# Hypothetical Accidents Conditions

## (*SAND-90-2406-III Methodology)*

**Presented By**

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# Presentation Outline

- Brief Summary of the Scope and Most Significant Results of SAND-2406-III
- Interpretation of RAI Questions B.4 and B.6
- Implication of SAND-2406-III Methodology for Questions B.4 and B.6
- What is Needed to Adapt SAND-2406-III Methodology to Question B.4 and B.6
- Structural Analyses That would be Required for Questions B.4 and B.6
- Response to Questions B.1, B.2 and B.3

# Sand-90-2406-III Methodology
## *(Scope and Main Findings)*

- **9-m Regulatory Drops for Transportation**
  - **End, Corner, Corner/Slapdown and Side**
- **0.3-m Side Drop for Handling**
- **B&W 15x15 PWR Assemblies, Bu < 40 GWD/MTU**
- **GE 7x7 BWR Assemblies, Bu < 35 GWD/MTU**
- **Cladding Mechanical Properties Function of Burnup (Fast Fluence) - Hydrogen Effects Implicit**
- **Two Failure Modes for PWR Assembly under Side Drop Dominated the Failure Frequency**
  - **Longitudinal Slit from Incipient PCI: 2.E-5 Failures / Rod**
  - **Transverse Pinhole: 2.E-4 Failures / Rod**

# Interpretation of RAIs
## *(Question B.4)*

- **Quantify Rod Failures and Associated Uncertainty Under Hypothetical Accidents**
  - **Considering High-Burnup Fuel Conditions**
    - **Degraded Ductility and Fracture Toughness due to Irradiation, Hydrides, and Hydrides Re-orientation**
    - **Pre-existing / Assumed Critical Flaws**
    - **Reduced Thickness due to Oxide and Hydride Rim**
  - **Tip-over Accident Identified as the Surrogate Event - Impact Surface is not Defined**
    - **Super-imposed on Pre-existing Hoop Stress of 66% of Yield**

# Interpretation of RAIs
## *(Question B.6)*

- **Evaluate Safety Margin Under Normal and Hypothetical Accidents**
  - **Consider Three Rods under Typical Pressure:**
    - **Radial Hydride in a Region with Unspalled Oxide**
    - **Multiple Axial Spalled Regions - No Radial Hydrides**
    - **Hydride Lens Region with Propagating I. D. Crack**
  - **Consider Combination of:**
    - **Tip-over Accident**
    - **Worst-type I. D. Flaw (Position and Size)**
    - **No Crack Blunting**
  - **Characterize Failure Mode and Failure Size**

# Sand-90-2406-III Methodology
## *(Implication for RAIs B.4 and B.6)*

- **B.4: Side-Drop Event - CG-over-Corner**
  - **Three Failure Modes are Possible**
    - **I - Transverse Tear Under Axial Bending**
      **(Governed by a Strain Failure Criterion)**
    - **II - Extension of Transverse Tear to Rod Breakage**
      **(Governed by Fracture Toughness)**
    - **III - Radial Extension of Incipient Planar PCI Crack**
      **(Governed by Fracture Toughness)**
  - **Modes I and II Do Not Engage Radial Hydrides**
  - **Mode III Engages Radial Hydride, but as a semi-elliptical Crack, i.e. $K_{IHYD} << K_{IPCI}$**

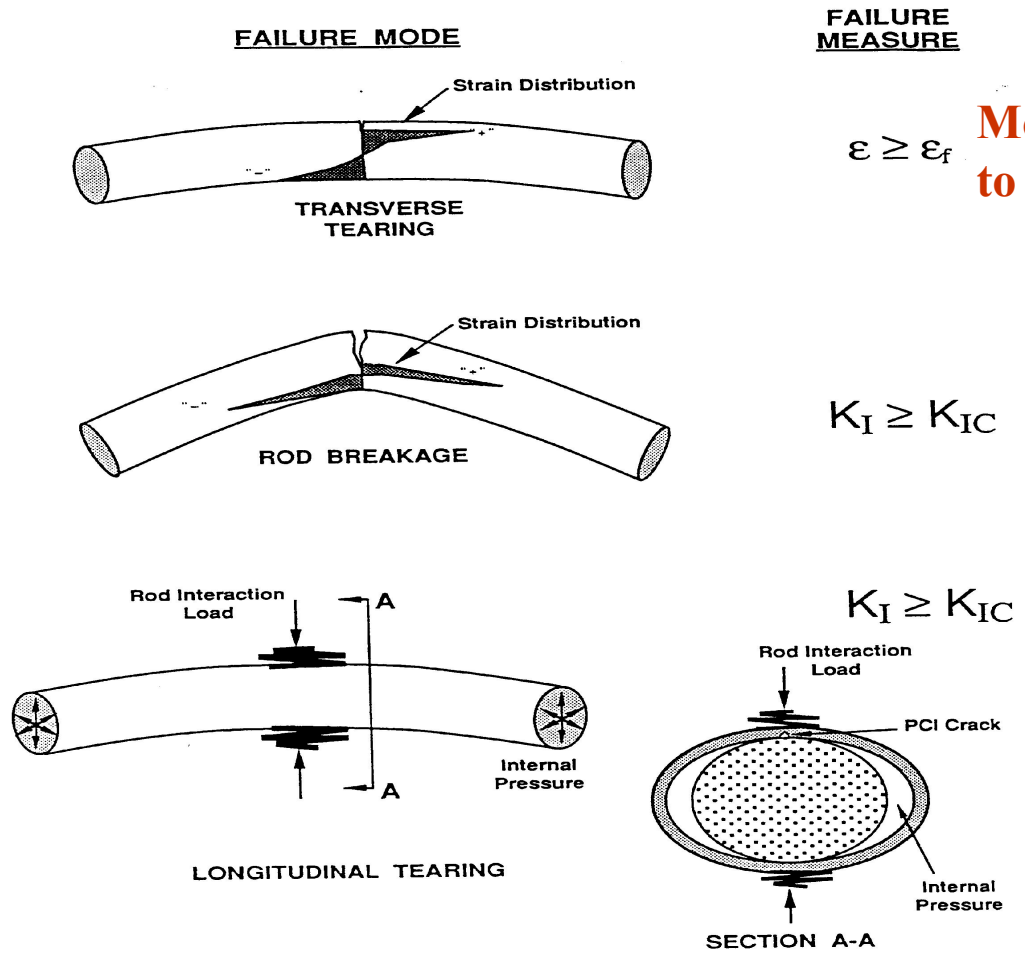



Figure III-29. Fuel Rod Failure Modes

# Sand-90-2406-III Methodology
## *(Implication for RAIs B4 and B.6)*

- **B6: Side-Drop Event - CG-over-Corner**
  - **Radial Hydride Leading to Mode-III Crack**
    - **Located in Unspalled Region**
    - **Located in Hydride Lens Ligament**
    - **Both Governed by Fracture Toughness or CSED**
  - **Several Axially Aligned Hydride Lenses Leading to Transverse Tear (Mode-I) / Rod Breakage (Mode-II)**
    - **Governed by Material Ductility or CSED**

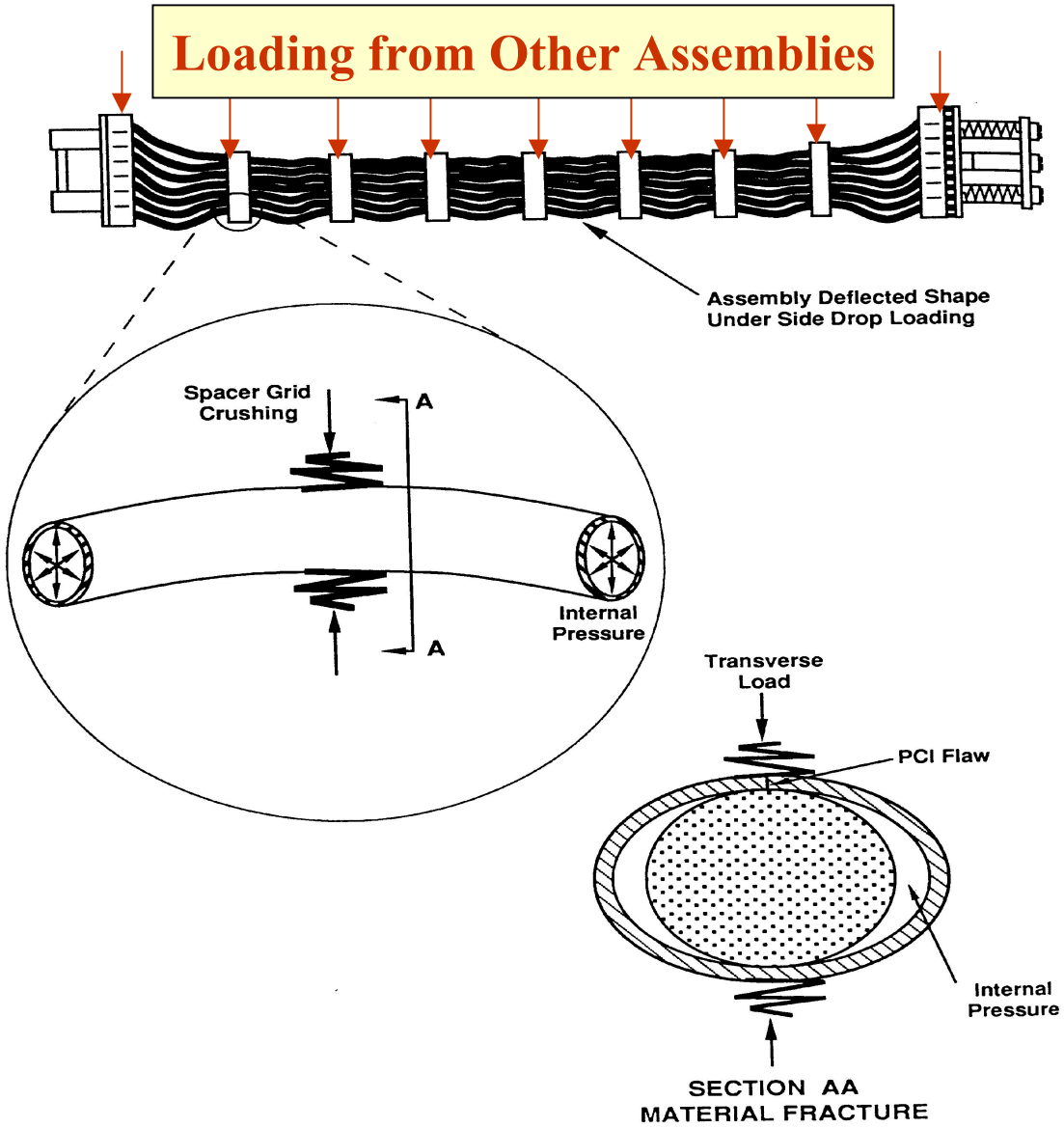



Figure III-28. Cladding Material Fracture Failure Mode

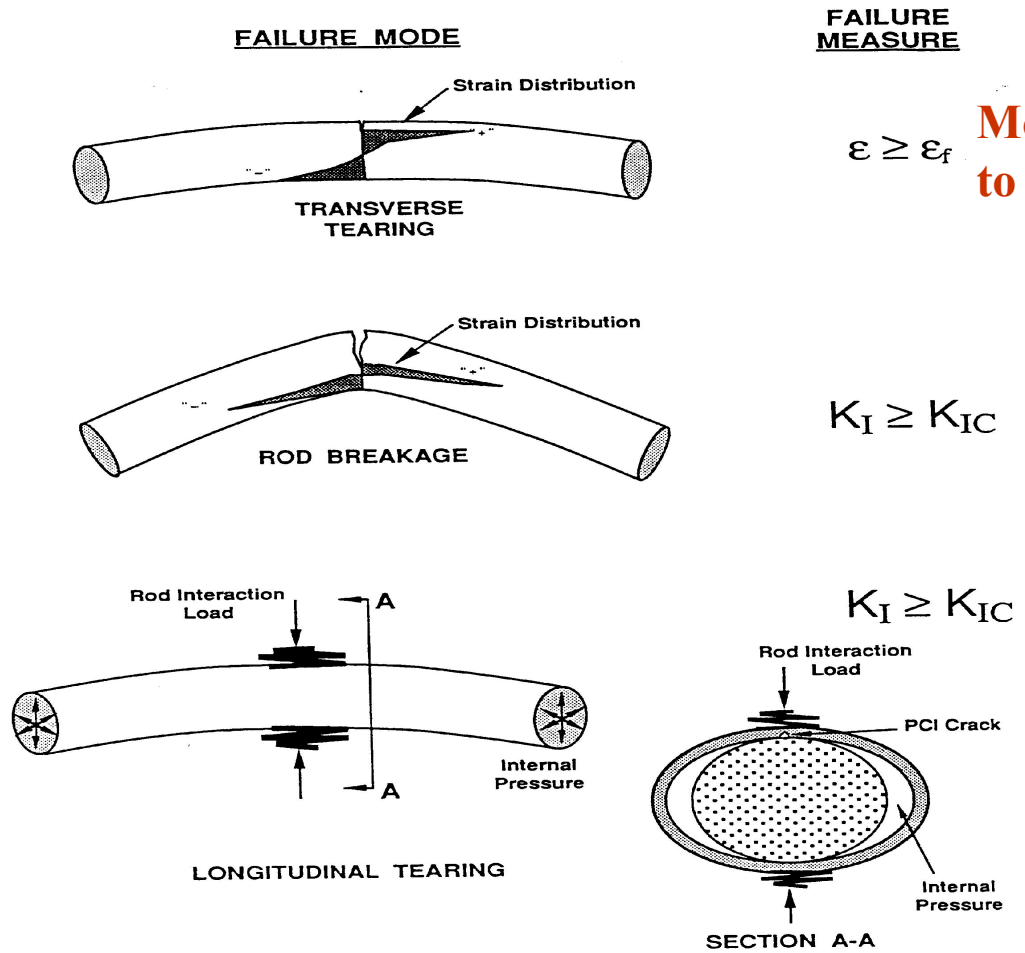



Figure III-29. Fuel Rod Failure Modes

# Deformations are Limited by the Fuel
# Fuel is Very Stiff Under Impact Load

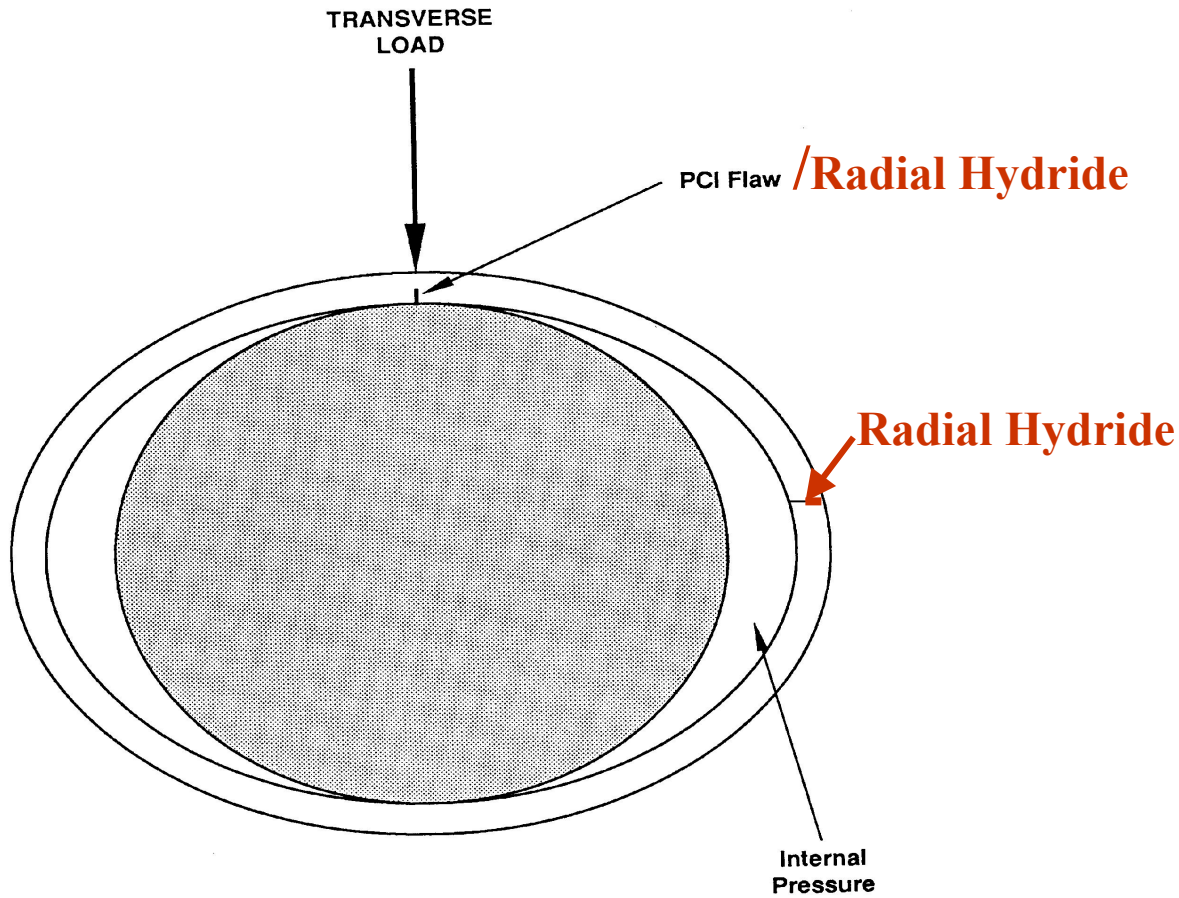



Figure III-35. PCI Flaw Under Pinch Load

# What is Needed to Adapt SAND-2406 Methodology to RAIs B.4 and B.6

- **Update (Due to High-Burnup & Hydrides Effects) Probability Distributions for:**
  - **Flaw Size**
  - **Fracture Toughness**
  - **Ductility (Strain Limit) / Critical Strain Energy Density**
- **Develop New Information and Material Data for:**
  - **Radial Hydrides**
    - **Concentration / Fraction $F_N$**
    - **Size and Distribution**
    - **Failure Criterion as Function of $F_N$**
  - **Oxide / Hydride-Rim: Thicknesses & Properties**
  - **Spacer Grids High-Burnup Properties**

# Flaw Size Distribution

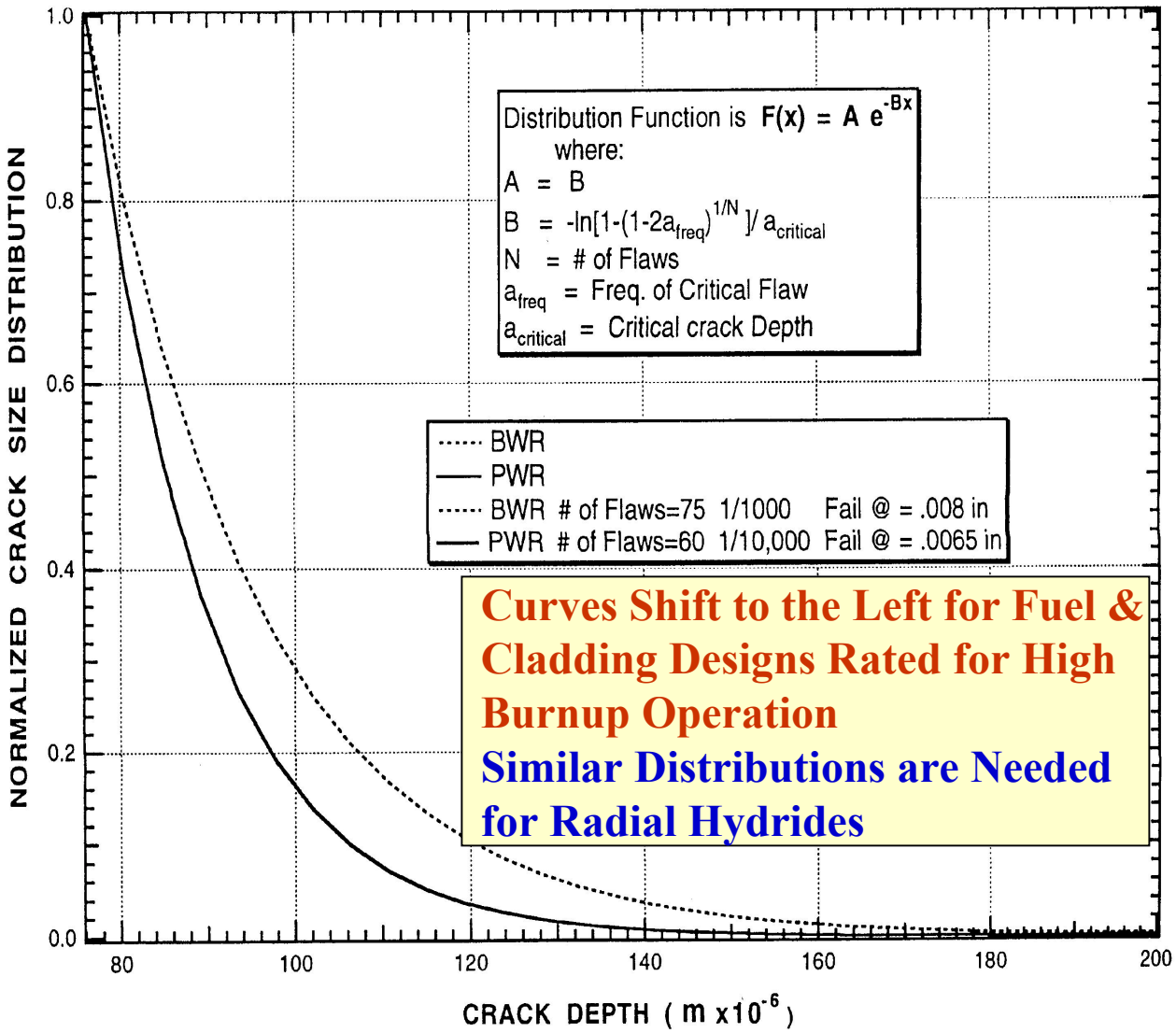
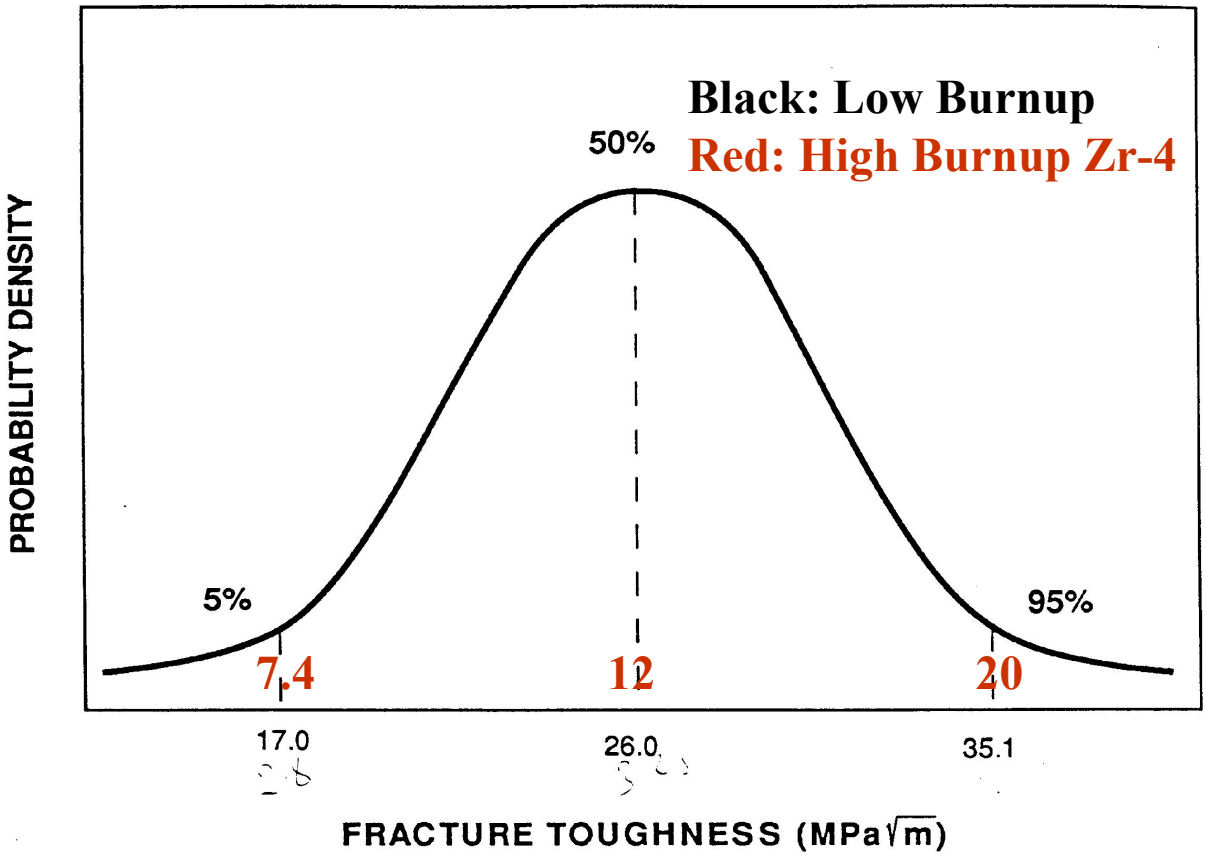
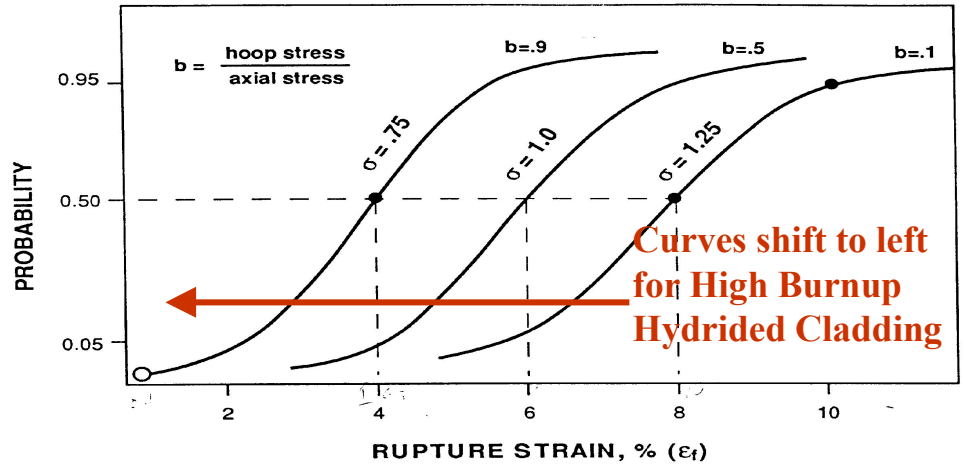



Figure III-34. Crack Size Distribution

# Fracture Toughness Probability Density Function



# Rupture Strain Probability Distribution




● - Experimentally based data points used to develop rupture strain failure curves

○ - Failure probability defined as $1 \times 10^{-6}$ at elastic limit strain = 0.8%

PROBABILITY OF FAILURE FOR STRAIN, x

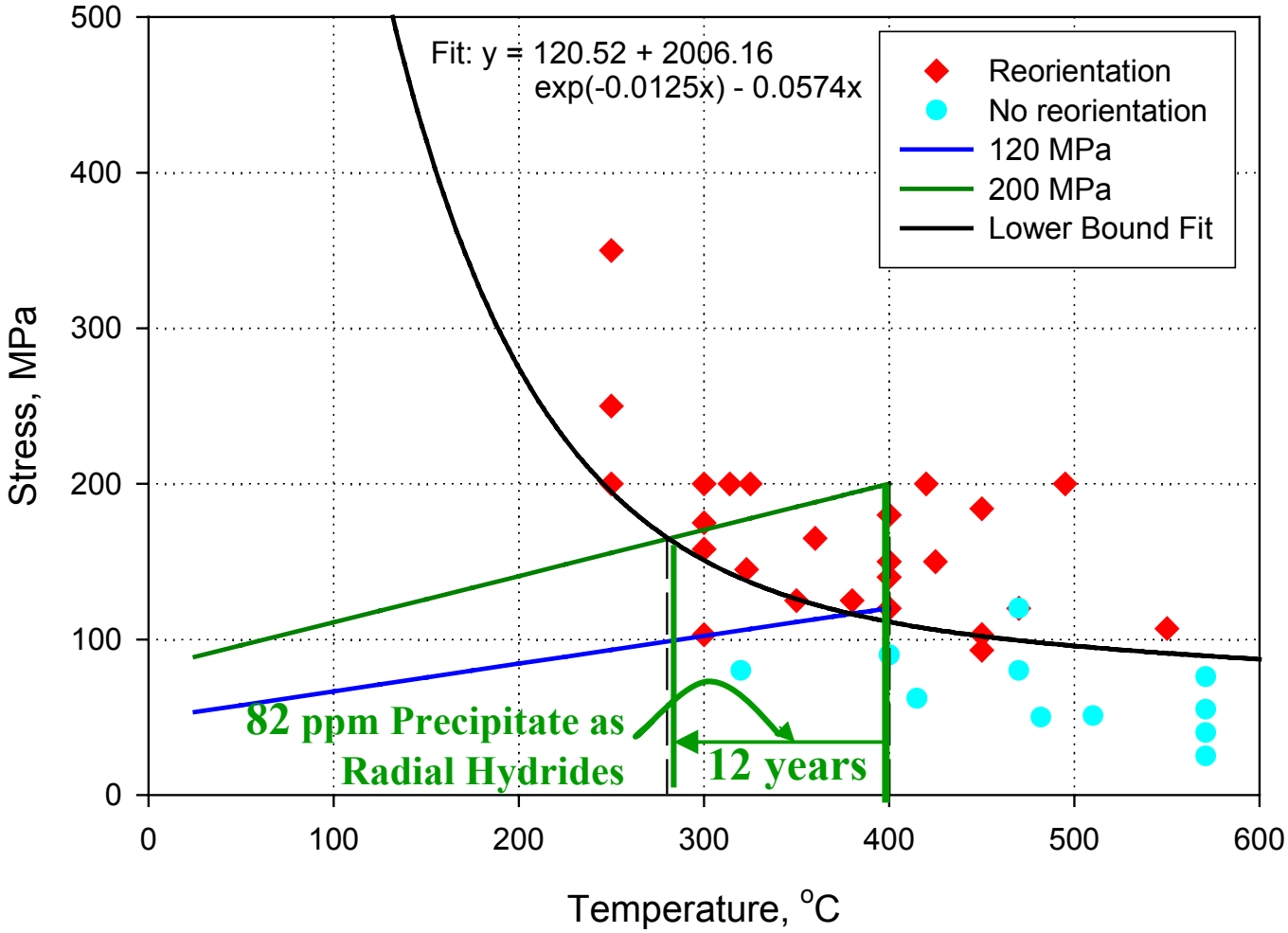
$$F(x) = \frac{1}{\sigma\sqrt{2\pi}} \int_{-\infty}^{x} \exp\left(\frac{-(y-\mu)^2}{2\sigma^2}\right) dy$$

$\mu$ = Mean Value of Distribution

$\sigma$ = Standard Deviation of Distribution

Figure III-30. Probability Distribution for Cladding Rupture Strain as a Function of Biaxial Stress Ratios

# Hydrogen Precipitation



# Sand-90-2406-III Type Analyses as Would be Required for RAIs B.4 & B.6

- **Limit Accident Events to the Following:**
  - **Side Drop from an Equivalent Height of CG-Over-Corner is Considered Bounding to Tip-over Accidents**
  - **Impact Surface: Typical Storage Pad on Soil**
- **Model Transportation Cask, Including Overpack, Canister, Basket & Assemblies**
  - **Bottom Assembly Modeled in Detail, All Others are Modeled as Beams with Equivalent Mass and Stiffness**
  - **Calculate Local Pinch/Bending Loads for Single Rod**
- **Develop Detailed Single-Rod Models and Calculate Each of the three Failure Modes**
  - **Calculate Failure Frequency Using Developed Distributions**

# Response to RAIs B.1 through B.3

Questions request clarification of materials presented in EPRI Report 1003135 with the exception of a sub-question in B.1, which is a request for a compilation of mechanical properties for high burnup cladding; this compilation will be folded in the response to Question B.4, as it will be used in the analysis of the loading conditions expected under accident conditions

# Partial Response to Question B.1

**"The statements in the last paragraph in page 23 are unclear. …"**

***A relevant question, from a risk assessment perspective, is how to quantify the damage, or conversely the residual capacity, of the cladding after undergoing a certain amount of creep, in order to determine the cladding capability to withstand subsequent loading challenges. The appropriate way to determine the cladding residual capacity is to conduct tensile tests for creep specimens that had undergone prior creep deformations under stresses in the elastic range, but terminated before reaching the plastic regime. The stress-strain data from such tests can then be treated in the usual way in deriving a mechanical failure criterion, using the Critical Strain Energy Density (CSED) approach or similar measures.***

**This paragraph is intended to further explain why the 1% strain limit in ISG-11, which was based on material property tensile tests, is not the appropriate measure for creep under stress in the elastic regime. To induce failure in the material, stress above the elastic limit is a necessary condition, and prior creep strain accumulated under "elastic stress" would not induce sufficient area reduction to affect the material's plastic-flow properties. This can be verified by conducting post-creep tensile test, which would show that the CSED or the Total Elongation, which define material capacity under accident loads, are hardly affected, i.e. creep strain and plastic-flow strain are not additive; rather the change in area from prior creep links the two quantities.**

# Response to Questions B.2 & B.3

***B.2: How is the temperature change treated during the vacuum drying cycle in the creep analysis.***

**The creep analysis methodology is a step-by-step time-history analysis, which treats all time dependent changes incrementally. These time-dependent changes include temperature, stress, creep rate, irradiation-damage recovery rate and recrystallization rate if present. Therefore, the vacuum drying cycle is merely the initial part of the thermal history. The fractional contribution of the creep during the drying cycle is not discernable because of the short time period of 24 hours.**

***B.3: Meaning and Significance of Peak Strain.***

**The peak strain and average strain refer, respectively, to the mid-wall strain in the hydride lens ligament (Point A in Figure) and the remaining wall (Point B in Figure). Because of the reduced cladding thickness at Point A, this part of the wall sees higher creep strain, faster time-evolution of the local stress, and consequently faster approach to creep rupture.**