

# **Characterization of High-Burnup Fuel and Cladding**

*Hanchung Tsai (htsai@anl.gov)*

*Review of ANL High-Burnup  
Cladding Performance Program  
July 16, 2003*

## **Argonne National Laboratory**



A U.S. Department of Energy  
Office of Science Laboratory  
Operated by The University of Chicago



# ***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**

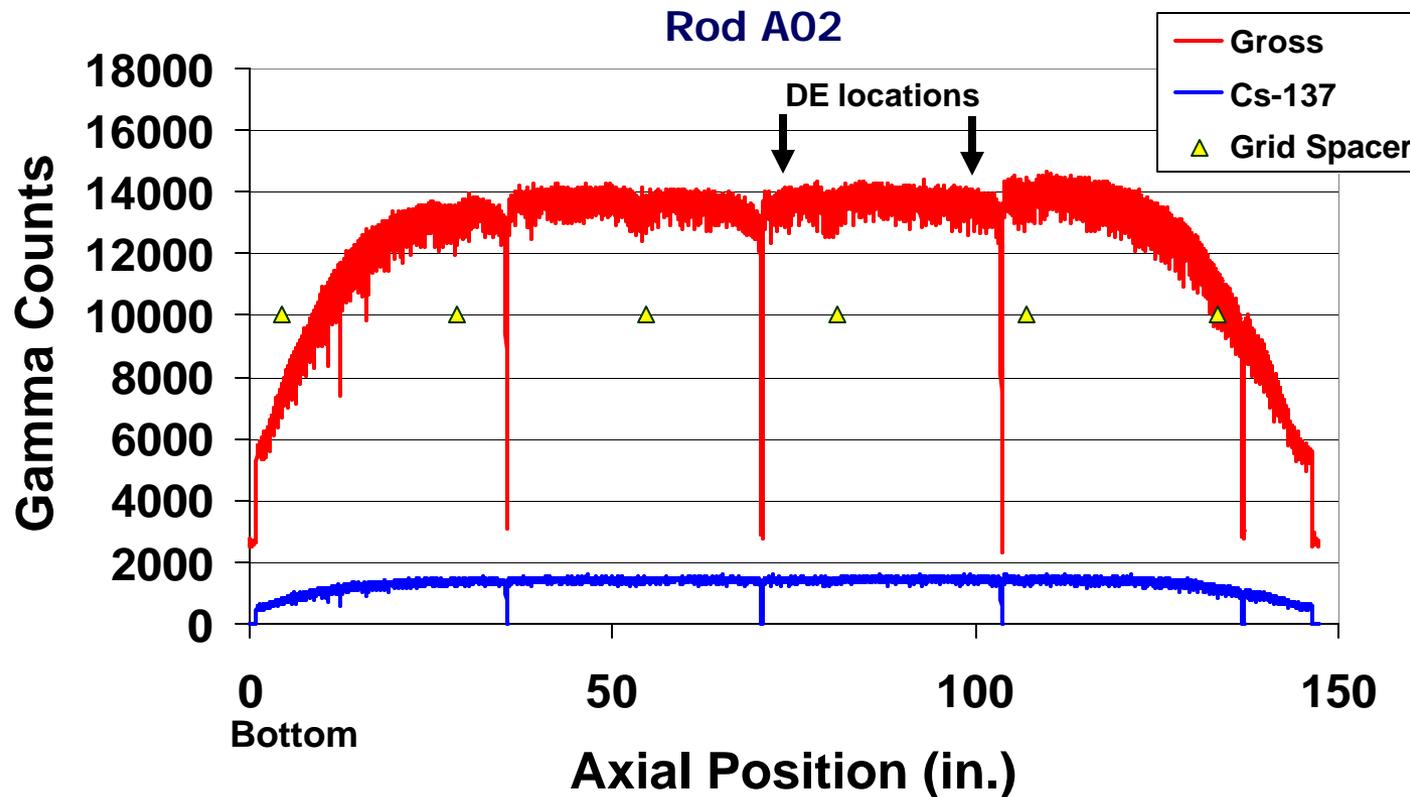
# *H. B. Robinson Characterization*

---

- **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)**

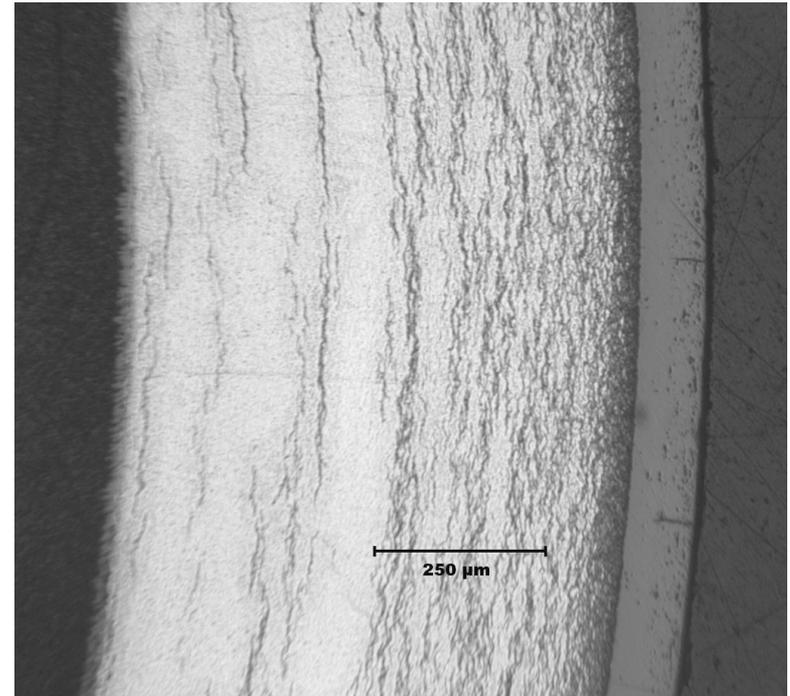
# H. B. Robinson Characterization

- Axial gamma profiles: distribution normal and as-expected



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

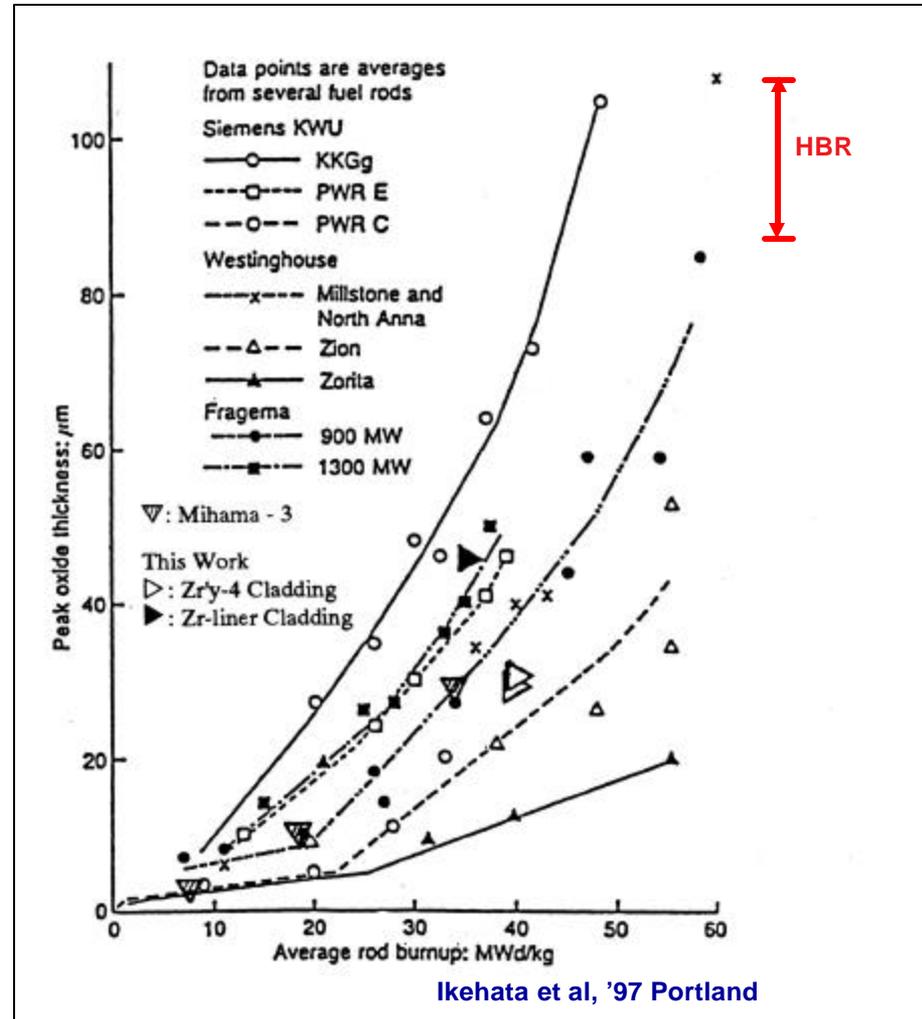
- **Cladding Corrosion and hydrogen uptake in Rod AO2**
  - **OD oxide thickness:**
    - ~ 70  $\mu\text{m}$  at axial midplane
    - ~ 100  $\mu\text{m}$  at 27 in. above
  - **Hydrogen uptake: ~ 20%**
    - ~ 580 wppm at midplane
    - ~ 750 wppm at 27 in. above
  - **Hydrides:**  
**circumferentially oriented**



HBR Rod AO2 27 in. above axial midplane

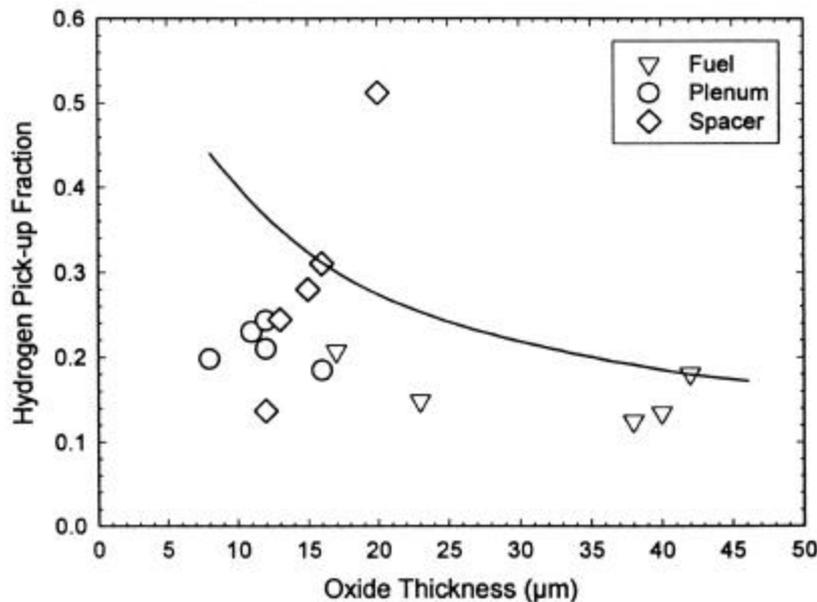
# H. B. Robinson Characterization (cont'd)

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

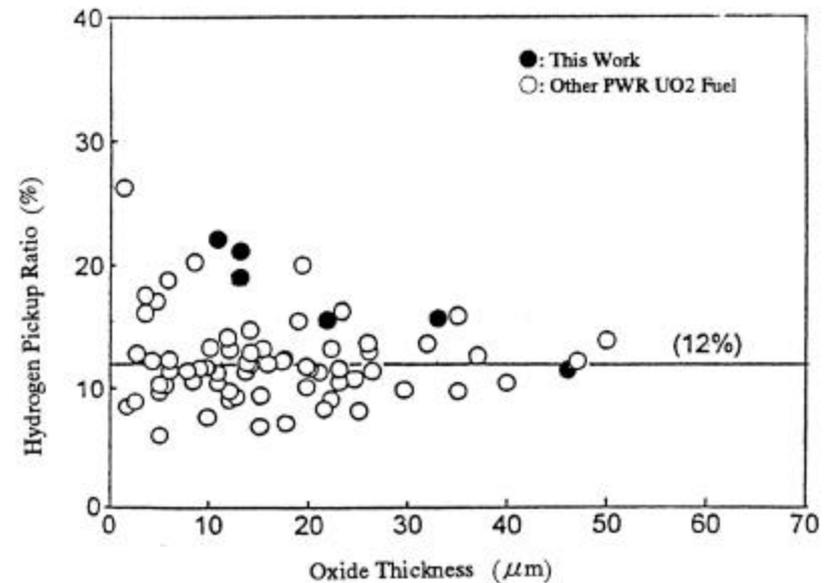


# H. B. Robinson Characterization (cont'd)

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



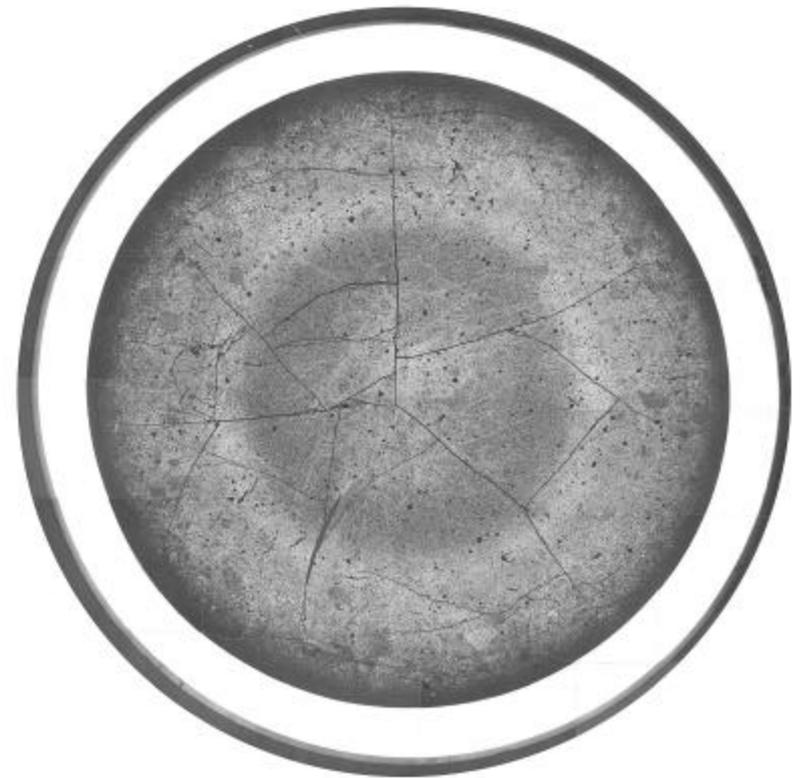
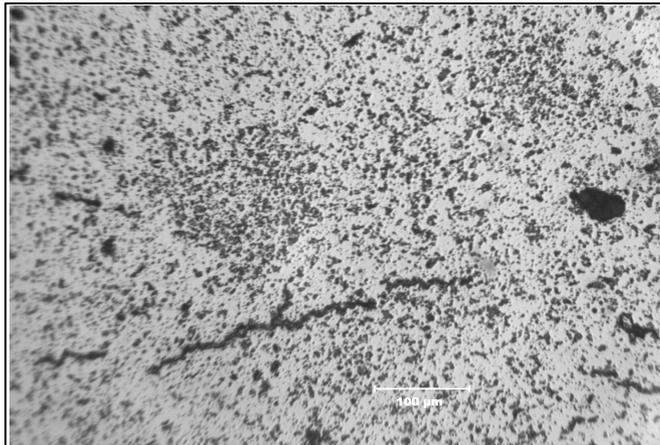
Van Swan et al, '97 Portland



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**

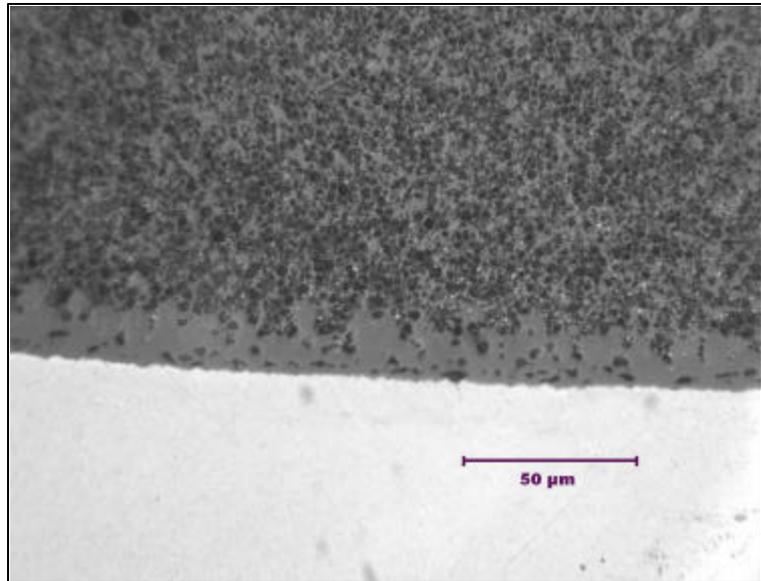


**27 in. above axial midplane**

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

- **Tight fuel-cladding bond**

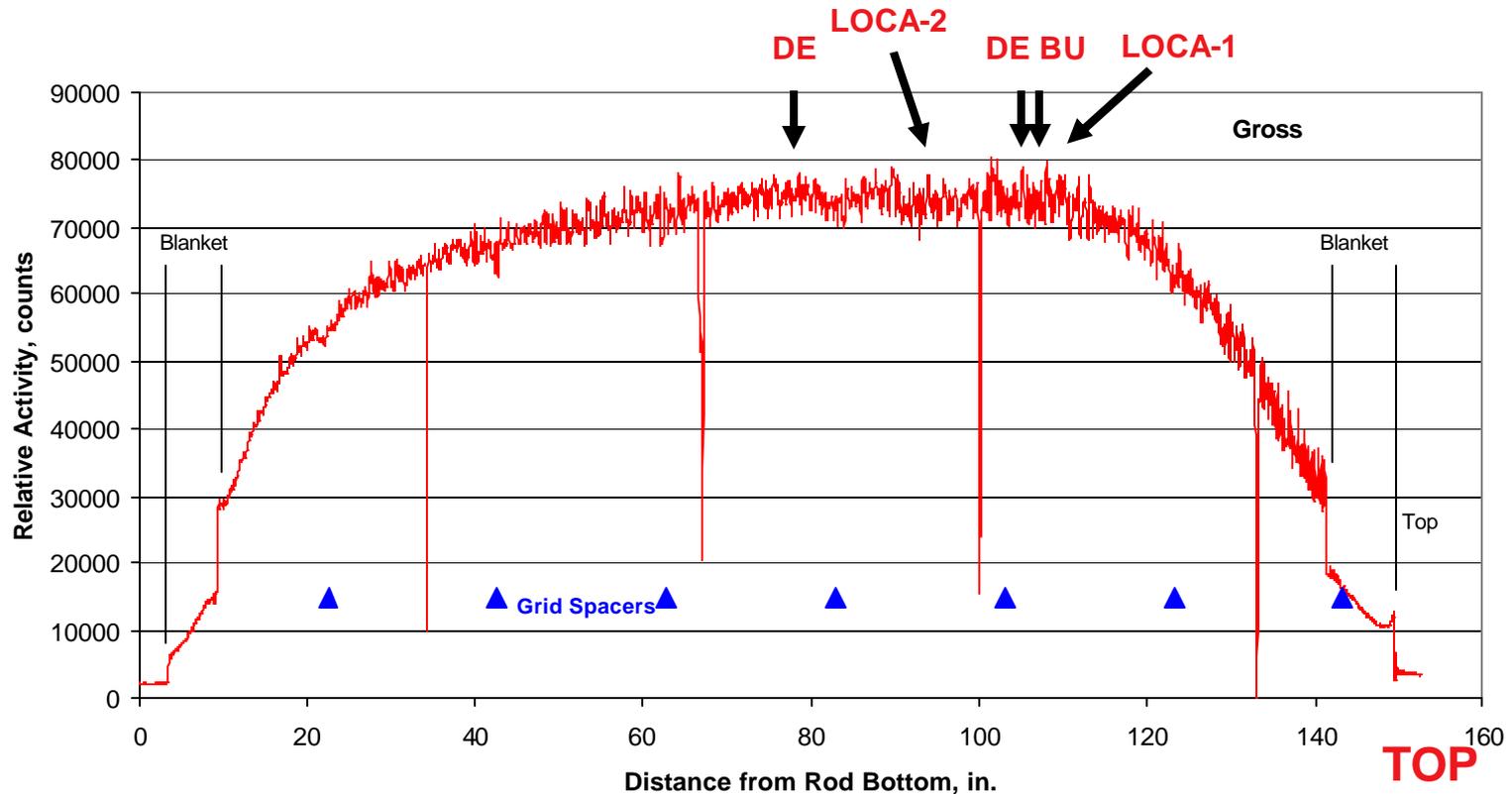
- Fission-product deposit in the fuel-cladding “gap”
- Minimal cladding ID corrosion
- Tight bond possibly impeded fission-gas release



27 in. above axial midplane

# Limerick Characterization

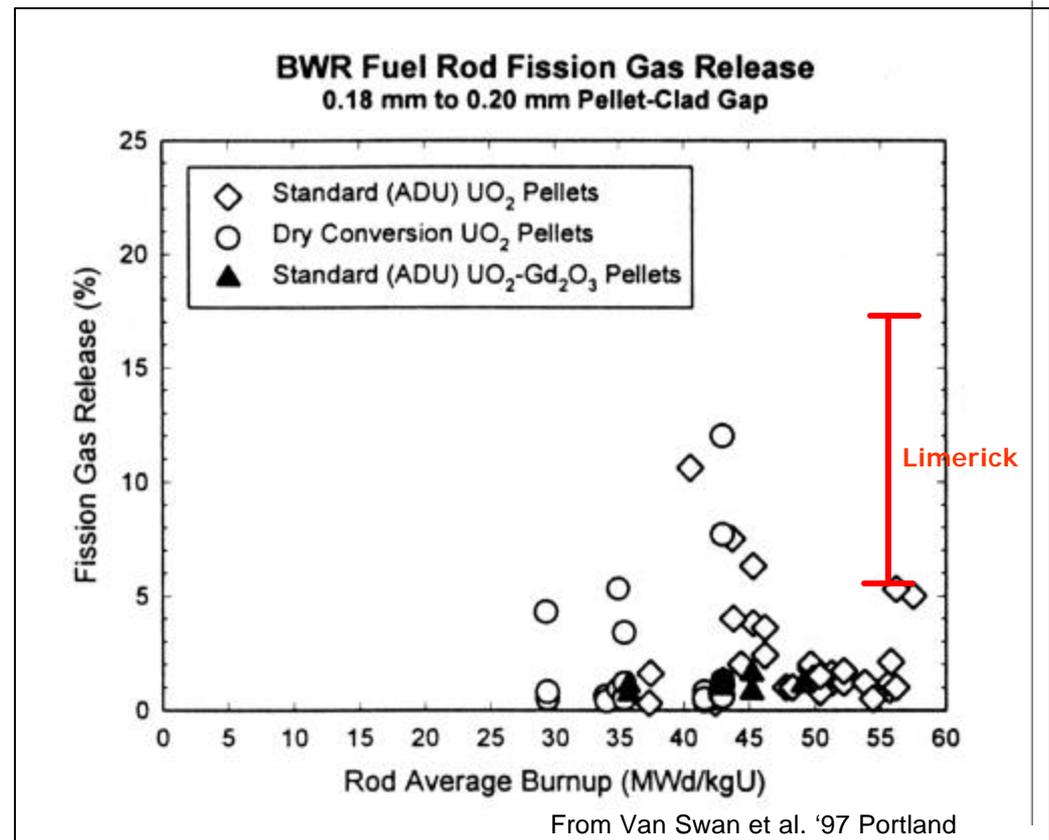
- Axial gamma profile for Rod F9 – features are normal
  - The two DE locations are 5 and 31 in. above axial midplane



# Limerick Characterization (cont'd)

- **Fission-gas release**

- Relatively high: 5-17%
- Attributable possibly to fuel restructuring



# *Limerick Characterization* (cont'd)

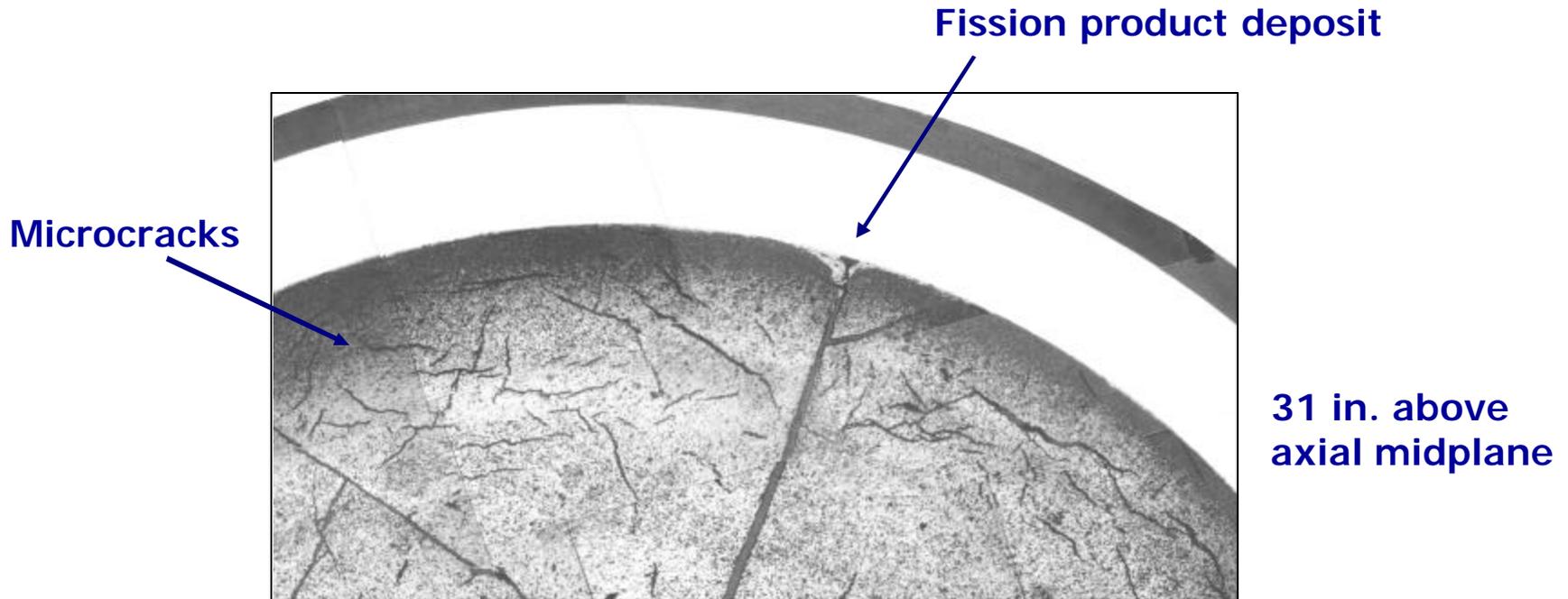
- **Rod F9, at 31 in. above midplane**

- 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



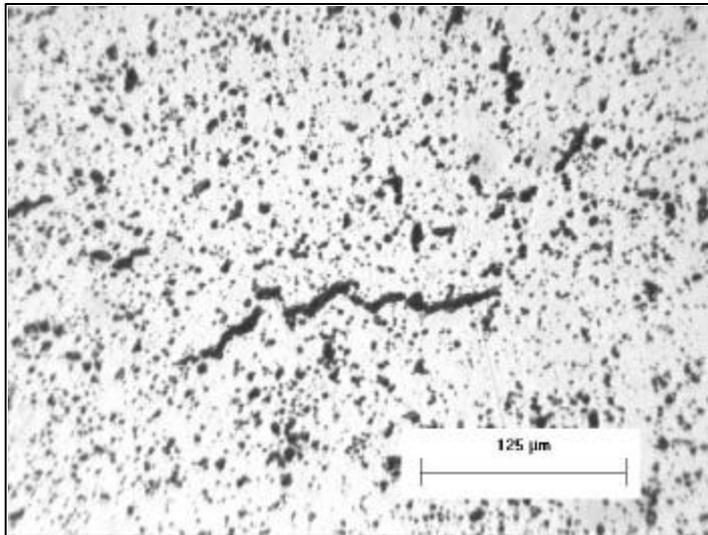
# *Limerick Characterization* (cont'd)

- 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

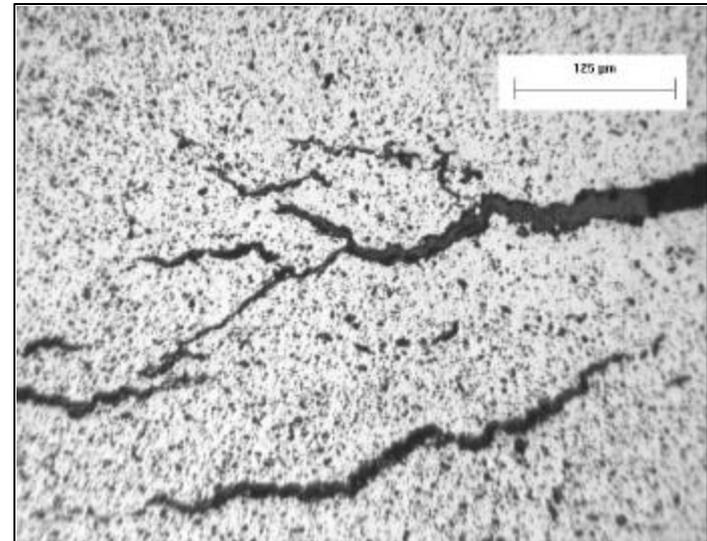


# *Limerick Characterization* (cont'd)

- Fuel microcracks in and near the rim in F9



Incipient



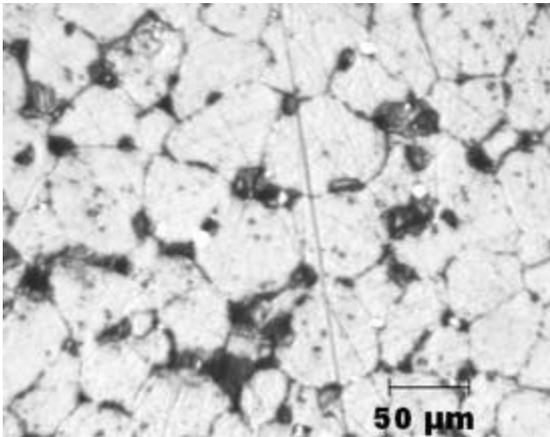
More developed

31 in. above axial midplane

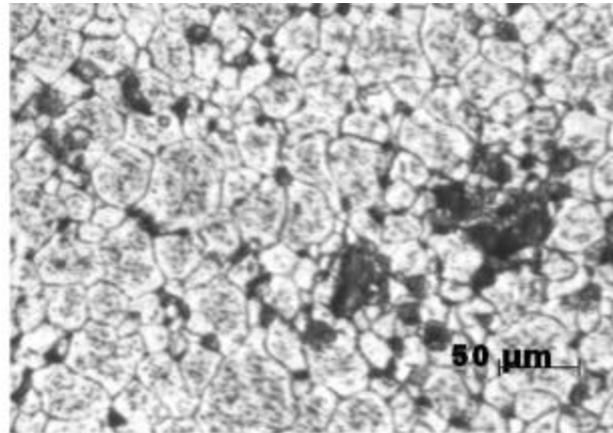
# *Limerick Characterization* (cont'd)

- **Fuel Structure**

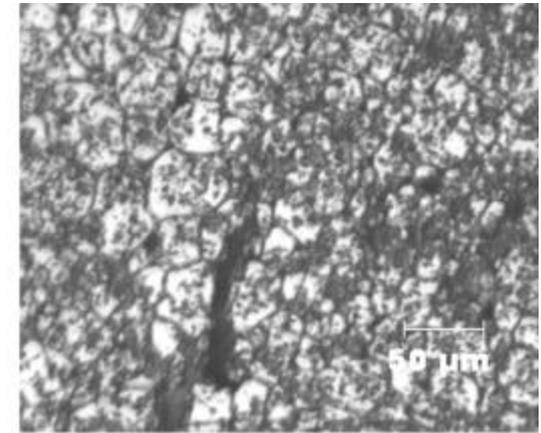
- Center – grain growth, large f.g. bubble on GB
- Midradius – numerous fine f.g. bubbles in grains
- “Rim” – small grains, numerous f.g. bubbles in grains and on GB



Center



Midradius

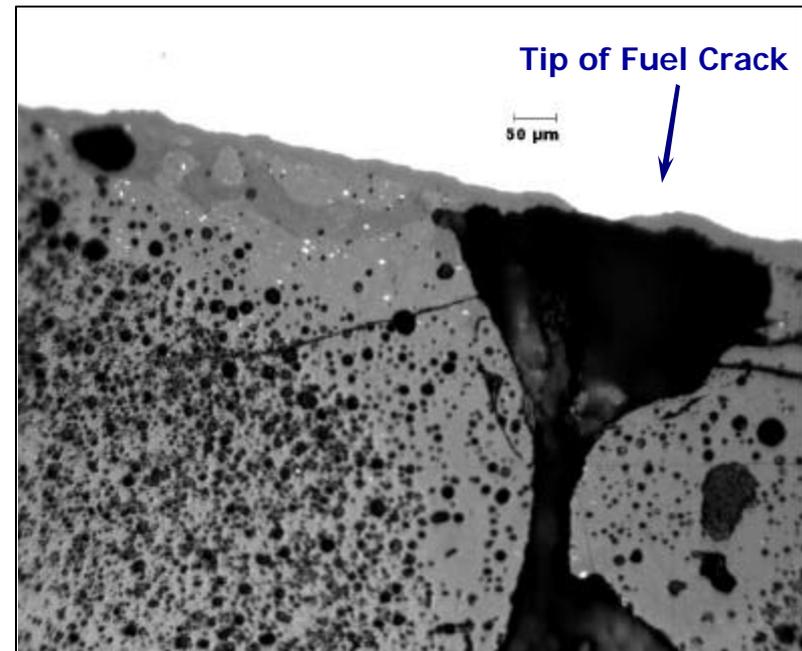
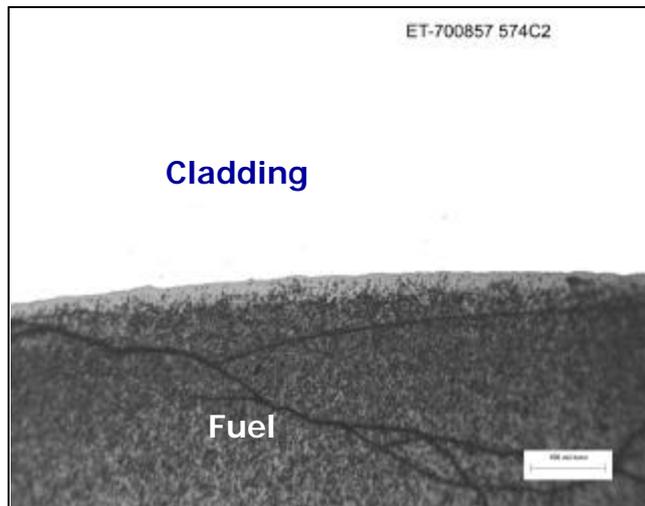


Rim

# *Limerick Characterization* (cont'd)

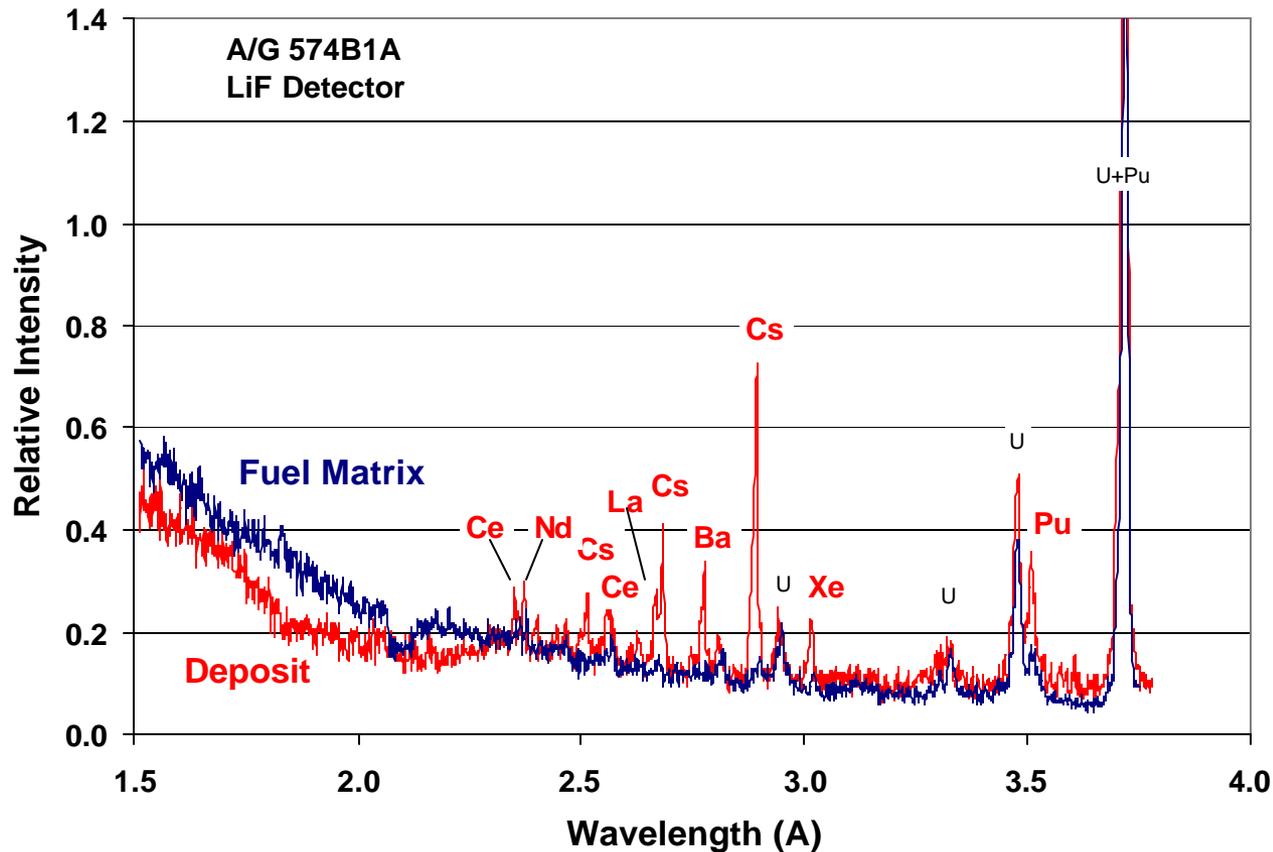
- **Fuel/Cladding Interface**

- 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

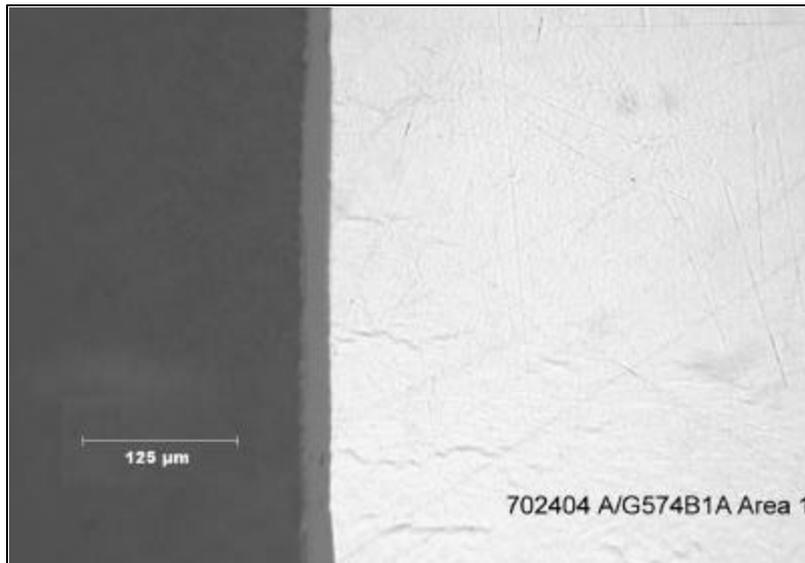


# Limerick Characterization *(cont'd)*

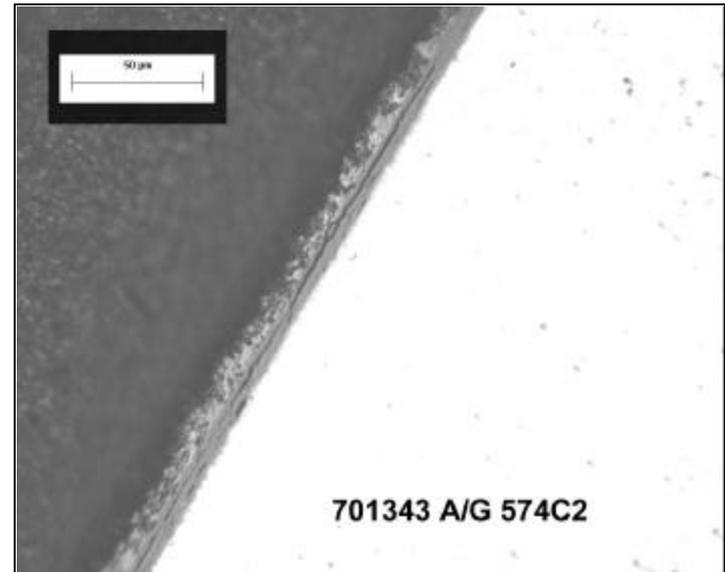
- **Cladding Corrosion**

- Oxide thin and variable. Max. thick. » 25  $\mu\text{m}$ ; average » 10  $\mu\text{m}$ .
- Tenacious crud (» 5 - 10  $\mu\text{m}$ ) occurs where oxide is thin. Crud contains Zn and (Fe, Ni, Co, Mn), likely a zinc ferrite.

Oxide

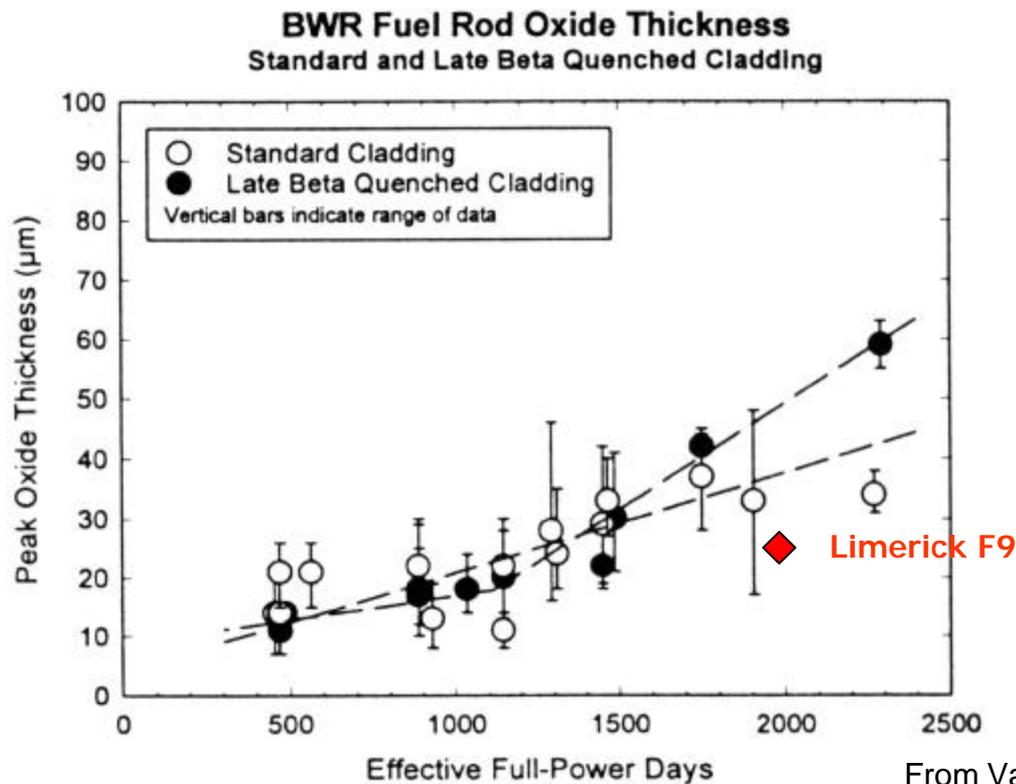


Crud over oxide



# Limerick Characterization (cont'd)

- Corrosion in Limerick - modest



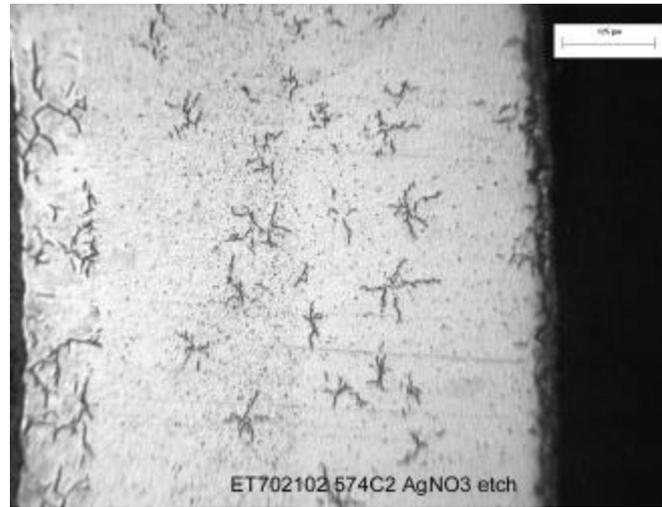
From Van Swan et al. '97 Portland

# *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  $\mu\text{m}$ .
- 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.