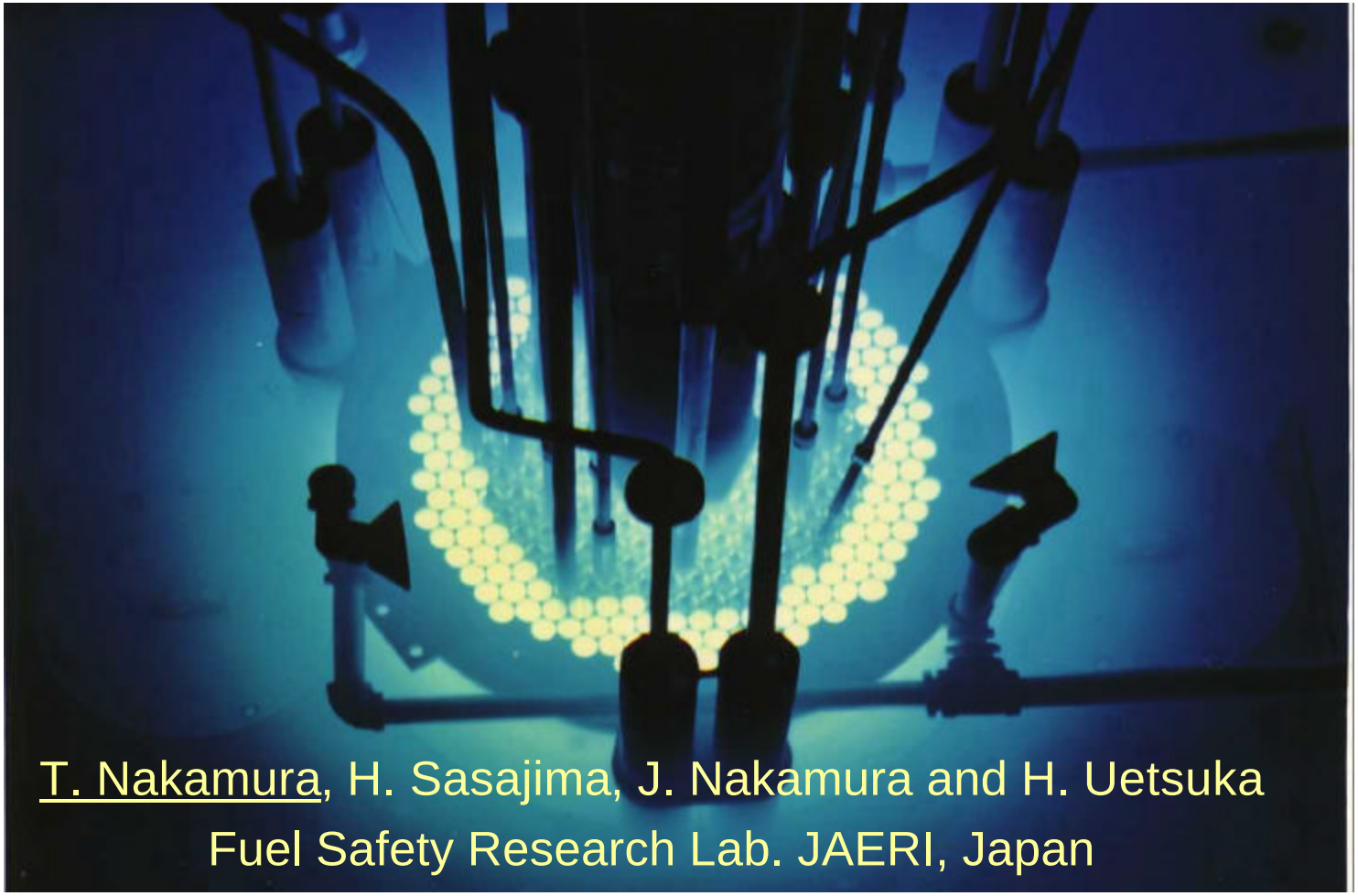
NSRR High Burnup Fuel Tests for RIAs and BWR Power Oscillations without Scram



T. Nakamura, H. Sasajima, J. Nakamura and H. Uetsuka

Fuel Safety Research Lab. JAERI, Japan

Prepared for NSRC 2002

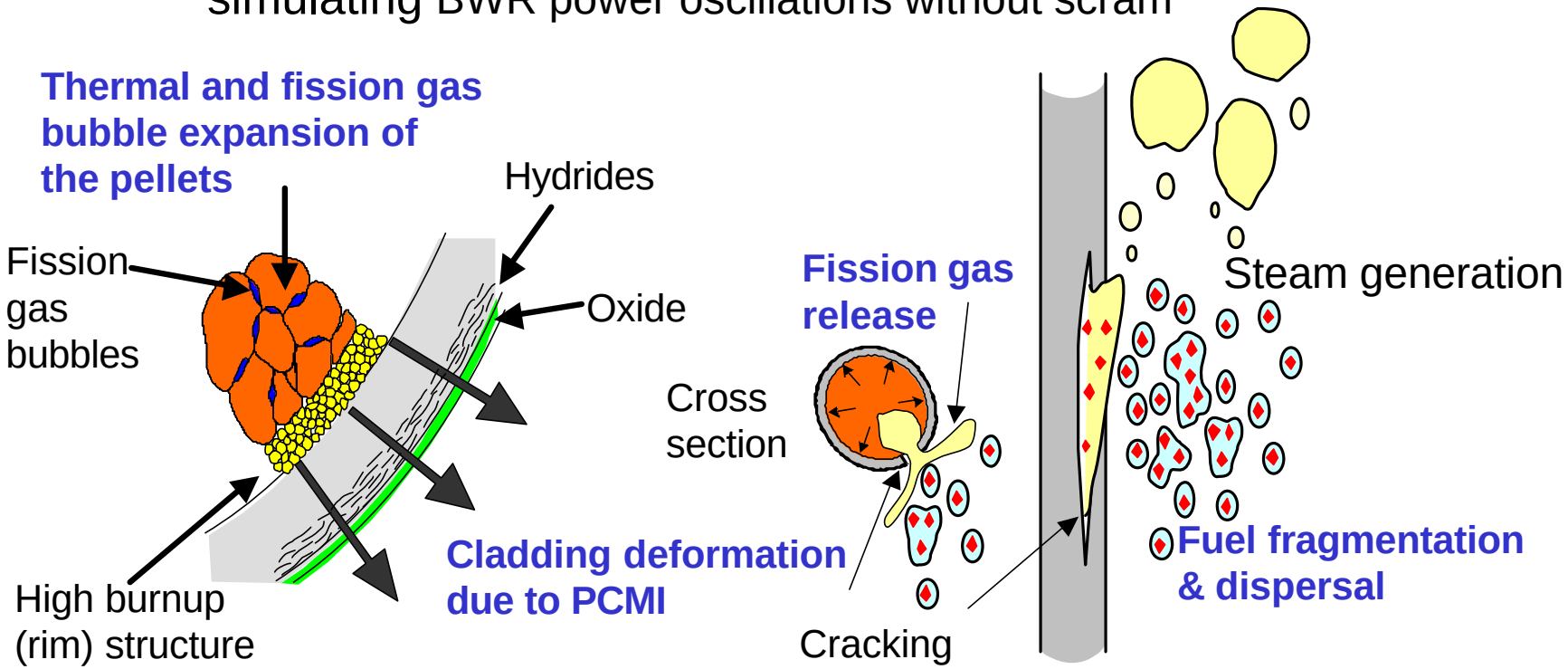
Oct. 29, 2002 at Washington D.C., USA

Objectives of the NSRR Tests

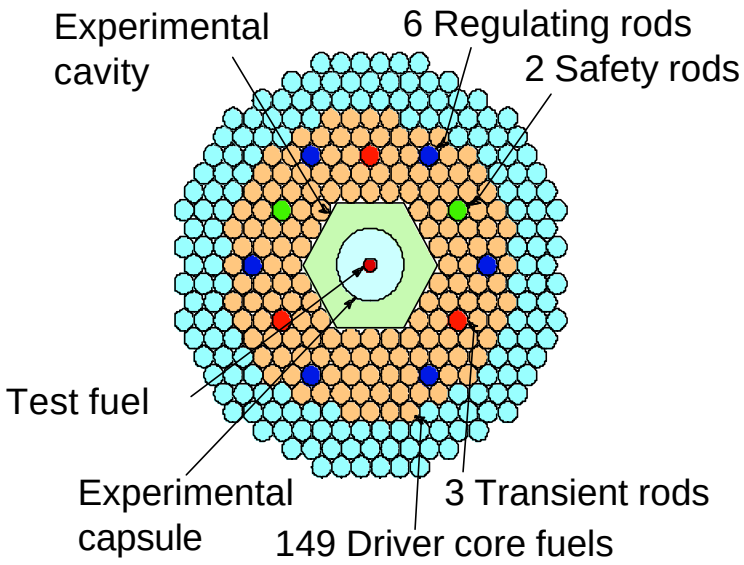
- Clarify influence of fuel burnups on
  - Fuel failure threshold and its mechanism
  - Consequence of the failure
    (Fission gas release, fuel fragmentation & dispersal, etc.)

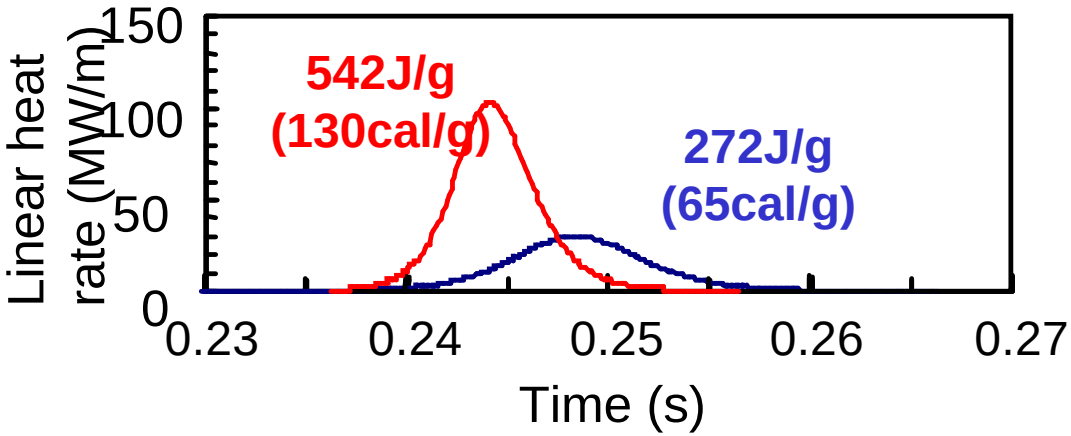
  under Reactivity-initiated accident (RIA), and to

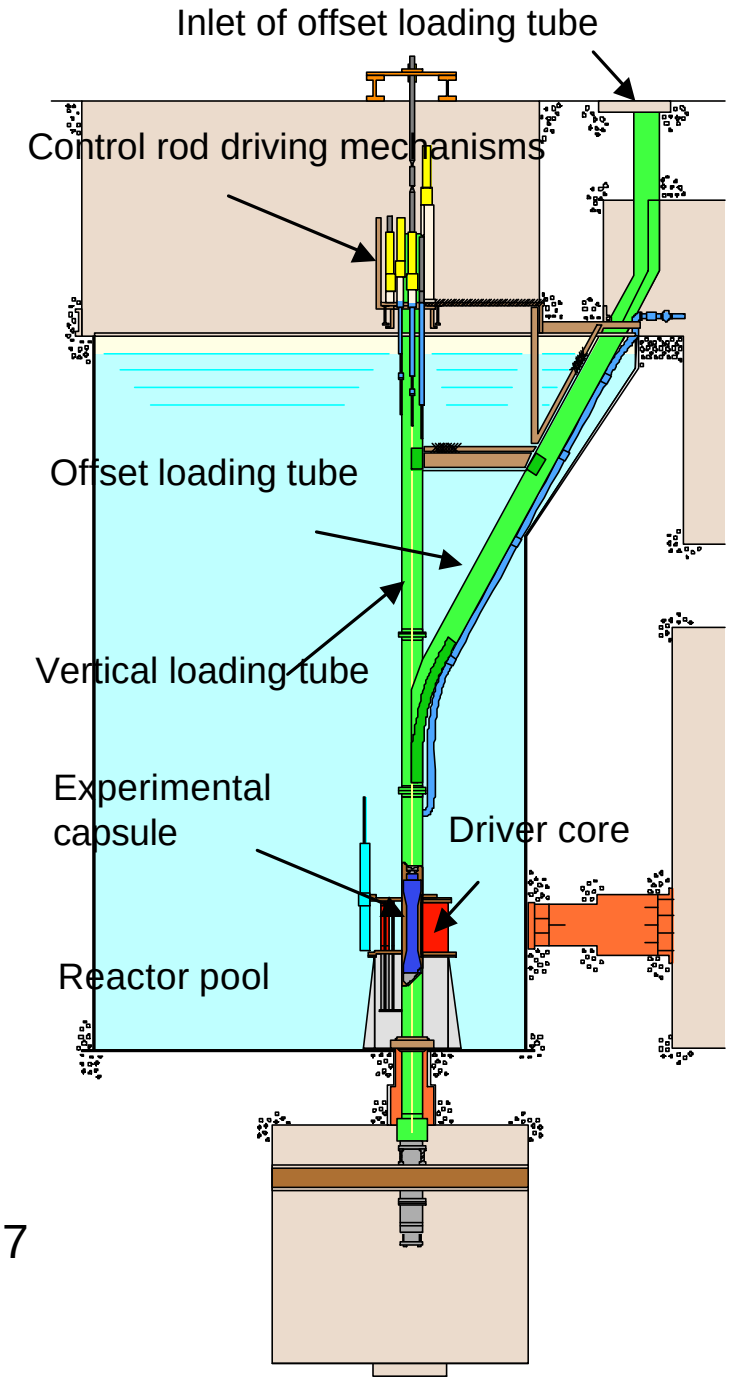
  Examine fuel behavior under cyclic power transient conditions simulating BWR power oscillations without scram



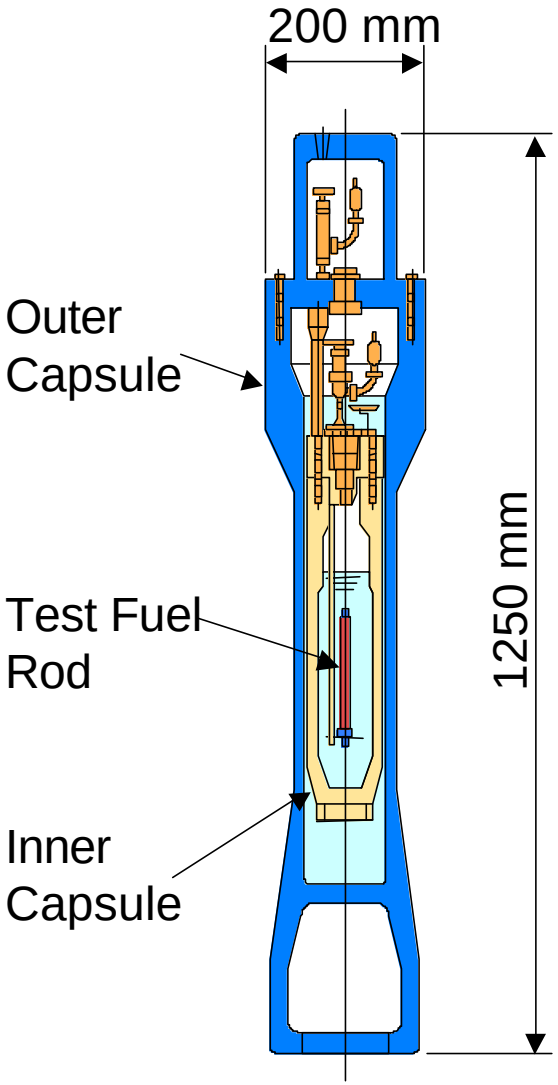
NSRR (Nuclear Safety Research Reactor)



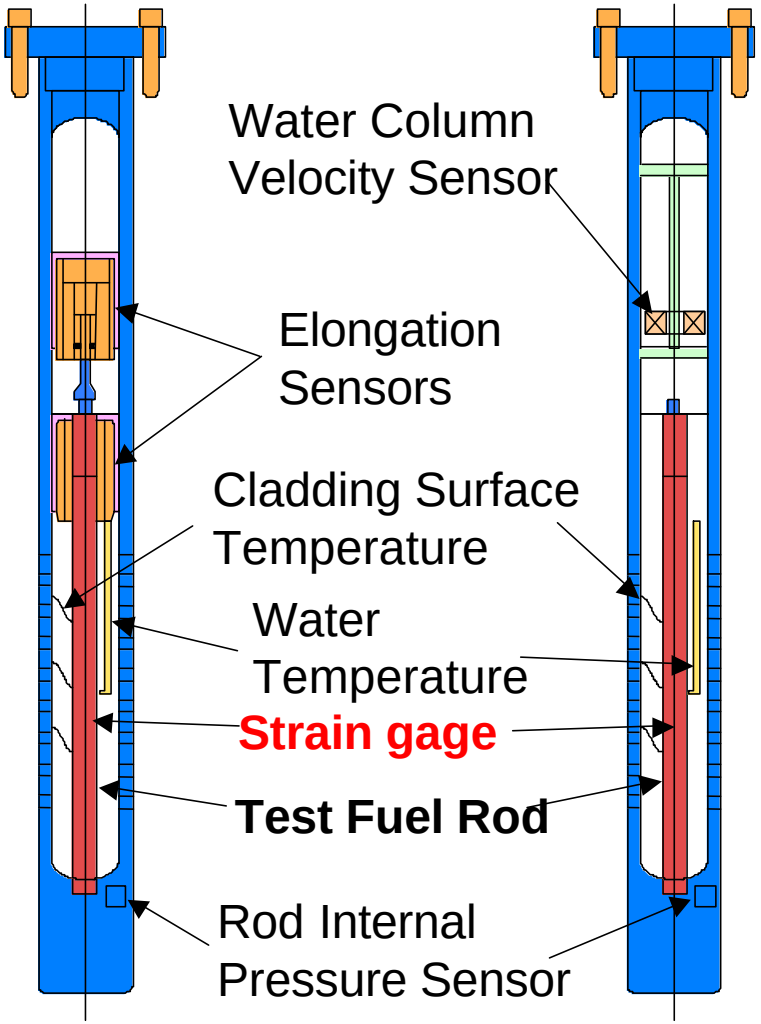




Irradiation Capsule and Instrumentation

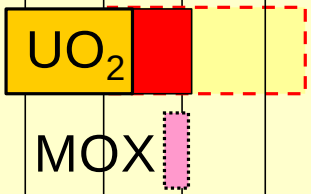
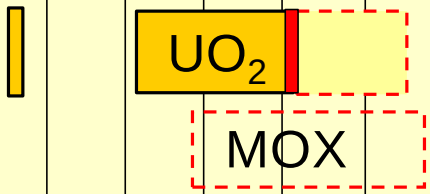
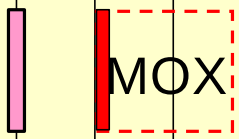
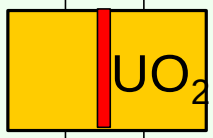


Test Capsule



Instrumentation

NSRR Test Fuel & Burnups

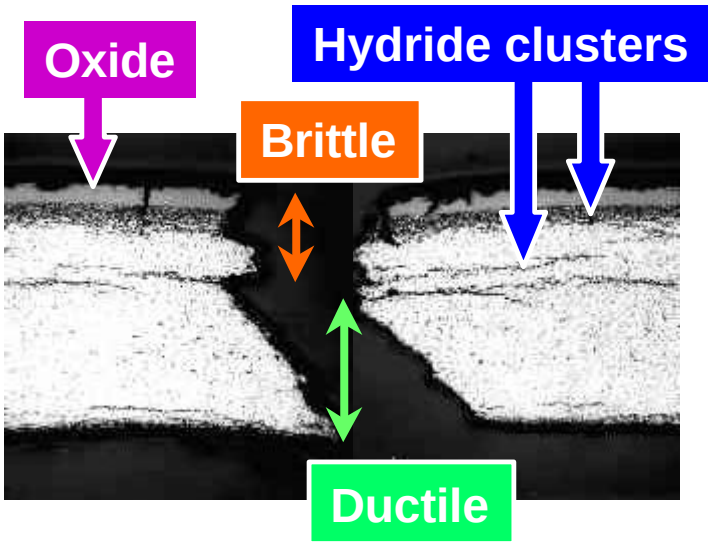
Fuel type	Pellet Burnup (GWd/t)	Number of tests Remarks	Test plan in 2002-2006
PWR		24 failure >60cal/g at 50GWd/t	UO_2 EU [<74GWd/t] JP [60GWd/t] MOX ALPS[59GWd/t]
BWR		16 failure >62cal/g at 61GWd/t	UO_2 EU [<75GWd/t] JP [61-65GWd/t] MOX EU[<78GWd/t]
ATR/MOX		5 no failure <140cal/g at 20GWd/t	MOX [30-45GWd/t]
Highly enriched UO_2 Irradiated in JMTR		22, failure >667J/g(160cal/g) at 38GWd/t	Power oscillation [25GWd/t]

EU: European fuel, JP: Japanese fuel

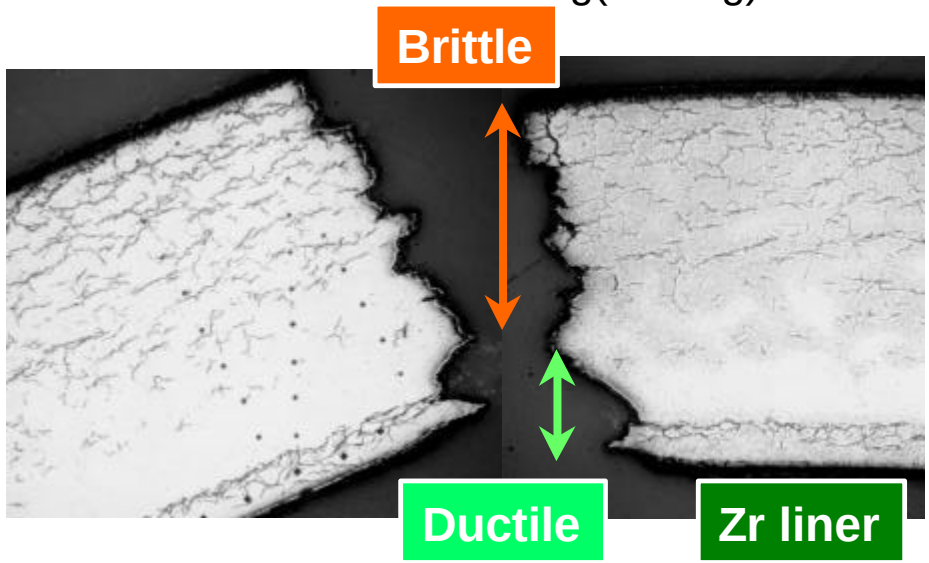
Tests to be conducted in 2002-2003

RIA Test Results

PWR 50GWd/t (hydrogen: about 400ppm) failed at 250J/g(60cal/g)



BWR 61GWd/t (Hydrogen: about 200ppm) failed at 292J/g(70cal/g)



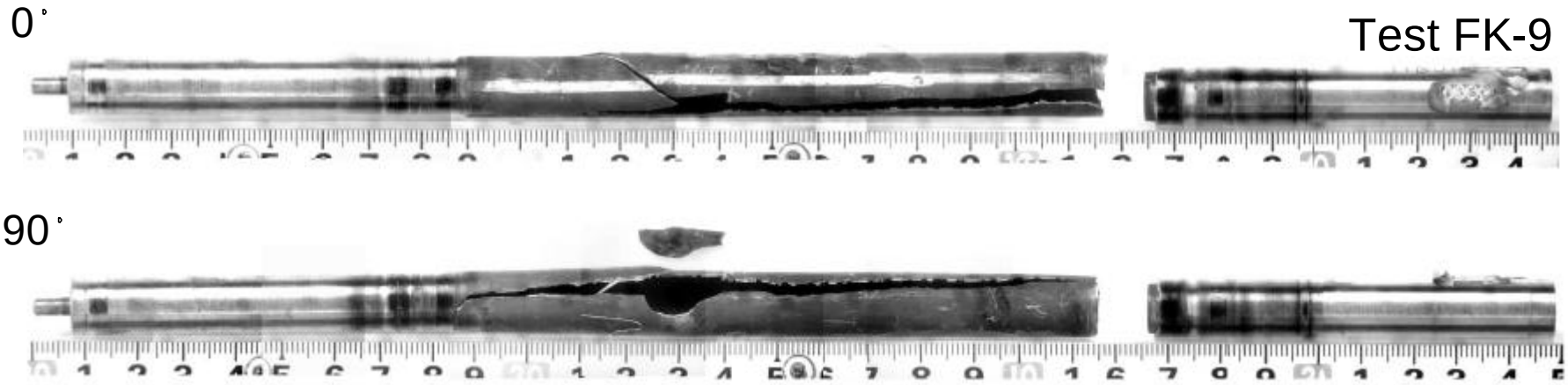
Key Observations in NSRR/RIA Tests

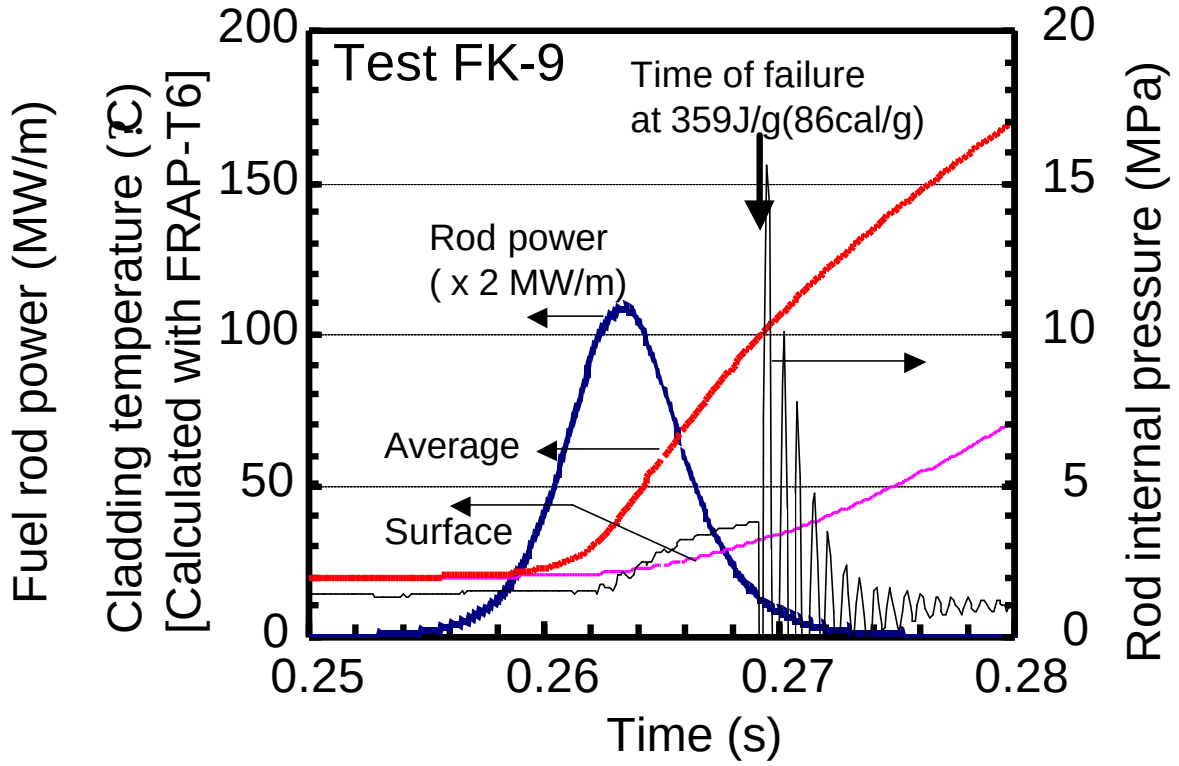
(1) Hydride-assisted PCMI failure at low enthalpies

(2) Consequence of fuel failure

- (i) Fission gas release
- (ii) Fuel fragmentation

(1) Hydride-assisted PCMI failure at low enthalpies

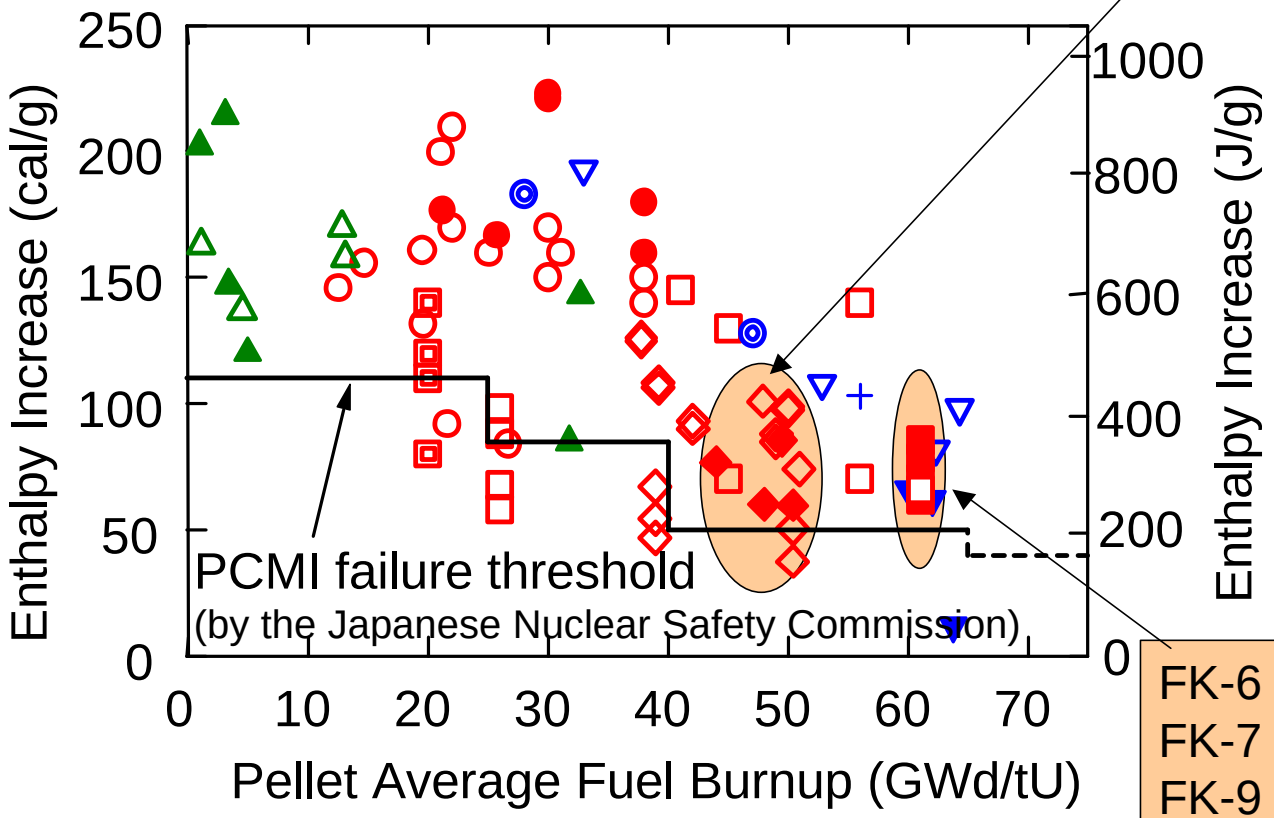




BWR fuel
at 61GWd/tU

PCMI Failure Thresholds

Test ID		No failure	Failure	Test ID	No failure	Failure
NSRR	PWR	◇	◆	SPERT, PBF	△	▲
	BWR	□	■	CABRI UO_2	▽	▼
	ATR/MOX	▣	—	CABRI MOX	◎	+
	JMTR	○	●	—	—	—



HBO-1 50GWd/t 250J/g(60cal/g)
HBO-5 44GWd/t 321J/g(77cal/g)
TK-2 48GWd/t 250J/g(60cal/g)
TK-7 50GWd/t 359J/g(86cal/g)

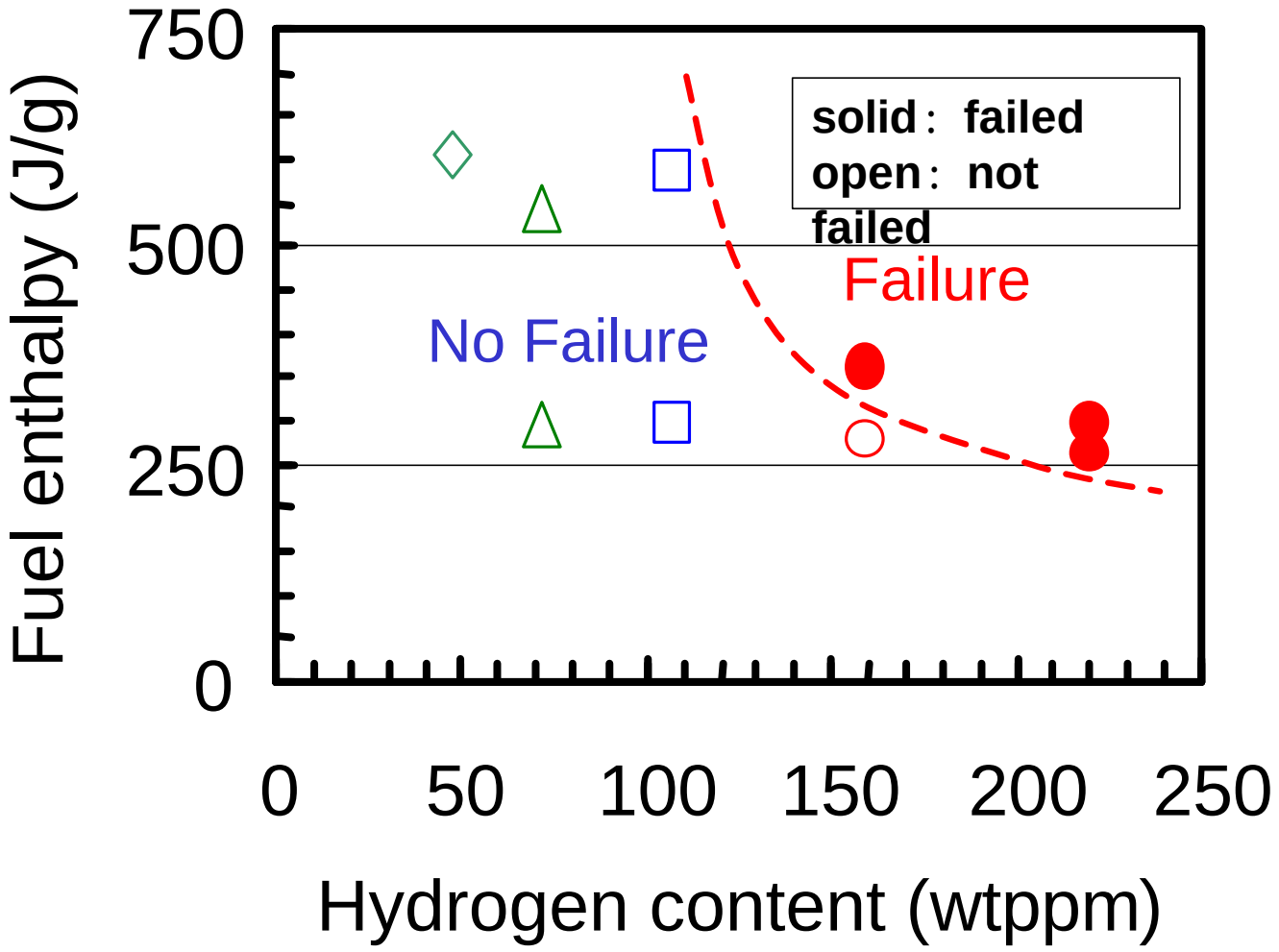
PWR fuel burnups and failure enthalpies

BWR fuel burnups and failure enthalpies

FK-6 61GWd/t 292J/g(70cal/g)
FK-7 61GWd/t 259J/g(62cal/g)
FK-9 61GWd/t 359J/g(86cal/g)
FK-10 61GWd/t 334J/g(80cal/g)

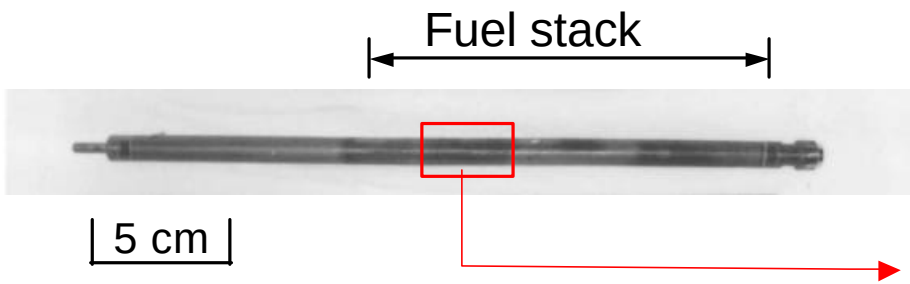
Failure Map in Terms of Hydrogen Content and Fuel Enthalpy for BWR Fuel

Fuel failure correlates well to hydrogen content in cladding in BWR fuel tests.

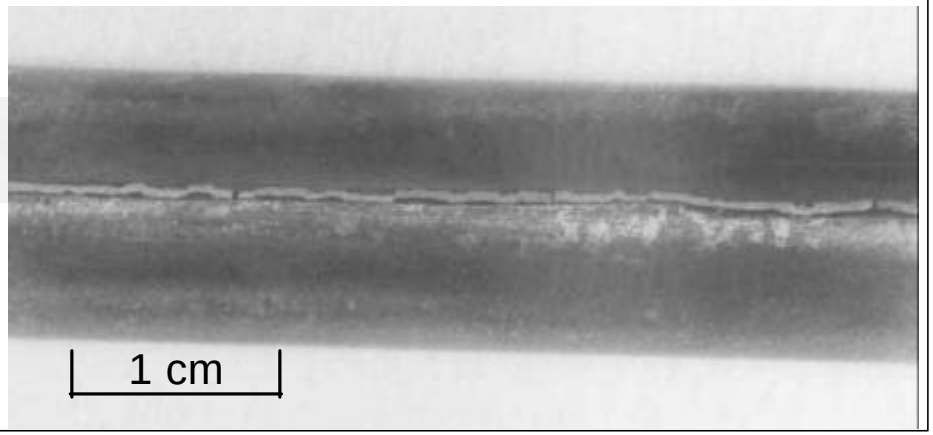


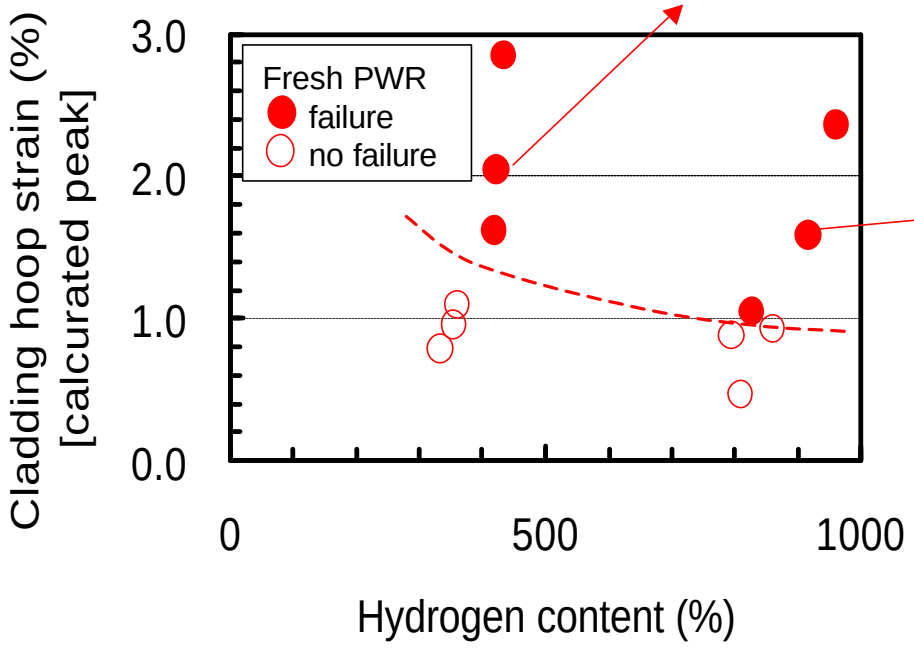
Fresh PWR Fuel Tests with Hydrided Cladding

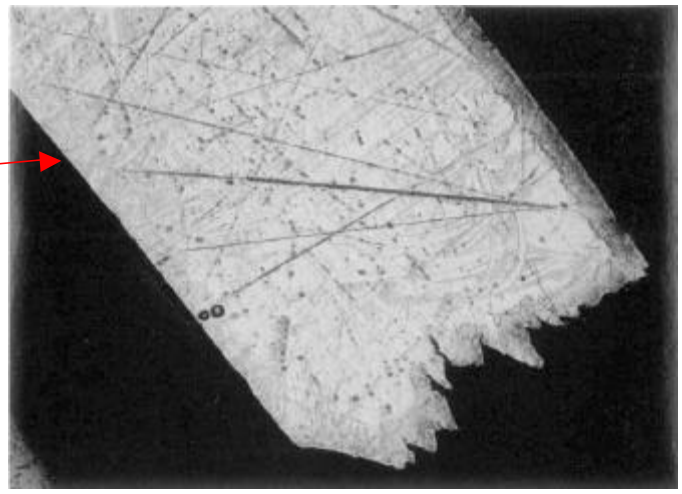
Brittle cladding fracture due to PCMI occurred in fresh PWR fuel tests with hydrided cladding, similar to high burnup fuel tests.



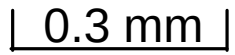
Longitudinal crack of about 10cm generated over the fuel stack







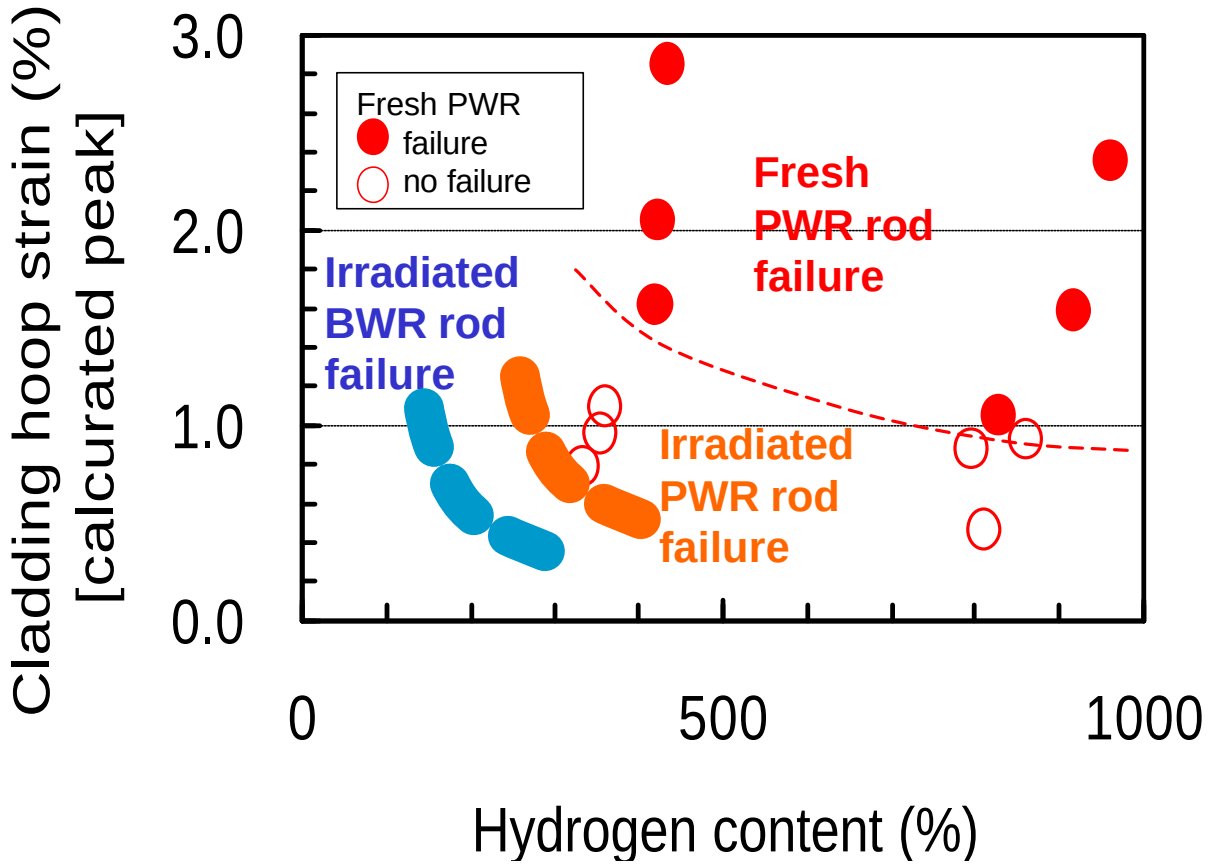
Cross section of crack



Failure Criteria of Hydrided Cladding

.Estimated peak strains to cause the failure was larger in fresh fuel tests, suggesting influence of the irradiation embrittlement of the cladding.

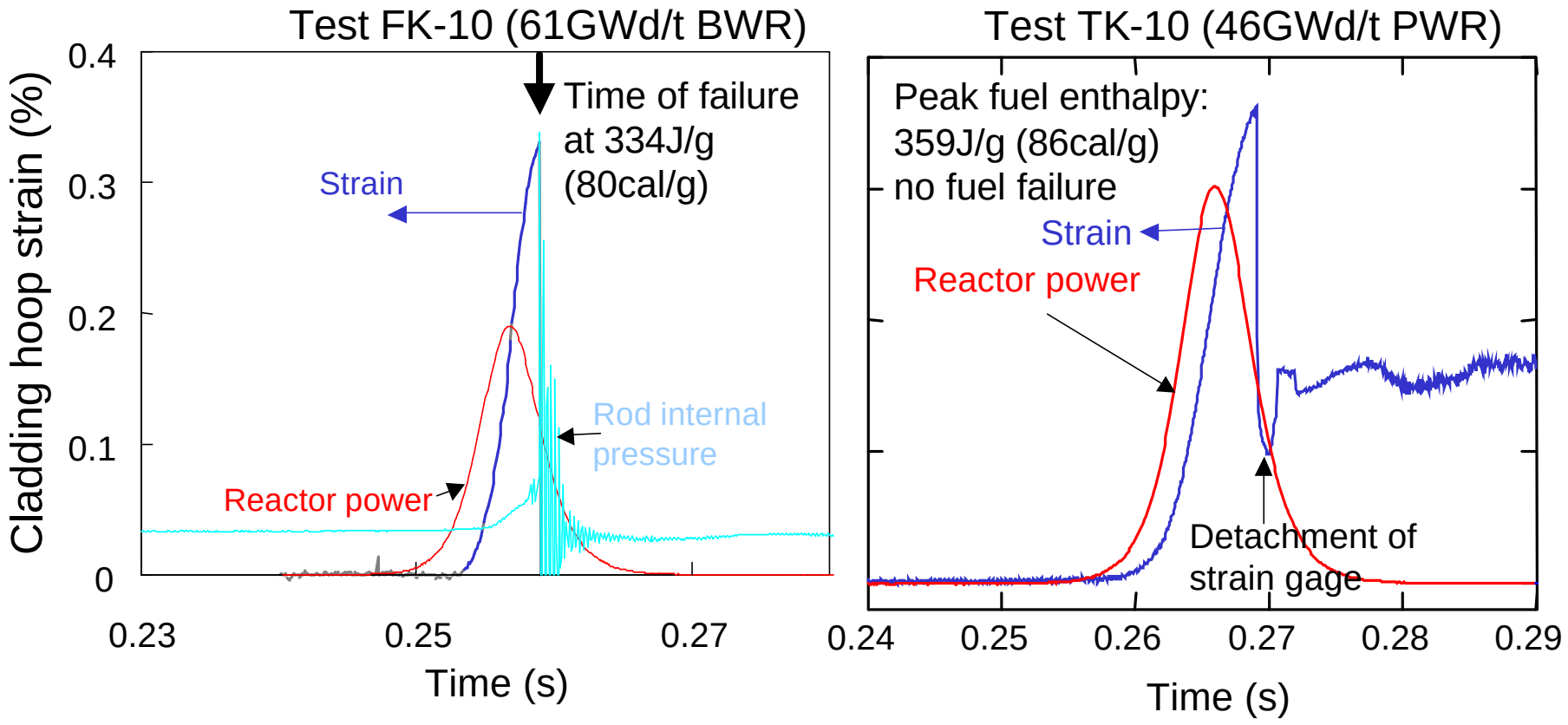
.Failure threshold differs depending on cladding type, suggesting hydride precipitation morphology effects.



Transient Hoop Strain Measurement

.Transient hoop deformation of irradiated fuel cladding by PCMI during early phase of RIA transient was measured for the first time.

.The hoop deformation was about 0.4% at fuel enthalpy of about 80cal/g.

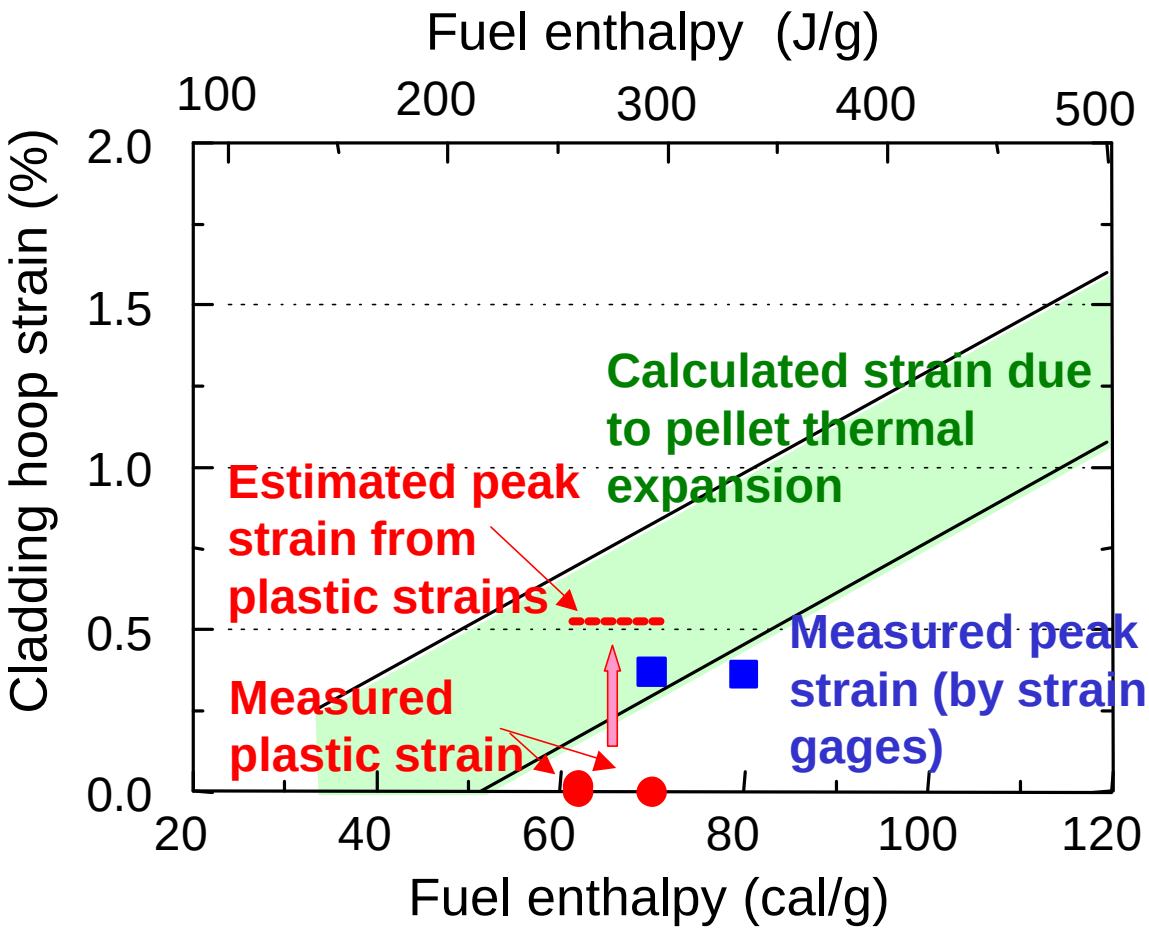


Cladding strains at failure

.Peak strain measured at 70-80cal/g was below 0.4%.

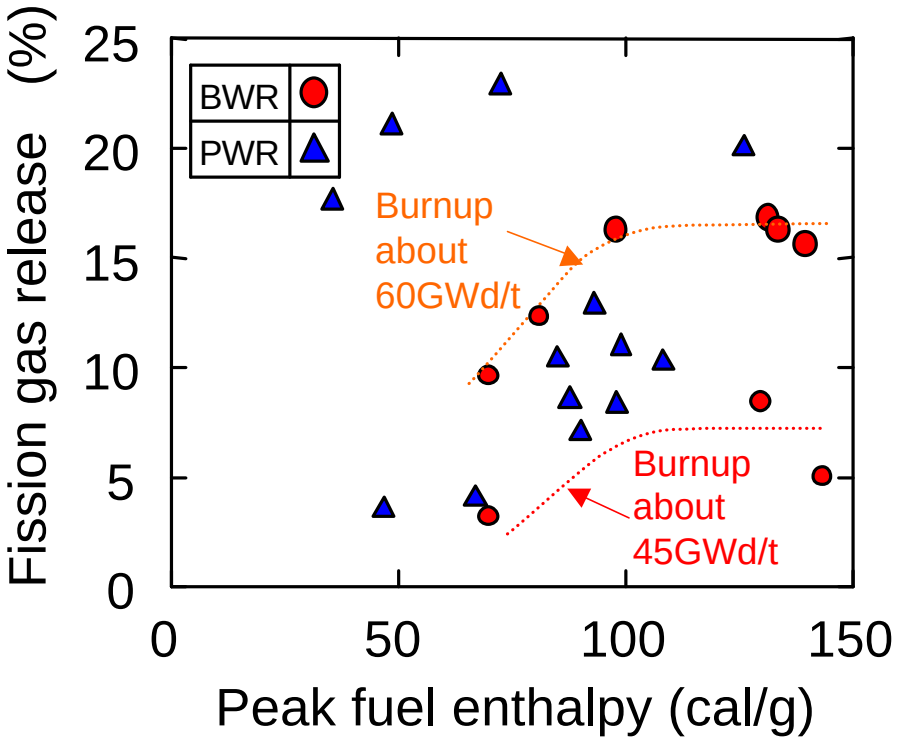
.Plastic hoop strain of the cladding failed was .0%.?(Elastic strain< 0.6%)

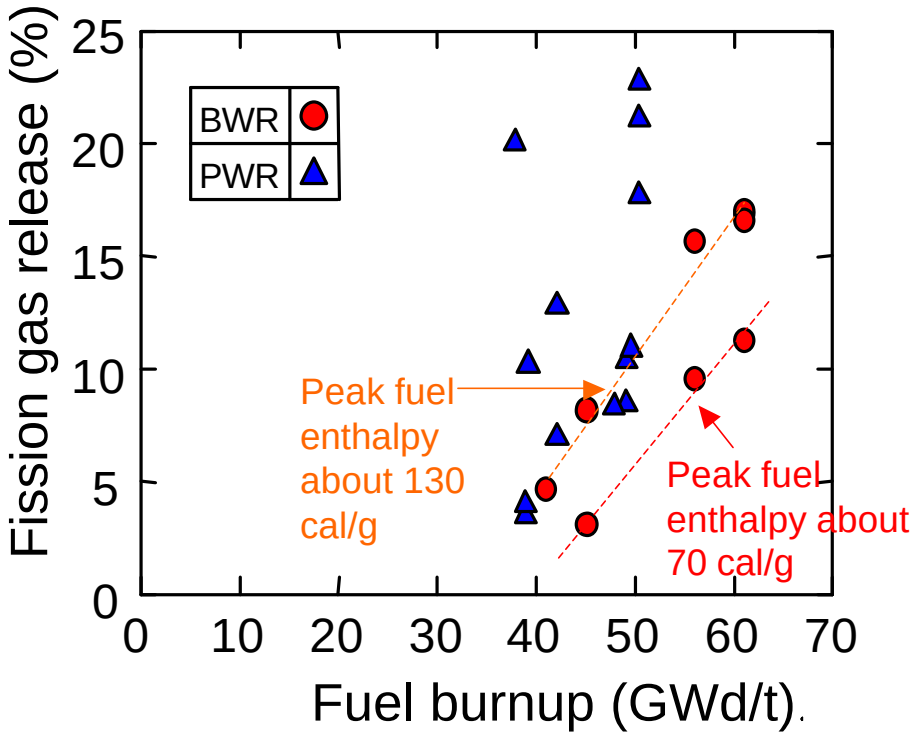
Deformation to cause the failure could be explained by thermal expansion of fuel pellets



(2) Consequence of the fuel failure
(i) Fission Gas Release in RIA Tests

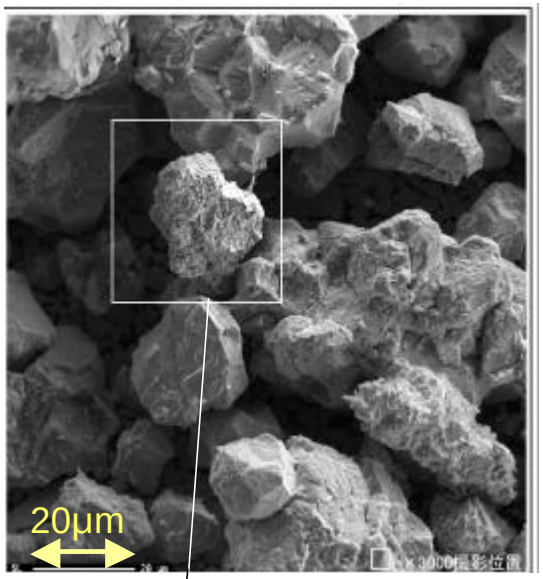
- Considerable fission gas release during RIA transient was observed.
- The release correlates with fuel enthalpy and burnup.

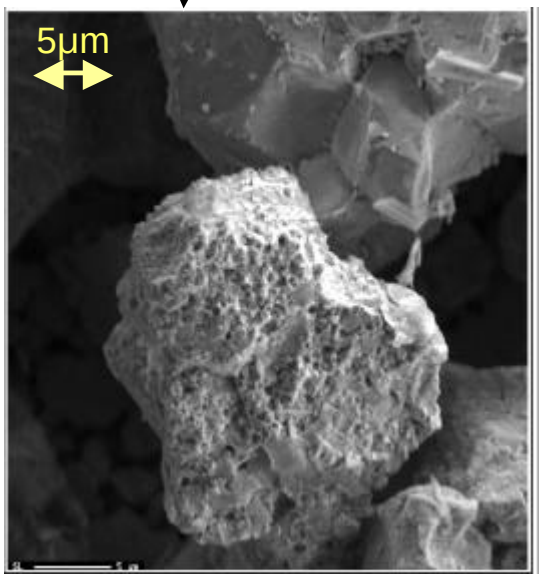




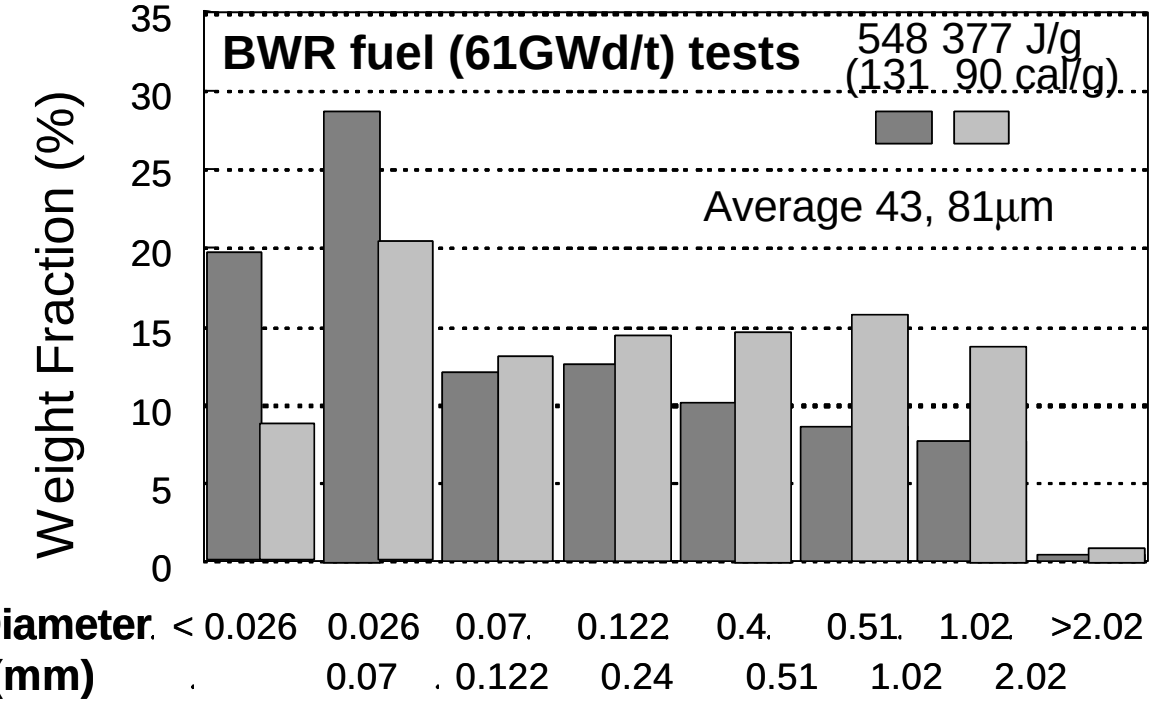
(ii) Fuel Fragmentation

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





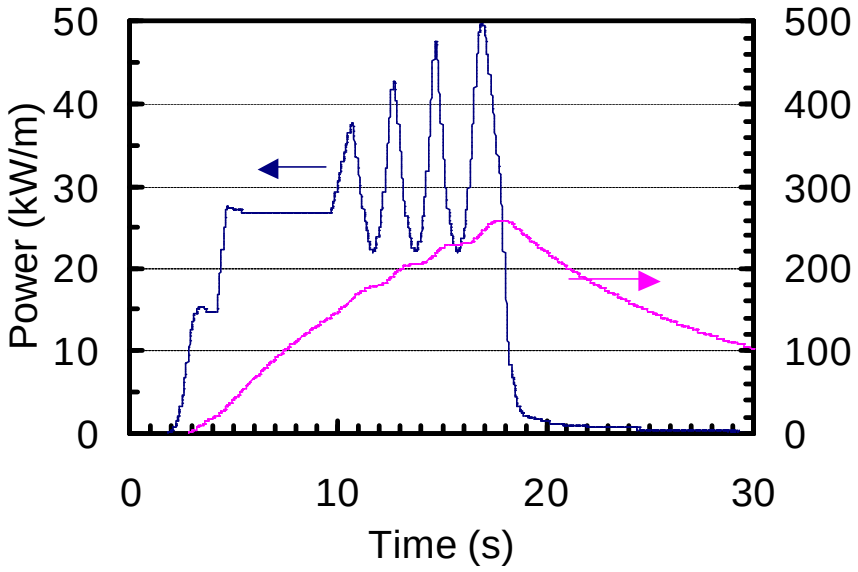
- Fine fuel fragmentation occurred when rod failed.
- Average size of the fragments was smaller in tests at higher fuel enthalpy (as small as 0.04 mm).
- Thermal interaction between fragments and coolant caused water hammer in the capsule.



Fuel Behavior Tests under Conditions Simulating BWR Power Oscillations without Scram

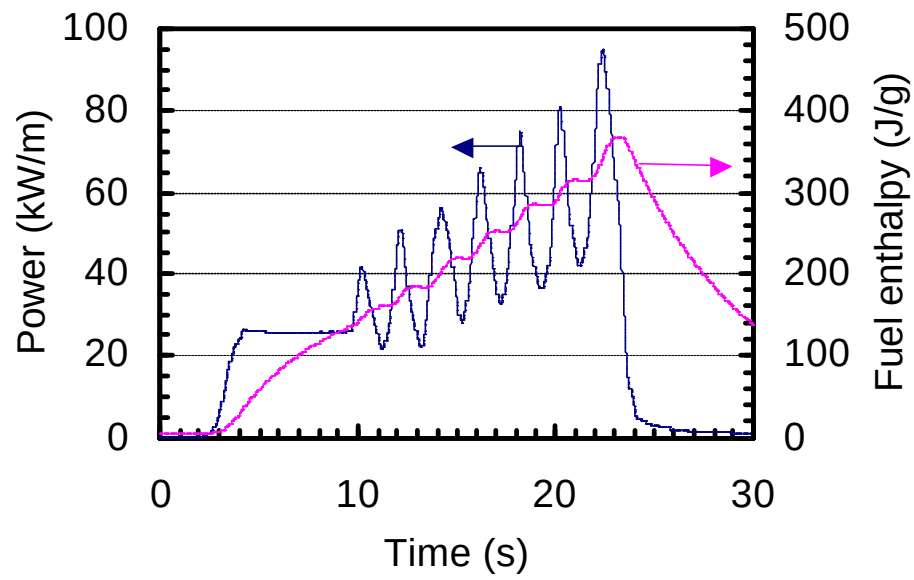
BWR fuel test

Burnup: 56 GWd/t
4 power oscillations
Peak power: 48kW/m
Fuel enthalpy: 256 J/g (61 cal/g)



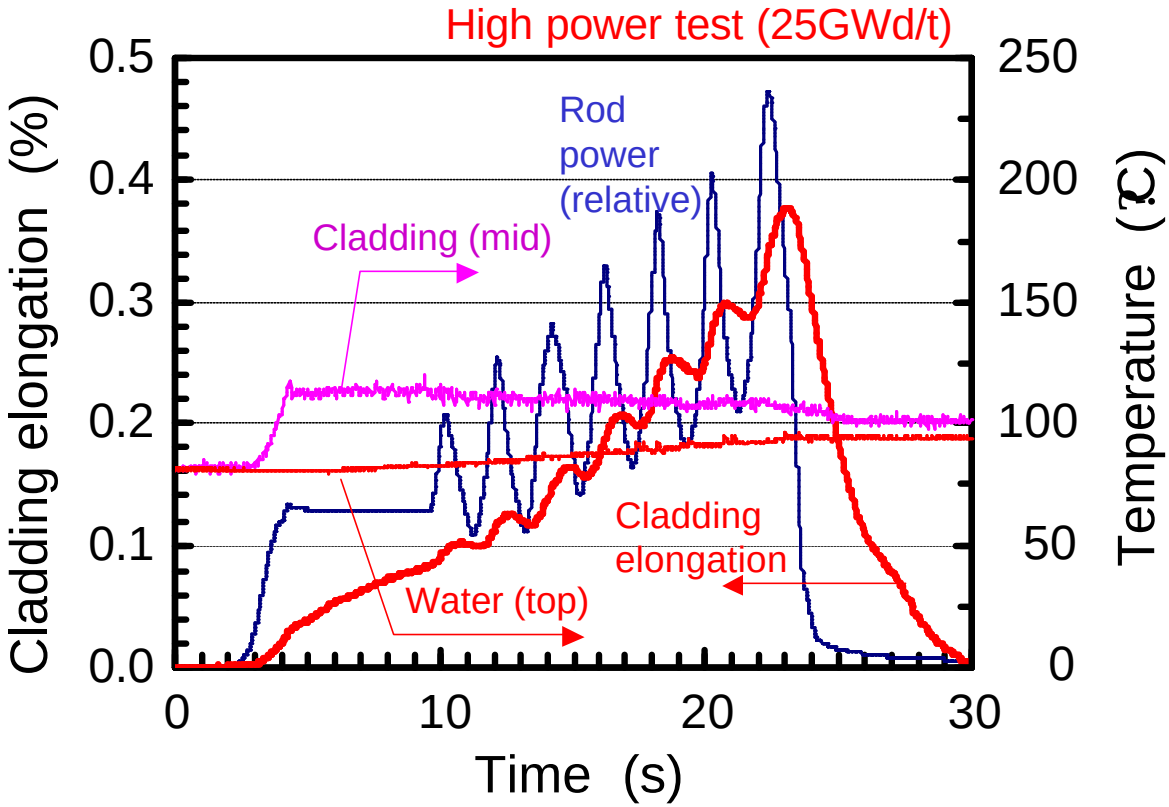
High power test

Burnup: 25 GWd/t
7 power oscillations
Peak power: 95kW/m
Fuel enthalpy: 368 J/g (88 cal/g)



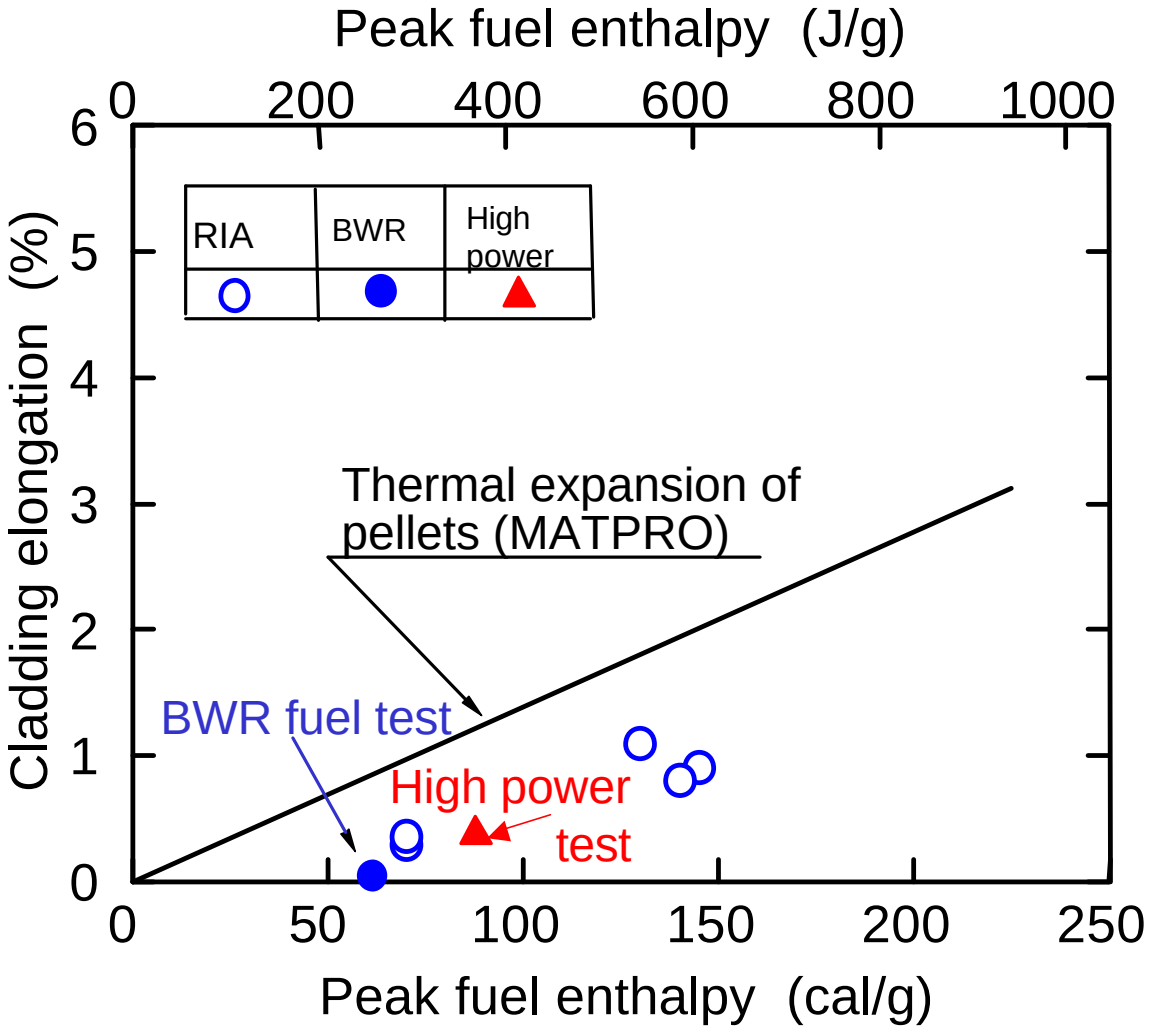
Transient Behavior in Power Oscillation Tests

- Clear sign of PCMI (Cladding deformation . fuel enthalpy)
- No plastic nor ratcheting deformation of cladding
- No DNB (departure from nucleate boiling)
- No failure



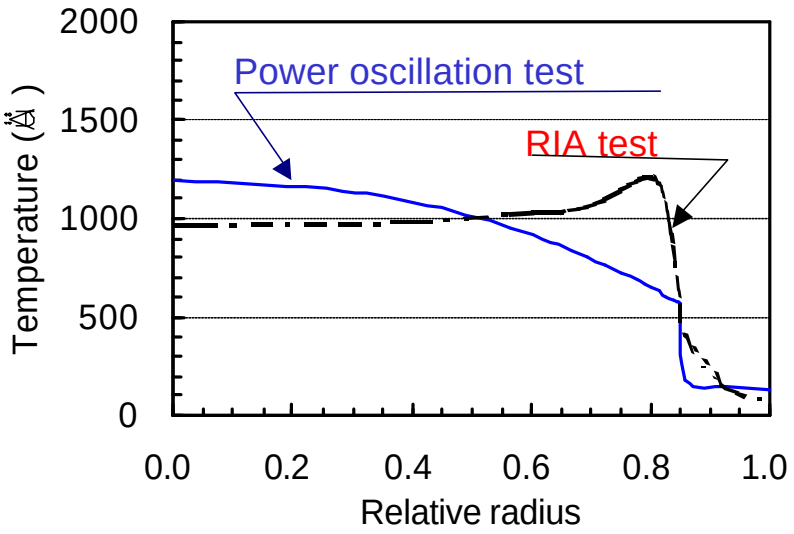
Cladding Deformation in Power Oscillation & RIA Tests

.Cladding deformation comparable to RIA tests (by PCMI in the two types of transients)

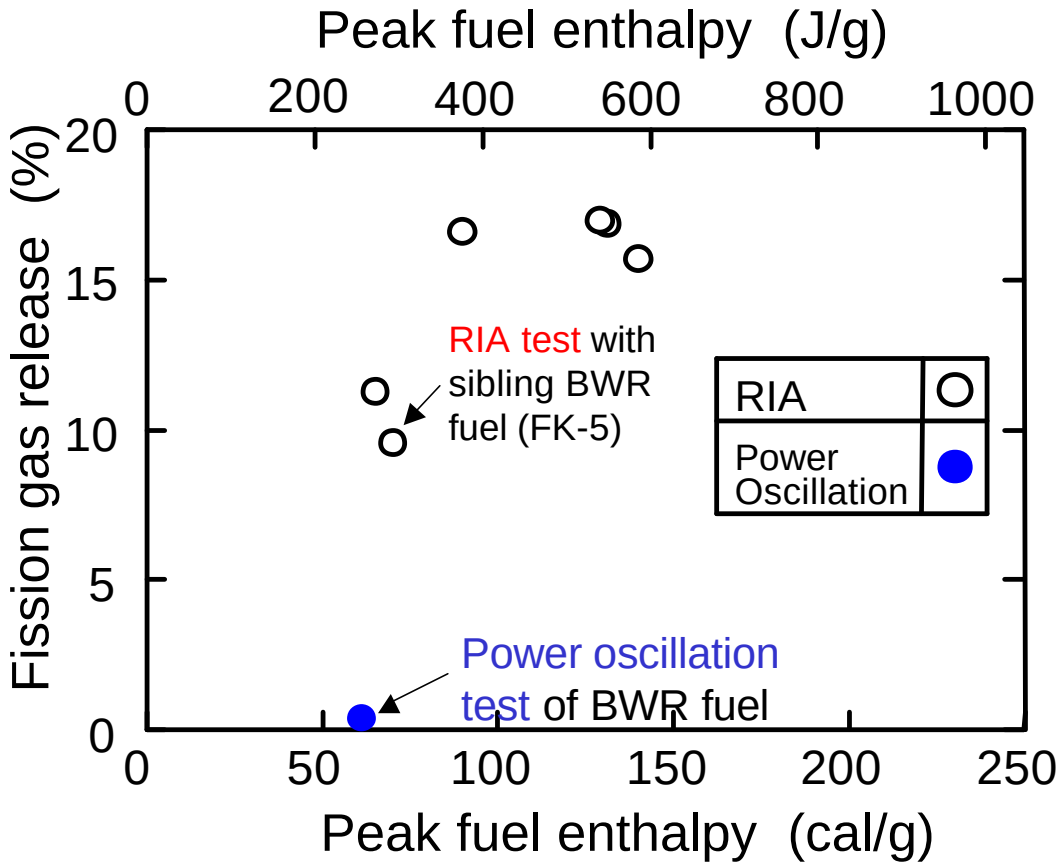


Fission Gas Releases in Power Oscillation Tests & RIA Tests

- Lower fission gas release during the power oscillation test
  - ?Lower temperature at fuel periphery
  - ?Smaller heat-up rate



Radial temperature distributions at time of enthalpy peaked
(Calculated with FRAP-T6)



Summary

RIA Tests

- Brittle cladding failure occurred in high burnup PWR and BWR fuel tests at fuel enthalpies as low as 60 cal/g.
- Same type of failure occurred in fresh PWR fuel rods with hydrided cladding. The failure thresholds, however, was higher in fresh fuel tests than irradiated fuel tests, suggesting the irradiation effects for the cladding embrittlement.
- Recent RIA tests with transient cladding hoop strain measurement suggested that the PCMI failure was caused mainly by thermal expansion of pellets. Contribution of fission gases to the failure seems limited.
- Considerable fission gas release and fine fuel fragmentation were observed in the tests. Consequence of the fuel failure would be influenced by these phenomena which should depend on fission gases and fuel morphology at high burnups.

Power Oscillation Tests

- First two tests under conditions of BWR power oscillations without scram were conducted in the NSRR.
- Cladding deformation was caused by PCMI and was comparable to those observed in RIA tests.
- Fission gas release was smaller than that observed in RIA test at a comparable fuel enthalpy.
- One more test in FY 2002 is planned under a condition with expected DNB.

Future plan to be continued

Future Tests on High Burnup Fuels

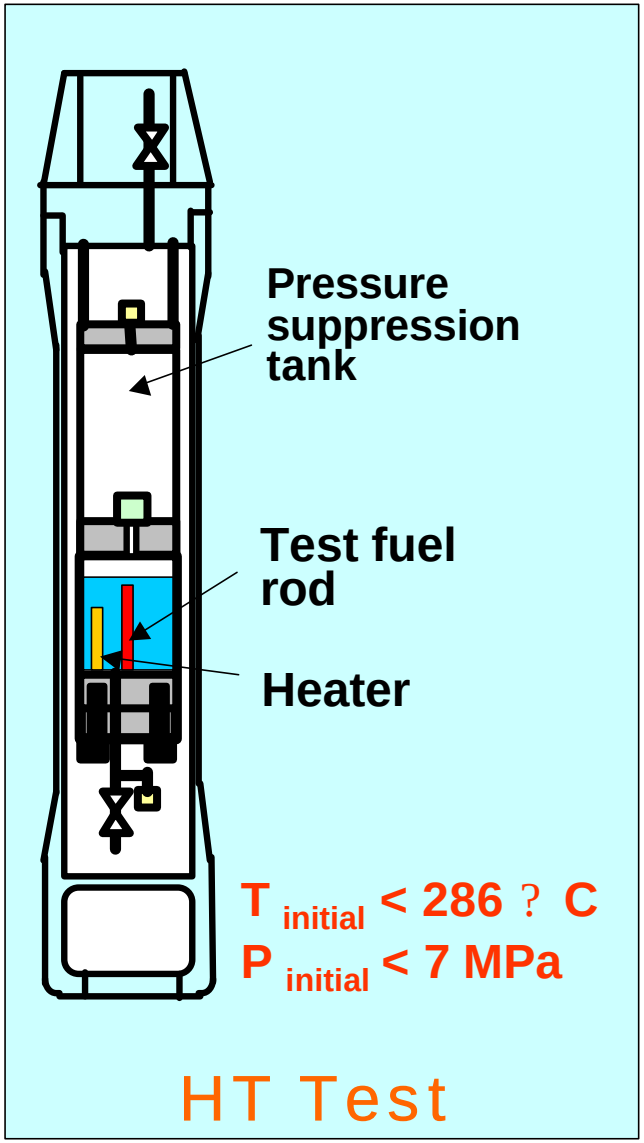
NSRR/RIA Tests

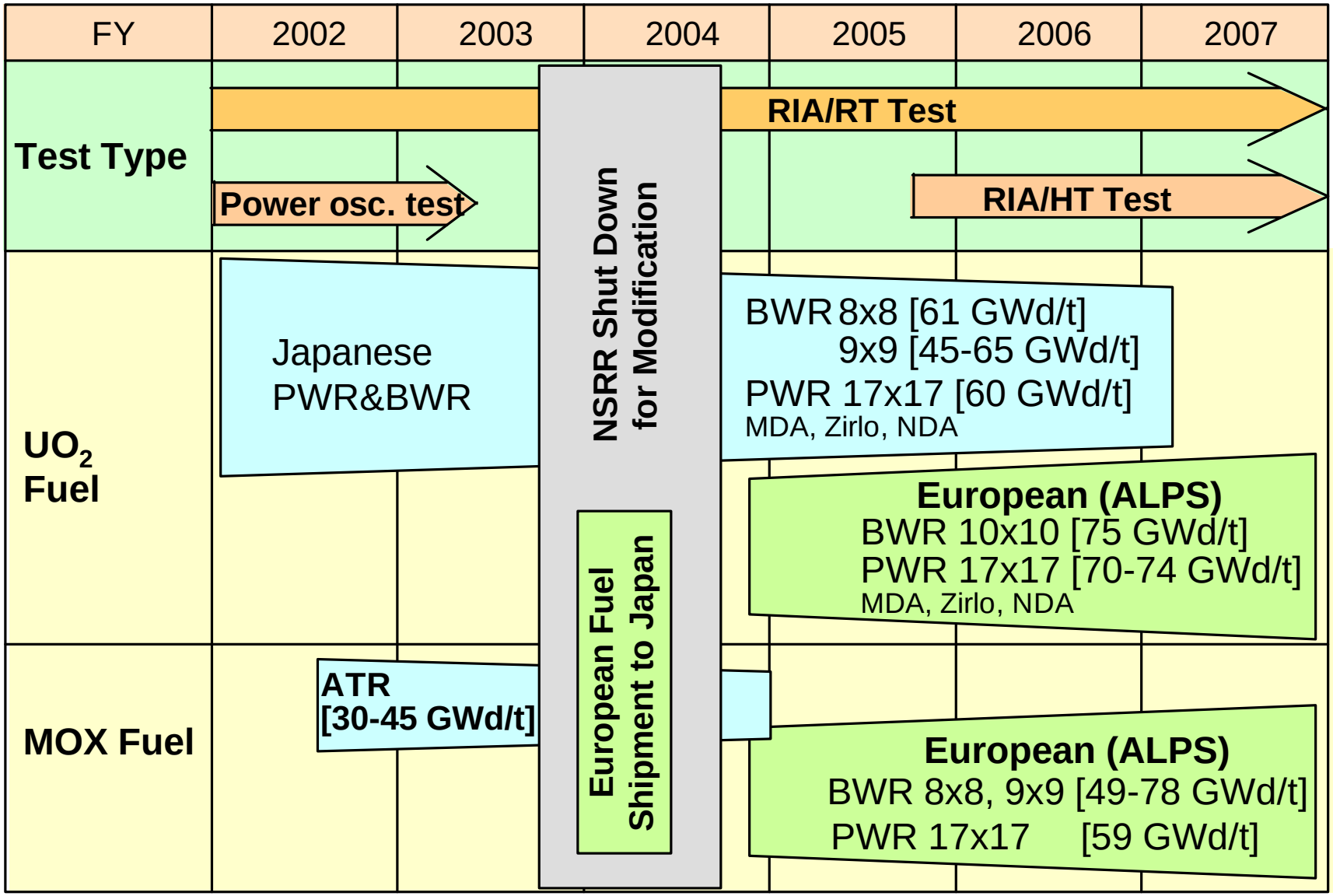
- Failure thresholds and its consequences
  - •Japanese UO_2 at 45-65GWd/t (Zirlo, MDA, NDA, Zry-2)
  - •Japanese MOX at 30-45GWd/t (Advanced Thermal Reactor type Zry-2)
  - •European* UO_2 at 70-74GWd/t (Zirlo, MDA, NDA, Zry-2)
  - •European* MOX at 49-78GWd/t (Zry-4, Zry-2)
- Tests at high temperature high pressure (HT Tests) conditions, in addition to room temperature conditions

Cladding Mechanical Testing

- Ring tensile, tube burst, etc.

***in ALPS (Advanced LWR Fuel Performance and Safety Research) program sponsored by METI of Japan**



MDA, NDA: Zr-Sn-Fe-Cr-Ni-Nb alloy developed by Japanese fuel vendors

NSRR Test Schedule