Nuclear Fuel Performance

NE-533

Spring 2022

Last time

- Larry gave a talk on NEAMS activities on U-Pu-Zr and UO2
- This guest talk will be included in the subject material for the third exam

- Previous lecture
- Cladding oxidizes, forming ZrO_2
- The limiting step for oxidation is the oxygen transport through the oxide layer
- Oxidation hurts cladding performance by restricting heat transport and converting zircaloy into a brittle oxide
- Hydrogen released by oxidation enters the cladding, due to low solubility hydrides form
- Hydrides are brittle, and so reduce the ductility of the cladding
- Hydrides preferentially form due to temperature and stress state

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
- 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
  - and 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
- 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 a 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

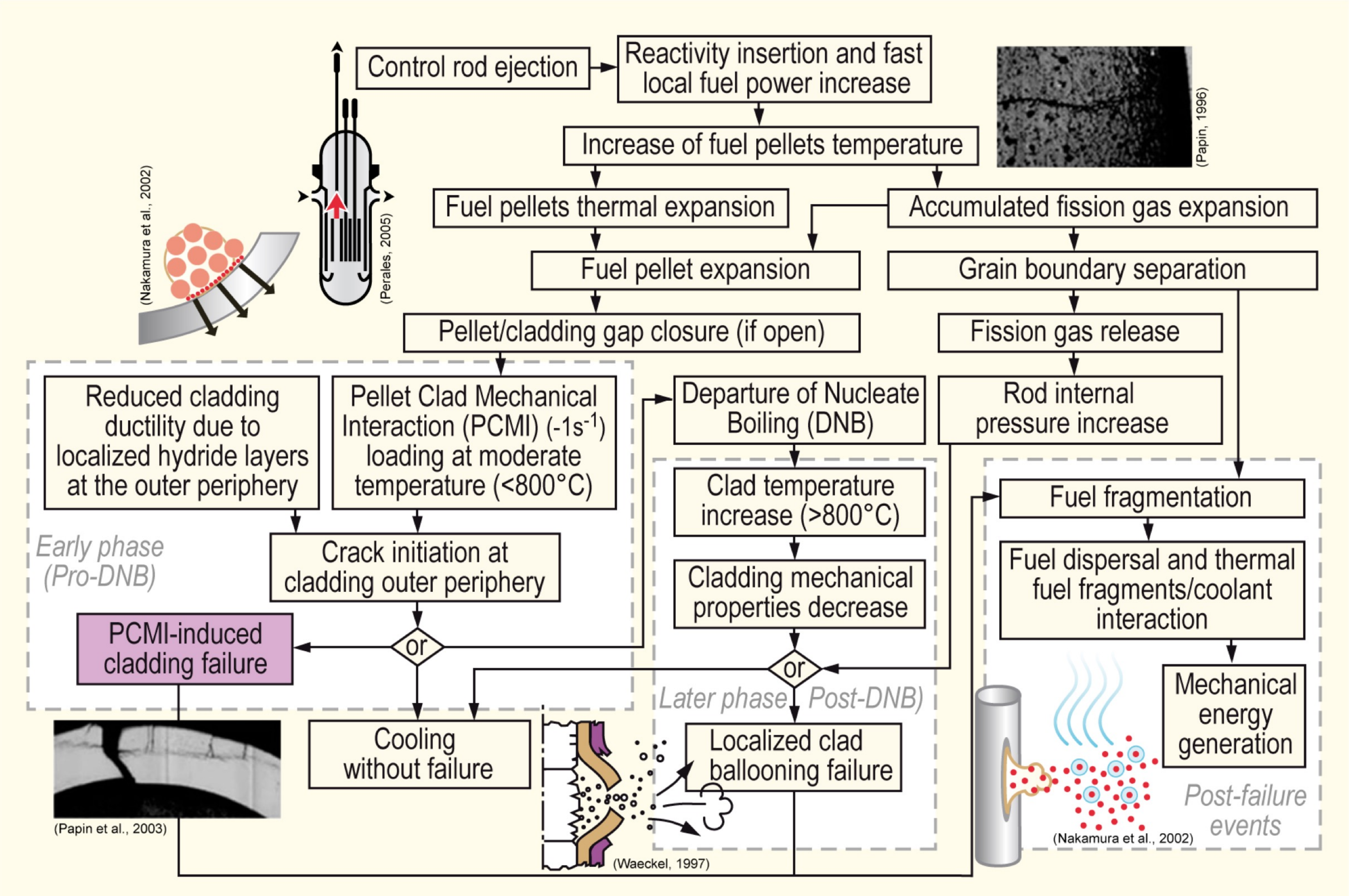
History of RIA

- 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

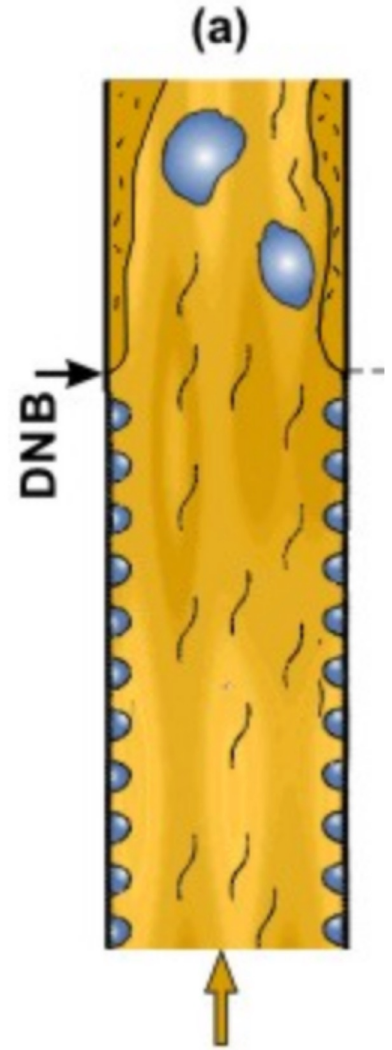
- Light water graphite moderated pressure tube design (RBMK)
- Severe consequences of the Chernobyl accident were due to the fact that RBMKs lack not only a reactor containment, but also some of the inherent feedback mechanisms
- Accident occurred under a reactor test, where normal operating guidelines 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

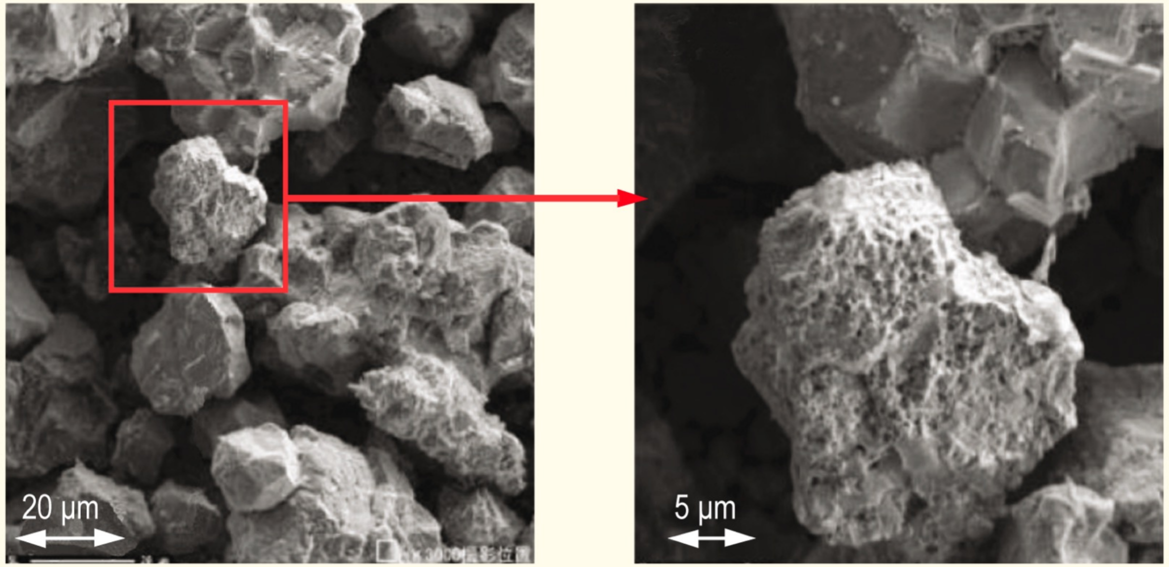
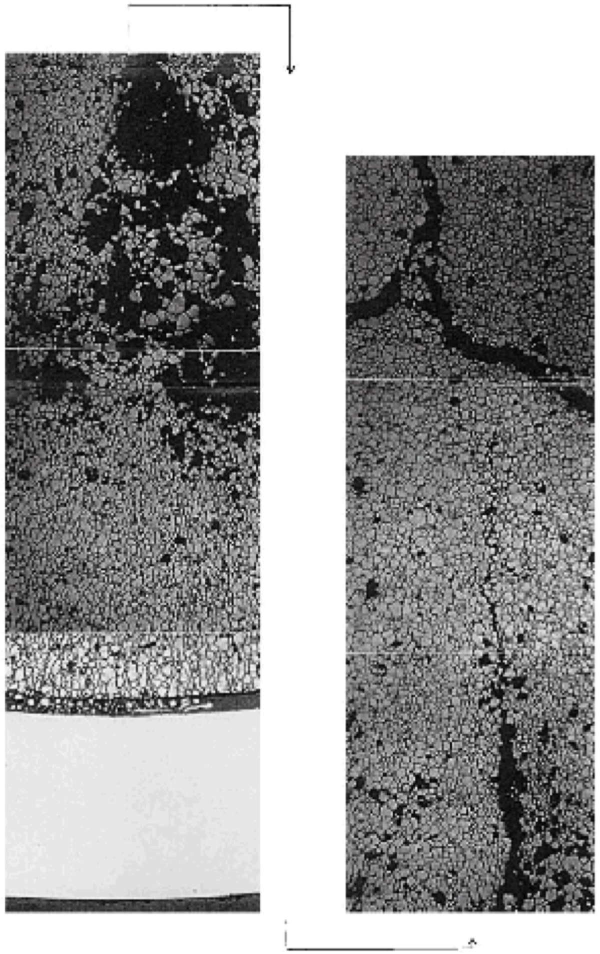
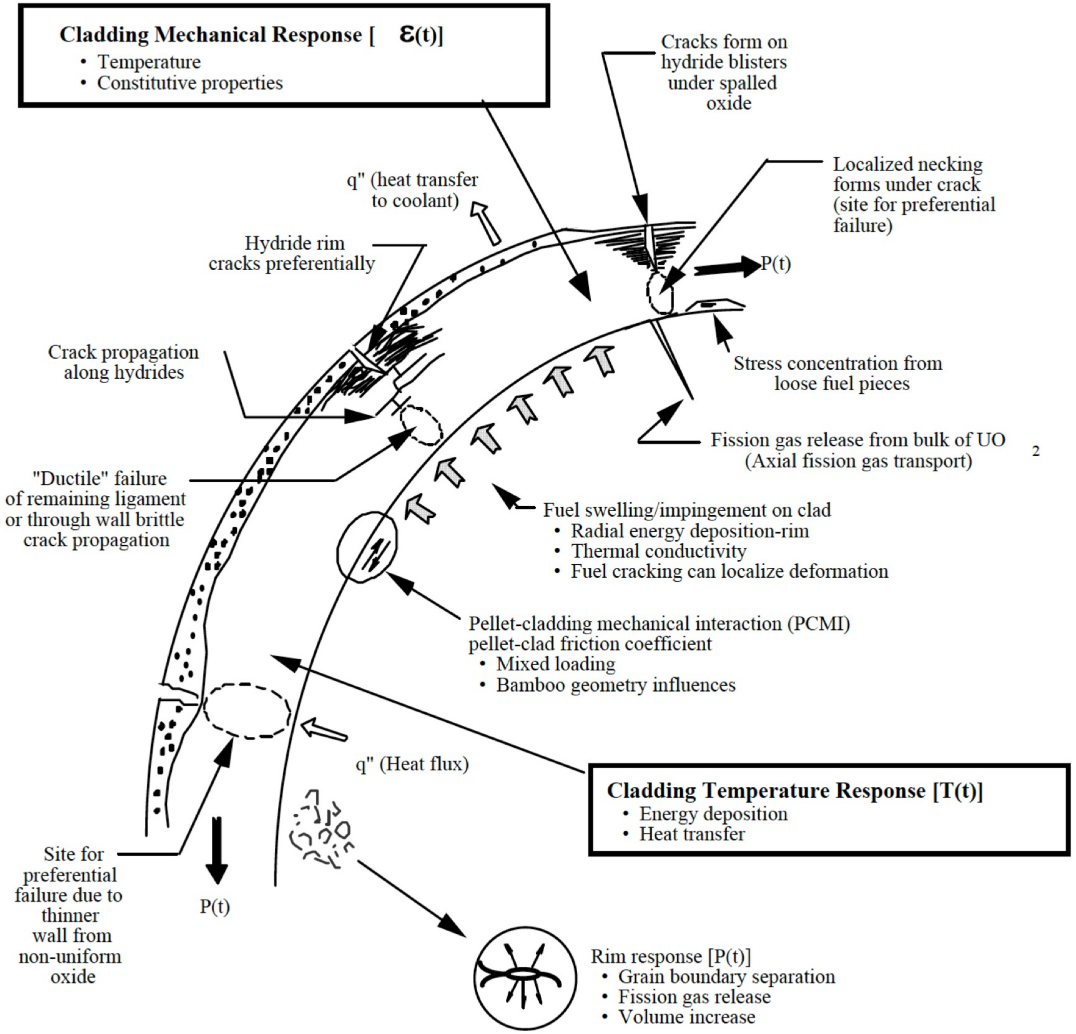


Figure – Redrawn and modified from original by A.N.T. INTERNATIONAL 2010



Cladding Response

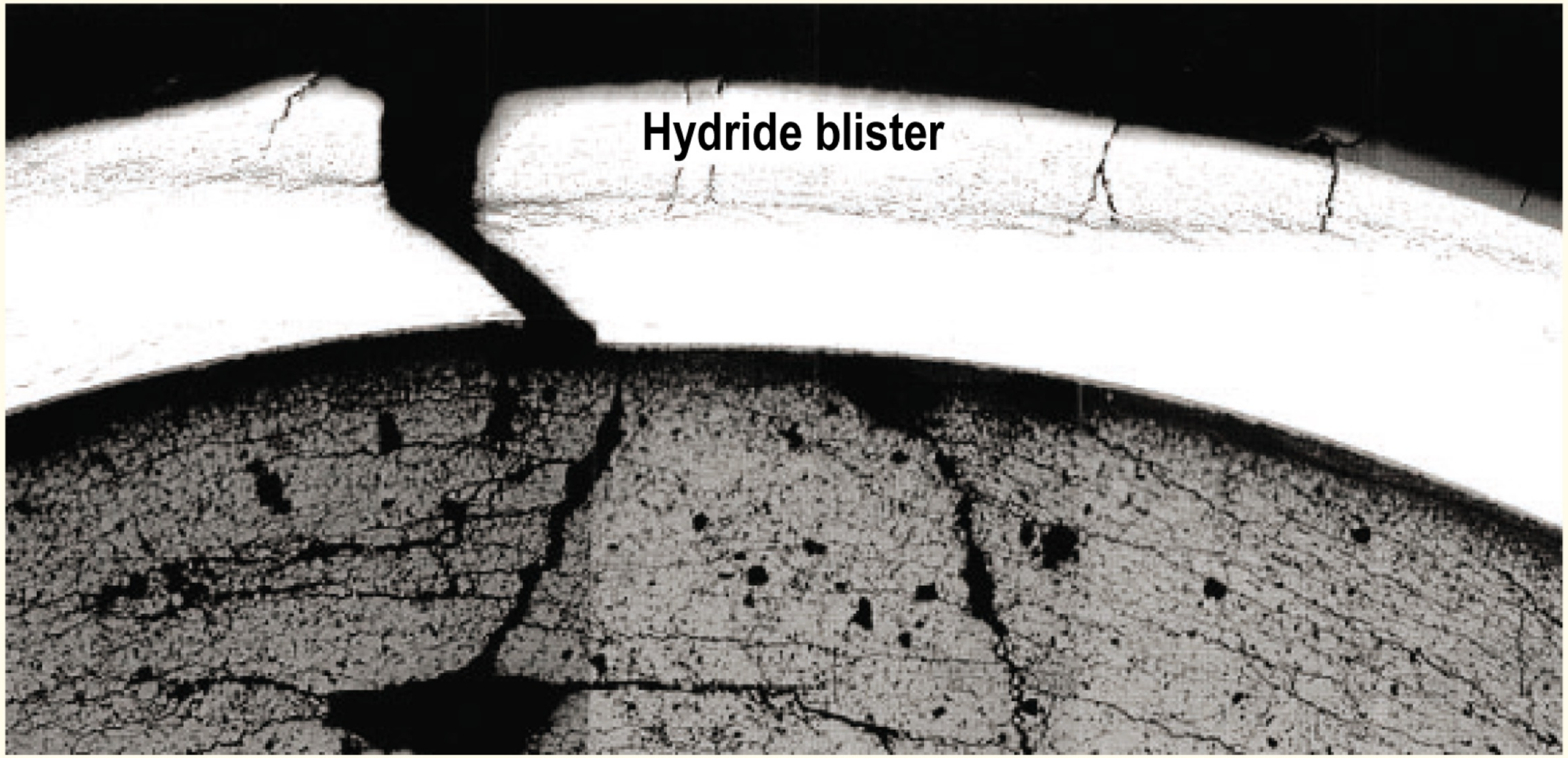
- Take into account burnup, corrosion (oxide layer and hydrides), damage accumulation, FCMI, internal pressure, etc. to properly evaluate strain in cladding
- Temperature spike leads to a stress spike, and higher likelihood of cladding failure



Cladding Response

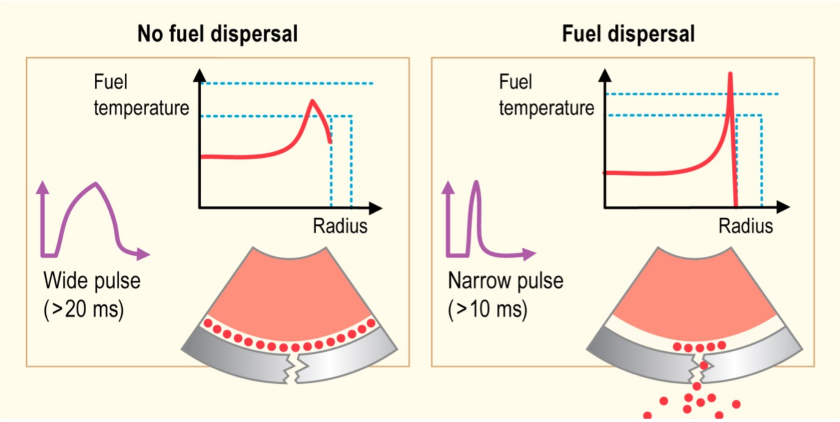
- PCMI failures results from the fuel pushing out on the cladding, causing it to break

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



Pulse Width

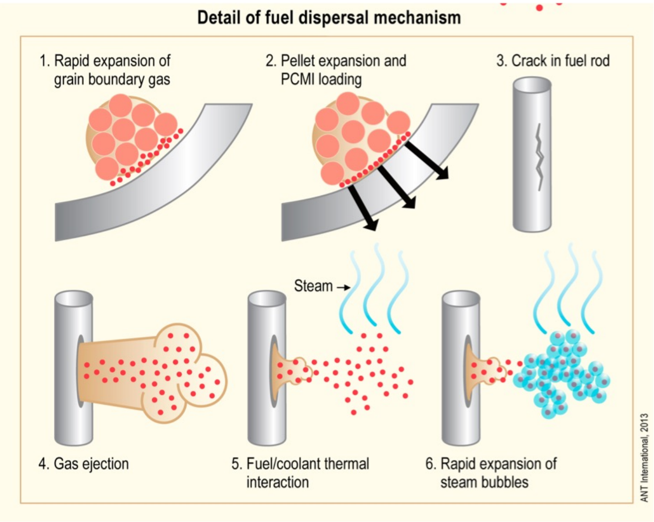
- The amplitude and width of the power pulse can have dramatic impacts on the effects of the RIA
- Pulse is typically defined by FWHM, and by total energy deposition (integration of pulse)
- More rapid temperature spike is more damaging
- Reactor state and type during typical accident scenarios determine pulse width



Estimated pulse widths and core-wide maxima of fuel pellet radial average enthalpy and enthalpy increase for various scenarios of CREA and CRDA. The data are compiled from realistic and moderately conservative computer analyses of cores with UO_2 fuel.

Reactor, accident scenario	Pulse width [ms]	Max fuel enthalpy [$J(gUO_2)^{-1}$]	Max ent. increase [$J(gUO_2)^{-1}$]	Rod worth [10^{-5}]	Literature sources [references]
PWR:					
CREA HZP	25–65	110–320	40–250	600–940	[9, 10, 14–18]
CREA HFP	400–4500	230–350	1–130	40–200	[10, 14, 17, 19–21]
BWR:					
CRDA CZP	45–75	140–460	130–450	700–1300	[10, 11, 14, 22]
CRDA HZP	45–140	160–00	90–320	600–1300	[10, 22, 23]
HZP: Hot zero power, **HFP**: Hot full power, **CZP**: Cold zero power					

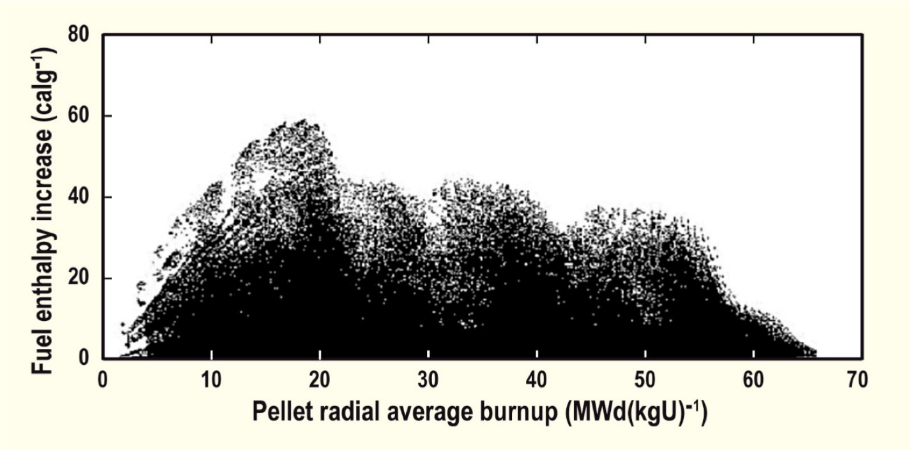
ANT International, 2016

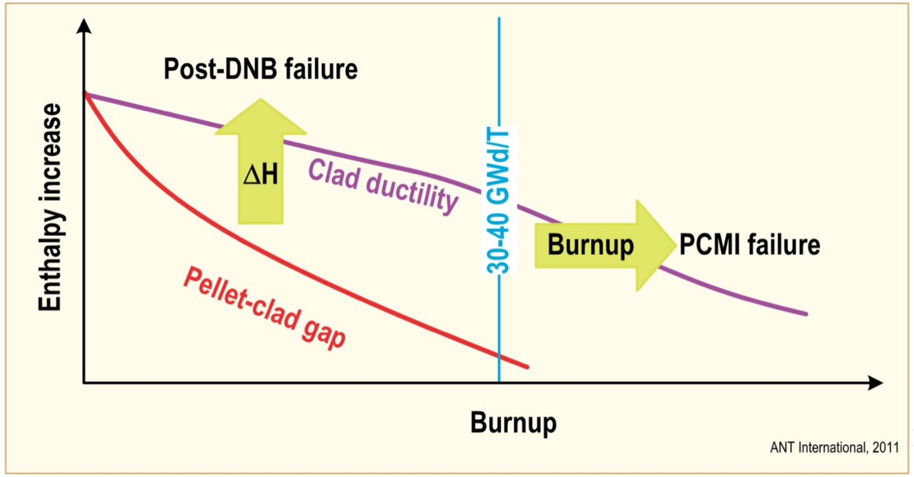


Effect of Burnup

$$h_f(T_f) = \int_{T_0}^{T_f} c_f(T)dT$$

- Fuel rod damage correlates with the peak value of fuel pellet specific enthalpy; the higher the enthalpy, the more extensive is the damage
- Cladding failure occurs at lower fuel enthalpies for irradiated than for fresh fuel rods, and that the susceptibility to failure increases with increasing fuel burnup
- The degree of cladding waterside corrosion, is very important for survivability of preirradiated fuel rods
- Safety criteria are defined in terms of limits on the radially averaged fuel pellet specific enthalpy, or the increase of this property during the accident





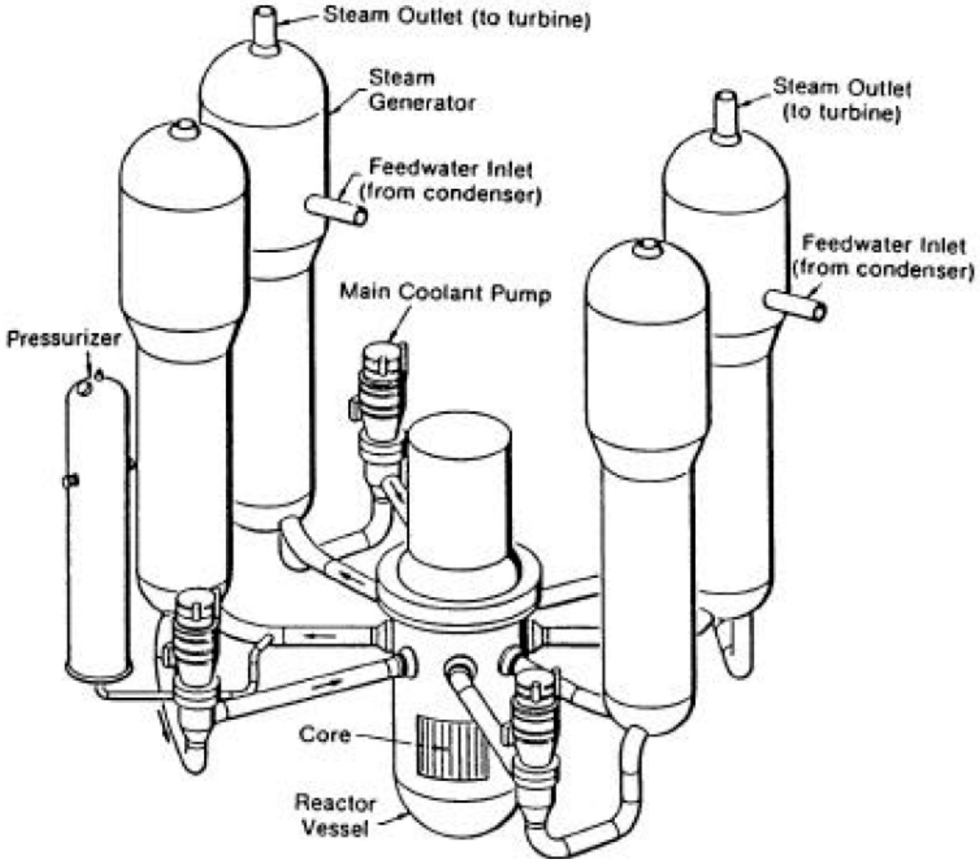
ANT International, 2011

RIA Summary

- Reactivity insertion accident
  - often in PWR/BWR dependent upon control rod ejection/drop
  - can be caused by changes in coolant
- Shorter pulses have greater impact than longer pulses (given same energy deposition)
- Effects of RIA depend on burnup
  - fission gas, FCMI, oxide layer, hydrides, cladding pressure, etc.

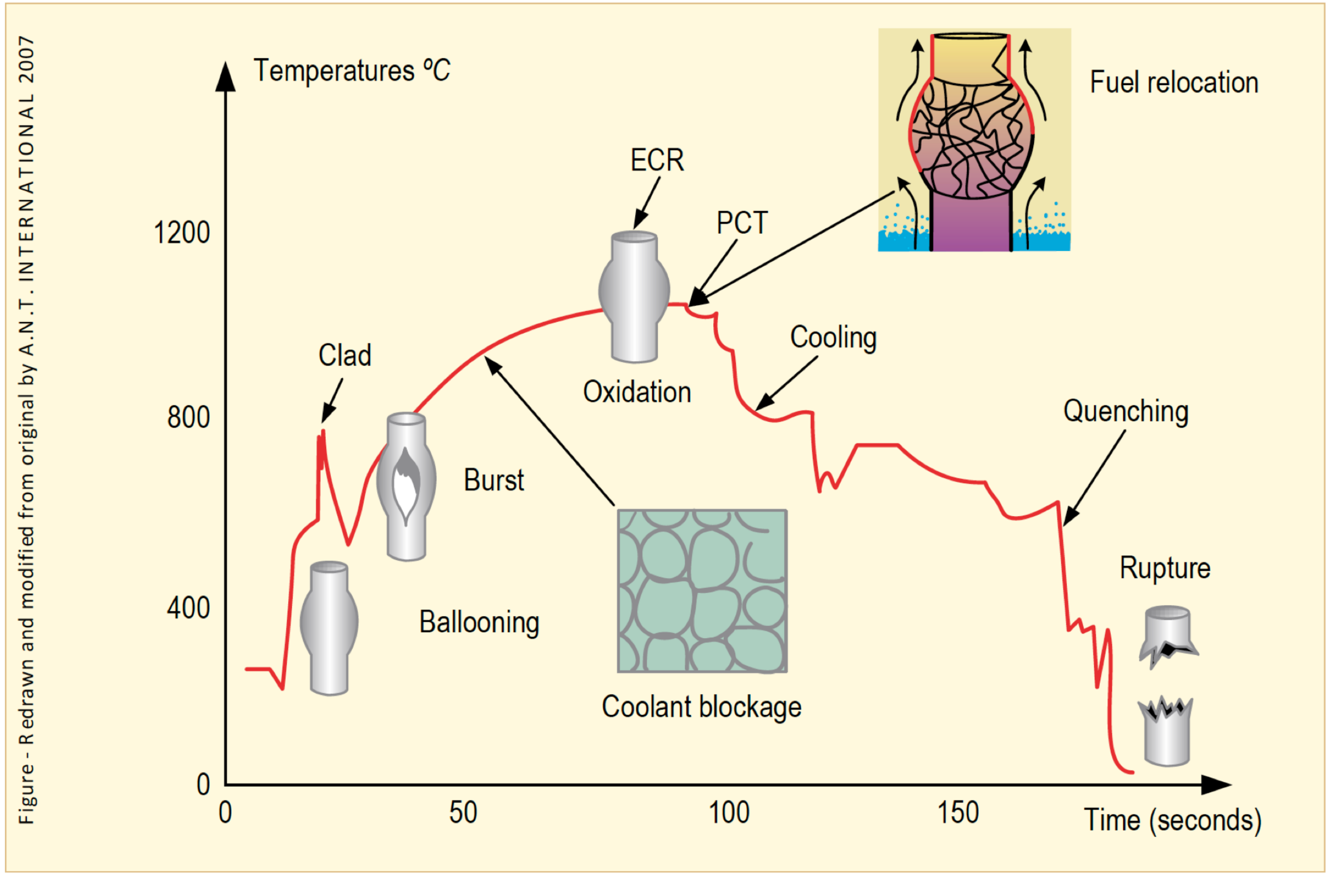
Loss of Coolant Accident (LOCA)

- In a LOCA, the coolant flow is reduced or lost altogether (e.g. coolant pipe break)
- When this occurs, pressure drops, causing the emergency shutdown system
- SCRAMS the reactor, stopping the fission chain reaction
- Also, the reactor water is expelled into the containment
- The emergency core cooling system (ECCS) begins to remove heat
- Requirement to maintain a coolable geometry



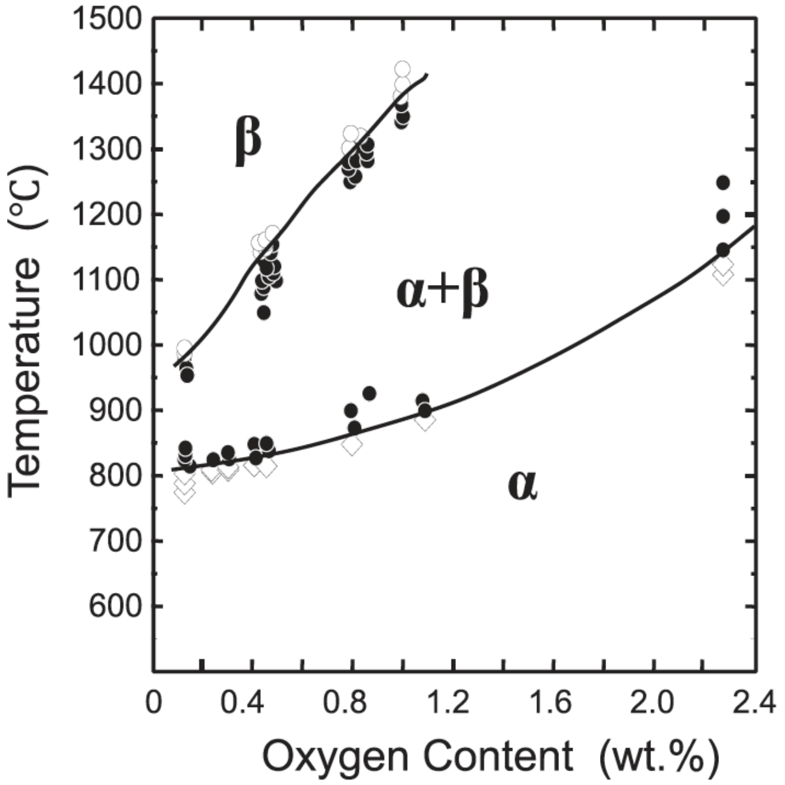
Loss of Coolant Accident (LOCA)

- The average temperature of the reactor continues to rise due to radioactive decay in the fuel and the lower cooling
- Decrease in coolant pressure and increase in internal pressure causes large plastic deformation
- Causes the cladding to balloon out and potentially burst
- Ballooning blocks coolant flow
- Cladding burst is significantly impacted by oxidation and hydride embrittlement



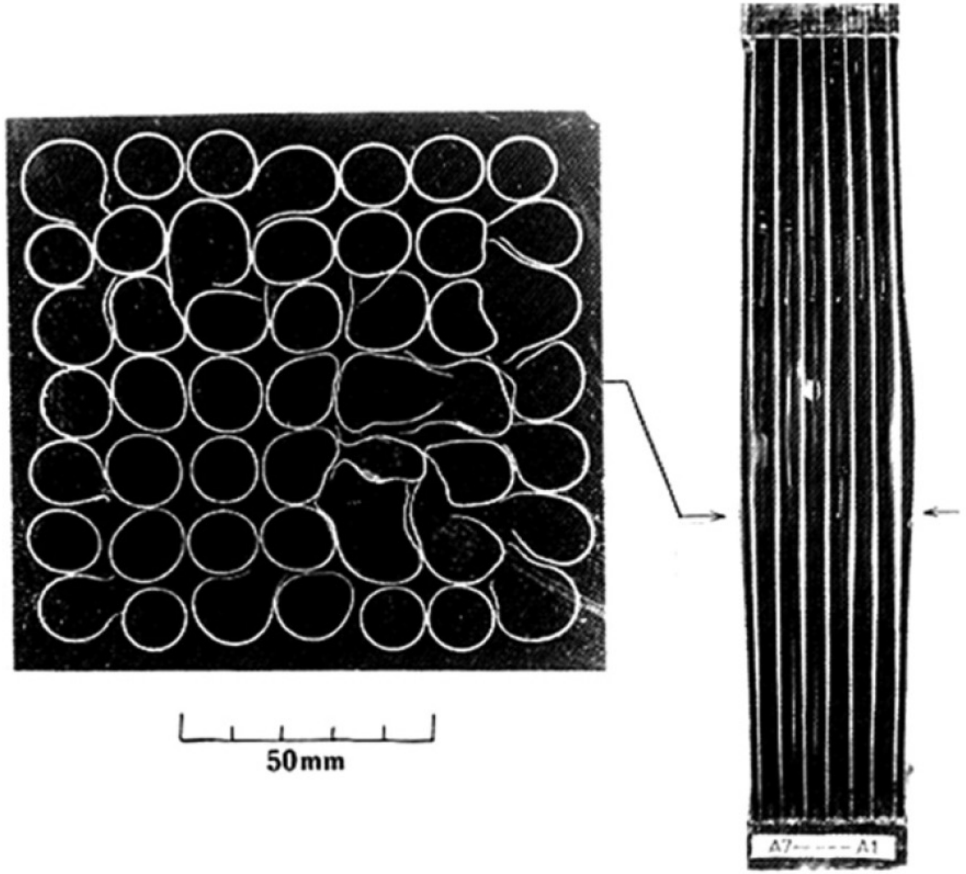
LOCA

- During the heat-up, the cladding plastically deforms (balloon and rupture) due to decrease of the system pressure outside the fuel rod and decrease in cladding strength
- The phase structure of Zircaloy transforms from alpha to alpha+beta above about 800C, and to beta above about 1000C
- The cladding reacts with steam or coolant at high temperatures and an oxide (ZrO2) layer is formed on the surface of the cladding
- In addition, absorbed oxygen stabilizes the alpha-phase and a layer of alpha-phase with a high content of oxygen begins to grow on the beta-phase, and the beta-phase becomes less ductile by the oxygen absorption



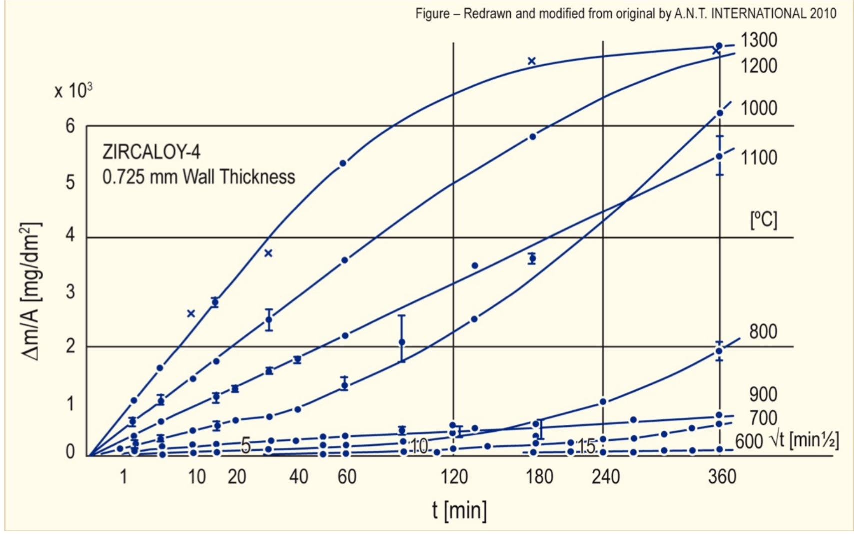
LOCA

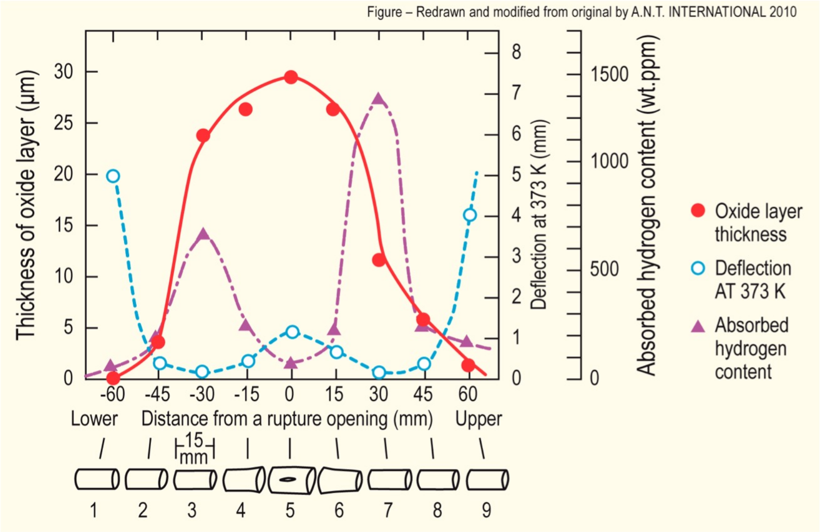
- The rod pressure becomes higher than the system pressure of the reactor due to a break of the coolant pressure boundary
- Creep strength of Zircaloy rapidly falls with the temperature
- The cladding plastically deforms in the radial direction (ballooning) during the heat-up and may finally rupture
- The beta phase has different creep properties than the alpha phase, and alpha+beta phase can exhibit superplastic behavior
- Large plastic deformation of the cladding in the radial direction results in blockage of the coolant channels between fuel rods

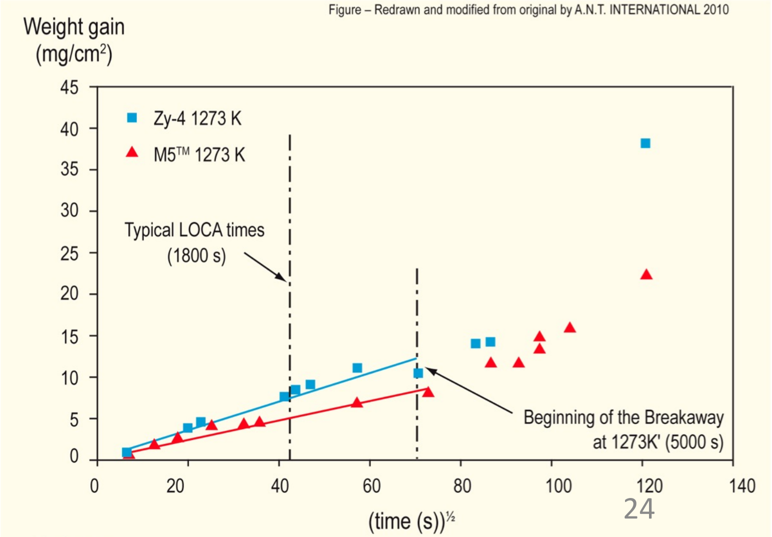


Oxidation

- Oxidation significantly increases at high temperatures
- Due to exothermic heat generated during oxidation of the cladding, at high enough temperatures, the rate of oxidation is so high that the heat can no longer be dissipated by cooling, leading to run-away oxidation (Three Mile Island)
- Breakaway oxidation also results in increased hydrogen pickup in the cladding, embrittling cladding

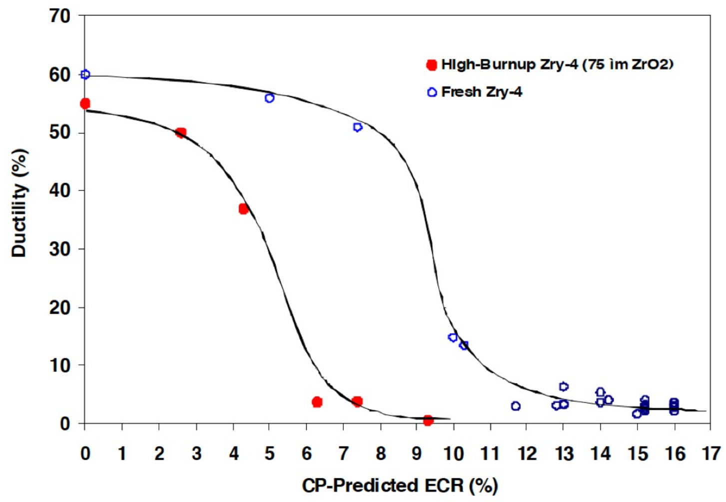


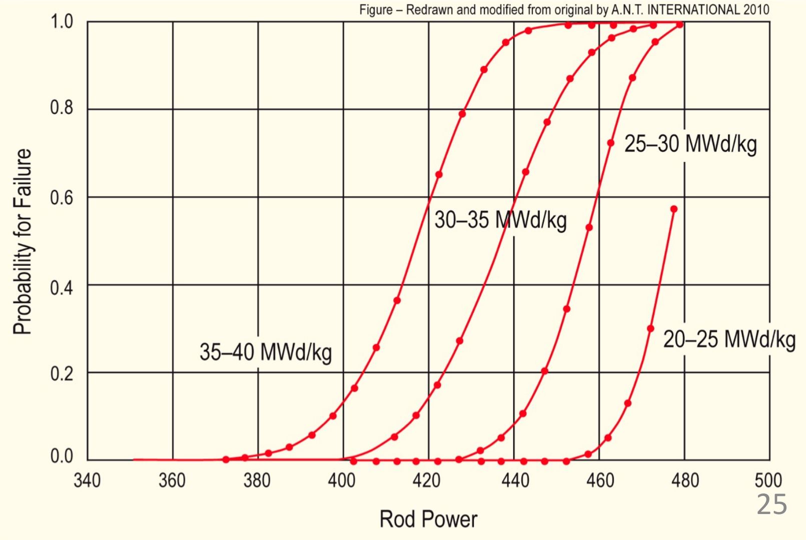




Effect of Burnup

- At high burnup, ductility of the cladding is significantly reduced due to existing corrosion and hydrogen embrittlement
- This leads to higher likelihood of failure for higher burnup conditions
- Similar to RIA (but more slow), temperature increases can lead to gas bubble pressure increases, fuel fragmentation, increased thermal expansion, FCMI, etc.





Mitigation through design

- Accident tolerant fuels aim to provide additional coping time
  - The time required for the water to boil away
  - The time required for the fuel to melt
  - The time required for the molten fuel to breach the primary pressure boundary
- Fuels with enhanced tolerance can tolerate loss of active cooling for a considerably longer period, while maintaining or improving performance during normal operation

Accident Tolerance

Improved Reaction Kinetics with Steam
- Decreased heat of oxidation
- Lower oxidation rate
- Reduced hydrogen production (or other combustible gases)
- Reduced hydrogen embrittlement

Improved Cladding Properties
- Resilience to clad fracture
- Robust geometric stability
- Thermal shock resistance
- Higher cladding melt temperatures
- Minimizing fuel-cladding interaction

Enhanced tolerance to loss of active core cooling

Improved Fuel Properties
- Lower fuel operating temperatures
- Minimized cladding internal oxidation
- Minimized fuel relocation/dispersion
- Higher fuel melt temperature

Enhanced Fission Product Retention
- Retention of gaseous fission products
- Retention of solid/liquid fission products

ATF options being pursued

- Cladding coatings/liners
  - protect the Zircaloy from steam: Ti_3SiC_2, etc.
- Alternate claddings
  - SiC, FeCrAl, refractory alloys
- UO_2 dopants
  - Cr, SiC, BeO, etc.
- Alternate fuels
  - USi, UN, UC, microencapsulated fuel

Summary

- In loss of coolant accidents (LOCA), the fuel and cladding experience
  - increases temperature
  - decrease in coolant pressure
- The primary negative effects are
  - Embrittlement and ballooning of the cladding
  - Relocation and fission gas release in the fuel
  - Cladding can burst and release fuel fragments
- Accident tolerant fuel includes different fuel and cladding materials to increase time before catastrophic behavior during an accident