Experimental needs for assessment and validation of new claddings

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Testing for qualifying new cladding materials

1. Out of reactor assessments
   a. Basic properties (cp, k, ρ) at various T conditions
   b. Mechanical properties, burst test vs. T
   c. Corrosion in water (air)
   d. High temperature behavior in steam

2. In-reactor material property assessments
   a. Stress corrosion cracking susceptibility
   b. Corrosion and irradiation growth
   c. Irradiation creep and stress relaxation

3. Rod behavior in normal operation
   a. Integrity of un-fuelled rods (for e.g. SiC qualification)
   b. Integrity of fuel rods, normal operation
   c. PCI/PCMI margin in power ramps

4. Integral rod behavior in transients
   a. DB LOCA
   b. BDB LOCA (Severe Accident scenarios)
   c. RIA transients

Previous experience

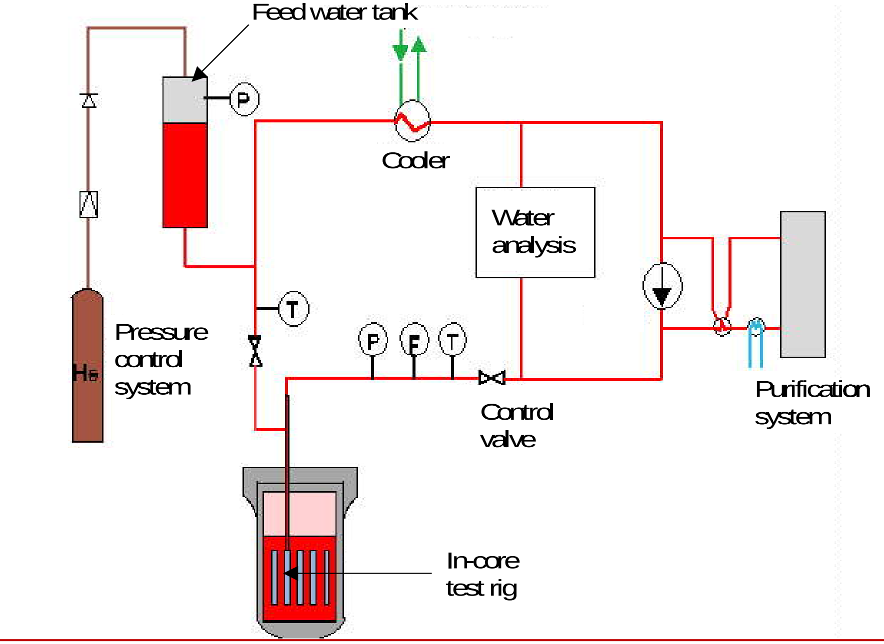
- The development of new accident tolerant fuel for LWRs is a long-term endeavor
- It will require a very extensive selection and validation process consisting of
  - Laboratory assessments
  - Out-of reactor testing
  - In-reactor testing
- Likely, the focus will be on new cladding materials, because the cladding is the weakest part in DB and BDB accident conditions
- This presentation outlines the types of testing that are likely to be required for cladding development, based on previous experience at Halden and elsewhere

Out of reactor assessments

a. Basic properties (cp, k, ρ) at various temperature conditions
b. Mechanical properties, burst test etc. at various temperatures
c. Corrosion in water (air) at representative T, P and water chemistry
d. High temperature behavior in steam

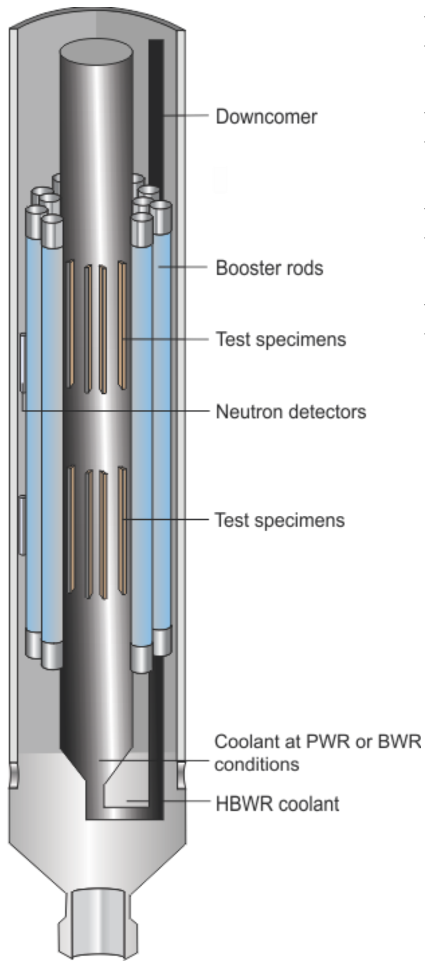
Corrosion and LOCA tests are done in autoclaves or in loops at given water chemistry conditions and at pre-determined temperature and pressure histories

Schematic of a loop for corrosion studies

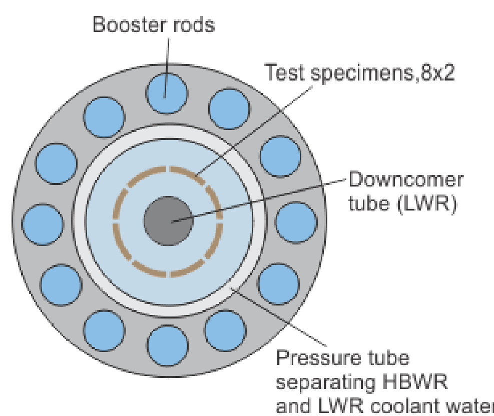


In-reactor corrosion and axial growth testing

Screening of different material variants



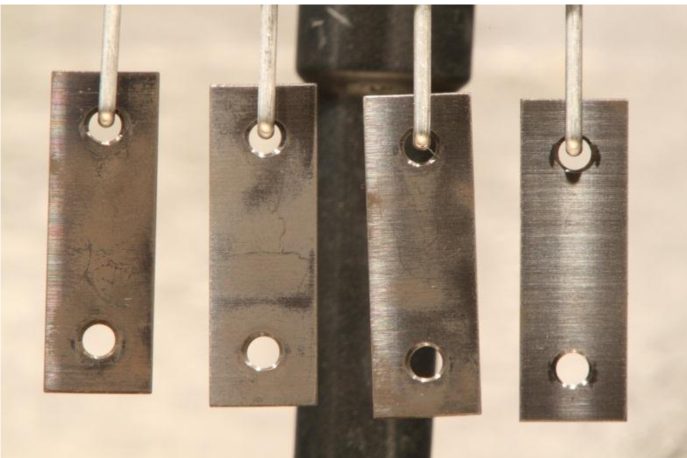
- Comparative, simultaneous testing of coupons with various material variants
- Representative LWR conditions, both for water chemistry and neutron flux
- Corrosion is assessed by weight change measurements carried out during outages
- Cladding growth is given by coupon length changes, also done during outages

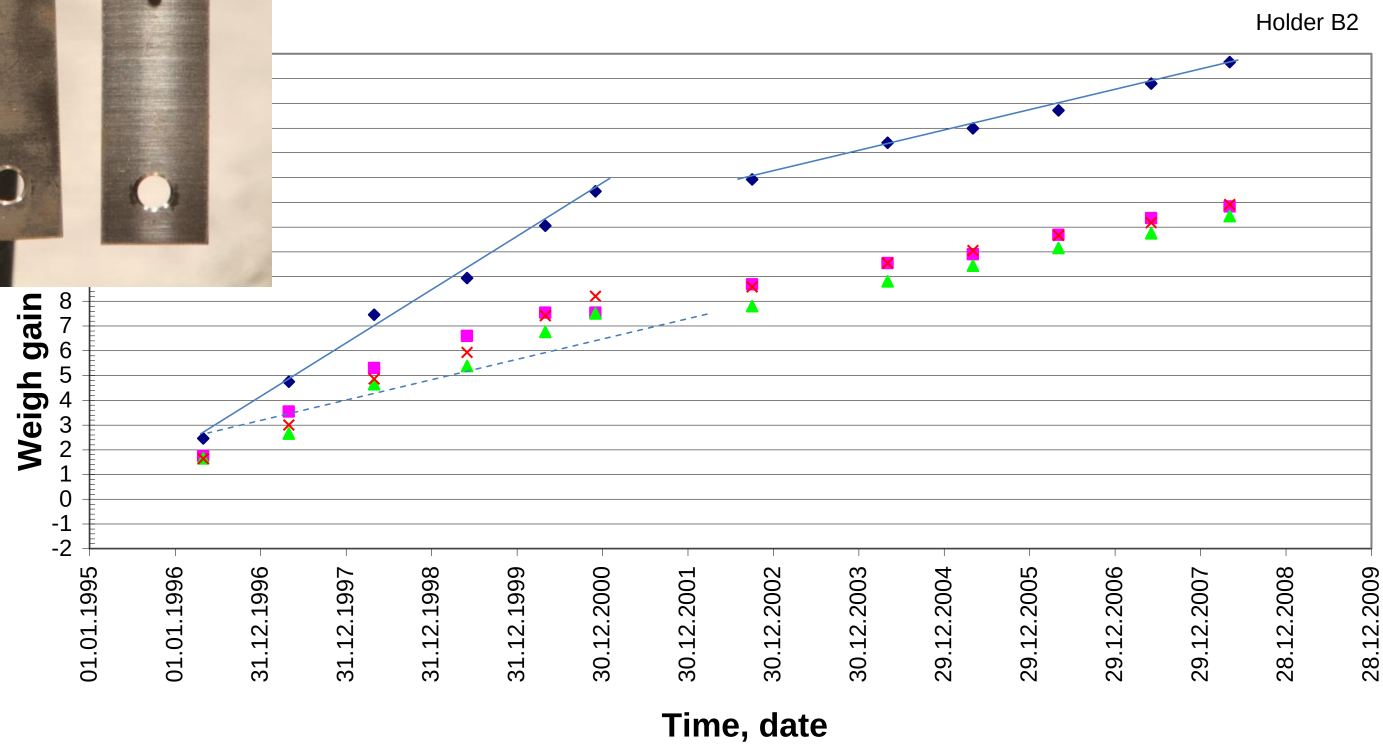


Cross Section

Example of corrosion assessment for 4 different Zr alloys

Weight gain data vs. time

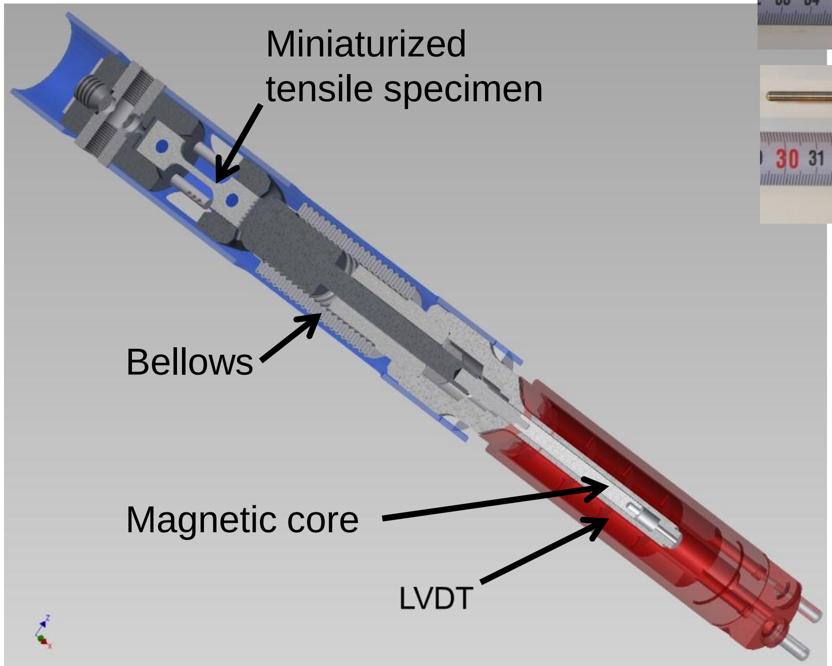




Test unit for in-reactor mechanical property assessment

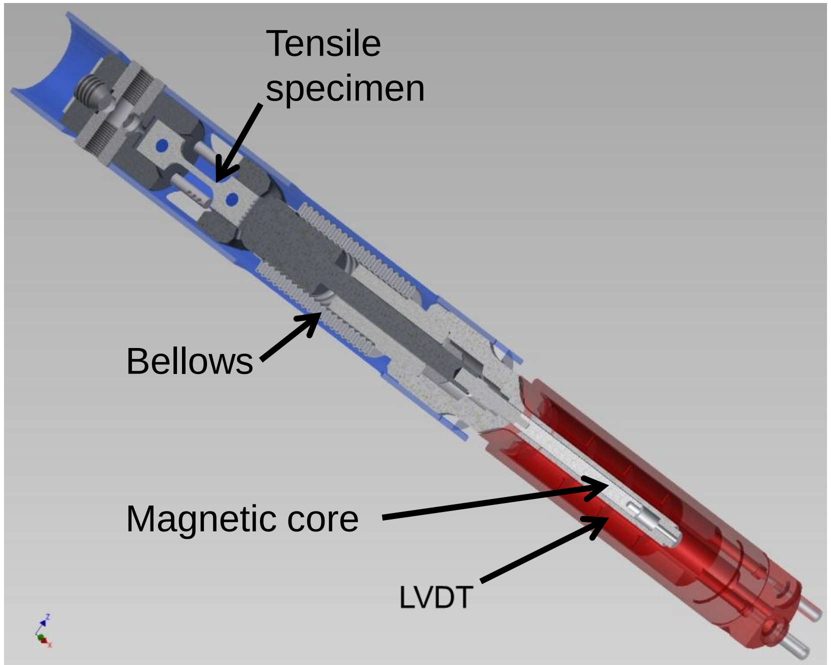
Can be used for:

- Stress corrosion cracking assessment
- Irradiation creep database
- Stress relaxation database



- Many of these test units can be loaded in the same rig, hence enabling simultaneous testing of various materials / conditions.
- Example of mechanical property assessments performed with this equipment are given in the following

Creep and stress relaxation under irradiation
Irradiation test unit



- Many miniaturized test specimens (of the type shown in the figure) are assembled in one test rig for repeatability and for comparative testing

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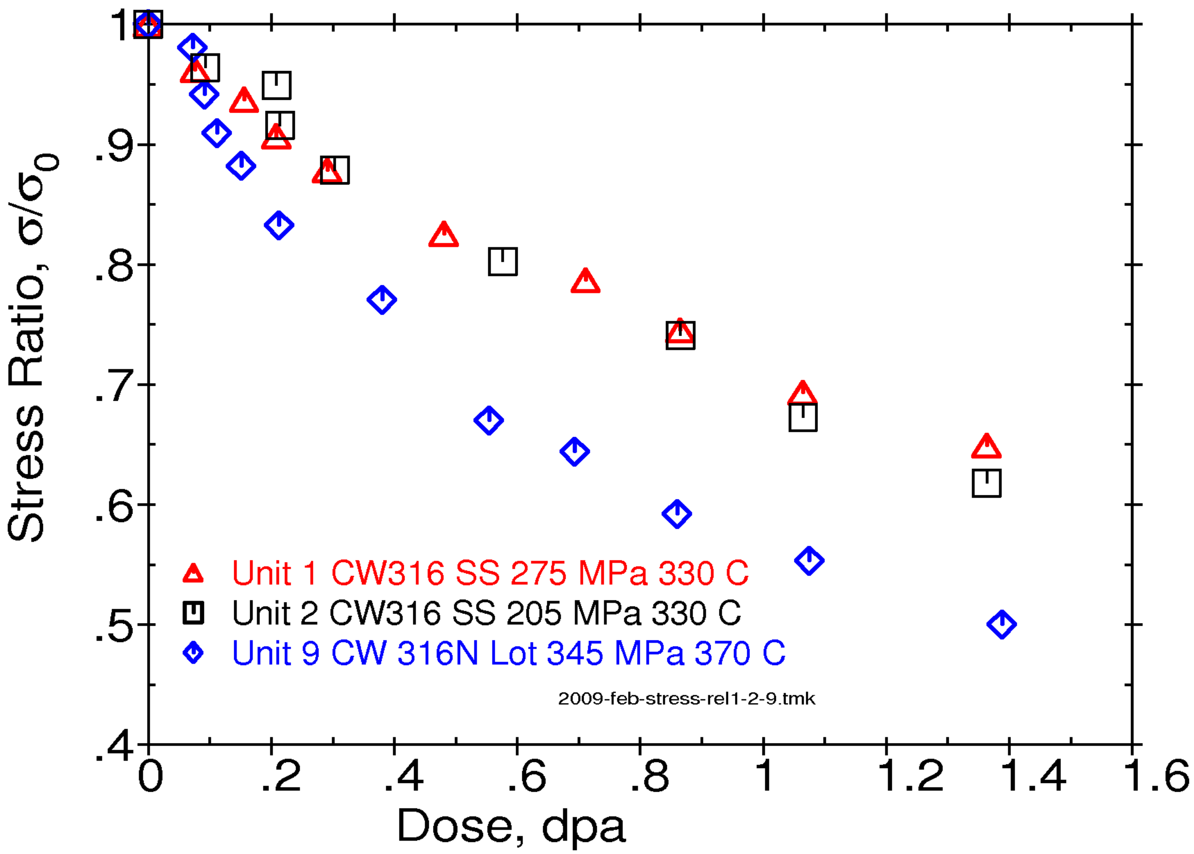
- Constant stress for determination of irradiation creep
- Constant total strain for determination of stress relaxation

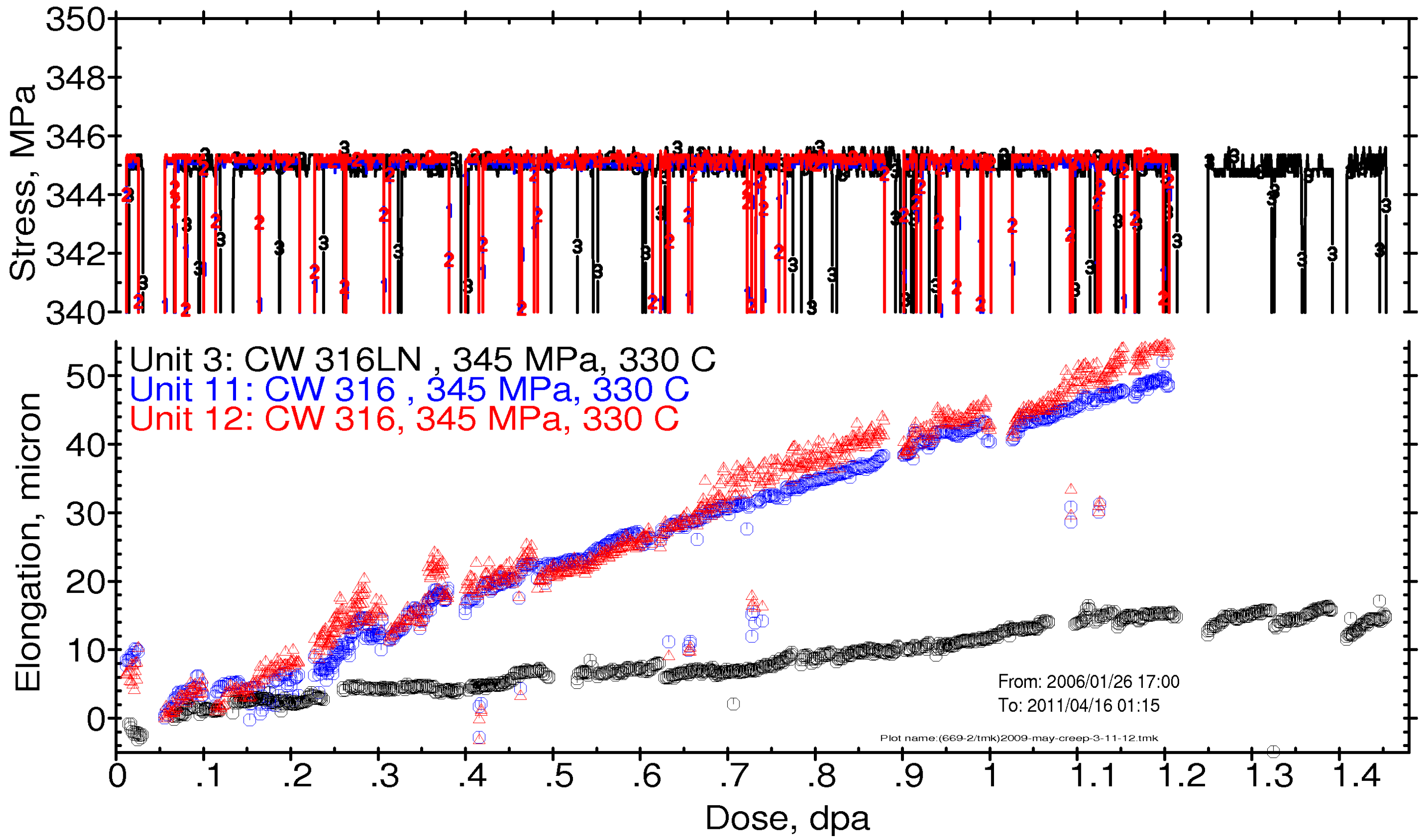
Example of stress relaxation assessment for 3 different SS alloys

Stress ratio data vs. fast neutron dose

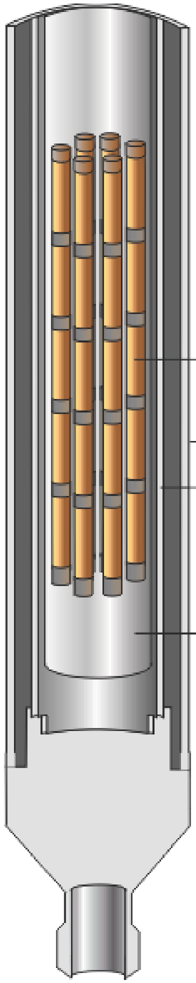


Example of irradiation creep assessment for 3 different SS alloys

Strain (elongation) data vs. dose

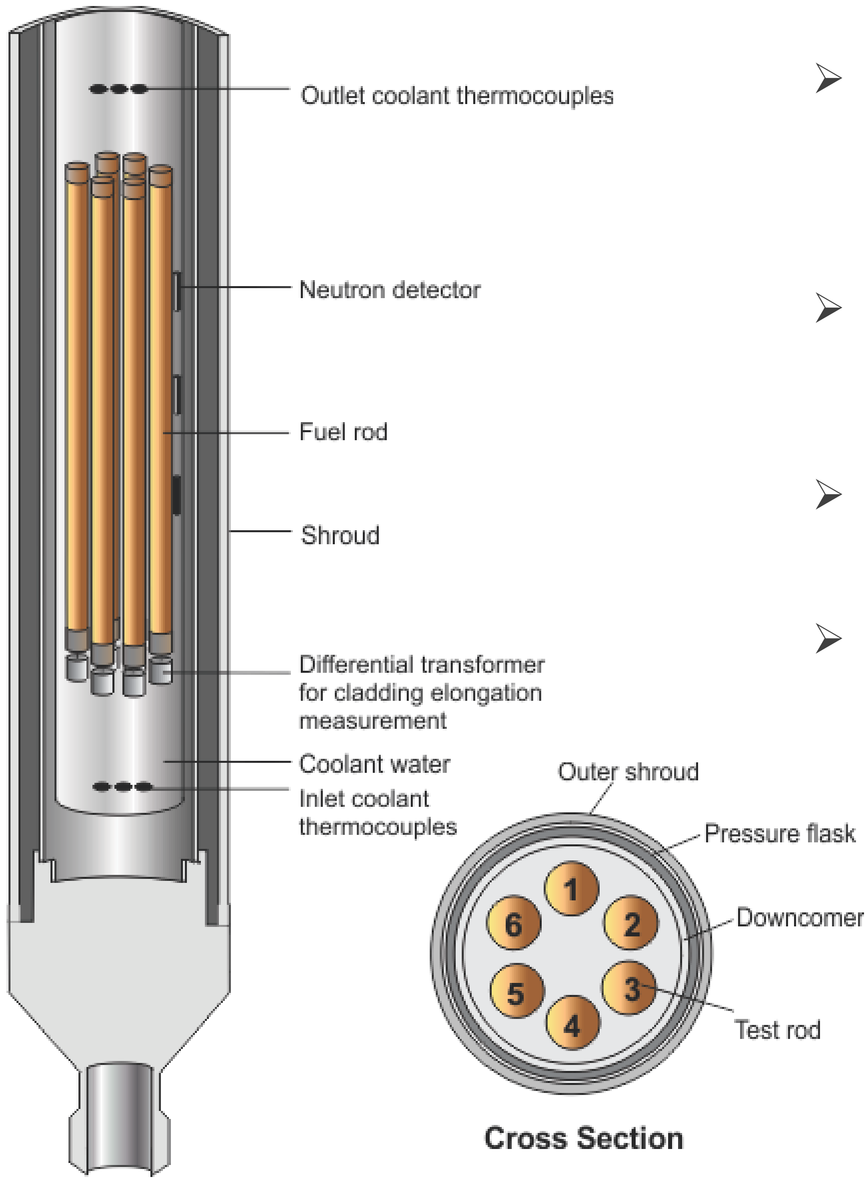


Rod assessments: Integrity of un-fuelled rods



- Irradiation of un-fuelled test rods can be a first step for the qualifi-cation of quite new cladding types
- Many rod segments can be tested at the same time enabling to:
  - Compare different claddings
  - Assess end-plug/ weld integrity
- The irradiation is carried out at prototypical LWR temperature, pressure and (where needed) water chemistry
- Rod loss of integrity is determined during outages (or possibly on-line)
- Other properties such as creep-down or corrosion can be determined in inspections or PIE

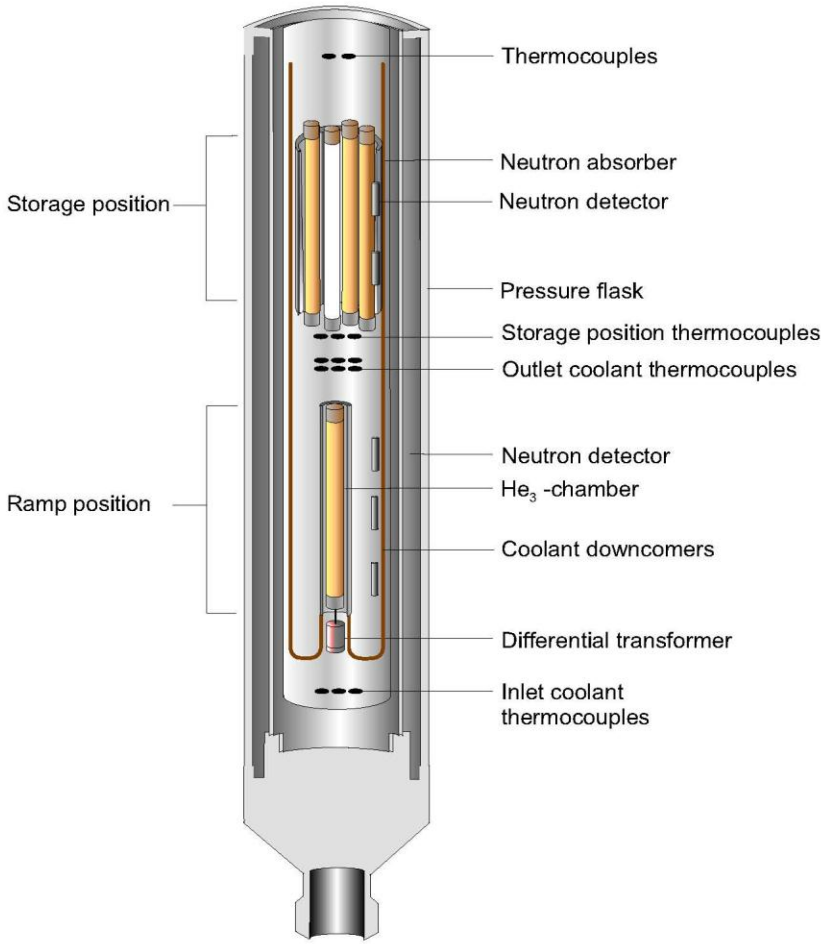
Integrity of fuel rods at base irradiation conditions



- Several fuel rods can be tested at the same time, hence enabling to compare different fuel rod variants, such as cladding type, fuel pellet type, pellet-cladding gap etc.
- On-line instrumentation provides relevant information on the fuel rod performance, e.g. on PCMI and rod integrity (and also FGR if needed)
- Additional information on other performance aspects can be obtained from PIE (dimensional & corrosion)
- The irradiation is carried out at constant power and can last for a long time (one or more years). After that, one or some of these rods can be a subjected to special testing, e.g. power ramp or even LOCA.

Integrity of fuel rods in power ramp conditions

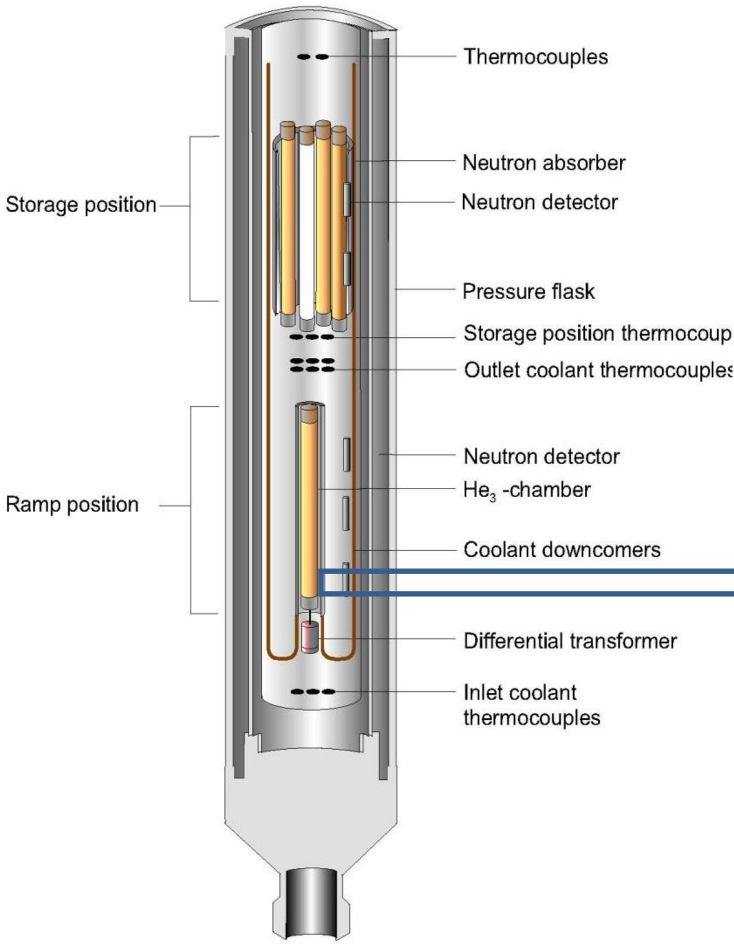
Assessment of PCI and PCMI margin

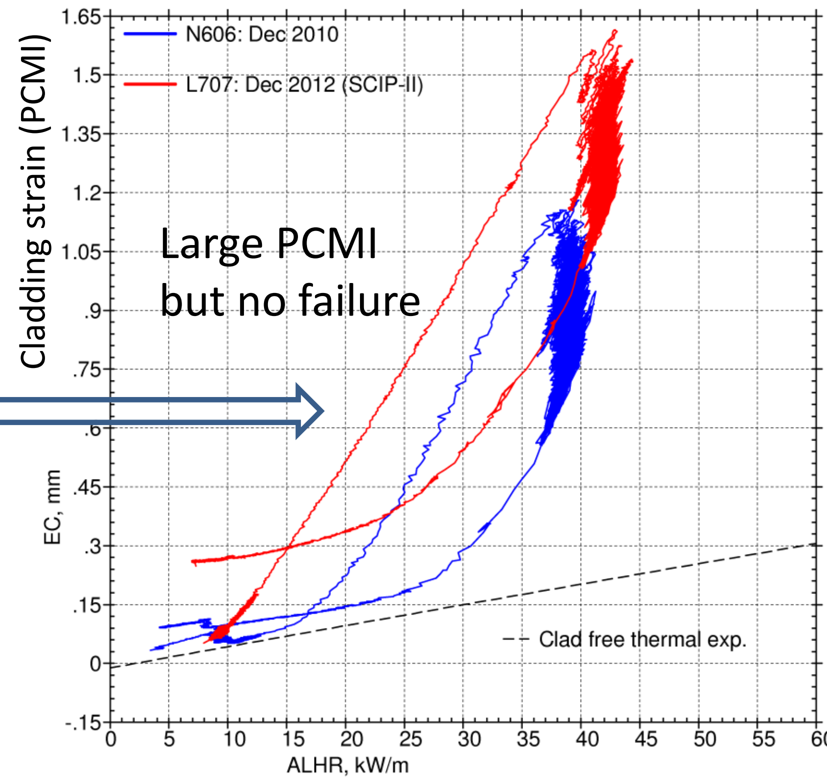


- A power ramp consists of a rapid and large power increment, e.g. 30kW/m in 1 minute
- Power ramps are currently used as standard test for assessing PCI/PCMI fuel margins.
- The Halden rig has four fuel rod storage positions in low-flux zone at the upper part of ramp rig (shielded).
  One fuel rod in ramp position.
- The rods can be 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
- The ramp rig contains instrumentation for failure detection (cladding elongation detector) and for monitoring environmental parameters (neutron / gamma flux and coolant temperatures)

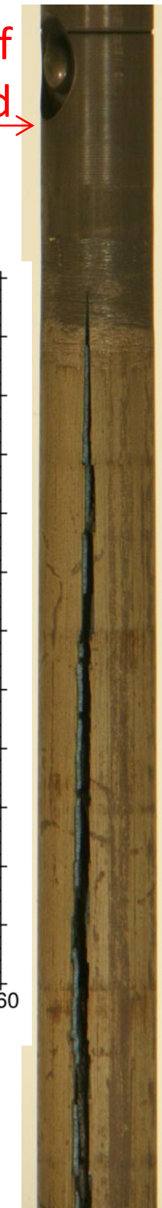
Integrity of fuel rods in power ramp conditions

Assessment of PCI and PCMI margin



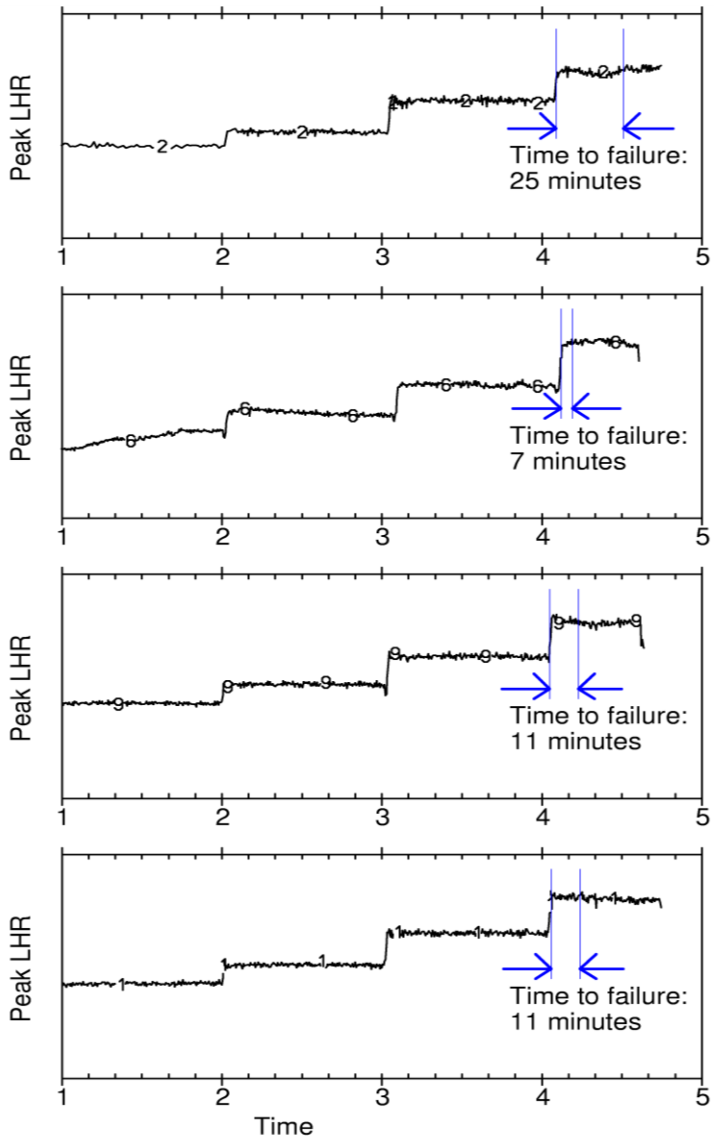


Example of
failed rod



Integrity of fuel rods in power ramp conditions

Assessment of PCI and PCMI margin



Past experience: Repeatability

Test-1: 1 STD rod, 2 additive fuel rods

- The STD rod failed after 25 minutes
- The two additive fuel rods survived

Test-2: 1 STD rod, 2 additive fuel rods

- The STD rod failed after 7 minutes
- The two additive fuel rods survived

Test-3: 1 STD rod, 2 additive fuel rods

- The STD rod failed after 11 minutes
- The two additive fuel rods survived

Test-4: 1 STD rod, 2 additive fuel rods

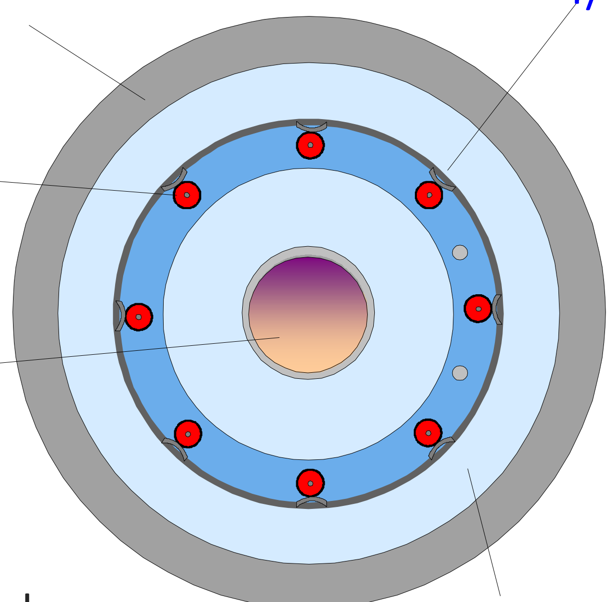
- The STD rod failed after 11 minutes
- The two additive fuel rods survived

Simulation of LOCA

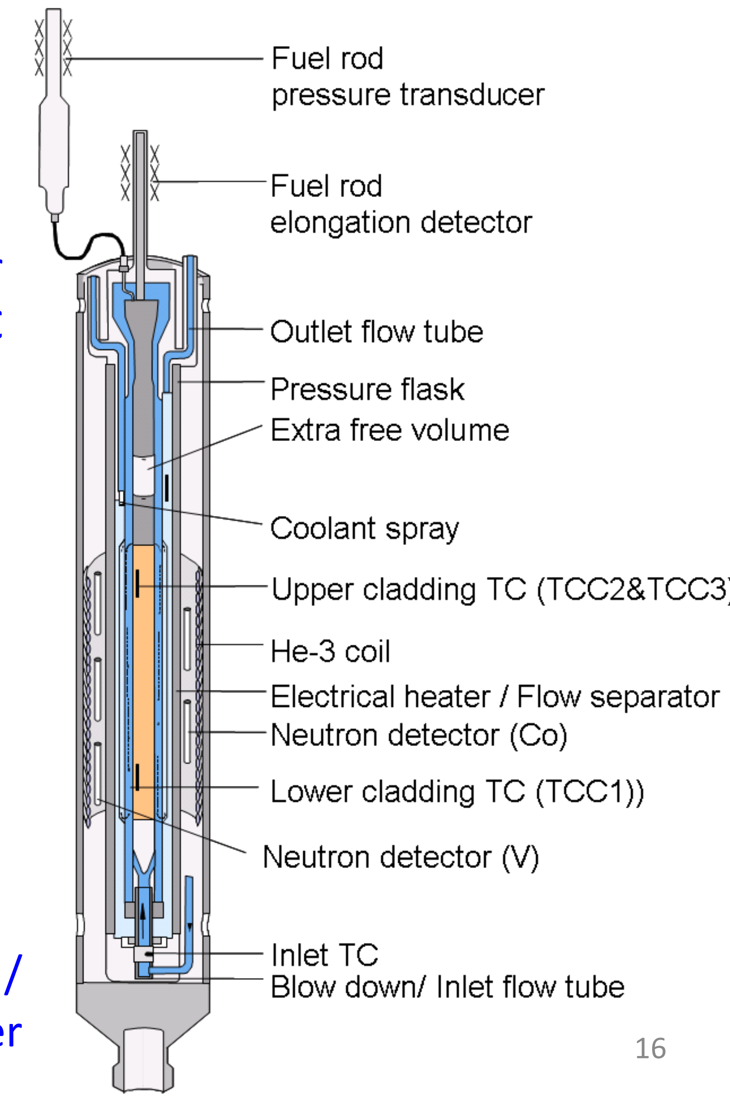
- May come at the end of the validation process
- Can be done in-or out of pile

Features of the Halden in-pile LOCA rig

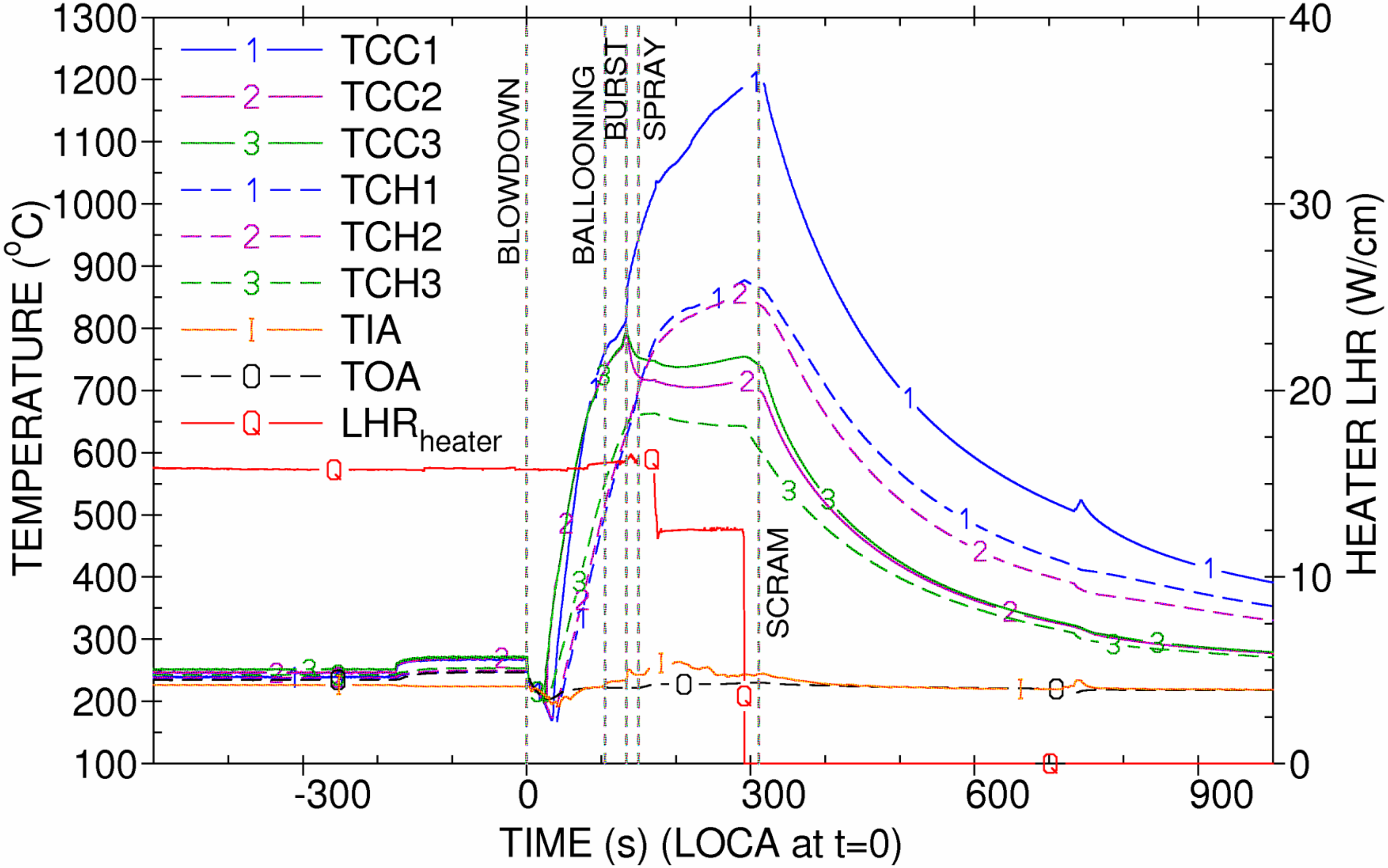
- Single rod experiment using high burn-up fuel
- Heating provided from within the rod by low level of nuclear power simulating decay heat



- 3 cladding TCs
- 3 heater TCs
- Fuel pressure transducer
- Cladding elongation detector



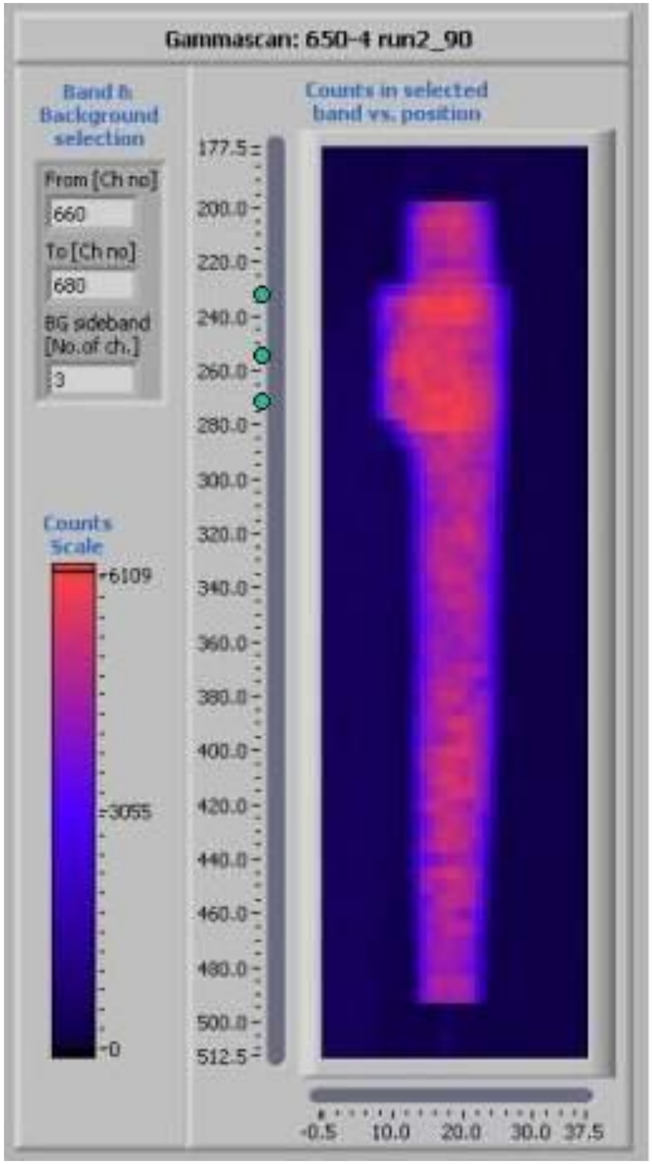
LOCA tests at Halden
Example of temperature measurements (Test 9)

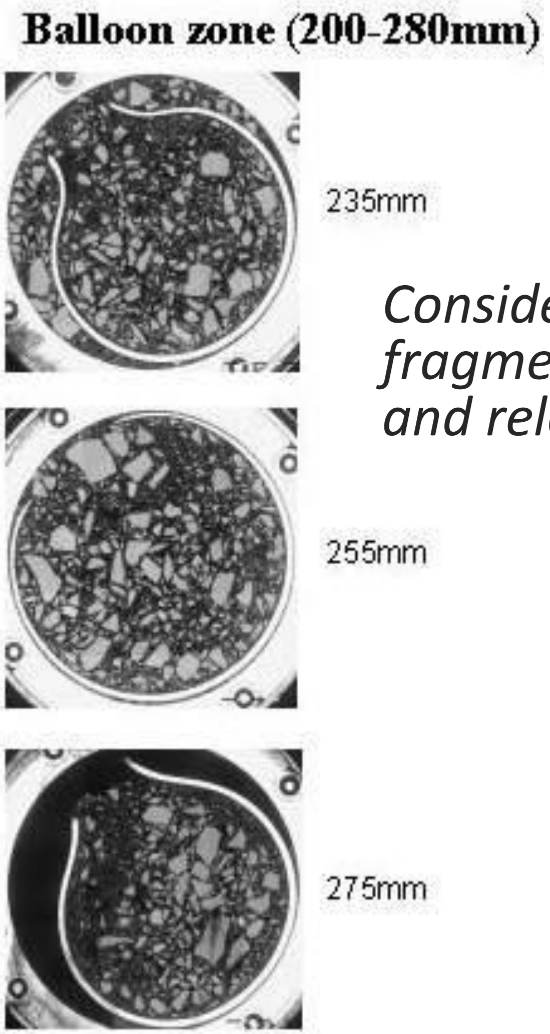


Hilary/Kolstad 56

Halden LOCA Test 4

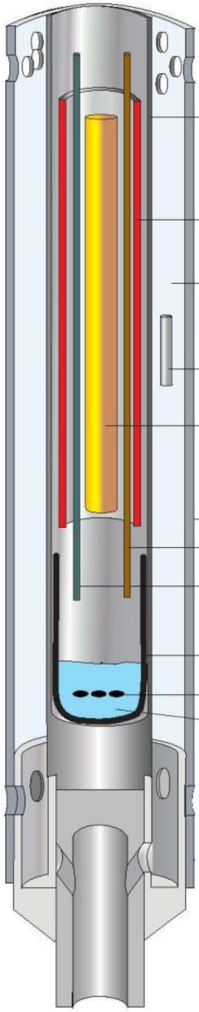
Large ballooning, extensive fuel fragmentation and ejection





Considerable fuel fragmentation and relocation

Beyond Design Base LOCA: Possible Test Goals



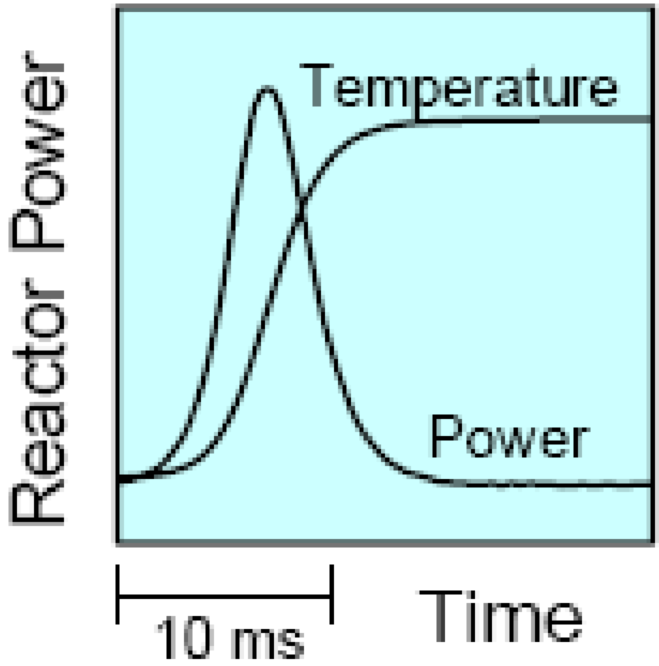
Beyond-LOCA studies

- ❑ Accident progression
  - Single rod
  - Temperature beyond 1200 ^{o}C
  - Different environment (air, steam, mixed)
  - Valuable instrumentation to feasible extent

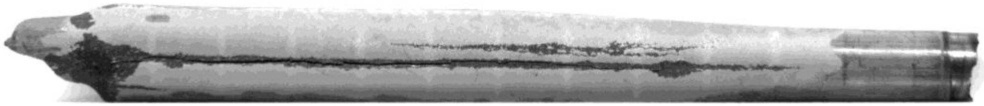
  - What happens to the fuel?
  - Until what stage it maintains its geometry?
  - How does the debris look like? Is it coolable?
  - Do we have H-release or other types of high temperature issues?
- ❑ Source term (including short-lived)

RIA transients

- For new fuels, RIA tests may be required at some point in time.
- These tests are run in specialized reactors, such as NSRR in Japan (see photo)
- Out-of-pile RIA simulations may also be carried out



NSRR pulse reactor for RIA tests



Example of RIA-failed rod

Summary

- The development of new accident tolerant fuel for LWRs is a long-term endeavor
- It will require a very extensive selection and validation process consisting of
  - Laboratory assessments
  - Out-of reactor testing
  - In-reactor testing
- Likely, the focus will be on new cladding, because the cladding is the “weakest” part in accident conditions
- The presentation summarized the types of in-reactor testing that are likely to be required in ATF developments, based on previous experience and addressing:
  - Material property assessment
  - Integrity in normal operation conditions
  - Behavior in accident conditions

Thank you