involved in pre-job brief for the fuel top nozzle inspections	Latent	Work package development, QA and use

3-4: D.C. Cook Unit 2 Event, February 12, 2002 (LER 2002-002-00)

On January 20, 2002 the control air headers had been cross-tied with air hose jumpers in preparation for leak rate testing of a containment isolation valve (CIV), to allow the #2 headers to be fed by the #1 headers while the CIV for the #2 headers was isolated for testing. The air hose jumper installation was not logged in the Proceduralized Temporary Modification Log in the control room as required by the Temporary Modification Procedure, but was left in place to support maintenance activities on the CIV. On January 26, 2002, in further preparation for the leak rate testing, the CIV was isolated from the rest of the control air system by closing the upstream shut off valve and the downstream shutoff valves for the control air containment ring headers, and test connection valves were also opened on both sides of the CIV, one inside containment and one outside. This alignment was left in place, via a clearance, to support maintenance activities the CIV. At the time, refueling integrity was established by an option that consisted of closing the CIV. On February 9, 2002, refueling integrity was reestablished by the procedurally preferred method by confirming that the penetration is actively pressurized by control air. Being pressurized, the penetration does not provide direct access from the containment to the outside atmosphere, but this method of verification was determined to be ineffective if the control air headers are cross-tied. Another method of establishing refueling integrity should have been chosen, one which closes the CIV or otherwise closes off the penetration. On February 12, 2002 during core alterations maintenance activities on the CIV, the valve was stroked open with test connections open on both sides of the penetration thus creating a path from the atmosphere inside containment to the atmosphere outside containment, resulting in a breach of refueling integrity [5].

Human Performance Issues

Description	Error Type	Error Subcategory
Failure to document control air header cross-tie jumper installation	Latent	Inadequate maintenance or maintenance practices
Inappropriate choice in method of reestablishing refueling integrity	Active	Work package development, QA and use
Procedures did not consider the possibility that the control air ring headers may be cross-tied	Latent	Procedures and procedure development

3-5: Dresden Unit 2 Event, August 20, 1998 (LER 1998-012-00)

On August 19, 1998, maintenance repair of a control room heating, ventilation and air conditioning (HVAC) refrigeration condensing unit (RCU) inlet valve was given a higher priority in the work schedule due to package leaking concerns. The operations out of service (OOS) group prepared an OOS for the valve repair in order to aid the work package preparation. The work scheduler failed to perform a review of the valve repair impact on overall work schedule, resulting in an upcoming fuel move being scheduled with the control room ventilation system OOS. On August 20, 1998, hanging of the OOS was completed and operations entered the Limiting Condition for Operation (LCO) for inoperable control room emergency ventilation. The unit supervisor did not recognize that the control room HVAC RCU LCO was in conflict with the upcoming scheduled fuel bundle move, and thus permission was given and the fuel was moved with the RCU inoperable. On August 21, 1998, a new operating crew denied permission to resume movement of the fuel bundle, recognizing the previous non-compliance with technical specifications [6].

Human Performance Issues

Description	Error Type	Error Subcategory
Failure to thoroughly review changes in work schedule	Latent	Work package development, QA and use
Failure to consider contingency measures in LCO review	Latent	Work package development, QA and use
Failure of unit supervisor to recognize violations of technical specifications	Latent	Inadequate knowledge of systems and plant operations
Work planning process placing over-reliance on operations department to manage technical specification adherence	Latent	Organizational structure
Failure of senior operator to recognize LCO's effect on refueling activities	Active	Inadequate knowledge or training

3-6: Farley Unit 1 Event, March 15, 2000 (LER 2000-003-00)

On March 15, 2000, with Unit 1 defueled, a valid high radiation alarm occurred on an SFP ventilation radiation monitor, resulting in an automatic start of the B-train penetration room filtration system (PRF). This also resulted in automatic shutdown of the normal SFP ventilation system, causing an automatic start of the A-train PRF system. The high alarm was caused by radioactive gases released from a fuel sipping activity being performed to identify leaking fuel assemblies. Small releases of radioactive gas are expected when sipping a fuel assembly with leaking pins. Although the release of radioactive gases into the SFP area was expected and the potential for radiation monitors alarming was communicated to the control room, the potential for the automatic start of the PRF was not recognized. The PRF system functioned as designed. No abnormal offsite radioactive release was indicated [7].

Human Performance Issues

Description	Error Type	Error Subcategory
Procedures for leak detection inadequate	Latent	Procedures or procedure development
Failure to consider effect of gas release when performing fuel sipping activity	Active	Work package development, QA and use

3-7: Farley Unit 1 Event, March 23, 2000 (LER 2000-004-00)

On March 23, 2000, it was determined that three spent fuel assemblies had been loaded in configurations contrary to technical specifications, with this condition first occurring during the core offload of the refueling cycle which had begun on March 13, 2000. Manual verification, as well as the review of the verification process, of the acceptability of proposed offload configuration failed to identify that the proposed configuration did not meet the acceptable configurations [8].

Human Performance Issues

Description	Error Type	Error Subcategory
Personnel responsible for developing, performing, and verifying SFP configuration did not recognize configuration as unacceptable	Active	Inadequate maintenance and maintenance practices
Personnel responsible for developing SFP configuration lacked sufficient knowledge to determine an acceptable configuration	Latent	Inadequate technical knowledge
Lack of detail in core offload procedure	Latent	Procedures and procedure development
Insufficient independent review in the verification process	Latent	Work package development, QA and use

3-8: Palisades Event, November 11, 1999 (LER 1999-005-00)

On November 6, 1999, with the plant in refueling shutdown, it was discovered that the charcoal filter for the fuel storage building ventilation system was not in operation during fuel handling activities. TS 3.8.4 requires the ventilation system and charcoal filter to be in operation whenever irradiated fuel which has decayed less than 30 days is being handled in the fuel storage building. A ventilation system checklist and a general checklist are used to ensure the ventilation equipment status meets the requirements for fuel handling activities. The ventilation system checklist specifies the ventilation alignment for both fuel handling and non-fuel handling activities. Since fuel handling was not in progress at the beginning of the shift in question, the completed ventilation system checklist reflected this condition. The general checklist ensures the proper ventilation lineup by confirming that the ventilation system checklist has been completed for fuel handling activities. The licensed operator who completed both checklists prematurely signed off on the general checklist when the ventilation system checklist had not been completed for fuel handling activities. The operator intended to properly align the charcoal filter upon notification that fuel handling activities were to commence, but was not notified when fuel handling activities were authorized by the control room supervisor [9].

Human Performance Issues

Description	Error Type	Error Subcategory
Operator prematurely completed checklist before ventilation requirements for fuel handling activities were met	Latent	Inadequate maintenance and maintenance practices
Lack of communication by control room supervisor when fuel moves were authorized	Active	Communications

3-9: Pilgrim Unit 1 Event, March 31, 1998 (LER 1998-006-01)

Reactor operators follow control sequences that limit the reactivity addition and core heat-up rate. Pilgrim has additional technical specification restrictions on control rod worth with respect to reactor power. On a particular fuel cycle, a rod drop accident was evaluated generically and not with plant specific information as had been done in the past. On March 31, 1998, plant personnel noticed that plant specific control rod worth values necessary to verify compliance with technical specifications were not provided [10].

Human Performance Issues

Description	Error Type	Error Subcategory
Lack of oversight by core design engineers in recognizing technical specification requirements on control rod worth	Latent	Inadequate technical knowledge
Inadequate review of plant design change led staff to omit control rod worth requirements from design criteria	Latent	Procedures and procedure development

3-10: Prairie Island Unit 1 Event, May 8, 1999 (LER 1999-05-00)

On May 8, 1999, with Unit 1 in refueling shutdown, during a reactor upper internals replacement procedure, personnel identified that the reactor upper internals were moved over the open fueled reactor vessel with the containment in-service purge system operating. Personnel inadvertently missed closing the containment in-service purge system CIVs and did not discovered this until after the upper internals had been set in the reactor vessel [11].

Human Performance Issues

Description	Error Type	Error Subcategory
Failure to review the procedure to identify the precautions, special considerations and procedure steps to the satisfaction of regulatory requirements	Latent	Procedures and procedure development
Inadequate review of procedure by work group supervisor	Latent	Inadequate supervision
Inadequate pre-job briefing	Latent	Work package development, QA and use

3-11: Salem Unit 1 Event, April 18, 2001 (LER 2001-005-00)

On April 18, 2001 the B 125 VDC battery disconnects were open, rendering the isolation dampers inoperable on an outside emergency air conditioning air intake. Fuel movement occurred in the SFP while the Control Room Emergency Air Conditioning System (CREACS) was available, but not operable. CREACS was available through the DC bus powered by the battery charger, but it was not operable due to the B 125 VDC battery disconnect being open to support maintenance on the battery. No isolation dampers were secured closed at the times when fuel moves occurred in the SFP. Technical specification requires that with isolation dampers on emergency air conditioning air intake duct inoperable, core alterations must be immediately suspended and movement of irradiated fuel assemblies halted until an isolation damper is secured closed to close the affected duct [12].

Human Performance Issues

Description	Error Type	Error Subcategory
Fuel movement occurred with CREACS inoperable	Active	Inadequate maintenance and maintenance practices
Lack of knowledge, by all individuals involved (licensed operators, outage control center), of control area ventilation system	Latent	Inadequate knowledge or training
Recent installation of battery disconnect switches and accompanying procedure changes without clarification on control area ventilation system requirements	Latent	Work package development, QA and use

3-12: San Onofre Unit 3 Event, January 20, 2001 (LER 2001-002-00)

On January 18, 2001, during refueling, fuel (both new and irradiated) movement began from the fuel handling building to the reactor vessel inside containment. Both trains of Post Accident Cleanup Unit (PACU) were operable at that time. On January 20, 2001, PACU train B was removed from service. Due to an equipment failure, fuel movements were stopped, and late restarted with train B still inoperable and without train A being placed into service. Technical specifications require two PACU trains to be operable during movement of irradiated fuel assemblies in the fuel handling building [13].

Human Performance Issues

Description	Error Type	Error Subcategory
Technical specification requirements not correctly implemented in plant procedures	Latent	Procedure and procedure development

3-13: Summer Event, April 12, 1999 (LER 1999-003-00)

On April 12, 1999, core alteration activities were begun, during which the refueling crew started the control rod unlatching revolution for the first drive shaft, when the weight indicated by the load cell was noted to be incorrect. The crew assumed the load indicator had failed and did not notice that "peak load" had been selected for the load cell switch position instead of "continuous." The crew installed a new load cell, for which the technical specification surveillance test required prior to use had not been performed, and unlatched the first control rod drive shaft without requesting permission. The crew requested permission to unlatch the second drive shaft and were denied, and core alterations were suspended for the required surveillance, the results of which were not satisfactory due to the "peak load" read out [14].

Human Performance Issues

Description	Error Type	Error Subcategory
Lack of familiarity with surveillance requirements and operational procedures	Latent	Work package development, QA and use
Set read-out switch to incorrect position	Active	Inadequate maintenance and maintenance practices
Lack of familiarity with load cell features	Latent	Inadequate technical knowledge

3-14: Susquehanna Unit 1 Event, July 26, 2002 (LER 2002-005-00)

On July 26, 2002, a maintenance mechanic observed that argon gas had been used to backfill a fuel storage Dry Shielded Canister (DSC) instead of helium gas. The DSC vent and siphon port covers and the outer top cover had been installed and welded into place when this was discovered, during preparations to move the DSC from the reactor building refueling floor to the Independent Spent Fuel Storage Installation (ISFSI). All dry fuel storage activities on the refueling floor were suspended, and a repair procedure was developed to breach the outer top cover, remove the argon gas from the DSC, backfill it with helium gas and weld repair the outer top cover. In the meantime a "feed and bleed" of the demineralized water in the DSC annulus was performed to keep the water temperature below 160 degrees Fahrenheit until restoration activities were complete. The repair technique was utilized August 9-11, 2002 and occurred without additional incident.

The DSC was transported to the ISFSI an August 16, 2002 [15].

Human Performance Issues

Description	Error Type	Error Subcategory
Argon and helium canisters same color, stored together (change in gas supply vendor)	Latent	Organizational
Erroneous supply hose connections	Active	Inadequate maintenance and maintenance practices
Mechanic tested a few canisters in the cart, erroneously assumed all were helium	Active	Inadequate maintenance and maintenance practices
Inspector only verified pressure, verifying the correct gas is used to backfill the DSC was not identified as a "critical" procedure step.	Latent	Procedures and procedure development
No peer check process	Latent	Procedures and procedure development

3-15: Watts Bar Unit 1 Event, March 11, 2005 (LER 2005-001-00)

On March 3, 2005, the containment hatch was opened and containment purge system activated for refueling outage support. On March 9, 2005, fuel movement began in the SFP for the inspection of fuel assemblies. On March 11, 2005, it was noticed that having the containment hatch open while the containment purge system was in operation made both trains of the Auxiliary Building Gas Treatment System (ABGTS) inoperable. ABGTS is required operable during the movement of irradiated fuel assemblies in the fuel handling area [16].

Human Performance Issues

Description	Error Type	Error Subcategory
Inadequate systems operation instruction	Latent	Inadequate knowledge or training
Inadequate fuel handling instruction	Latent	Inadequate technical knowledge

Table 3-3: Categorical Summary of Active and Latent Failures for Specific Events

	Inadequate Knowledge or Training (Operations)	Communications	Work Package Development, QA and Use	Inadequate Maintenance and Maintenance Practices	Inadequate Technical Knowledge (Maintenance)	Inadequate Procedures and Procedure Development	Inadequate Supervision	Inadequate Knowledge of Systems & Plant Operations	Organizational Structure	
Facility/LER	Operations		Maintenance Practices and Work Control			Procedures	Management and Supervision			Total
Arkansas Nuclear 2 2000-003-00 2000-003-00				Active		Latent				2
D.C. Cook 1 2001-005-01				Active Latent (2)						3
D.C. Cook 2 2000-011-00		Active	Latent (2)							3
D.C. Cook 2 2002-002-00			Active	Latent		Latent				3
Dreden 2 1998-012-00	Active		Latent (2)					Latent	Latent	5
Farley 1 2000-003-00			Active			Latent				2
Farley 1 2000-004-00			Latent	Active	Latent	Latent				4
Palisades 1999-005-00		Active		Latent						2
Pilgrim 1 1998-006-01					Latent	Latent				2
Prarie Island 1 1999-05-00			Latent			Latent	Latent			3
Salem 1 2001-005-00	Latent		Latent	Active						3
San Onofre 1 2001-002-00						Latent				1
Summer 1999-003-00			Latent	Active	Latent					3
Susquehanna 1 2002-005-00				Active (2)		Latent (2)			Latent	5
Watts Bar 1 2005-001-00	Latent				Latent					2
Number of Events	3	2	8	8	4	8	1	1	2	
Percentage of Events	20.0	13.3	53.3	46.7	26.7	53.3	6.7	6.7	13.3	
Total Errors	3	2	10	11	4	9	1	1	2	43

4. Event Analysis Discussion

4-1. Dominant Human Error Categories

Maintenance practices were by far the leading contributor in the fuel-handling events analyzed, with maintenance practice and work control issues occurring in 14 of the 15 events. This is reasonable since fuel-handling issues are likely to actively result from specific issues directly involving the materials-handling process. Most events are initiated by an active error, and since most fuel-handling processes do not directly involve operations staff, the primary initiator of an event is likely to come about through maintenance practice issues. Issues such as inadequate knowledge, procedures, or supervision are usually latent precursors to these initiators and will contribute to an event, but alone will not cause an event. Eight of the 15 events had active errors in the maintenance practices and work control category, which were generally mistakes specific to the given situation, having developed from the latent precursors. The Farley 1 event on March 23, 2000, displays these concerns, since the inappropriate fuel assembly configuration stemmed latent errors including underdeveloped core offload procedures and personnel verifying SFP configuration possessing inadequate knowledge and experience for the task, directly contributing to an active error in maintenance practices as the spent fuel assemblies were loaded in an inappropriate configuration.

Inadequate procedures were also a large contributor, affecting just over half the events. A common latent issue was procedures that were underdeveloped and lacking sufficient detail. Either the procedures did not clearly specify and detail work activities, such as the refueling machine calibration procedures for the Arkansas Nuclear 2 event on November 16, 2000, or the procedures failed to consider a specific condition requiring alternative treatment as a possibility, such as the procedures for reestablishing refueling integrity failing to incorporate the condition of cross-tied control ring air headers for the D.C. Cook 2 event on February 12, 2002.

4-2. Significance of Latent Errors

Although most events are initiated by active errors of the part of personnel, in many cases latent errors were large contributors to the event. Some of the events could have been prevented by correction of latent errors prior to the event. In other cases the correction of latent errors would not have such s dramatic effect. Properly developed refueling machine calibration procedures, correctly implemented, could have prevented the Arkansas Nuclear 2 event on November 16, 2000. More thorough pre-job briefings for the D.C. Cook 1 event on July, 20, 2000, would have better informed personnel on the specifics of the work activities being performed, although this would likely not have prevented the event, since the main instigator of the event, miscommunication with control room personnel, may not have been prevented. In the case of the D.C. Cook 2 event on February 12, 2002, proper documentation of the control air header cross-tie jumper installation would have assisted personnel in realizing that the procedurally preferred method of reestablishing refueling integrity was inappropriate given that condition. For the Dresden 2 event on August 20, 1998, a more thorough scheduling review would have identified that the upcoming fuel move had been scheduled an LCO with the control room ventilation system operations out of service. Identifying that conflict would have resulted in a delay of fuel movement that would have completely prevented the event.

4-3. Risk Significance of Events

Most of these events were considered to have minimal risk significance, since they had no effect on public health and safety and only inconvenienced plant operations, but some of these events could possibly have become larger concerns in combination with other occurrences. The redundancy of many systems, as well as multiple safety barriers preventing an accident from becoming a catastrophe, help reduce the effect of any single failure. Since the events ranged from underdeveloped procedures to inappropriate operation of the SFP ventilation system, some events exhibited no direct effect on worker health and safety, while more significant errors created a larger concern for plant operations.

4-3-1: The Arkansas Nuclear 2 event on November 16, 2000 has minimal safety significance since the refueling machine does not provide any function directly related to reactor safety; overload cut-off limits function to prevent excessive lifting forces from damaging to the reactor vessel during fuel assembly lifting operations. The discrepancy between the calibration values was judged small enough such that it would not be expected to result in significant damage to the reactor vessel or core internals in the case of inadvertent engagement [2].

4-3-2: The D.C. Cook 1 event on November 19, 2001 is considered to be of minimal safety significance since the fuel-handling manipulation equipment interlocks are designed to prevent drops that would damage the fuel. The auxiliary safety chain securing the RCCA tool to the crane hoist would have prevented the RCCA tool from dropping, so there were multiple barriers present to prevent damage to the fuel [3].

4-3-3: For the D.C. Cook 2 event on July 20, 2000, radiological dose consequence calculations showed that the potential dose to control room personnel would be well below the design criteria limits even without the SFP exhaust filtration in operation. This low dose is due to the low spent fuel source term over the short length of time fuel movement occurred without the SFP exhaust ventilation charcoal filter in operation since both units were shutdown. Doses from a fuel-handling accident in the SFP area would have resulted in considerably low radiological doses, so dose limits are met even without charcoal filtration through the SFP ventilation system, such that the event was of minimal safety significance and would have remained such even in the event of a fuel-handling accident [4].

4-3-4: For the D.C. Cook 2 event on February 12, 2002, the loss of refueling integrity was limited to the time it took to the CIV open and closed. Operability and closure restrictions restrict radioactive releases from an element ruptures from lack of containment pressurization in refueling mode. Requirements on containment building penetration closure ensure that radioactive releases within containment do not leak to the environment, so there was minimal impact on public health and safety [5]. However, this is still of concern since there was a pathway from the atmosphere inside containment to the atmosphere outside containment, and in the event of a pressure failure, radioactive releases leaking to the environment could possibly have occurred.

4-3-5: For the Dresden 2 event on August 20, 1998, a primary concern was that the potential existed to achieve criticality during inspection of the damaged fuel bundle or cleanup activities. A second concern would be the accidental dropping of damaged fuel bundles onto the fuel storage racks, resulting in damage to intact fuel assemblies. The depleted fuel stored within the SFP had sufficient time to decay since removal from the core, with the only concern for release being the release of radioactive krypton. The SBGTS and secondary containment remained operable, ensuring that potential releases from the refueling floor would be routed through the SBGTS charcoal beds, adsorbing radioactive krypton released from damaged fuel. Calculation and analysis of these potential risks concluded that there was minimal safety significance [6].

4-3-6: In the Farley 1 event on March 15, 2000, no abnormal radioactive releases resulted. Public health and safety were not affected. The SFP radiation monitor alarm was set well below the TS required limit. The workers were aware of and prepared for small releases of radioactive gases resulting from fuel sipping activities, and had only failed to consider the potential of the PRF to start automatically due to those releases [7].

4-3-7: The Farley 1 event on March 23, 2000, was of minimal safety significance. The boron concentration was sufficient to prevent criticality, even neglecting the Boraflex neutron adsorber located in the SFP racks [8].

4-3-8: The Palisades event on November 11, 1999, had minimal safety significance. In the event that a fuel-handling incident had occurred, fuel-handling accident operations procedure directs immediate action to place the charcoal filter in service if it is not already, which would have mitigated any potential radioactive release [9]. In the event of an additional error where a fuel-handling accident occurred and the charcoal filter was not placed in service, either through a lapse or because it was assumed to be in service since that was required by the current fuel work activities, it could escalate into a much more severe incident.

4-3-9: The Pilgrim 1 event on March 31, 1998, had minimal safety consequences. The fuel enthalpy limits and control rod worth requirements following a rod drop accident could not have been exceeded at any power level [10].

4-3-10: For the Prairie Island 1 event on May 8, 1999, a conservative assessment of the consequences of dropping the reactor vessel upper internals onto the fuel within the reactor vessel with the containment inservice purge system in operation found that radioactive releases resulting from damage to spent fuel from a heavy load drop were well within regulatory limits. Therefore, the event has minimal consequences for worker and public health and safety [11].

4-3-11: The Salem 1 event on April 18, 2001, had no associated safety consequences, since the dampers were closed and would remain such in case of power loss from the battery. In the event of a fuel-handling accident at Unit 1 the dampers on the Unit 2 side would open placing the Unit 1 control room in accident pressurized mode [12].

4-3-12: The San Onofre 3 event on January 20, 2001, had minimal safety significance, since one train of PACU was operable and available in the case of a fuel-handling accident. Having PACU train B inoperable would not affect the ability of the unit to mitigate a fuel-handling accident [13]. If both trains had been rendered inoperable, then the plant would have a significant concern over filtering of airborne radioactive particulates and gases from the SFP area following a fuel-handling accident.

4-3-13: The Summer event on April 12, 1999, had a minimal impact on plant safety since the originally load cell had passed the initial surveillance test. Improper switch condition only affects the readout, and not the function of capabilities of the load cell. The crane and load cell adequately handled necessary loads during core alteration activities [14].

4-3-14: In the Susquehanna event on July 26, 2002, could potentially have resulted in a significant reduction in the effectiveness of the storage confinement system due to the backfilling of argon gas instead of helium. The DSC contains 52 fuel assemblies that had been stored in a SFP greater than ten years. The design heat load for that DSC is 19.24 kW, while the heat load generated by the fuel assemblies 9.152kW. The DSC water temperature was kept below 160 degrees Fahrenheit until restoration activities were complete, to limit peak fuel-cladding temperatures. The maximum cladding temperature that the fuel stored in the DSC was determined to be below the design basis fuel cladding temperature limits. The argon gas had no short-term adverse chemical effects on the fuel. Since there was no fuel damage or radiological releases resulting from filling the DSC with argon gas, after corrective actions were taken, there were no adverse consequences to public health and safety, although the potentially consequences could have largely impacted fuel storage reliability [15].

4-3-15: The Watts Bar 1 event on March 11, 2005 was considered to have minimal safety consequences. The ABGTS filters airborne radioactive particulates from the SFP area following a fuel-handling accident. An evaluation of a fuel-handling accident with ABGTS inoperable, assuming all fuel rods are damaged, determined the dose rates to be within regulatory limits [16].

4-4. Limitations of Present Analysis

The analysis of these results is somewhat limited by a number of factors, including the level of depth permitted by LERs and the subjective nature of categorization. The LERs used as a primary source for event analysis do give thorough investigation into events, focusing mostly on the event description, with some details on the root cause of the event, a brief safety consequence analysis, and corrective actions that have been taken to remedy the situation and will be taken to prevent its reoccurrence. The limitations of this source material cause this analysis to necessarily be incomplete. Also, the categorization of events into specific classifications is by nature subjective. There are specific errors that could be classified in more than one category, and errors that could be broken down into component errors in multiple categories. Other systems of classification could also be utilized effectively. The focus here is to break down the events to best understand the human reliability issues that contributed to the event, so this classification system, describing the errors by the general work category followed by a more specific classification within that category to illuminate the contributing factors to the event, appropriately meets the goals of this report. Decisions were made with the intent that the event error breakdown would best describe the occurrence of errors in the context of the event. As a result, different structures to categorize the event could encompass an entirely different analysis than the one presented here.

5. Findings and Implications of Analysis

5-1. Ventilation

Five of the 15 events involved some a ventilation system in some manner. The functionality of the ventilation systems in the waste handling and waste treatment buildings at the proposed geologic repository for SNF and HLW will be highly important to preclosure safety analysis. Proper design, maintenance and operation of ventilation systems in fuel-handling areas are necessary to mitigate radiological concerns in the event of a fuel-handling accident.

Ventilation systems are important to repository preclosure safety analysis. Extended forced and natural ventilation of emplacement drifts will be utilized to prevent boiling fronts from forming in rock pillars between emplacement drifts, and also to achieve lower temperature operating goals [19]. The extent of ventilation necessary depends on the waste package spacing and maximum thermal loading, ranging from 50 to 125 years forced ventilation after the start of emplacement plus up to more than 250 years of natural ventilation after the forced ventilation period. Technical issues concerning natural air passages connecting the repository to the surface will need to be addressed. However, the emplacement drift ventilation will be more important to postclosure than preclosure safety analysis.

The repository surface facilities' ventilation systems will be of greater importance in the preclosure safety analysis than the emplacement drifts. The waste handling building and waste treatment building ventilation systems are necessary for maintaining environmental conditions appropriate for waste-handling operations, as well as worker health and safety, and for prevention of the release of radiological contaminants to the environment and public. Both buildings would have uncontaminated and potentially contaminated divisions with separate ventilation systems to prevent the spread of radioactive particulates [19]. Inoperable ventilation systems could have detrimental effects on worker health and safety, as well as environmental health concerns, in the event of a fuel handling accident in either of these building.

5-2. Fuel-Handling Activities

Almost all of the events occurred during fuel-handling activities, including fuel inspections, core off-loading and reloading, fuel bundle movements, and other refueling processes. While refueling will not be a concern for a repository, procedures developed for waste treatment, packaging, handling, and movement will be important. SNF and HLW will arrive at the repository in various transportation casks. The fuel assemblies would be unloaded from the casks at the waste handling building and transferred to a holding pool, essentially a short-term SFP, and later repackaged in a standardized container, classified as a waste package, and transported for subsurface storage [19]. With many activities involving cask preparation, decontamination, cask unloading, and transferring, involving handling of various sizes and shapes of containers, clear procedures need to be developed to safely control and manage work activities. The waste handling building systems to support these activities include the ventilation system, pool water treatment and cooling systems, electrical power system, and the monitoring and control system [19]. Appropriate knowledge of the operation of these systems and how they can affect proper fuel-handling activities, and completeness in incorporating possible failures of relevant systems into waste-handling procedures, can prevent formation of latent conditions that could develop into fuel-handling events.

In addition, the waste treatment building would be handling waste, both liquid and solid, resulting from repository operations. Low-level liquid radioactive waste resulting from cask decontaminations in the unloading pool would be recycled, if possible, or otherwise disposed off-site in dry form. Supporting systems in the waste treatment building would include the radiological safety system, radiological monitoring, sampling, and analysis systems, ventilation system, and the radiological control and management systems [19]. Like the waste-handling building, proper knowledge of the operation of these systems and the work activities being performed can significantly reduce the potential for latent conditions to develop that could result in uncontained radioactive particulates.

5-3. Conclusion

This study details the effect human error can have on fuel-handling activities, emphasizing how latent conditions can directly contribute to active events. In particular, procedural inaccuracies often create conditions that directly contribute to causes of errors related to maintenance work practices, by lack of completeness or lack of clarity. This could be of significant concern for a pre-closure safety assessment for a repository where many fuel-handling work activities would be performed, where procedural inadequacies could be latent precursors that aid in the development of fuel-handling events. Of specific interest are fuel movement activities and appropriate ventilation systems, which could significantly impact worker and public health and safety in the case of a fuel-handling accident. Ventilation systems are important because they manage the flow of airborne particulates. Proper ventilation allows for controlled containment of radiological contaminants. Fuel-handling events occurring under conditions of insufficient ventilation could potentially impact worker health and safety significantly. Fuel movement activities would occur quite frequently at a repository, and require a coordinated effort on the part of fuel-handling personnel. Thorough pre-job briefings and precise procedural documentation can ensure that tasks are completed efficiently and with minimal error. By preventing the development of latent human error precursors, the effect of human errors on fuel-handling activities can be lessened.

6. References

[1] Gertman, David I. et. al. *Review of Findings for Human Error Contribution to Risk in Operating Events.* NUREG/CR-6753, US Nuclear Regulatory Commission, Washington, D.C., 2001

[2] "Arkansas Nuclear One, Unit 2, Overload Cut Off Limits for the Refueling Machine Were Not Set as Required by Technical Specifications Due To An Incorrect Dummy Fuel Assembly Weight Being Used for Calibration." LER 2000-003-00, US Nuclear Regulatory Commission, Washington, D.C., 2000.

[3] "Donald C. Cook Nuclear Plant Unit 1, RCCA Tool Over Spent Fuel Pool Racks Technical Specification Violation." LER 2001-005-01, US Nuclear Regulatory Commission, Washington, D.C., 2001.

[4] "D. C. Cook, Unit 2, Spent Fuel Pool Exhaust Ventilation System Inoperable During Fuel Movement." LER 2000-011-00, US Nuclear Regulatory Commission, Washington, D.C., 2000.

[5] "Donald C. Cook Nuclear Plant Unit 2, Technical Specification 3.9.4.c Was Violated During Core Alteration." LER 2002-002-00, US Nuclear Regulatory Commission, Washington, D.C., 2002.

[6] "Dresden Nuclear Power Station, Unit 2, Fuel Bundle Movement permitted during Control Room Ventilation outage due to programmatic failures within the Work Planning and Execution Process." LER 1998-012-00, US Nuclear Regulatory Commission, Washington, D.C., 1998.

[7] "Joseph M. Farley Nuclear Plant, Unit 1, Penetration Room Filtration Automatic Start During Fuel Sipping." LER 2000-003-00, US Nuclear Regulatory Commission, Washington, D.C., 2000.

[8] "J. M. Farley, Unit 1, Three Spent Fuel Assemblies in Spent Fuel Pool Locations Not Allowed by Technical Specifications 3.7.15." LER 2000-004-00, US Nuclear Regulatory Commission, Washington, D.C., 2000.

[9] "Palisades Plant, Charcoal Filter Not In Service During Movement Of Irradiated Fuel Assemblies." LER 1999-005-00, US Nuclear Regulatory Commission, Washington, D.C., 1999.

[10] "Pilgrim Nuclear Power Station, Failure to Verify Compliance with Technical Specification Limits on Control Rod Worth." LER 1998-006-01, US Nuclear Regulatory Commission, Washington, D.C., 1998.

[11] "Prairie Island Nuclear Generating Plant Unit 1, Containment Inservice Purge System Not Isolated During Heavy Load Movement Over Fuel." LER 1999-005-00, US Nuclear Regulatory Commission, Washington, D.C., 1999.

[12] "Salem Generating Station, Unit 1, Control Room Emergency Air Intake Dampers Inoperable During Spent Fuel Pool Moves." LER 2001-005-00, US Nuclear Regulatory Commission, Washington, D.C., 2001.

[13] "San Onofre Unit 3, Starting the Movement of Irradiated Fuel With One Train of PACU Inoperable Causes TS Violation." LER 2001-002-00, US Nuclear Regulatory Commission, Washington, D.C., 2001.

[14] "Virgil C. Summer Nuclear Station, Missed Surveillance on Manipulator Crane Load Cell." LER 1999-003-00, US Nuclear Regulatory Commission, Washington, D.C., 1999.

[15] "Susquehanna, Dry Fuel Storage Container Filled With Incorrect Gas Due To Human Error." LER 2002-005-00, US Nuclear Regulatory Commission, Washington, D.C., 2002.

[16] "Watts Bar, Unit 1, Regarding Two Trains of ABGTS Inoperable." LER 2005-001-00, US Nuclear Regulatory Commission, Washington, D.C., 2005.

[17] *Babcock and Wilcox Plants, Rev. 3.1 STS, Vol. 1, Specifications.* NUREG-1430, US Nuclear Regulatory Commission, Washington, D.C., 2001

[18] *Yucca Mountain Review Plan.* NUREG-1804, Rev. 2, US Nuclear Regulatory Commission, Washington, D.C., 2002

[19] *Yucca Mountain Science and Engineering Report.* DOE/RW-0539, US Department of Energy, Washington, D.C., 2001