IFE and OECD Halden Reactor Project - Experimental Capabilities

Facilities for Fuels and Materials Safety Research

Halden Boiling Water Reactor
LWR loops and online instruments

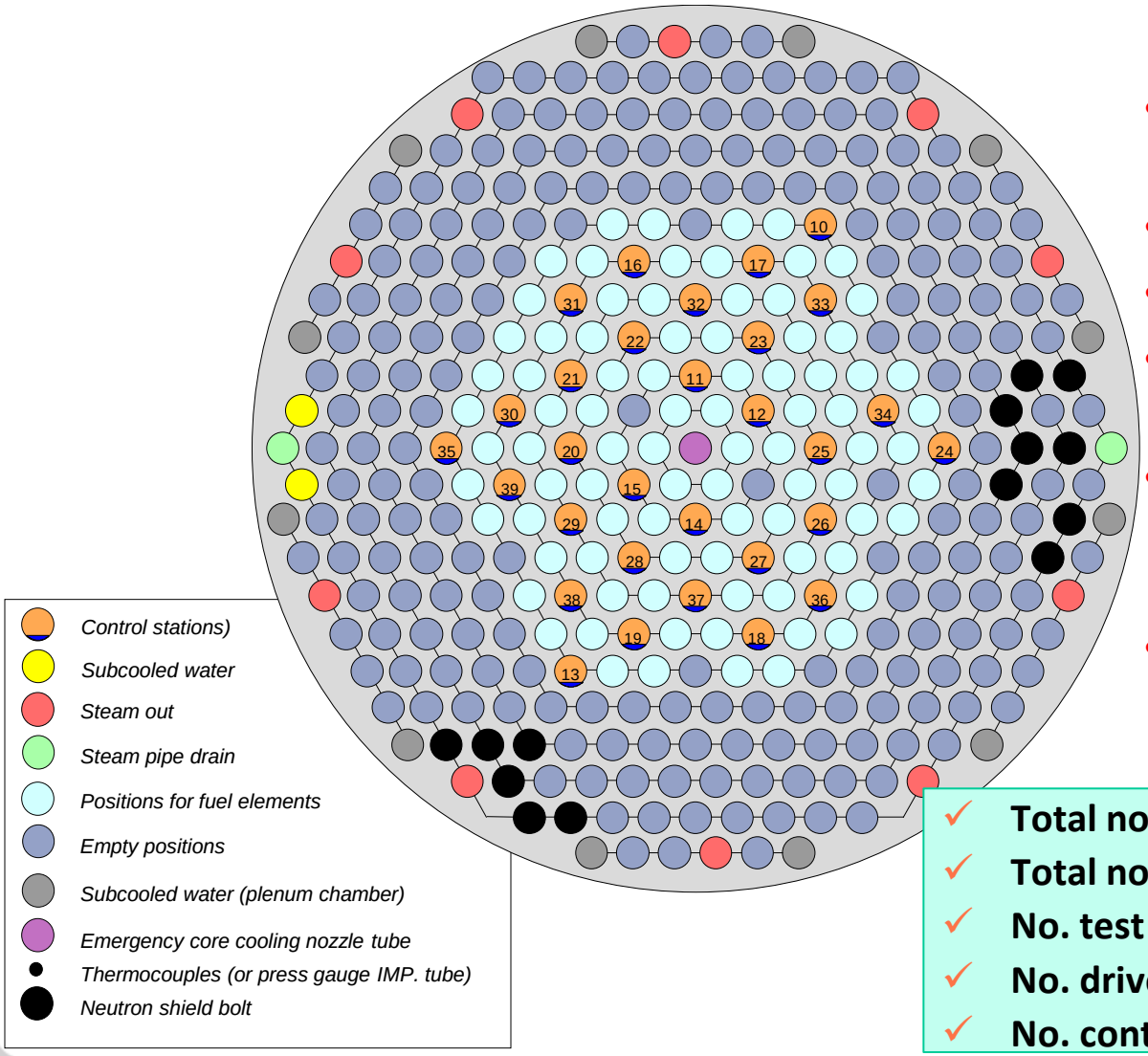
Design Office, Workshops, Chemistry labs,
Hot Labs, Fuel fabrication and Re-fab.

Halden Boiling Water Reactor (HBWR)

- Managed and owned by the Institute for Energy Technology (IFE), Norway
- Research facility for the **OECD NEA Halden Reactor Project**
- Also used for **contract work** for utilities, vendors, licensing authorities and R&D centers
- There have been more than 400 test assembly loadings with several thousand instrumented fuel rods and material specimens
- All experimental data since 1972 are available in electronic format

HBWR used exclusively for reactor fuel and materials safety research

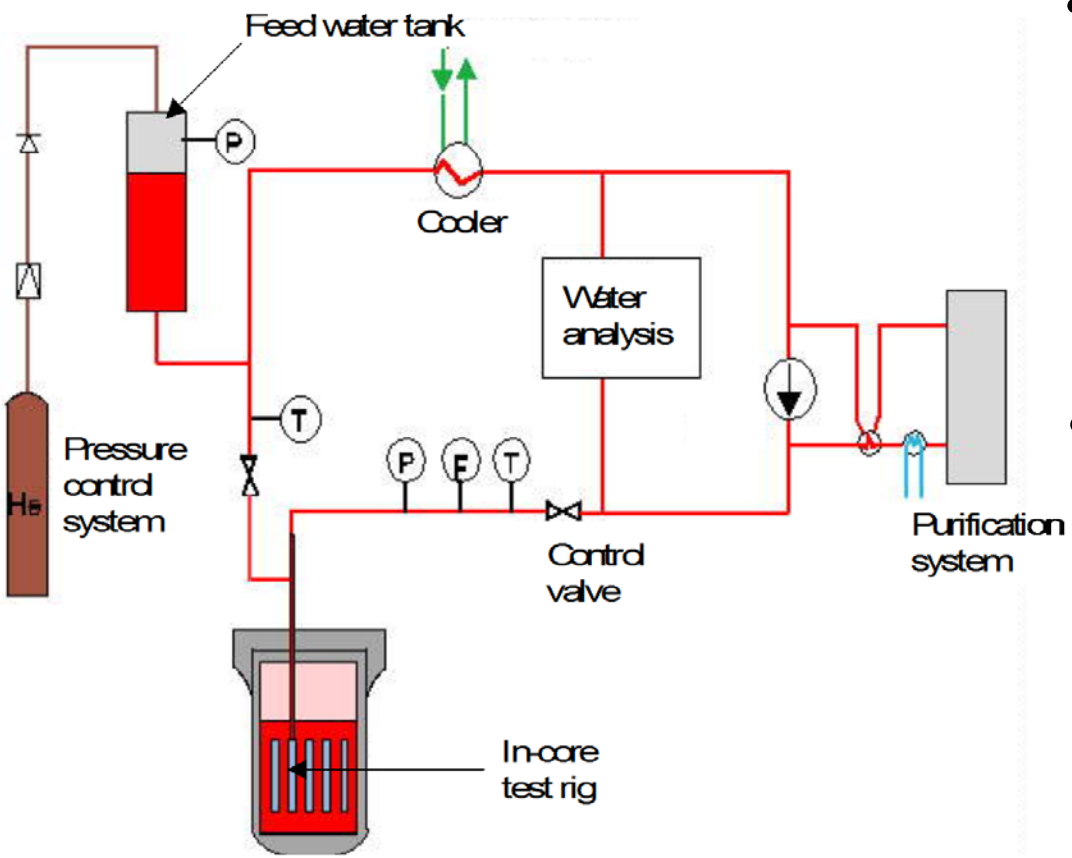
Characteristics of the Halden Reactor



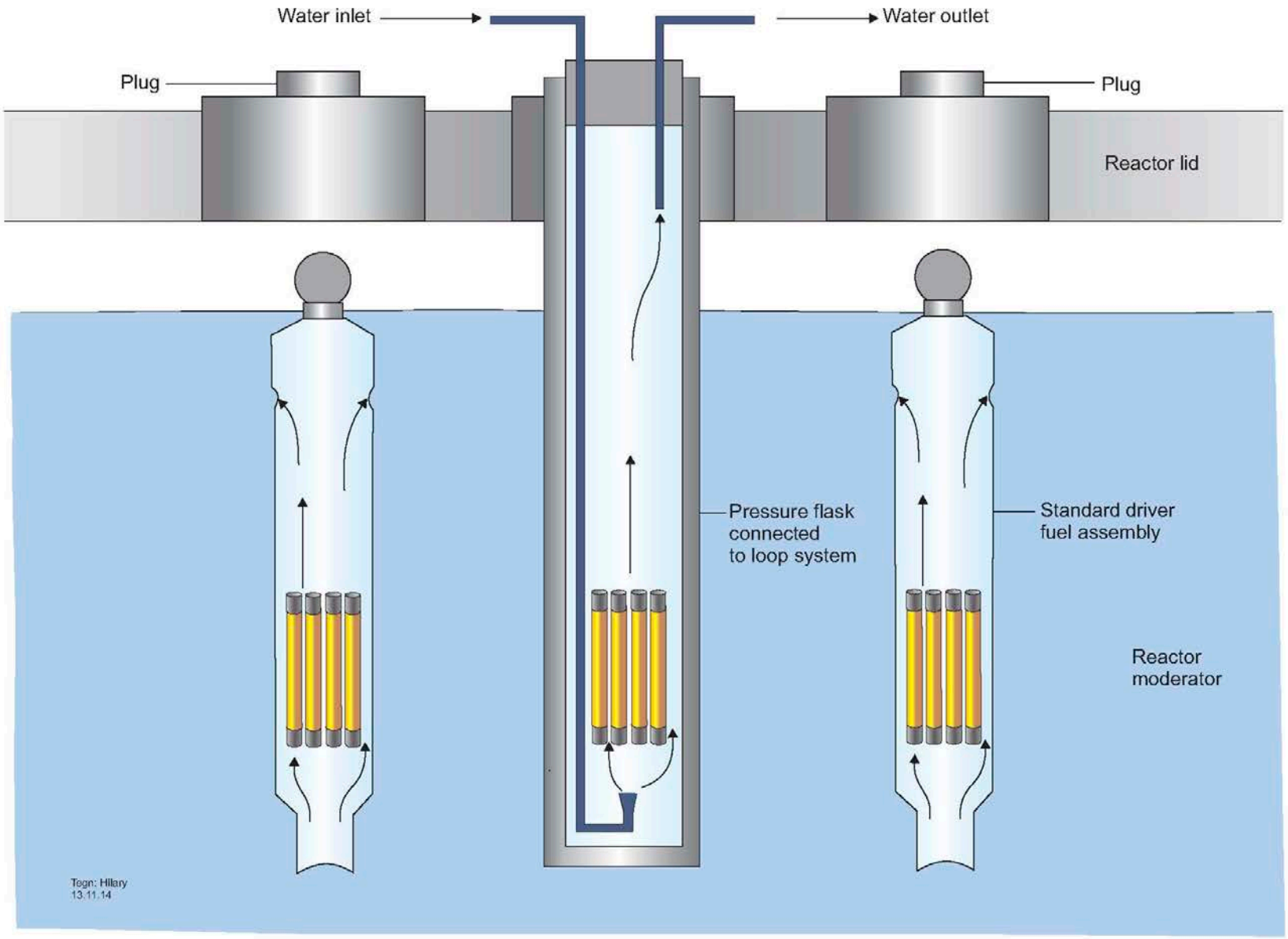
- 20 MW heavy water reactor, 34 bar and 235°C
- Height of active core 80 cm
- 1-8 E+13 n/cm2.s
- Test rigs directly in HBWR coolant have 71 mm ID
- Test rigs in pressure flasks connected to loop systems have 33 or 43-57 mm ID
- 10-11 water loops in operation at any given time

✓ **Total no. of channels:**	**329**
✓ **Total no. fuel assemblies:**	**80 – 110**
✓ **No. test rigs:**	**15 – 35**
✓ **No. driver fuel rigs (6 wt% UO_2):**	**65 – 75**
✓ **No. control rods (Cd/Ag):**	**30**

Loop Systems in the Halden Reactor



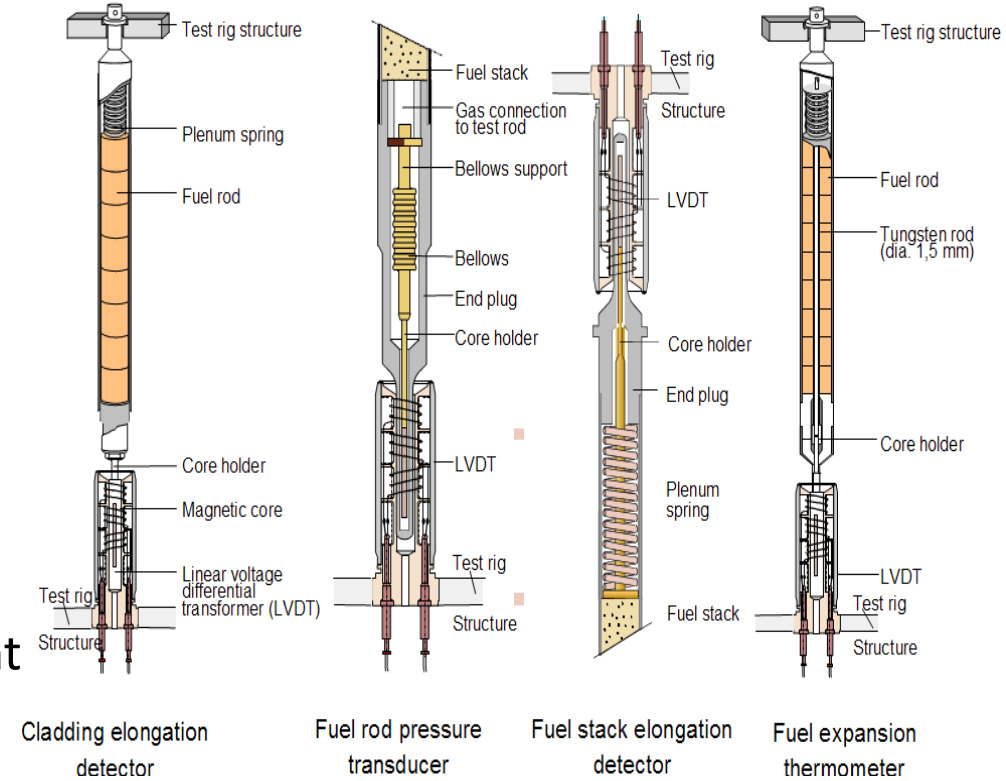
- Test rigs placed in pressure flasks connected to a loop
- Allows testing under simulated BWR, PWR, VVER or PHWR conditions:
  - Coolant pressure
  - Coolant temperature
  - Water chemistry (not VVER)
- Used for
  - IASCC of core internals
  - Corrosion studies
  - PCMI testing
  - Fuel ramp testing (to fail)
  - Fuel degradation tests
  - Dry-out and LOCA tests


Water inlet
Water outlet
Plug
Plug
Reactor lid
Pressure flask
connected
to loop system
Standard driver
fuel assembly
Reactor
moderator
Tegn: Hilary
13.11.14

A key factor in Halden reactor experimental work is:

Making In-Pile Fuels Measurements

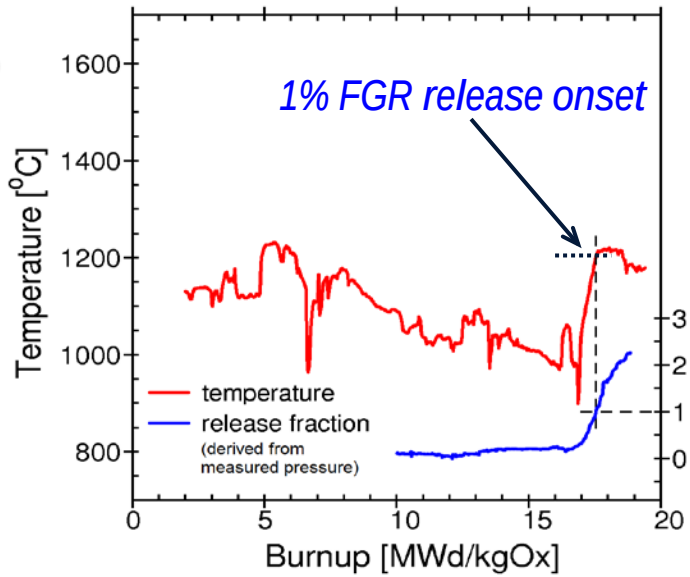
- All test assemblies are equipped with in-pile instruments to monitor fuel behavior:
  - ✓ Pressure in fuel rods
  - ✓ Fuel temperature
  - ✓ Elongation of fuel and clad
  - ✓ Change of cladding diameter
- Test assemblies create a controlled testing environment within the Halden Reactor

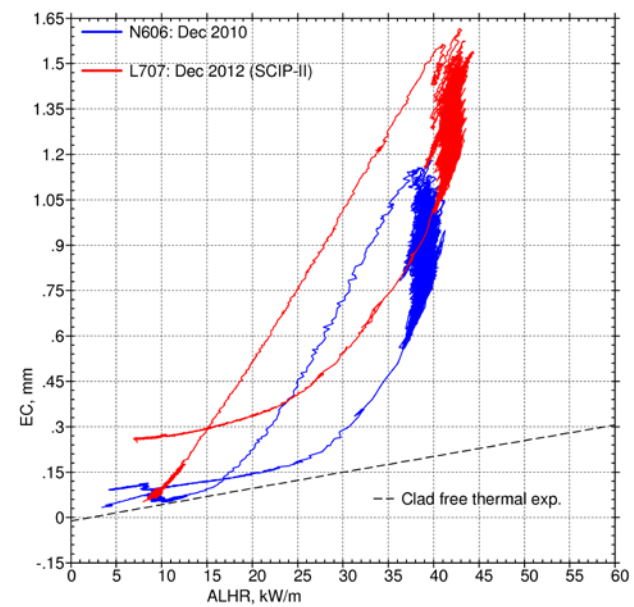


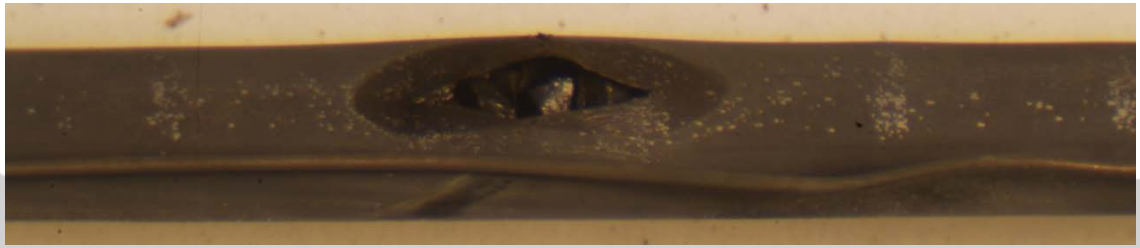
'On-line' measurements are the speciality of Halden's experimental work: reliable instrumentation provides direct insight into phenomena while they develop

Typical HRP Fuels Tests

- *Fuel (pellets) performance*
  - Fission gas release
  - Thermo-mechanical behaviour
  - Comparing different fuel types
- *Cladding performance*
  - Clad creep, growth, corrosion, hydriding
  - Comparing different cladding types
- *Safety margins and criteria*
  - Power transients - PCMI and to failure (PCI-SCC)
  - T-H transients – dryout / DNB
  - Overpressure conditions (EOL RIP)
  - Fuel rod behaviour under LOCA conditions
  - Code development and validation



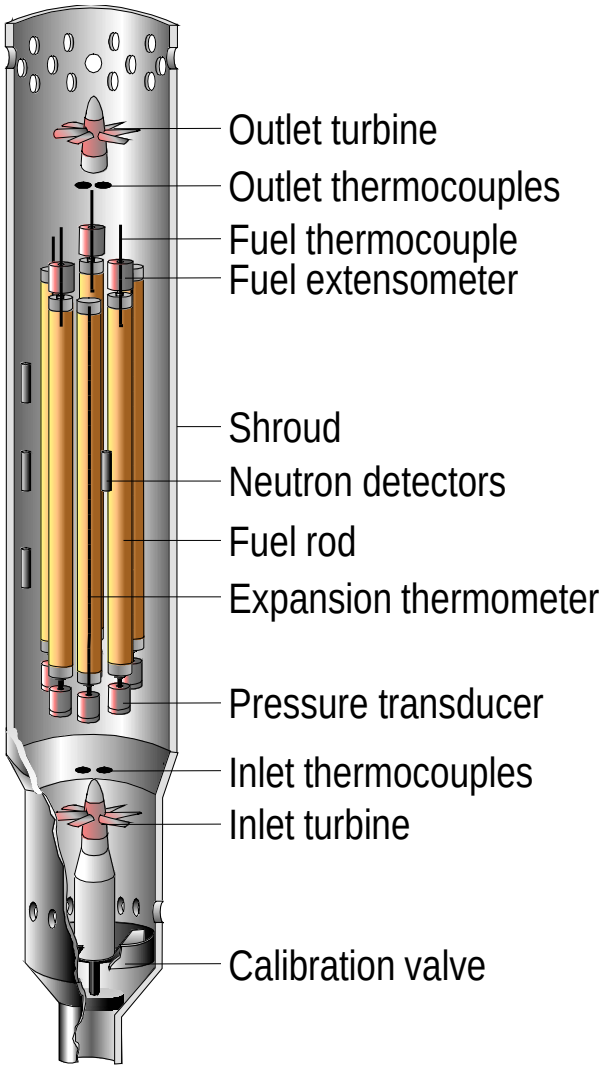




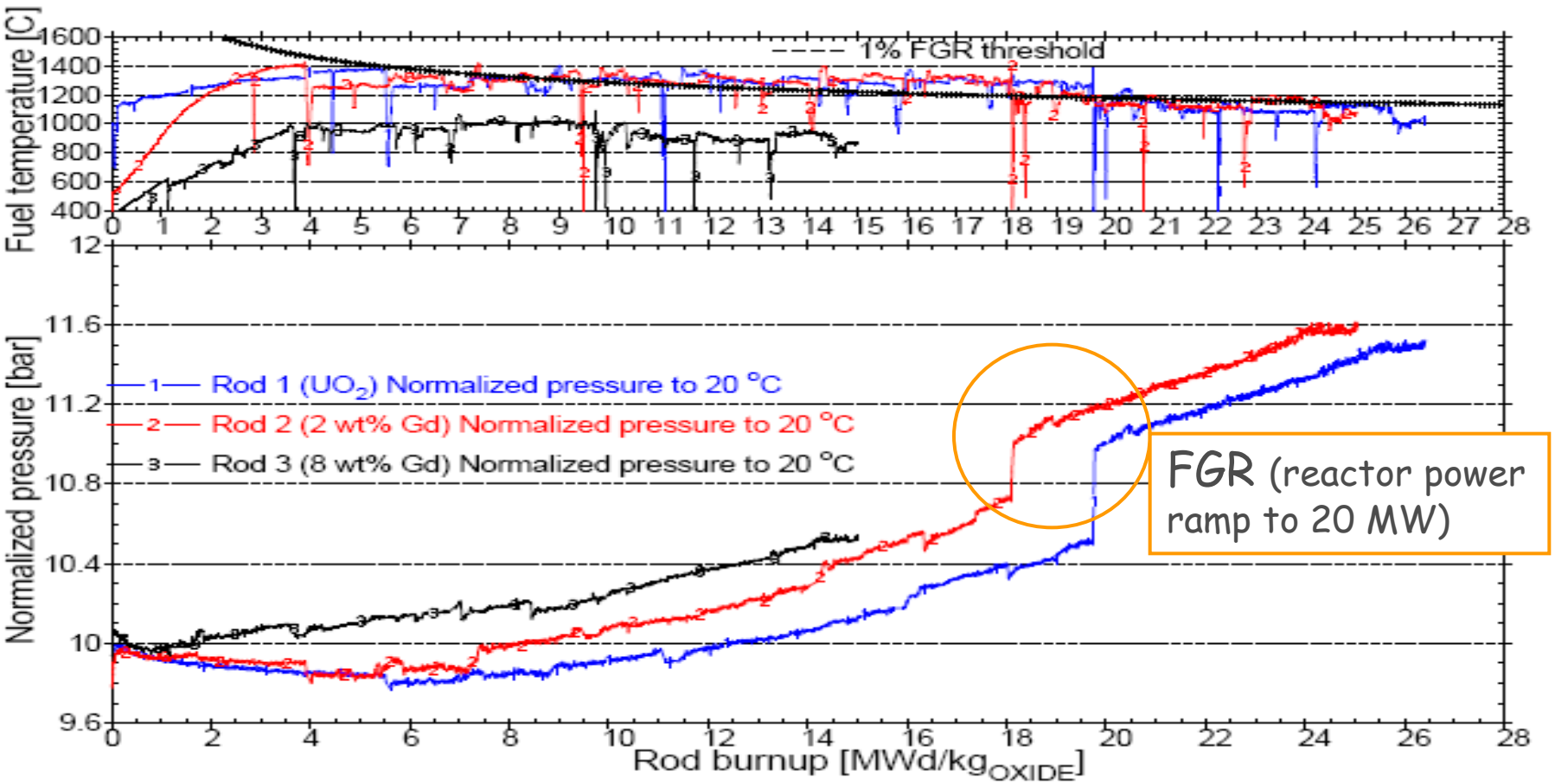
Fuel Performance Research

Long-term fuel tests aimed at:

- determining fuel and cladding performance under normal and extended operating conditions by monitoring through-life fuel behavior with extensive instrumentation
- generating a large database for design & licensing and used by modellers
  - fuel thermal conductivity, fuel and clad dimensional stability, FGR, PCMI
- Recent and future focus on:
  - Gd-bearing fuels, Cr-doped fuels, VVER fuel, MOX, Th-MOX and optimised pellets for PCI resistance, fission gas retention, improved fuel thermal conductivity and higher U-235 density



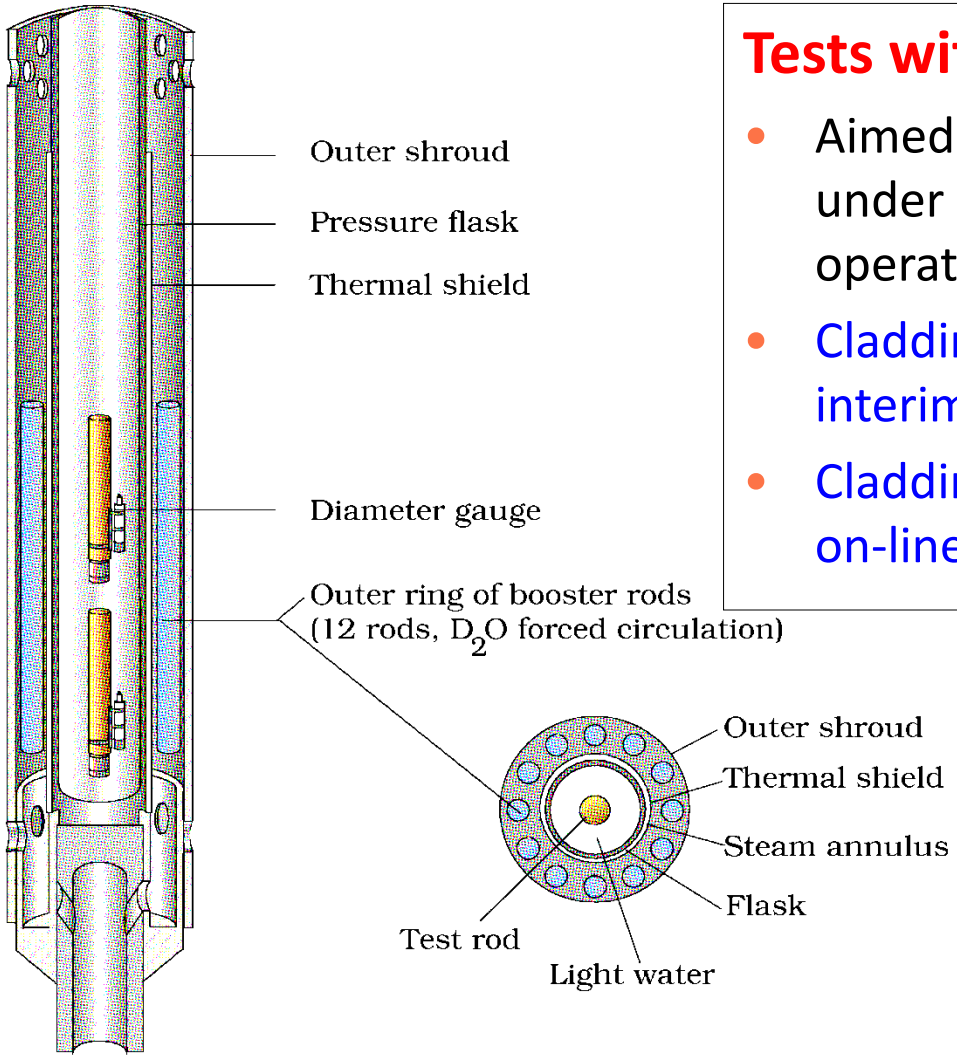
Testing thermo-mechanical and FGR behaviour of different fuels with Gd-additive



*Signs of densification in rods **1** and **2***

*Different behaviour for **8%wt Gd** because $T < T_{threshold}$*

Fuel Cladding Performance Research

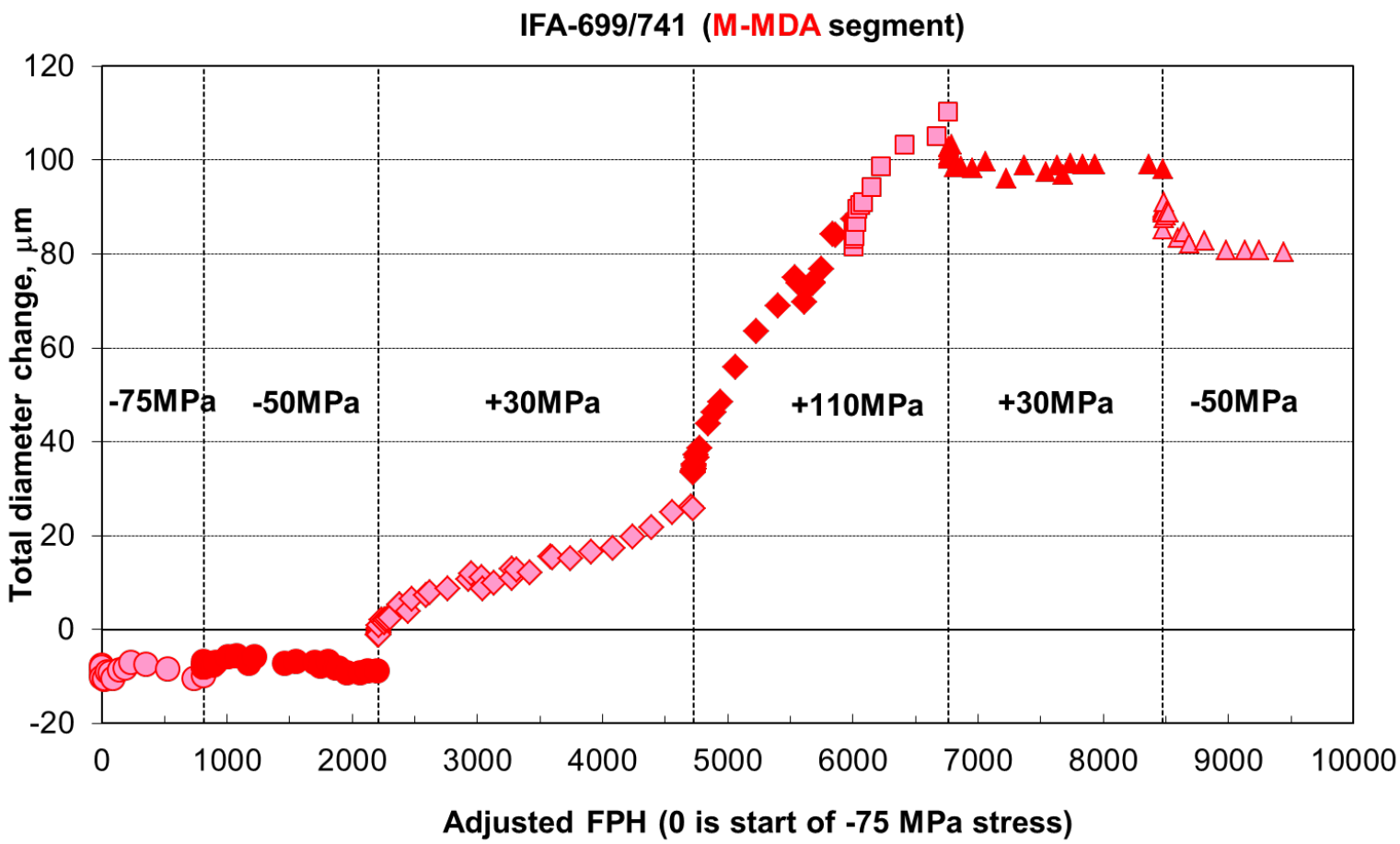


Tests with cladding as the focus:

- Aimed at determining cladding performance under normal and also more demanding operating conditions
- Cladding corrosion behaviour monitored via interim inspections or EIS
- Cladding creep behaviour monitored on-line with diameter gauge

- Recent and future focus on:
  - Zirlo & Opt. Zirlo, E110, M5, M-MDA, “ATF” claddings
  - High Li water chemistry
  - On-line corrosion monitoring

Example: creep of M-MDA under variable stress

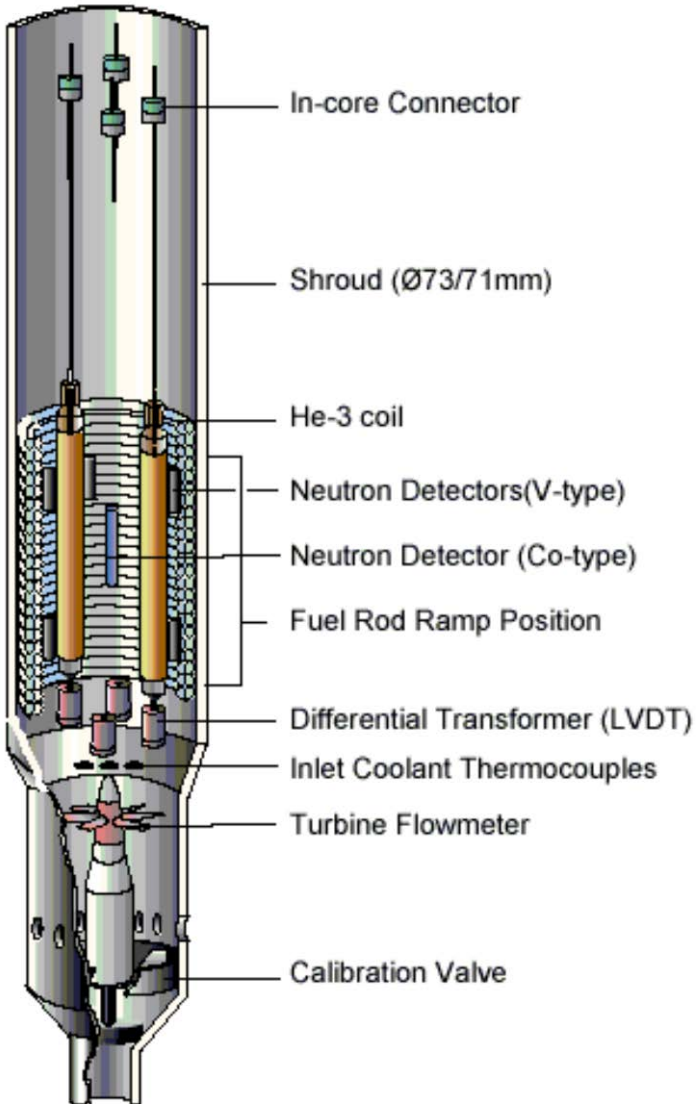


Recurring primary creep depends on stress change, secondary creep depends on stress level.

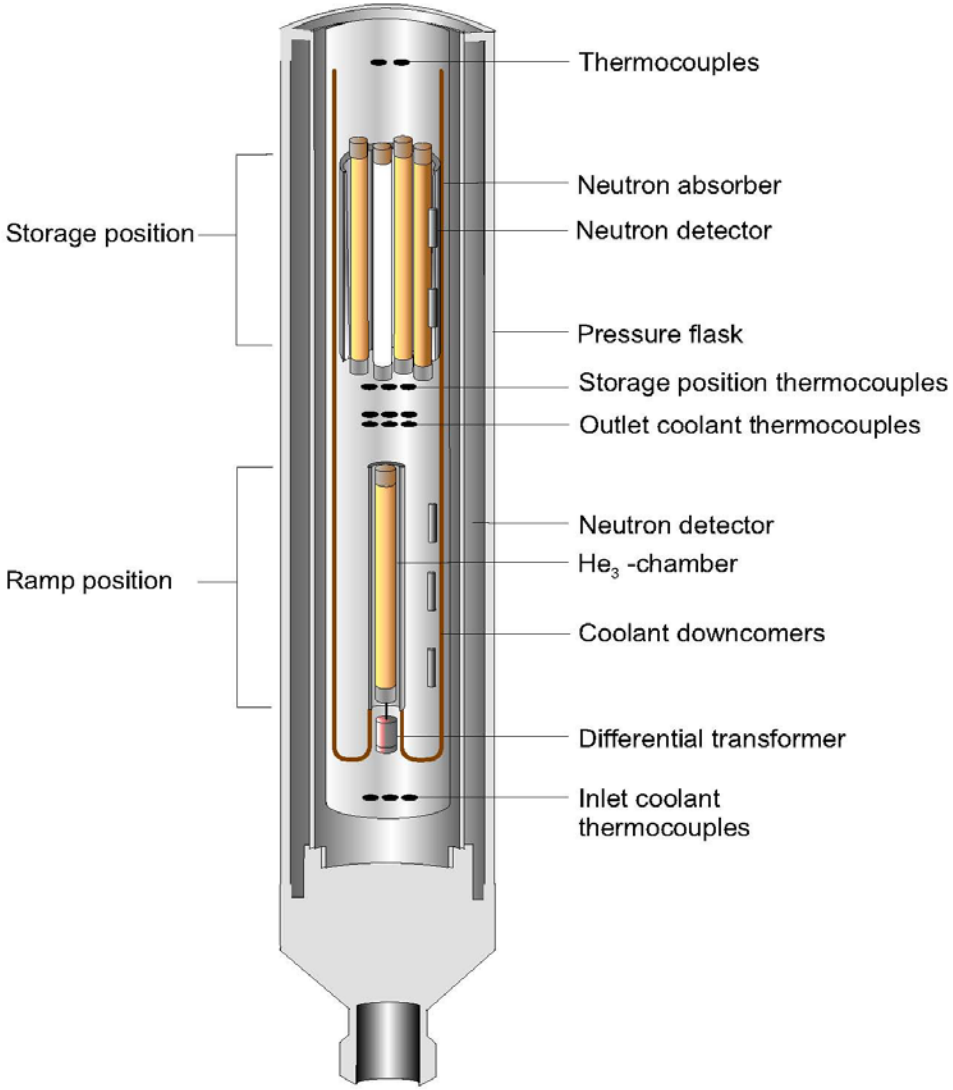
Fuels Safety Margins Research

Tests with pre-irradiated fuel / segments of NPP fuel rods aimed at:

- determining behavior under specific types of operation conditions
  - Rod overpressure "lift-off" testing
  - Power transients – PCMI, FGR, PCI-SCC
  - Secondary degradation
  - Cooling transients – dry-out
- dedicated instrumentation attached to pre-irradiated fuel segments
- pre- and post irradiation examinations
- data of practical use for utilities as well as for licensing/regulatory issues



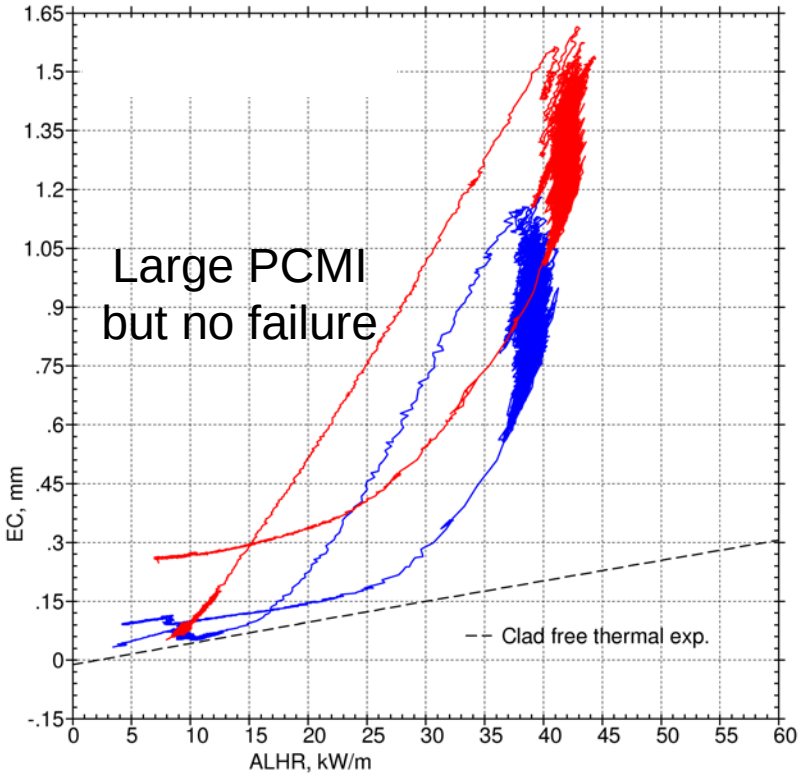
Power Ramps - PCI and PCMI Margins



Integral fuel rod behaviour under transient conditions

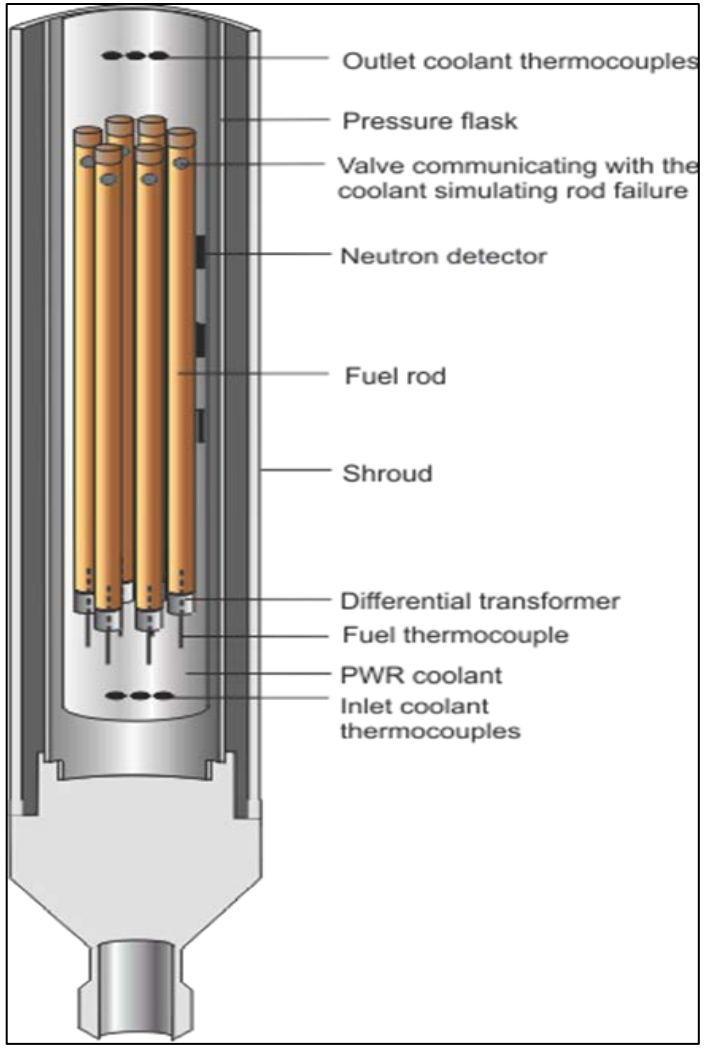
- Power ramps currently used as standard test for assessing PCI/PCMI fuel margins
- Rapid and large power increment e.g. 100 W/cm in 1 minute
- Rods moved (one at a time) from storage position to ramp position
- Helium-3 chamber surrounding fuel rod ramp position provides:
  - local power control (power level and ramp rate)
  - insulation for reducing power calibration uncertainties

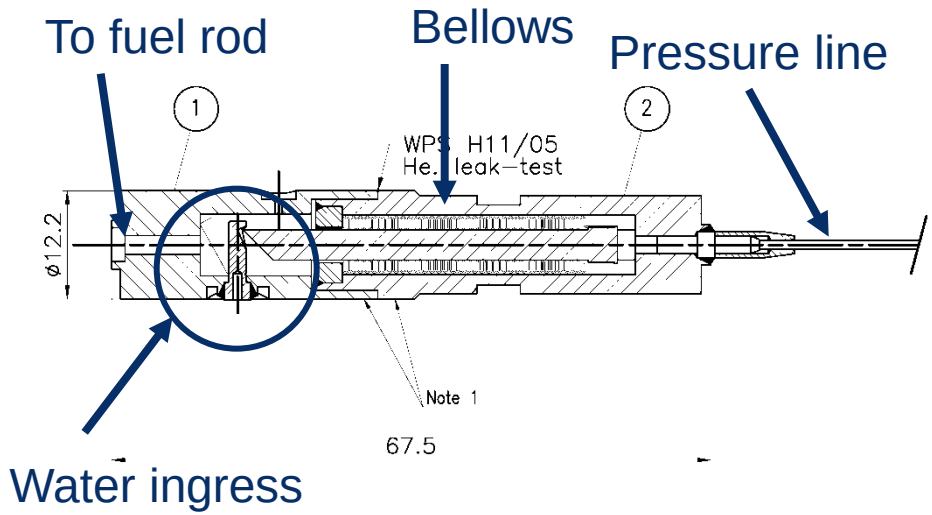
Examples from PCI / PCMI margins ramp testing



Example of failed rod visual inspection

Fuel secondary degradation test

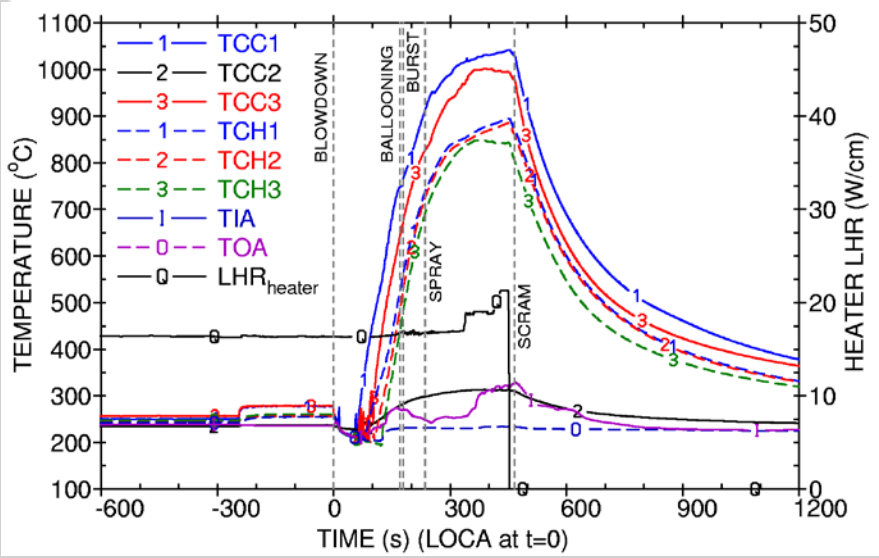


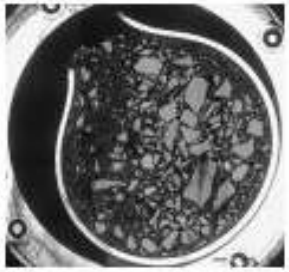


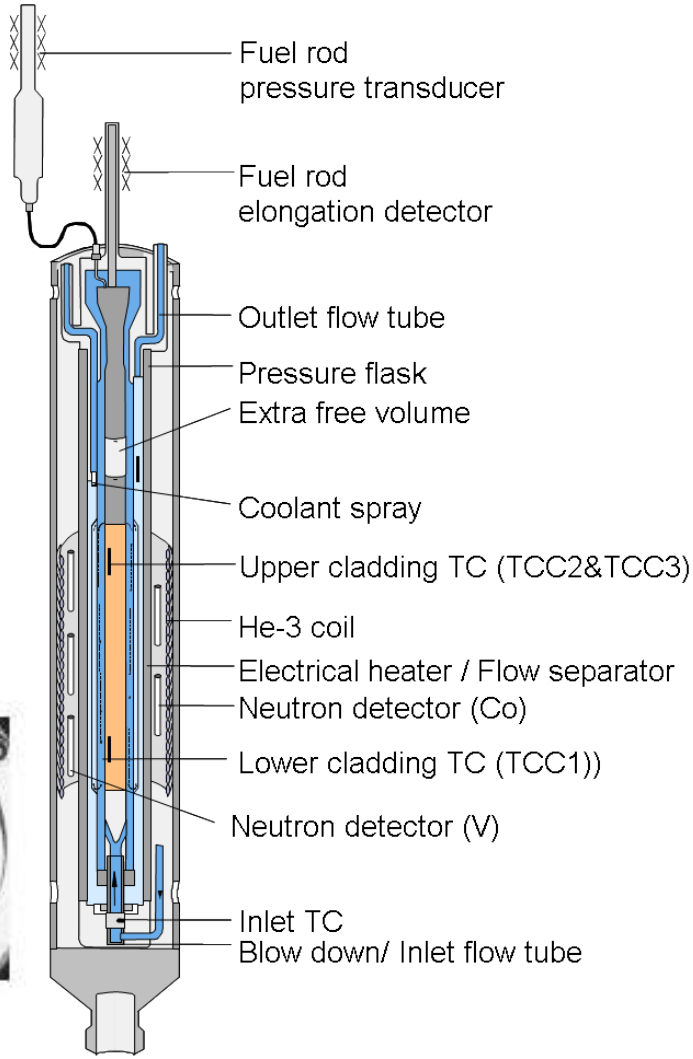
- **Connected to one end of fuel rods**
- **Controlled water ingress by pressurizing bellows to break seal**

LOCA Testing - Assessing Safety Criteria

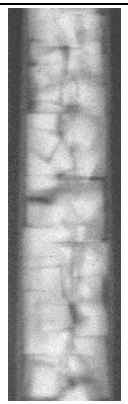
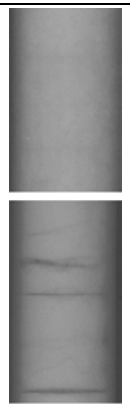
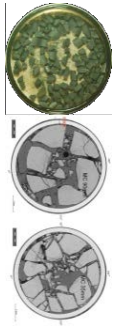
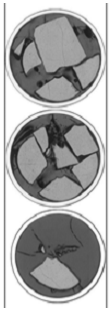
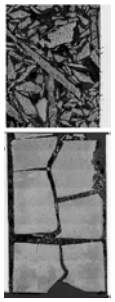
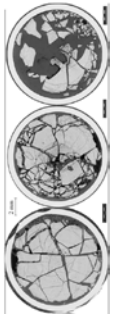
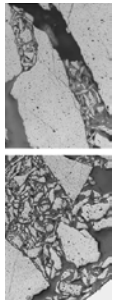
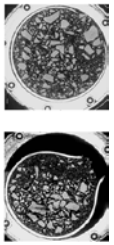
- Aimed at demonstrating performance of different fuels in accident situations
  - effect of fuel/clad burn-up on clad ballooning & burst, and fuel fragmentation, relocation and dispersal
  - effect of fuel relocation to balloon region on over-heating, oxidation, secondary hydriding







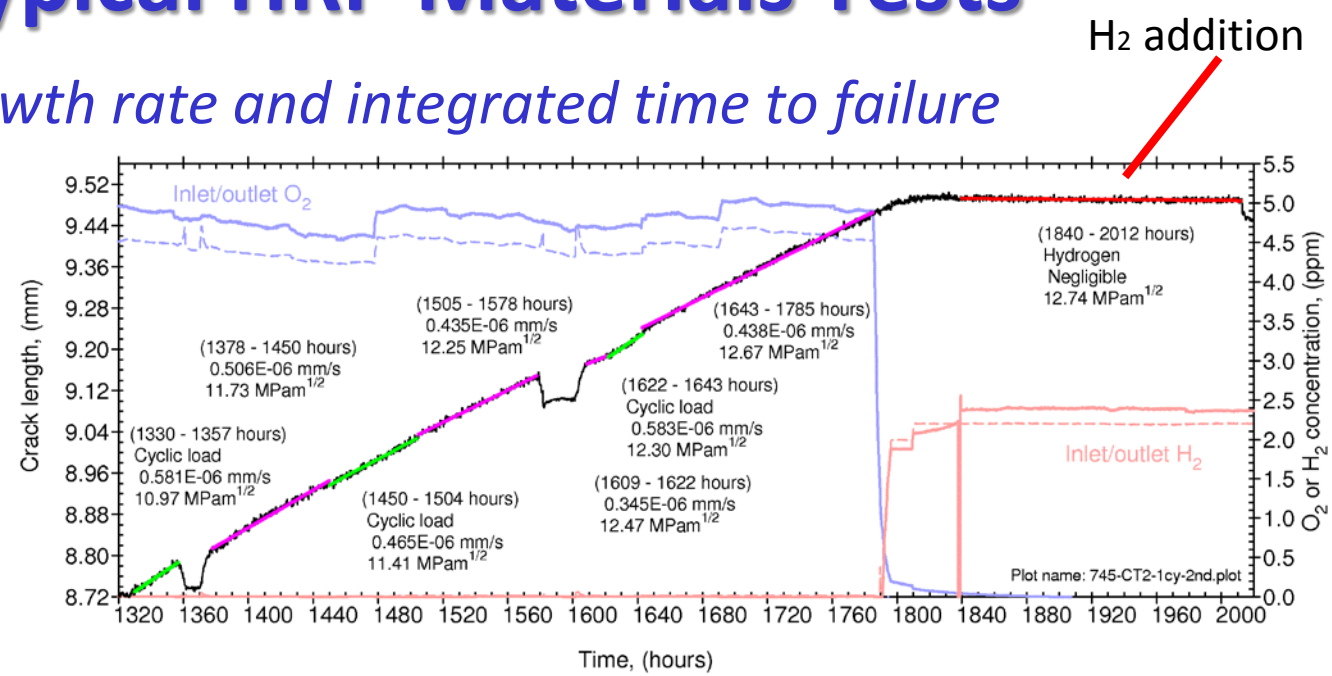
Making an overview from multiple tests: LOCA

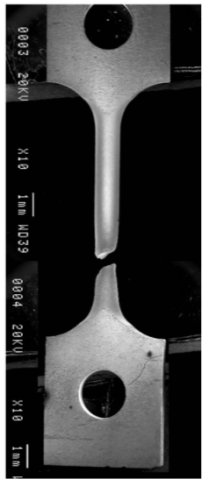
test #	2	7	6	11	10	12	13	3	5	9	4
burnup, MWd/kg	0	44.3	55.5	56	60	72.3	74.1	81.9	83	90	92
balloon strain, %	54	23	49	25	15	40	45	8	15	61	62
radio-graphy											
ceramo-graphy							not yet available				
fragment size	coarse	coarse	coarse	coarse	coarse & some fine	coarse & fine	coarse (& fine?)	medium & fine	medium & fine	medium & fine	medium & fine

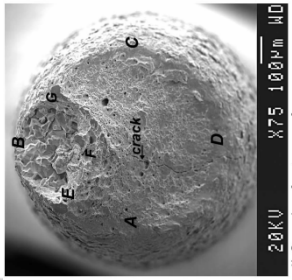
VVER segments

Typical HRP Materials Tests

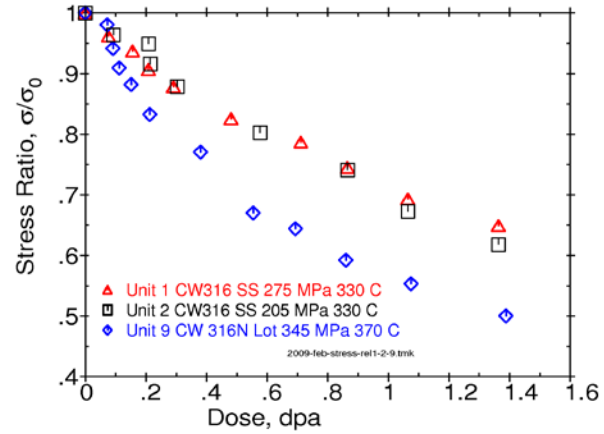
- *IASCC crack growth rate and integrated time to failure*
  - Environment
  - Stress
  - Microstructure







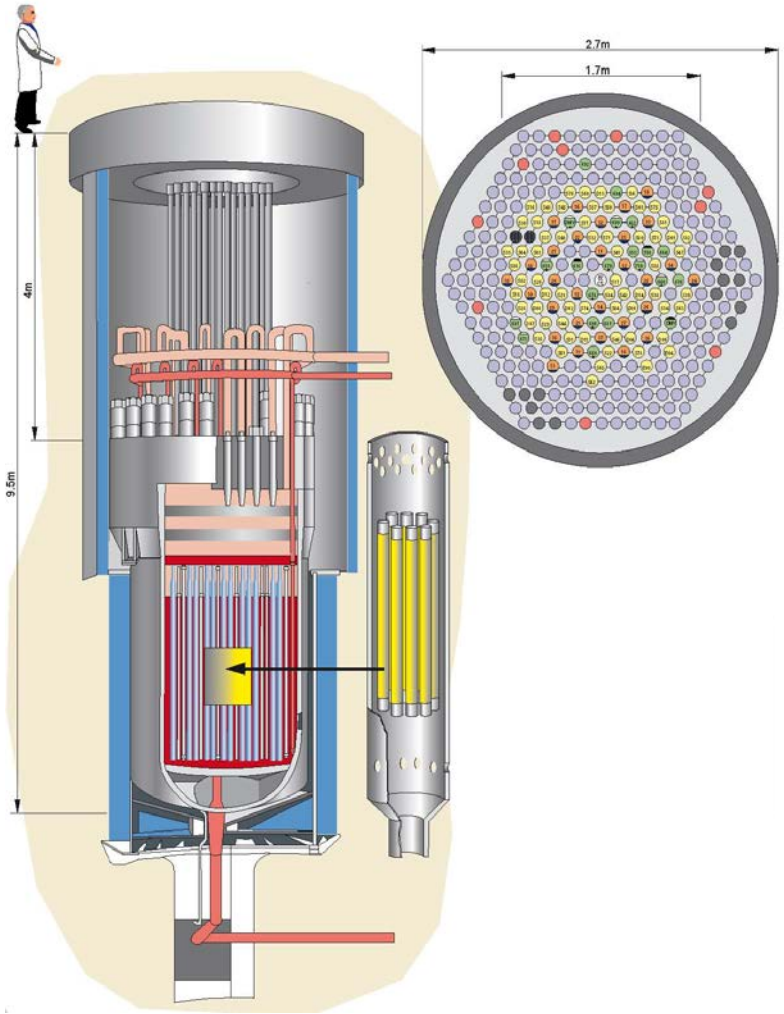
4) Overview fracture surface



- *Stress relaxation*
  - Temperature, flux, fluence
  - Alloy types

Summary of the Capabilities of the Halden Reactor

- Reactor operation dedicated to fuel and materials testing
- Reliable and versatile in-core instrumentation together with capability to implement different modes of operation
- Ability to simulate operation conditions of commercial NPPs with multiple loop systems
- Generation of directly applicable data for evaluation of performance, safety margins and safety criteria



The Halden Reactor is used for a broad spectrum of Fuels & Materials studies

FUEL		CLAD		Control Materials	Core Comp. Materials
Standard UO_2 *UO_2 + additives* *MOX, inert matrix*		*Zirconium alloys, new ATF claddings*		*B_4C*	*Stainless steels* *Nickel based alloys*
Fission gas release Fuel temperature - conductivity - stored energy Fuel densification Fuel swelling	Rod pressure, lift-off Gap conductance Axial gaps (clad collapse, power peaks) SCC/PCMI	Creep & Growth Failure Corrosion Crud, AOA	Guide tube bowing IRI Graphite	He release, pressure, swelling	Crack initiation & Time to failure Crack growth rate (IASCC) Mechanical prop. changes Embrittlement, annealing (RPV)

high burnup, operating conditions — *water chemistry*