Characterization of High-Burnup Fuel and Cladding

Hanchung Tsai (htsai@anl.gov)

Review of ANL High-Burnup Cladding Performance Program
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Characterization of High-Burnup Fuel and Cladding

- **Objective: Generate baseline data for LOCA, dry-cask storage, and other LWR-related efforts**
  - **H. B. Robinson PWR Rods**
    - **15x15 FRA-ANP, 5-7-cycle, 67 GWd/MTU**
    - **Zircaloy-4 cladding, CW/SR**
  - **Limerick BWR Rods**
    - **9x9 GE, 3-cycle, 56 GWd/MTU**
    - **Zircaloy-2 cladding, Zr-lined**
  - **Rods were sectioned into 5 segments before shipment to ANL**

Characterization of High-Burnup Fuel and Cladding

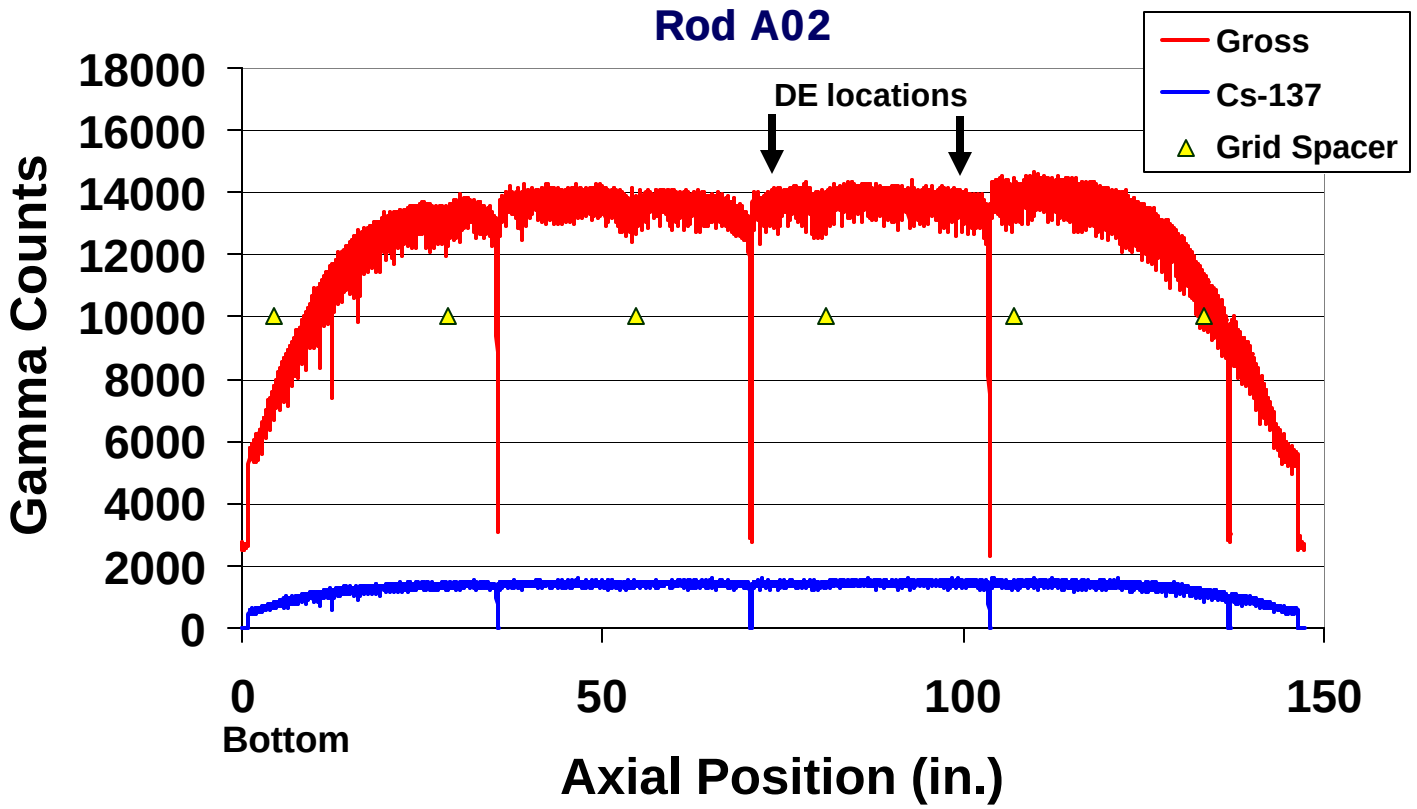
- **Scope of Characterization**
  - Fission-gas release
  - Axial gamma scanning
  - Optical metallography
    - Fuel, fuel/cladding interface, cladding corrosion, hydrides, and microhardness
  - Cladding hydrogen and oxygen analyses
  - Microprobe analysis
    - U, Pu, and fission product distribution
  - Isotopic analysis

H. B. Robinson Characterization

- **Fission-gas Release**
  - **Determined with pool-side Kr-85 scans**
  - **Release fraction relatively low: 1.4 to 2.5%**
    - **Due primarily to low linear power (~ 8 kW/ft BOL , ~ 3-4 kW/ft EOL)**
  - **Estimated rod internal pressure at operation: <1000 psi (with 290 psi initial He fill)**

H. B. Robinson Characterization

- **Axial gamma profiles: distribution normal and as-expected**



H. B. Robinson Characterization *(cont'd)*

- **Cladding Corrosion and hydrogen uptake in Rod AO2**

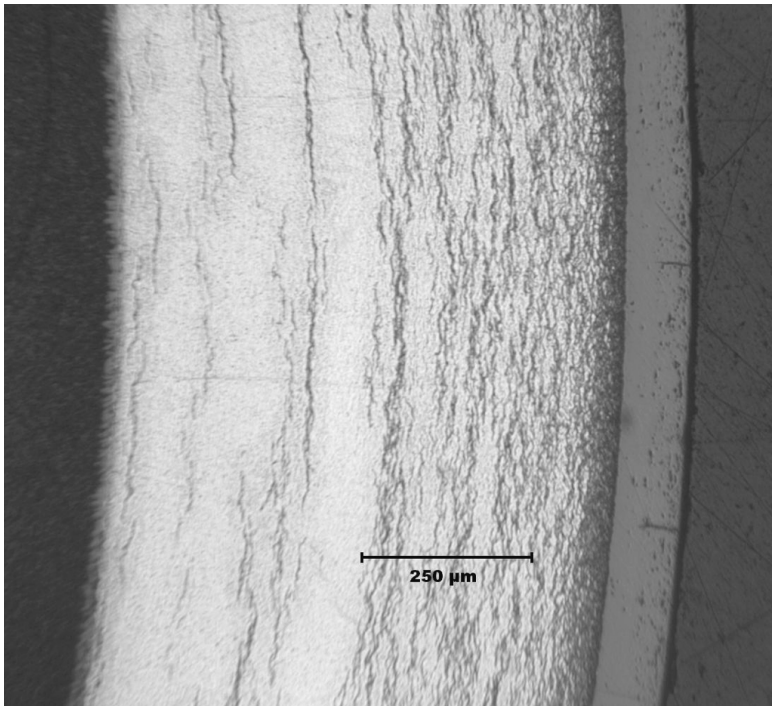
  - **OD oxide thickness:**

    ~ 70 µm at axial midplane
    ~ 100 µm at 27 in. above

  - **Hydrogen uptake: ~ 20 %**

    ~ 580 wppm at midplane
    ~ 750 wppm at 27 in. above

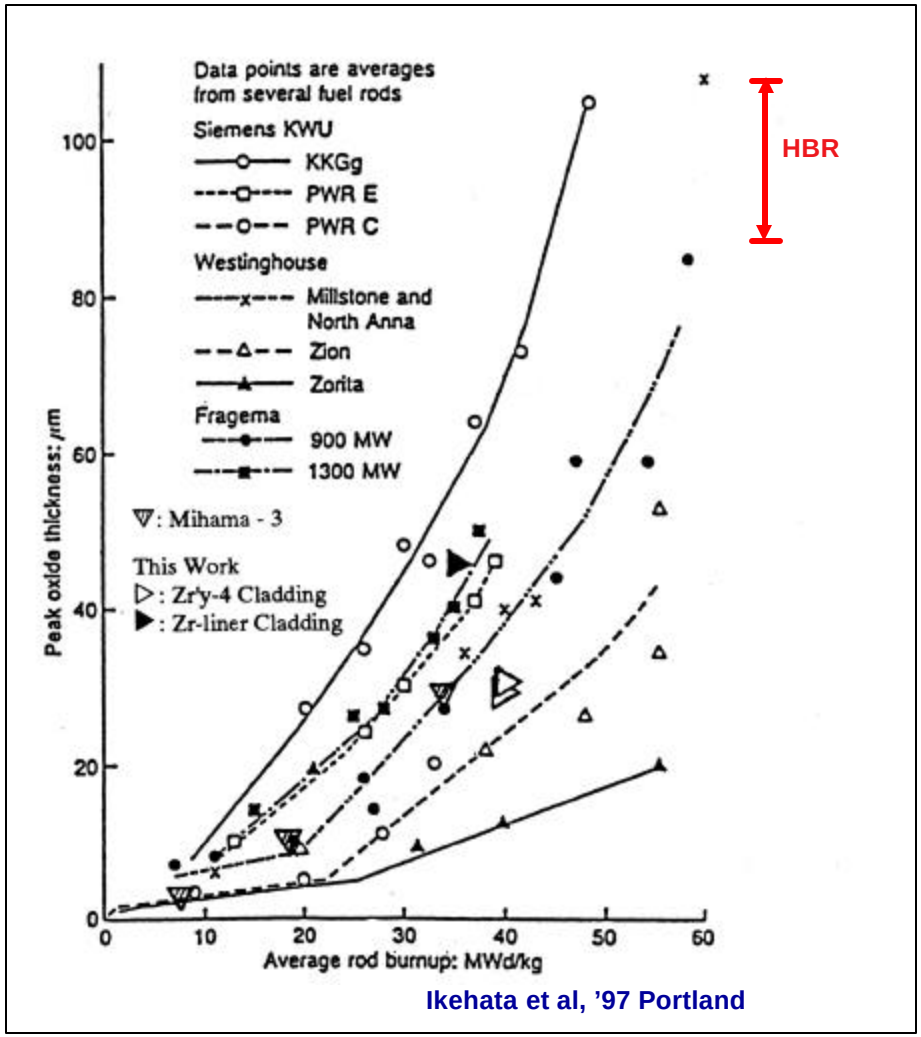
  - **Hydrides:**
    circumferentially oriented



HBR Rod AO2 27 in. above axial midplane

H. B. Robinson Characterization *(cont'd)*

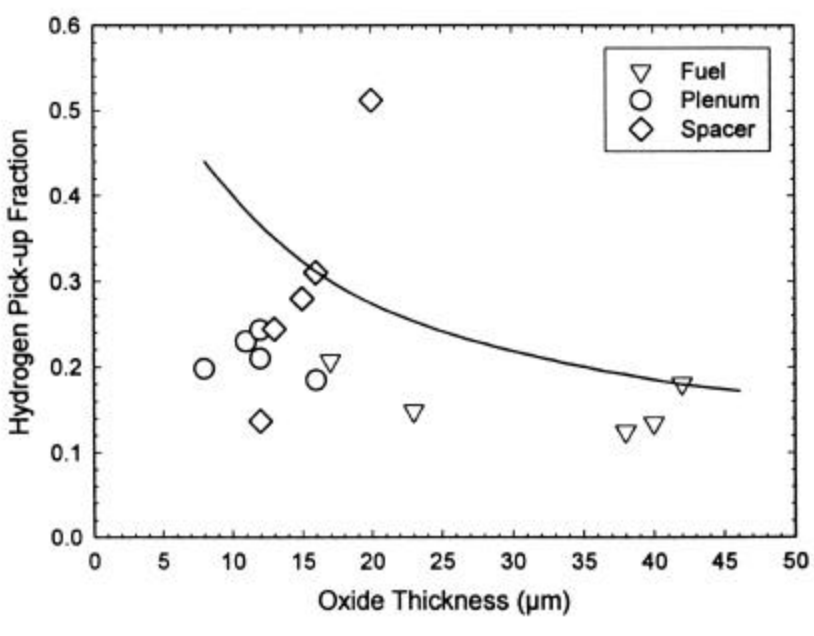
- **Oxide thickness within the published high-burnup data band.**



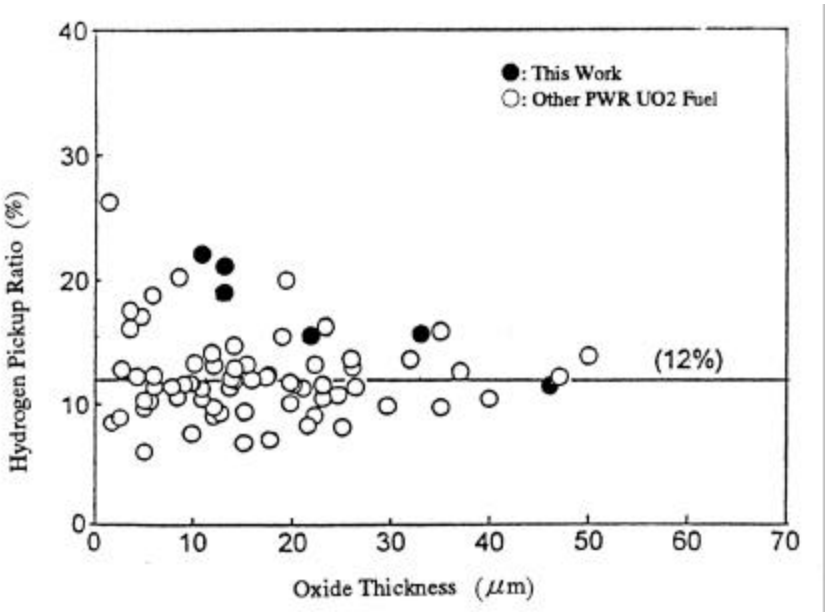
Ikehata et al, '97 Portland

H. B. Robinson Characterization *(cont'd)*

- **Hydrogen uptake of ~ 20% (in Rod A02) appears to be on the high side**



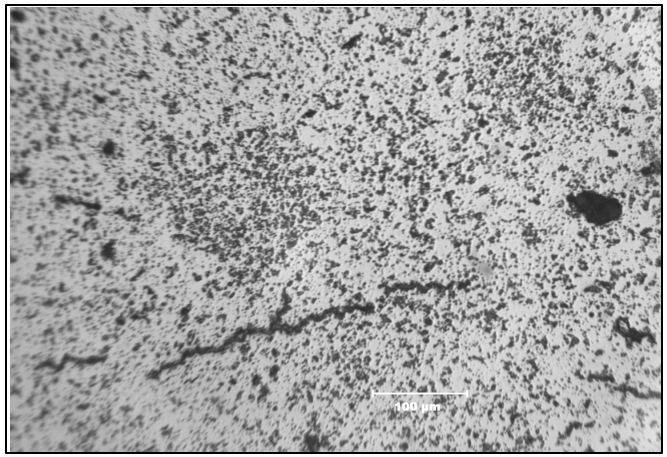
Van Swan et al, '97 Portland

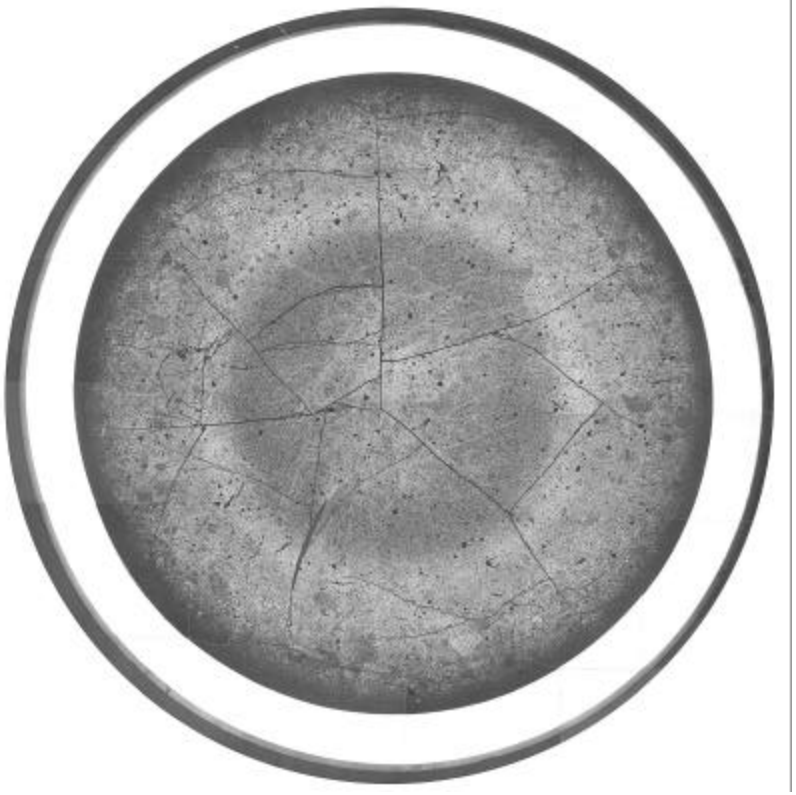


Ikehata et al, '97 Portland

H. B. Robinson Characterization *(cont'd)*

- **Fuel structure - typical of high-burnup rods**
  - **"Rim" formation**
  - **Microtearing of fuel at gassy mid-radius**

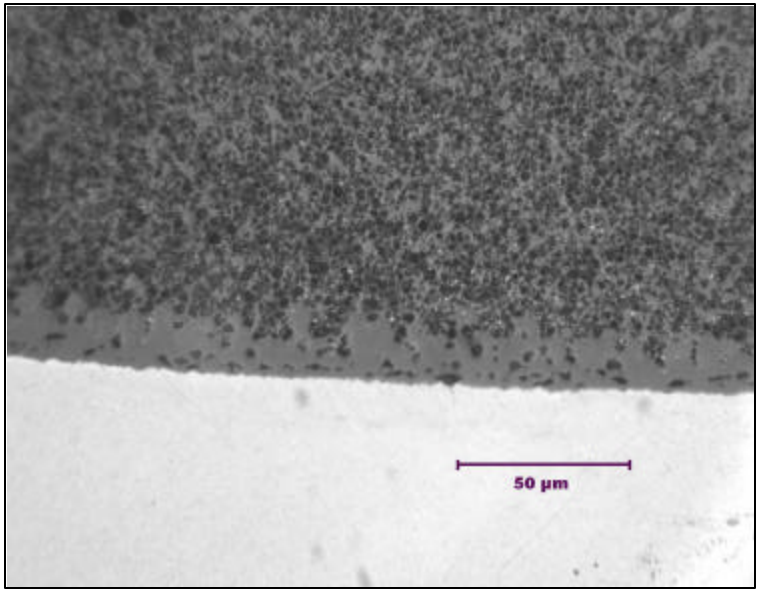




27 in. above axial midplane

H. B. Robinson Characterization *(cont'd)*

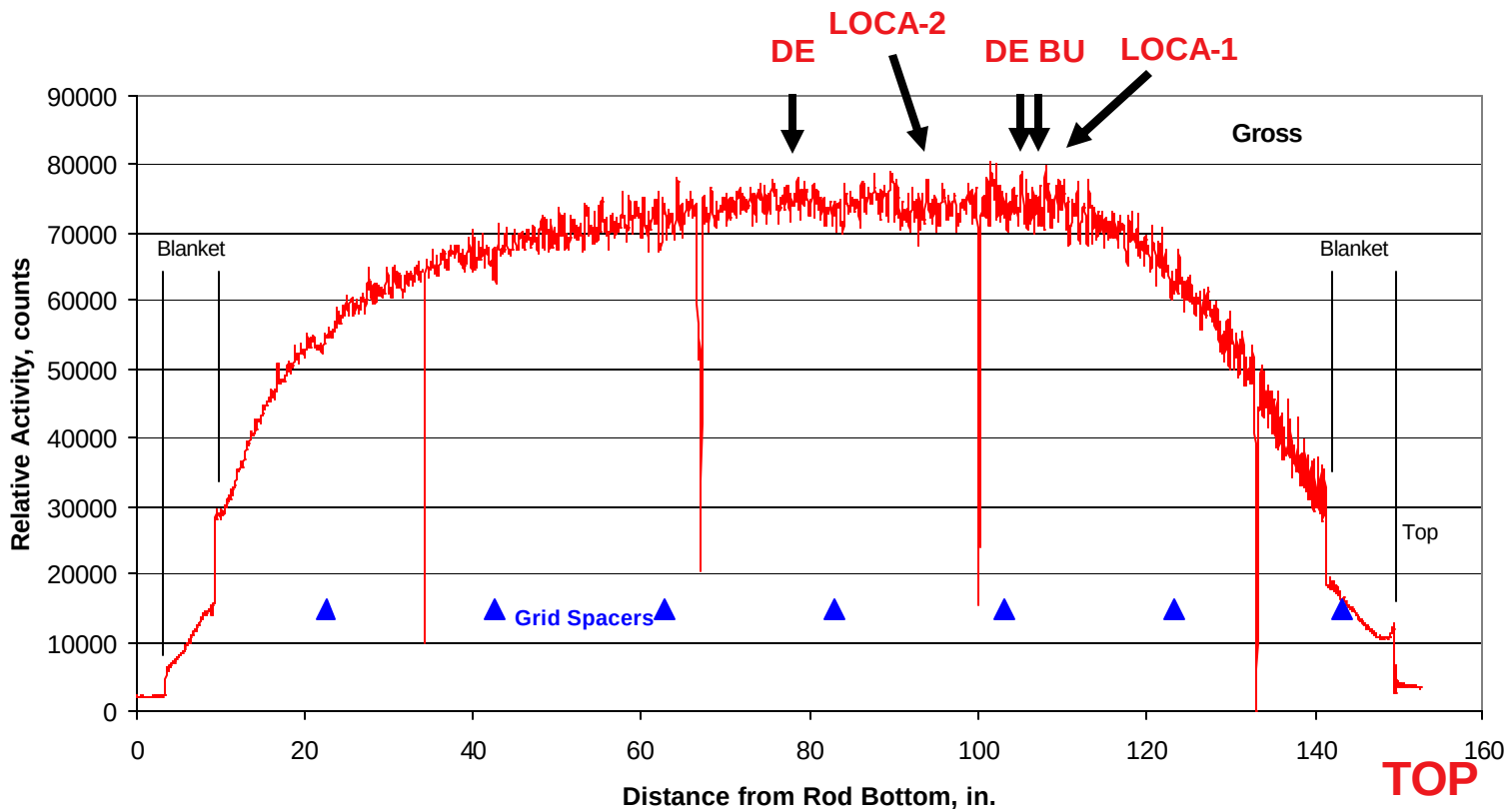
- **Tight fuel-cladding bond**
  - **Fission-product deposit in the fuel-cladding "gap"**
  - **Minimal cladding ID corrosion**
  - **Tight bond possibly impeded fission-gas release**



27 in. above axial midplane

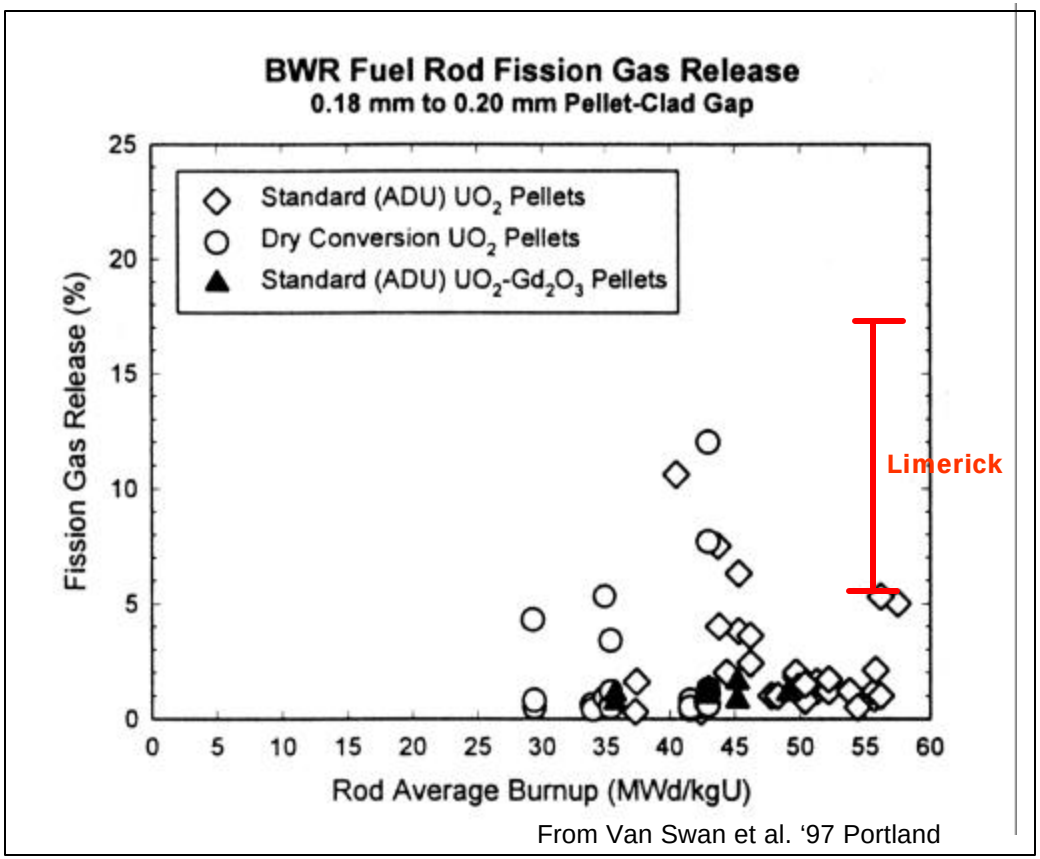
Limerick Characterization

- **Axial gamma profile for Rod F9 – features are normal**
  - **The two DE locations are 5 and 31 in. above axial midplane**



Limerick Characterization *(cont'd)*

- **Fission-gas release**
  - **Relatively high: 5-17%**
  - **Attributable possibly to fuel restructuring**



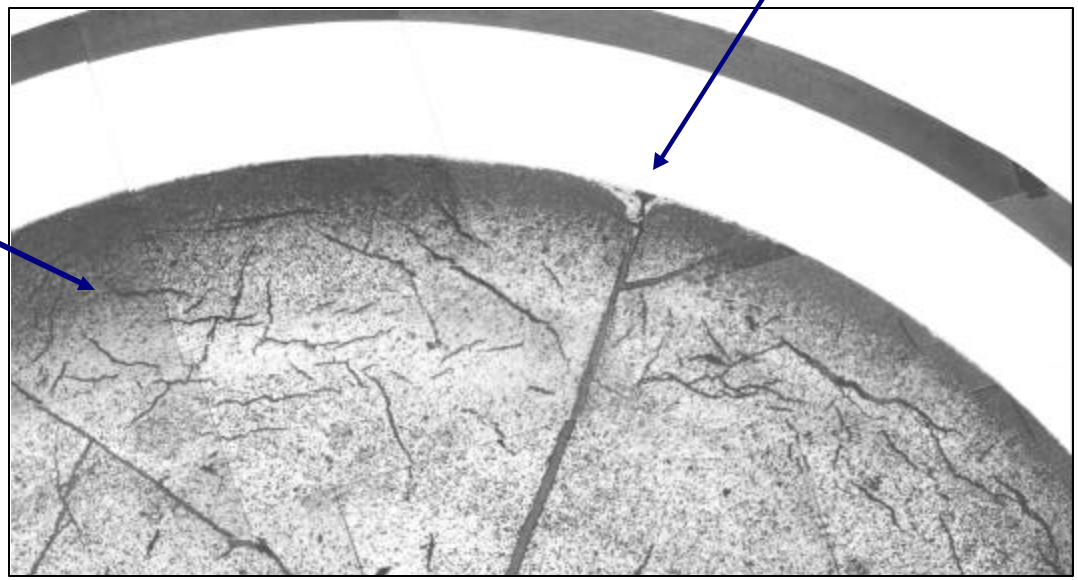
From Van Swan et al. '97 Portland

Limerick Characterization (cont'd)

- **Rod F9, at 31 in. above midplane**
  - **Fuel cracking: normal**
  - **Discontinuous and off-centered "temperature markers" in fuel**
    - **F9 was an edge rod**
  - **Porous fuel "rim"**
  - **Numerous fuel microcracks in the gassy outer region**
  - **Tight fuel/cladding bond**

Limerick Characterization (cont'd)

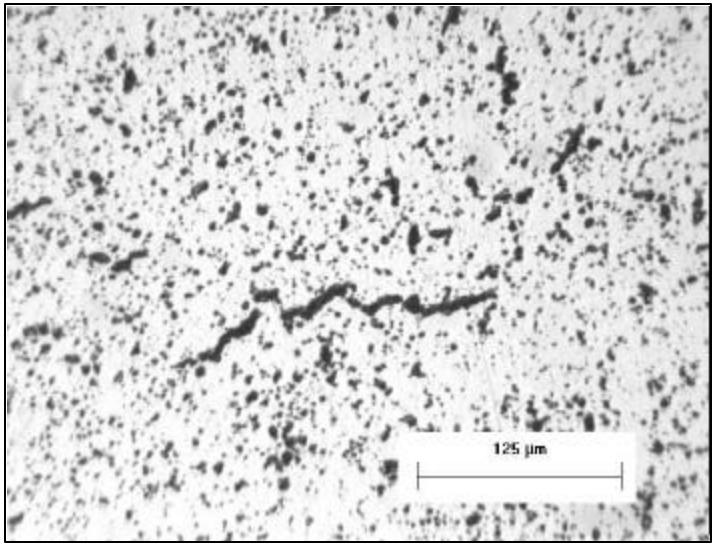
- **Fuel microcracks in and near the rim**
  - **Formed on grain boundaries weakened by fission-gas bubbles**
  - **May enhance gas connectivity and fuel relocation in LOCA**



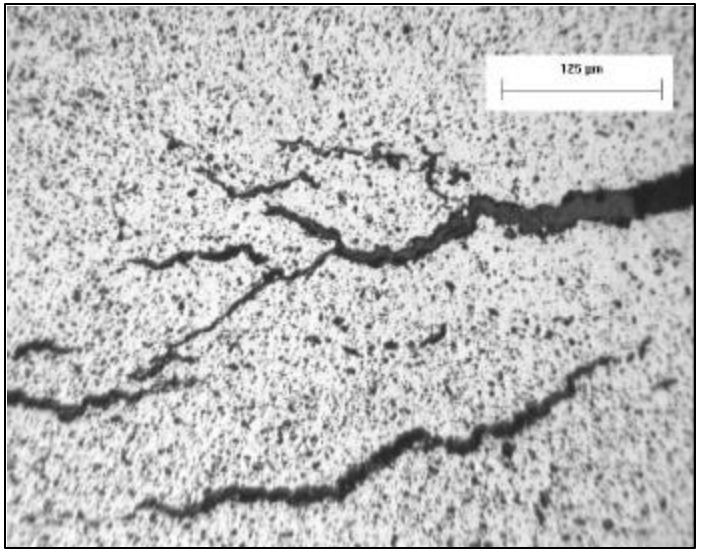
31 in. above axial midplane

Limerick Characterization (cont'd)

- **Fuel microcracks in and near the rim in F9**



Incipient

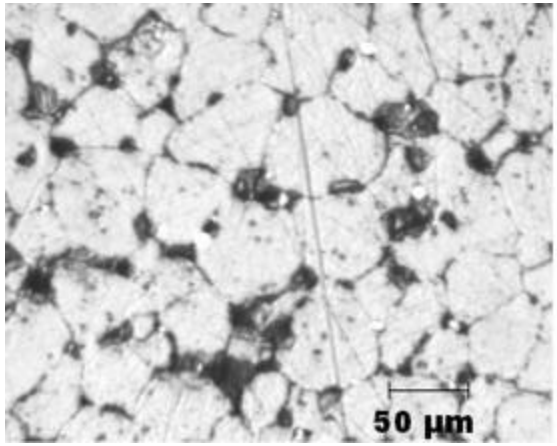


More developed

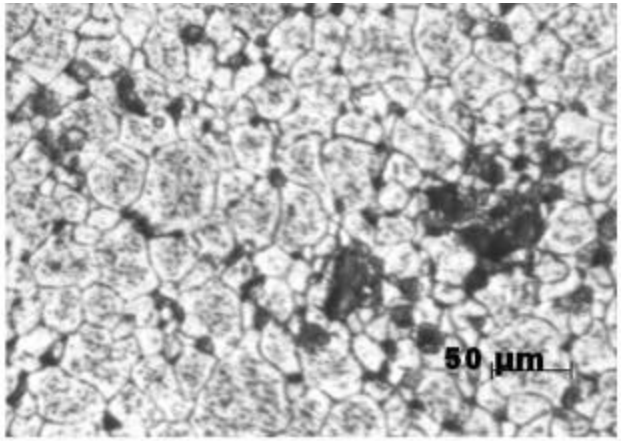
31 in. above axial midplane

Limerick Characterization (cont'd)

- **Fuel Structure**
  - **Center – grain growth, large f.g. bubble on GB**
  - **Midradius – numerous fine f.g. bubbles in grains**
  - **"Rim" – small grains, numerous f.g. bubbles in grains and on GB**



Center

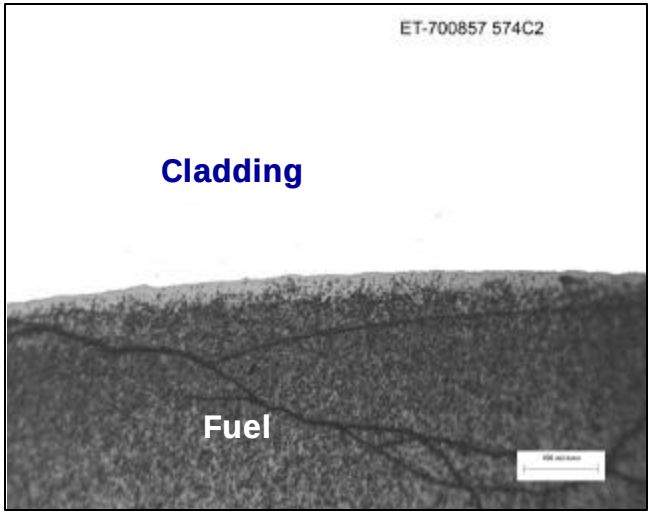


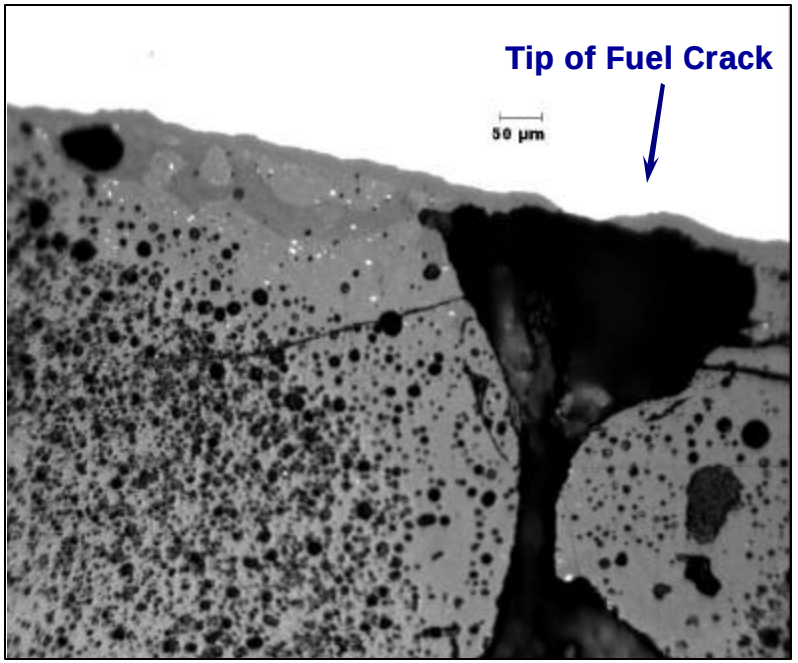
Midradius

Rim

Limerick Characterization *(cont'd)*

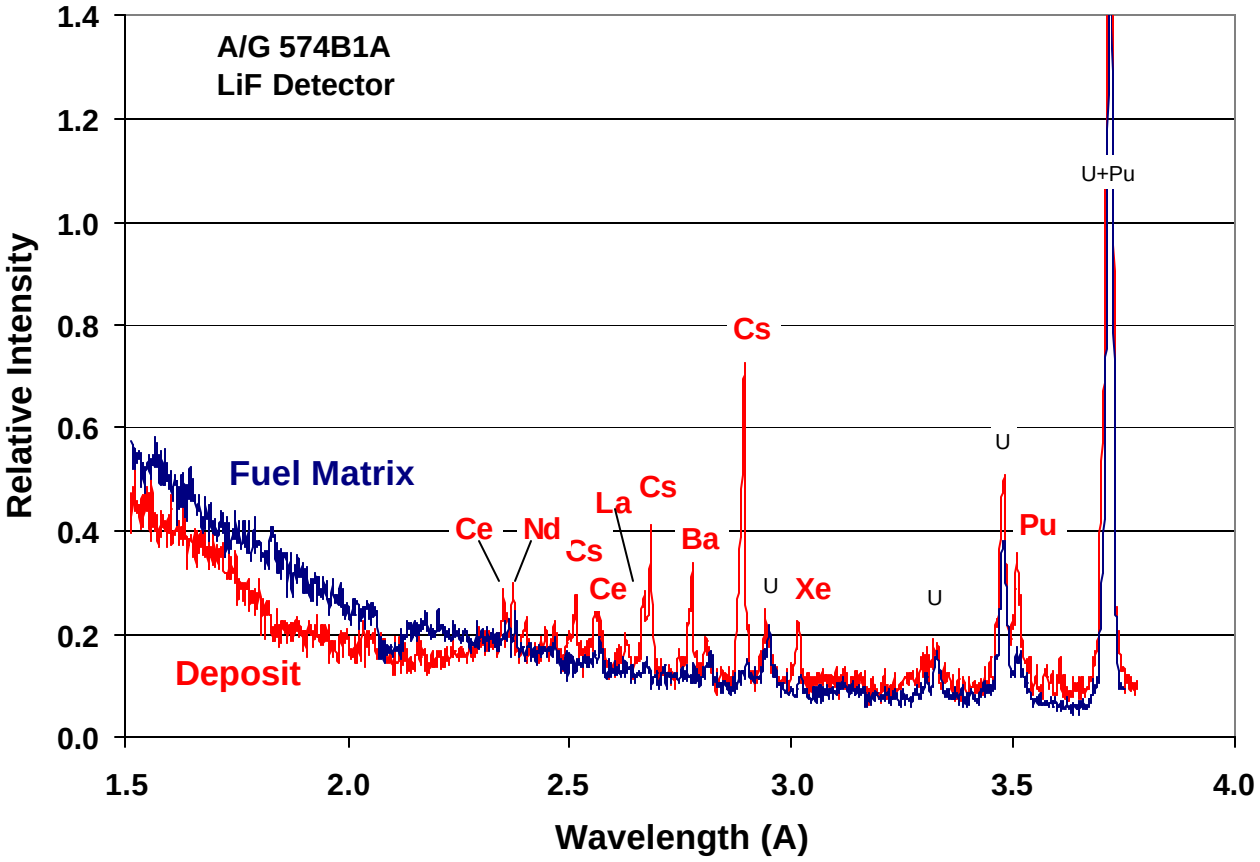
- **Fuel/Cladding Interface**
  - Tight fuel/cladding bond
  - Fission-product deposit in "gap" and at the tips of some radial fuel cracks
  - No significant cladding interaction





Limerick Characterization *(cont'd)*

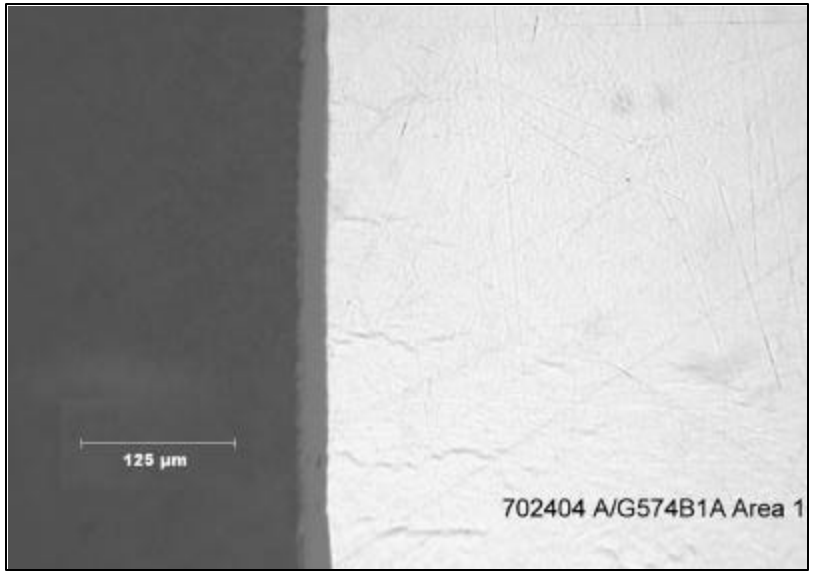
- **Microprobe Analysis: Deposit at fuel crack tip contains Pu and fission products**



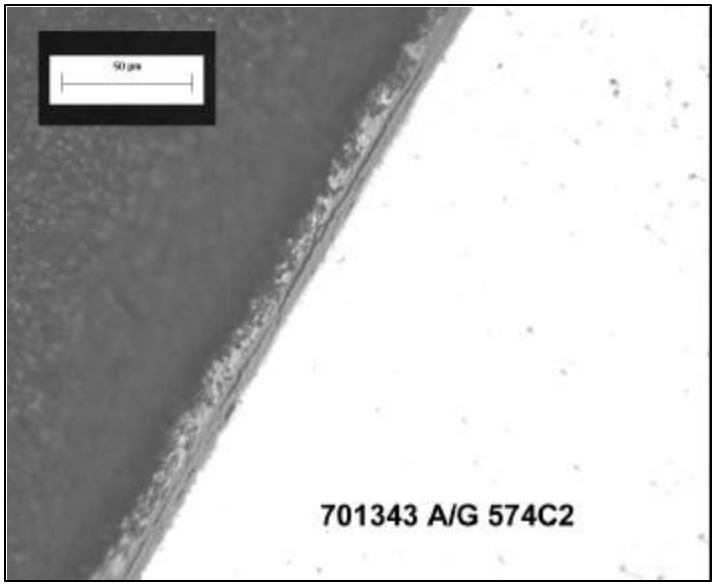
Limerick Characterization *(cont'd)*

- **Cladding Corrosion**
  - **Oxide thin and variable. Max. thick. »25 µm; average »10 ㎛.**
  - **Tenacious crud (»5 - 10 ㎛) occurs where oxide is thin. Crud contains Zn and (Fe, Ni, Co, Mn), likely a zinc ferrite.**

Oxide

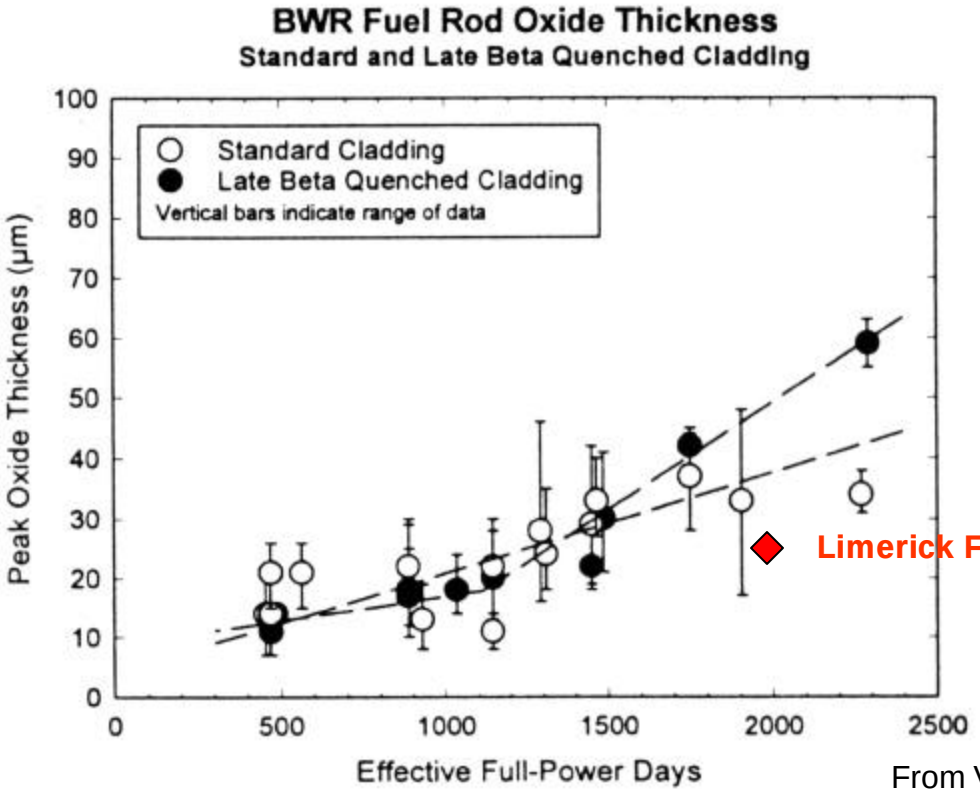


Crud over oxide



Limerick Characterization *(cont'd)*

- **Corrosion in Limerick - modest**

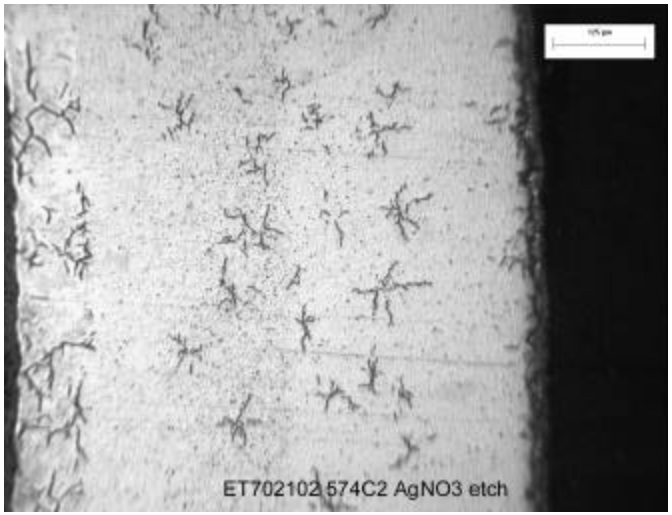


From Van Swan et al. '97 Portland

Limerick Characterization (cont'd)

- **Hydrides in Limerick F9 Cladding**
  - **H preferentially precipitated in the low-O (i.e., low solubility) Zr liner.**
  - **Platelets are small, some near the outer surface.**
  - **Measured H content is low, »70 wppm.**

Zr Liner ⟶



Summary and Conclusions

- **H. B. Robinson**
  - Low fission-gas release.
  - Tight fuel/cladding bond. Gap filled with a deposit phase.
  - Max. OD oxide thickness ~ 100 μm.
  - Max. cladding hydrogen content ~ 750 wppm.
  - Effects of hydrogen on cladding behavior being evaluated in
    - Cladding thermal creep tests
    - Integral LOCA criteria tests
    - Cladding tensile tests.

Summary and Conclusions

- **Limerick**
  - **Oxide and crud layers both thin.**
  - **H content in cladding low (~ 70 wppm), commensurate with the thin oxide layer.**
  - **Fission-gas release relatively high, possibly attributable to fuel microcracking.**
  - **Tight fuel/cladding bond. Gap filled with fission products. No significant cladding interaction.**
  - **Sound overall condition in spite of the high burnup.**