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Criticality Risks During Transportation of Spent Fuel

Albert Machiels, EPRI

Andy Dykes, ABS Consulting

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Topics

Objective

Issues

Transportation – Accident Conditions

Fuel Reconfiguration

Impact of Misloading

Structural Analysis

Probability of Criticality During Transportation

Conclusion

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Objective

- Provide results from criticality risk assessments during transportation of spent nuclear fuel in the context of resolving issues associated with:
  - High-burnup
  - Burnup credit
  - Moderator exclusion
- "… this study demonstrates so much margin between the apparent risk estimates (which are surely conservative rather than realistic) and any reasonable risk level of concern that a change in the NRC regulatory position should be easy to support and defend." (reviewer's quote)

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Issues

- Transportation of Spent Fuel
  - Cladding considerations associated with spent high-burnup (i.e., >45 GWd/MTU) fuel
  - Burnup credit
  - Moderator exclusion
- Issue attributes
  - Regulations and regulatory practices/guidance
  - Risk information
  - Public perception

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Transportation - Accident Conditions

- Key Regulatory Requirement: Maintain Subcriticality Under Transportation Accident Conditions
- Multi-faceted issue:
  1. Risk Information: Criticality Risks During Transportation
     - ✓ Accident probabilities (transport mode, frequency, severity, location)
     - ✓ Reactivity considerations (misloads, geometric effects, …)
  2. Potential impact of fuel reconfiguration on criticality
     - ✓ Reactivity changes due to fuel reconfiguration
  3. Structural response of spent fuel to accident impact loads
     - ✓ Potential for rod breakage and fuel relocation (reconfiguration) under accident conditions
  4. "Full" Burnup Credit
     - ✓ Ability to realistically account for depletion of fissile material and buildup of most neutron absorbers (actinides and fission products)
  5. Moderator Exclusion
     - ✓ No moderator = No potential for criticality of LWR fuel

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NUREG/CR-6835

Table 6: Maximum increase in k_{eff} for each fuel failure scenario*

Scenario	MPC-24 *(fresh fuel)*	GBC-32 (45 GWd/MTU)	MPC-68 *(fresh fuel)*
Single missing rod	0.0010	<0.0010	0.0036
Multiple missing rod	0.0140	0.0130	0.0120
Cladding removed from all fuel rods	0.0468	0.0349	0.0441
Fuel rubble (no cladding)	0.0563	0.0233	0.1149
Assembly slips 8” above or below neutron poison panels	0.0021	0.0435	0.0362
Variation in pitch (without cladding)	0.0709	Not calculated	0.1225

* “Although the scenarios considered go beyond credible conditions, they represent a theoretical limit on the effects of severe accident conditions” (NUREG/CR-6835, p. 1)

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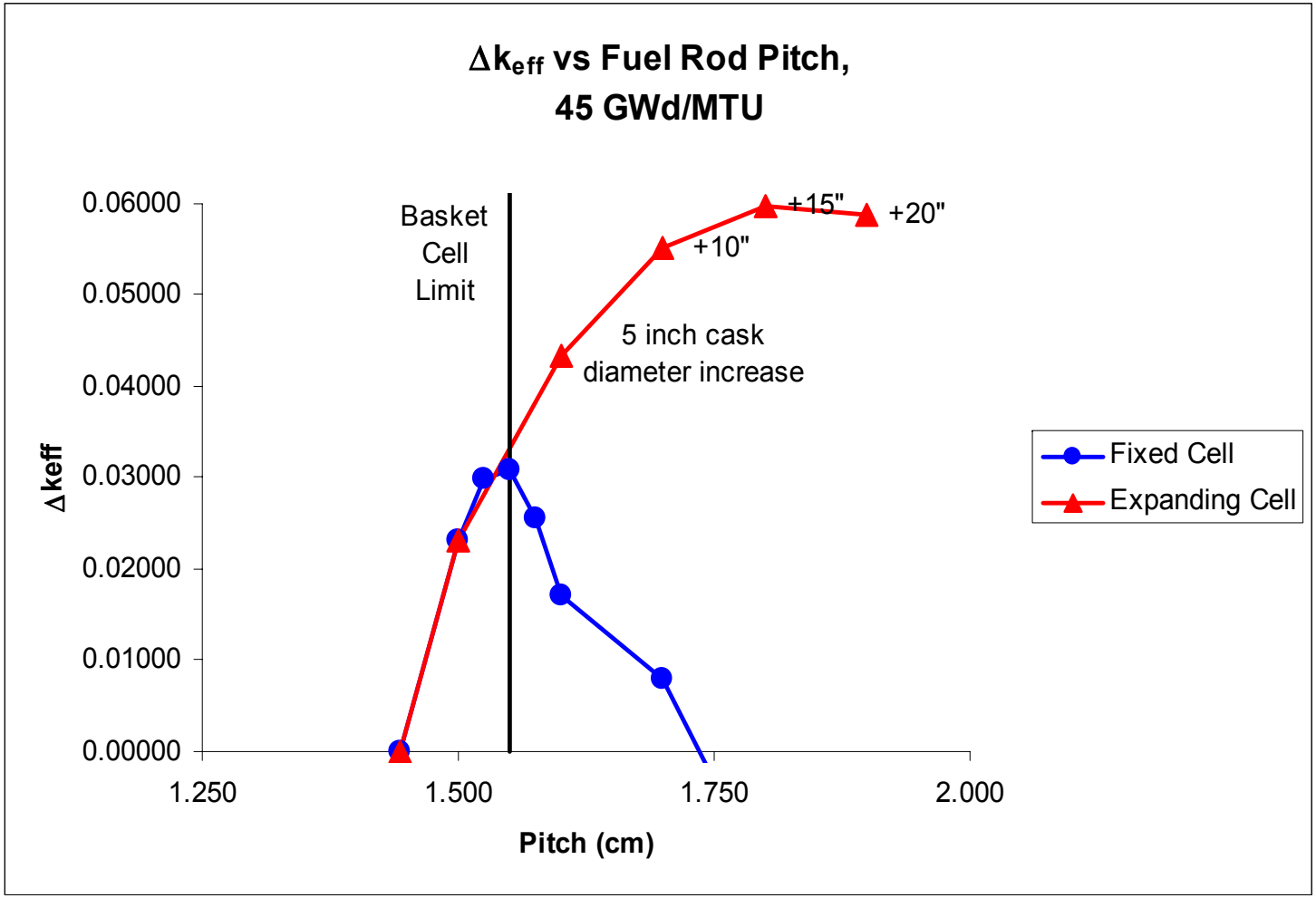
EPRI Report 1015050



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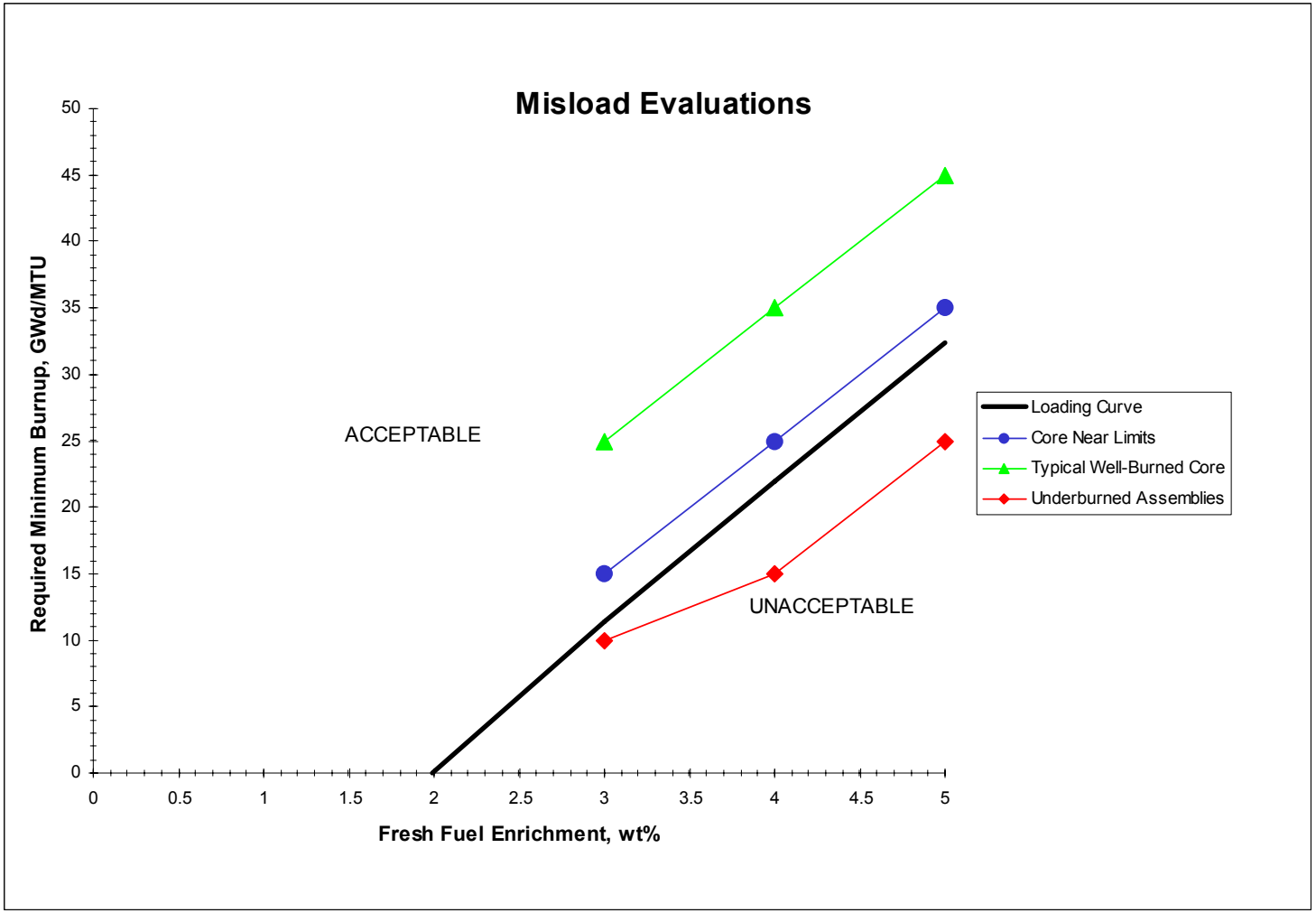
EPRI Report 1003418 "Technical Basis for Spent Fuel Burnup Verification" (Dec. 2003)



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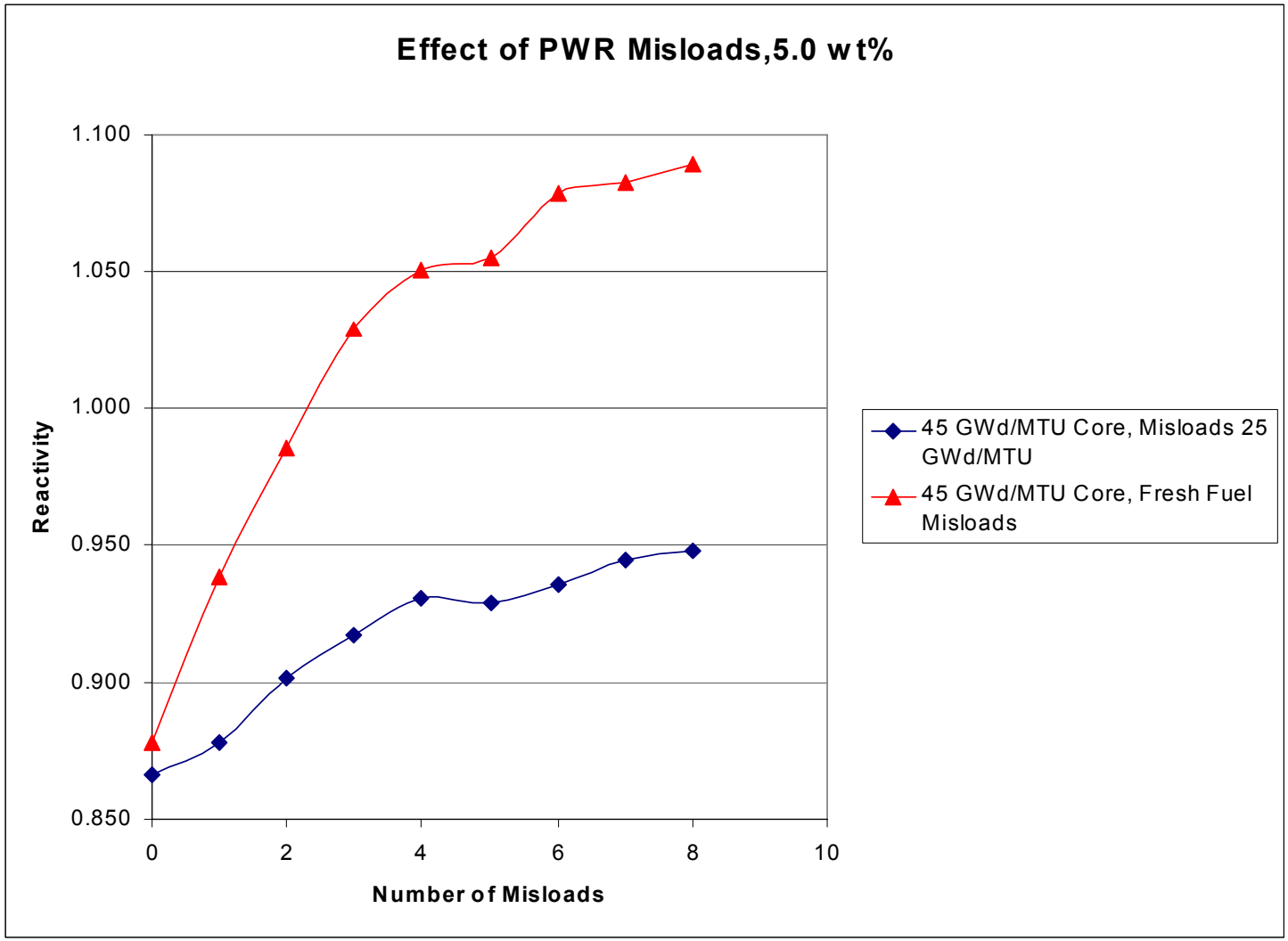
From EPRI Report 1003418 (Dec. ’03) -- Fresh and Underburned Assembly Misloadings



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Unpublished NRC-Sponsored Work

- Results of EPRI Report 1003418 were presented at the NEI Dry Storage Information Forum on May 3, 2004
- W. Hodges, SFST Deputy Director in 2004, responded by stating that an ongoing NRC-sponsored study (unpublished) by ORNL appeared to confirm EPRI's results, i.e., the impact of misloading of underburned assemblies would not violate nuclear safety (i.e., criticality)

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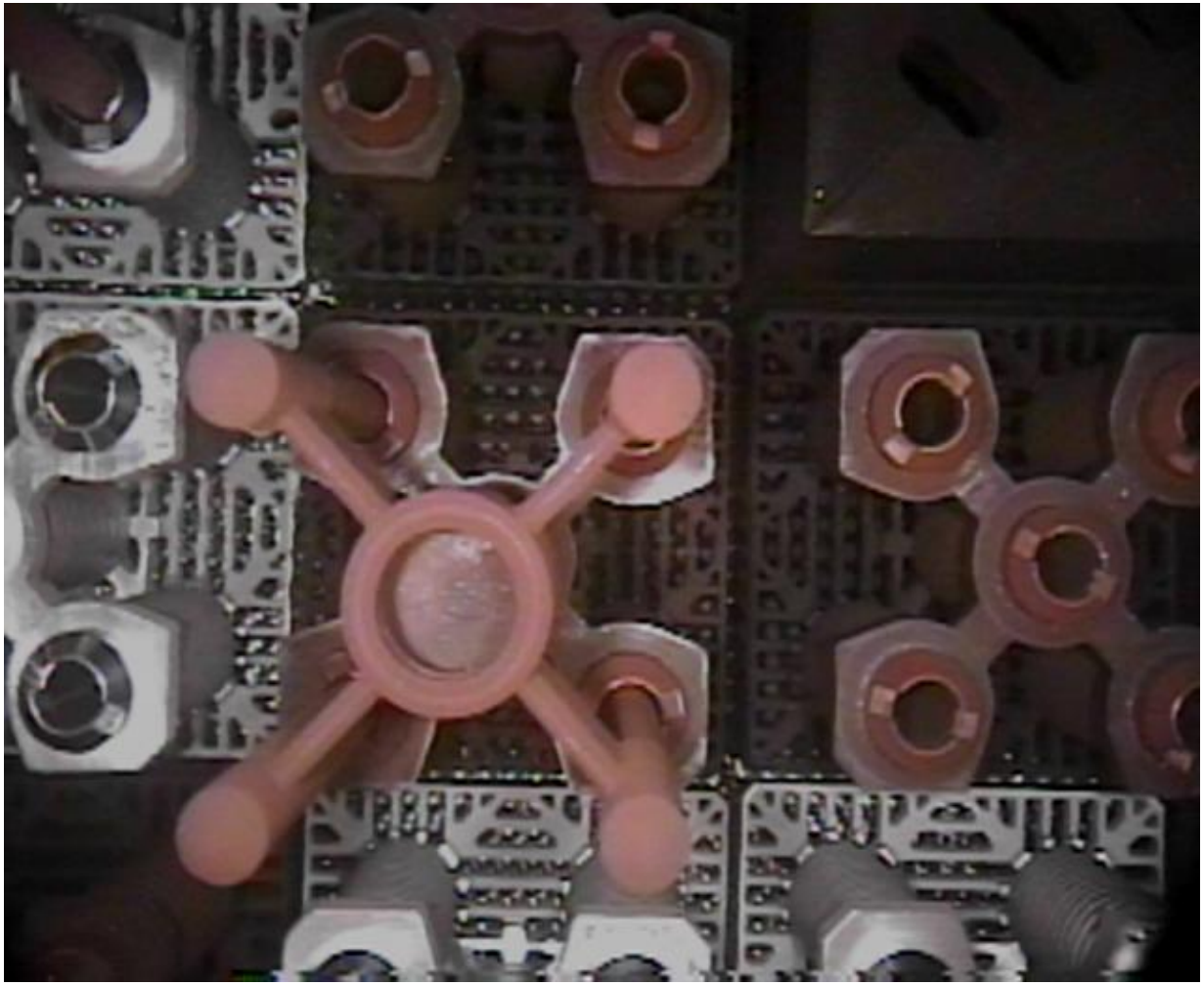
Visual Distinction Between New and Once Burned Fuel*



*NOT from a video scan for verification of fuel assembly S/N

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Fuel Rod Response Modeling - Objective

Satisfy NRC's RAIs Dated 4/17/02: Questions B.4 & B.6:

- Question B.4: "Quantify the percentage of fuel pin failures, and the associated uncertainty, caused by stresses imparted to the high burnup fuel under hypothetical accident conditions *[(such as a cask tip over event) on a per storage cask basis.]* … The staff considers the approach used in Appendix III of the SAND90-2406 report, …, to be acceptable to quantify the percentage of fuel pin failures under hypothetical accident conditions *[of storage.]* …"
- Question B.6: "… Also, provide information regarding the type of failure that can be expected in such a scenario, …"

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Fuel Rod Response Modeling – 2004-2007 Deliverables

- 1009694 (June ’04) – *Development of a Metal/Hydride Model for Zircaloy Cladding With Mixed Hydride Structure*
- 1009693 (Dec. ’04) – *Failure Criteria for Zircaloy Cladding Using a Damage-based Metal/Hydride Mixture Model*
- 1009929 (June ’05) – *Fuel Rod Failure Evaluation Under Simulated Cask Side Drop Conditions*
- 1011816 (Sept. ’05) – *Application of Critical Strain Energy Density to Predicting High-burnup Fuel Rod Failure (Response to NRC Staff Comments)*
- 1011817 (Dec. ’05) – *Global Forces Acting on Spent Fuel Rods and Deformation Patterns Resulting from Transportation Accidents*
- 1013447 (Oct. ‘06) – *Transverse Tearing and Rod Breakage Resulting from Transportation Accidents*
- 1013448 (Dec. ’06) – *Longitudinal Tearing Resulting from Transportation Accidents – A Probabilistic Treatment*
- 1015049 (June ’07) – *Normal Conditions of Transport*
- 1015048 (Dec. ’07) – *Assessment of Cladding Performance – A Synthesis Report*

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EPRI Report 1013449 *Criticality Risks During Transportation of Spent Nuclear Fuel* (Dec. '06)

- Objective
  - To provide a realistic perspective on criticality risks during railroad transportation of spent nuclear fuel casks
    - Administrative controls for loading spent-fuel transportation packages
    - Railroad accident rates combined with robustness of waste packages
    - Limited nuclear reactivity of spent fuel

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How Could a Criticality Event Possibly Occur?

- Cask is misloaded at plant
  - Introduces more reactive fuel than allowed by transportation package Certificate of Compliance
  - Error not detected prior to shipment
- Accident occurs during transportation
  - Produces sufficient damage to breach cask
  - Location near water
  - Damaged cask becomes submerged in water
  - Water leaks in
- Sufficient reactivity present to result in a criticality event

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Scope of Risk Assessment

- Addresses only commercial power reactor operations
- Examines both in-plant operations and rail transportation
  - EPRI reports on fuel assembly burnup and criticality
  - Detailed assessment of human failure events during fuel handling at an example plant
  - Sandia reports on railroad transportation accidents
  - Bounding assumptions regarding physical conditions not explicitly quantified
- Result: a conservative bounding point estimate of the frequency of a criticality event during rail transportation of 11,000 spent fuel casks an average of 2,000 miles.

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Bounding Assumptions

- Any fuel assembly that is not on a selection document verified to conform to the Certificate of Compliance (CofC) for the Spent Fuel Cask (SFC) will have excess reactivity
- If one fuel assembly is misloaded, sufficient additional fuel assemblies will also be loaded to make the SFC susceptible to criticality (Total dependence between the human failure events during loading).
- If a SFC is sufficiently damaged and submerged in water as the result of an accident, water will leak into the cask to produce the moderation and reflection needed to achieve criticality

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Activities at Nuclear Power Plants that Affect Reactivity of Spent Fuel Casks

- Maintain accurate records of fuel assembly burnup
- Select fuel assemblies
  - Meet criticality criteria: enrichment, burnup within limits of Certificate of Compliance (CofC)
- Load the Spent Fuel Cask (Dry Storage Canister)
  - Insure that only selected assemblies are loaded
- Prepare the Spent Fuel Cask for storage/shipment
  - Verify that assemblies in cask are those selected

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Effect of Human Error While Loading Dry Storage Canisters

	Create Cask Fuel Loading Pattern form	Load Cask IAW Cask Fuel Loading Pattern Form	Misload Includes High Reactivity Fuel Assemblies
Assemblies selected to meet CofC	Completed without error	Cask loaded IAW form	No possibility of criticality
	Assemblies not selected directed to be loaded	Cask has unselected assemblies	Insufficient reactifity for criticality
			Sufficient reactivity for criticality
		Cask has assemblies not selected	Insufficient reactifity for criticality
			Sufficient reactivity for criticality

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Record of Fuel Burnup

- Special Nuclear Material Database maintains a permanent record of every movement of each fuel assembly and its burnup at that point.
- Core Follow software periodically updates assembly burnup based on flux measurements and the time integrated reactor power output
- Startup flux measurements verify accuracy of burnup in previous cycle:
  - Upon restart after be shuffled in core
  - Influence on remaining assemblies when discharged

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Fuel Selection Process

- Query identifies assemblies in Special Nuclear Material database meeting CofC burnup and cool down requirements.
- Fuel management engineer and refueling engineer select fuel assemblies from that list based on operational considerations.
- Fuel management engineer generates the fuel selection document from/using the Special Nuclear Material database.
- Third person independently verifies that selected assemblies meet the criteria of the CofC.

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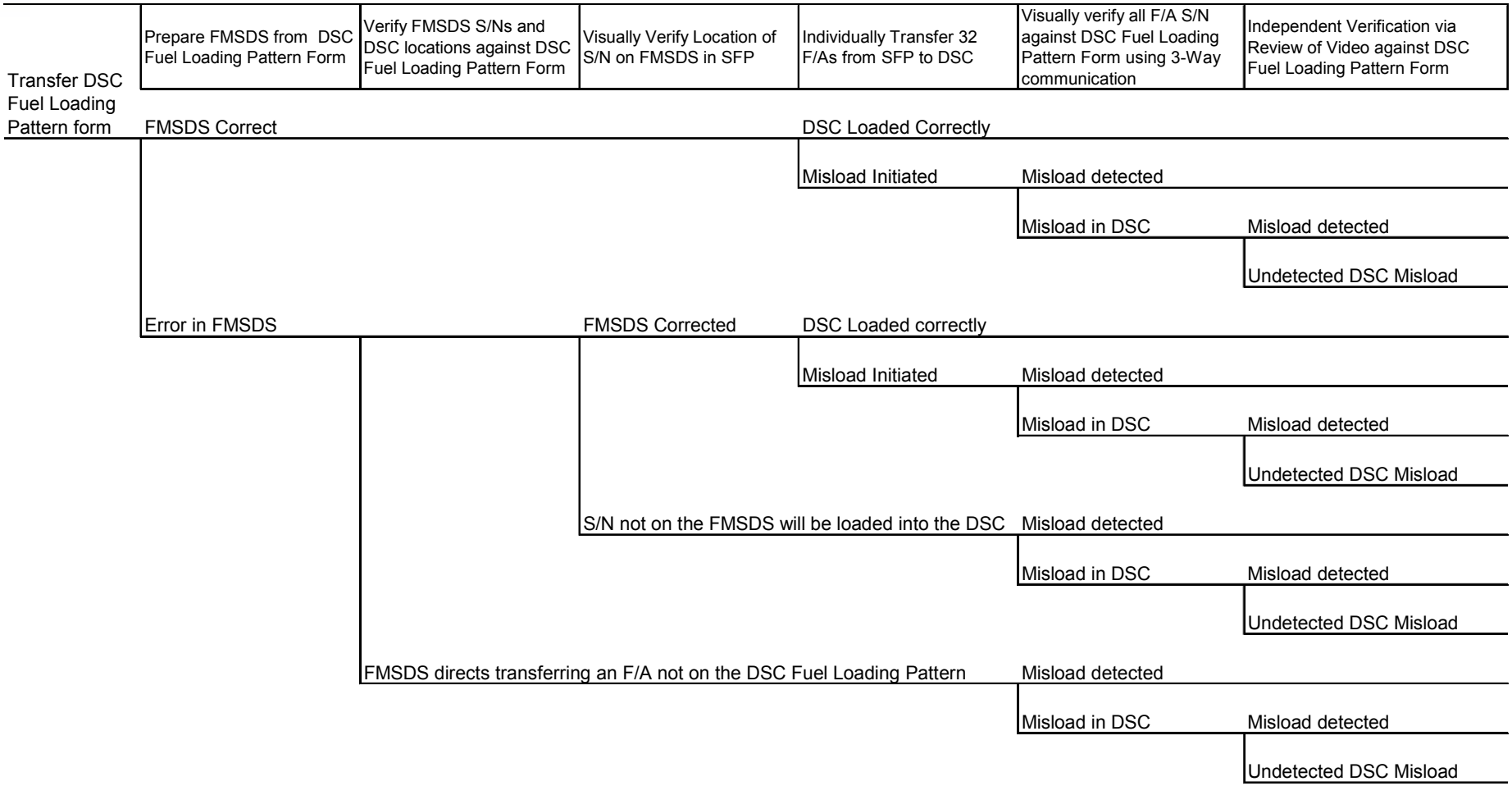
Evaluation of Human Failure Events During Fuel Loading at Example Plant



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Quantification of Loading Event Tree (Human Error Probabilities modeled as Type A Errors)

Transfer DSC Fuel Loading Pattern form	Prepare FMSDS from DSC Fuel Loading Pattern Form	Verify FMSDS S/Ns and DSC locations against DSC Fuel Loading Pattern Form	Visually Verify Location of S/N on FMSDS in SFP	Transfer 32 CofC Verified F/As from SFP to DSC	Visually verify all F/A S/N against DSC Fuel Loading Pattern Form using 3-Way communication	Independent Verification via Review of Video against DSC Fuel Loading Pattern Form	Likelihood of DSC Closure with one or more misloaded F/As
	9.9E-01	NA	NA	9.9E-01	NA	NA	
				9.4E-03	1.0E+00	NA	
					2.8E-03	9.3E-01	
						7.4E-02	1.9E-06
	1.3E-02	9.3E-01	9.9E-01	9.9E-01	NA	NA	
				9.4E-03	1.0E+00	NA	
					2.8E-03	9.3E-01	
						7.4E-02	2.3E-08
			1.3E-02	Guaranteed Failure	1.0E+00	NA	
					2.8E-03	9.3E-01	
						7.4E-02	3.3E-08
		6.6E-02	Guaranteed Failure	Guaranteed Failure	1.0E+00	NA	
					2.8E-03	9.3E-01	
						7.4E-02	1.8E-07
	Likelihood that an error has occurred up to this point in the loading process that, if not detected, would lead to a misloaded DSC						
	1.3E-02		1.0E-03	1.0E-02	**2.9E-05**	2.1E-06	**2.1E-06**

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Accident Sequence During Transport

	Accident during transport	Accident produces conditions for criticality	Cask sufficiently moderated and reflected for criticality	End State
Cask has Sufficient Ractivity	Load arrives safely			No criticality
	Evaluate accident conditions	Insufficient damage OR exposure to water		No criticality
		Cask breached AND submerged in water	Insufficient leakage into cask	No criticality
			Sufficient conditions for criticality	Criticality Accident

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Update of Railroad Accident Rates (FRA data reported for all types of trains, track classes and speeds)

Source Document	Data Time Period	Reported Accident Rate (Events/Train-Mile)	Extracted from FRA On-Line Database		
			Accident Rate (Events/Train-Mile)	Number of Reportable Accidents	Total Railroad Train-Miles
NUREG/CR-4829 (Modal Study)	1975-1982	1.19E-05	1.19E-05	68,489	5,762,577,462
NUREG/CR-6672	1988-1995	4.57E-06	4.57E-06	22,594	4,948,189,617
This Report	2000-May 2006		4.33E-06	20,779	4,803,036,079
This Report (Freight Train Accidents and Mileage)	2000-May 2006		2.67E-06	9,697	3,635,445,944

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Conditional Probability that Accident Produces Conditions Needed for Criticality

- Statement in NUREG/CR-4829, the "Modal Study"
  - "Any reduction in criticality safety depends on both the cask and fuel basket design. However, since the margins used to prevent criticality are very high, and since careful evaluations of the criticality analysis and the design features are performed during cask licensing, the possibility of a criticality event is small even under extreme loading conditions. Using probabilistic methods in Section 5.0, the probability of a rail cask's having a structural response greater that 2% strain (S2) and becoming submerged in water is estimated to be 0.00000078%, given an accident. "

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Quantification of Criticality Risk 1 of 2

Failure Event	Cask Loaded Without Independent Verification of Video Recording		Cask Loaded With Independent Verification of Video Recording	
	All Trains	Freight Trains	All Trains	Freight Trains
Misload of at least one fuel assembly into a Spent Nuclear Fuel/Cask	2.9E-05		2.1E-06	
Probability of misload adding reactivity Sufficient for Criticality (Bounding Assumption)	1.0E+00			
Train Accidents per Train-Mile (All Accidents, All Speeds, All Track Classes), 2000 - May 2006.	4.3E-06	2.7E-06	4.3E-06	2.7E-06
Frequency of trains accidents containing a spent fuel cask susceptible to criticality per 2,000 mile shipment	2.5E-07	1.5E-07	1.8E-08	1.1E-08

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Quantification of Criticality Risk 2 of 2

Failure Event	Cask Loaded Without Independent Verification of Video Recording		Cask Loaded With Independent Verification of Video Recording	
	All Trains	Freight Trains	All Trains	Freight Trains
Frequency of trains accidents containing a spent fuel cask susceptible to criticality per 2,000 mile shipment	2.5E-07	1.5E-07	1.8E-08	1.1E-08
Probability that accident produces sufficient cask damage and immersion (per Modal Study)	7.8E-09			
Probability that water leaks into cask and produce sufficient moderation for crticality	1.0E+00			
Frequency of Criticality Accidents/Shipment	2.0E-15	1.2E-15	1.4E-16	8.7E-17
Number of Shipments per Year = 11,000/24 Years (from NUREG/BR-0292, Reference 13)	458			
Frequency of Criticality Accidents per Year	9.0E-13	5.5E-13	6.5E-14	4.0E-14
Likelihood of a Criticality Accident over all 11,000 Shipments	2.2E-11	1.3E-11	1.6E-12	9.6E-13

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Technical Reviewers (after December 2006 Publication of EPRI 1013449)

- Overall PRA approach - utilization of evidence and integration of technical areas. (Karl Fleming)
- Plant procedures – applicability of the example plant's procedures to generic industry practice (Zita Martin, TVA)
- HRA quantification – consistency with currently accepted practices (Jeff Julius, SCIENTEC)
- Railroad accidents – Interpretation of NUREG/CR-4829 and NUREG/CR-6672 (Doug Ammerman, Sandia)
- Criticality assessment – Validity and interpretation of referenced documents. (Laurie Waters, LANL)
- Spent fuel transportation requirements – Applicability of findings to the future management of spent fuel shipping. (Bob Budnitz, LLL)

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Significant Reviewer Comments

- The assessment of human failure events and error probabilities for spent fuel cask loading is thorough.
- The frequency of failure to prepare an accurate fuel selection document should be assessed and quantified.
  - This task will be undertaken in a revision to EPRI 1013449
  - The task will account for the role Special Nuclear Material control requirements in cask loading and shipping operations
- The probability of significant cask damage and submergence in water (7.2 E-09) is a major assumption and should be justified.
  - See next slide “Is Modal Study Value Reasonable?”
  - Re-quantification would involve considerable time and effort.
  - Control of train routes, dispatching, and speed can minimize the susceptibility to damage and submersion
- Uncertainty is not explicitly quantified.
  - This is an open question.

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Is the Modal Study Value Reasonable?

- No specific calculations supporting value of 7.8E-09 available, however, FRA train accident rate is generic
  - All types of trains
  - All speeds (threshold for damage is at least 60 MPH)
  - All types, classes, and locations of track
- Damage and submersion require
  - Need for impact on hard object
  - Threshold for damage is at least 60 MPH
  - Close proximity of reasonably deep water
- Conclusion: YES. It is a reasonable representation of the fraction of all train accidents that could produce the severe end states needed for criticality.

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Observations

- The probability of a criticality accident during rail transportation is negligibly small
- The estimates assume a bounding condition for the effect of misloading, which could lower the estimate further, if needed.
- Existing controls at nuclear plants ensure that the likelihood of misloaded casks being shipped are small
- Controls on rail shipments, such as routes on adequately classed track and reasonable speed limits will further assure that the severe accidents needed to breach and flood spent fuel casks will not occur

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Conclusion

- What have we learned?
  - Risk information:
    - Criticality risks during transportation are negligible
  - Reconfiguration effects can be dismissed
    - Even assuming *non-physical* reconfiguration does not lead to a critical configuration
    - Cladding damage is bounded
      - Elements most susceptible to damage typically have the least nuclear reactivity

Evidence suggests that there are opportunities to rationalize the transportation regulations or their interpretation, which would result in lower overall risks and reduce the effort, time, and resources needed for obtaining regulatory approvals for transporting spent fuel

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