Response To NRC Staff Review of NEI/EPRI Reports On Creep and Fracture Toughness of Zircaloy SNF Cladding

NRC/NEI Meeting

April 18, 2001

SCC Mechanism

- Role of Chemistry - No Review Comments
  - Implication: Staff Agrees That SCC Cannot Occur Without Presence of Corrosive Species?
  - Lack of Stress Environment is an Added Support
- Role of Stress and Time-At-Stress
  - ***Issue 1***: Without Debating the Issue of Crack Initiation by Other Means, the Report Addresses Pre-Existing Cracks Using FM Analysis Applying Compounded Conservatism
  - ***Issue 2***: Prevention of Crack Initiation Not Crack Propagation is the Issue. If a Crack is Initiated by SCC, Failure is Almost Assured
  - ***Issue 3:*** Again, Crack Initiation is the Issue, and Once a Crack is Initiated, How it Propagates Becomes Irrelevant
  - ***Issue 4:*** This is Reflected in the Data and is Discussed in the Report. See Reference to Cox's Work (41)

SCC Mechanism

- Role of Stress and Time-At-Stress (cont.)
  - ***Issue 5***: This is Compounding the Effects of Pre-Cracking. The Referenced Figure Clearly Shows 200 MPa Threshold Stress for Pre-Cracked Specimens.
  - ***Conclusions:***
    - **(1) The Issues Raised in the Review Are Shown to Have Already Been Adequately Covered in the Report with Supporting Literature**
    - **(2) The Staff Review Ignores the Fact That the Corrosive Environment Needed to Initiate SCC is Not Present In Spent Fuel**
    - **(3) The Staff Concludes that the Report's Summary 2.6(b) Has Not Been adequately Supported, yet It Curiously States that *"literature information indicate that SCC...is unlikely...."* If the Staff already know that SCC is unlikely, why take issue with the Report's literature-based arguments? Also, we are curious to know the literature being referred to by the Staff!**

SCC Mechanism

- Effect of Irradiation/High Burnup
  - ***Issue 1:*** Reference to Dissolution of Hydrides as a Condition of Dry Storage Claimed in the Report is Incorrect. The Report Simply Refers to Cox's Experiment
  - ***Issue 2:*** There is no Circular Calculations Here. The Calculations are as Follows: $K_I = 1.12\ \sigma\ (\pi a)^{1/2}$, where $\sigma = 150$ MPa, $a = 73\mu m$. This Gives $K_I = 2.54$ MPa $m^{1/2}$ as Stated in the Report
  - ***Conclusions:***
    - (1) The Above Stated "Issues" are Shown to be Non-Issues
    - (2) Consequently, The Staff Conclusions Regarding 2.6 (c) are not Valid
    - (3) Conclusion (3) From the Previous Viewgraph Applies Here Also.

DHC Mechanism

- Evolution of DHC Mechanism
  - ***Issue 1:*** Figure 7 Indeed shows the Intermittent Crack Advance. Each dot in the Figure Represents a Sonic Signal. This is the Fundamental Behavior of DHC
  - ***Issue 2:*** (a) The K_{IC} - CSED is a Correlation Similar to Many Other Correlations Found in Fracture Mechanics, e.g. K_{IC} - CVN Correlation of Barsum and Rolfe, and Paris's Tearing Modulus,... It is no more and no less valid than any Empirical Correlation.

    (b) Data Scatter in the Nuclear Industry is a Fact-of-Life. That is Why we Rely on Correlations as Engineering Tools.

    (c) Not Only There Is Not Sufficient Fracture Toughness Data for High Burnup Cladding, There is no Accepted Standard for the Fracture Testing of Cladding Geometry. This is the Main Motivation for Developing the K_{IC} - CSED Correlation.

DHC Mechanism

- Re-Orientation of Hydrides
  - ***Issue 1:*** This is Not the Way DHC Evolves
  - ***Issue 2:*** DHC Evolves by The Hydrogen-in-Solution Diffusing Up the Stress Gradient to the Crack Tip Which is in a State of Triaxial (At Least Biaxial) Tension
  - ***Issue 3:*** This Repeats What is Already Discussed at Length in the Report. The Report States That Hydrides Re-Orientation Can Occur and It Describes the Conditions Under Which It Occurs in Dry Storage. It Simply Says that the Experimental Evidence is Against Massive Re-orientation.
  - ***Issue 4:*** DHC Can Occur at Any Hydrogen Level. The Report Makes No Claim Regarding Hydrogen Concentration and Temperature. It Simply Quotes Experimental Results. How Can Such Information be Raised as an ISSUE?

DHC Mechanism

- ***Conclusions:***
  - (1) The Report Clearly States that the Thermal History in Dry Storage is Troublesome with Respect to DHC. It Clearly Points Out Under What Conditions DHC Can Occur.
  - (2) The Report Made No Claims That Hydride Re-Orientation Could Not Occur.
  - (3) The Staff Review Totally Ignored the Role of the Stress in DHC, and Made no Reference to the Report's Claim That the Main Line of Defense Against DHC is K_{IH} for Stage-I DHC and K_I for Stage-II DHC. The 73 μm Crack Size Determined From SCC Consideration and The Maximum Hydride Length of 100 μm were Used in the Discussion of the Role of The Stress on DHC, Not The K_{IC} - CSED Correlation.

Creep Data Of Zircaloy Cladding

- Acceptance Criterion - Creep Based Limit
  - ***Issue 1:*** This Requires High Stresses, in the Instantaneous Plasticity Regime. Are There Any Data for DCCG at Stress Levels Below, say, 30% of Yield Stress?
  - ***Issue 2:*** The 1.7% is a Measurement Not a Material Limit of Any Kind.
  - ***Issue 3:*** This is the Whole Misunderstanding. The Strain Limits quoted are In the Instantaneous Plasticity Regime Where the Stress is at Ultimate Tensile Strength. Elementary Mechanics Dictate That Plastic Instability Cannot Occur at Stress Levels Below The Ultimate Strength. This is Clearly Shown by Recent French Creep Rupture Tests as Shown in the Following Figures.
  - ***Issue 4:*** Strain Rate Has a Well Known Effect on Mechanical Response. A factor of 2 is Easily Justifiable

Creep Data Of Zircaloy Cladding

- Acceptance Criterion - Creep Based Limit
  - ***Issue 5:*** The Goll Data is From Creep Rupture Tests Initiated at or Near the Yield Strength. Therefore the Measured Strains Belong to the Instantaneous Plasticity Regime. Again, the Stress Should Be Invoked Here. See Figures
  - ***Issue 6:*** Nothing Can be Worse Than the Data from the EPRI Hot Cell Program. Garde's Measurements Show 3% Plastic Strain in the Ligament Beneath the Hydride Lens.
  - ***Issue 7:*** All Fracture Mechanics Calculations are Based on Idealized Flaws. This is the Accepted Practice.
  - ***Conclusions:*** We Believe The Issues Can Be Resolved Using Well Known and Accepted Mechanics Principles. The Above Explanations are Aimed in That Direction

Creep Data Of Zircaloy Cladding

- Pin-Hole Equivalent Failur Mode
  - ***Issue 1:*** One Pin-hole is Enough to Depressurize the Rod. The Probability of Having a String of Pin-holes Occurring at Exactly the Same Time is Nearly Zero.
  - ***Issue 2:*** It Seems That a Dynamic Event is Implied Here. How?
  - ***Issue 3:*** This was Covered in a Previous Comment
- ***Conclusions:***

  (1) A Strain Limit as Restrictive as the 1% is Not Sufficient In Itself as a Criterion. It Was Based on Plastic Instability Considerations, Therefore Requiring Definition of the Stress State.

Creep Data Of Zircaloy Cladding

- ***Conclusions:***

  (1) An Acceptance Criterion as Restrictive as the 1% Strain Limit is Not Sufficient In And By Itself. It Was Based on Plastic Instability Considerations, Therefore, Requiring Definition of the Stress State.

  (2) The Staff Reviewers Dismissed, Without Mention, the Analysis of Strain Localization and the Interpretation of The Measurements on Which the Strain Limit is Based?

  (3) The Larson-Miller Parameter is a Stress-Time-To-Failure Criterion, Which is Totally Empirical. Is it Being Proposed as A Replacement to a Strain-Based Criterion?

Fracture Toughness Data

- CSED Approach - Issues Related To Cladding
  - ***Issue 1:*** Good Question, The Report Should Have Shown It on the Figure. It is the Radius of the Plastic Zone Surrounding the Crack Tip Assuming Elastic/Perfectly Plastic Material.
  - ***Issue 2:*** Equation (8) is Correct. The Total Elongation in the First Term is the Elastic+Plastic
  - ***Issue 3:*** Elastic/Perfectly Shape of the Stress-Strain Curve is a Good Approximation for Highly Irradiated Zircaloy
  - ***Issue 4:*** We Agree! Stress-Strain Curves By Themselves Do Not Provide "Fracture Mechanics" Information. However, The Area Under the Curve Represents the Energy Capacity of the Material, and as Part of a Correlation, They are Shown to Give Fracture Information.

Fracture Toughness Data

- CSED Approach - Issues Related To Cladding (cont.)
  - ***Issue 5:*** Equation 9 is Correct. It is Obtained From Equation 8 by Direct Substitution of Parameters
  - ***Issue 6:*** The Strain and Stress Measures in the CSED are the True Strain and True Stress in the Uniaxial Case, and are the True Tensorial Quantities in the Multiaxial Case.
  - ***Issue 7:*** Equation 13 Has Balanced Units If we Remember that the 3.5 Factor Came From ρ, r and E, Where ρ Has the Units of m, E Has Units of MPa and r is unitless.

Fracture Toughness Data

- CSED Approach - Issues Related To Cladding (cont.)
  - ***Issue 8:*** There is No Limitation on How The CSED is Quantified. The Uniaxial Test is all that is Available in Most Cases. However, the Material Ductility is Dependent on the Biaxiality or Triaxiality of the Stres State. A Biaxiality Factor is Applied to the Uniaxial Data When it is Combined with Biaxial Tests To Quantify CSED. However, One Should Keep In Mind that Energy is a Scalar, and Multiaxial Tests Reduce to a Scalar Quantity When Integrated.
  - ***Issue 9:*** Aluminum and Titanium Alloys Have Very Similar Stress-Strain Curves to Zircaloy. They Differ From Ferretic Steels. Austinetic Steels Exhibit Significant Hardening Unlike Irradiated Zircaloy. The CSED-K_{IC} Correlation Has Been Developed Implicitly for Irradiated Zircaloy-Like Materials

Fracture Toughness Data

- CSED Approach - Issues Related To Cladding (cont.)
  - ***Issue 10:*** We Obtained Different Values From Those Shown In the Figure. Our Values are Shown on the Figure in x, and the Values From the Rolfe-Barsum Correlation in Circles. As Can Be Seen, Despite the Fact that the Correlation was not Meant for Steels, the Agreement appears to be Not Bad
  - ***Issue 11:*** The Scatter is Typical For High Burnup Cladding, But It Can Be Explained. However, The Best-Fit Curve Works Remarkably Well.
  - ***Issue 12:*** Good Observation

Fracture Toughness Data

- Summary of Staff Analysis
  1. We Do Not Agree With This Assessment
  2. The Report Shows a Couple of Examples Where the Correlation Gave Excellent Agreement. Certainly More is Needed and Attempts Will be Made to Seek More Comparisons.
  3. We Agree Totally, and We Welcome This Type of Positive Feedback.