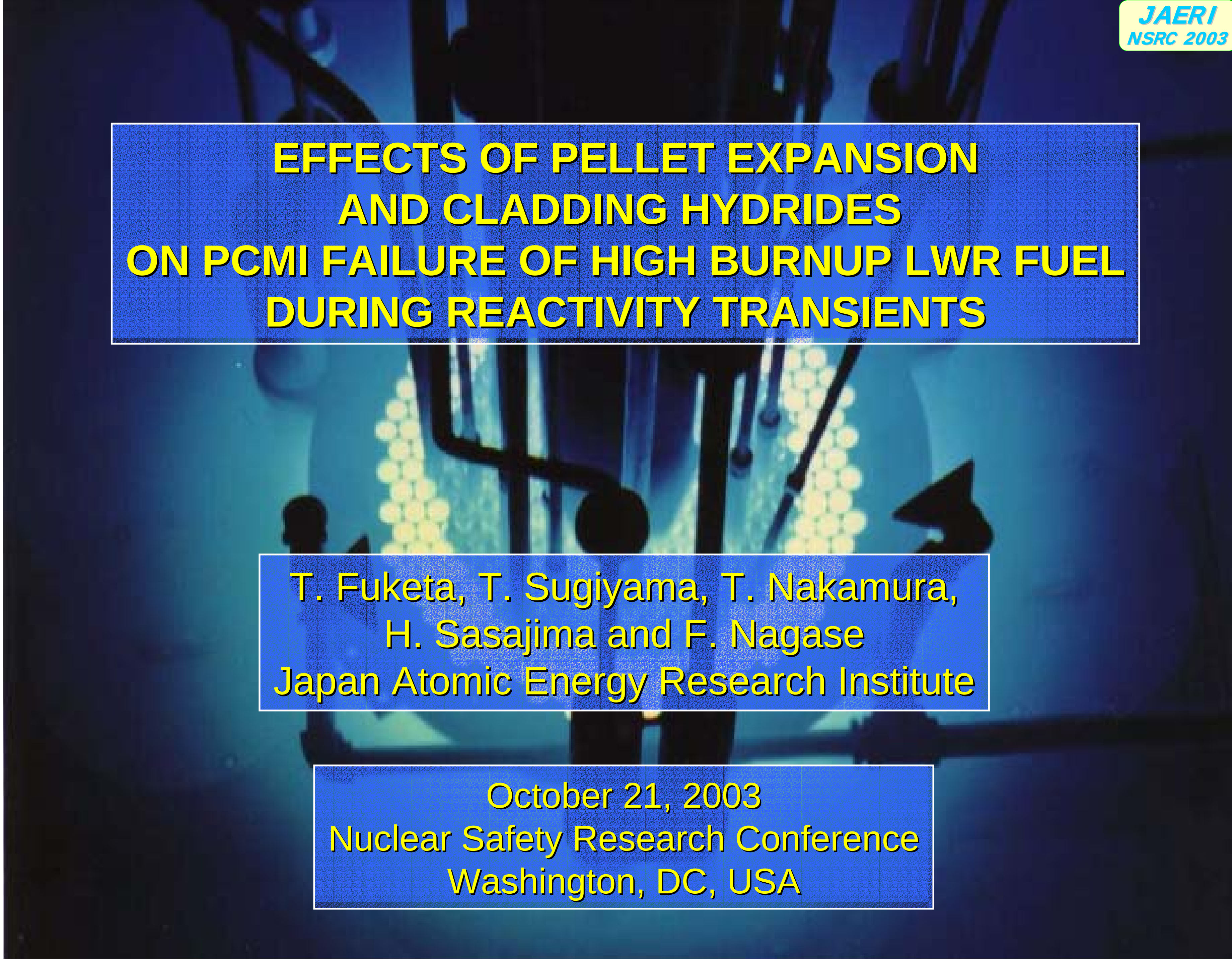

EFFECTS OF PELLET EXPANSION AND CLADDING HYDRIDES ON PCMI FAILURE OF HIGH BURNUP LWR FUEL DURING REACTIVITY TRANSIENTS

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Washington, DC, USA

This presentation covers;

- ✓ Recent results from pulse tests in the NSRR
  OI-10 and -11 with MDA and ZIRLO^{TM}, respectively

- ✓ Peak hoop strain at cladding failure in the NSRR experiments

- ✓ Tube burst test, ring-tensile test and NSRR test with un-irradiated, artificially-hydrided cladding

- ✓ Future NSRR experiments
  including tests with fuels shipped from Europe and with newly developed high-temperature capsule

NSRR pulse irradiation tests

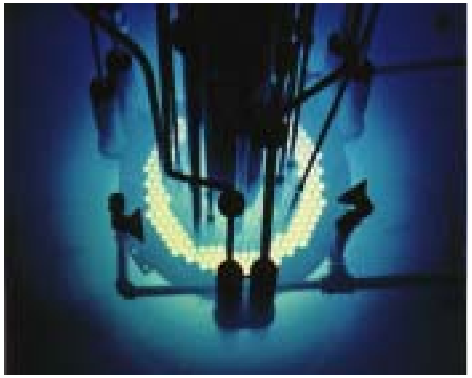
2

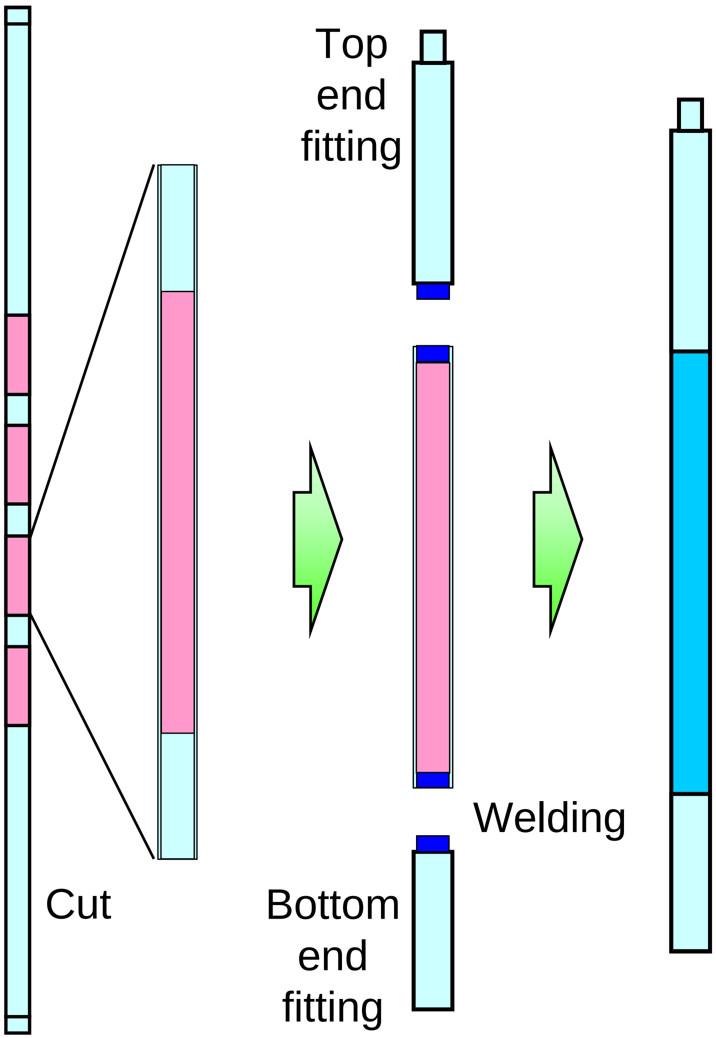
Pulse irradiation

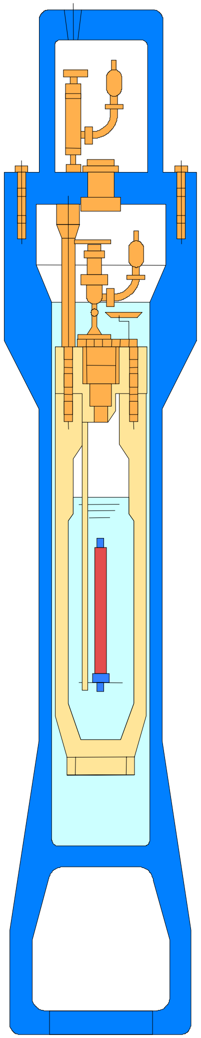
Irradiated rod from power plant ~4m

Test fuel rod
Total length: ~280 mm
Fuel stack: ~135 mm

Test capsule





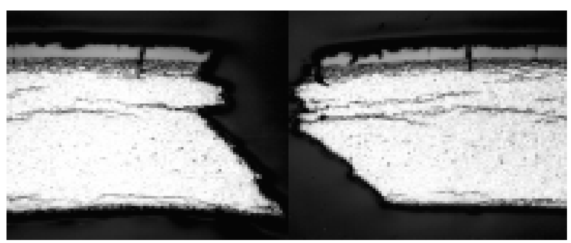


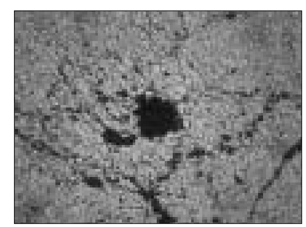
Transient measurements:

- Cladding surface temperature
- Coolant Water temperature
- Rod internal pressure
- Capsule internal pressure
- Fuel stack elongation
- Cladding elongation
- Cladding hoop strain
- Water column velocity

NSRR Experiments with irradiated LWR fuels

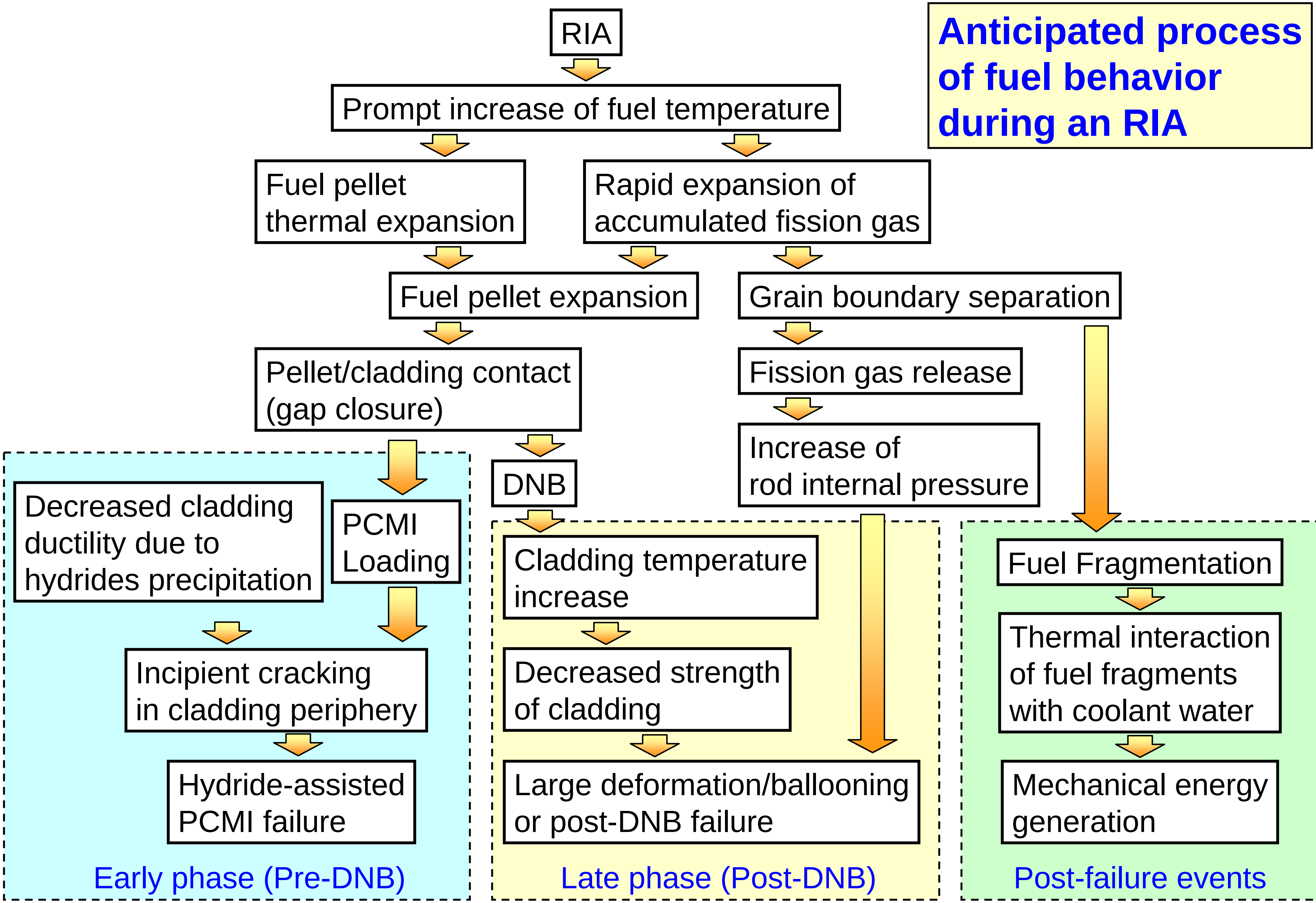
Test fuels	Fuel burnup (MWd/kg) 10 20 30 40 50 60	Number of tests
PWR (14x14, 17x17)		26
BWR (7x7, 8x8)		16
ATR/MOX		5
JMTR pre-irradiated		22





- ✓ **Hydride-assisted PCMI failure**
- ✓ **Fuel dispersal and mechanical energy generation**
- ✓ **Large rod expansion and fission gas release**
- ✓ **Possible MOX effect (Role of Plutonium agglomerates)**

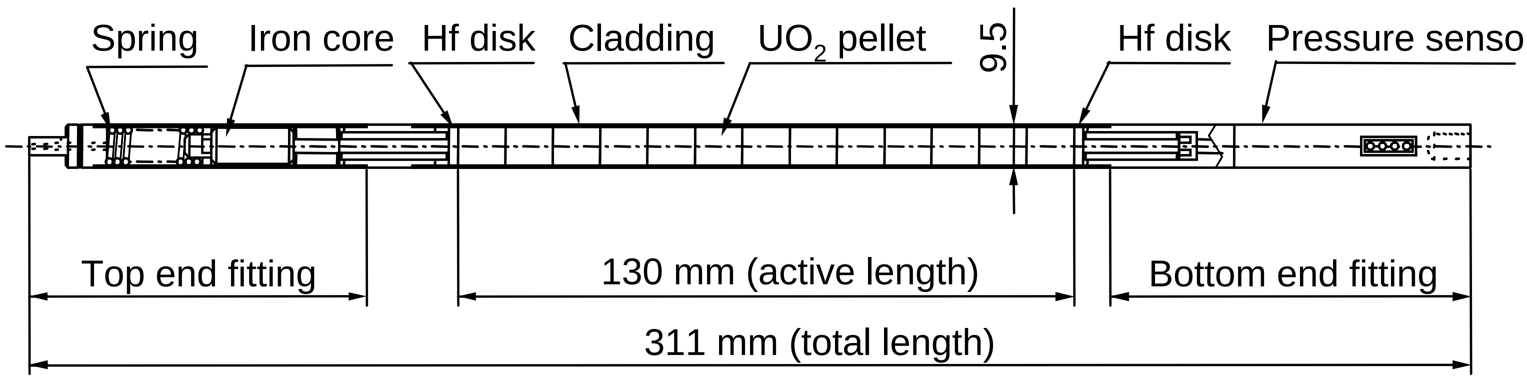
Anticipated process of fuel behavior during an RIA



Tests OI-10 and OI-11

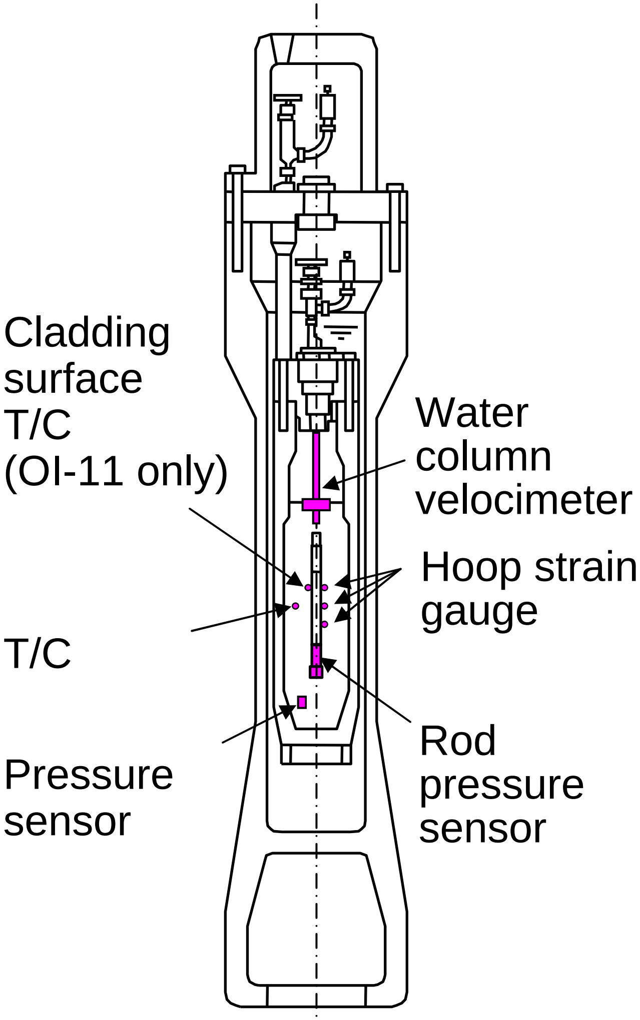
PWR 55 GWd/t lead-use fuel rods (Ohi unit 4)

Test ID	OI-10	OI-11
Fuel type	PWR 17x17	
Cladding material	MDA	ZIRLO
Initial enrichment	4.5%	4.5%
Pellet grain size (μm)	~25	~8
Operation period	4 cycles from Mar.97 to Mar.02	
Test rod sampling position	2nd span from the top	
Test rod burnup (GWd/t)	60	58
Average / Max. heat rates (kW/m)	15.6 / 19.5	15.2 / 20.3
Heat rate in last cycle (kW/m)	13.0	13.2
Cladding oxide thickness (μm)	~30	~30



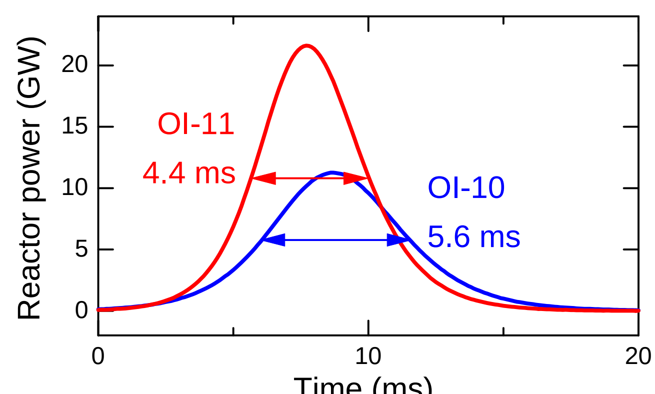
Rod of OI-10 is 10 mm shorter in total and active lengths.

Tests OI-10 and OI-11



Instrumentation

	OI-10	OI-11
Coolant conditions	Stagnant ~20 deg C, 0.1 MPa	
Pulse irradiation		
Inserted reactivity($)	3.67	4.6
Peak fuel enthalpy (J/g)	435	657
(cal/g)	104	157
Test results	No failure No significant deformation	Failure at 120 cal/g Cladding axial crack Fuel fragmentation



Test OI-11

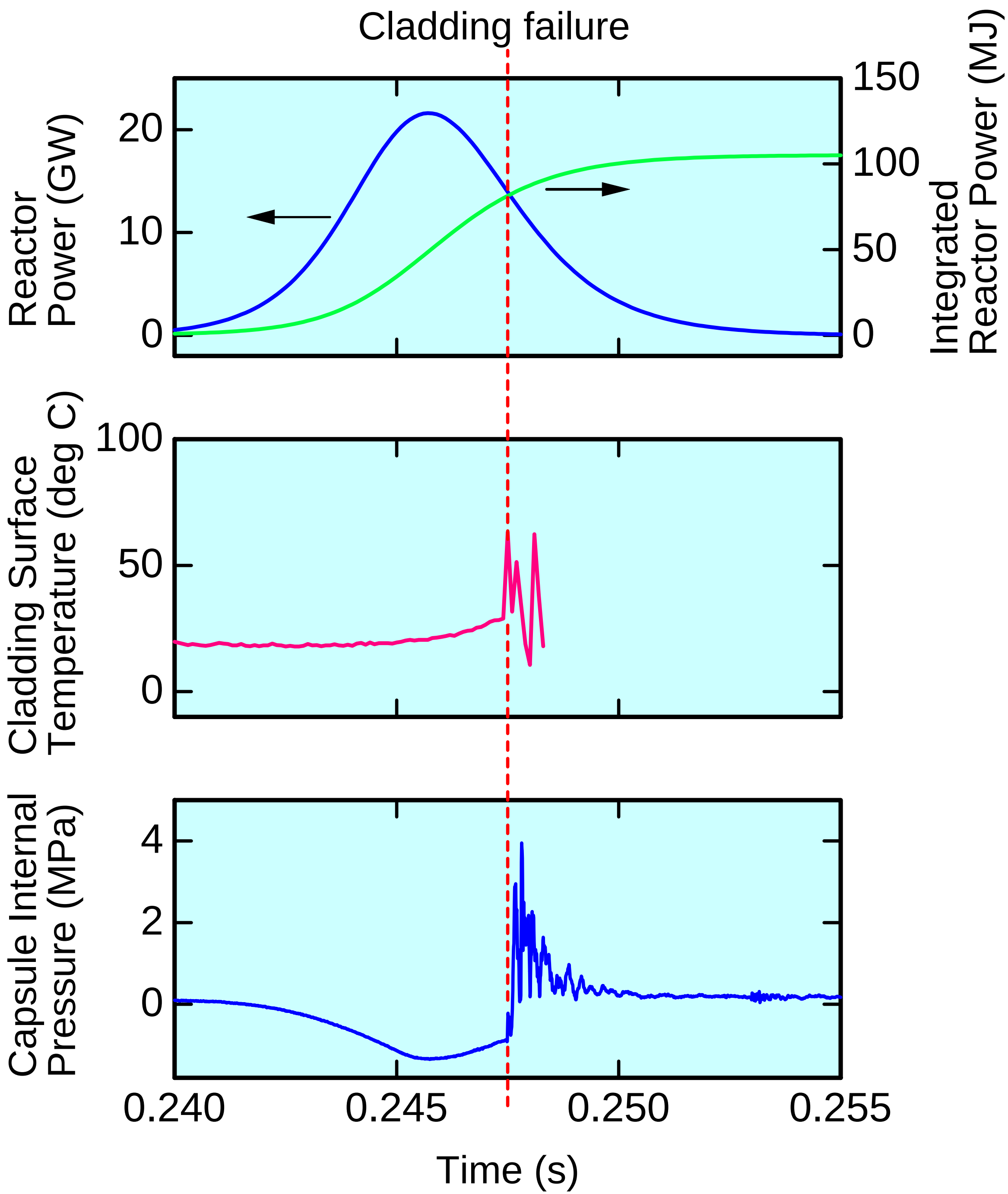
PWR

58 GWd/tU

$P_{rod, ini}$ 0.1 MPa

Peak Enthalpy 157 cal/g

Failed at 120 cal/g



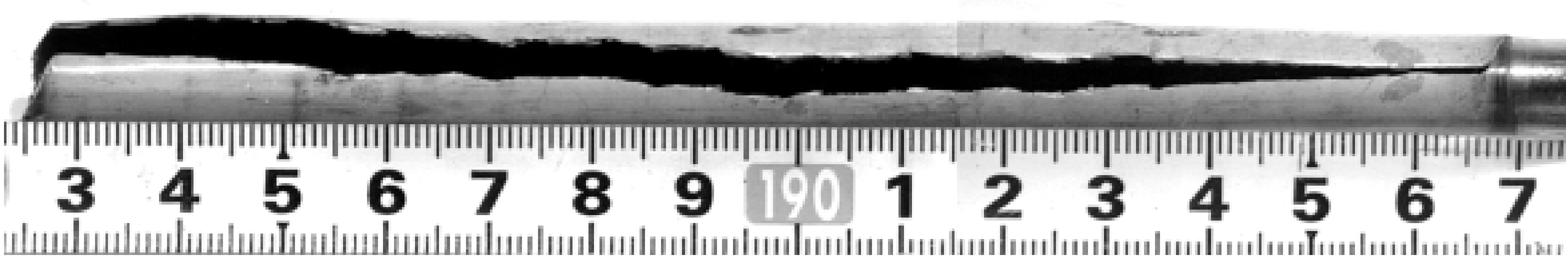
Test OI-11
- Post-pulse rod appearance -

Bottom

Top

Fracture close to the welding position

Axial crack over the fuel stack



Tests OI-10 and OI-11
- Summary 1/2 -

✓ High burnup PWR fuels with new cladding were subjected to the NSRR experiments. Test OI-10 rod has an MDA (Mitsubishi Developed Alloy, Zr-0.8Sn-0.2Fe-0.1Cr-0.5Nb) cladding and Test OI-11 rod has a ZIRLO^{TM} cladding.

✓ A test rod of the OI-10 has a burnup of 60 GWd/t and cladding oxide thickness of ~30 µm. The fuel was pulse-irradiated with conditions of 104 cal/g (0.44 kJ/g) for a peak fuel enthalpy and 5.6 ms for a pulse-width. The fuel remained intact in the OI-10.

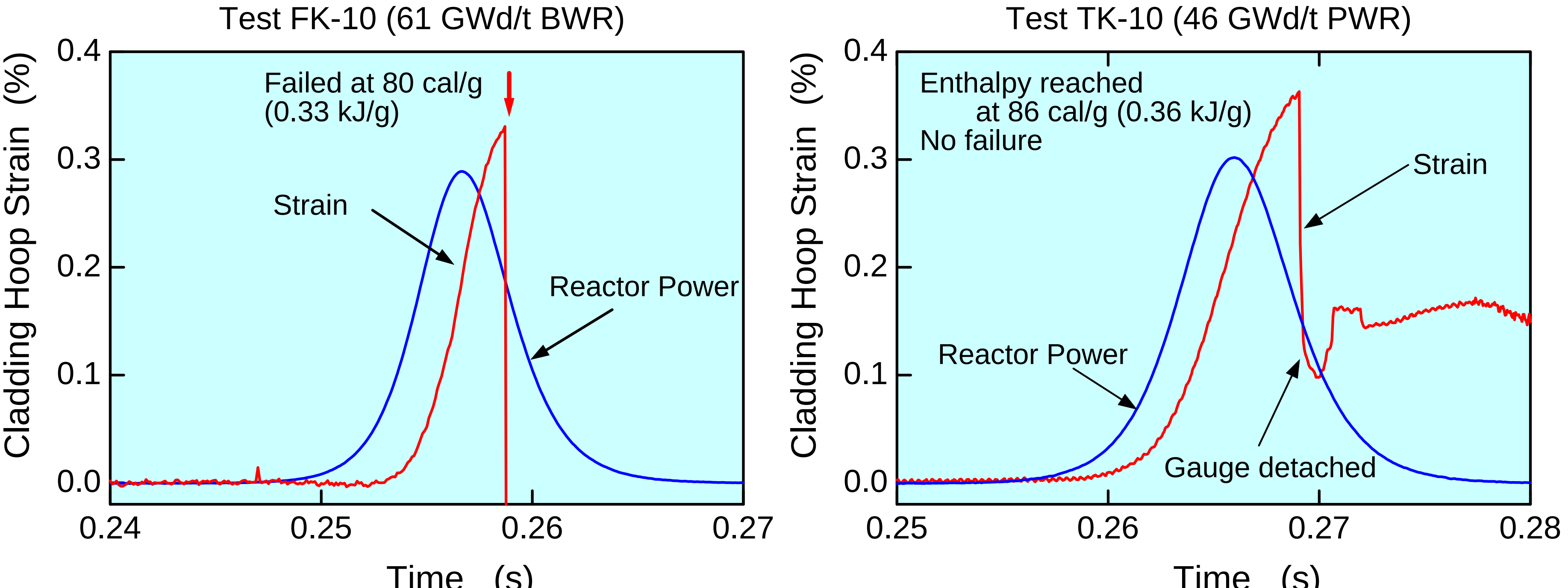
Tests OI-10 and OI-11
- Summary 2/2 -

✓ A test rod of the subsequent OI-11 has a burnup of 58 GWd/t and cladding oxide thickness of ~30 μm. The fuel was tested with conditions of 157 cal/g (0.66 kJ/g) for a peak fuel enthalpy and 4.4 ms for a pulse-width. The Test OI-11 resulted in fuel failure, pellets fragmentation and mechanical energy generation. Transient records showed that a fuel enthalpy at a time of failure was higher than those observed in previously tested fuels with Zircaloy-4 cladding and exceeded 120 cal/g (0.50 kJ/g).

✓ Results from the two tests, no failure in the OI-10 and the higher failure energy in the OI-11, reflects the better performance of these new cladding materials in terms of corrosion, the thinner oxides and accordingly lower hydrogen content generated during irradiation in the PWR.

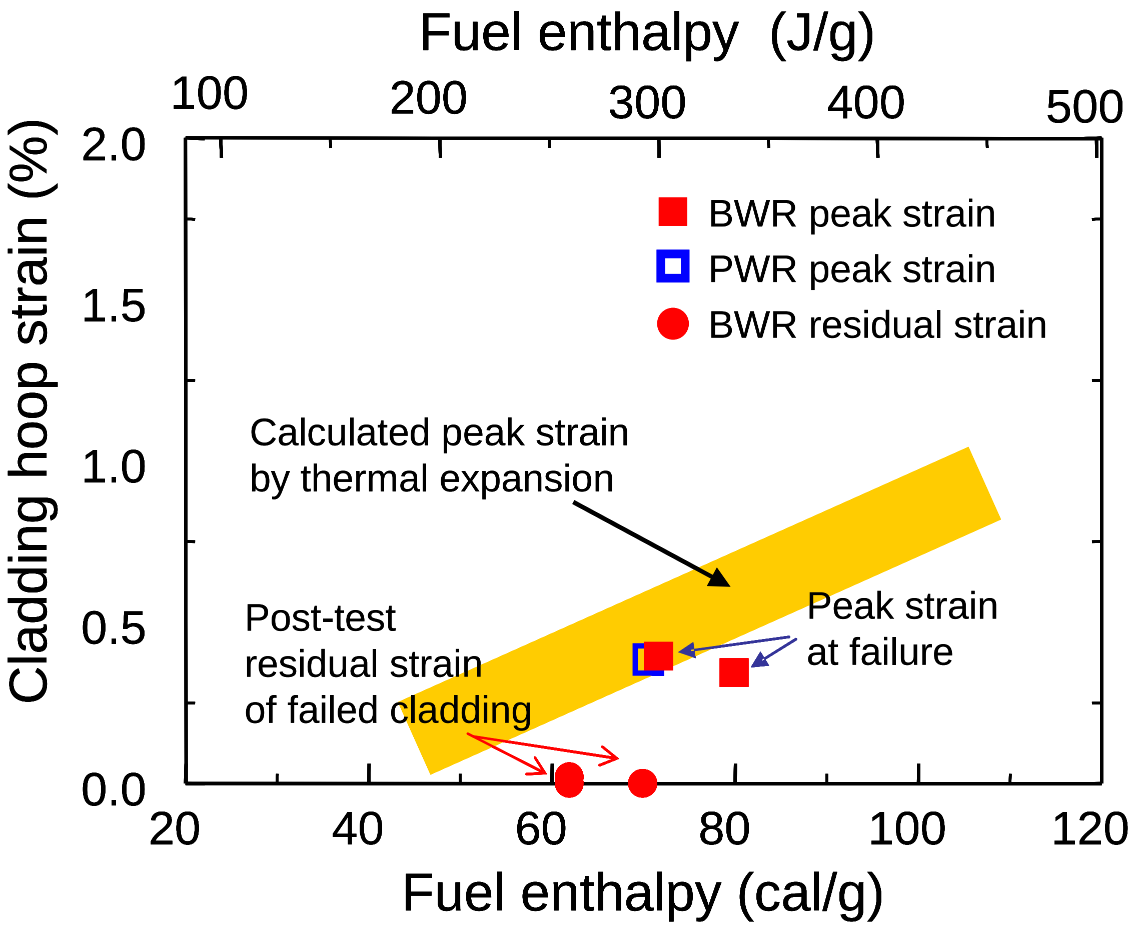
Transient Hoop Strain Measurement

- ✓ Transient hoop deformation due to PCMI in early phase of RIA transient was measured with strain gauges on irradiated fuel rod.
- ✓ The hoop stain was about 0.4% at fuel enthalpy of about 80cal/g.



Cladding strains at failure

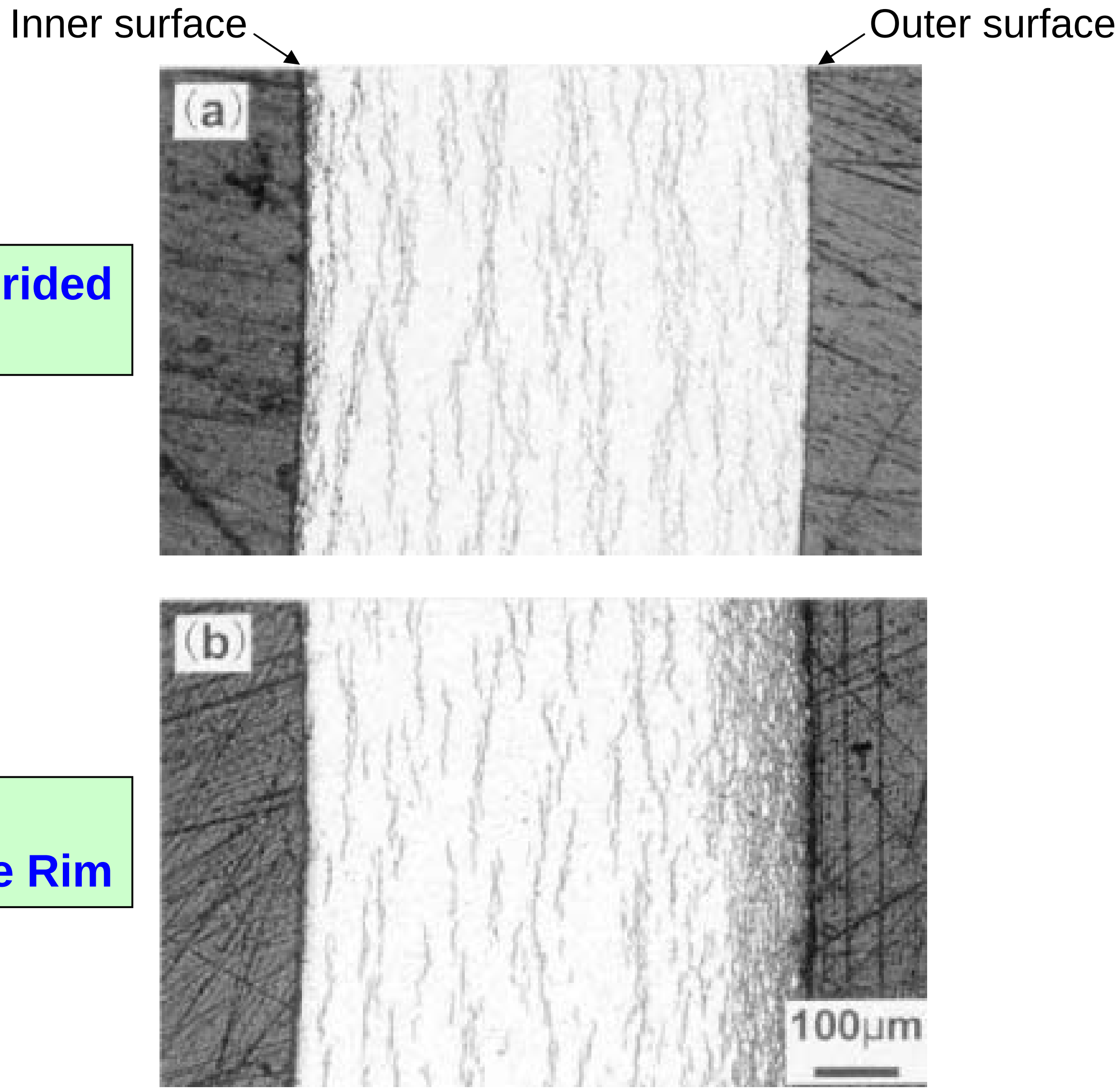
- Peak strain measured in 70 to 80 cal/g was below 0.4%.
- Residual strain of failed cladding was ~0%.



The deformation resulting in cladding failure in early phase of transient can be explained only by thermal expansion of fuel pellets

Tests with artificially-hydrided cladding

Radial cross-section of artificially hydrided cladding samples



Uniformly Hydrided Sample

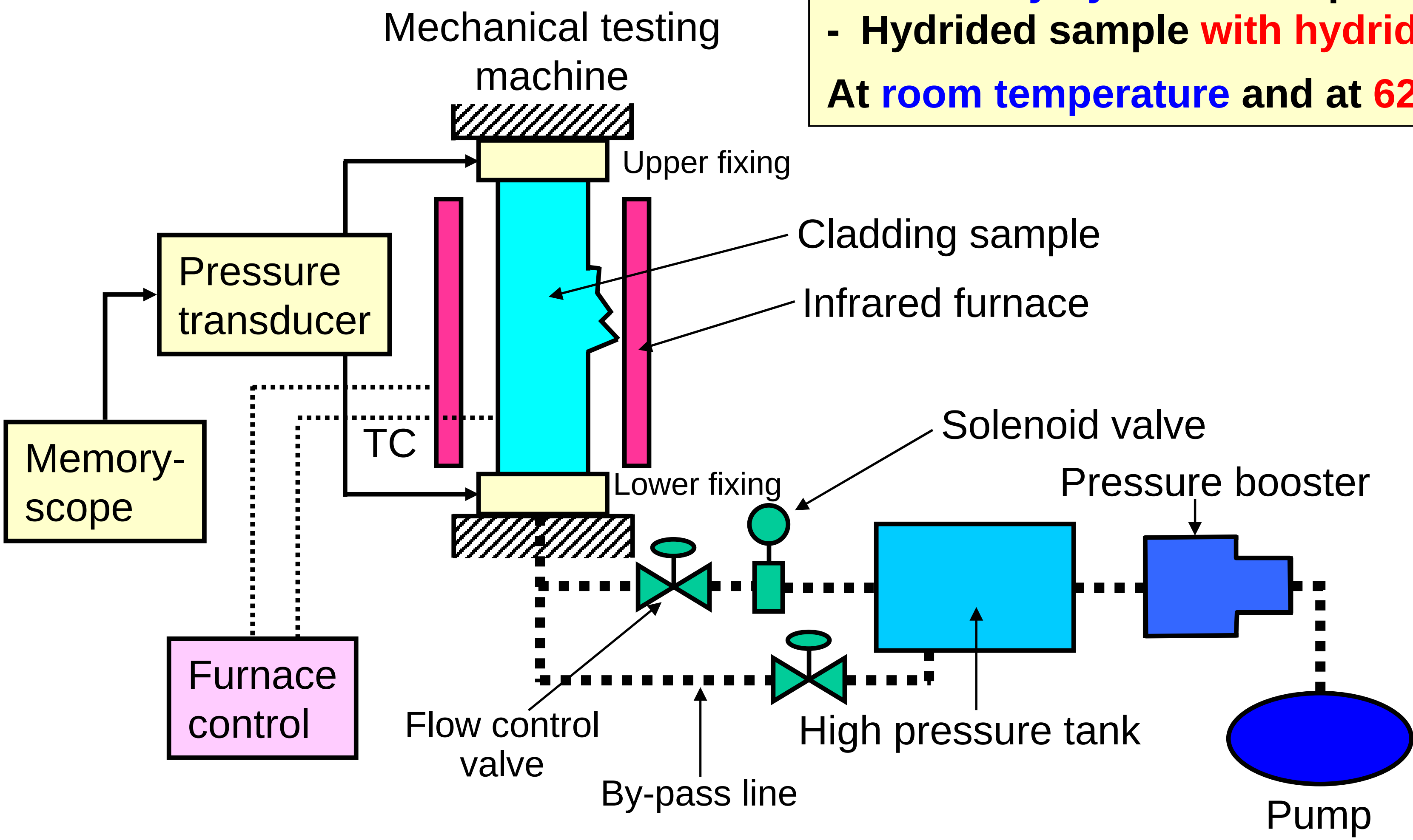
Sample with Hydride Rim

Tube Burst Test

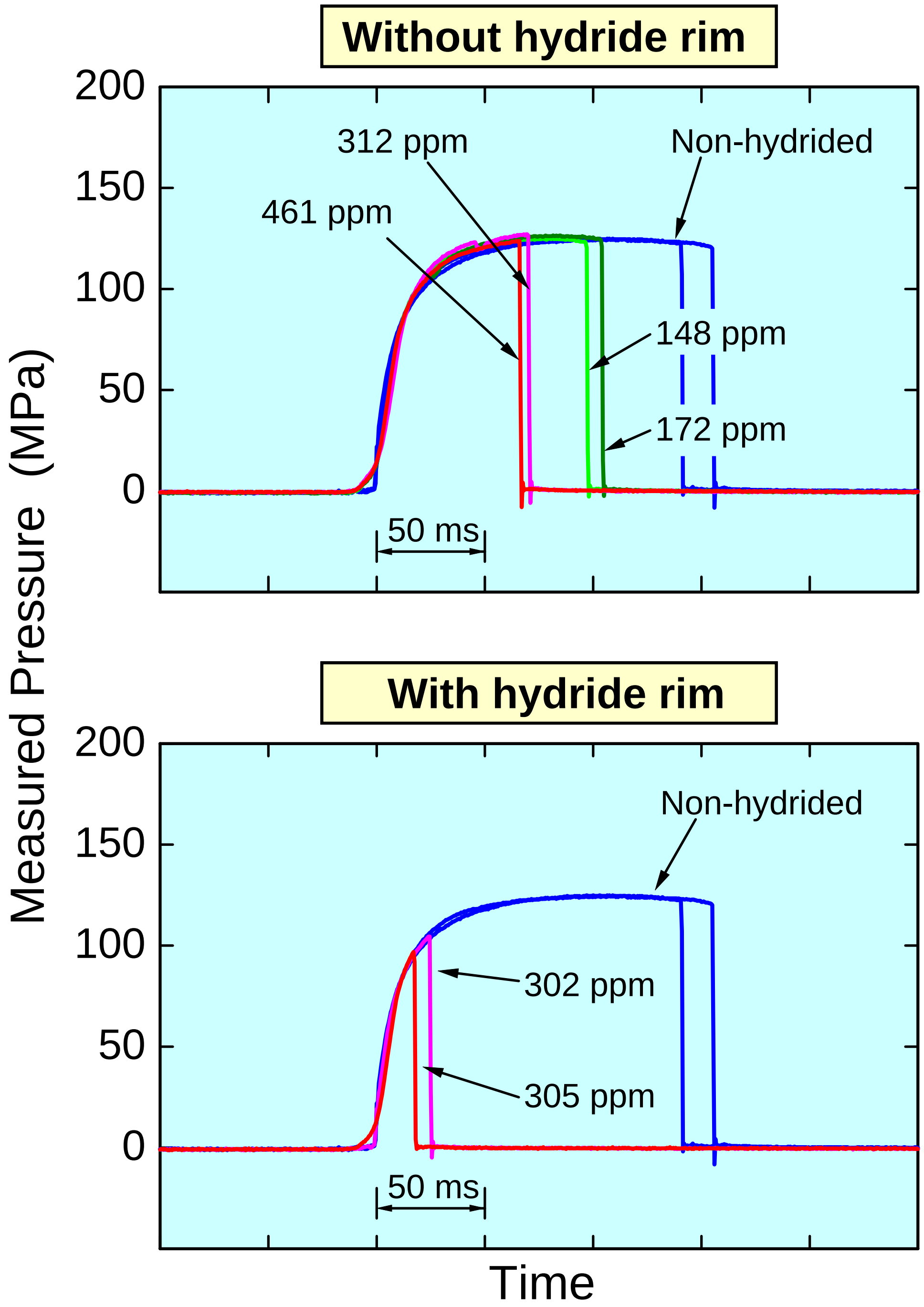
Un-irradiated 17x17 PWR
low tin Zry-4 cladding

- **As-received, non-hydrided sample**
- **Uniformly hydrided sample**
- **Hydrided sample with hydride rim**

At room temperature and at 620 K



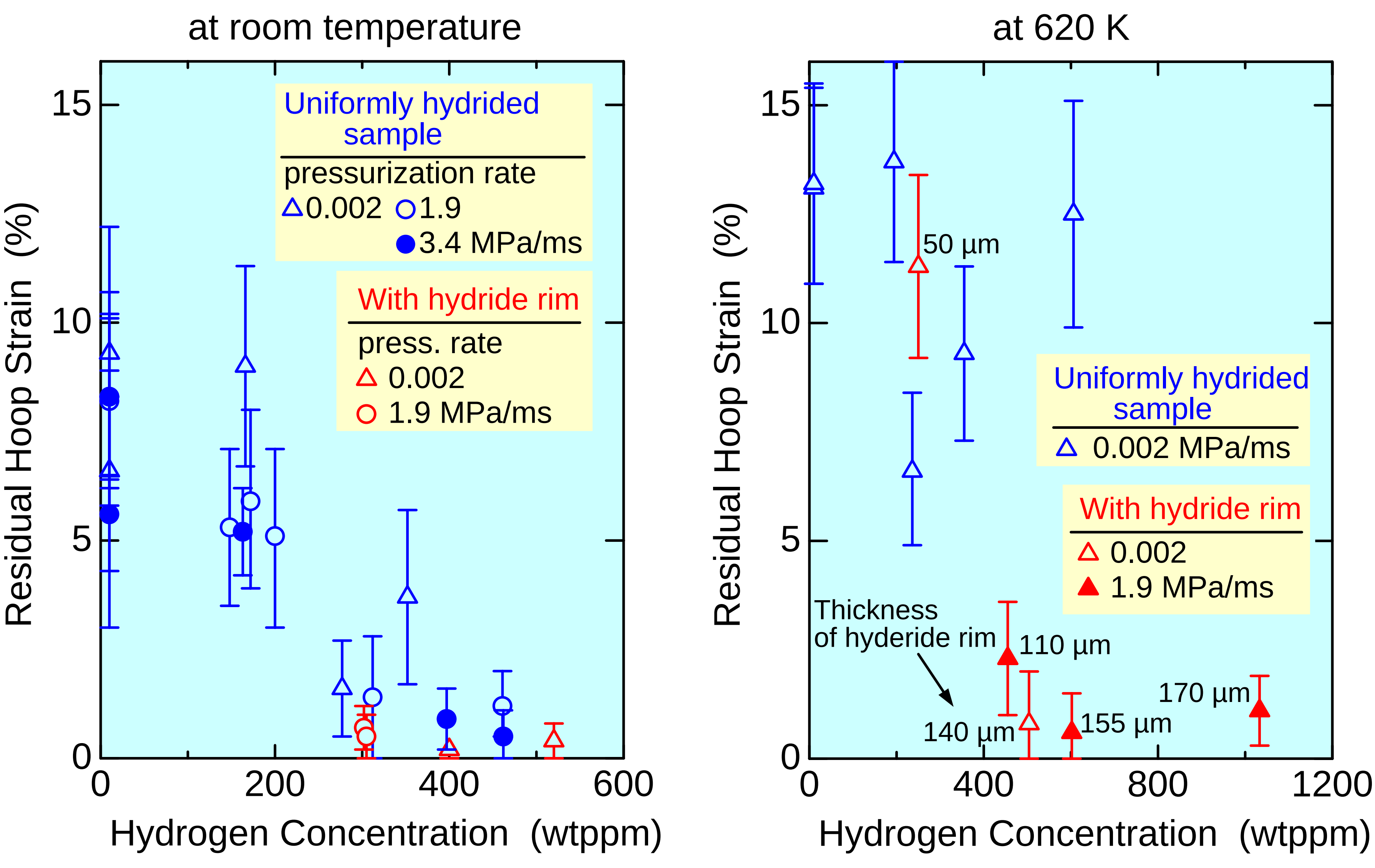
Transient histories of sample internal pressure during tube burst tests



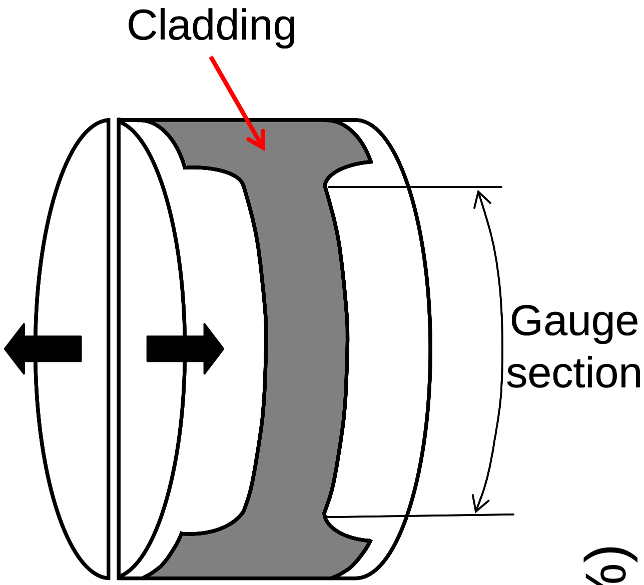
1.9 MPa/ms
room temperature

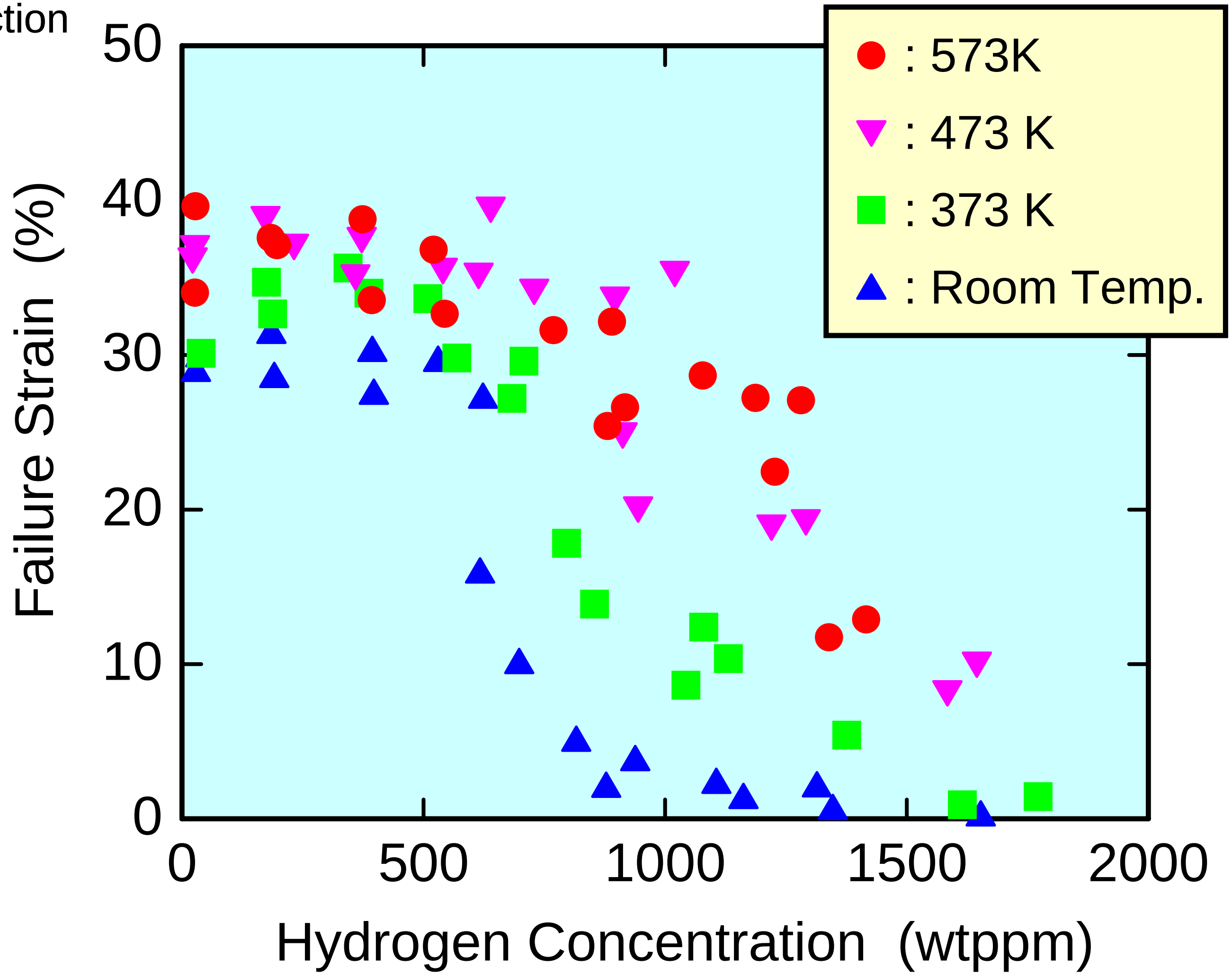
Tube Burst Test

Residual Hoop Strain
as a function of
Hydrogen Concentration

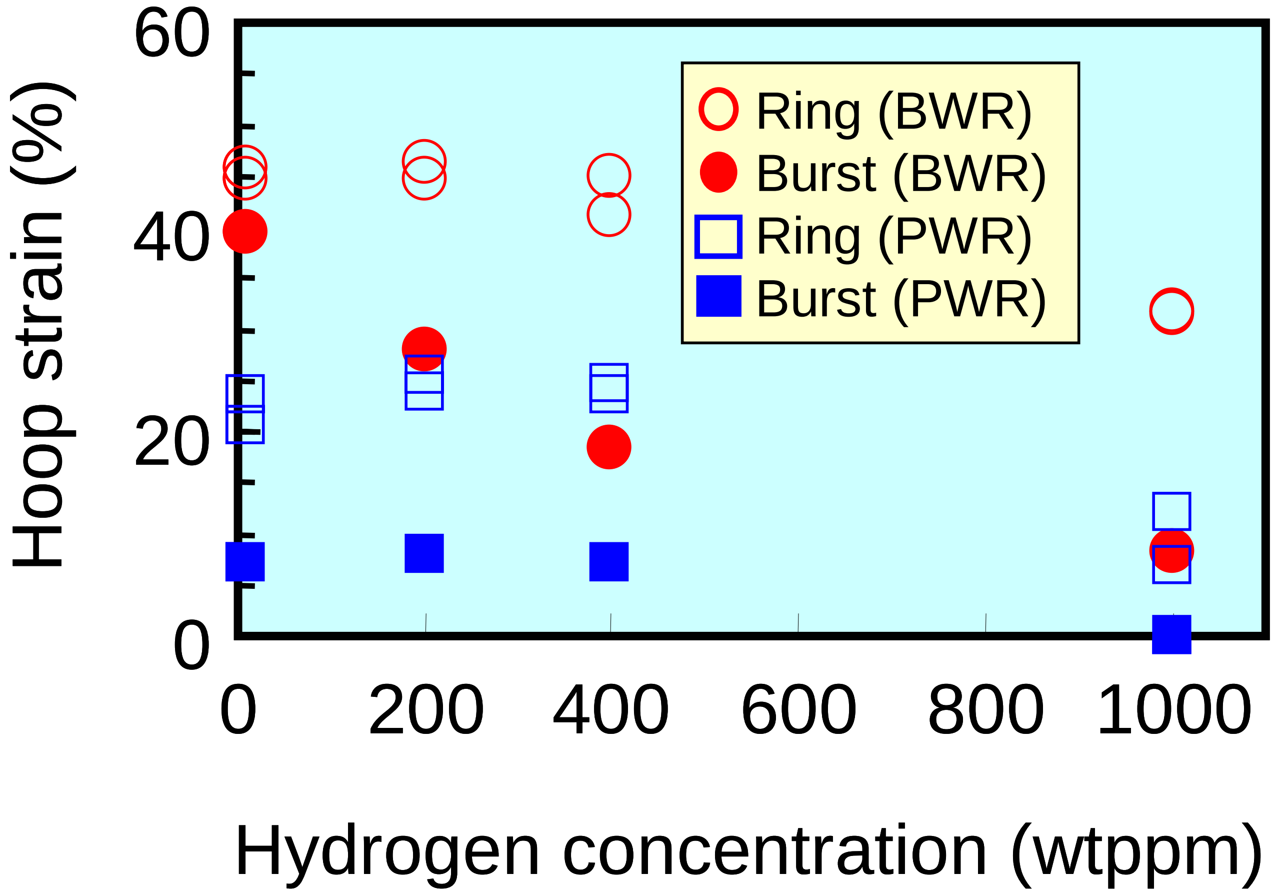


Ring Tensile Test

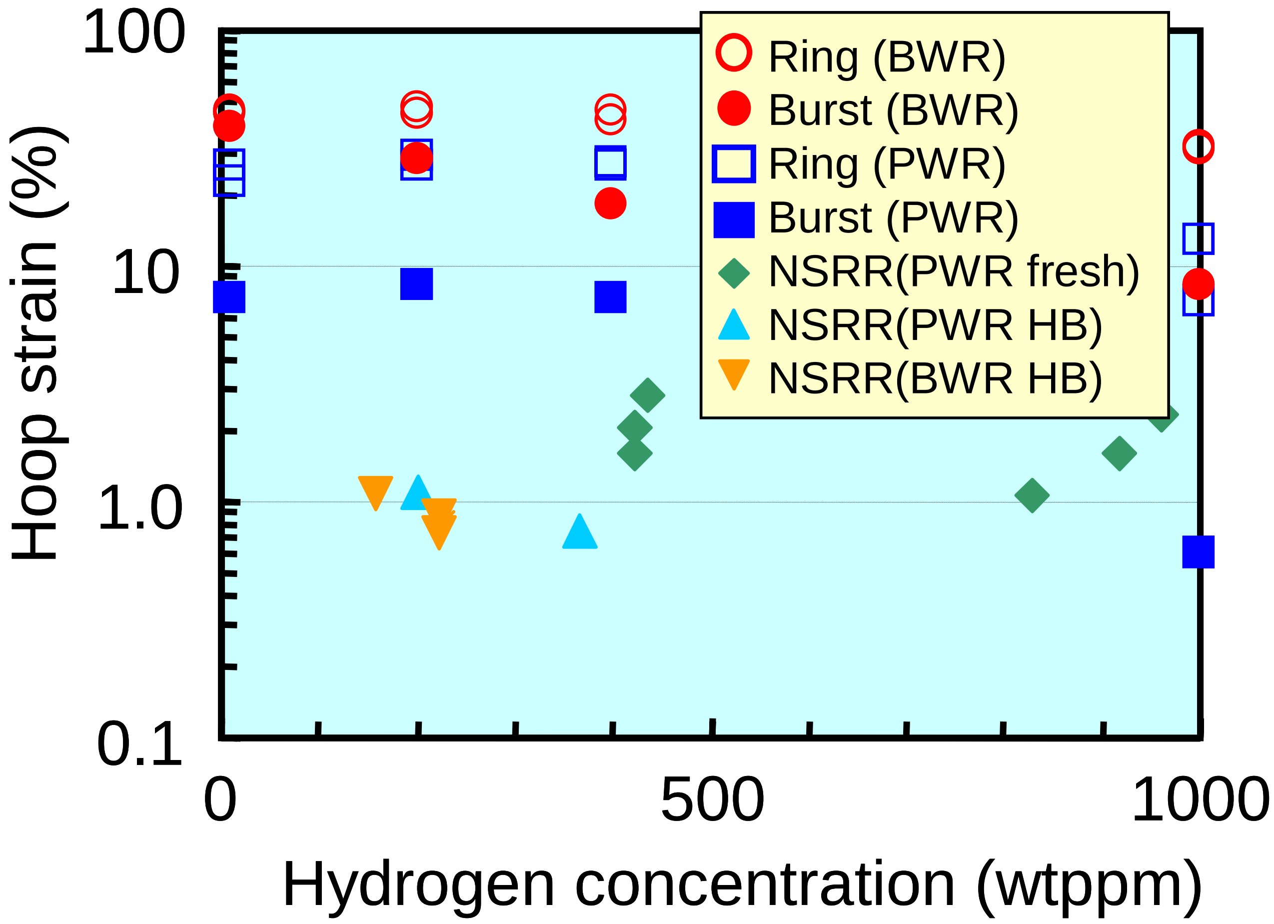




Tube burst and ring-tensile tests with artificially-hydrided cladding



Tube burst, ring-tensile and pulse tests with artificially-hydrided cladding



Tests with artificially-hydrided cladding Summary

- ✓ Influence of hydriding of Zircaloy claddings on their failure behavior under RIA conditions was examined in out-of-pile mechanical tests and pulse tests with un-irradiated, artificially-hydrided claddings.
- ✓ Results suggest that strong influence of the hydrides but also irradiation induced embrittlement.
- ✓ In the mechanical tests, failure limits in hoop strain decreased significantly at increased hydrogen concentration. Sensitivity to the hydrogen content was larger under bi-axial stress conditions in tube burst tests and in pulse-irradiation tests.
- ✓ The sensitivity also varied depending on cladding materials. Recrystalized Zircaloy-2 cladding of BWR fuel rods generally shows larger failure strains than those of stress-relieved Zircaloy-4 cladding of PWR fuel rods. Stronger influence of hydrides, however, was observed in the BWR cladding than in the PWR cladding.
- ✓ Cladding failure limits under RIAs should be examined under bi-axial stress conditions which simulate cladding deformation due to PCMI.

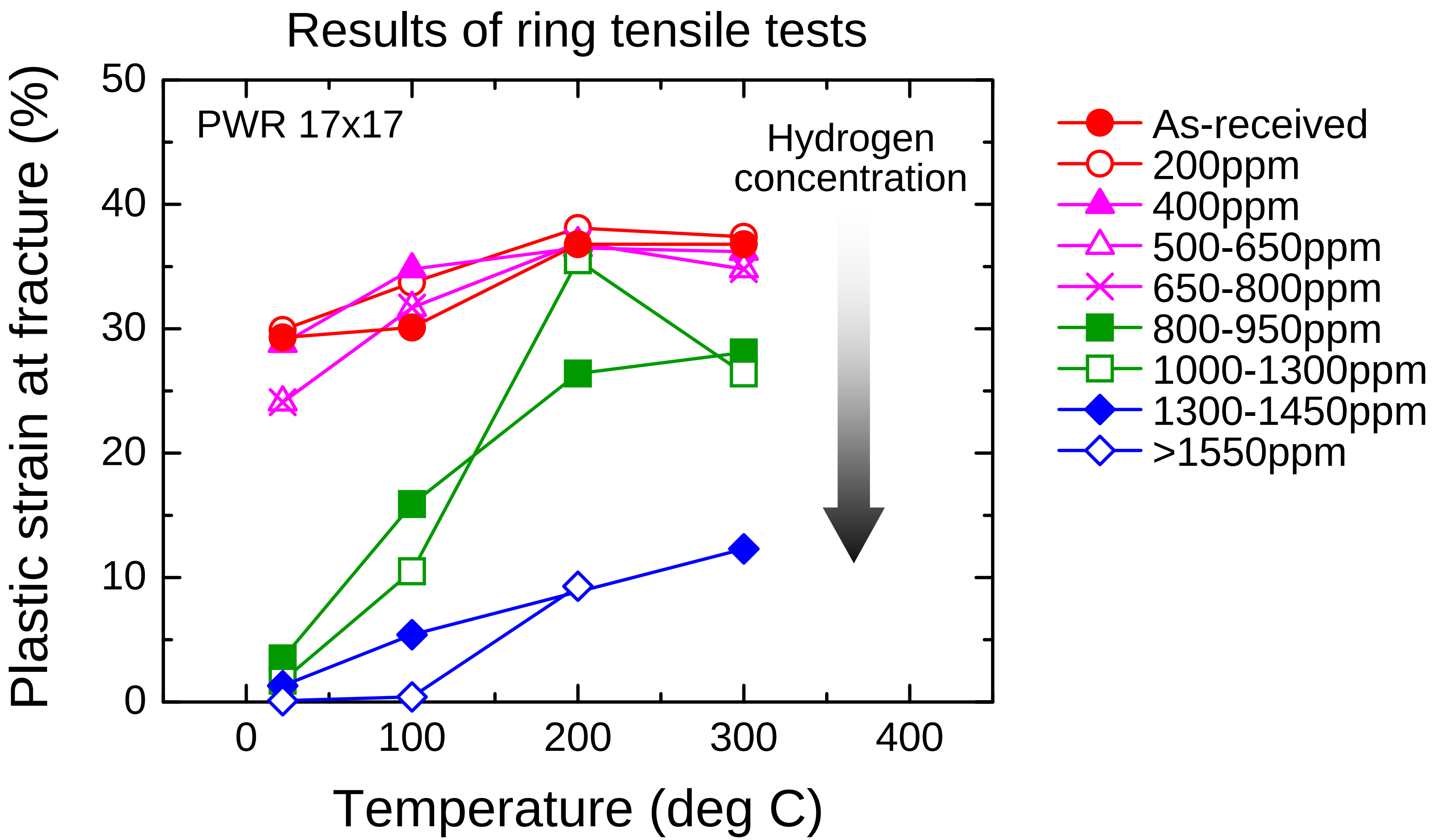
Fuel rods to be tested in FY2004 to 2007

Specification			Power plant (country)	Burnup*	Cladding	Number of RIA test	
Fuel	Reactor	Type		GWd/t		RTRP**	HTHP***
UO_2	PWR	17×17	OI, unit 4 (Japan)	~60	NDA	1	0
			Vandellos (Spain)	74	MDA	2	1
					ZIRLO	1	0
			McGuire (USA) R2 (Sweden)	71	NDA	1	0
			Graveline (France)	66 - 69	M5	1	1
	BWR	10×10	Leibstadt (Switzerland)	63	Zry-2	1	1
MOX	ATR	-	Fugen (Japan)	43	Zry-2	1	0
	PWR	14×14	Beznau (Switzerland)	59	Zry-4	1	1
				44	Zry-4	1	0
	BWR	8×8	Dodewaard (Netherlands)	46	Zry-2	1	0
						11	4

* Segment average for OI, Fugen and R2, rod average for the others.

** Room-temperature/pressure. *** High-temperature/pressure.

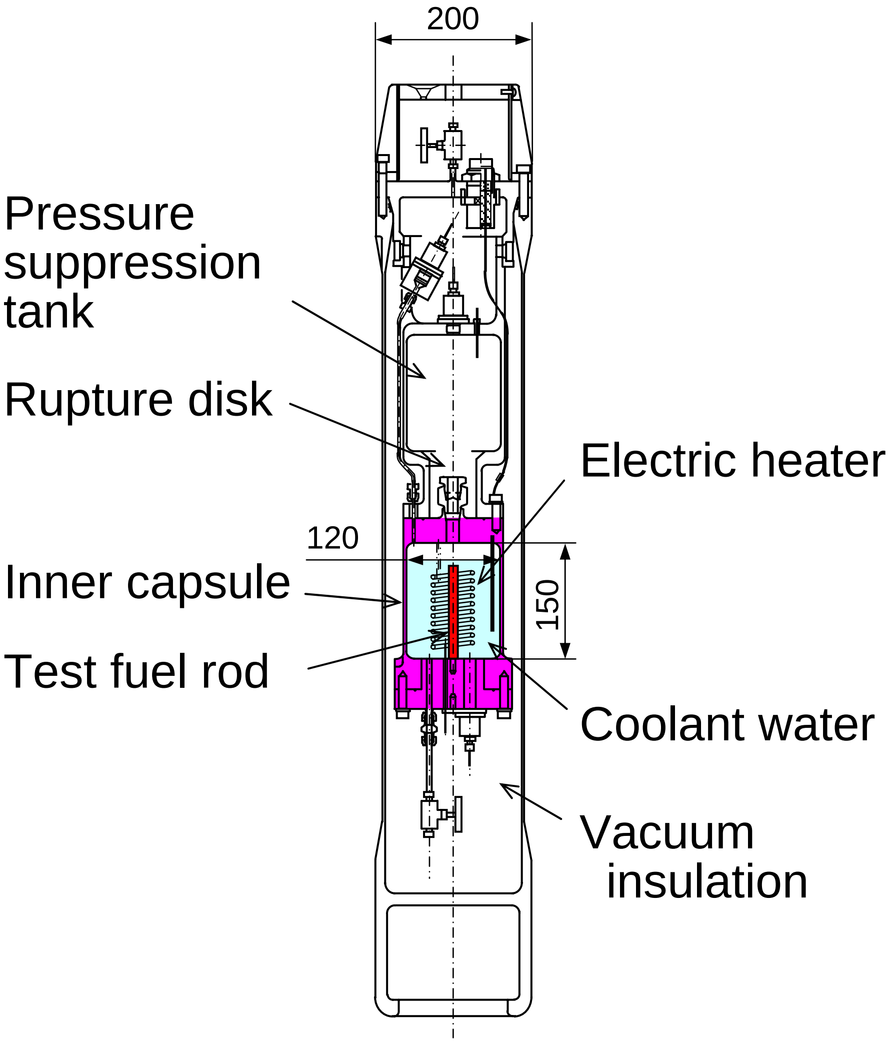
Temperature effect on cladding ductility



- Influence of hydrogen concentration and temperature on the cladding ductility

➢ High-temperature capsule in NSRR experiments

High temperature capsule



HTHP capsule

Test fuel rod

- Rod length ~120 mm
- Stack length ~50 mm

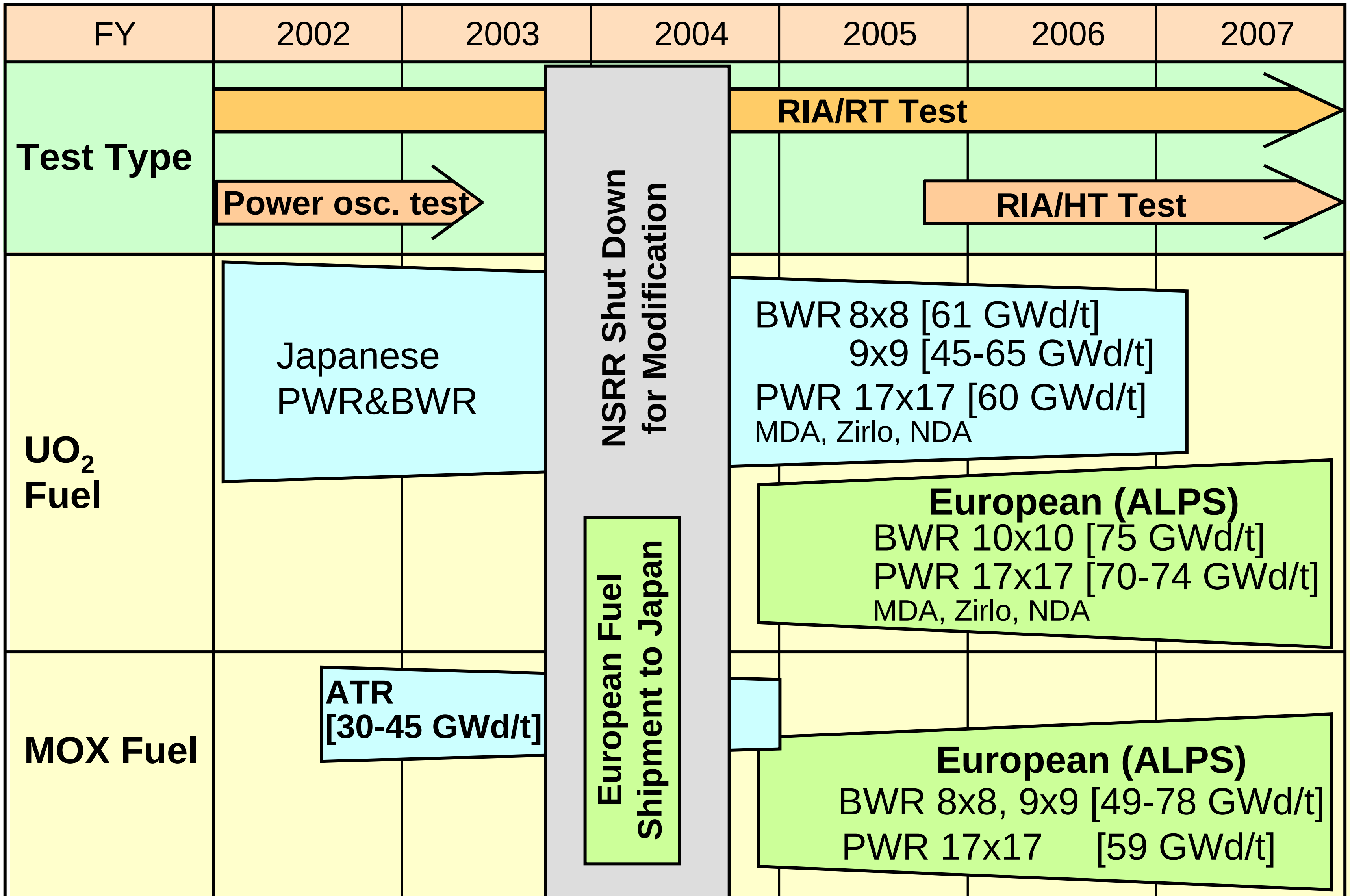
Coolant water

- Stagnant
- 286 deg C, 7 MPa
  (BWR conditions)

Instrumentation

- Cladding surface thermocouple
- Coolant thermocouple
- Capsule pressure sensor

NSRR Test Schedule



NSRR experiments

Data at higher burnups

(pellet burnup: GWd/t)

		FY2003			
UO_2 :	PWR	60	→	~80	until FY2005
	BWR	61		66	
MOX :	ATR	30	→	PWR 62	until FY2006
				BWR 48	

Test at higher temperature

Coolant water temperature

From 20 (room temp.) to 90 deg C → 286 deg C