Nuclear Fuel Performance

NE-533

Spring 2025

Housekeeping

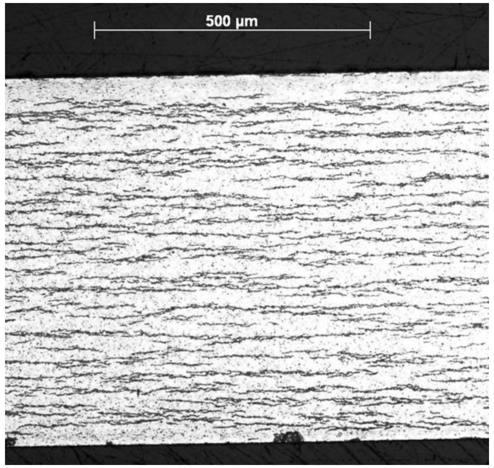
- Class eval is open:
  - http://go.ncsu.edu/cesurvey
  - You should have gotten an email requesting that you fill this out
  - This helps me improve as a professor and provides critical feedback for the course
- Have sent out a survey for my personal feedback (also here)
  - Anonymous, but email me a confirmation of your completion, and you will receive a +5 on the final exam
- Exam 3 grades
  - Avg: 84.7. Curve of 5 points.
  - Need to pay attention to units! Many simple units mistakes

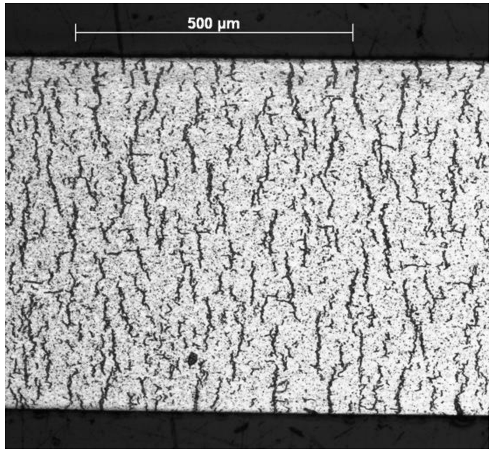
Last time

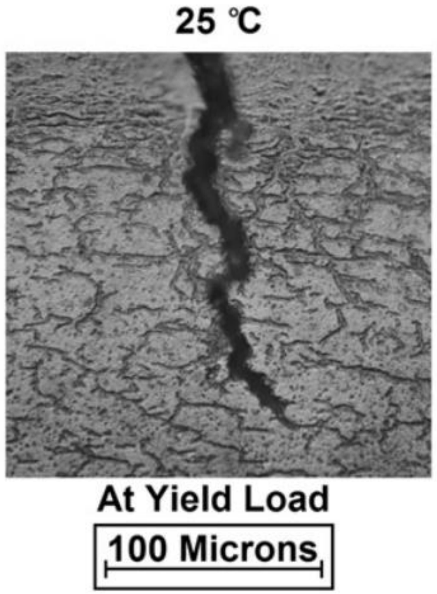
- Cladding oxidizes, forming ZrO_2
- The limiting step for oxidation is
  - the oxygen transport through the oxide layer
- Relationships for oxide thickness based on weight gain and for prediction of oxide layer growth based upon power law kinetics
- Hydrogen released by oxidation enters the cladding
- Hydrides preferentially form:
  - in areas of tensile stress and lower temperature (solubility and Soret effect)
- Mechanical effect of hydrides:
  - hydrides are brittle, and so reduce the ductility of the cladding

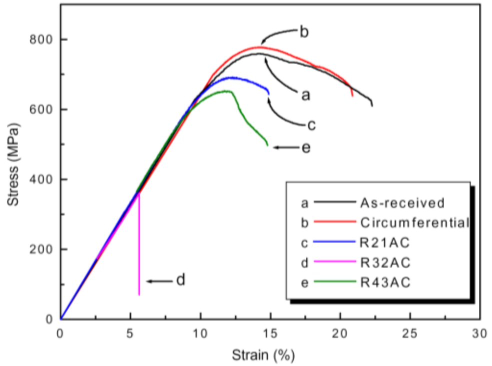
Circumferential vs Radial Hydrides

- Under reactor conditions, hydride platelets precipitate circumferentially
- In used fuel after drying, the hydrides can reprecipitate with a radial orientation
- The hydrides reform in a radial direction due to the tensile radial stress
- Radial hydrides provide easy crack paths and significantly decrease the ductility of the cladding



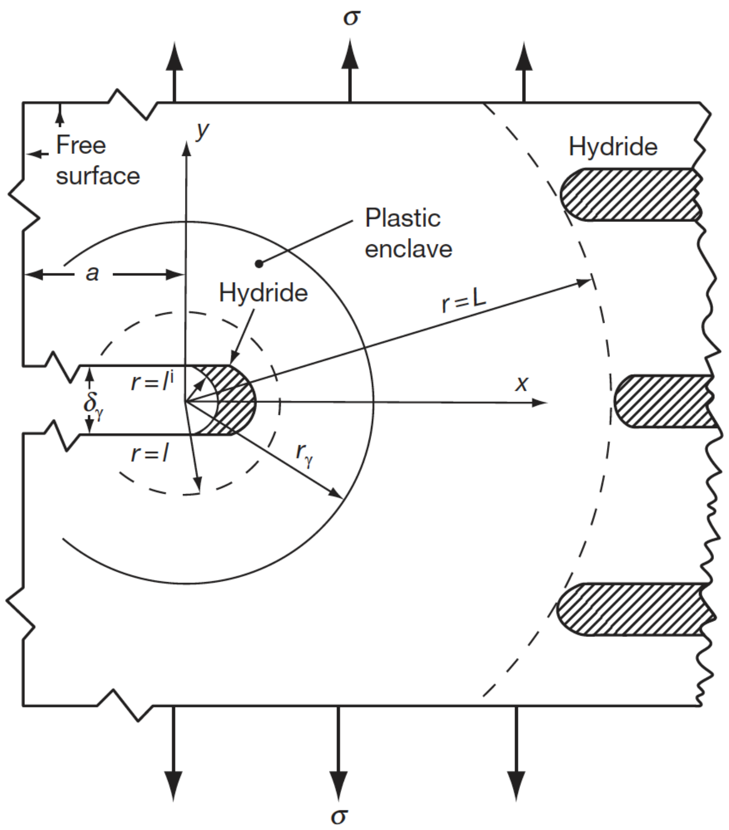






Delayed Hydride Cracking

- The theory of DHS is that the crack tip hydride grows as hydrogen migrates from hydrides in the bulk of the material to the crack tip
- The driving force for the diffusion of the hydrogen is the difference in the chemical potential of hydrogen between the bulk material and the crack tip hydride in response to stress
- An increasing hydrostatic tensile stress reduces the chemical potential of hydrogen in the hydride relative to the bulk
- This chemical potential difference causes hydrogen in solution to diffuse to the crack tip where it precipitates



Hydrogen Pickup

- The fraction of the produced hydrogen that enters the cladding is defined by the pickup fraction:

$$f_H = \frac{H_{absorbed}}{H_{generated}}$$

- Hydrogen is produced twice as fast as oxygen
  - $J_H = 2\, f\, J_O$
- We can estimate the hydrogen content in the cladding from the oxide thickness δ and the pickup fraction f

$$C_H^{clad}[wt.ppm] = \frac{m_H}{m_{Zr}} = \frac{2\, f m_O}{m_{Zr}} = \frac{2f \times \delta \times \rho_{oxide} \times f_{ZrO_2}^{O} \times M_H / M_O}{\left(t - \frac{\delta}{PBR}\right) \times \rho_{metal}} x10^6$$

C_H^{clad} concentration (wt ppm)

ρ_{oxide} oxide density

ρ_{Zr} Zr metal density

$f_{ZrO_2}^{O}$ Fraction of oxygen in ZrO2 mass

PBR Pilling-Bedworth Ratio

M_H moelcular mass of H

M_O molecular mass of O

t cladding thickness

Given a thickness of oxide, how can we predict the hydrogen pickup?

- A cladding with an initial thickness of 600 microns that initially has 40 wt. ppm H undergoes corrosion to a total oxide thickness of 80 microns. What is the overall hydrogen content in wt. ppm if the hydrogen pickup fraction is 15%?
- First, we must determine the weight of H that has entered the cladding
  - ρ_{ZrO2} is 5.68 g/cm^3, of which 32/(91+32)= 0.26 = 26% is O, thus 1.47 g/cm^3 of O
  - A 1 micron oxide layer corresponds to a weight gain of 14.7 mg/dm^2 and thus with an 80 micron layer, weight gain = 14.7*80 = 1176 mg/dm^2
  - This mass corresponds to 1.176 N_A/16 atoms of oxygen = 4.42 x 10^{22} atoms/dm^2
  - f = 15%, so the ingress of hydrogen will be 0.15*2*4.42e22 = 1.33e22 atoms of hydrogen/dm^2, or 0.022 g of H.
- Now, we determine the fraction in wt. ppm in a 10 cm square cross section w/ PBR = 1.56
  - The uncorroded thickness is 600 – 80/PBR = 600 – 80/1.56=549 microns
  - The volume of zirconium is 549 x 10^{-4} (cm)*10*10 =5.49 cm^3
  - ρ_{Zr} = 6.5 g/cm^3, so the total mass of Zr is 6.5*5.49 =35.7 g.
- Thus the hydrogen concentration is 0.022/35.7 =6.18e-4= 618 wt. ppm, which, added to the original 40 wt. ppm, is 658 wt. ppm

Hydrides Summary

- Hydrogen released by oxidation enters the cladding and quickly diffuses throughout the cladding
- Due to low solubility (that is a function of temperature), hydrides form
- Hydrides are brittle, and so reduce the ductility of the cladding
- Hydrides form circumferentially under operating conditions due to the tensile hoop stress in the cladding
- Radial hydrides can form in used fuel after drying, and reduce ductility much more than circumferential hydrides
- DHC is a phenomenon based upon increased solubility of hydrogen in the high tensile stress around a crack tip
- Have the ability to predict hydrogen pickup in oxidized Zr cladding

ACCIDENT SCENARIOS

Kinds of Accidents

- Design basis accident: DBA
  - are postulated, credible accidents with low probability that are used to establish the design basis for the reactor and to define safety limits for its operation
  - two main kinds are RIA and LOCA
- Beyond design basis accident: BDBA
  - accidents that fall outside of what is designed for, because they are deemed too unlikely to be included in design

Reactivity Initiated Accident (RIA)

- Reactivity is the fractional departure from criticality: $\delta k = (k - 1)/k$
  where k is your effective multiplication factor
  - k = (Neutrons produced in one generation)/(Neutrons produced in the previous generation)
  - $k = \varepsilon L_f\, p\, L_{th}\, f\, \eta$ – this is your six-factor formula
  - ε = fast fission factor
  - L_f = fast non-leakage factor
  - p = resonance escape probability
  - L_{th} = thermal non-leakage factor
  - *f* = thermal fuel utilization factor
  - η = reproduction factor

Reactivity

- Reactivity = rho = r = $\delta k = (k - 1)/k$
- At steady state, k=1, rho=0
- Reactivity is affected by the temperature and density of coolant, moderator, and fuel
- Ideally, nuclear reactors are designed so that a power increase will generate negative reactivity feedback
  - an increase in the reactivity (higher k) leads to material changes, which in turn force a negative reactivity (lower k)

RIA-PWR

- Design Basis Accident: Large and rapid insertion of reactivity caused by inadvertent ejection (PWR) or drop (BWR) of a control rod
- A control rod ejection or drop can occur by mechanical failure of the control rod drive mechanism or its housing, and the reactivity of the core can rapidly increase due to decreasing neutron absorption of non-fuel
- PWR
  - Control rod ejection accident (CREA)
  - Caused by mechanical failure of a control rod mechanism housing, such that the coolant pressure ejects a control rod assembly completely out of the core
  - Reactivity increase to the core occurs within about 0.1 s in the worst possible scenario
  - The most severe CREA would occur at normal coolant temperature and pressure, but with nearly zero reactor power

RIA-BWR

- BWR
  - Control rod drop accident (CRDA)
  - Initiated by the separation of a control rod blade from its drive mechanism
  - Detached blade remains stuck in position until it suddenly becomes loose and drops out of the core in free fall
  - Most severe CRDA would occur at with the coolant close to room temperature and atmospheric pressure, and the reactor at nearly zero power
- Other RIAs
  - inadvertent changes in coolant/moderator temperature and/or void fraction may add reactivity to the core

RIA

- RIA leads to a fast rise in fuel power and temperature
- This power ramp can lead to failure of fuel rods and release of radioactive material (or potentially fuel) into coolant
- Release of hot fuel into water can cause rapid steam generation and pressure pulses, damaging other core internals
- Coolant pressure pulse could break the reactor coolant pressure boundary or damage the fuel and other core internals so that long-term cooling of the core would be impaired
- To prevent such consequences, safety criteria are set up to limit energy injection into the fuel

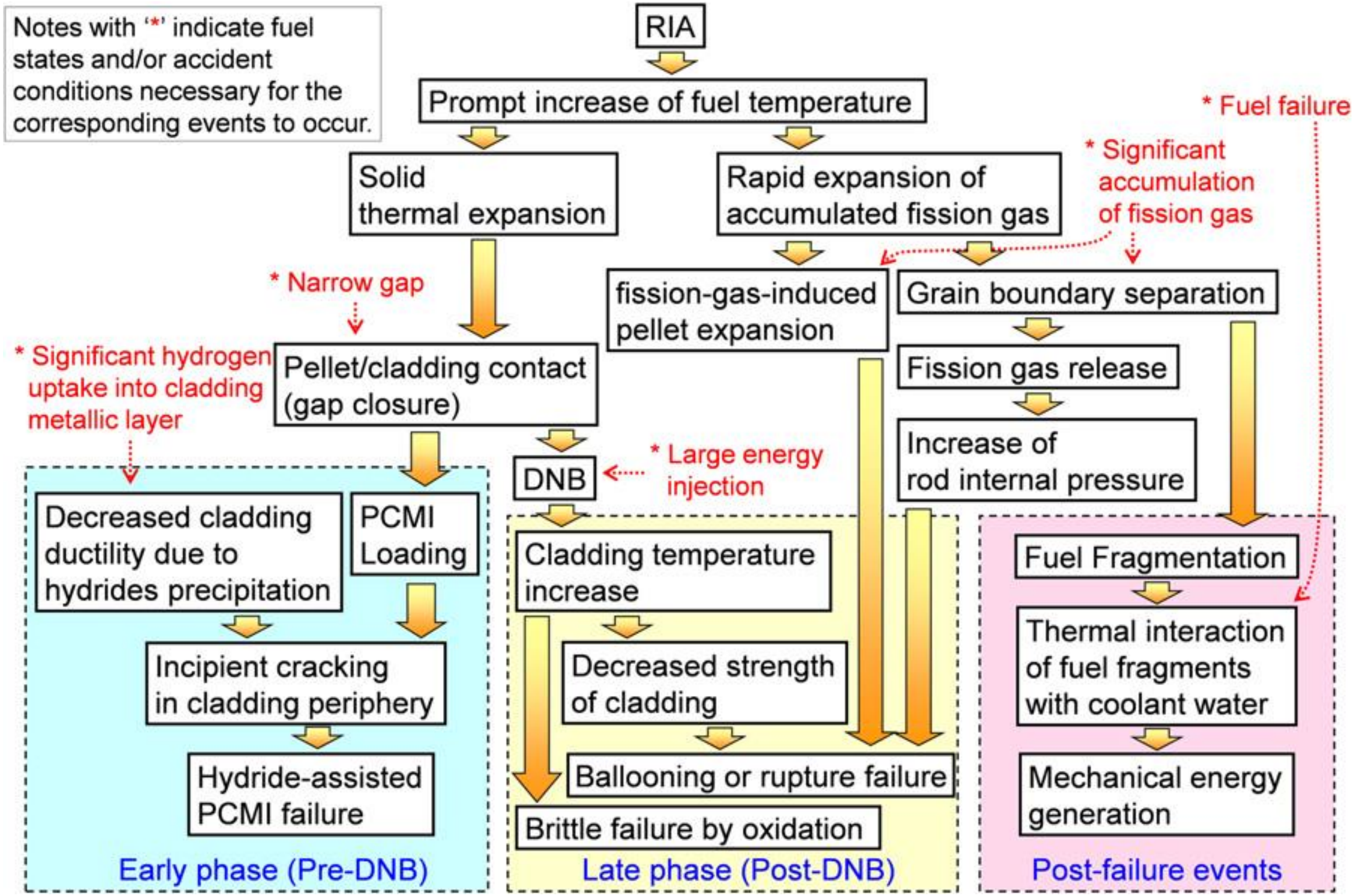
History of RIA

- No RIA with severe consequences has occurred in PWRs or BWRs
- The first reactivity-initiated accidents occurred in the 1950s and 1960s and concerned the first generation of research reactors
  - 1952 accident in the NRX reactor at Chalk River
  - 1961 SL-1 accident in Idaho Falls
- Both resulted in severe damage and disruption of the reactor, and led to design improvements for later generations of RRs and commercial reactors
- Did not eliminate RIAs
  - K-431 Russian Echo-II nuclear powered submarine in 1985
  - Chernobyl nuclear power plant, Ukraine, in 1986

Chernobyl RIA

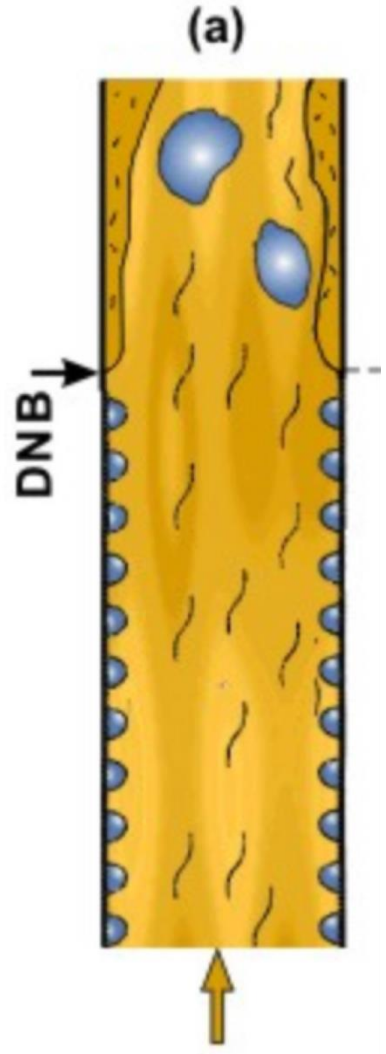
- Light water graphite moderated pressure tube design (RBMK)
- Severe consequences of the Chernobyl accident were due to the fact that RBMKs lack not only a reactor containment, but also some of the inherent feedback mechanisms
- Accident occurred under a reactor test, where normal operating guidelines were ignored and safety systems were shut off
- Chernobyl accident prompted new research into reactivity-initiated accidents
  - focused on high burnup fuel, where previous safety standards had largely been on fresh fuel or low BU

Sequence of RIA



Departure from Nucleate Boiling

- If the heat flux of a boiling system is higher than the critical heat flux (CHF) of the system, the bulk fluid may boil, or in some cases, regions of the bulk fluid may boil where the fluid travels in small channels
- Large bubbles form, sometimes blocking the passage of the fluid
- This results in a departure from nucleate boiling (DNB) in which steam bubbles no longer break away from the solid surface of the channel, bubbles dominate the channel or surface, and the heat flux dramatically decreases
- Vapor essentially insulates the bulk liquid from the hot surface, increasing surface temperatures



Microstructural Effects

- Rapid increase in temperature increases pressure of bubbles
- PV = nRT
- Rapid pressure increase leads to cracking in fuel

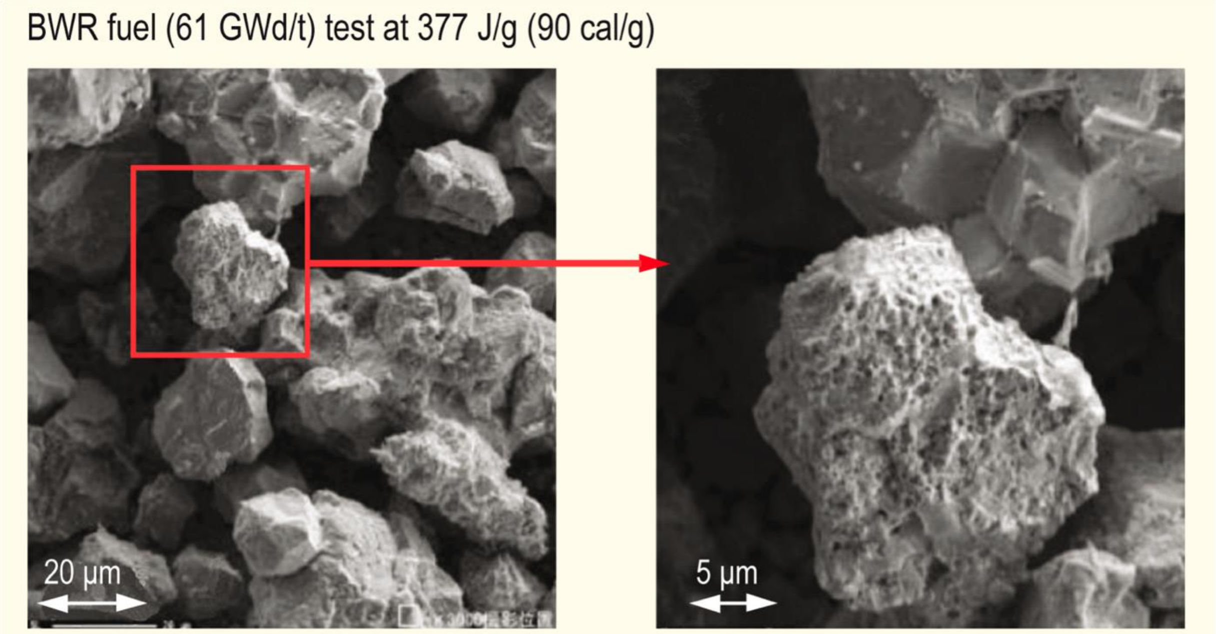
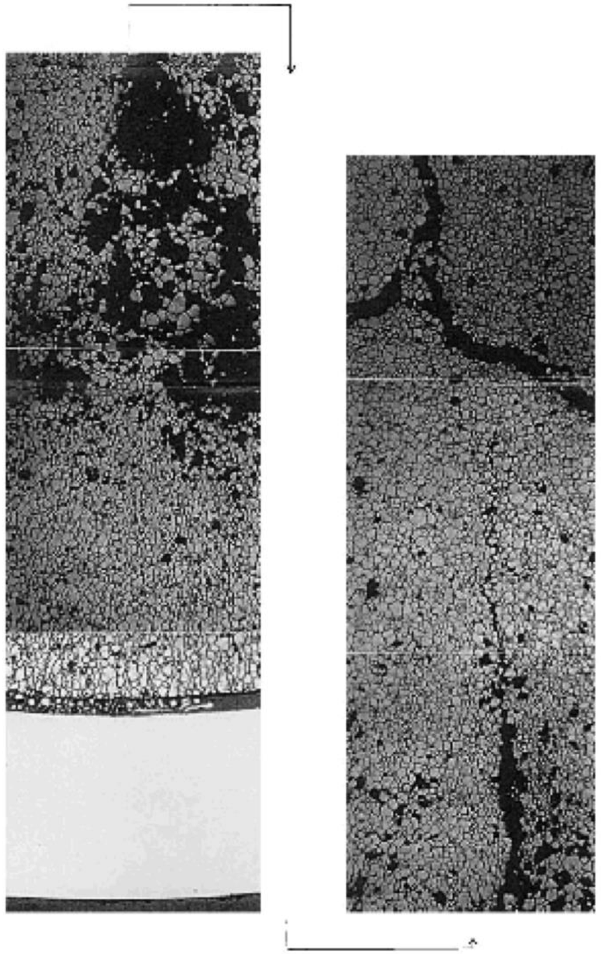


Figure – Redrawn and modified from original by A.N.T. INTERNATIONAL 2010



Cladding Response

- Take into account burnup, corrosion (oxide layer and hydrides), damage accumulation, PCMI, internal pressure, etc. to properly evaluate strain in cladding
- Temperature spike leads to a stress spike, and higher likelihood of cladding failure
- Cladding fails either due to PCMI, ballooning/burst, severe oxidation, or partial melting