NucE497: Reactor Fuel Performance

Reactivity Initiated Accident(RIA)

Muhammet Ayanoglu
Department of Mechanical and Nuclear Engineering
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Prepared with the significant contribution of Prof. Tonks.
Content taken from Prof. Motta's and Prof. Tonks' slides, slides from ANT international, and an IAEA report on SCC.

Course content

- Module-1: Fuel basics
- Module-2: Heat transport
- Module-3: Mechanical Behavior
- Module-4: Materials issues in the fuel
- Module-5: Materials issues in the cladding
- Module-6: Accidents, used fuel, and fuel cycle

First, let's summarize from last time

- In nuclear industry, the acronym 'CRUD' corresponds to:
  a) A substance that is disgusting or unpleasant
  b) Create, Read, Update and Delete
  c) $\boxed{\text{Chalk River Unidentified Deposits}}$
  d) None of the above

- Which one is a bad effect of CRUD deposition:
  a) Reduced heat transport
  b) Power shift
  c) Localized corrosion
  d) $\boxed{\text{All of the above}}$

Outline of today's lecture:

- Definition of reactivity
- Reactivity Initiated Accident(RIA)
- Impact of RIA on fuel and cladding

Reactivity, ρ, is the fractional departure of a reactor system from criticality:

$$\rho = \frac{k_{eff} - 1}{k_{eff}}$$

- What is k_{eff}?
- At steady state, $k_{eff} = 1$ (critical reactor) $\longrightarrow \rho = 0$
- Reactivity is affected by the temperature and density of the coolant, moderator and fuel.
- Nuclear reactors are designed so that a power increase will generate negative reactivity feedback

Reactivity Initiated Accident(RIA)-General Overview

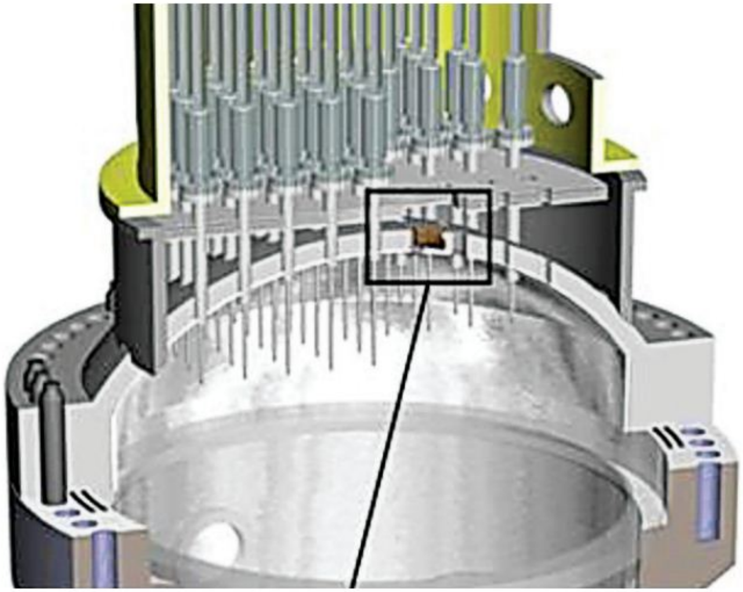
- Design Basis Accident: **Large and rapid insertion of reactivity** caused by inadvertent ejection (PWR) or drop (BWR) of a control rod.

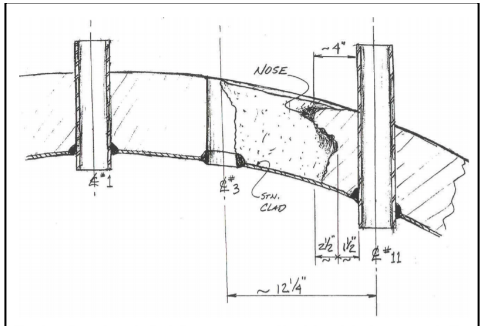
SPERT(Special Power Excursion Reactor Test)

The most severe RIA scenario depends on the reactor type

- 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.
- 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.

Example: Davis-Besse Nuclear Reactor Pressure Vessel Degradation

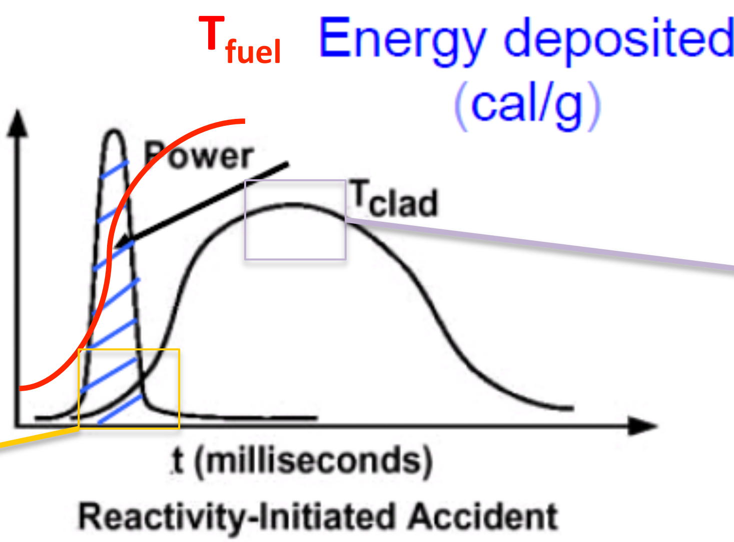




The above figure shows the Davis Besse reactor vessel head degradation between nozzle #3 and nozzle #11. This sketch was provided to the NRC by the Licensee.

Sequence in Reactivity Initiated Accident(RIA)

Control rod ejection/drop → Large and rapid reactivity insertion → Fission rate and fuel temperature rise → Fuel expands in milliseconds and hits the cladding → Cladding Failure?



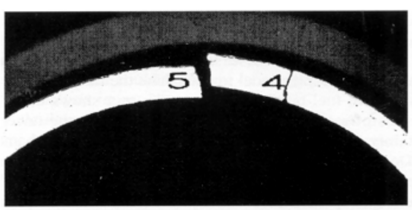


Fig. 2 Crack tip from test REP-Na1 (Table 1) showing brittle character of a PCMI fracture.

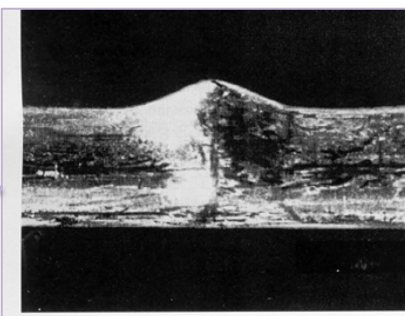


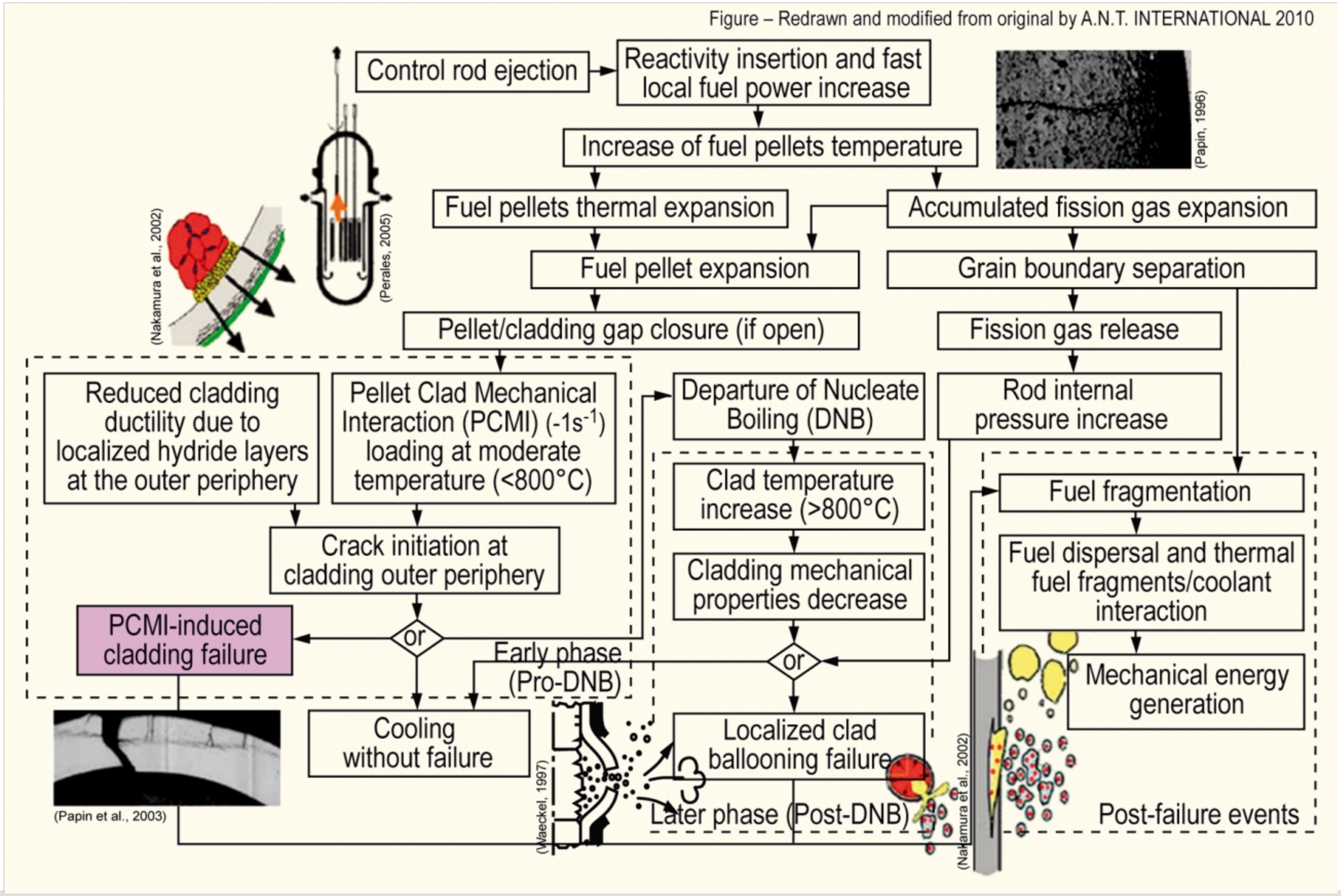
Fig. 6 Ballooned region of ruptured fuel rod from test H7T (Table 5).

1 cal ≈ 4 Joules

Reference: Meyer et al. "A Regulatory Assessment of Test Data on Reactivity Initiated Accidents", Nuclear Safety 37 (4) 1996, 271,

B. E. Boyack, et al. "Phenomenon Identification and Ranking Tables (PIRTs) for Reactivity Initiated Accidents in Pressurized Water reactors Containing High Burnup Fuel," Nuclear Regulatory Commission NUREG/CR-6742, 2001.

RIA has a large impact on the fuel pellet



The sudden jump in temperature causes a pressure jump in the fission gas and results in cracking

BWR fuel (61 GWd/t) test at 377 J/g (90 cal/g)

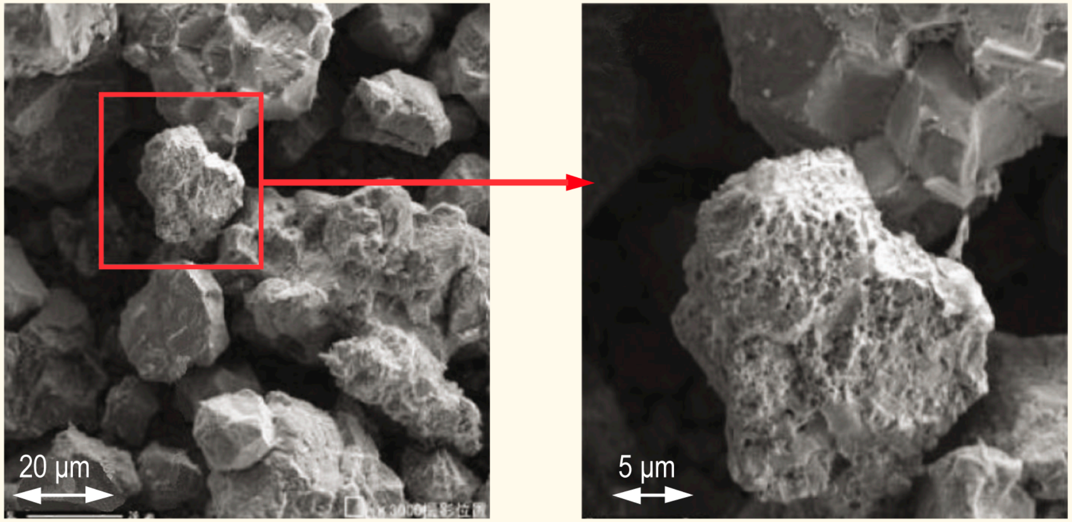


Figure – Redrawn and modified from original by A.N.T. INTERNATIONAL 2010

[Nakamura et al, 2002a]

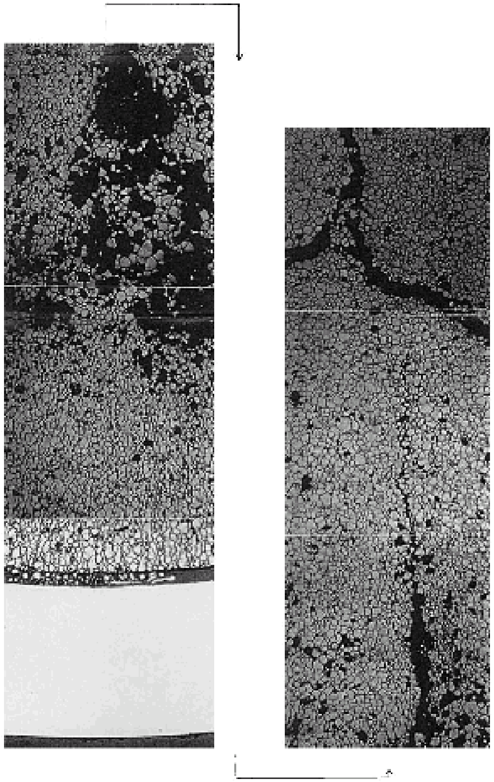
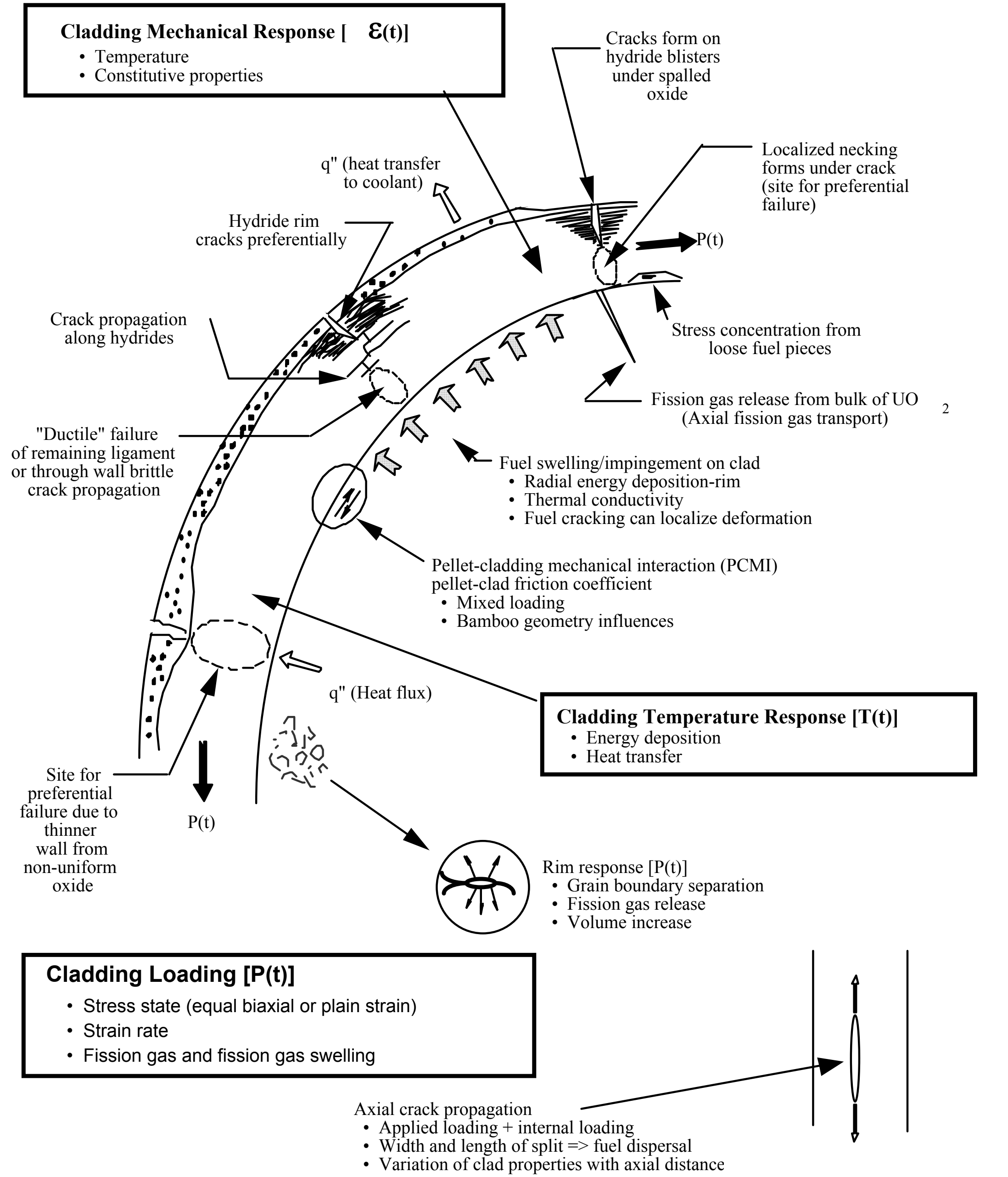
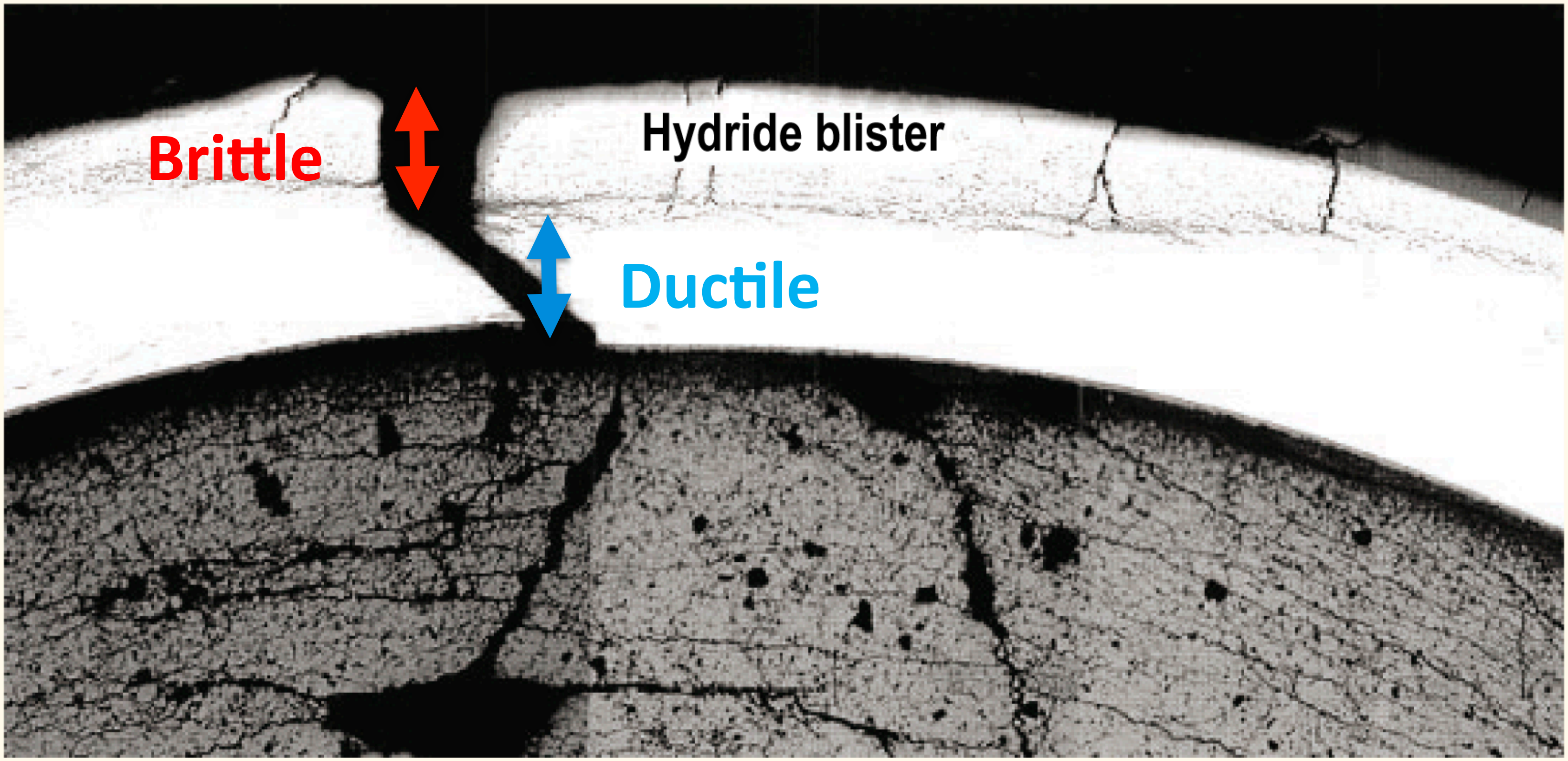


Fig. 5. Metallographic section of the REP-Na2 rod after CABRI testing. The grain decohesion and the loss of a large number of grains during preparation of the metallography demonstrate the fuel fragmentation. The fission gases accumulated in the fuel grain boundaries are the driving force of the transient fragmentation.


Cladding Mechanical Response [ε(t)]
• Temperature
• Constitutive properties
Cracks form on hydride blisters under spalled oxide
Localized necking forms under crack (site for preferential failure)
q" (heat transfer to coolant)
Hydride rim cracks preferentially
P(t)
Crack propagation along hydrides
Stress concentration from loose fuel pieces
Fission gas release from bulk of UO_2 (Axial fission gas transport)
"Ductile" failure of remaining ligament or through wall brittle crack propagation
Fuel swelling/impingement on clad
• Radial energy deposition-rim
• Thermal conductivity
• Fuel cracking can localize deformation
Pellet-cladding mechanical interaction (PCMI)
pellet-clad friction coefficient
• Mixed loading
• Bamboo geometry influences
q" (Heat flux)
Cladding Temperature Response [T(t)]
• Energy deposition
• Heat transfer
Site for preferential failure due to thinner wall from non-uniform oxide
P(t)
Rim response [P(t)]
• Grain boundary separation
• Fission gas release
• Volume increase
Cladding Loading [P(t)]
• Stress state (equal biaxial or plain strain)
• Strain rate
• Fission gas and fission gas swelling
Axial crack propagation
• Applied loading + internal loading
• Width and length of split => fuel dispersal
• Variation of clad properties with axial distance

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



All of our accident data comes from testing at conditions we think are like accident conditions

	SPERT US	PBF US	IGR KZ	BIGR RU	NSRR JP	CABRI FR	PWR/ BWR
Test conditions							
Coolant medium	Stagnant water	Flowing water	Stagnant water	Stagnant water	Stagnant water	Flowing sodium	Flowing water
Coolant temperature [K]	293	538	293	293	293*	553	553 (BWR) 563 (PWR)
Coolant pressure [MPa]	0.1	6.45	0.1	0.1	0.1*	0.5	7(BWR) 15.5 (PWR)
Power pulse width [ms]	13-31	11-16	600-950	2-3	4-7	9-75	25-75

Short pulses tend to cause fuel dispersal

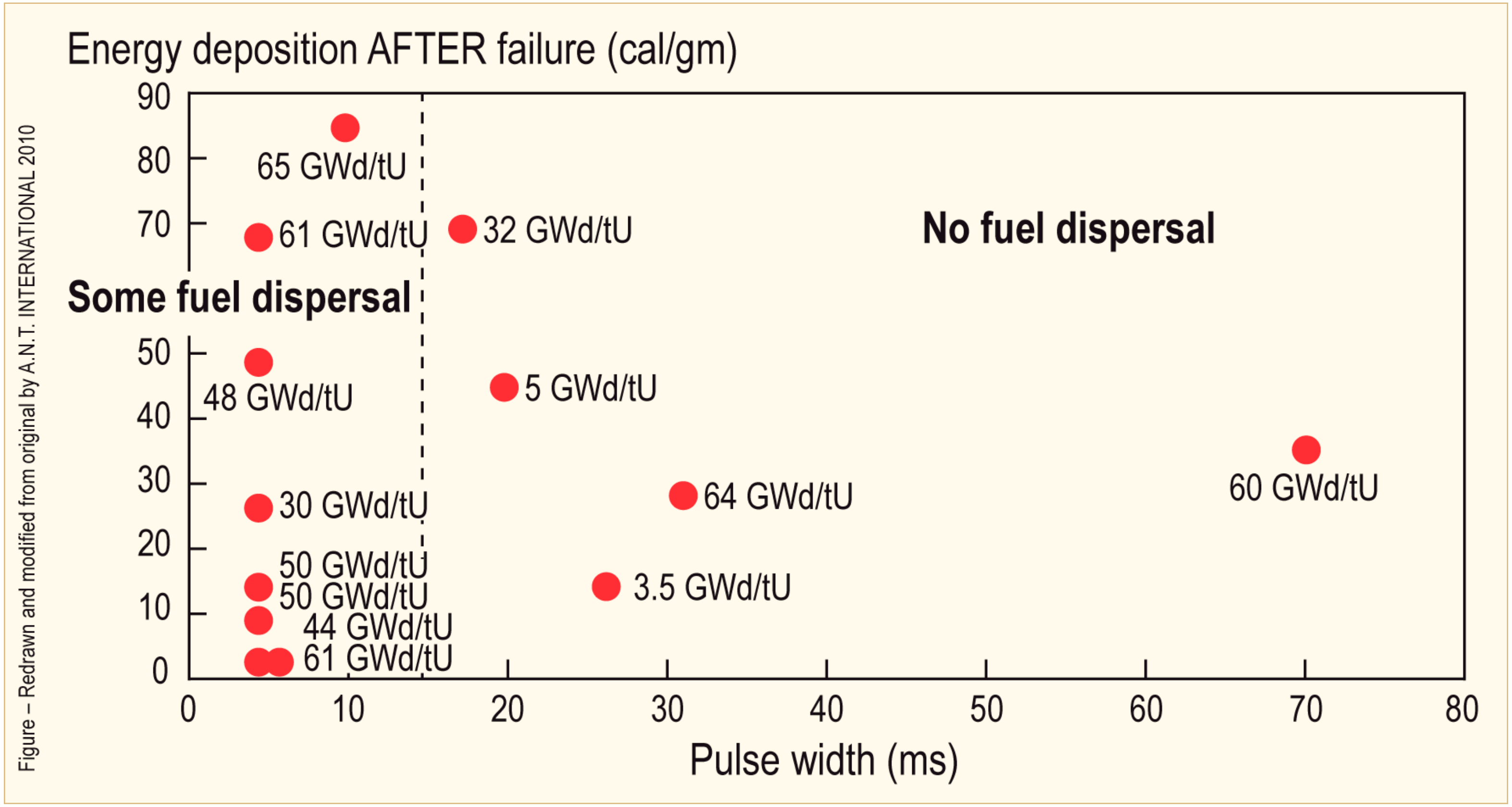


Figure 1-44: Pulse width effect on fuel dispersal for UO_2 fuel [Montgomery et al, 2003].

Failure mode is related to available cladding ductility.

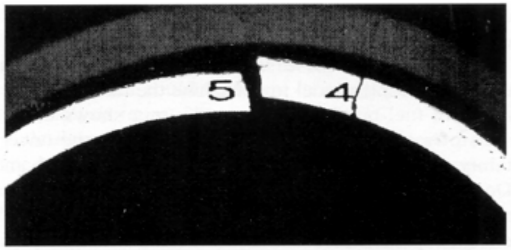


Fig. 2 Crack tip from test REP-Na1 (Table 1) showing brittle character of a PCMI fracture.

Low Temperature Failures

High Temperature Failures

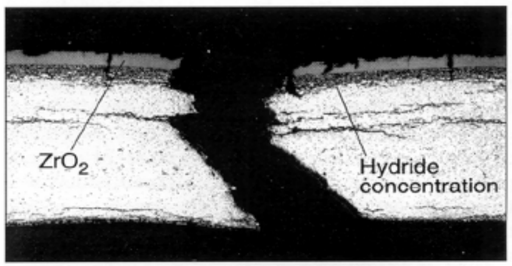


Fig. 3 Crack tip from test HBO-1 (Table 2) showing partly brittle and partly ductile character of a PCMI fracture.

Fig. 4 Crack tip from test RIA 1-4 (Table 6) showing ductile character of a PCMI fracture and postfailure oxidation.

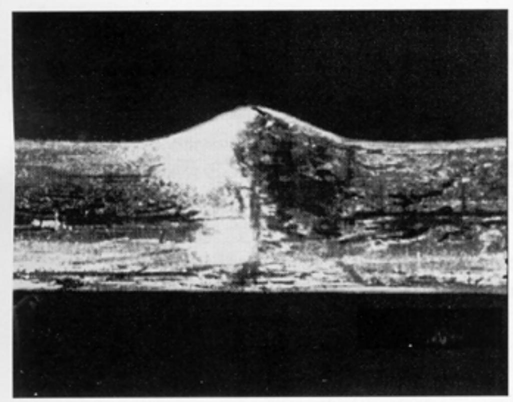
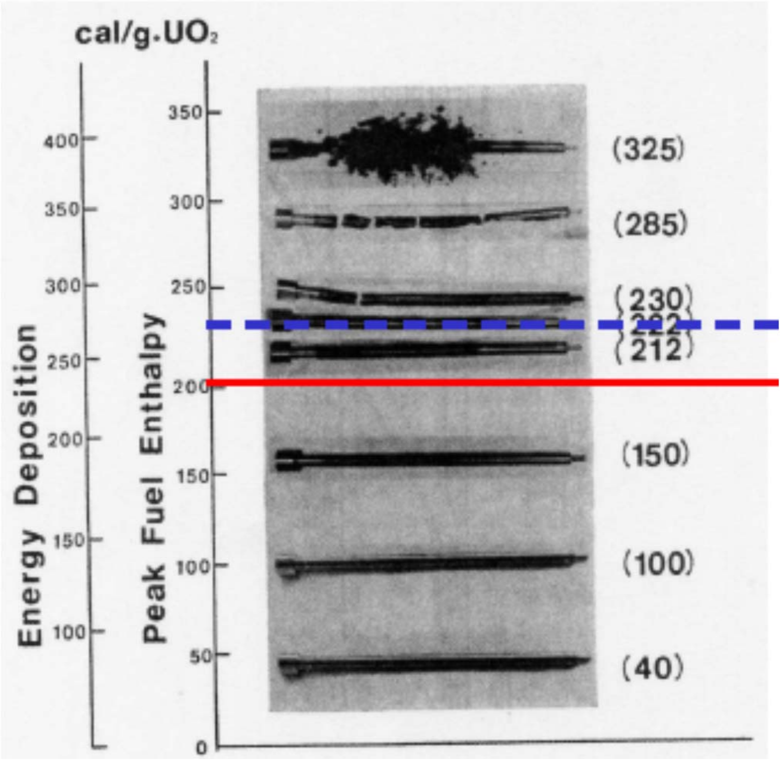


Fig. 6 Ballooned region of ruptured fuel rod from test H7T (Table 5).

Standards have been set for the reaction behavior during a RIA, but they are for fresh fuel

- **Design basis accident**: Do not need to ensure fuel will remain intact; but simply that the consequences are acceptable.
- Materials tested from 0-30 GWd/t
- Fuel Limits were 180 cal/g for failure and 280 cal/g for failure with fuel dispersal; not much change between 0 and 30 Gwd/ton
- (SPERT experiments)



P. E. MacDonald, S. L. Seiffert, Z. R. Martinson, R. K. McCardell, D. E. a. Owen, and S. K. Fukuda, Nuclear Safety, vol. 21, pp. 582, 1980.

Rep-Na-1 test from IRSN (CABRI Facility, 1994)

- Cladding irradiated for 5 cycles (67 GWd/ton)
- 100 microns of oxide
- 700 wt. ppm hydrogen
- Brittle failure at 30 cal/g fuel (limit is 280 cal/ g fuel)
- Fuel dispersal occurred

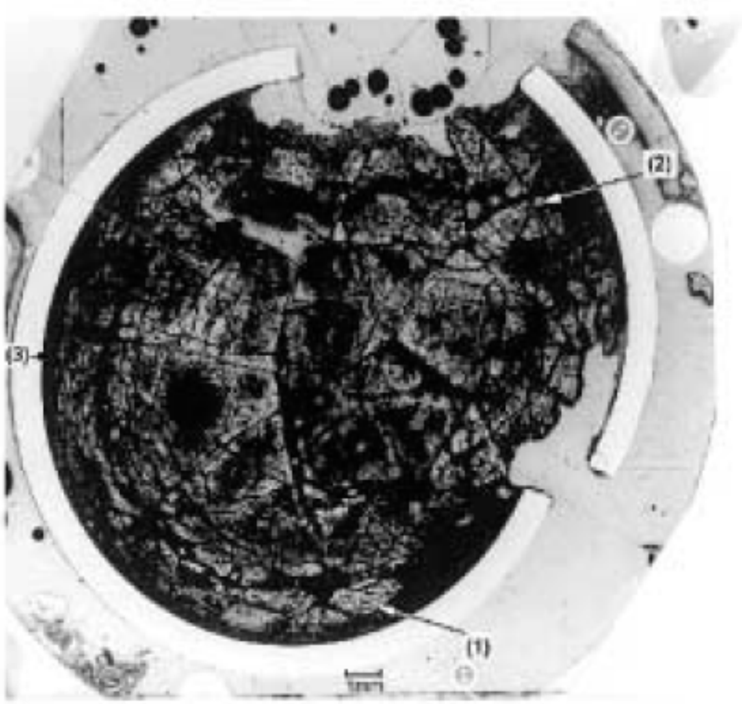


Fig. 3. Metallographic section (X4) of the REP-Na1 rod after test. The brittle aspect of the ruptures (perpendicular cracking) and the fuel fragmentation constitute outstanding facts of this observation. The numbers indicate locations of detailed examination: (1) RIM structure, (2) fragmented fuel, (3) intact cladding.

Recent results show the deposited energy needed to cause failure decreases with reactor exposure

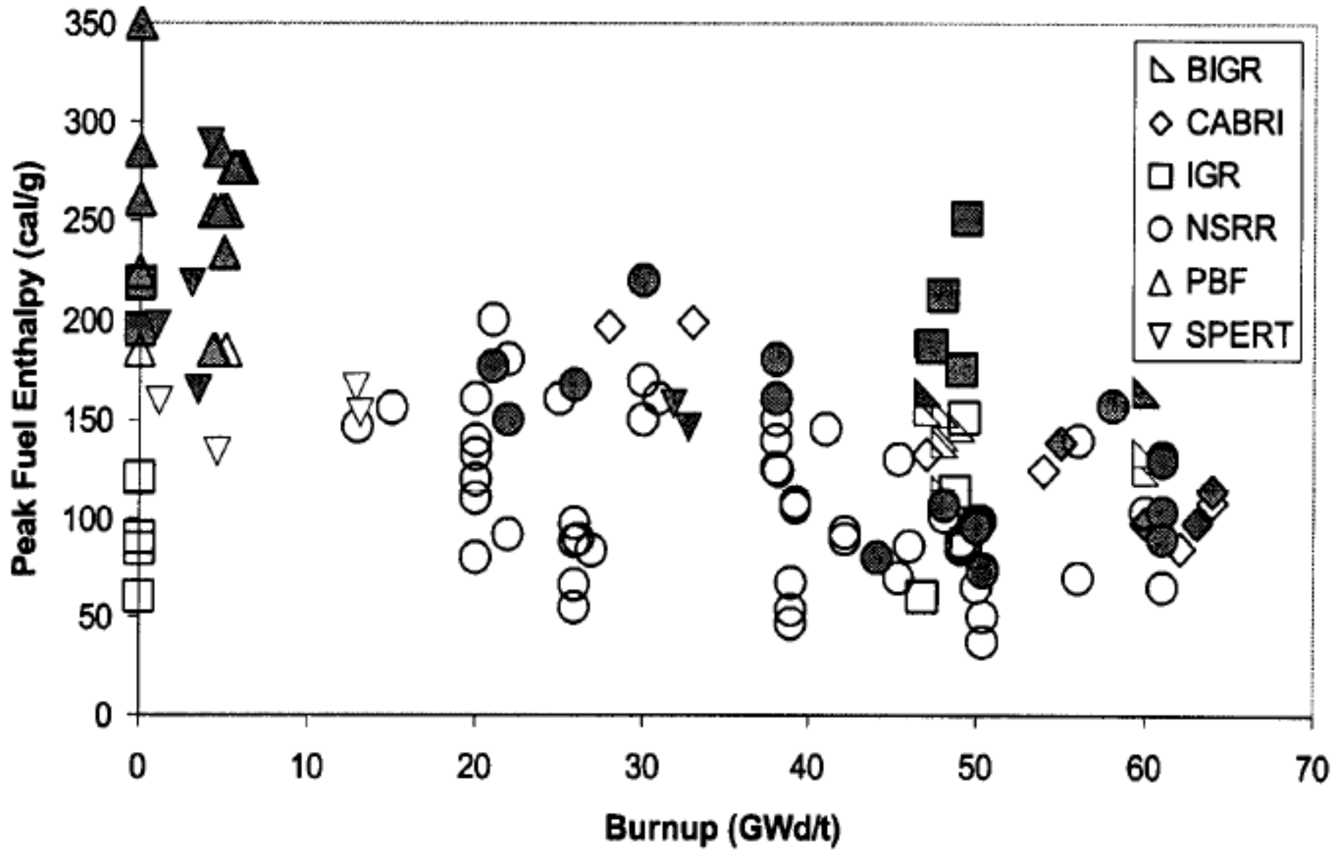


Figure 1. Test data, plotted as peak fuel enthalpy (total) as a function of burnup.

RIAs have a much larger impact on high burnup fuel due to various factors

Cladding	Corrosion Hydriding Radiation Damage	→	Mechanical Property Changes (lower ductility)
Fuel/Clad	Fuel/Clad Bonding Rim Structure in Fuel	→	PCMI Loading Path State of Stress
Fuel	Fission Gas Increase Reactivity Decrease	→	Loading due to FG Lower available enthalpy

→ different limit?

Very difficult to model but attempts are ongoing

Summary

- A reactivity initiated accident (RIA) results when there is a sudden change in reactivity
  - PWRs – Control rod ejection
  - BWRs – Control rod drop
- A RIA requires a rapid transient with large reactivity change
- RIA can result in
  - Fuel breaking to pieces
  - Cladding bursting
  - Fuel dispersal
- Two primary types of failures have been observed in tests
  - Ballooning and burst – occur with fresher fuel
  - PCMI – occurs with high burnup fuel