

Characterization of High-Burnup Fuel and Cladding

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*Review of ANL High-Burnup
Cladding Performance Program
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Argonne National Laboratory



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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

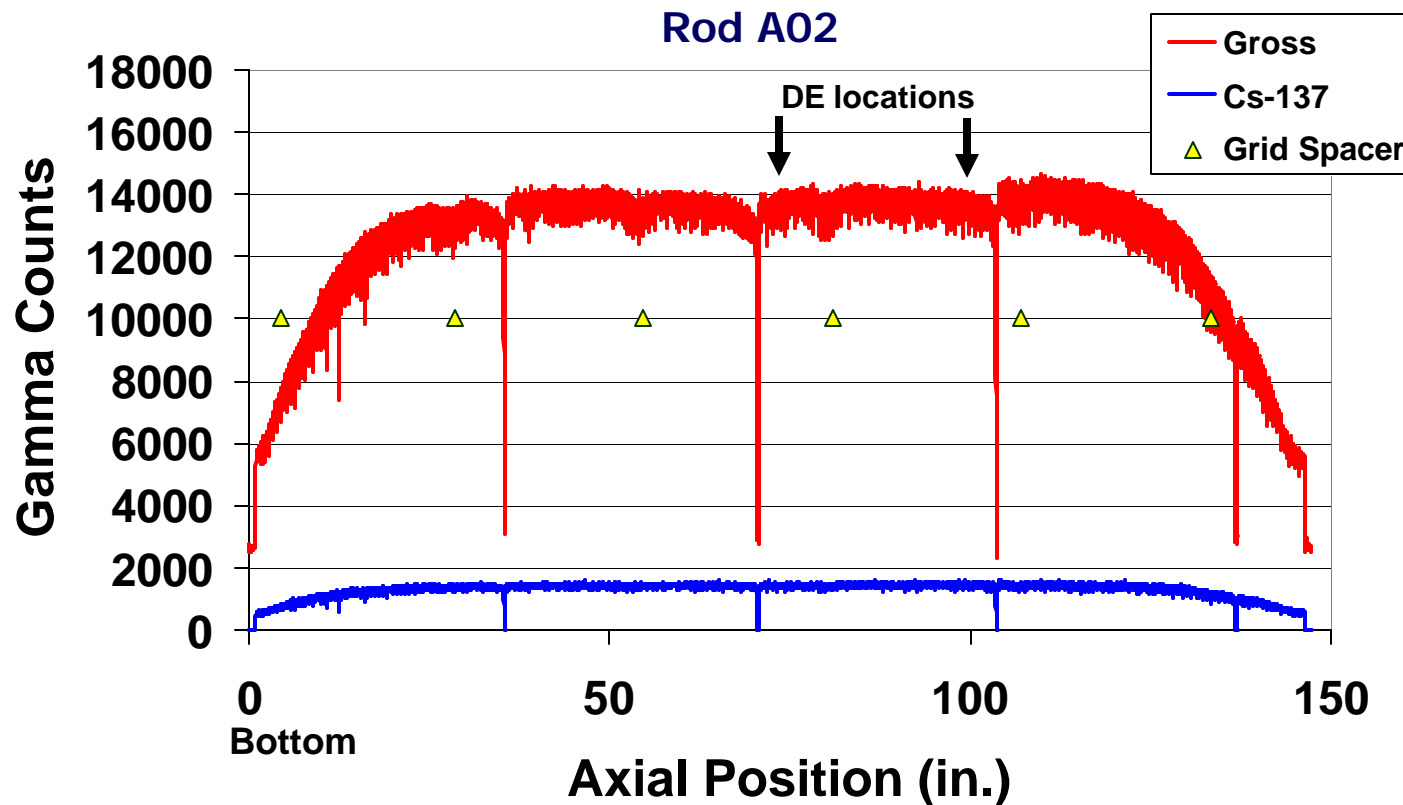
- **Scope of Characterization**
 - **Fission-gas release**
 - **Axial gamma scanning**
 - **Optical metallography**
 - **Fuel, fuel/cladding interface, cladding corrosion, hydrides, and microhardness**
 - **Cladding hydrogen and oxygen analyses**
 - **Microprobe analysis**
 - **U, Pu, and fission product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

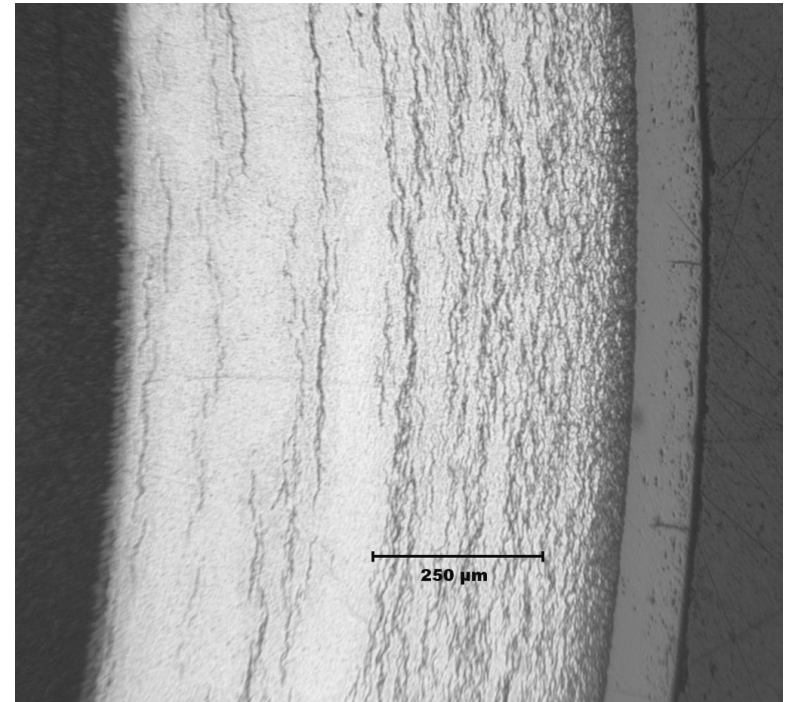
H. B. Robinson Characterization

- Axial gamma profiles: distribution normal and as-expected



H. B. Robinson Characterization (cont'd)

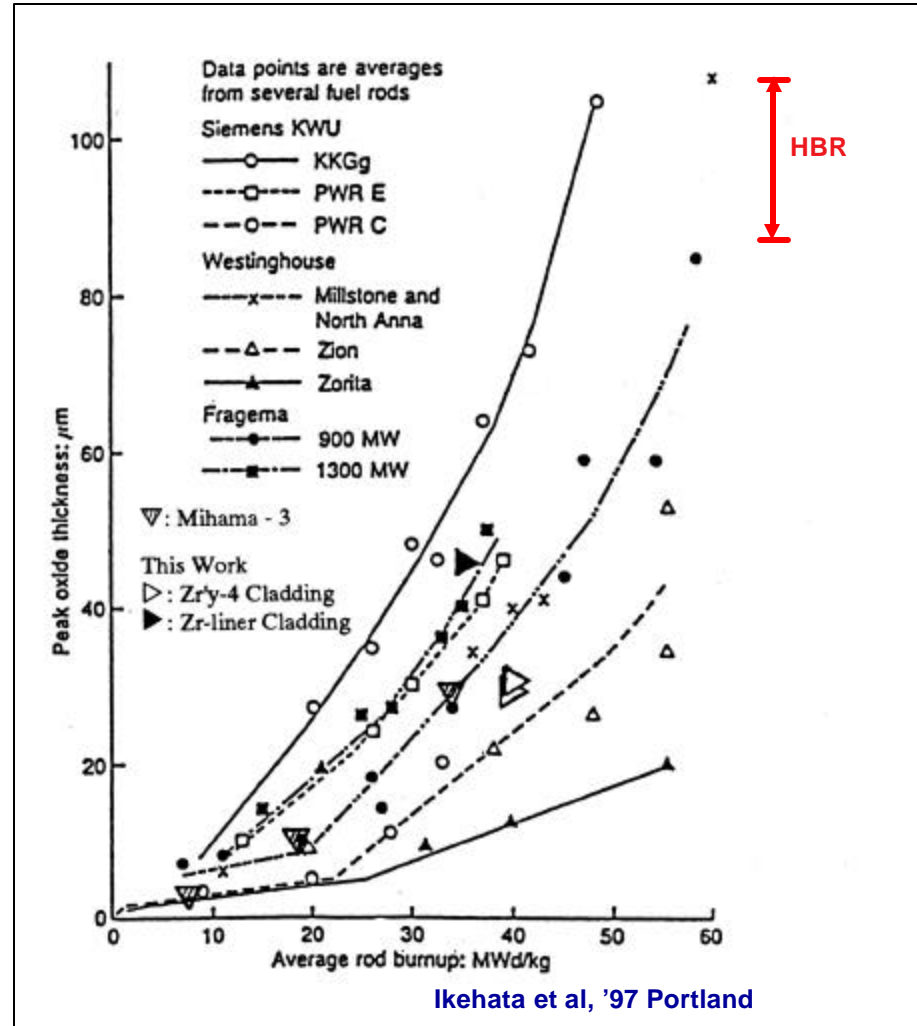
- Cladding Corrosion and hydrogen uptake in Rod AO2
 - OD oxide thickness:
 - ~ 70 μm at axial midplane
 - ~ 100 μm at 27 in. above
 - Hydrogen uptake: ~ 20%
 - ~ 580 wppm at midplane
 - ~ 750 wppm at 27 in. above
 - Hydrides:
circumferentially oriented



HBR Rod AO2 27 in. above axial midplane

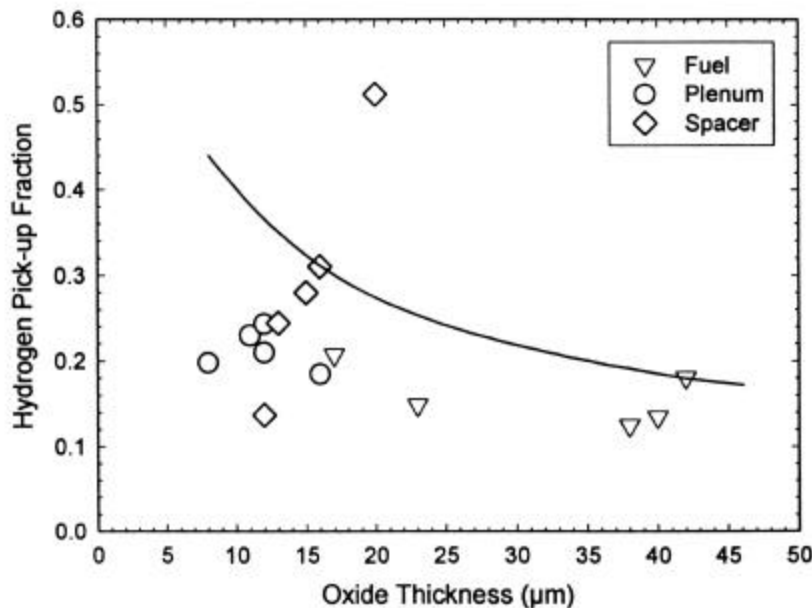
H. B. Robinson Characterization (cont'd)

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

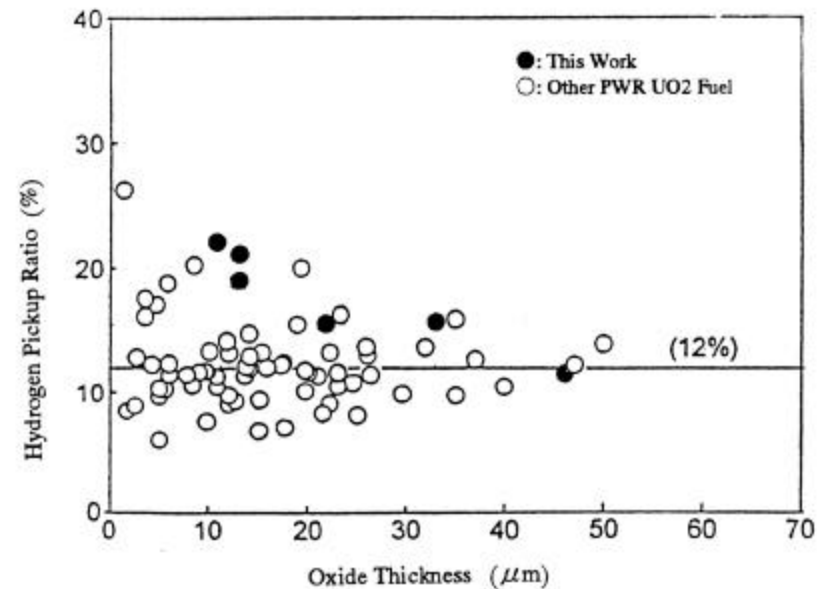


H. B. Robinson Characterization (cont'd)

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



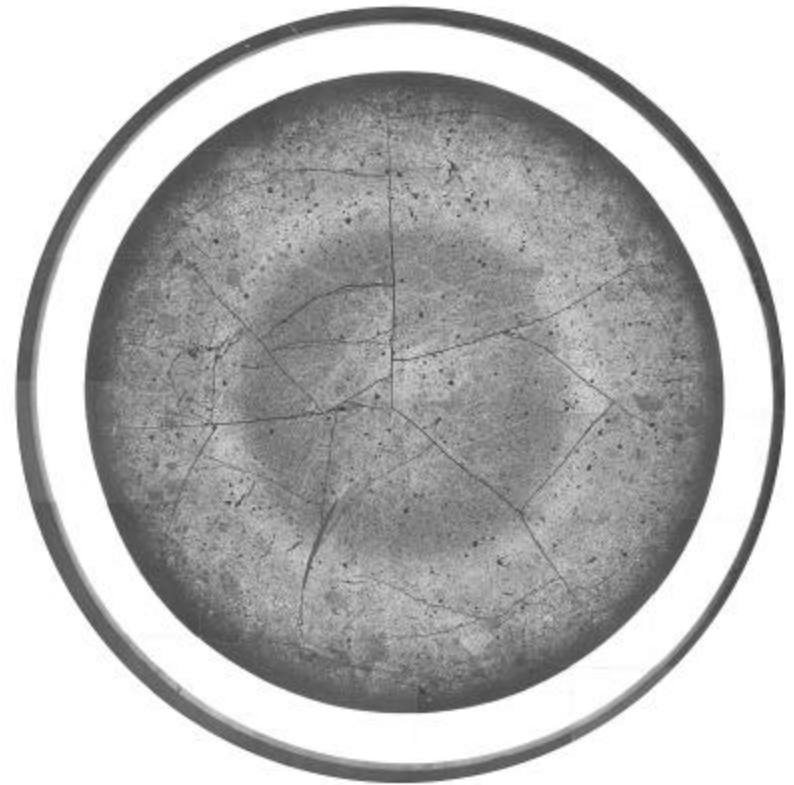
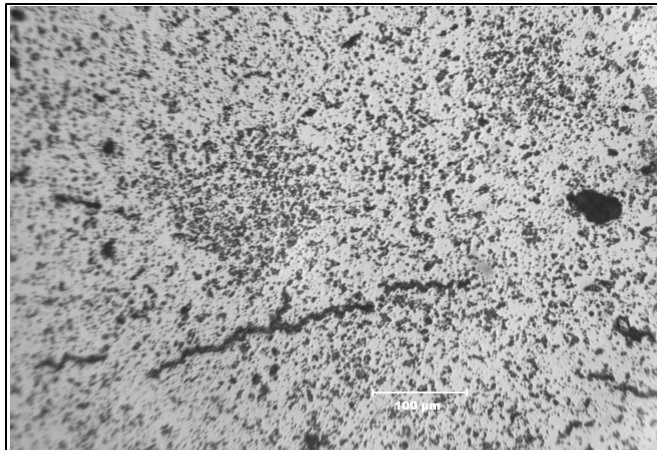
Van Swan et al, '97 Portland



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

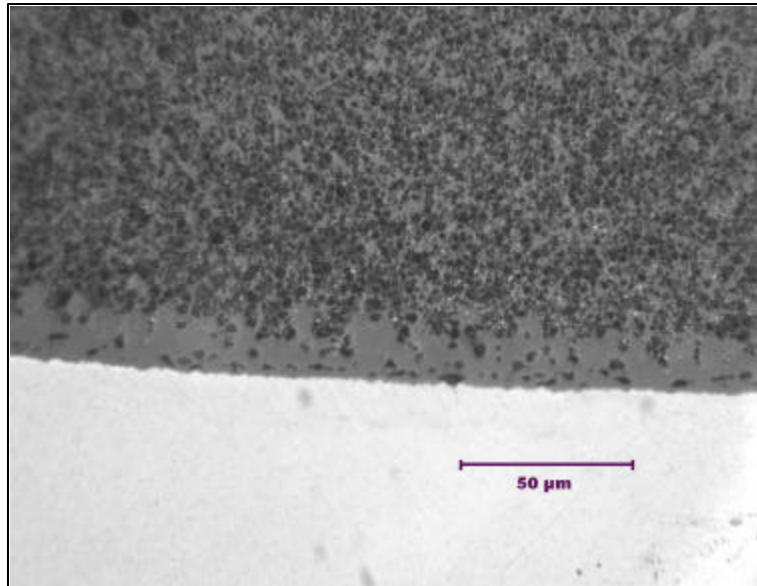


27 in. above axial midplane

H. B. Robinson Characterization (cont'd)

- **Tight fuel-cladding bond**

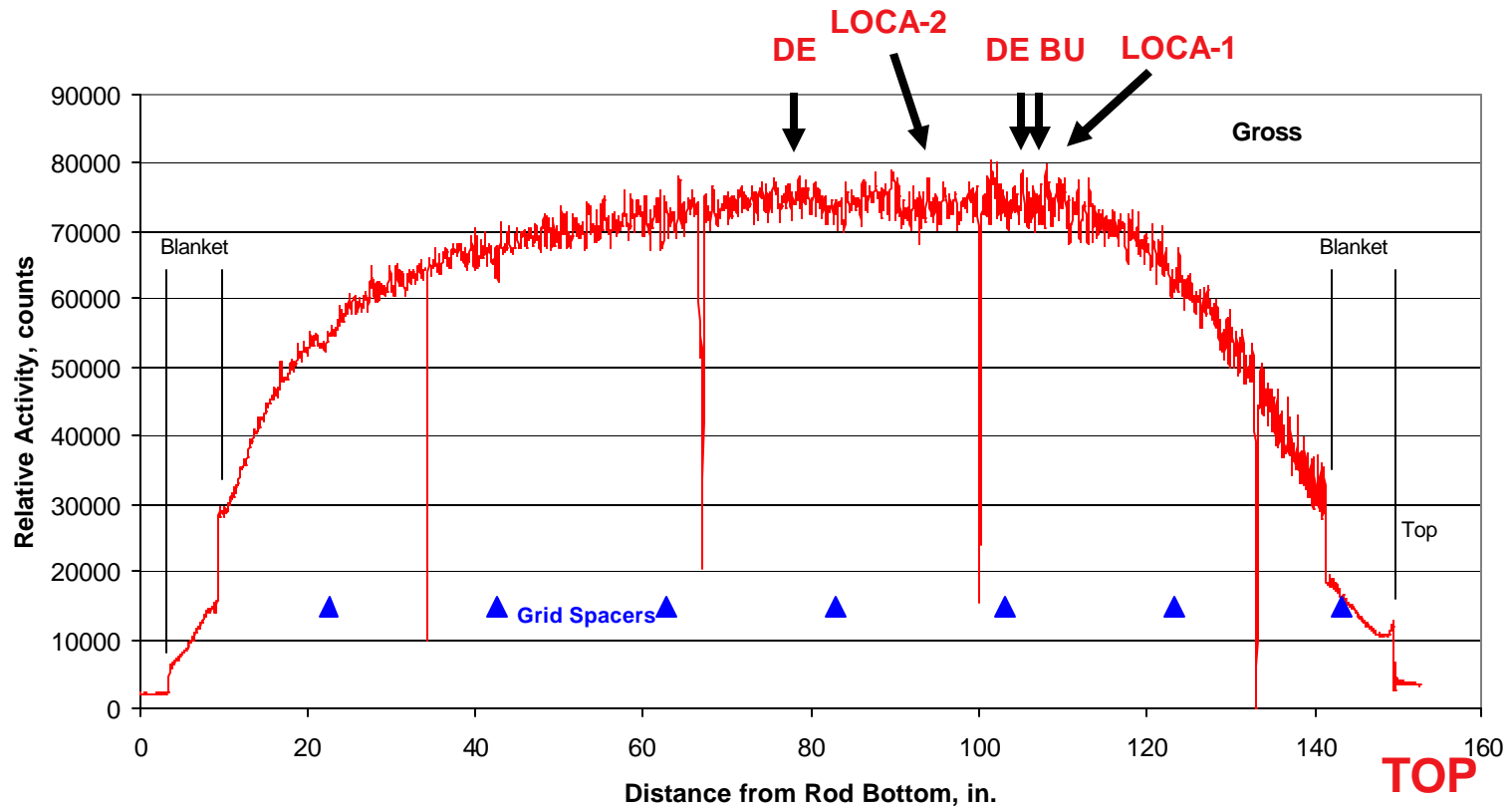
- Fission-product deposit in the fuel-cladding "gap"
- Minimal cladding ID corrosion
- Tight bond possibly impeded fission-gas release



27 in. above axial midplane

Limerick Characterization

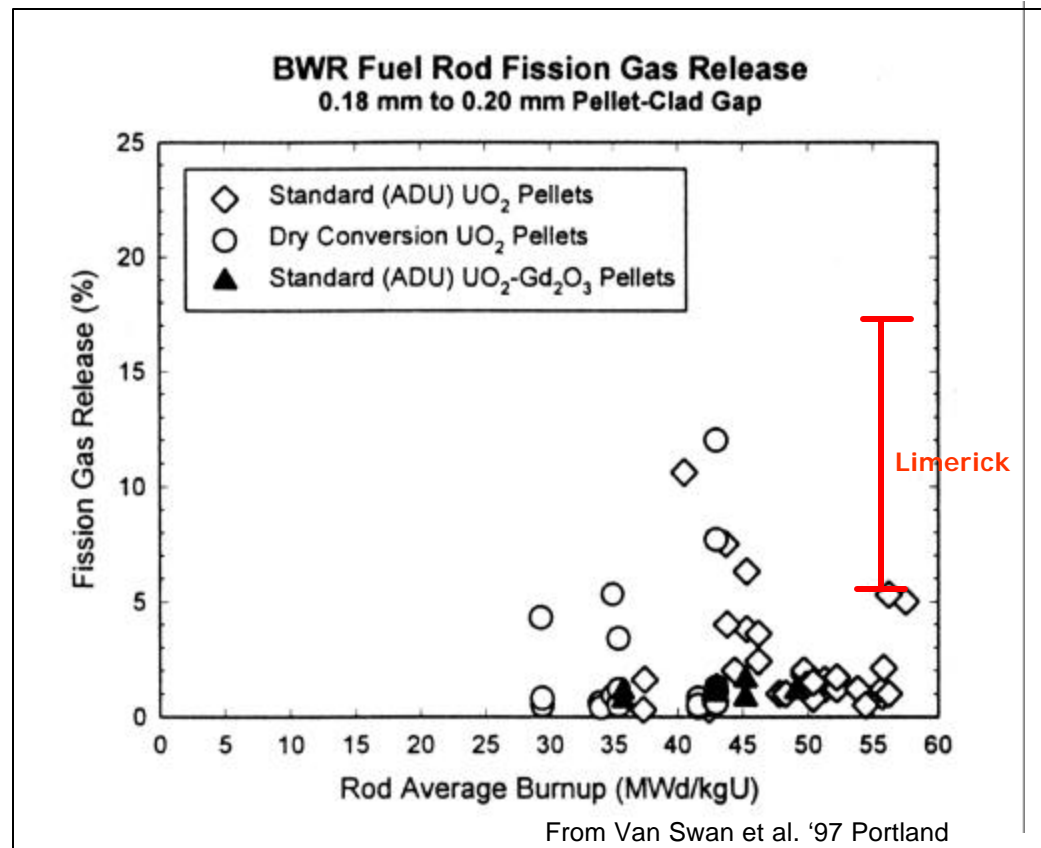
- Axial gamma profile for Rod F9 – features are normal
 - The two DE locations are 5 and 31 in. above axial midplane



Limerick Characterization (cont'd)

- **Fission-gas release**

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



Limerick Characterization (cont'd)

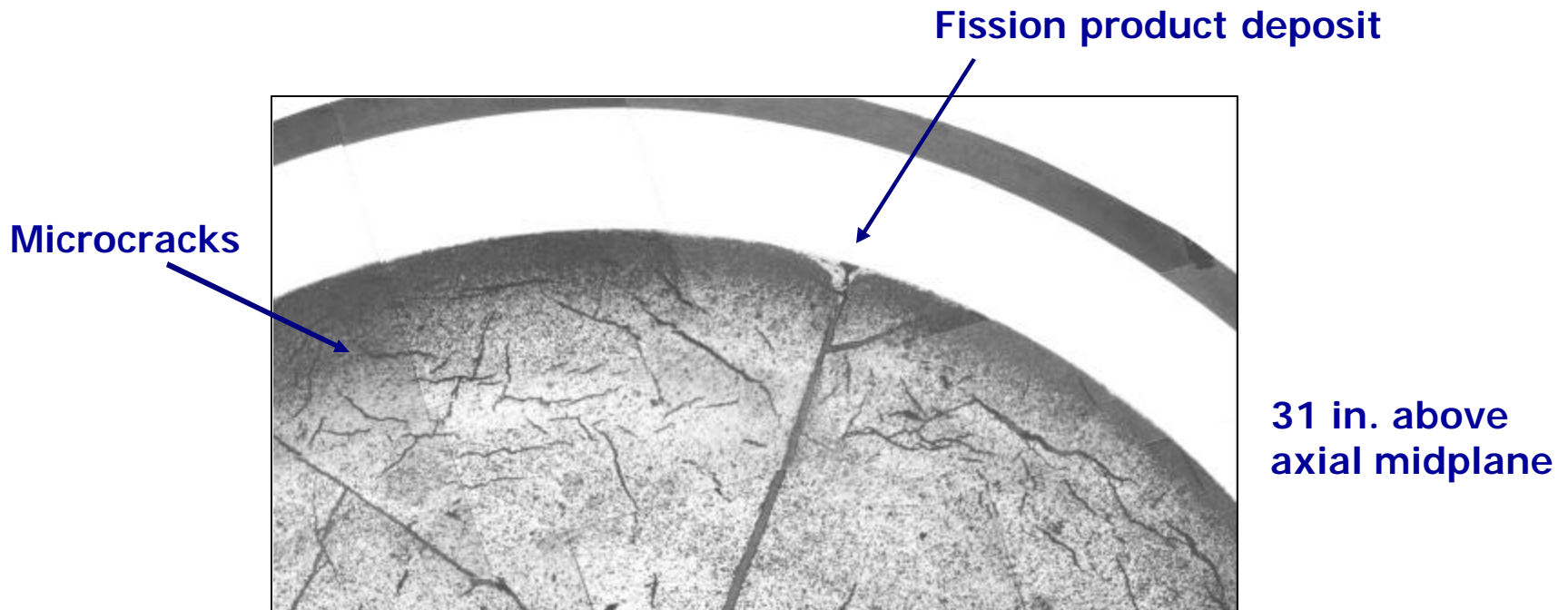
- **Rod F9, at 31 in. above midplane**

- 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



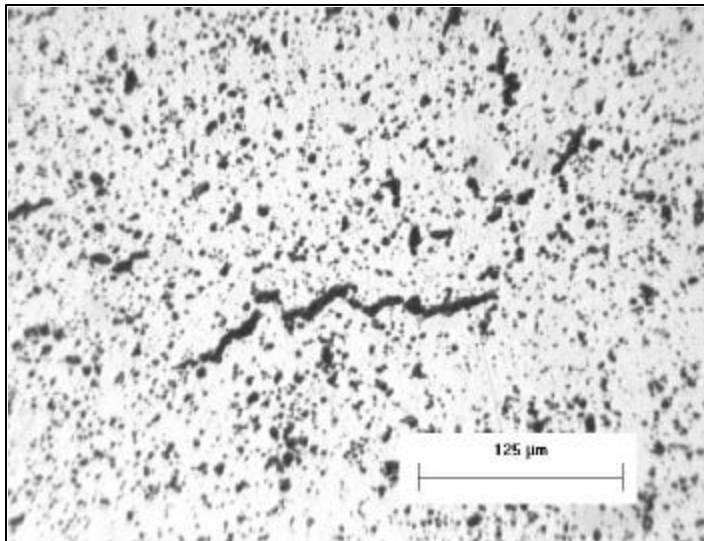
Limerick Characterization (cont'd)

- **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

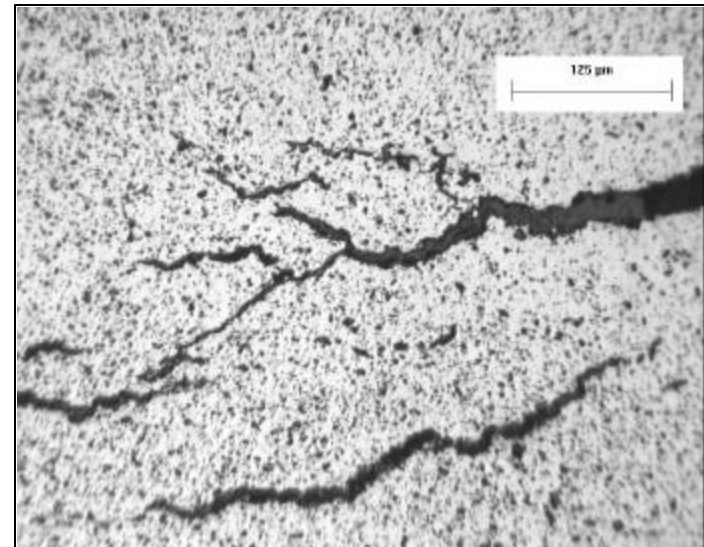


Limerick Characterization (cont'd)

- Fuel microcracks in and near the rim in F9



Incipient



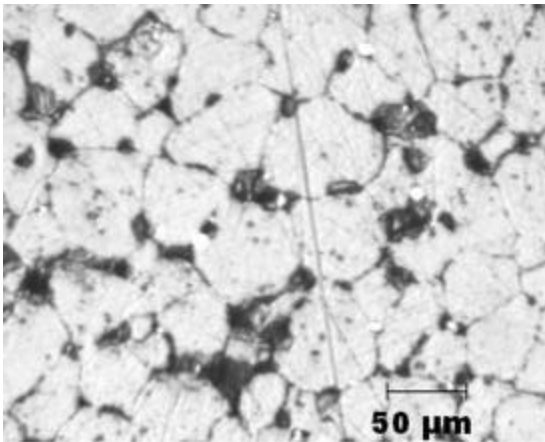
More developed

31 in. above axial midplane

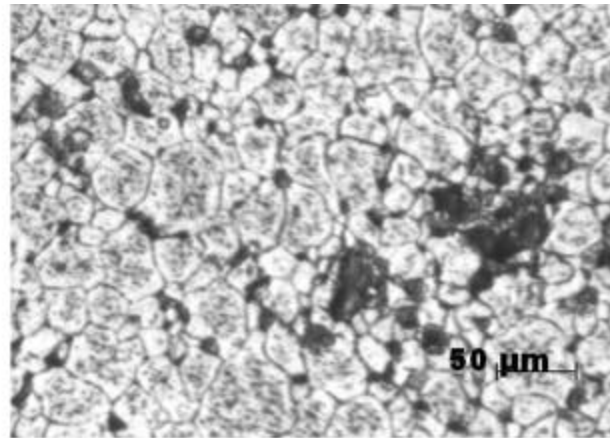
Limerick Characterization (cont'd)

- **Fuel Structure**

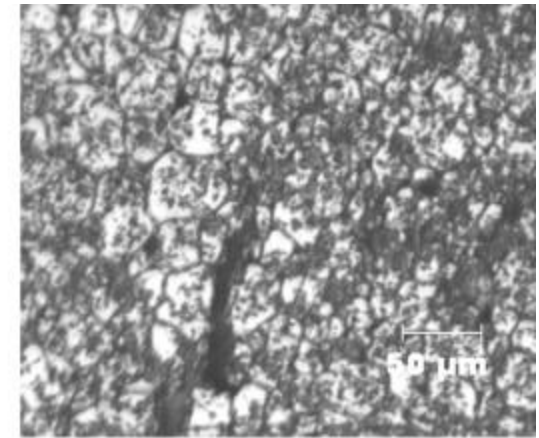
- Center – grain growth, large f.g. bubble on GB
- Midradius – numerous fine f.g. bubbles in grains
- “Rim” – small grains, numerous f.g. bubbles in grains and on GB



Center



Midradius

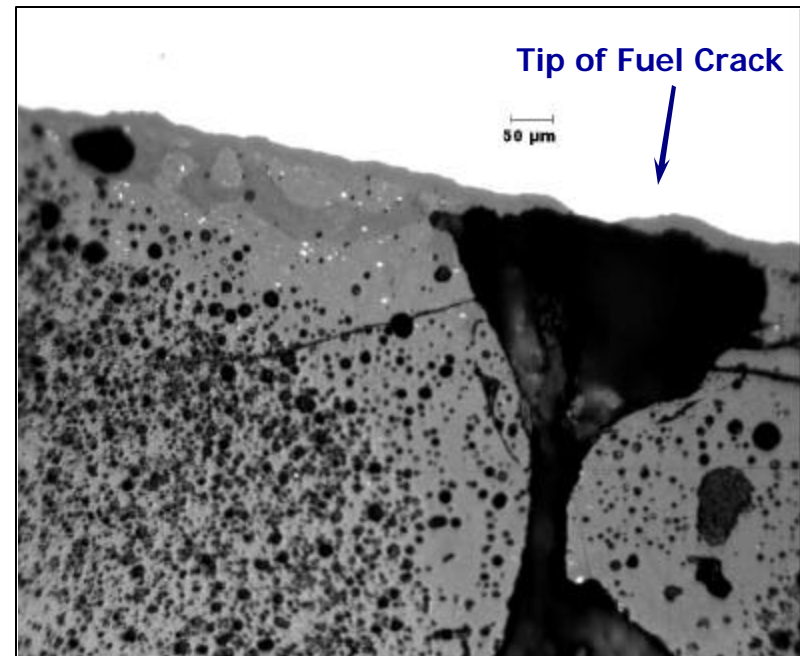
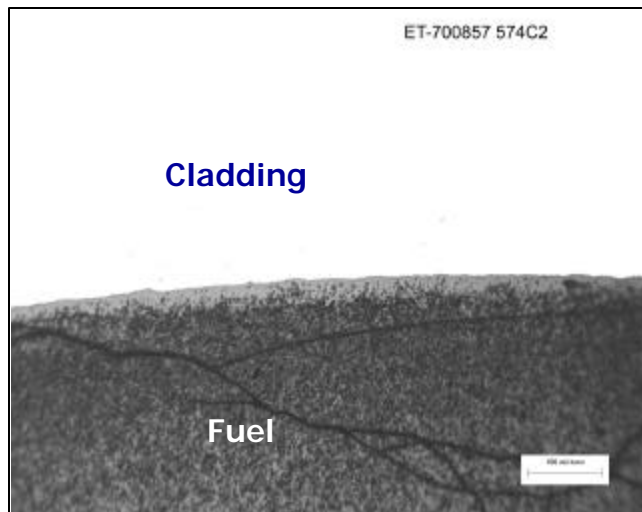


Rim

Limerick Characterization (cont'd)

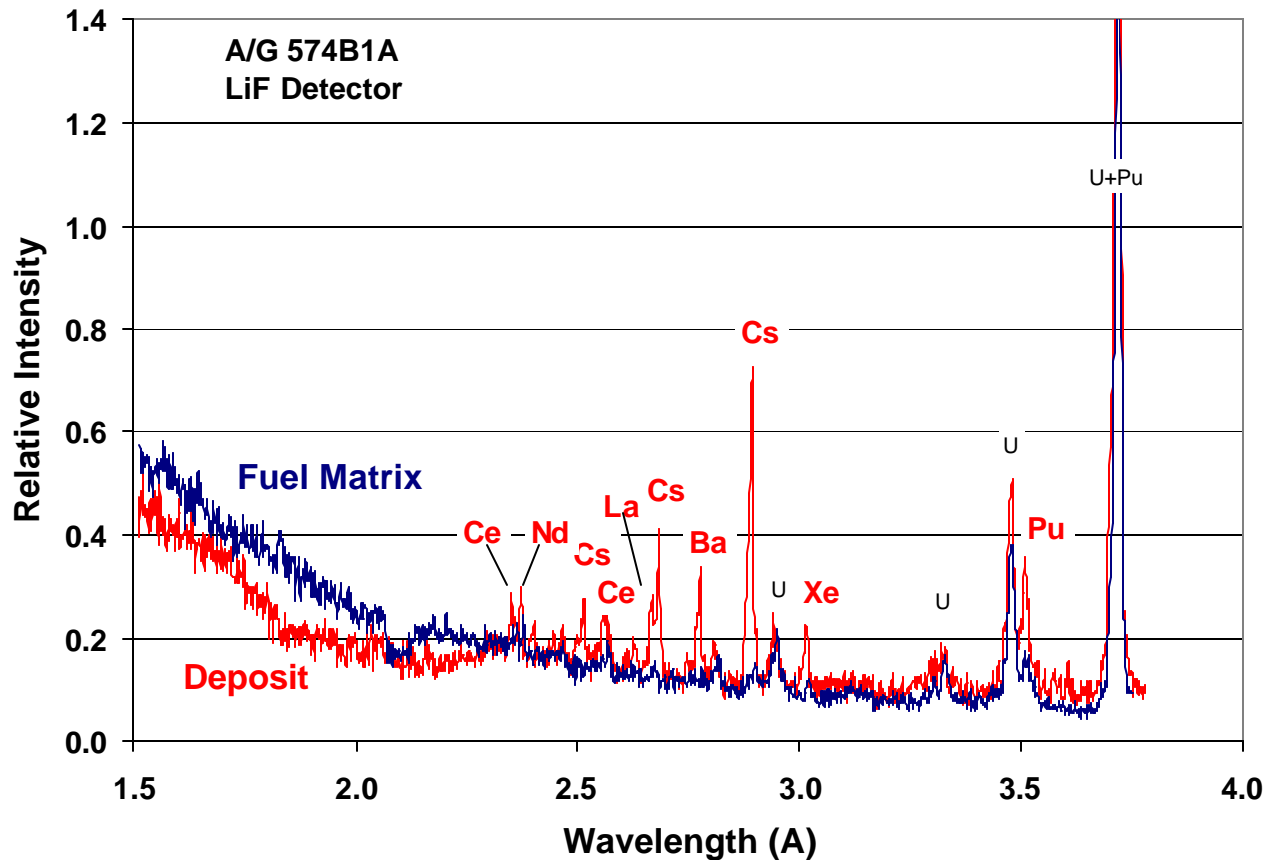
- **Fuel/Cladding Interface**

- 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

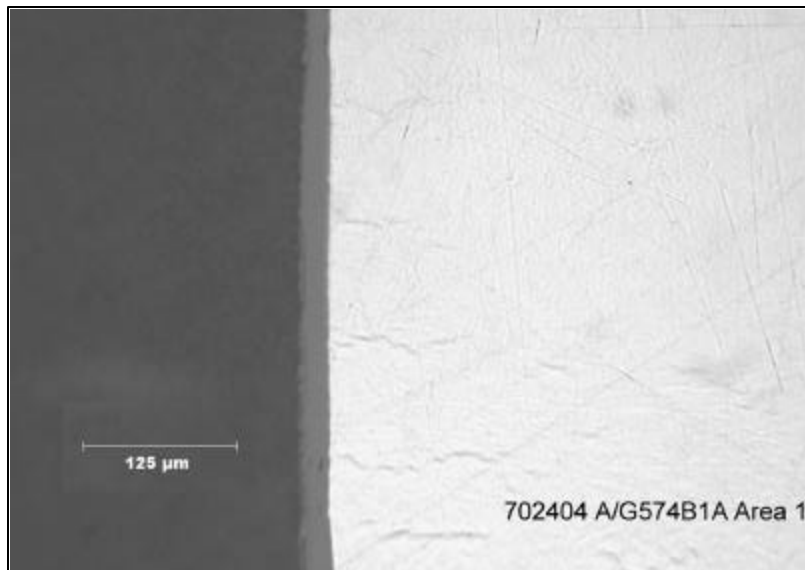


Limerick Characterization (cont'd)

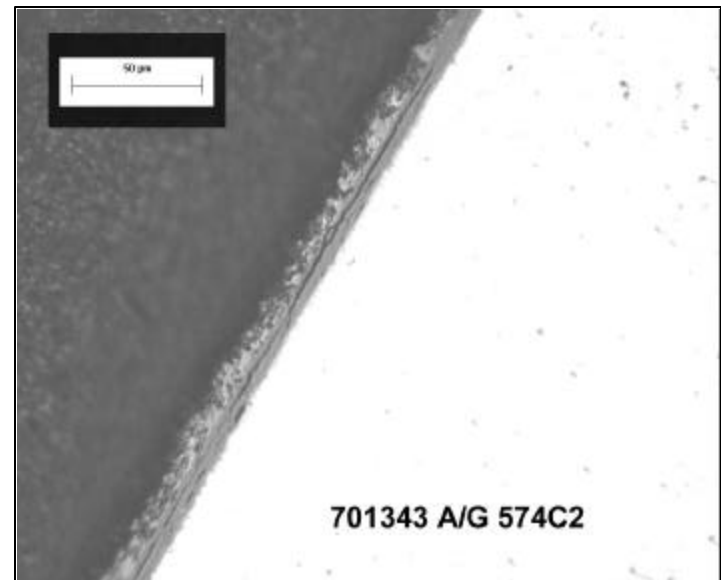
- **Cladding Corrosion**

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

Oxide

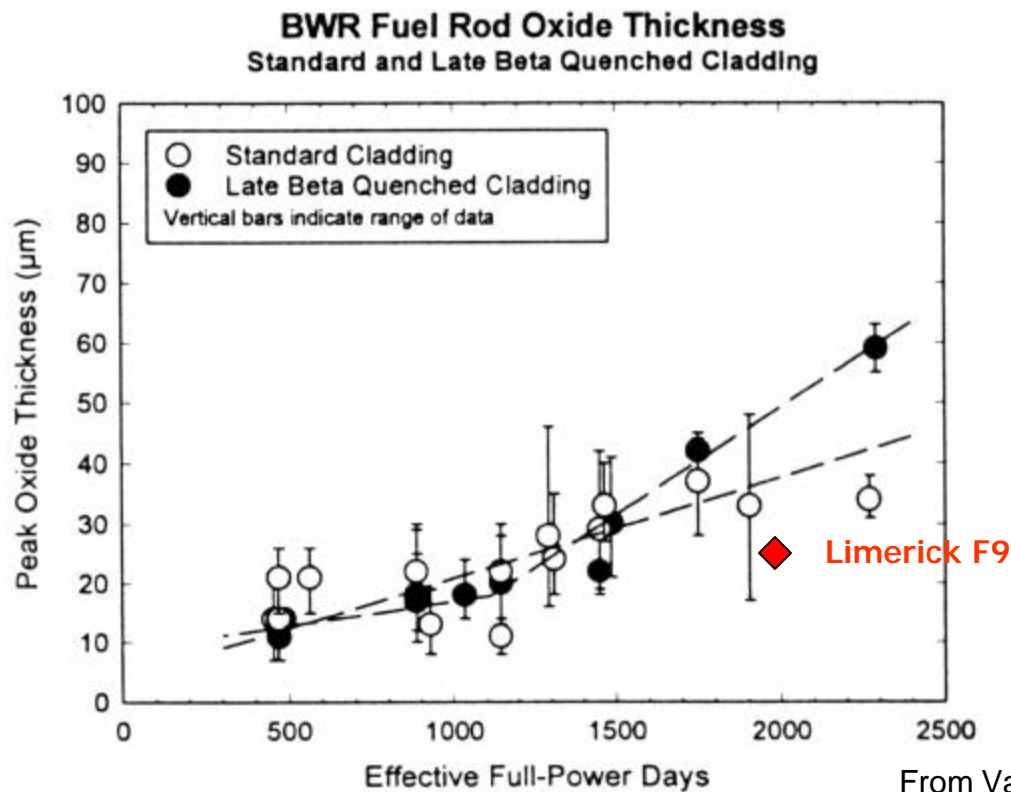


Crud over oxide



Limerick Characterization (cont'd)

- Corrosion in Limerick - modest

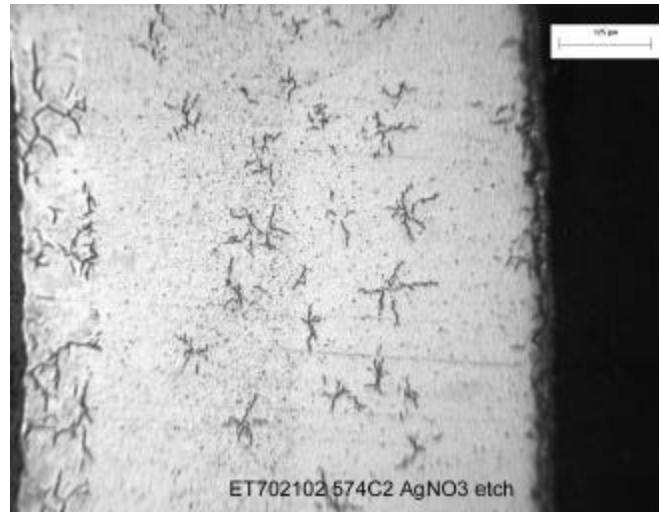


From Van Swan et al. '97 Portland

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 $\sim 100 \mu\text{m}$.
- Max. cladding hydrogen content $\sim 750 \text{ wppm}$.
- 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.