Analysis of High-Burnup Spent Fuel Subjected to Hypothetical Transportation Accidents

--------------Part 1--------------

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------ Outline ------

• Definitions
  – Transportation Accidents - Regulatory Definition
  – Transportation Accidents - Realistic Definition
  – Scope of Problem

• Analytical Approach
  – Description of Analysis Method
  – Modeling Needs and Data Availability

• Expected Results

• Conclusions
1. Hypothetical Accident - Regulatory Definition

- **Design Basis**: Addresses Cask Integrity
  - **Accident Loads**: Bounded by 9-m Drop of Cask on Essentially Unyielding Surface
  - **Normal Handling Loads**: Bounded by .3-m Drop

- **Compliance with the regulations**:
  - Impact-limiters Specifically Designed to limit g-loading
  - 1-foot limit on lifting height of bare casks and containers
  - Single-failure-proof cranes

- **Based on Simplified Methods**
  - Test-Based Crush Strength of Limiters Determine G-Levels
    - Directly Used for the Design of the Cask Body and End Closure
    - Satisfy Shielding Requirements

- **Fuel Integrity Is Not Explicitly Addressed?**
2. Hypothetical Accident - Realistic Definition

*(Addresses Fuel Integrity Explicitly)*

- Side Drop from cg-over-corner Equivalent Height of a Cask Impacting 3-ft. Concrete Storage Pad on Soil
- Safety Justification
  - Side Drop Bounds Other Drop Orientations for Design Basis
    - Gives Maximum Failure Probability (Sand-90-2406-III) *(Table)*
  - Concrete Pad is a Realistic Target During Transportation, and was Shown to behave Like an Impact Limiter
    - NRC- and Industry-sponsored Full-scale Tests by BNFL Show G-load to be Asymptotically Bounded (EPRI TR-108760) *(see Figure)*
- Analytical Justification
  - Can be Reliably Analyzed Using State-of-the-Art Methods
  - Only Way to Quantify Fuel Failures under High-Rate Loading
  - Results Are Generically Applicable
3. Problem Definition

- Quantify the Effects on Accident **Consequences** of the **Extent of Damage** and **Failed-Rods Geometry** During **Post-Storage** Transportation of **High-Burnup** Spent Fuel Considering **Hypothetical Drop Accidents**
  - 3.1 Consequences: Fuel Reconfiguration?
  - 3.2 Extent of Damage: Fuel Rod Failure Frequency
  - 3.3 Failed-Rods Geometry: Failure Modes and Sizes
  - 3.4 Post-Storage: Effects of Radial Hydrides and Prior Creep Deformations or Creep Rupture
  - 3.5 High Burnup: Degraded Cladding Mechanical Properties
  - 3.6 Hypothetical: Bounding (Regulatory) Event
  - 3.7 Drop Accident: Impulsive Loading Resulting in High Strain-Rate Material Response
Analytical Approach: Modeling and Data Needs
(3.6 & 3.7 Hypothetical Drop Accident)

• Fuel Response to Dynamic Loading Requires Modeling of Cask, Canister, Basket, Assemblies & Fuel Rods
  – Design-basis G-Loading Based on Limiter Crush Strength does not Describe Impulsive Loading (see below)

• The Dynamic Event is Governed By the Impulse Momentum Computed from the Force-Time History

\[ I = M \Delta V = \int_0^T F \, dt = M \int_0^T g \, dt \]

  – Known: Cask Total Mass \( M \) and Impact Velocity \( V \)
  – Unknown: Force Amplitude, Pulse Shape, \( T \) and \( \Delta V \)

• G-Loading Based on Impact Limiter Crush Strength is the Steady Deceleration Given by:

\[ g_{\text{steady}} = \frac{1}{T} \int_0^T g \, dt = \Delta V / T \]
Modeling and Data Needs - cont.
(3.6 & 3.7 Hypothetical Drop Accident)

• Short Pulse Duration (High Loading Rate) May Lead to Higher Strain Rate in the Cladding
  
  – Depends on Magnitude of the Rod’s Fundamental Period $T_R$ Relative to Pulse Duration $T$: Two Cases are Possible
    
    • Case 1 - $T_R < T$: Rod Maximum Response Occurs During the Pulse
      – Generally True for Direct Impact, e.g. Fuel Rodlet Hitting the Floor
    • Case 2 - $T_R > T$: Rod Maximum Response Occurs after the Pulse
      – True for Fuel Assemblies in the Cask, Dynamic Force is Transmitted Indirectly through Cask Wall, Canister, Basket & Grids
    
  • Case-1 Loading Can be Significantly Higher and More Damaging than Case-2.
    
    – In Either Case, Cladding Response should be Judged Against a Strain-Rate Dependent Failure Criterion *(See Later Slides)*
    
  • Places Significant Demands on the Veracity of Analysis Method
Analytical Approach: Modeling and Data Needs
(3.5 High Burnup Effects)

• High Burnup Effects - Considered in Accident Analysis
  – Irradiation Hardening Effect on Stress-Strain Curve
    • Increases Yield and Ultimate Strengths (+), Reduces Ductility (-)
  – Fuel-Clad Bonding Affects Rod Stiffness and Crack Size (+)
  – Corrosion
    • Rod Stiffness Change Due to Reduction in Cladding Thickness (-)
    • Spalled Oxide Leads to Hydride Lens Formation (-) (see below)
  – Hydrides Amount and Distribution
    • Uniform Circumferencial Hydrides (+ & -, net negative)
      – Incremental Effect on Cladding Ductility
      – Hydride Rim on the O. D. Affect Failure Modes (Discussed Later)
    • Non-uniform Circumferencial Hydrides Have Probabilistic Effect
      – Hydrides Lenses are Random - Form Incipient Damage Sites (-)
    • Radial Hydrides are Not Burnup Effects (Discussed Later)
Analytical Approach: Modeling and Data Needs
(3.4 Post Storage - Prior Creep Effects)

• Post Storage Creep Strain Has Little or No Effect on Cladding Integrity under Dynamic Loading
  – Tests in France Show no Change in Post-Creep $\sigma$-$\varepsilon$ Curve
  – Verification Tests are Planned by ANL

• If Creep Rupture Occurs, Failure is a Pinhole
  – Small Local Reduction in Stiffness, Benign in the Presence of Fuel-Clad Bonding
  – Crack Extension under Dynamic Load is Unlikely but Possible for one of the Three Failure Modes *(see later slide)*
    • Probabilistic: Depends upon Pinhole Position, Azimuthally and Axially, with Respect to Potential Failure Location
    • Is Inhibited by the Fuel Regardless of Fuel-Clad Bonding
  – Can be Incorporated in the Analysis Model as an Initial Through-wall Flaw similar to Hydride Lens
Analytical Approach: Modeling and Data Needs
(3.4 Post Storage - Radial Hydrides Effects)

- Radial Hydrides Precipitation Model
  - Model (*see Next 2 Slides*) Predicts Amount and Precipitation Rate - Requires further Development and Validation
    - Available Data is for Total Precipitation During Fast Cooling to Room Temperature under Constant Stress
    - Precipitation Rate Would Require a Large Number of Tests (10s)
  - Radial Hydrides Morphology (Length and Spacing)
    - Repository Model by K. S. Chan, Results Unrealistic Unverifiable

- Effects of Radial Hydrides on Cladding Integrity under Hypothetical Accidents (*Discussed Later*)
  - Cladding Ductility/CSED
  - Fracture Toughness
  - Dependent on Cladding Failure Modes (*see Later Slides*)
Radial Hydride Precipitation Model
Results for 400°C
Model Results for Various Temperatures

Hydrogen Precipitation as Radial Hydrides Under Cooling to Room Temperature ($F_0 = 0.05$)
Hydrogen Precipitation Under Cooling to 20°C

Temperature, °C

Stress, MPa

Reorientation
No reorientation

120 MPa
200 MPa
Lower Bound Fit

Fit: \( y = 120.52 + 2006.16 \exp(-0.0125x) - 0.0574x \)

82 ppm Maximum Available
Actual: Less than 40 ppm
12 years

0% Precipitation Based on Data in Figure
100% Precipitation Based on Model
Data Compiled by NRC Staff

σ-T History with no Precipitation

Precipitation under Constant Temperature and Variable Stress
Precipitation under Decaying Temperature and Constant Stress
Analytical Approach: Modeling and Data Needs
(3.3 Failed-Rod Geometry: Failure Modes and Sizes)

• Adapt Sand-90-2406-III Methodology to
  – Side drop from an equivalent height of cg-over-corner
  – Impact target: Typical Storage Pad on Grade

• Model Transportation Cask, Including Overpack, Canister, Basket, Assemblies & Fuel Rods - see figures
  – Bottom Assembly Modeled in Detail, All Others are Modeled as Beams with Equivalent Mass and Stiffness
  – Perform Dynamic Analysis, Calculate Single-Rod Force Distributions
    • Using High-Burnup Strain-Rate Dependent Material Properties

• Develop Detailed Single-rod Models and Calculate each of the Three Potential Failure Modes - see figure
  – Using Failure Criteria Appropriate for Each Failure Mode
Model of Storage Cask & Canister - Similar Transport Cask Model will be Developed

Side-Drop Model
Cut-Away View of Cask Showing Canister and Basket
Basket & Fuel Assemblies Details

Cut-Away View of Basket Showing Equivalent-Beam Models of Fuel Assemblies as Red Lines

Bottom assembly modeled in detail (not all rods are shown) - next slide
Symmetry Section of Cask Modeled for Side Drop

Assembly modeled as a beam with equivalent mass and stiffness

17 x 17 Fuel Assembly: Rods and grids are modeled in detail
Sand-90-2406-III Methodology Failure Modes

(An Artist View of Deformed Bottom Assembly)

Side-Drop Event from an Equivalent Height of CG-over-Corner is Bounding
Sand-90-2406-III Side-Drop Potential Failure Modes

Mode I Extending to Mode II, does not engage r-hydrides

Mode II, does not engage r-hydrides

Mode III, can engage r-hydrides

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Analytical Approach: Modeling and Data Needs
(3.3 Failed-Rod Geometry: Failure Modes and Sizes)

• Three Failure Modes are Possible (Previous Slide)
  – I - Transverse Tear Under Axial Bending
    (Governed by a Strain or CSED Failure Criterion)
  – II - Extension of Transverse Tear to Rod Breakage
    (Governed by Fracture Toughness)
  – III - Radial Extension of Incipient Planar PCI-Type Crack
    (Governed by CSED)

• Modes I and II Do Not Engage Radial Hydrides
• Mode III Engages Radial Hydride, but as Incipient
  Flaws for which CSED is Directly Applicable
• Failure Criteria Dependent on Strain-Rate
  – CSED is Insensitive to Strain Rate, at Least not as Sensitive as
    the Total Elongation Strain
Radial Hydrides are Discontinuous Inclusions which Assist a Crack to Extend Radially by CSED Then Axially by $K_{IC}$ of Zr.

Fuel Inhibits Crack Extension Radially and Axially

Figure III-35. PCI Flaw Under Pinch Load
Figure III-36. Example Stress Intensity Values Versus Part-Wall Cracks Under Pinch Loads
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Analytical Approach: Modeling and Data Needs
(3.3 Failed-Rod Geometry: CSED Failure Criterion)

Failure of a cladding with a flaw or a defect can be predicted by calculating the Strain Energy Density (SED) in the cladding, without modeling the flaw or performing fracture analysis, and comparing it to the Critical Strain Energy Density (CSED) determined from material data.

Proof for the Above Statement is Presented on the Next Two Slides.
Reference: IAEA Meeting Paper (Attached)
\[ J = \int_U Udy - \int_\Gamma F \cdot \frac{\partial u}{\partial x} \, ds \]

\[ U = \int \sigma_{ij} \, d\varepsilon_{ij} \]

**Flat Surface Notch in Two-Dimensional Strain Field**

\[ F = 0 \quad \text{at} \quad r = r_0 \]
\[ F \approx 0 \quad \text{at} \quad r = r_i \]
\[ F^+ = F \quad \text{at} \quad \theta = 0 \]

\[ J = \int \frac{\partial U}{\partial x} \, dx \, dy \]

\[ J = \frac{2\pi}{r_0} \cos \theta (r_0 U(r_0, \theta) - r_i U(r_i, \theta)) \, d\theta \]

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\[ J = \int_{0}^{2\pi} \cos \theta \left( r_o U(r_o, \theta) - r_i U(r_i, \theta) \right) d\theta \]

\[ U(r_i, \theta) = \overline{U} + f(\theta) \]

\[ U(r_o, \theta) = \overline{U} - f(\theta) \]

\[ J = -\int_{0}^{2\pi} (r_i + r_o) f \cos \theta d\theta \]

\[ J = -2 (r_i + r_o) \int_{\pi-\varphi}^{\pi} \overline{U} (\theta - \pi + \varphi) \cos \theta d\theta \]

\[ = 2 (r_i + r_o) \overline{U} \frac{1 + \cos(\pi - \varphi)}{\varphi} = S_u (r_i + r_o) \overline{U} \]

This says fracture resistance \( J \) is totally Prescribed by \( U \), QED

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SED (Cladding Response) vs. CSED (Criterion)

- SED is a measure of loading intensity in the cladding
  - SED is a calculated response parameter
    \[ SED = \int \sigma_{ij} \, d\varepsilon_{ij} \]
- CSED is a measure of cladding failure potential or cladding residual ductility
  - determined from mechanical property tests
  - depends mainly on fast fluence, Temperature, Hydrogen level and Hydride morphology
- Cladding failure occurs when SED reaches the CSED for a given clad material
CSED is Calculated from True $\sigma$-$\varepsilon$ Curve

Higher strain rate moves curve up and to the left such that Area (CSED) stays nearly constant.

Schematic of the Stress-Strain Curve Illustrating CSED Calculation

$$CSED = \frac{\sigma_y^2}{2E} + \sigma_y \varepsilon_c \left[ (\varepsilon_e + \varepsilon_{te})^{n+1} - \varepsilon_e^{n+1} \right]$$
Best Fit, Non-Spalled, and Spalled Data for CSED vs. Oxide/Cladding Thickness Ratio

Data from CC/ANO-2, Prometra, and NFIR
Critical Strain Energy Density Values from Mechanical Property Tests Below 150º C
Analytical Approach: Modeling and Data Needs
(3.3 Failed-Rod Geometry: Fracture Toughness)

- Available Fracture Toughness Data
  - EPRI-1001281 Survey Report
- How to Compensate for Lack of Data
  - $K_{IC}$-CSED Correlation
- Ductile-Brittle Transition - What does it Mean for Zircaloy Materials?
  - Hydride Morphology
Analytical Approach: Modeling and Data Needs
(3.3 Failed-Rod Geometry: Fracture Toughness

Literature Data for Irradiated Zircaloy - [EPRI-1001281]

• ASTM-Qualified $K_{IC}$ data for:
  – Zr-2 and Zr-2.5 Nb Pressure Tubes
  – Zr-2 and Zr-4 Plates

• Non-ASTM-Qualified $J_{IC}$ data for cladding geometry

• Recommended estimates based on literature data
  – $K_{IC} \approx 18 \text{ MPa} \sqrt{\text{m}}$ for $T < 100^{\circ}\text{C}$, $100 < H < 500$ ppm
  – $K_{IC} \approx 50 \text{ MPa} \sqrt{\text{m}}$ for $T > 280^{\circ}\text{C}$, $H < 500$ ppm
  – $K_{IC} \approx 30 \text{ MPa} \sqrt{\text{m}}$ for $T > 280^{\circ}\text{C}$, $100 < H < 500$ ppm
  – $K_{IC} \approx 20 \text{ MPa} \sqrt{\text{m}}$ for $T > 280^{\circ}\text{C}$, $500 < H < 750$ ppm
  – $K_{IC} \approx 7.4-12 \text{ MPa} \sqrt{\text{m}}$ for any Temperature, $750 < H < 1200$ ppm
    • Apply penalty factor of 3 on charged-hydrogen concentration
Engineering Derivation of $K_{IC}$ - CSED Correlation

$$\sigma = \frac{K_I}{(2\pi \rho)^{1/2}} \rightarrow \sigma_y = \frac{K_{IC}}{(2\pi \rho_y)^{1/2}} \quad K_{IC}^2 = 4\pi E U_c \rho_y / (2r-1)$$

$$r = \frac{\varepsilon_{TE}}{\varepsilon_y} \quad \rho_y / (2r-1) = 10 \times 10^{-6} \quad K_{IC} = 0.01121 E^{1/2} (U_c)^{1/2}$$
Analytical Approach: Modeling and Data Needs

(3.3 Failed-Rod Geometry: Fracture Toughness

__--------------------K_{IC}-CSED Correlation ---------------------__

- The $K_{IC}$ for the Most Important Fracture Mode, namely Radially Extending Crack, is not Represented by the Data, and has no Known Test Method, Except Through the $K_{IC}$- CSED Correlation $K_{IC} = A \ (CSED)^{1/2}$

$$K_{IC} = 0.01121 \sqrt{E}\left(U_{c}\right)^{1/2} = 3.5\left(U_{c}\right)^{1/2}$$

- Examples:
  - $K_{IC} = 7.8 \text{ MPa}\sqrt{m}$ from CSED for Spalled Oxide
  - $K_{IC} = 7.4 \text{ MPa}\sqrt{m}$ - Kreyns et al. for Charged Hydrogen
  - See Next Slide for Aluminum Alloys
Experimental $K_{IC}$ vs. $K_{IC}$ Derived from the Critical Strain Energy Density for Aluminum Alloys [Sih, Czoboly and Gillemot, 1980]
Analytical Approach: Modeling and Data Needs

(3.3 Failed-Rod Geometry: Fracture Toughness)

------Fracture Toughness Ductile-Brittle Transition------

- **Zircaloy Materials Do Not Have Nil Ductility Temperature**, i.e., $K_{IC}$ Changes Gradually with Temperature. Ductile-Brittle Transition Behavior Observed is Due to Hydride Morphology
  - Zircaloy with *Orientation Index* Greater than 0.5-0.6 Exhibit Ductile-Brittle Transition for Temperatures Below 240°C. Wallace et al., ASTM STP-1023.
  - For High *Orientation Index*, the “Upper Shelf” – “Lower Shelf” Transition may Vary with the Amount of the Oriented Hydrides, but Indications are that this Variation is Small.
Analytical Approach: Modeling and Data Needs
(3.2 Fuel Rod Failure Frequency, 3.1 Consequences)

• Consequences on Fuel Reconfiguration are Determined from the Failed-Rod Geometry First and Failure Frequency, Second
• Results may or may not Justify Going to the Next Step
• Next Step: Use Sand-90-2406-III Probabilistic Approach to Calculate Damage Frequency