High Burnup Cladding Integrity

What We Know

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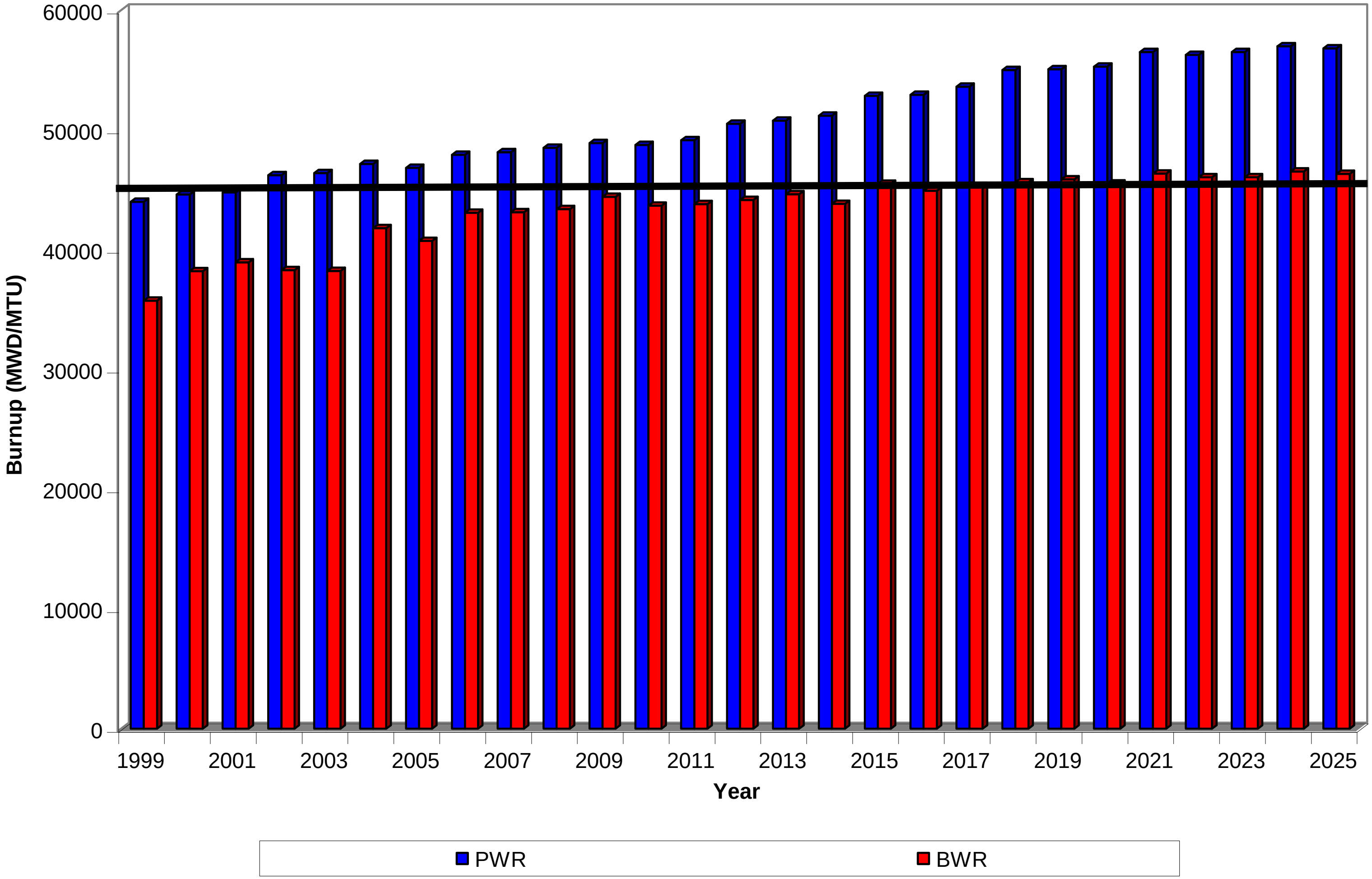
Outline

- Background
- EPRI approach to “expected” high burnup fuel performance
- Regulatory and Technical Issues
  - Regulatory requirements for storage and transportation
  - Potential high burnup fuel degradation mechanisms
    - Hydride reorientation
    - Criticality
      - Geometric reorientation
      - Burnup credit
- Conclusions

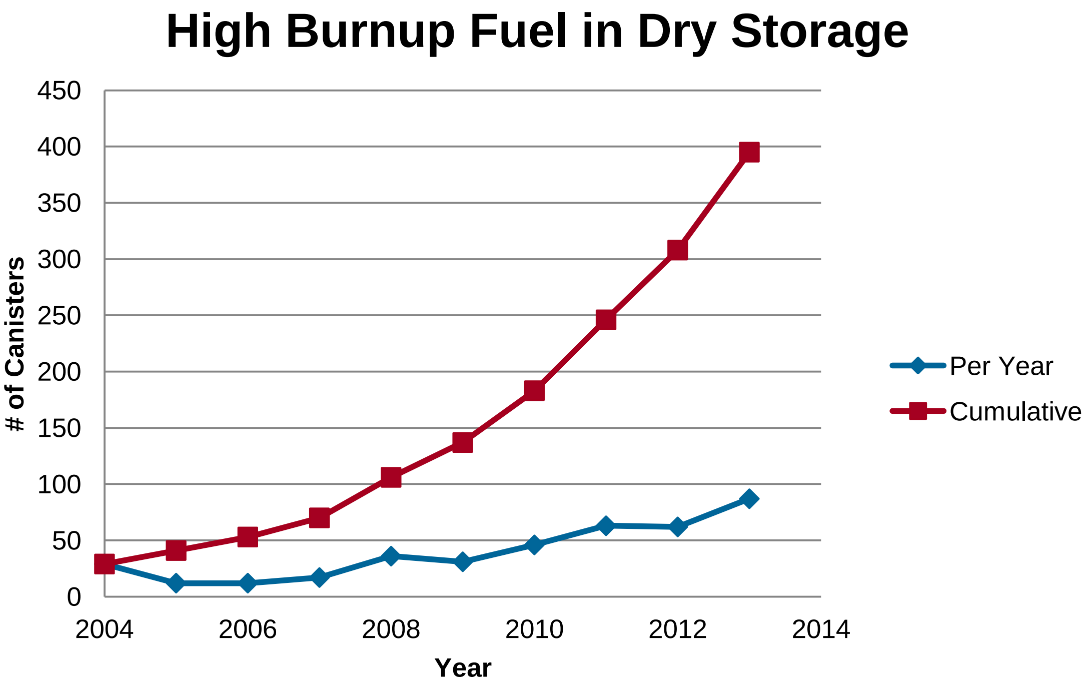
Batch Average Projected SNF Discharge Burnup at or Exceeding 45 GWd/MTU



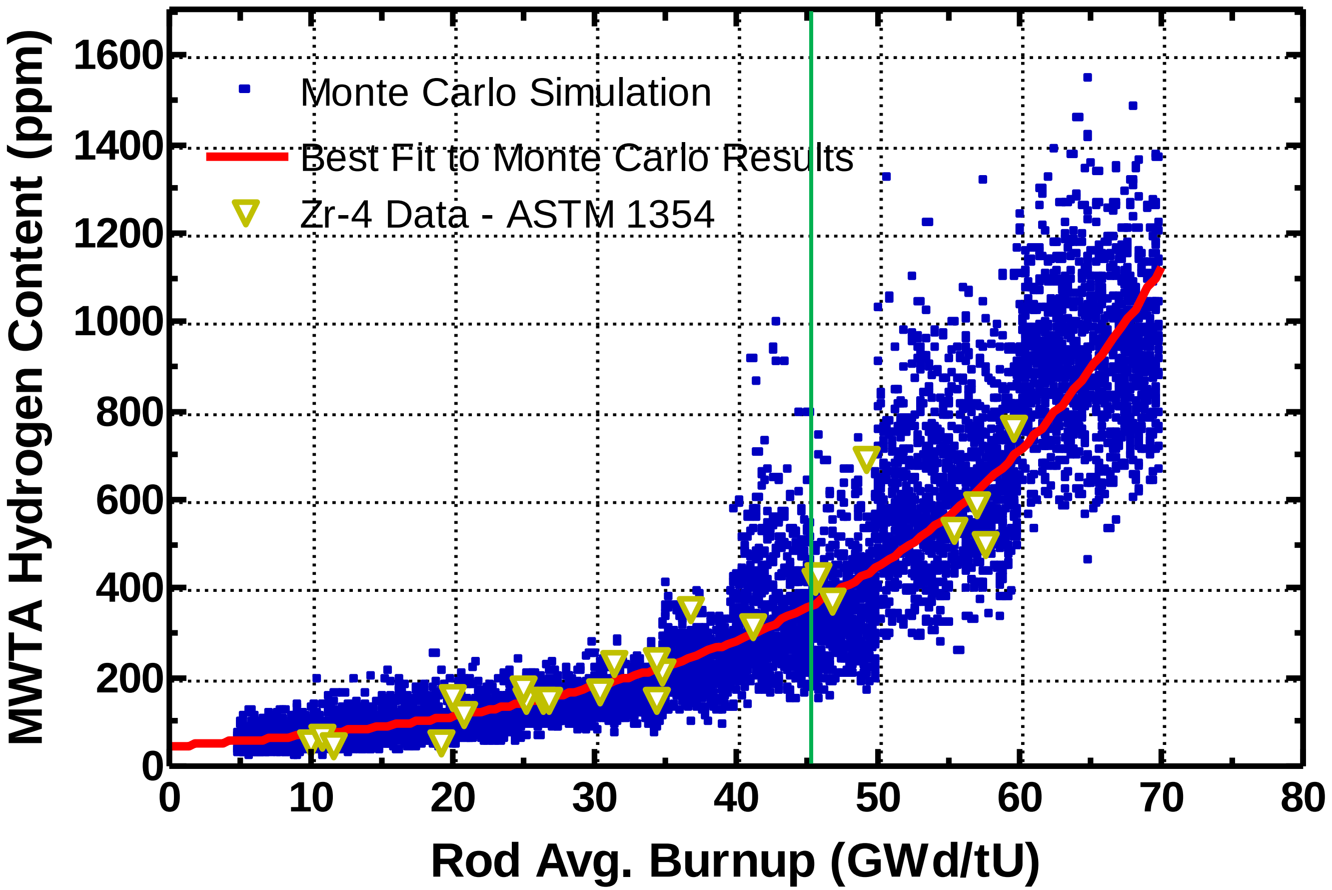
High Burnup Nuclear Fuel in Dry Storage is Increasing

US data as of December 2013, courtesy Nuclear Energy Institute

- HBU ISFSI storage
  - ~6000 assemblies
  - ~400 casks/modules loaded
  - At 27 Operating ISFSIs
  - Up to 57.6 GWD/MTU
- HBU storage projections for 2020
  - ~15,000 assemblies
  - > 1,000 casks/modules loaded

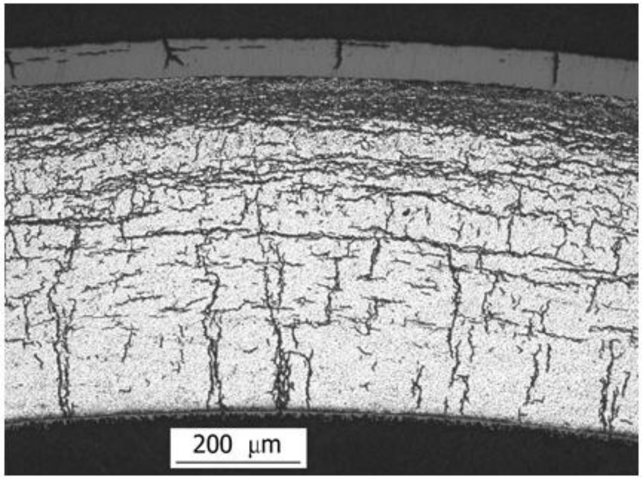


Low→High Burnup Fuel Properties: No Dramatic Step Change at 45 GWd/MTU

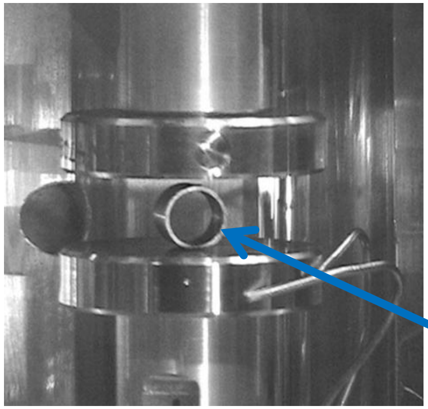


NRC Concern: *High* BU Cladding Loss of Ductility During Extended Storage

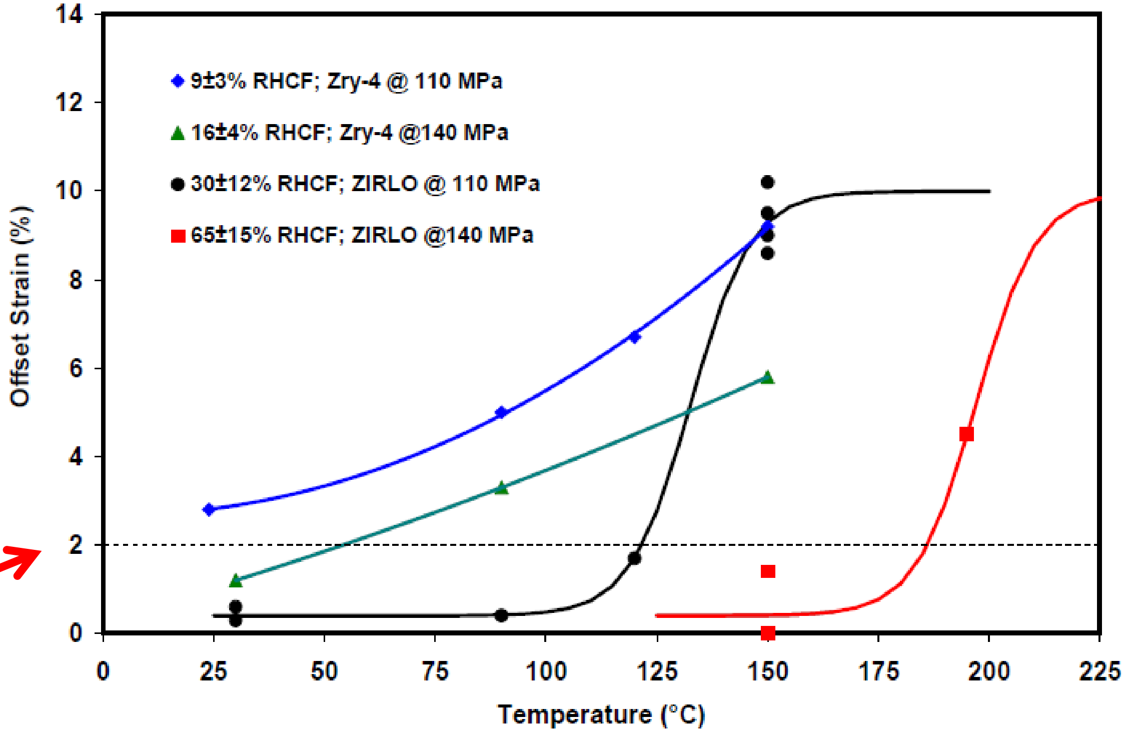
(followed by transportation)



Used fuel cladding cross-section showing hydride embrittlement



LABORATORY TESTS



Ductile-to-Brittle transition data from ring compression tests (fuel removed)

Ring compression test machine using a section of cladding with fuel removed

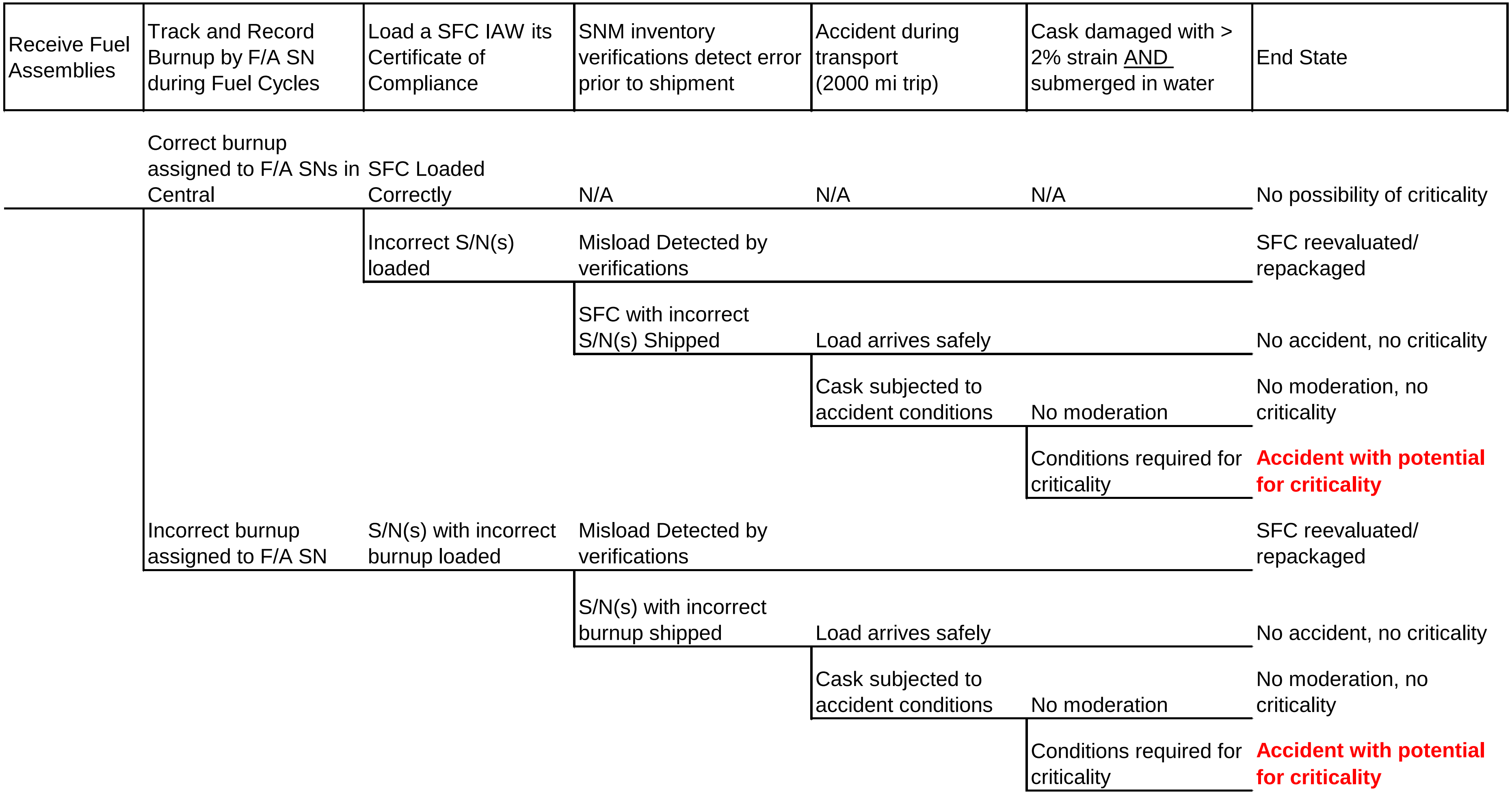
Transportation Issues Resolution – Technical Approach

Multi-pronged approach:

1. Criticality Risks During Transportation
   - ✓ Risk information
2. Moderator Exclusion
   - ✓ No moderator = No potential for criticality of LWR fuel
3. “Full” Burnup Credit
   - ✓ Ability to account for depletion of fissile material and buildup of most neutron absorbers
4. Structural response of cladding to impact loads
   - ✓ Potential for rod breakage and fuel relocation (reconfiguration) under accident conditions
5. Potential impact of fuel reconfiguration on criticality
   - ✓ Maximum reactivity increase due to fuel reconfiguration cannot result in a critical configuration

Sequence of Events Necessary to Produce a Potential Criticality During Railroad Transport

Technical Report 1016635 *“Criticality Risks During Transportation of Spent Nuclear Fuel – Revision 1” 12/08*



Receive Fuel Assemblies	Track and Record Burnup by F/A SN during Fuel Cycles	Load a SFC IAW its Certificate of Compliance	SNM inventory verifications detect error prior to shipment	Accident during transport (2000 mi trip)	Cask damaged with > 2% strain AND submerged in water	End State
	Correct burnup assigned to F/A SNs in Central	SFC Loaded Correctly	N/A	N/A	N/A	No possibility of criticality
		Incorrect S/N(s) loaded	Misload Detected by verifications			SFC reevaluated/ repackaged
			SFC with incorrect S/N(s) Shipped	Load arrives safely		No accident, no criticality
				Cask subjected to accident conditions	No moderation	No moderation, no criticality
					Conditions required for criticality	**Accident with potential for criticality**
	Incorrect burnup assigned to F/A SN	S/N(s) with incorrect burnup loaded	Misload Detected by verifications			SFC reevaluated/ repackaged
			S/N(s) with incorrect burnup shipped	Load arrives safely		No accident, no criticality
				Cask subjected to accident conditions	No moderation	No moderation, no criticality
					Conditions required for criticality	**Accident with potential for criticality**

Probability of Criticality during Rail Transport

EPRI Report 1016635 “Criticality Risks During Transportation of Spent Nuclear Fuel – Revision 1 (December 2008)

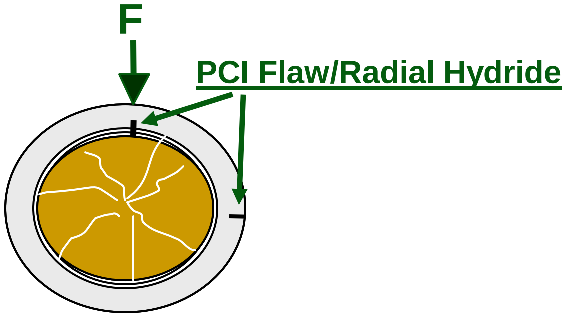
Description	All Trains	Freight Trains
Frequency of Accidents of Interest for Criticality/Shipment	6.8E-11	4.2E-11
Likelihood of Shipping a Misloaded Spent Fuel Cask	2.6E-06	2.6E-06
Likelihood of an Accident with a Potential for Criticality per Shipment	1.8E-16	1.1E-16

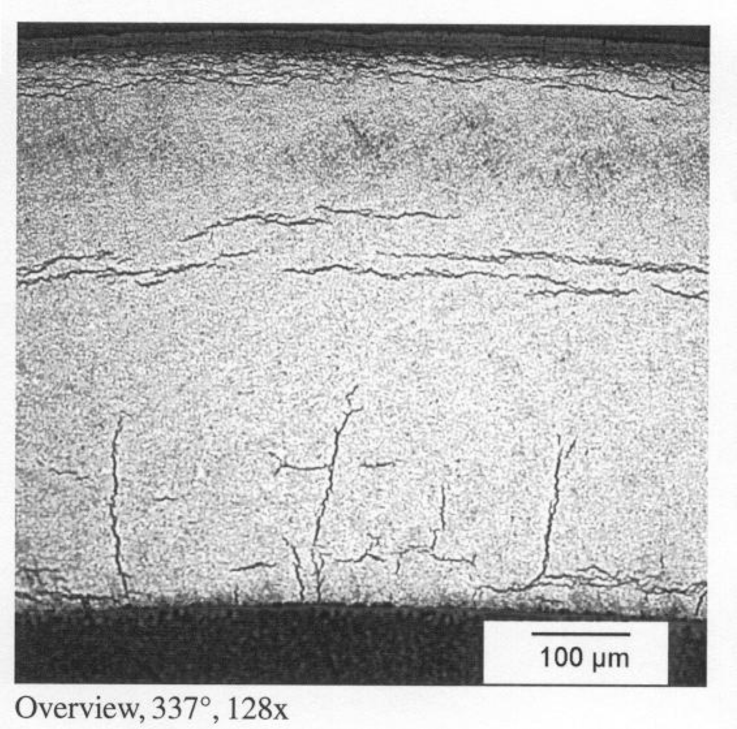
NRC report NUREG-2125 does not consider event trees that would lead to a criticality event

Probability of a Criticality during Transportation is Low because a Series of Failures Must Occur Altogether

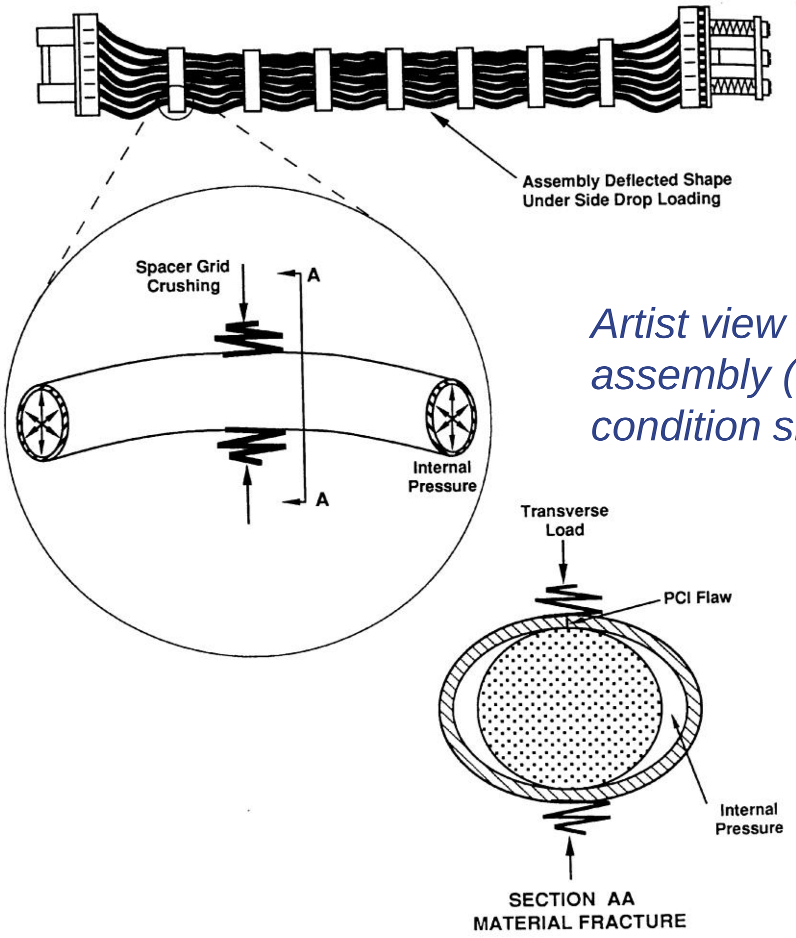
- **Water must enter the cask/canister**
  Casks/canisters are specifically designed to exclude water – even for hypothetical accident scenarios
- **Enough water must be present**
  Even if some water enters the cask/canister, the amount of water is likely to be low
- **The fuel must be sufficiently damaged such that it "reconfigures"**
- **The reconfiguration must result in a high enough neutron multiplication factor (k-effective)**
  Reconfiguration is much more likely to reduce than increase k-eff
- **Spent fuel must have enough fissile material and only a small amount of non-fissile material that absorbs neutrons**
  - Unlikely both criteria will be present at the same time
  - When both criteria are not met, neutron poison material is put inside the cask/canister
  - What remains is the probability of mis-loading more fissile fuel with the intended, less fissile fuel

Transportation Stresses: Pinch Loading Imparts Maximum Cladding Stresses – *radial direction*)



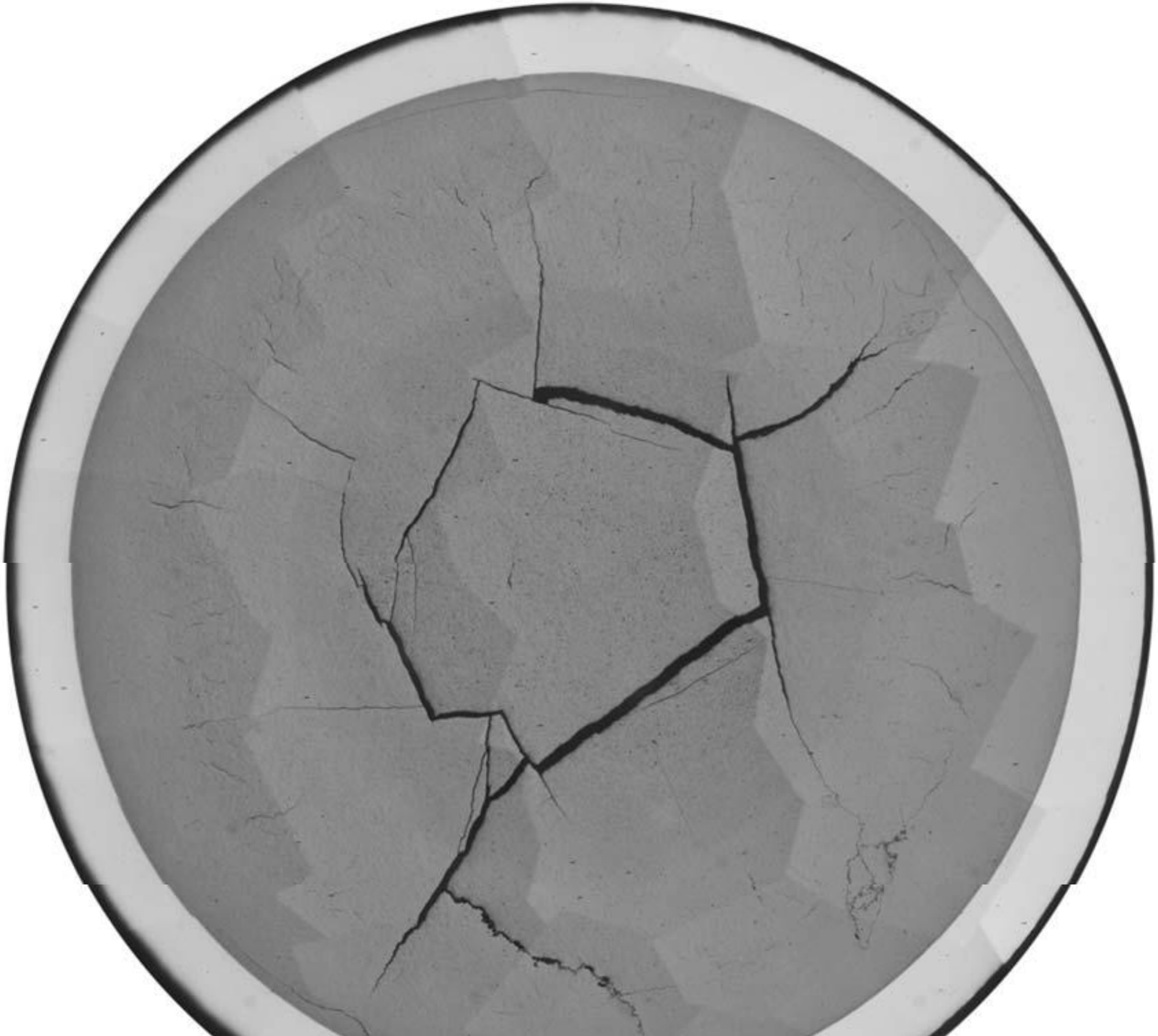


Overview, 337°, 128x



Artist view of deformed assembly (accident condition simulation)

Figure III-28. Cladding Material Fracture Failure Mode



“Longitudinal Tearing Resulting from Transportation Accidents – A Probabilistic Treatment”

(EPRI report 1013448, December 2006)

- Through-wall failure: probability of ~10^{-5} per rod
- **Probability of just one rod failure after the hypothetical transportation accident: ~10%**
  - Probability of one rod failing (~10^{-5}) X
    number of rods per cask (~10^{4}) = ~0.1

Conclusions - Storage

- Independent EPRI and NRC analyses of the risk (probability X consequence) of a latent cancer fatality from HBU used fuel in storage is ~10^{-11} per year
  - Accounts for normal, off-normal, and accident storage scenarios
- No valid technical reasons why assemblies would *not* be retrievable from the storage system

Conclusions: Transportation Risks

- No credible sequence of events lead to a critical configuration during the transportation of spent nuclear fuel, *whether it is classified as low or high burnup*.
  - Probability of ~10^{-16} per shipment
- HBU cladding damage will likely be small after hypothetical transportation accident (probability of just one rod failing: ~10%)
- <u>Non</u>-radiological risks, such as injuries to people and property damage, dominate the overall calculated risks.
  - Non-radiological risks are directly proportional to the number of shipments.
  - Lower risk if the number of spent fuel assemblies per shipment were maximized.

Transportation Issues Resolution

- Based on EPRI’s body of work, an approach for resolving remaining transportation issues was proposed

- EPRI Report 1016637 “Transportation of Commercial Spent Nuclear Fuel – Regulatory Issues Resolution” (December 2010)

Potential R&D Topics

- Laboratory
  - New claddings: pRXA and RXA cladding with no liner
  - Recovery of ductility with temperature
  - DHC: improved estimates of K_{IH}
- Confirmatory full-scale, long-term demo
  - Benchmarking data for improved thermal modeling
  - Detection of rod failures during drying and subsequent storage
  - Pre- and post-storage fuel exams will determine if cladding properties have changed, and if cladding is on the verge of failure
- More extensive operational data
  - Distribution of end-of-life rod internal pressure
  - Plenum temperature (demo project)