Nuclear Fuel Performance

NE-533

Spring 2025

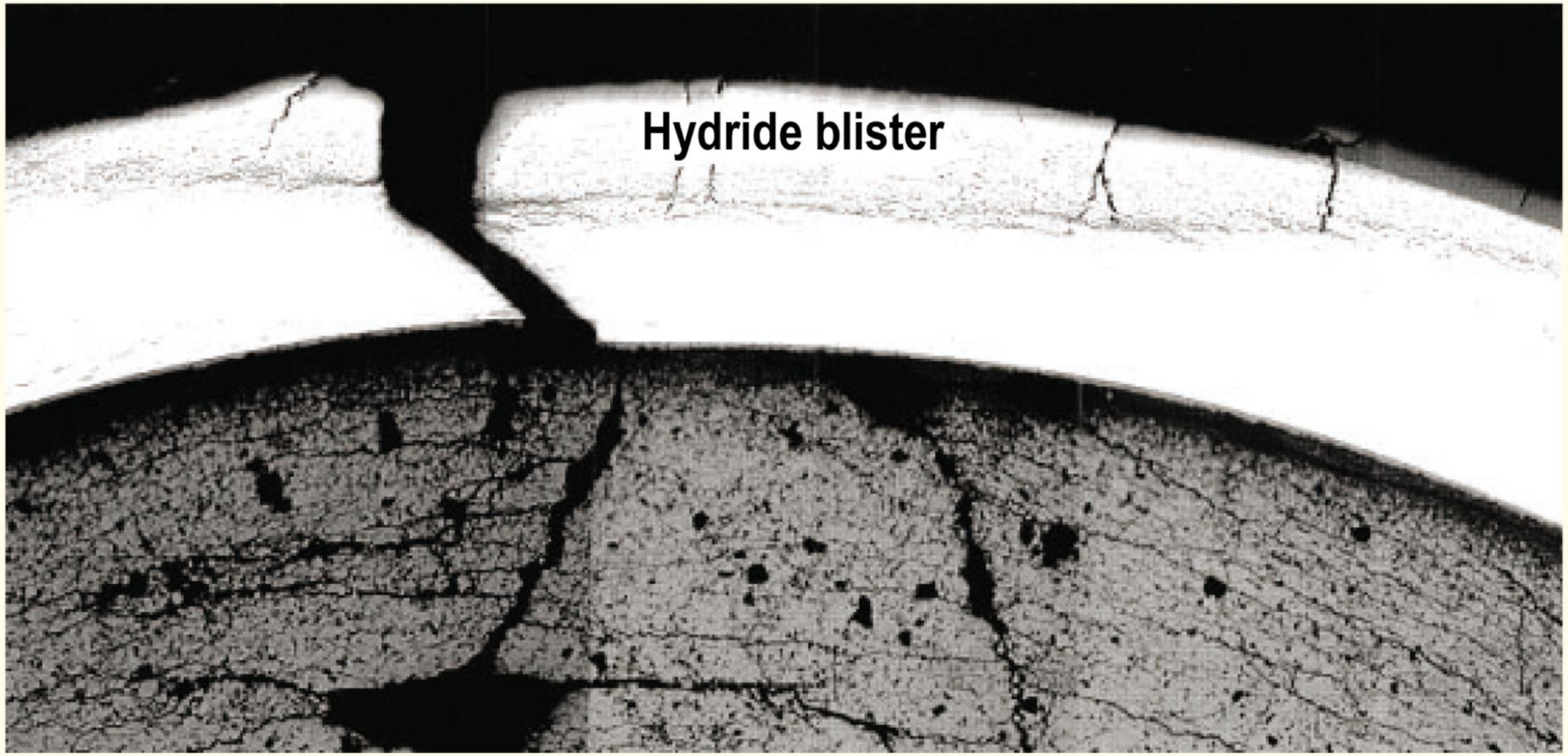
Last time

- 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
- Defined RIA/LOCA
- RIA is often caused in PWR/BWR by control rod ejection/drop
  - RIA is a fast event, can lead to PCMI failures, ballooning, and in worst case scenarios, fuel dispersal
  - Effects of RIA depend on burnup include fission gas, FCMI, oxide layer, hydrides, cladding pressure, etc

Cladding Response

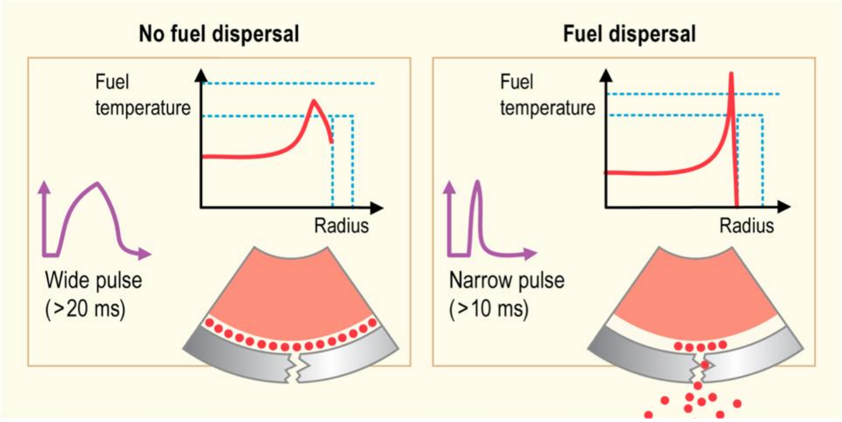
- PCMI failures results from the fuel pushing out on the cladding, causing it to break

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



Pulse Width

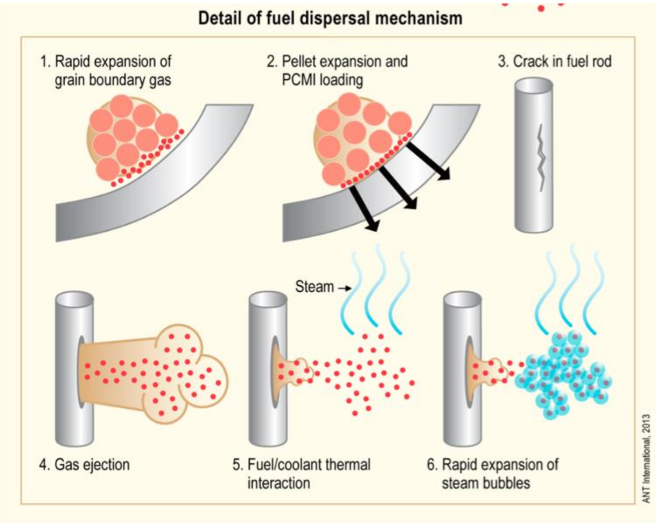
- The amplitude and width of the power pulse can have dramatic impacts on the effects of the RIA
- Pulse is typically defined by FWHM, and by total energy deposition (integration of pulse)
- More rapid temperature spike is more damaging
- Reactor state and type during typical accident scenarios determine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

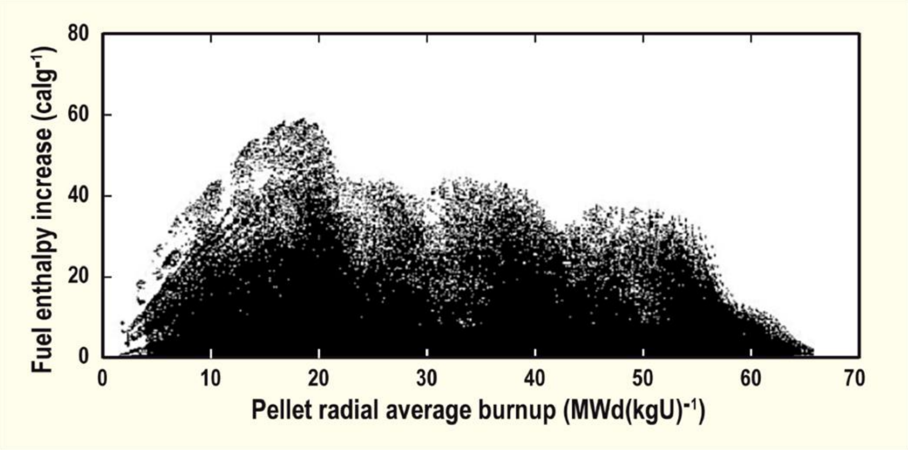
ANT International, 2016

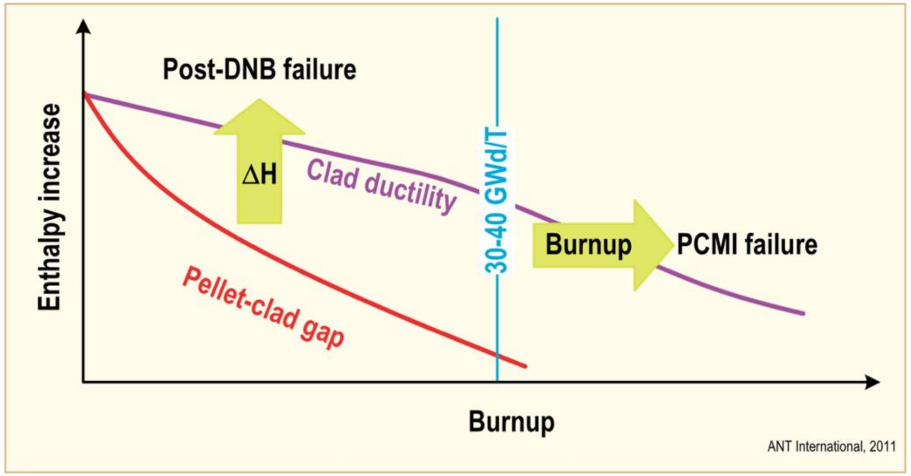


Effect of Burnup

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

- Fuel rod damage correlates with the peak value of fuel pellet specific enthalpy; the higher the enthalpy increase, the more extensive is the damage
- Fuel enthalpy increases are higher in fresh fuel
- Cladding failure occurs at lower fuel enthalpy increases for irradiated than for fresh fuel rods, thus, 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



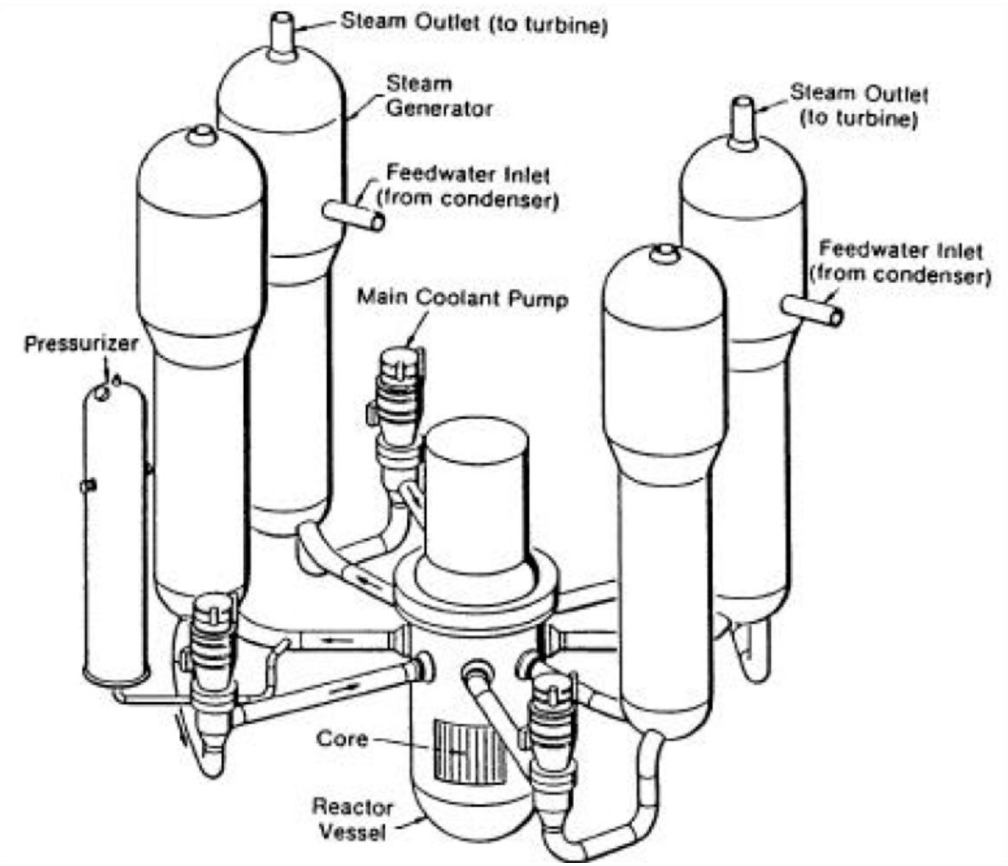


RIA Summary

- Reactivity insertion accident
  - In PWR/BWR often initiated by control rod ejection/drop
- Shorter pulses have greater impact than longer pulses (given same energy deposition)
- Fast accident, causing temperature spike, pellet expansion, gas expansion
- Can lead to PCMI or DNB failure events, and in worst case fuel ejection
- Effects of RIA depend on burnup
  - fission gas, PCMI, oxide layer, hydrides, cladding pressure, etc.

Loss of Coolant Accident (LOCA)

- Design basis accident for LWRs
- In a LOCA, the coolant flow is reduced or lost altogether (e.g., coolant pipe break)
- When this occurs, pressure drops, engaging the emergency shutdown system
- SCRAMS the reactor, stopping the fission chain reaction
- The reactor water is expelled into the containment
- The emergency core cooling system (ECCS) begins to remove heat
- Safety requirement is 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

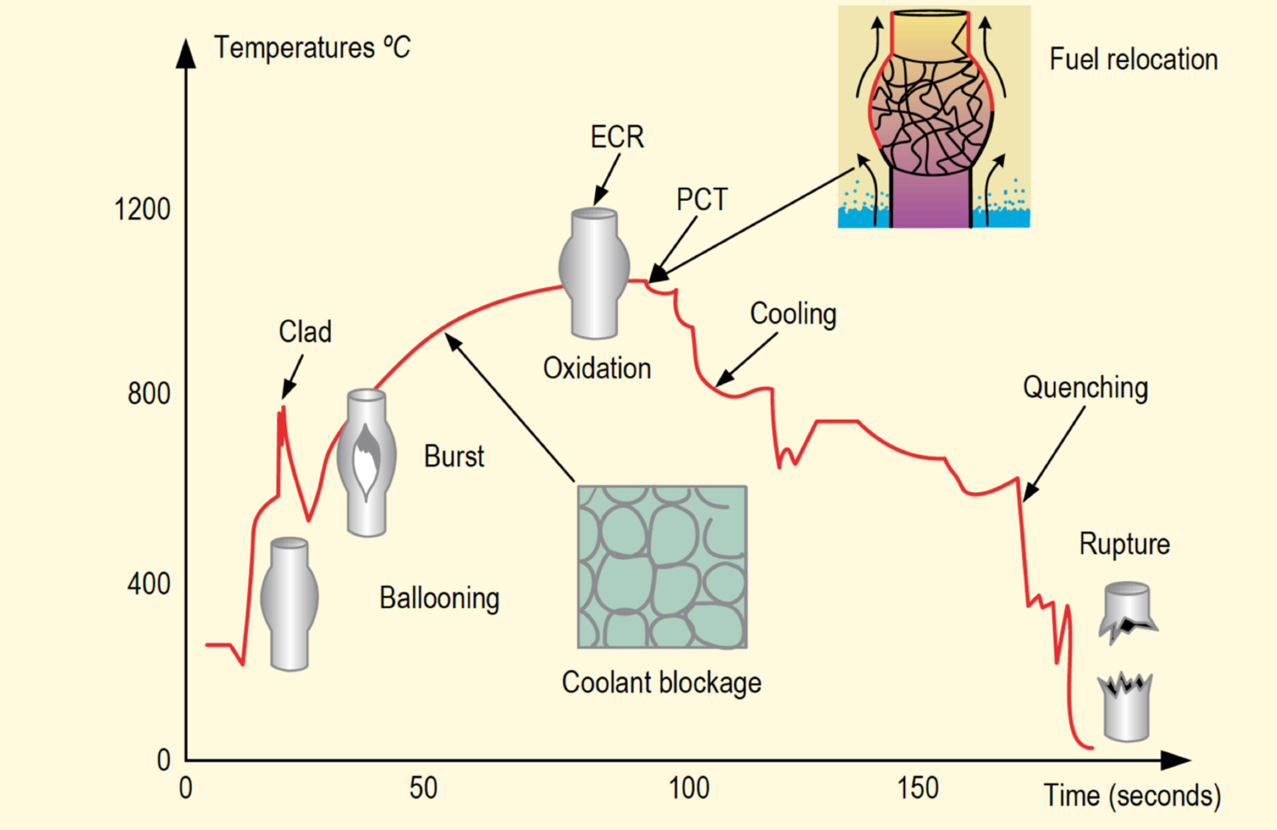
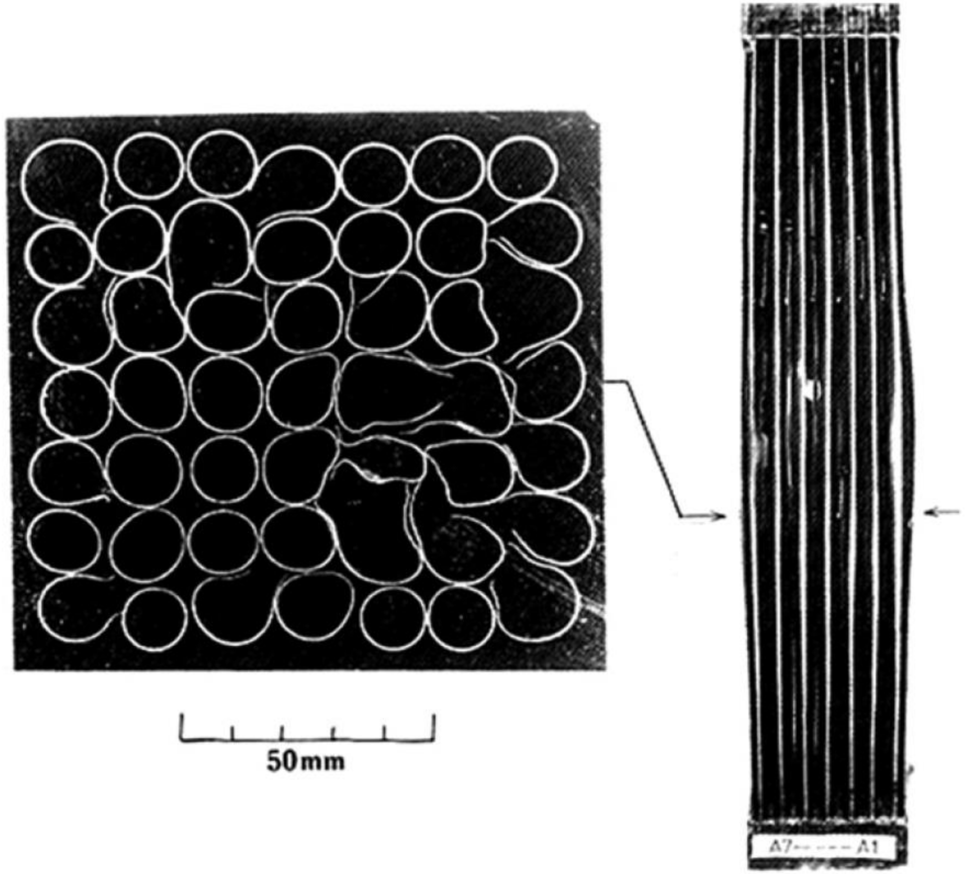


Figure - Redrawn and modified from original by A.N.T. INTERNATIONAL 2007

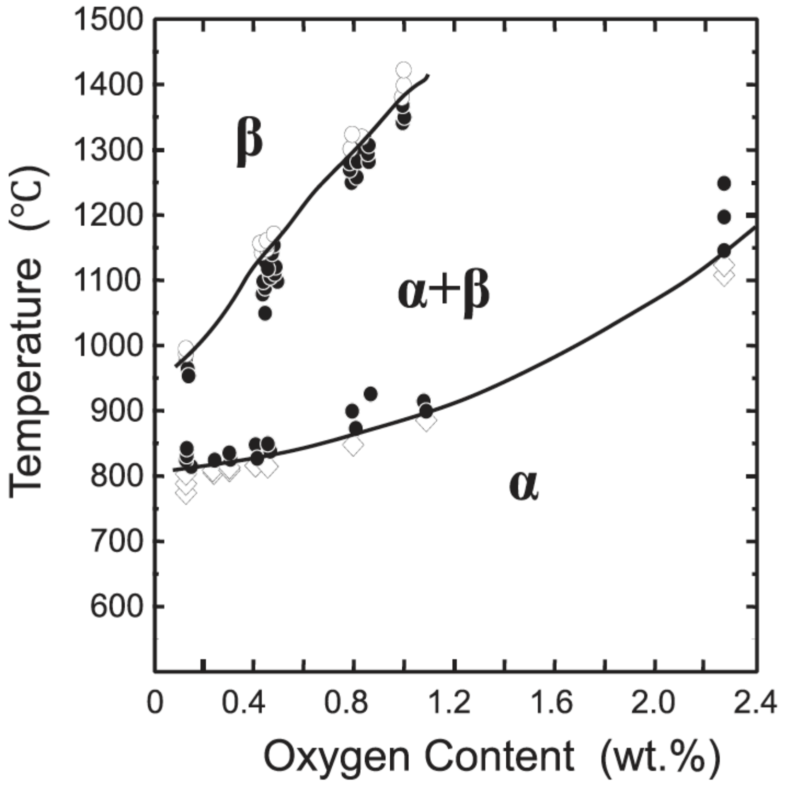
LOCA Blockages

- 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 - rod pressure becomes higher than the system pressure
- Creep strength of Zircaloy rapidly falls with the temperature
- 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



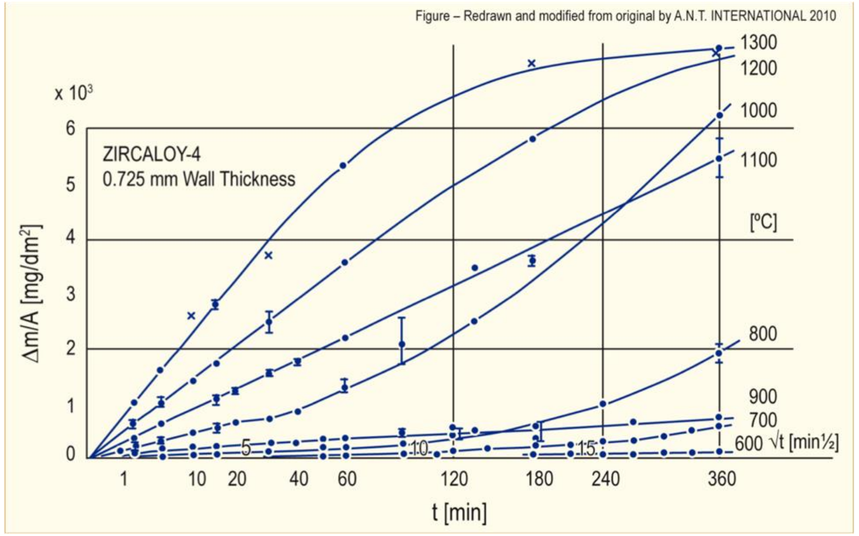
LOCA Phase Transformations

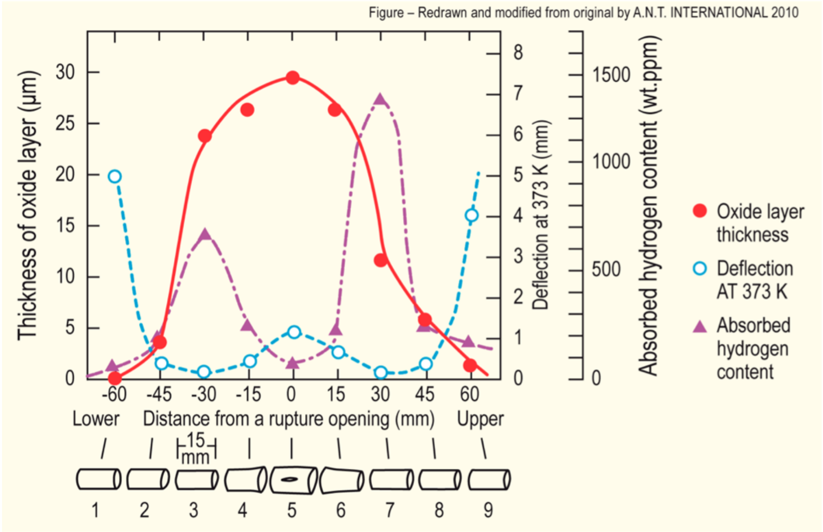
- The phase structure of Zircaloy transforms from alpha to alpha+beta above about 800C, and to beta above about 1000C
- The cladding reacts with steam or coolant at high temperatures, and an oxide (ZrO2) layer is formed on the surface of the cladding
- In addition, absorbed oxygen stabilizes the alpha-phase 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

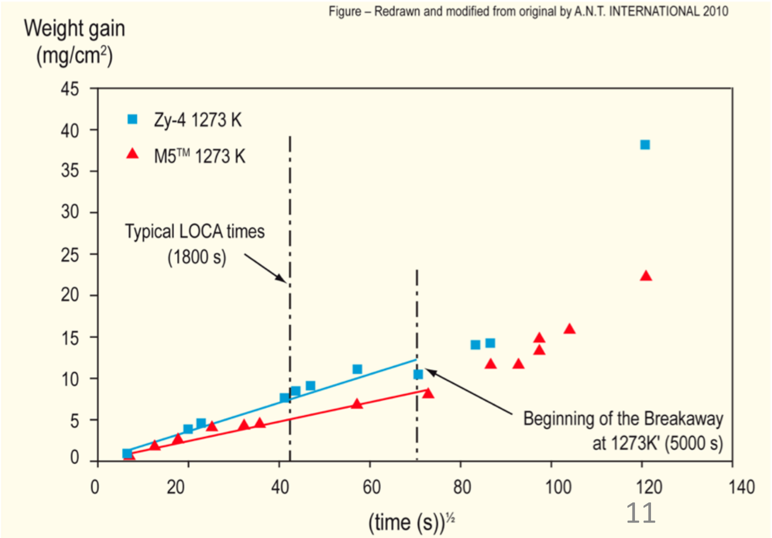


LOCA Oxidation

- 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 results in increased hydrogen pickup, embrittling the cladding
- Excess H generation can lead to H2 gas accumulation inside the containment

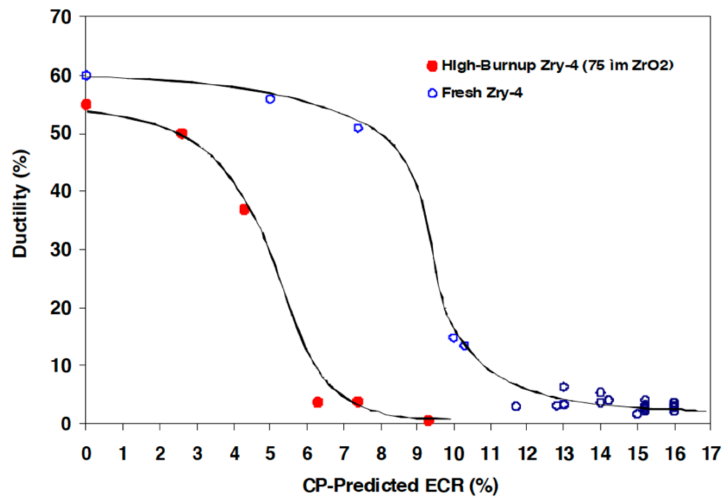


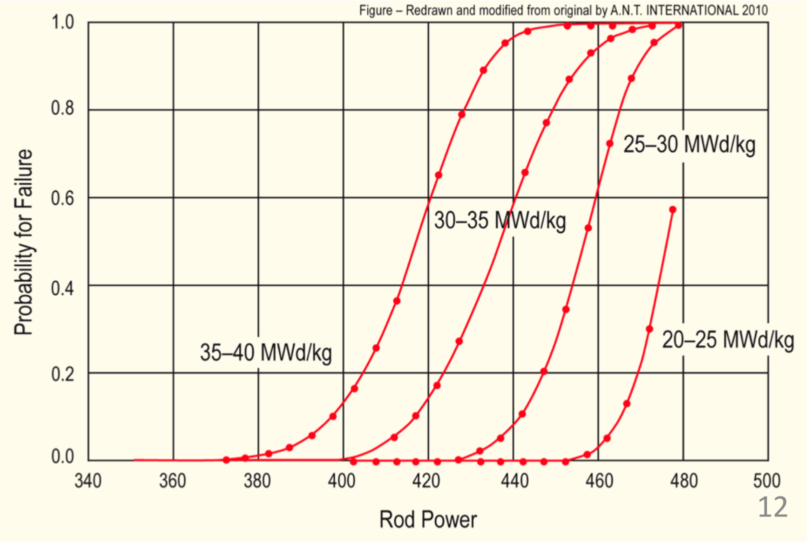




Effect of Burnup

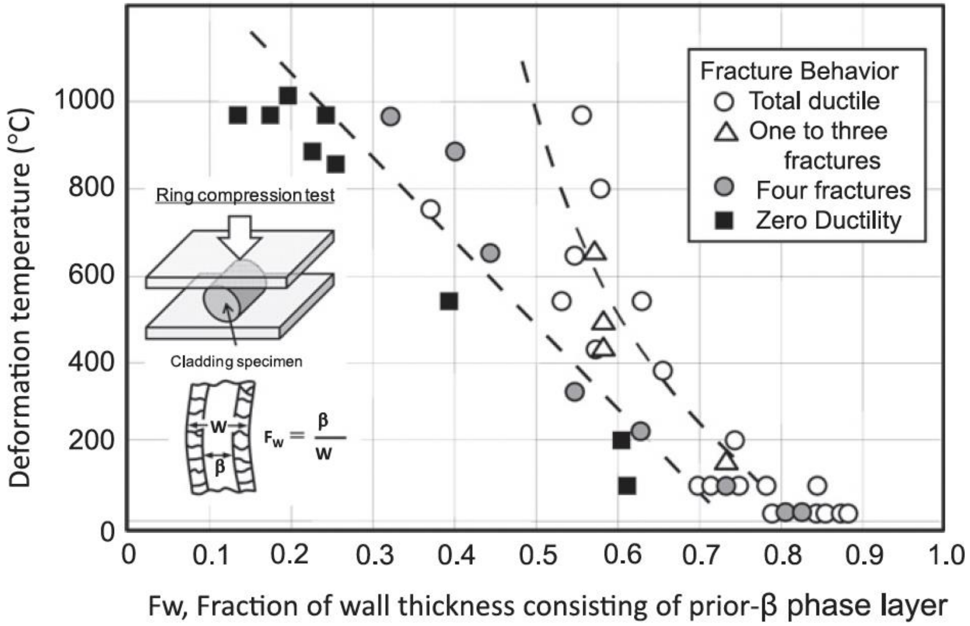
- At high burnup, ductility of the cladding is significantly reduced due to existing corrosion, hydrogen embrittlement, and irradiation hardening
- This leads to higher likelihood of failure for higher burnup conditions
- Alloys with lower corrosion could potentially go to higher burnup, and retain ductility under a LOCA
- Similar to RIA (but more slow), temperature increases can lead to gas bubble pressure increases, fuel fragmentation, increased thermal expansion, PCMI, etc.





Embrittlement

- On rewetting of the cladding by ECCS water, a thermal shock by quenching is induced
- If the cladding is severely oxidized at temperatures above 1000C, the embrittled cladding may be fragmented by the quenching
- The ductility decreases as the fraction of the unoxidized layer decreases
- There are limits imposed on the amount of oxidation to limit brittle failure on ECCS quenching



LOCA Summary

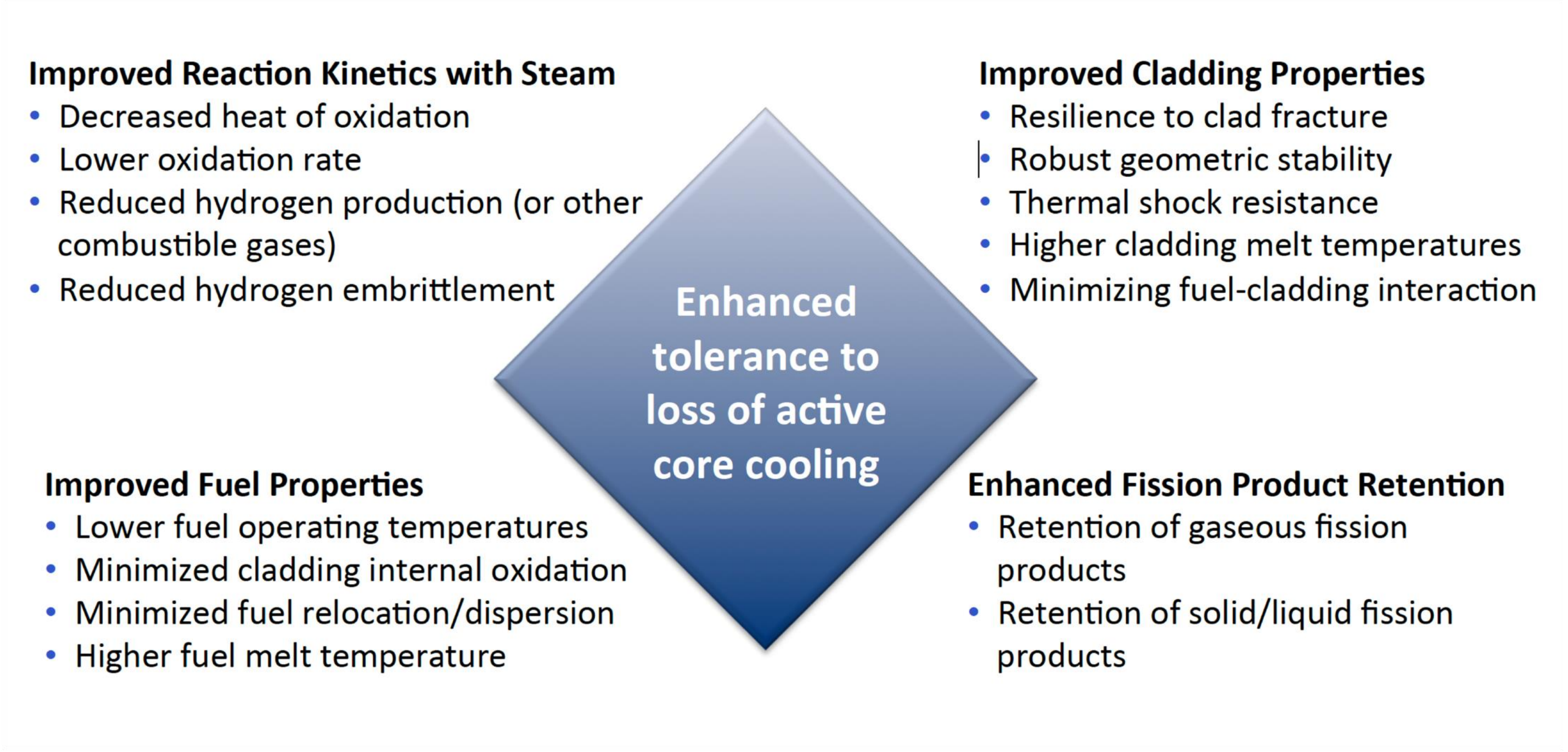
- LOCA, pipe break resulting in loss of coolant/flow
  - Increase in temperature, decrease in coolant pressure
  - High temperatures lead to increased oxidation, producing additional hydrogen, this can lead to embrittlement, ballooning, and burst of the cladding
  - LOCA occurs over a timescale of minutes, much longer than a RIA

ACCIDENT TOLERANT FUELS

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
- Can also widen the existing safety margin for nuclear plants and improve nuclear plant performance with fuel that lasts longer

Accident Tolerance



Categories of ATF Concepts

- ATF can be divided into three main categories
  - near-term ATF improvements
  - novel fuel and cladding materials
  - transformational fuel and cladding concepts

- Near-term ATF improvements
- Zirconium-based cladding
  - coatings to improve corrosion resistance, especially under high T steam
- Urania-based fuel
  - additives to increase thermal conductivity
- These changes are mean to be drop-in replacements that are compatible with existing systems

Categories of ATF Concepts

- Novel fuel and cladding materials
  - U_3Si_2 fuels
  - FeCrAl alloys for cladding
  - Minimal changes needed for LWR designs, could be deployed in 10ish years

- Transformational fuel and cladding concepts
  - fully ceramic micro-encapsulated (FCM) fuels
  - SiC/SiC composite cladding
  - drastically differ from traditional LWR fuel systems
  - may require significant modifications to reactor design and operation, but offer potentially large benefits to performance and/or safety

Summary

- In loss of coolant accidents (LOCA), the fuel and cladding experience
  - increases temperature
  - decrease in coolant pressure
- High temperatures lead to increased oxidation, producing additional hydrogen
- This can lead to embrittlement, ballooning, and burst of the cladding
  - Fuel relocation and fission gas release in the fuel
- Accident tolerant fuel includes different fuel and cladding materials to increase time before catastrophic behavior during an accident

ACCIDENT SAFETY LIMITS

Accident Safety Limits

- Fuel cladding temperature cannot exceed 1204 C
- Local cladding oxidation cannot exceed 17% of wall thickness
- H generated must be less than 1% of the total amount that could be generated if all Zr were oxidized
- Limits on radiation dose to staff

- The response to steam oxidation, specifically on oxide growth and H generation is critical to evaluate safe performance (and potentially qualify new materials)

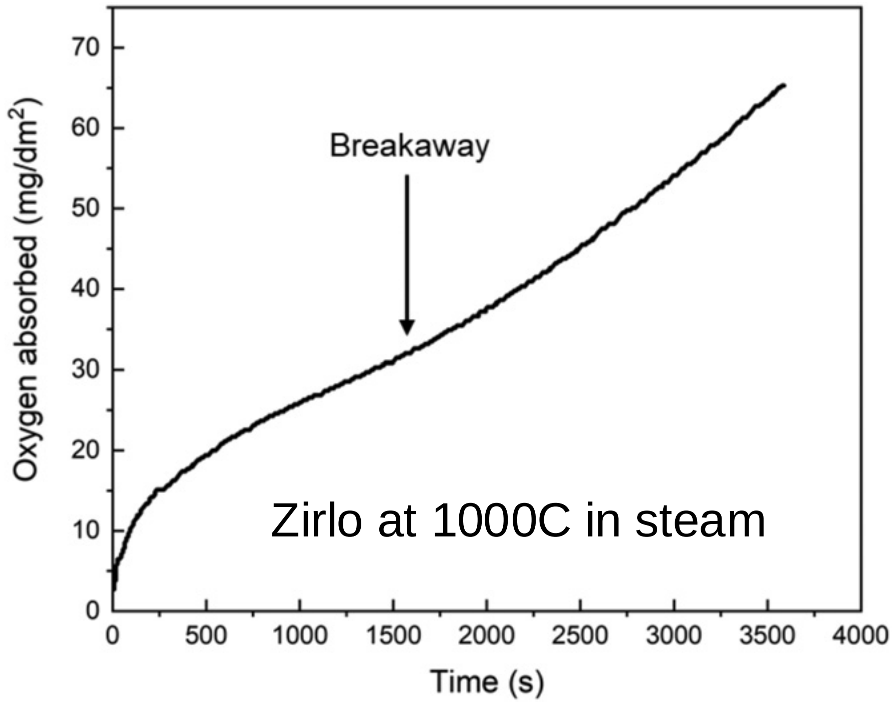
Steam Oxidation

- High temperature steam oxidation will follow defined kinetic theory
- Linear kinetics are followed with a thin oxidation layer, and parabolic kinetics are followed when the oxide layer is sufficiently thick to slow diffusive processes: Linear: $\delta \propto Kt$; Parabolic: $\delta^2 \propto Kt$
- Paralinear or sigmoidal kinetics can be followed for systems which can develop volatile oxides or intermediate oxides, respectively
- Breakaway or accelerated oxidation can result from sustained exposure to high T steam; include the failure of the oxide layer, exposing the bare material, and increasing the oxidation rate

Steam Oxidation

- Zr oxidizes with an exothermic reaction
- Below 600C, the reaction follow a parabolic or cubic rate law resulting in a uniform and passivating oxide layer
- At higher T, the oxide layer can crack due to surface stresses, resulting in breakaway oxidation
- At loss of passivation, the oxidation rate can become linear and localized

$$Zr + 2H_2O \rightarrow ZrO_2 + 2H_2 + 586 \ \text{kJ/mol}$$



Steam Oxidation

- Right is an image of Zircaloy-2 after steam oxidation for 8 hours at a) 800 C, b) 1000 C, c) 1200 C
- At 800C, the oxide layer is intact and passivating
- At higher temperatures, the oxide layer is thicker and cracked
- At 1200C, everything has been oxidized