Performance of Commercial Zircaloy-Clad Fuel Assemblies

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Tae:
Here are the slides that EPRI gave at YMP on 8/19/99
Eric

SAND 90-2406: transportation

main/Legacy- RD

Background

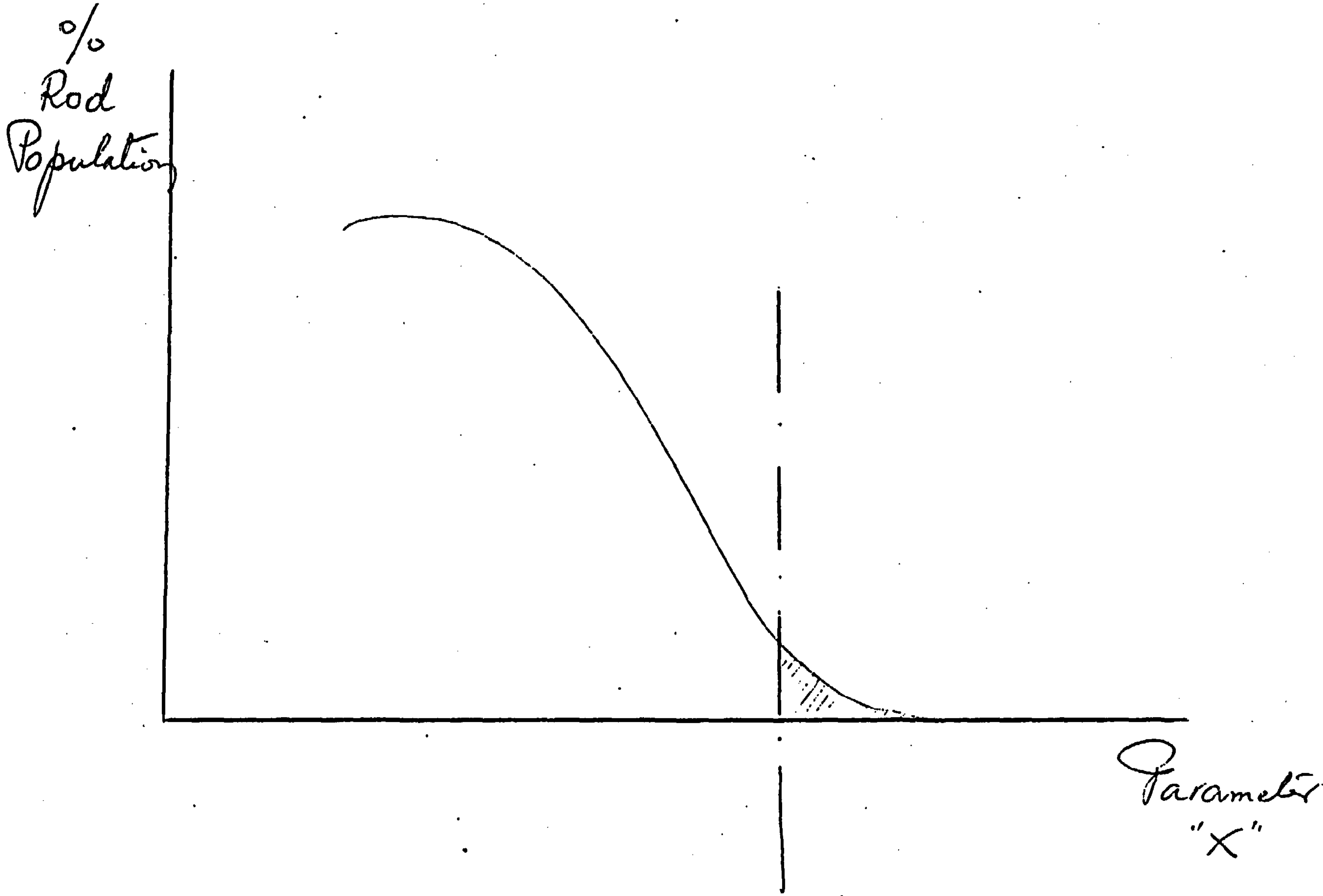
- Meeting at EPRI on July 20 to discuss "Cladding Performance of Commercial Spent Nuclear Fuel"
- EPRI invited to make a presentation at an internal meeting involving M&O staff

Background (cont.'d)

- Summary (Stahl's Presentation, July 1999)
  - "The failure fraction of Zircaloy cladding received at the repository is expected to be low based on utility and DOE experience
  - The NRC, EPRI and others believe that cladding performance can be assumed if degradation mechanism uncertainties are reduced
  - An approach to utilizing cladding performance in the MGR performance analyses have been developed and tests are underway or have been initiated to support the approach"

Background (cont.'d)

- General Comments by EPRI Staff
  - Strongly supportive for including cladding performance, to the maximum possible extent, in the License Application
  - Use, or develop, best-estimate understanding of fuel rod parameters/properties that are important for predicting cladding performance


% Rod Population
Parameter "X"

Background (cont.'d)

- Topics of Interest
  - Condition of the spent fuel cladding as the fuel is received at the repository
    - Fraction of (un)failed fuel
    - Fraction of fuel with incipient cladding defects or wall thinning
    - Properties of the cladding (mechanical, microstructural characteristics)

Background (cont.'d)

- Topics of Interest (cont.'d)
  - Expected behavior of the cladding during the initial thermal pulse and during subsequent storage
    - Possible degradation modes prior to waste package failure (creep, delayed hydrogen cracking, etc...)
    - Degradation modes after waste package failure (contact with concentrated J-13 water) including localized corrosion and clad unzipping
    - Fraction of fuel expected to remain (un)failed during storage

Condition of the Spent Fuel As It Is Received at the Repository

- Information exists with regard to fuel rod failure <u>types</u> and failure rates
  - PWR
    - Debris
    - Baffle-Jetting
    - Grid Fretting
    - Primary Hydriding
    - Fabrication Defects
    - Excessive Oxidation
    - ...

Condition of the Spent Fuel As It Is Received at the Repository

- Information exists with regard to fuel rod failure types and failure rates
  - BWR
    - Crud-Induced Localized Corrosion (CILC)
    - Pellet-Cladding Interactions
    - Fabrication
    - ...

Condition of the Spent Fuel As It Is Received at the Repository

- Generally, failures are the result of:
  - Presence of a "threshold" feature or event such as fabrication defect, excessive power ramp, presence of debris, assembly resonance, gaps between baffle plates, excessive residual moisture in the pellets, ...
  - Acceleration of waterside corrosion (CILC in BWRs; accelerated uniform corrosion in PWRs)

Condition of the Spent Fuel As It Is Received at the Repository

- Incipient defects (cracks) do not appear to be much of an issue
  - Failure rates do not trend up with rod burnup, but cladding wastage does
  - Principal in-reactor fuel performance concern is cladding oxidation, assuming that assembly design (flow-induced vibration) and fabrication (vacuum drying, welding) are not issues
  - Special consideration needs to be given to hydrogen concentration in cladding

Condition of the Spent Fuel As It Is Received at the Repository

- Cladding wastage (wall thinning)
  - Fuel-cladding interaction layer
    - Fuel-cladding interaction layer starts to appear at pellet average burnup of ~35 GWd/t and is fully defined by 50 GWd/t
      - Consists of an inner zirconium oxide layer (~10 μm) and U-Cs-Zr compounds
  - Waterside corrosion
    - In PWRs, peak oxide corrosion thicknesses are kept (well) below 100 μm, or below threshold thickness resulting in oxide spallation

Condition of the Spent Fuel As It Is Received at the Repository

- Waterside corrosion reaction produces hydrogen:

  $Zr + 2H_2O \text{ ---> } ZrO_2 + 2H_2$

- Approximately 15% of the hydrogen produced by the oxidation reaction ends up in the cladding
- Hydrogen distribution and subsequent hydride precipitation and orientation leads to the consideration of "incipient" defects

Condition of the Spent Fuel As It Is Received at the Repository

- Hydrogen distribution within the cladding is influenced by the presence of temperature gradients (Soret effect)
- Hydrogen distribution within the cladding may be influenced by the presence of stress gradients (especially in the presence of thermal cycling)
- Upon cooling, zirconium hydrides precipitate, typically in a circumferencial orientation

Condition of the Spent Fuel As It Is Received at the Repository

- Mechanical Properties
  - Irradiation effects
  - Hydrogen content effects (hydride distribution and orientation)
- Microstructural Properties
  - In-reactor corrosion results in a memory effect affecting subsequent out-of-reactor oxidation rate

Condition of the Spent Fuel As It Is Received at the Repository

- In addition to in-reactor service, fuel assemblies experience:
  - Handling (unloading/reloading)
  - Wet Storage
  - Dry Inert Storage (handling, vacuum drying, transfer, dry storage)
  - Transportation (handling, transfer, re-packaging, truck or rail transport, …)

Condition of the Spent Fuel As It Is Received at the Repository

- Few data points exist that would form a basis for justifying a meaningful increase in the number of rod failures
  - Reasonable confidence that at-reactor operational practices lead to fuel failures (even in unusual circumstances), although there have been events leading to an increase in the severity of the failure

Condition of the Spent Fuel As It Is Received at the Repository

- Few data points exist …
  - Feedback from experience with dry storage operations is limited (DOE/EPRI/VEPCO Program at INEEL)
    - Surry fuel in CastorV/21 cask
    - Dry consolidation operations resulted in a small number of failures
    - Ongoing NRC/EPRI/DOE project expected to provide much needed data on the evolution of hydrogen in the cladding during dry, inert storage

Condition of the Spent Fuel As It Is Received at the Repository

- Few data points exist ...
  - Experience with transportation of irradiated assemblies or rods under inert conditions does not indicate much cause for concern at this time
    - SAND90-2406 estimates the failure probability per rod, under normal transport conditions, at $2x10^{-7}$ (pinhole failure) and $2x10^{-12}$ (rod breakage)

Condition of the Spent Fuel As It Is Received at the Repository

- Expectations are that the condition of the spent fuel received at the repository is expected to be pretty much the same as when it was discharged from the reactor
- Potential incipient defects to consider:
  - hydride platelets with radial orientation
    - presence or absence of re-orientation of hydride platelets due to dry storage (NRC/EPRI/DOE project)
  - hydride clusters due to spalling are not likely to be significant
  - high-burnup (>60 GWd/t) fuel designs (?)

Cladding Behavior During the Initial Thermal Pulse and Subsequent Storage

- Potential Degradation Modes
  - Intact Waste Package
    - Creep
    - Delayed Hydrogen Cracking
    - (DCCG/PCI/…)
  - Degraded Waste Package
    - Uniform corrosion
    - Localized corrosion
    - Failures due to impact loads
    - ...

Cladding Behavior During the Initial Thermal Pulse and Subsequent Storage

- Primary parameters to consider
  - Hoop stress [internal rod pressure, cladding thickness)
  - Temperature
  - Time at temperature
- Materials Properties
  - Cladding fracture toughness
  - Creep behavior
  - Rupture mode

Cladding Behavior During the Initial Thermal Pulse and Subsequent Storage

- Temperature history during the initial pulse: the lower, the better
  - 300°C and below generally regarded as the temperature regime at which creep deformation is not likely to be significant
- Value of the hoop stress (in combination with high enough temperatures) will impact creep deformation rate, critical flaw size (DHC), hydride re-orientation
  - Assumed fission gas release is a key issue (PWR)

Cladding Behavior During the Initial Thermal Pulse and Subsequent Storage

- Advocate a better understanding of the fuel rod parameters/properties that are important for predicting cladding performance
  - especially, fission gas release for PWR rods
- Confident that uniform corrosion is unlikely to be an issue, but offer no comments on localized corrosion (low pH, ferric solutions?), clad unzipping (fuel oxidation?), and mechanical failure by rockfall