Recent results from LOCA study at JAERI

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ANL Review Meeting
July 16 – 17, 2003

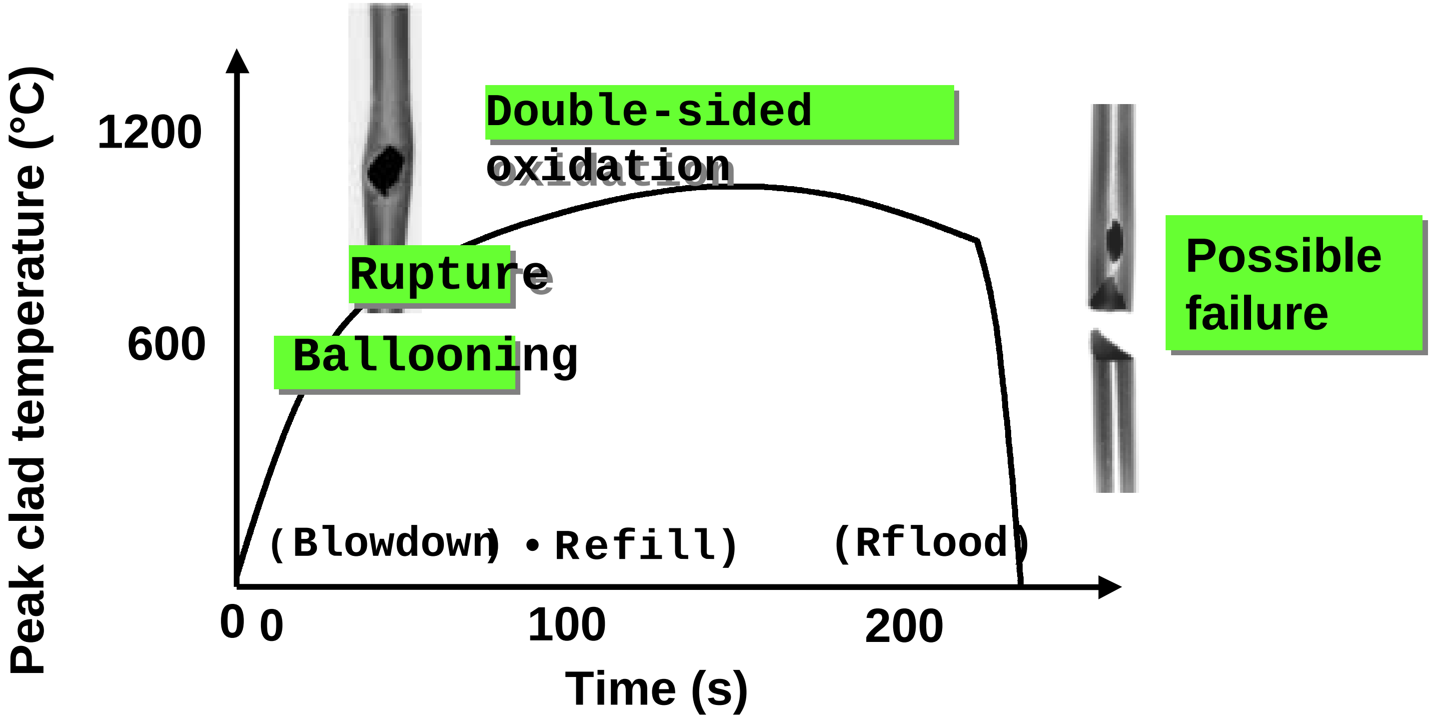
Background

- **Burnup extension**
- **Lack of database on high burnup fuel behavior under LOCA conditions**

Objective

To accumulate data for regulatory judgment corresponding rationally to high burnup fuel

Behavior under LOCA conditions



Ballooning (Wall thinning), Rupture, Double-sided oxidation, Secondary hydriding induced by inner surface oxidation

→ Embrittlement of cladding

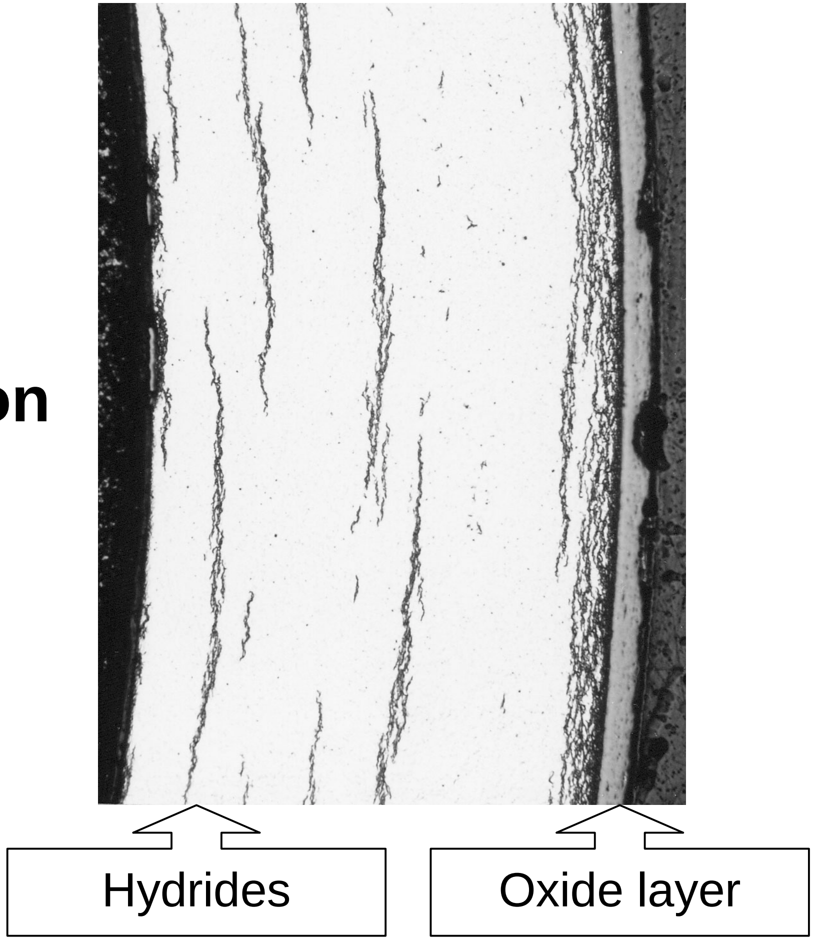
→ Possible spilt failure or fragmentation on quenching when severely embrittled

Key items to be examined related to high burnup fuel behavior under LOCA conditions

Comparing with fresh cladding tested on establishment of ECCS acceptance criteria

<u>Cladding embrittlement</u>

- **Corrosion**
  →Metal-wall thinning and oxygen absorption
- **Hydriding**
- **Neutron irradiation**
- **New alloys**



Separate effects of hydriding on cladding behavior under LOCA conditions

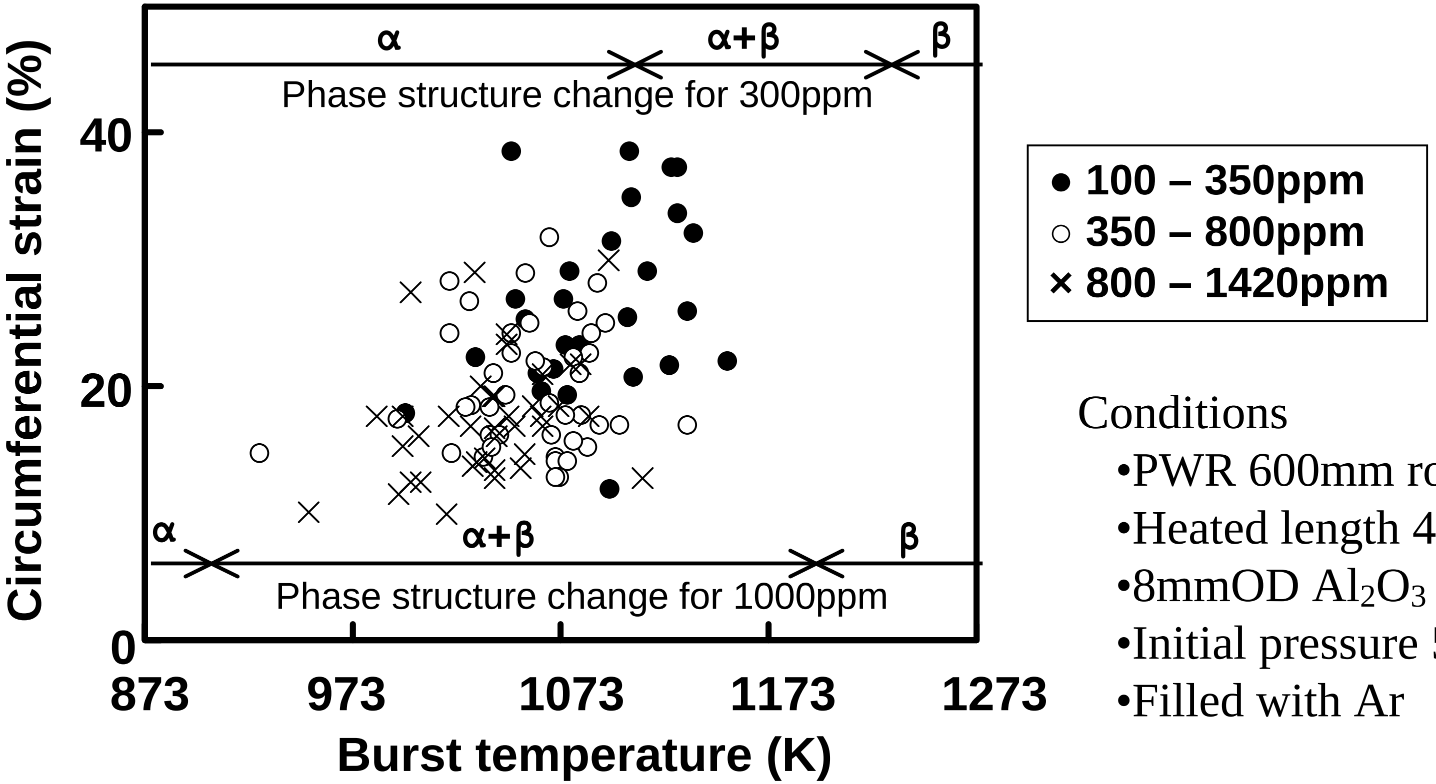
High temperature oxidation

Pre-hydriding may enhance oxidation, but the extent is negligible for the realistic hydrogen concentration and time ranges.

Rupture behavior

Increase of hydrogen concentration causes decrease of rupture temperature and shift of phase structure boundaries, resulting in decrease of burst strain.

Hydrogen effect on burst strain



Conditions
- PWR 600mm rod
- Heated length 450mm
- 8mmOD Al_2O_3 pellet
- Initial pressure 5MPa
- Filled with Ar

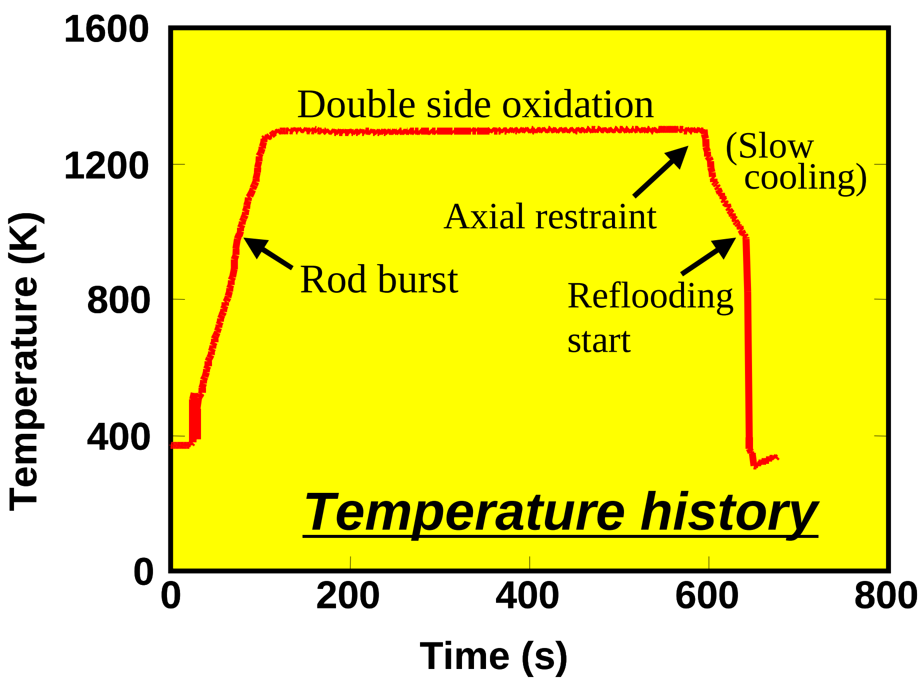
Increase of hydrogen concentration causes
- Decrease of burst temperature
- Shift of phase structure boundaries
- Consequent decrease of burst strain

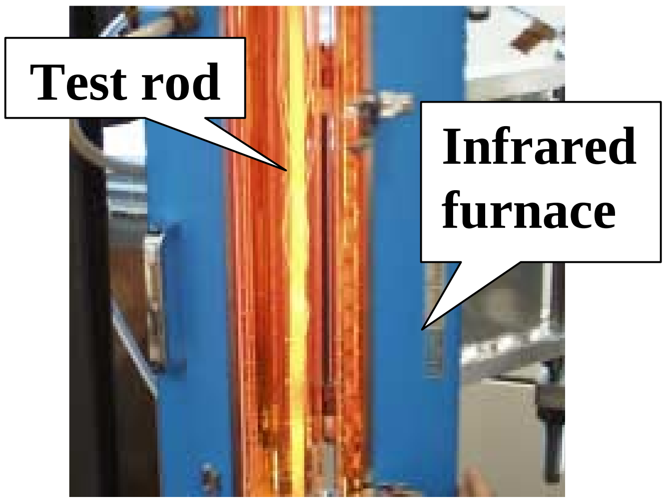
Separate effects of hydriding on cladding behavior under LOCA conditions

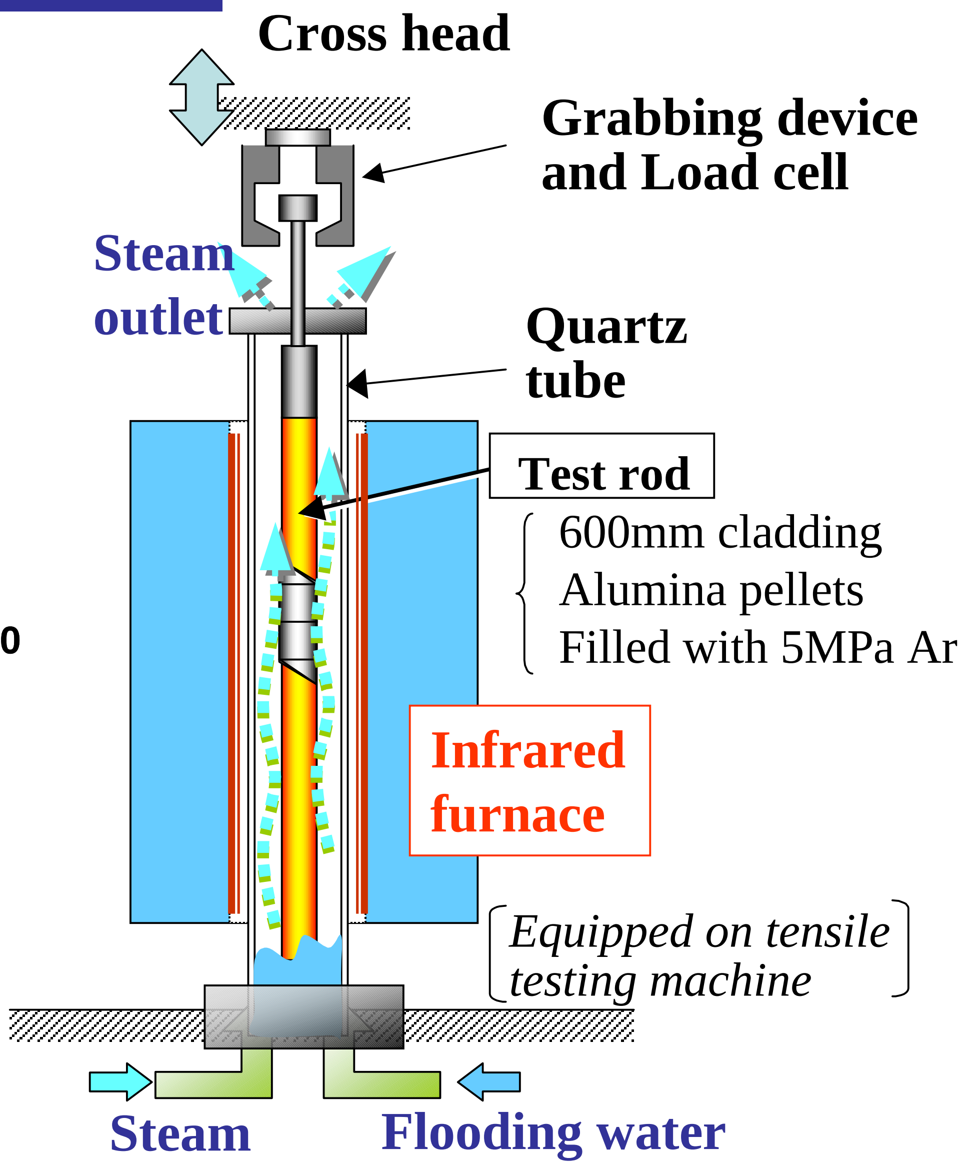
Failure under LOCA-simulated conditions

The influence of pre-hydriding was obviously seen on the failure threshold value under restraint conditions, while it was not seen under non-restraint condition.

Integral thermal shock test

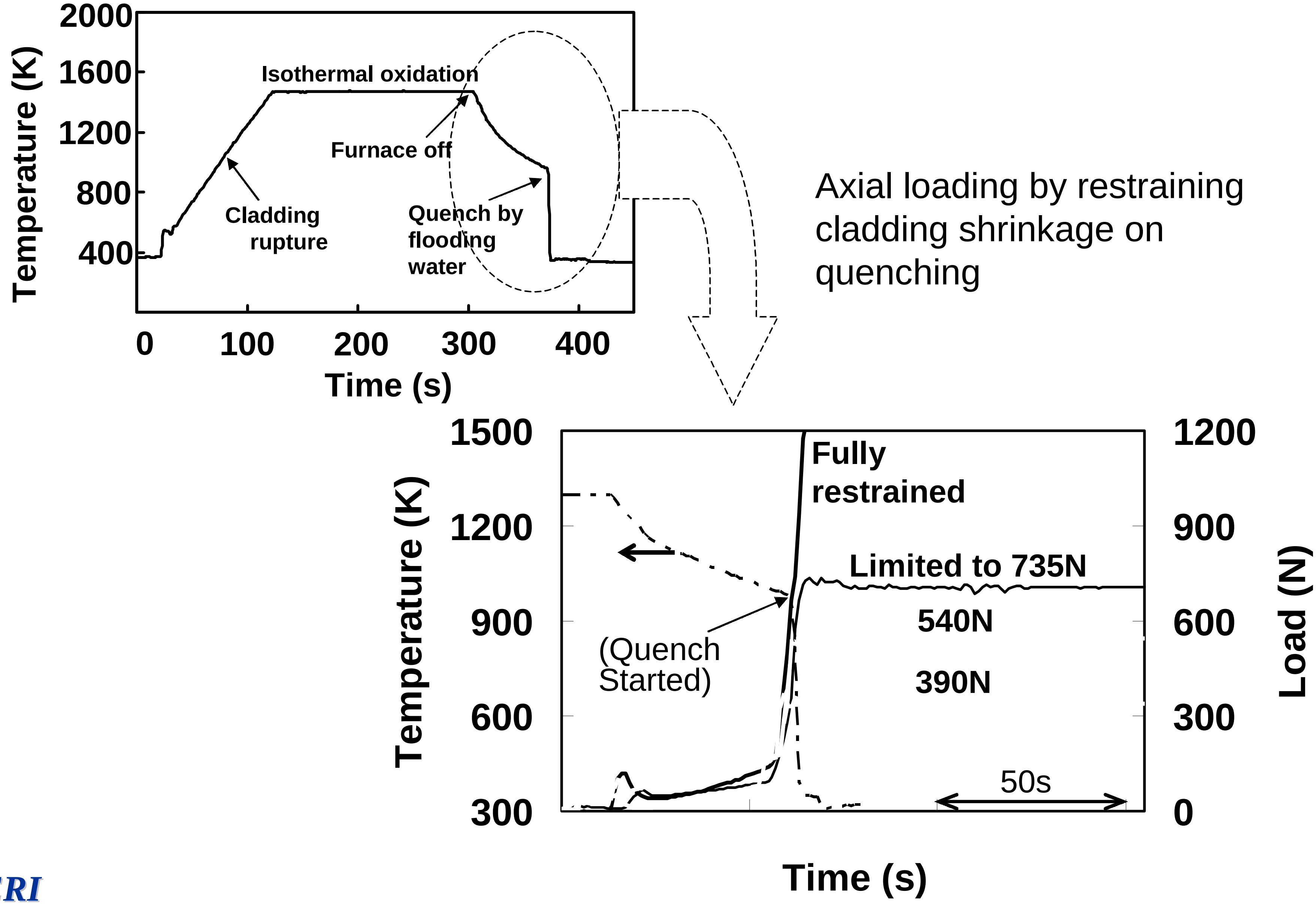






Schematic drawing of test apparatus

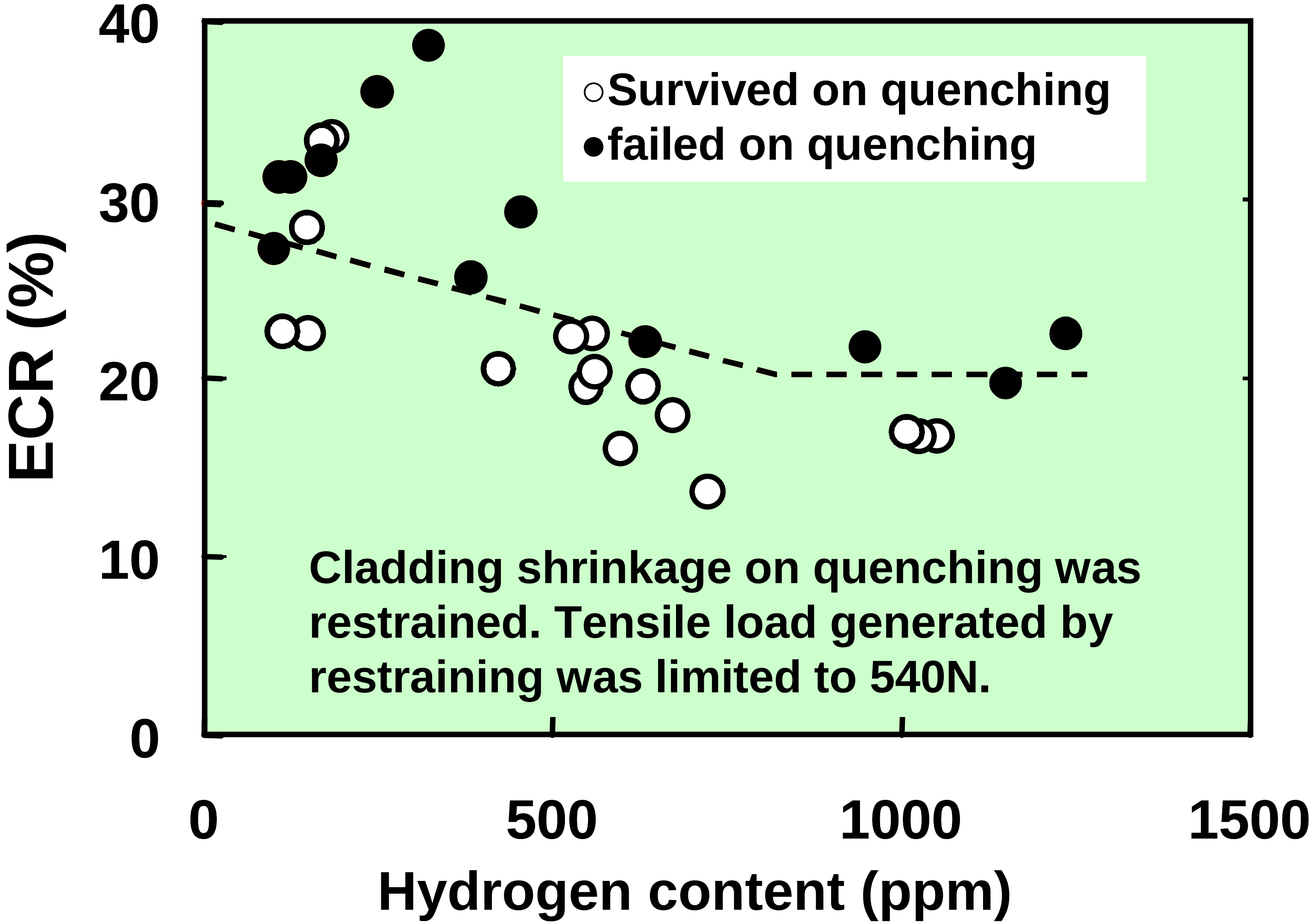
Restraint load control under integral thermal shock tests



Axial loading by restraining cladding shrinkage on quenching

Hydride effect on failure boundary

Results from the tests under restraint condition for artificially hydrided (unirradiated) Zircaloy-4 cladding



Integral thermal shock tests with claddings irradiated in commercial reactors

- **48 GWd/t PWR cladding (low-Sn Zircaloy-4)**
- **55 GWd/t PWR cladding (ZIRLO™ , MDA, NDA)**

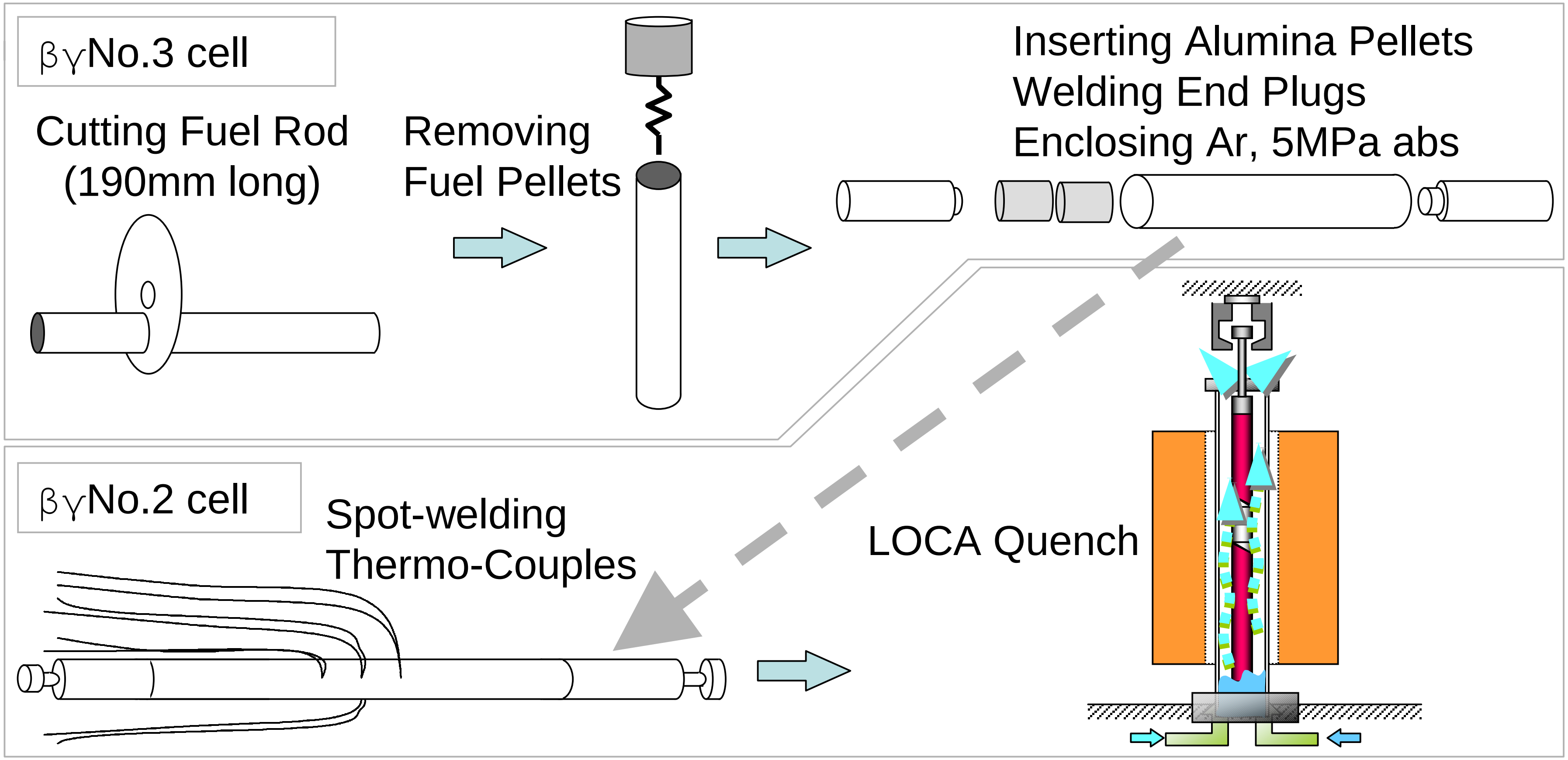
  MDA developed by Mitsubishi, NDA developed by NFI
- **71 – 75 GWd/t PWR cladding (ZIRLO™ , MDA, NDA)**
- **63 GWd/t BWR cladding (Zircaloy-2)**

Integral thermal shock tests on 48GWd/t PWR claddings

Three tests have been performed out of planned 10 tests.

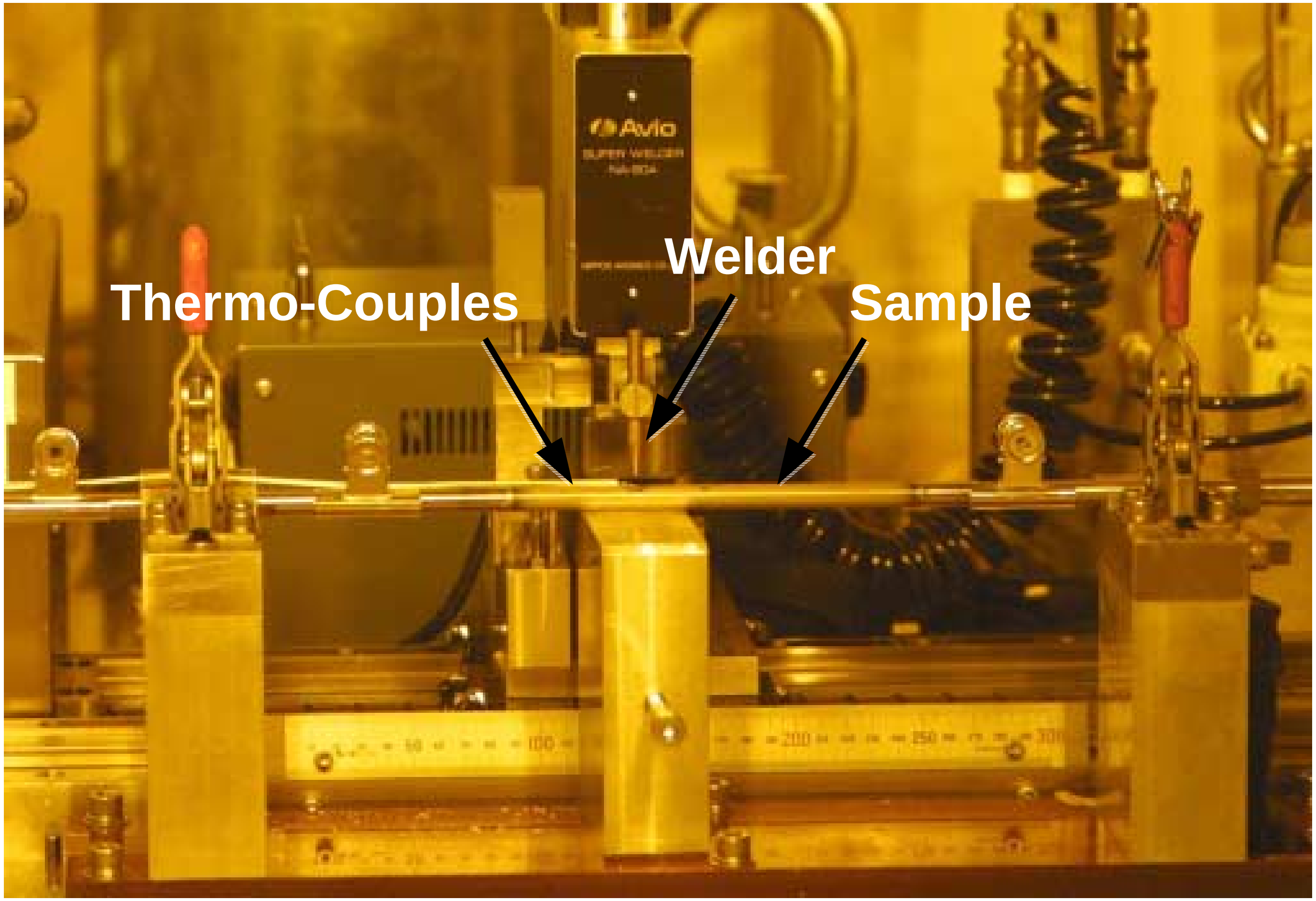
Test No.	1	2	3
Sample No.	ALOCA 3-1	ALOCA 1-2	BLOCA L-3
Reactor	Takahama unit 3 (KEPCO)		
Fuel Type	17×17		
Rod Average Burn up (GWd/t)	43.9		39.1
Fuel Cladding	Low tin Zircaloy-4		
Sampling Span No. from Top	4	2	2
Initial Oxide Layer Thickness (μm)	20	25	18
Zircaloy Thickness Remained (μm)	558	554	629

LOCA Quench Test Procedure for Irradiated Cladding



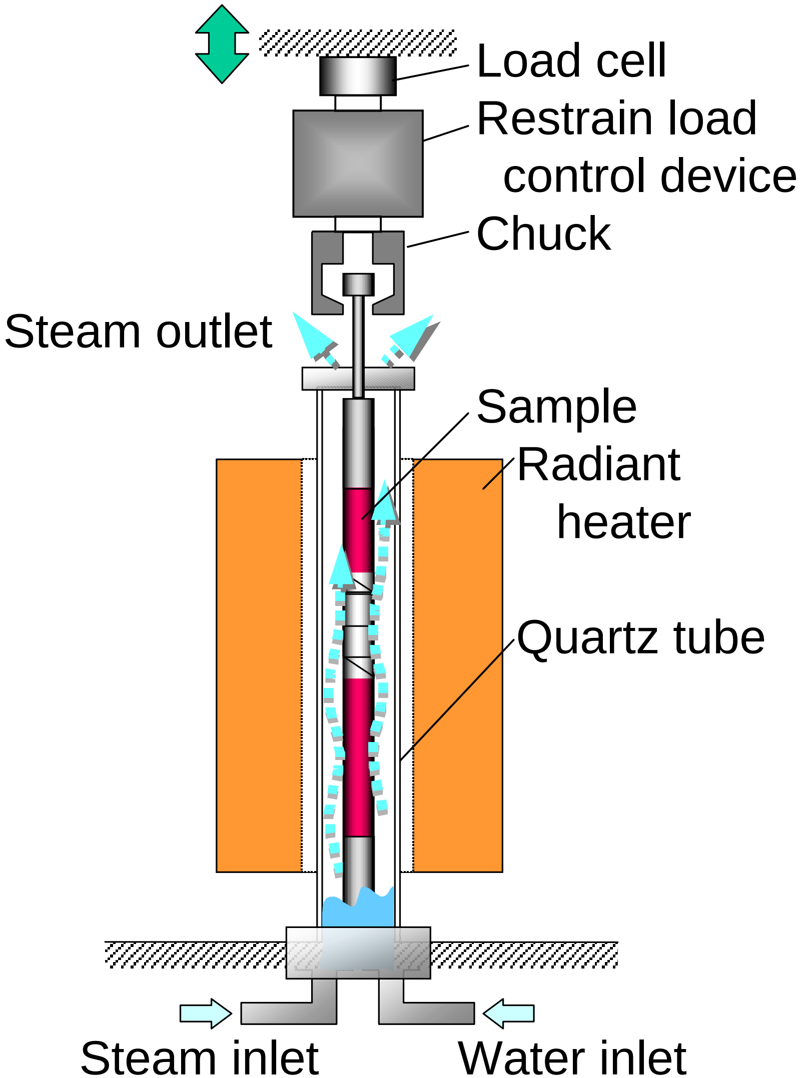
Test rod before test

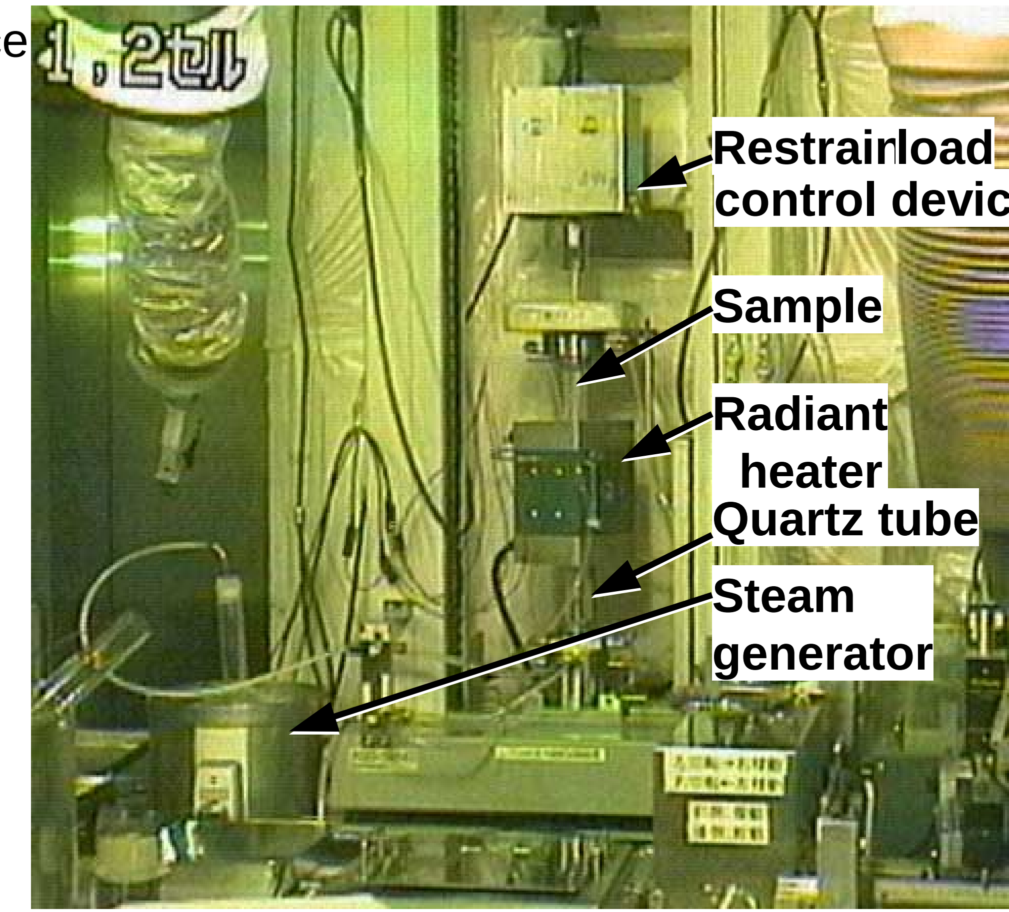
Thermo-Couples Spot-welding Apparatus



Four TCs are welded at different axial and circumferential positions.

LOCA Quench Test Apparatus for Irradiated Cladding



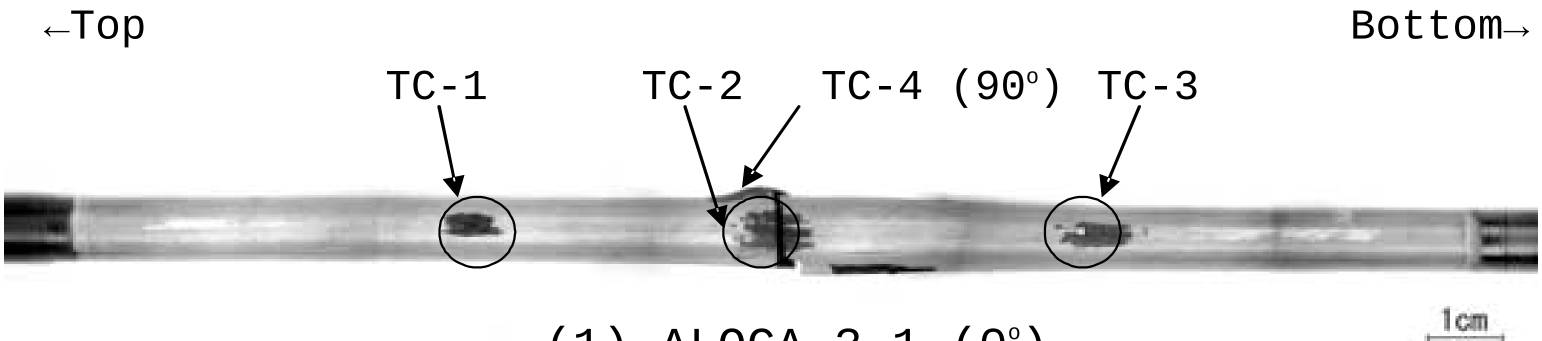


Summary of test results

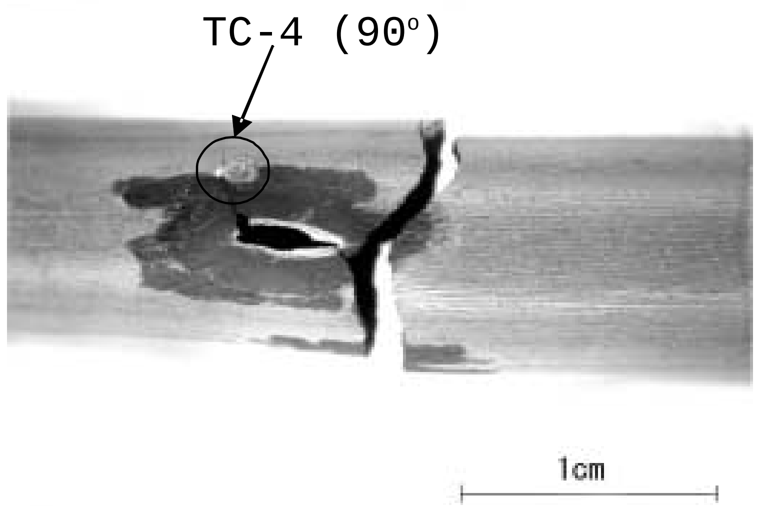
Test No.	1	2	3
Sample No.	ALOCA 3-1	ALOCA 1-2	BLOCA L-3
Initial Internal Pressure (MPa abs)	5.0		
Hearing Rate (K/sec)	10		
Burst Temperature (K) [(°C)]	1053 [780]	1053 [780]	1083 [810]
Burst Strain (%)	14.1	27.7	24.3
Oxidation Temperature (K) [(°C)]	1453 [1180]	1465 [1192]	1430 [1157]
Exposure Time during High Temperature (sec)	486	120	200
Equivalent Cladding Reacted (%ECR)	30.0*	17.9*	16.4*
Failed / Intact	Failed	Intact	Intact
Load at Failure (N) [(kgf)]	498 [50.8]	---	---

*：Estimated values by Baker-Just equation taking account of double sided oxidation and wall thinning by ballooning.

LOCA Quench Test Results

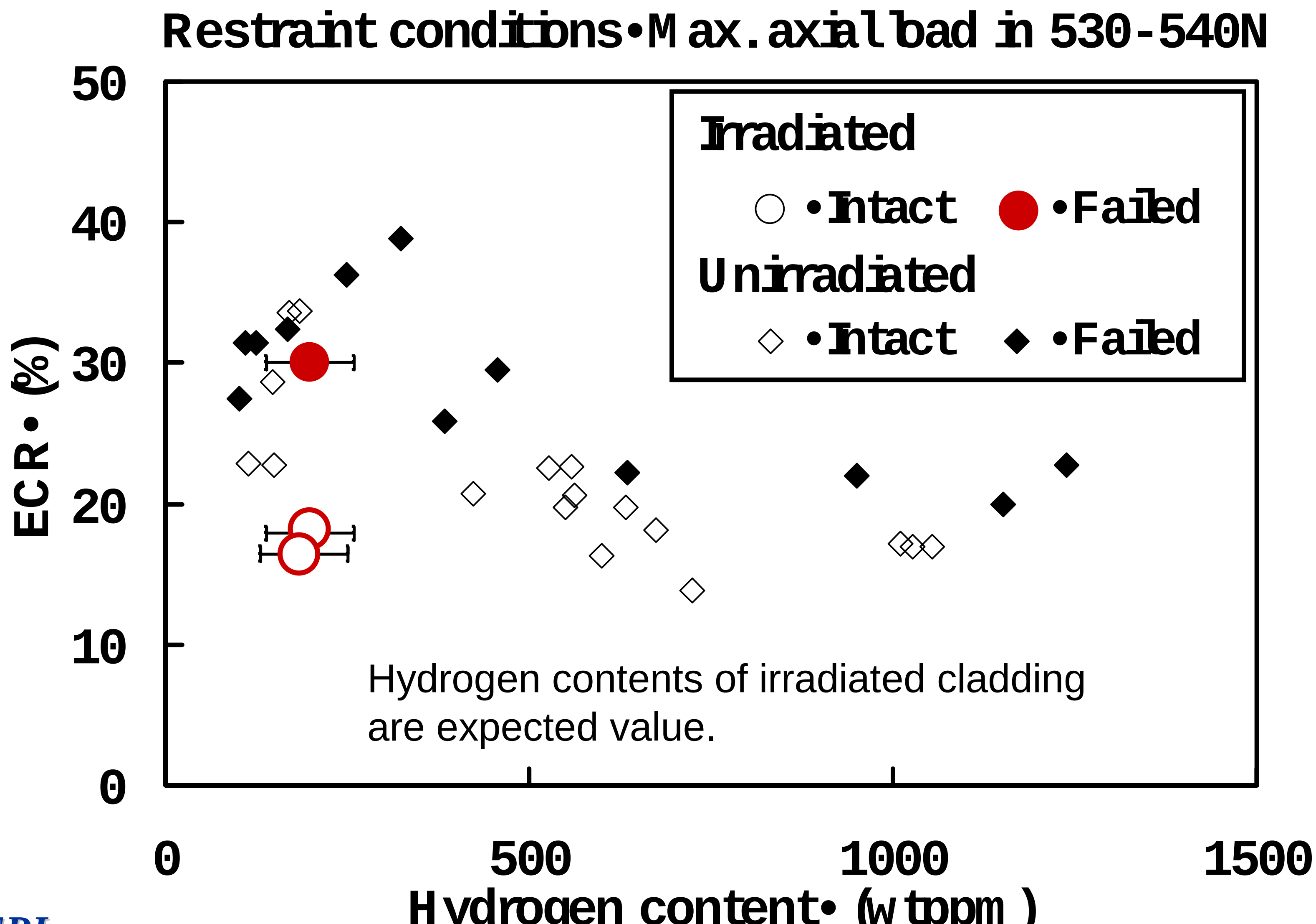


(1) ALOCA 3-1 (0°)



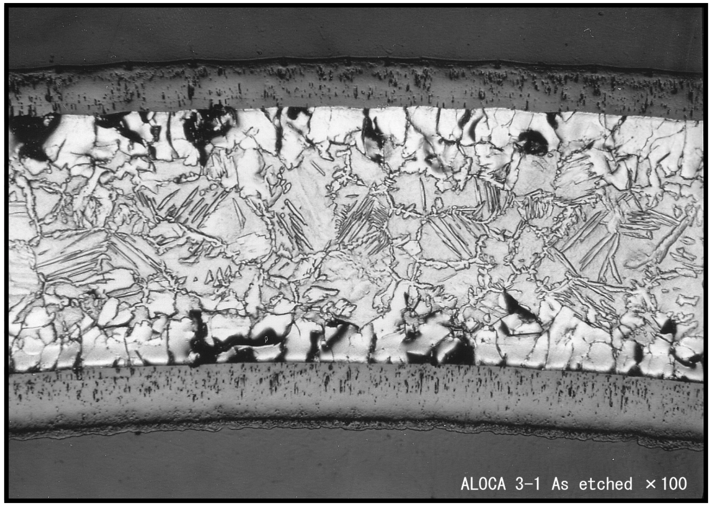
(2) Burst and failure position of ALOCA 3-1 (90°)

LOCA Quench Test Results



Microstructure of fuel cladding after integral thermal shock test

48GWd/t PWR cladding

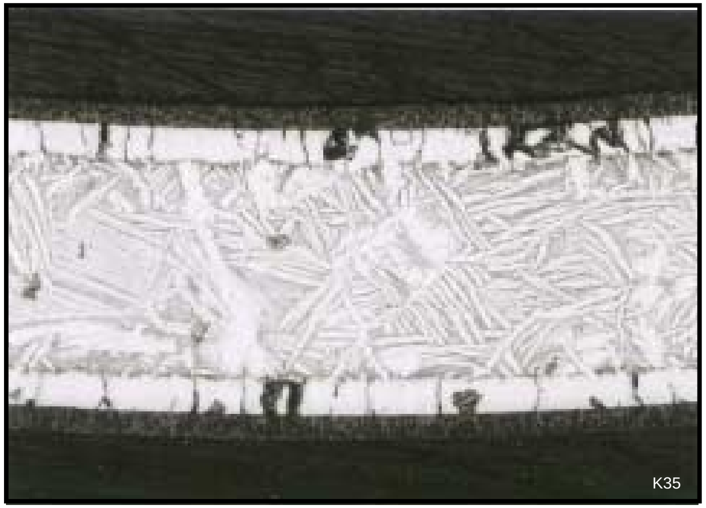


1453K, 486sec, 30.0%ECR

1465K, 120sec, 17.9%ECR

Pre-hydrided unirradiated cladding

1428K, 425sec, 28.7%ECR, 148ppmH



1463K, 134sec, 20.4%ECR, 311ppmH

Objective and limits of ECCS acceptance criteria

To maintain coolability of reactor core

↓

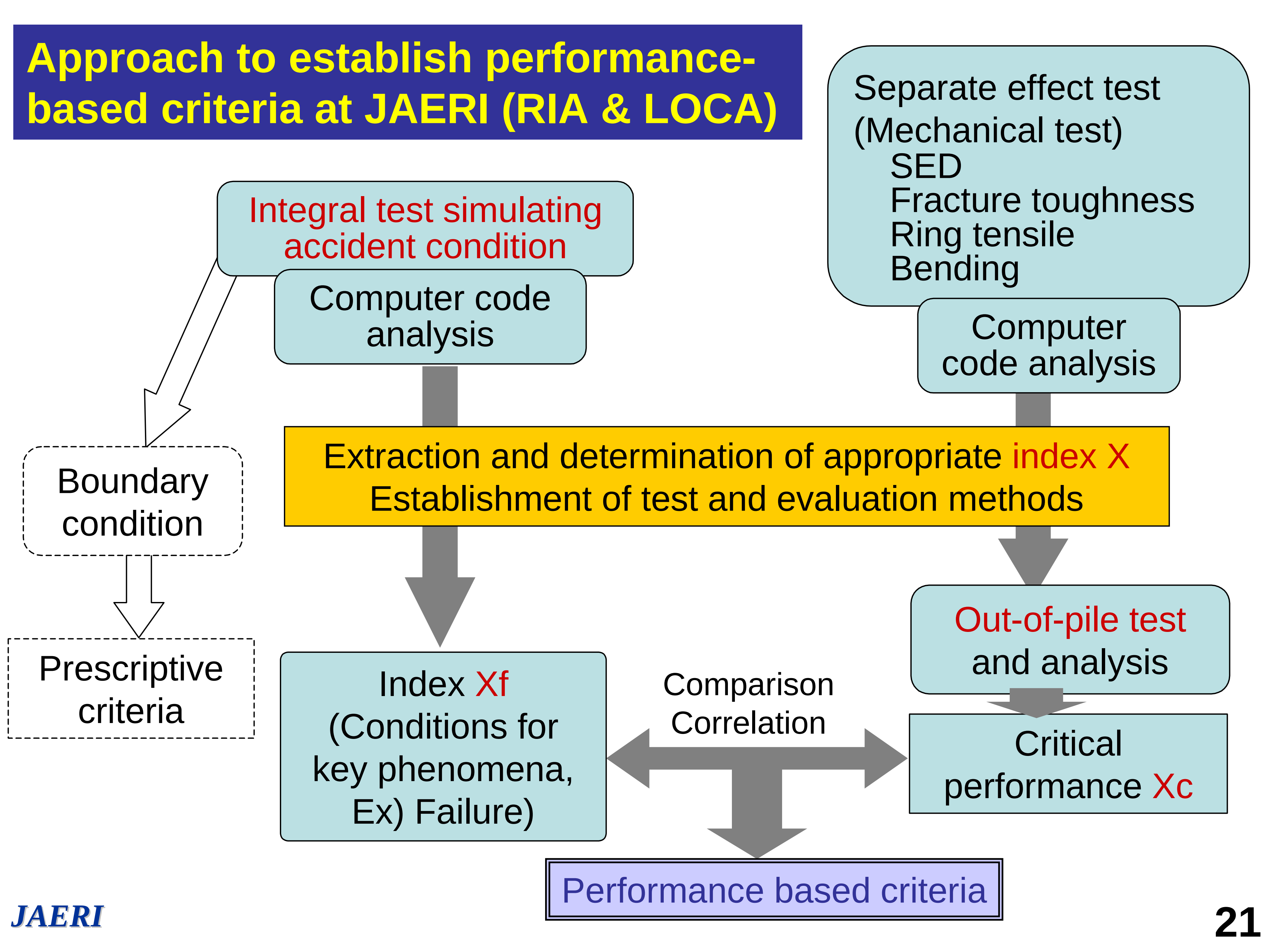
To avoid remarkable embrittlement of cladding

Criteria to define performance (to quantify "remarkable embrittlement")
→Independent of burnup

↓

<1200°C, <15%ECR
(US <2200°F, <17%ECR)
Determined for fresh Zircaloy

Applicable to
High burnup fuel cladding?
(Burnup dependence?)


Approach to establish performance-based criteria at JAERI (RIA & LOCA)
Separate effect test
(Mechanical test)
SED
Fracture toughness
Ring tensile
Bending
Integral test simulating accident condition
Computer code analysis
Computer code analysis
Extraction and determination of appropriate index X
Establishment of test and evaluation methods
Boundary condition
Prescriptive criteria
Out-of-pile test and analysis
Index Xf
(Conditions for key phenomena, Ex) Failure)
Comparison
Correlation
Critical performance Xc
Performance based criteria
JAERI
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Code Development for the Analysis of Fuel Behaviors in LOCA

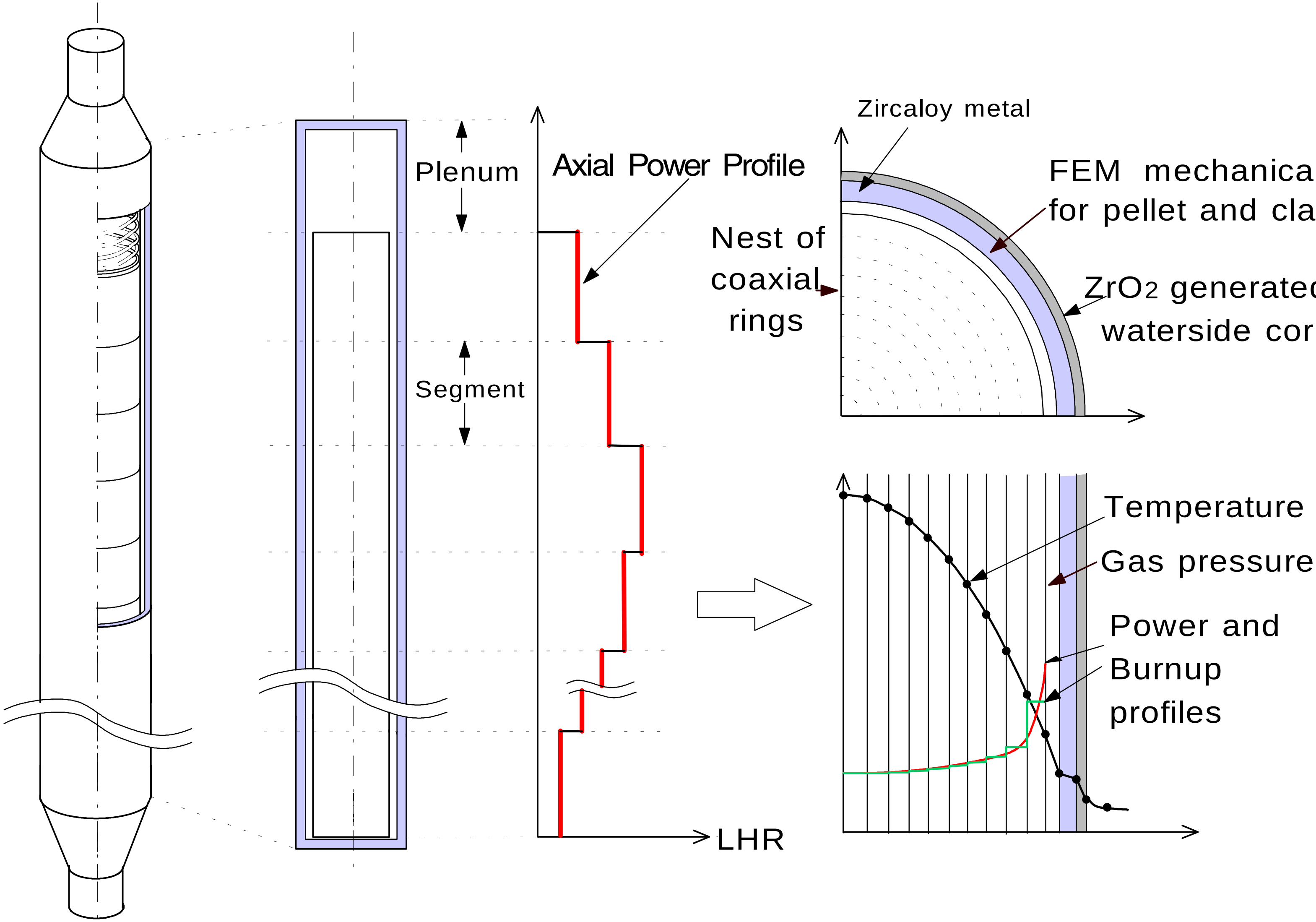
FURBEL [FUel Rod BEhavior in LOCA]

1. Prediction of stress in cladding generated on quenching (under non-restraint and restraint conditions).

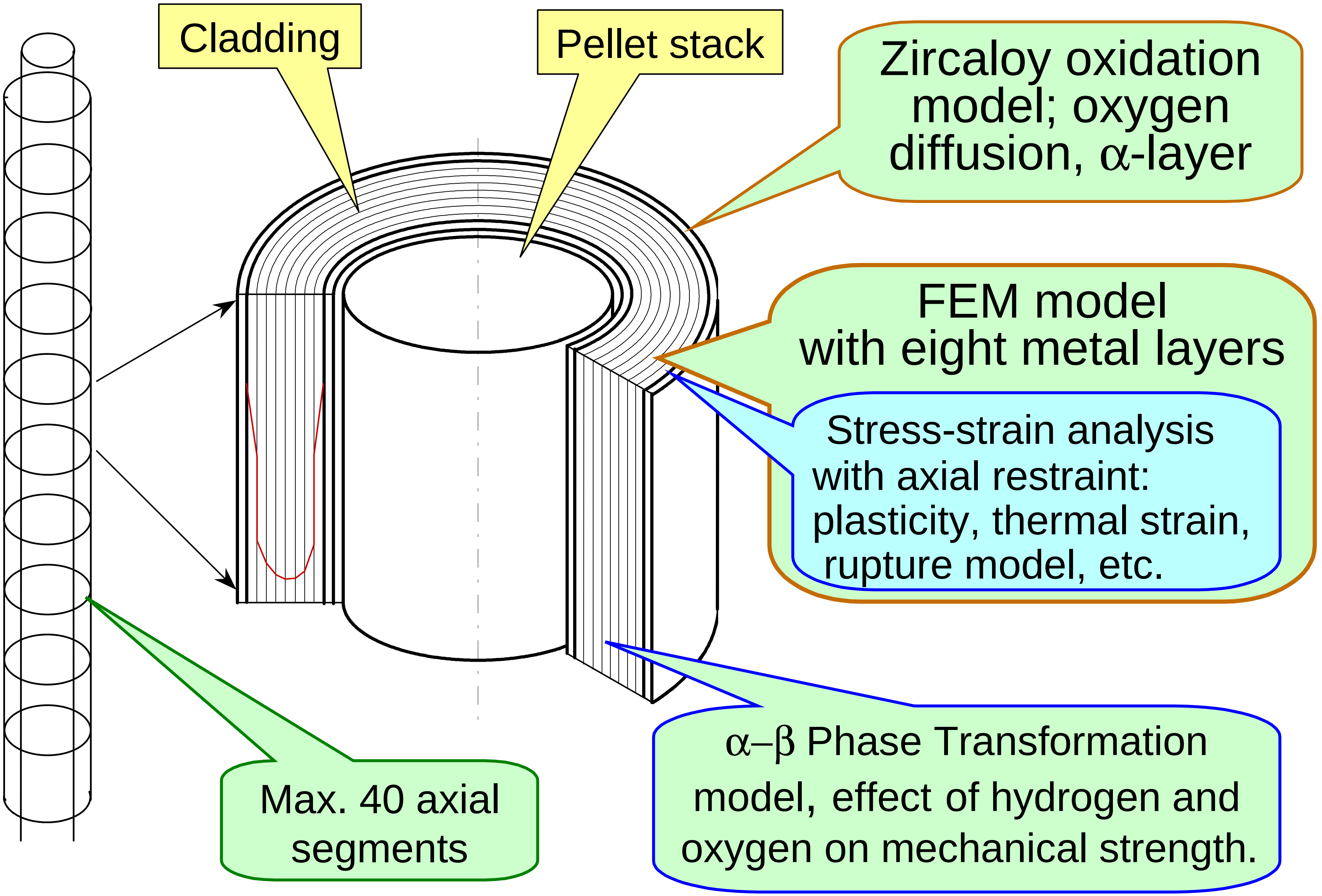
2. Basic structure has taken over that of the fuel performance code FEMAXI-6.
   Cladding consists of 8-layer finite element in the radial direction.

3. Experimental analysis and evaluation is in progress.

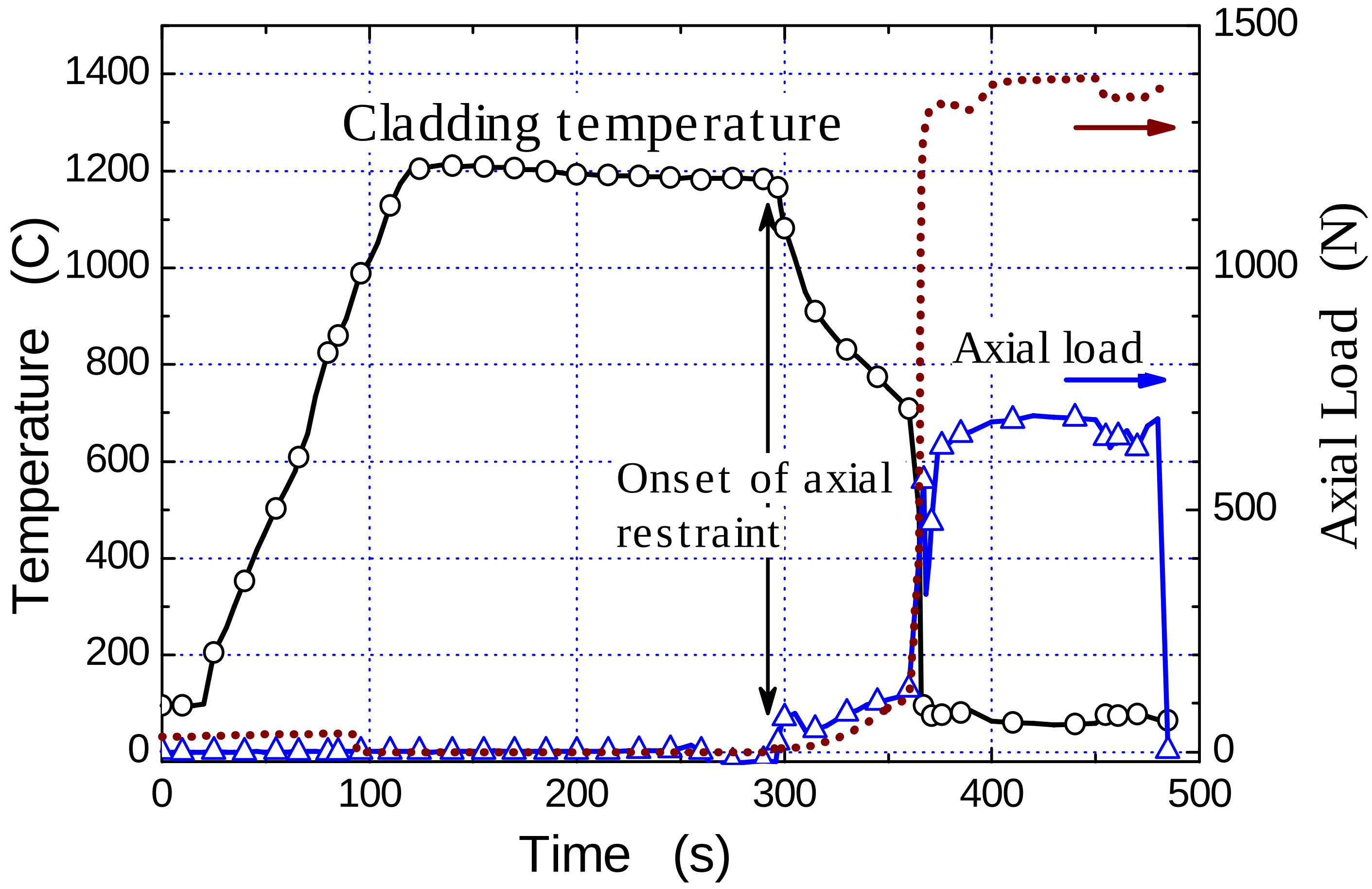
Analytical System taken over from FEMAXI-6 for FURBEL



FURBEL Model in detail



A Preliminary Result of Experimental Analysis by FURBEL



Cladding temperature measured in Quench-after-Oxidation test as input data for FURBEL analysis and comparison of axial load between measured (blue) and calculated (brown dots) values.

The difference of axial loads suggests that the evaluation of cross section area of cladding generating the axial force is to be improved.

Summary

- **With a view to accumulating data for regulatory judgment corresponding rationally to high burnup fuel, LOCA-related experiments are conducted at JAERI with non-irradiated and irradiated cladding tubes.**
- **Hydrogen effects on high burnup fuel behavior under LOCA conditions have been especially examined and clarified.**
- **The tests have been started with irradiated claddings and preliminary results were obtained for 48 GWd/t PWR fuel claddings.**
- **Further investigations including computer code analysis will be done to establish performance-based criteria.**