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Test facilities and on-line instrumentation capabilities for core component materials investigations at the Halden Reactor Project

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Outline of Presentation

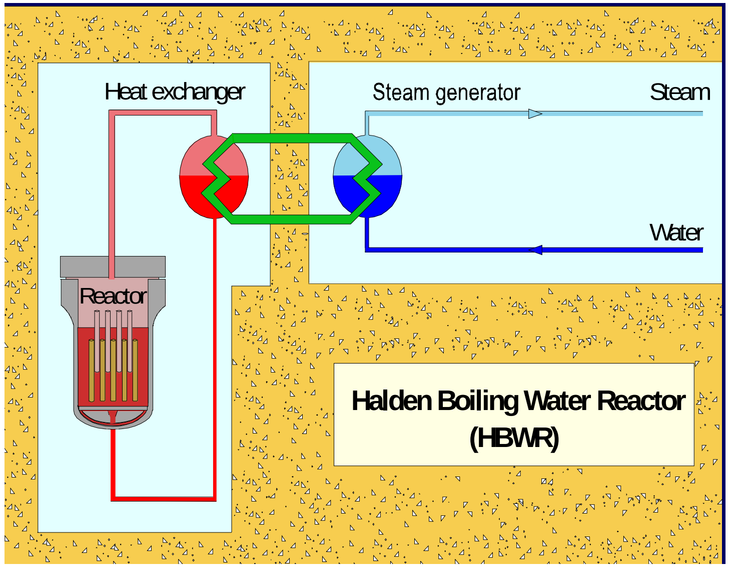
- Background
  - OECD Halden Reactor Project
  - Halden Boiling Water Reactor (HBWR)
- Studies on core component materials
  - Instrumentation techniques
  - Examples of results

OECD Halden Reactor Project

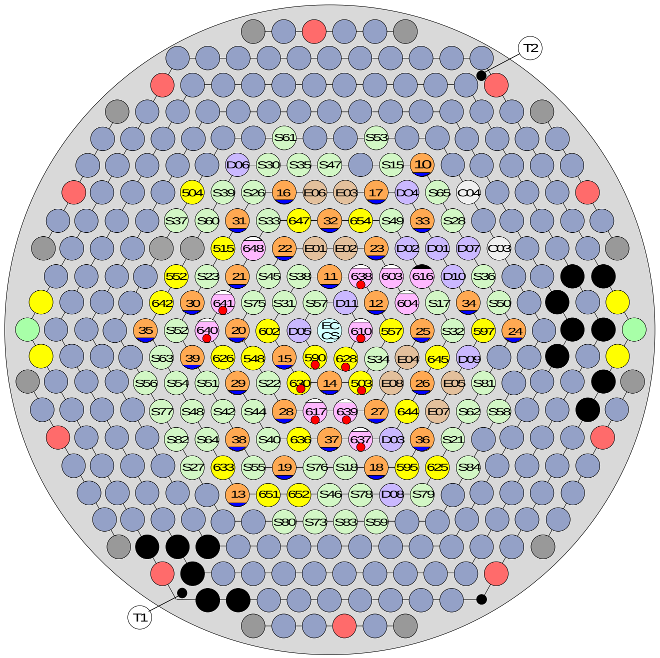
- Established 1958
- International co-operative effort
  - under auspices of OECD-NEA
  - aim to improve safety & economy for operation & design of NPPs
- Jointly funded by 18 member countries
  - more than 100 organisations
  - utilities, vendors, licensing authorities, R&D centers
- 3 year program periods
  - current period 2003-2005
- Finances experimental safety programmes
  - HBWR, HAMMLAB, VR-Lab

The Halden Boiling Water Reactor (HBWR)

Power: 20 MW_{th}
Operating conditions:
235 °C and 34 bar
Moderator/coolant:
D_2O (natural circulation)
Fuel: UO_2
Power adjustment: Ag/Cd
control rods (30)
Reactor operation:
2 ~100-day cycles/year



HBWR contd

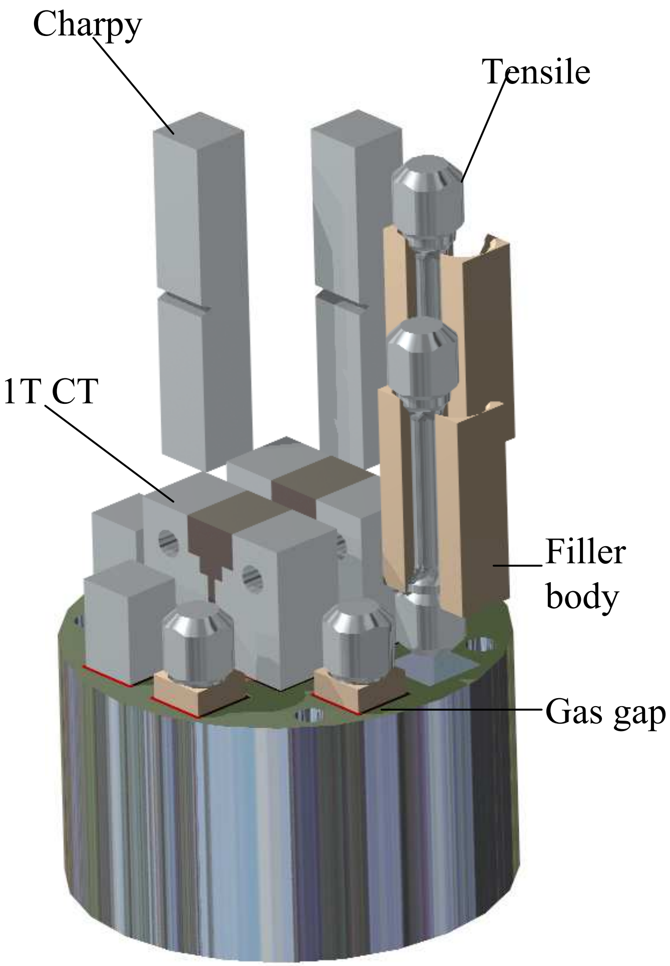


- More than 300 positions individually accessible
- ~110 positions in central core
- ~30 positions for experimental purposes (any of 110/300)
- Height of active core 80cm
- Usable length within moderator ~160cm
- Experimental channel Ø:
  - 70mm in HBWR moderator
  - 35-45mm in pressure flask

Studies on Core Component Materials

- Crack growth rate
- Crack initiation
- Stress relaxation / creep
- (Studies on RPV materials)

Studies on Core Component Materials



- Dry irradiation (inert atmosphere, tailored temperature & fast flux environments)
- Fast neutron flux: ~$5x10^{12}$ n/cm^{2}s to $7x10^{13}$ n/cm^{2}s (> 1 MeV)
- Irradiation of RPV or core component materials; subsequent testing out-of-pile
- 1T-CT, 0.5T CT, Charpy & tensile specimens; SSRTs and 0.25T CTs

Studies on Core Component Materials

Experimental Facilities contd

- Representative PWR or BWR conditions

(coolant chemistry, radiation, thermal hydraulics)

- 11 loop systems in operation

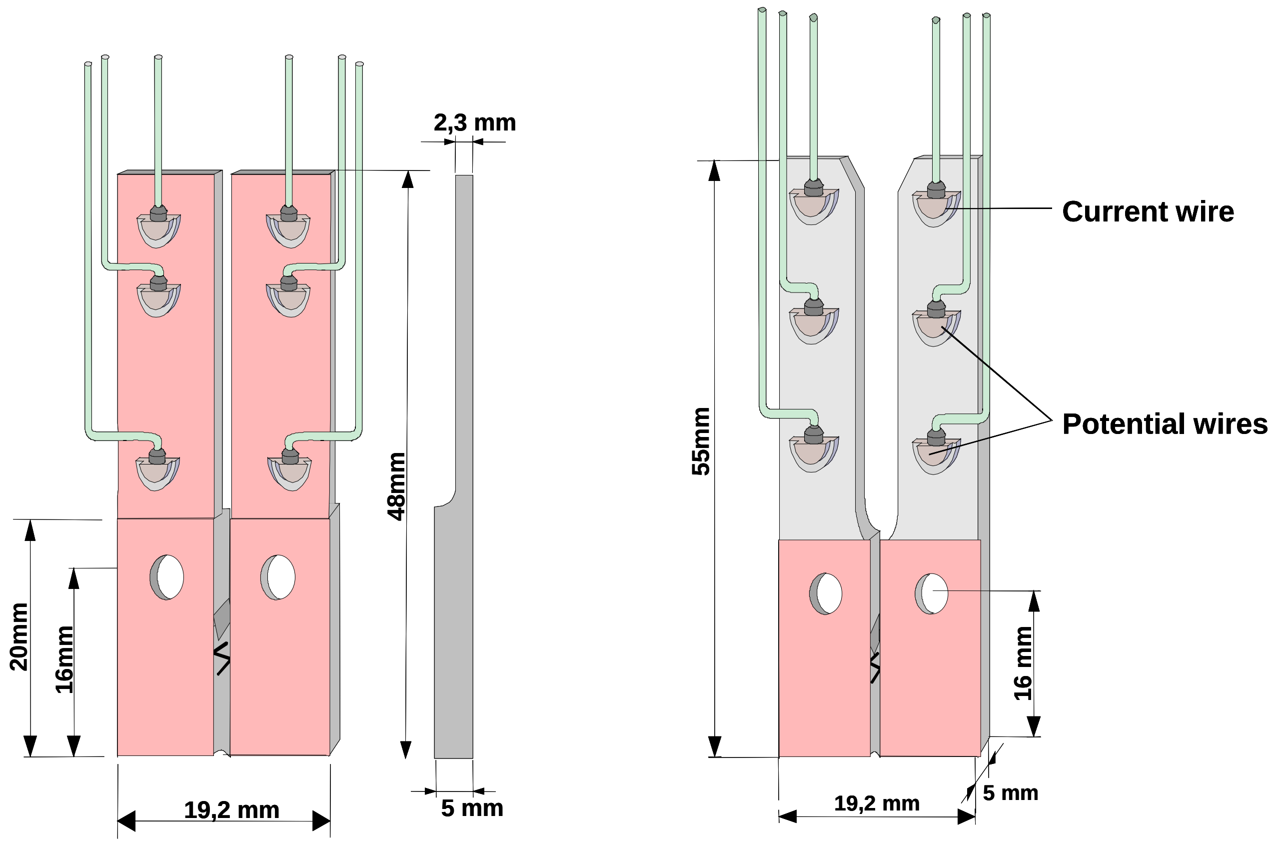
- On-line monitoring of specimen performance

  (crack growth rates, crack initiation, stress relaxation, creep)

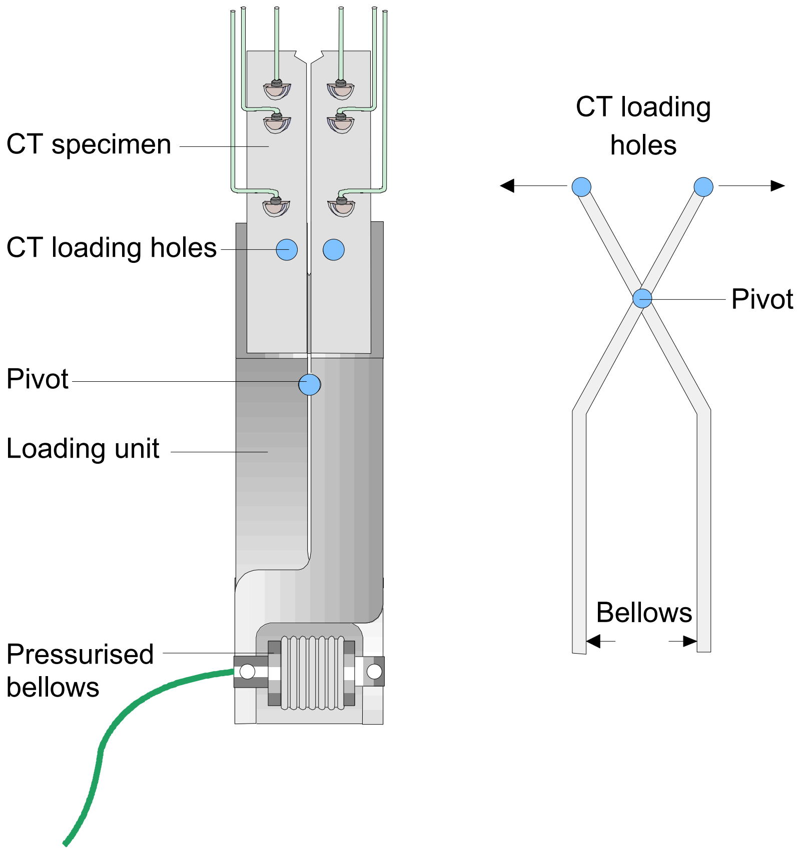
Irradiation Assisted Stress Corrosion Cracking (IASCC) Studies

- Address IASCC susceptibility of components in BWRs and PWRs
- Generation of practical data for representative core materials as a function of temperature, corrosion potential, stress intensity, fluence (RIS, radiation hardening)
- Assess benefits of countermeasures (e.g. H_2 in BWRs)
- Test specimens prepared from materials from commercial plants (fluences 7×10^{19} to 2.5×10^{22} n/cm^2 (> 1 MeV))
- Crack growth rate and crack initiation studies
- Essential features: representative environments, active loading and on-line monitoring

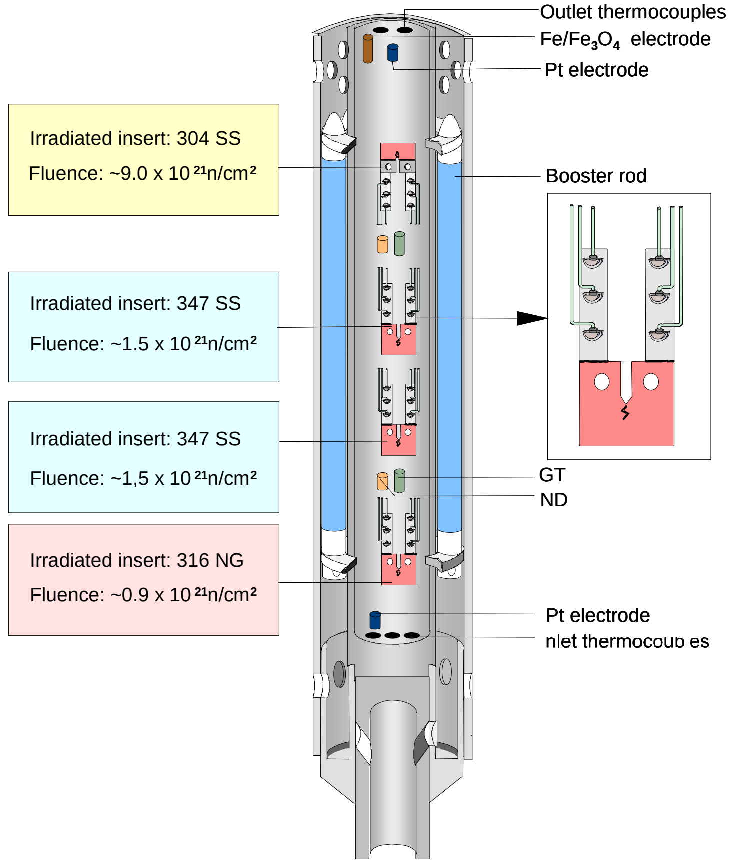
Compact Tension (CT) Specimen Geometries for crack growth rate studies. Crack propagation measured using dc potential drop method



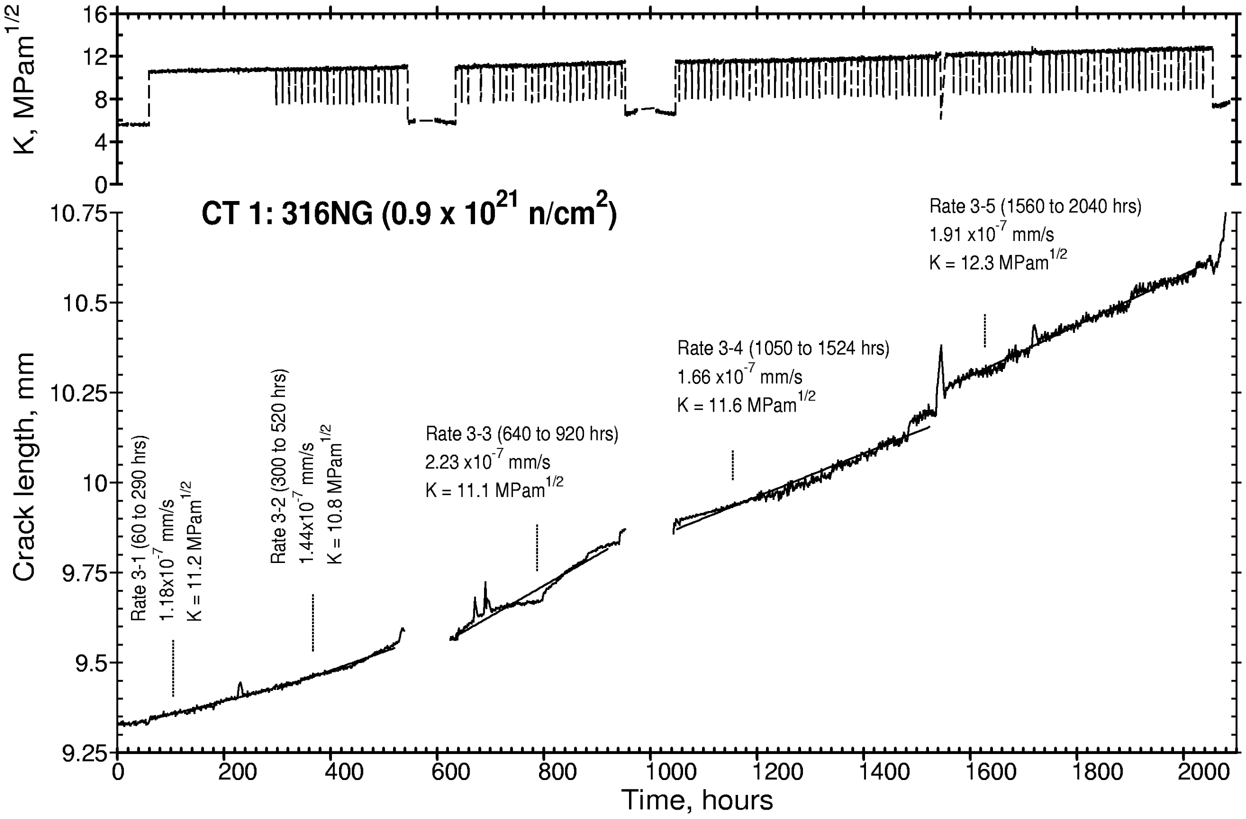
Specimen loading: pressurised bellows



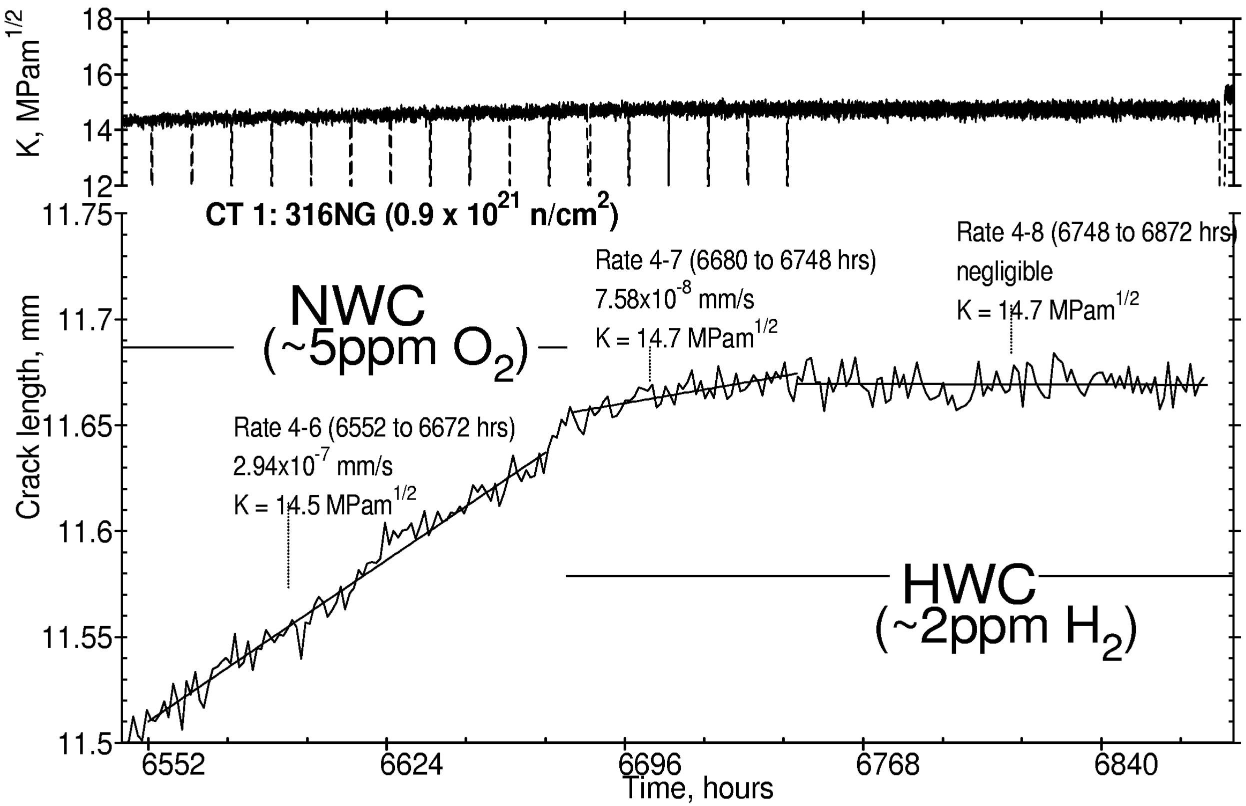
In-core test assembly



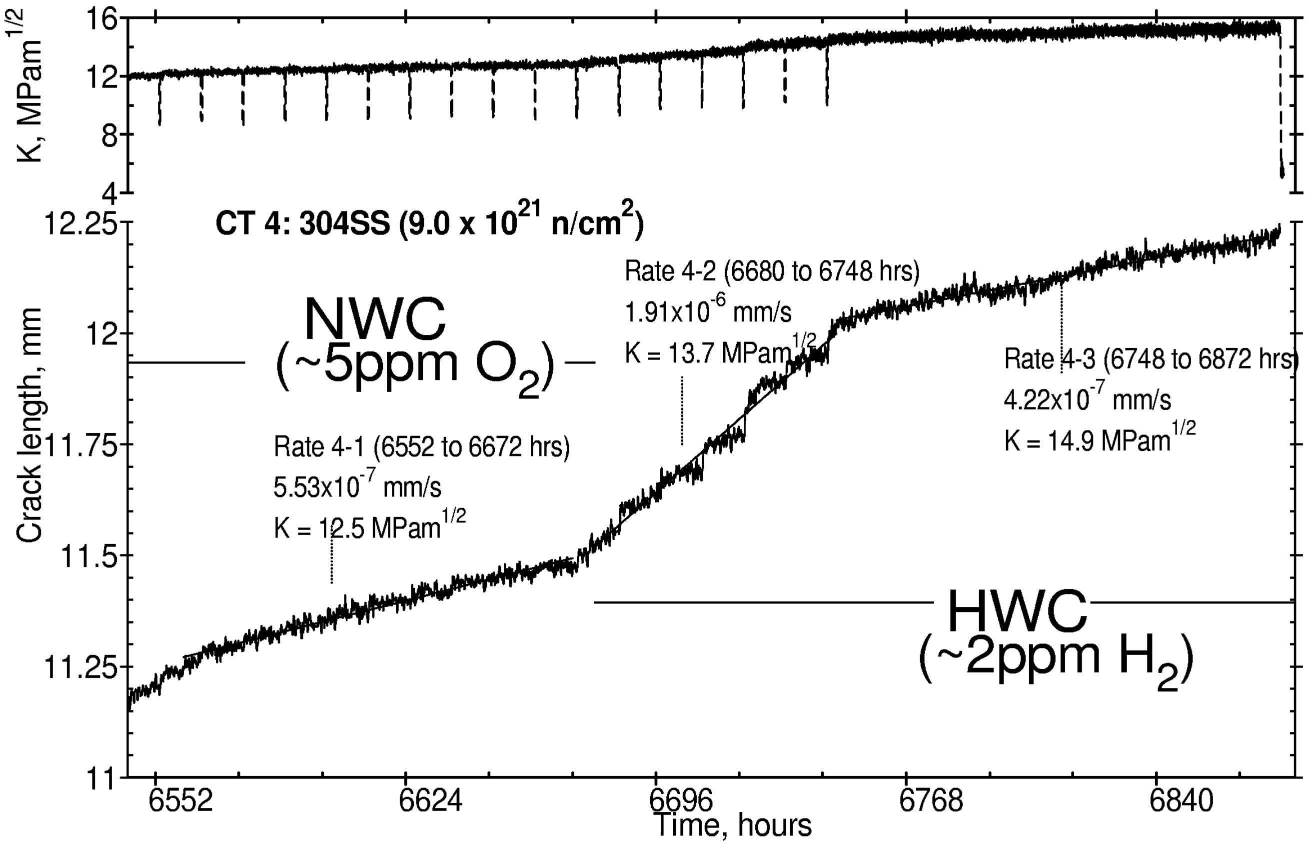
Example of long-term, in-pile crack growth data for irradiated CT specimen in BWR oxidising conditions



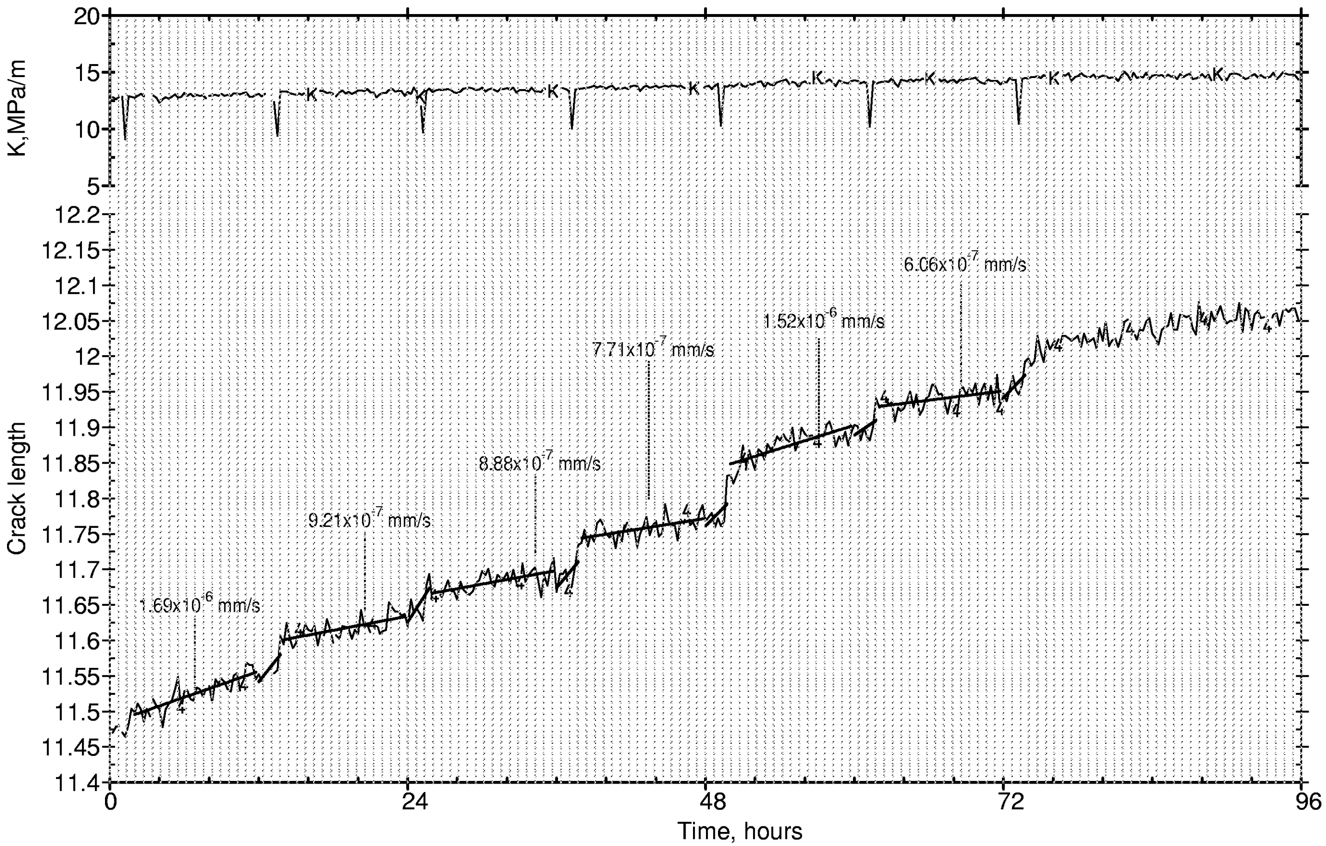
Response of low fluence CT to the addition of H_2. A clear reduction in growth rate is evident.



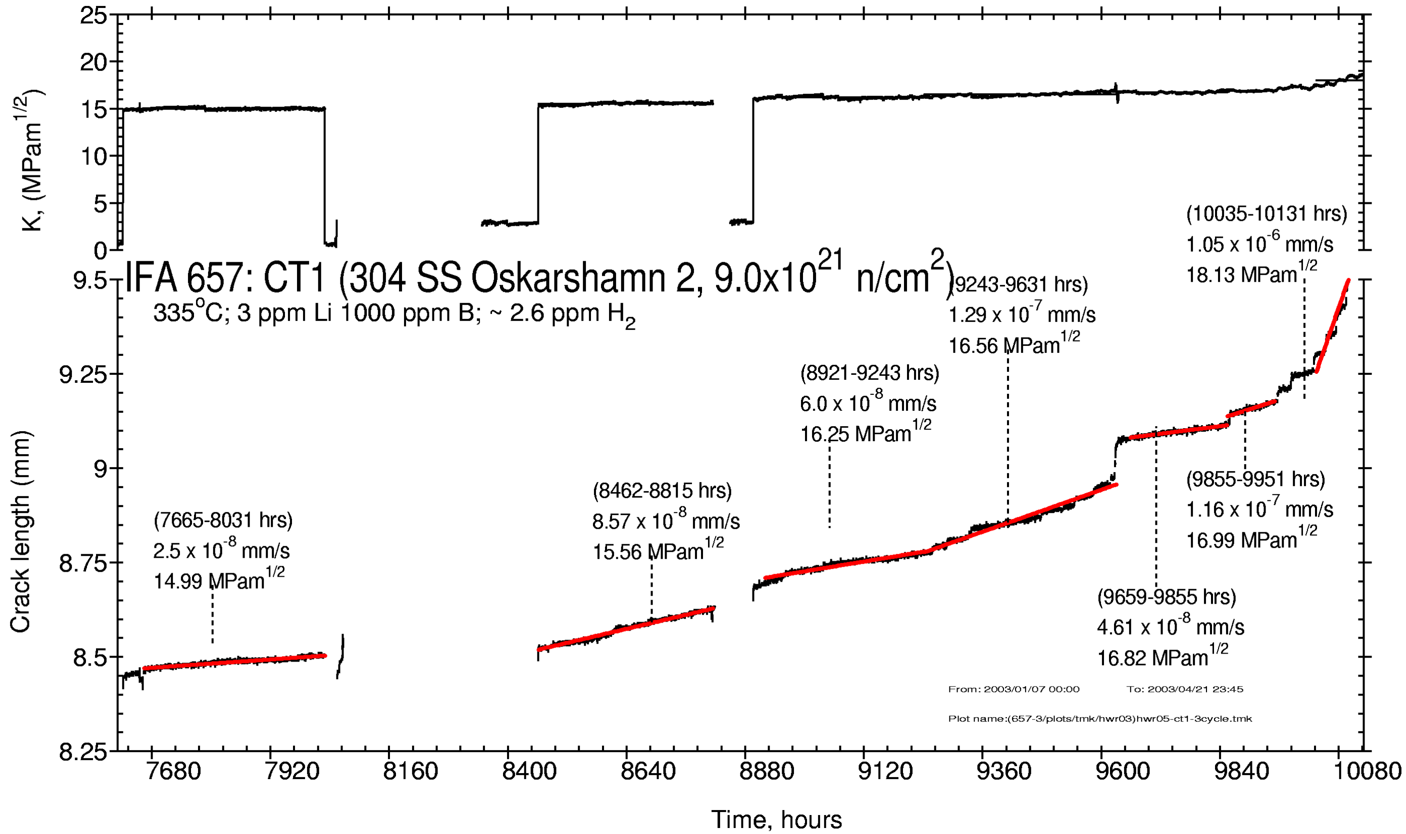
Response of high fluence CT to the addition of H_2. No significant change in growth rate is recorded.



Step-like increments in crack length associated with unloading cycles for high fluence CT

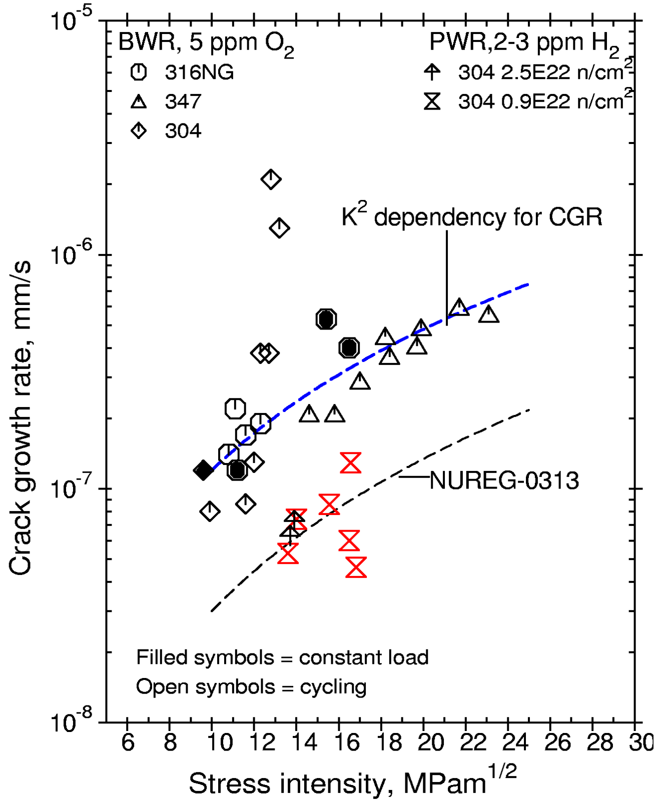


Example of long-term, in-pile crack growth data for irradiated CT specimen in PWR conditions



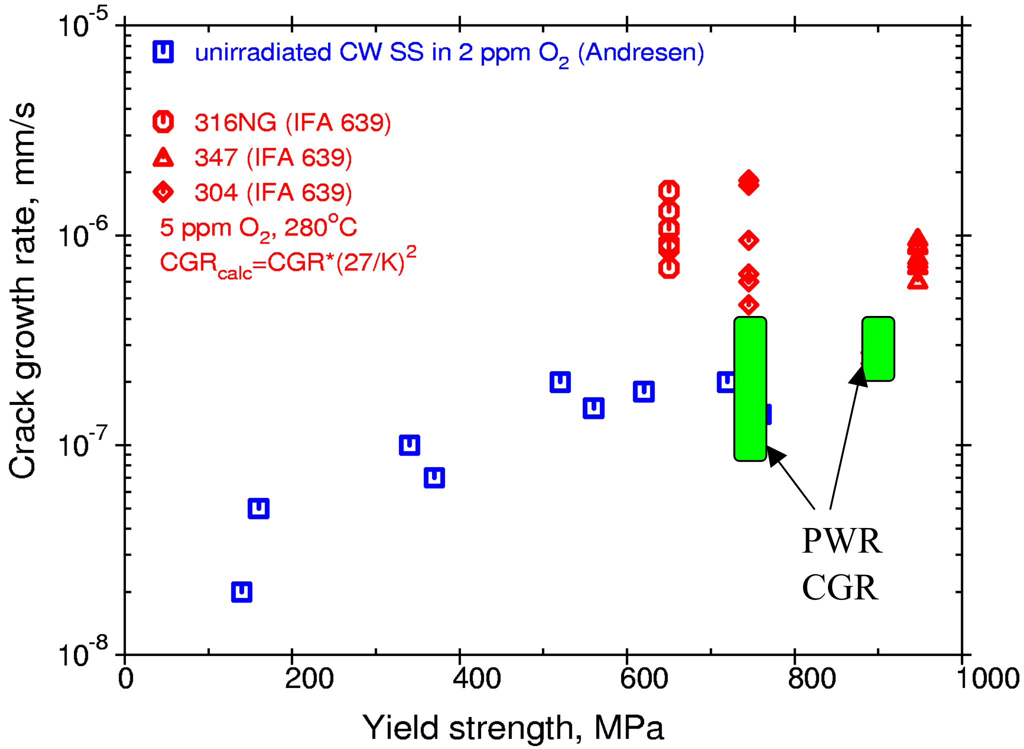
Summary of some in-pile crack growth data for irradiated CT specimens in BWR oxidizing conditions and in PWR conditions

- Comparison with NUREG-0313 (unirradiated sensitised SS)
- In O_2 , CGR measured on irradiated CTs ~4-5x higher than NUREG-0313 (comined effect of ↑ YS & RIS)
- In H_2 (PWR primary water) CGRs measured on irradiated CTs similar to NUREG-0313 (effect of ↑ YS)



Effect of increasing yield strength on CGR

Growth rates at high potential (BWR O_2) and low potential (PWR) consistent with yield strength effect



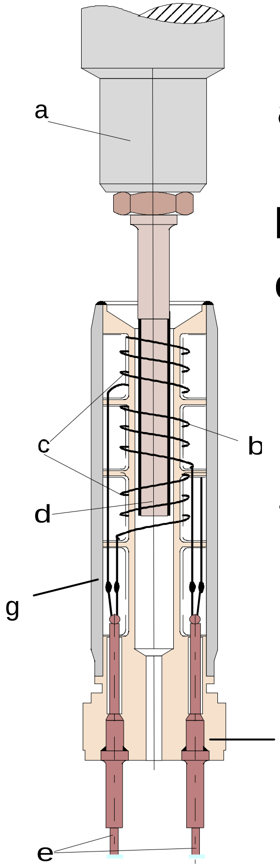
Crack initiation studies

- Use of pressurised tube specimens
– Effects of material, stress + fluence on susceptibility to crack initiation

- Use of tensile specimens for integrated time-to-failure (crack initiation, propagation, final failure) test
– Effects of water chemistry on susceptibility to crack initiation

- Both investigations with on-line instrumentation (LVDTs)

Linear Variable Differential Transformer (LVDT)



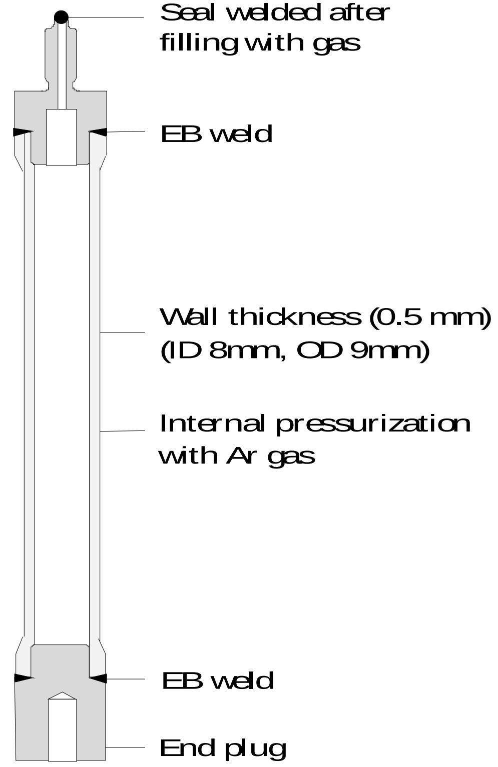
a: End plug assembly
b: Primary coil
c: Secondary coils
d: Ferritic core
e: Twin-lead signal cables
f: Body
g: Housing

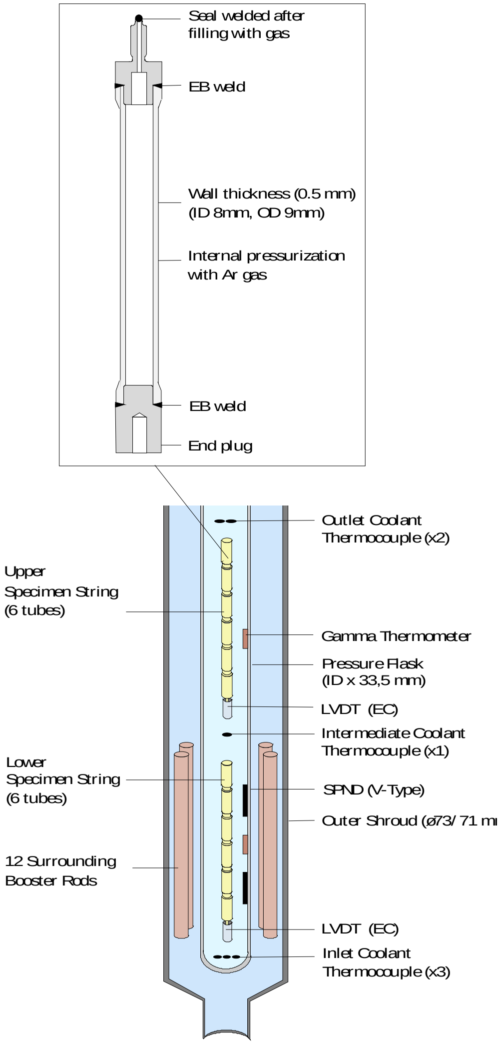
- Primary coil with two secondary coils connected in opposition. Movable magnetic core concentrically located inside coil system.

- Core movement affects the balance of the secondary coils and generates the signal output.

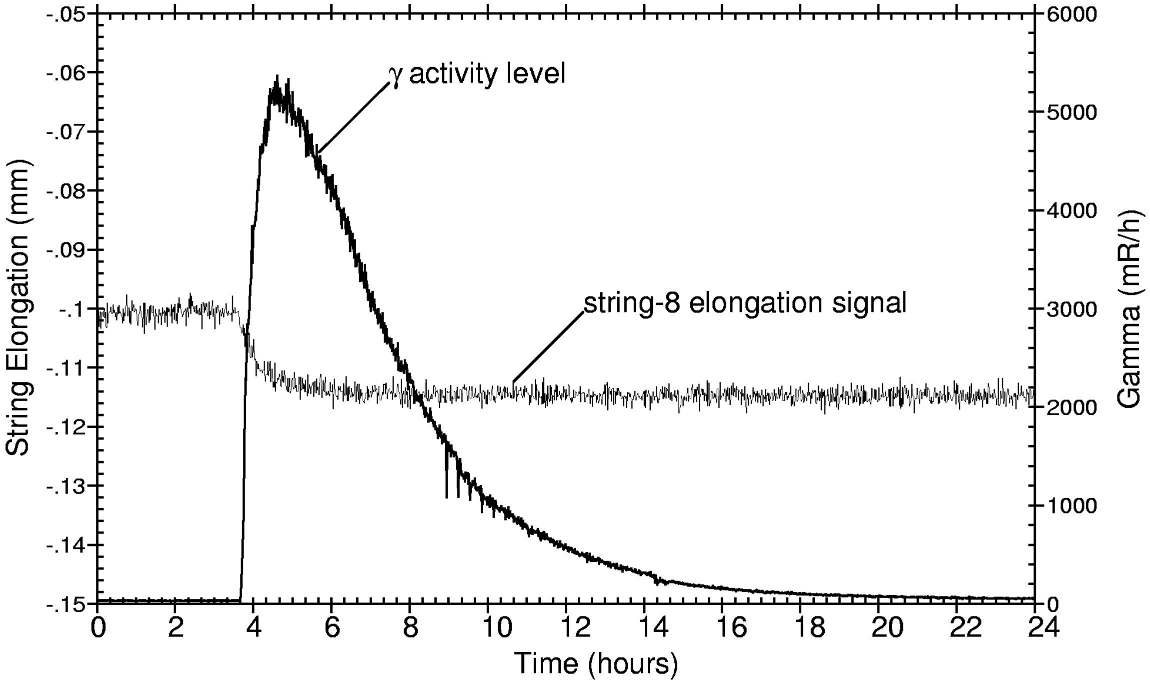
Crack Initiation Study

- determine susceptibility to crack initiation in pressurised tube specimens (pre-pressurised or with gas lines) as a function of fluence, stress level and material
- sensitised + s.a 304 SS, 316 SS, cw 347 SS
- stress levels 0.8 to 2.75 x YS
- exposure to BWR NWC conditions





On-line detection of specimen failure by means of change in elongation signal + release of activated Ar-41 filler gas into loop system



Crack Initiation (Integrated Time-to-Failure) Study

Objective

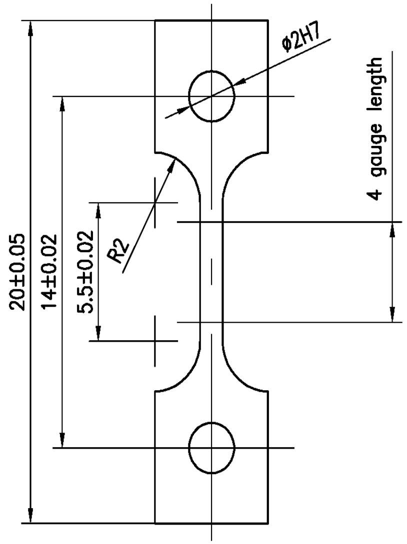
- Determine effectiveness of HWC in reducing susceptibility to the *initiation* of cracks in irradiated material

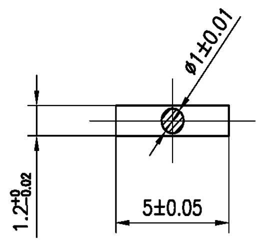
Experimental

- 30 miniature tensile specimens prepared from 304L SS (from Barseback 1 NPP, 8×10^{21} n/cm^2, YS 718 MPa)
- Load (77- 97% of YS) applied by means of bellows
- On-line monitoring of specimen failures (LVDTs)
- 1st loading: NWC for 6 cycles; record no. of failures
- 2nd loading: HWC for 6 cycles; record no. of failures

Comparison → effectiveness of HWC

Crack Initiation (Integrated Time-to-Failure) Study





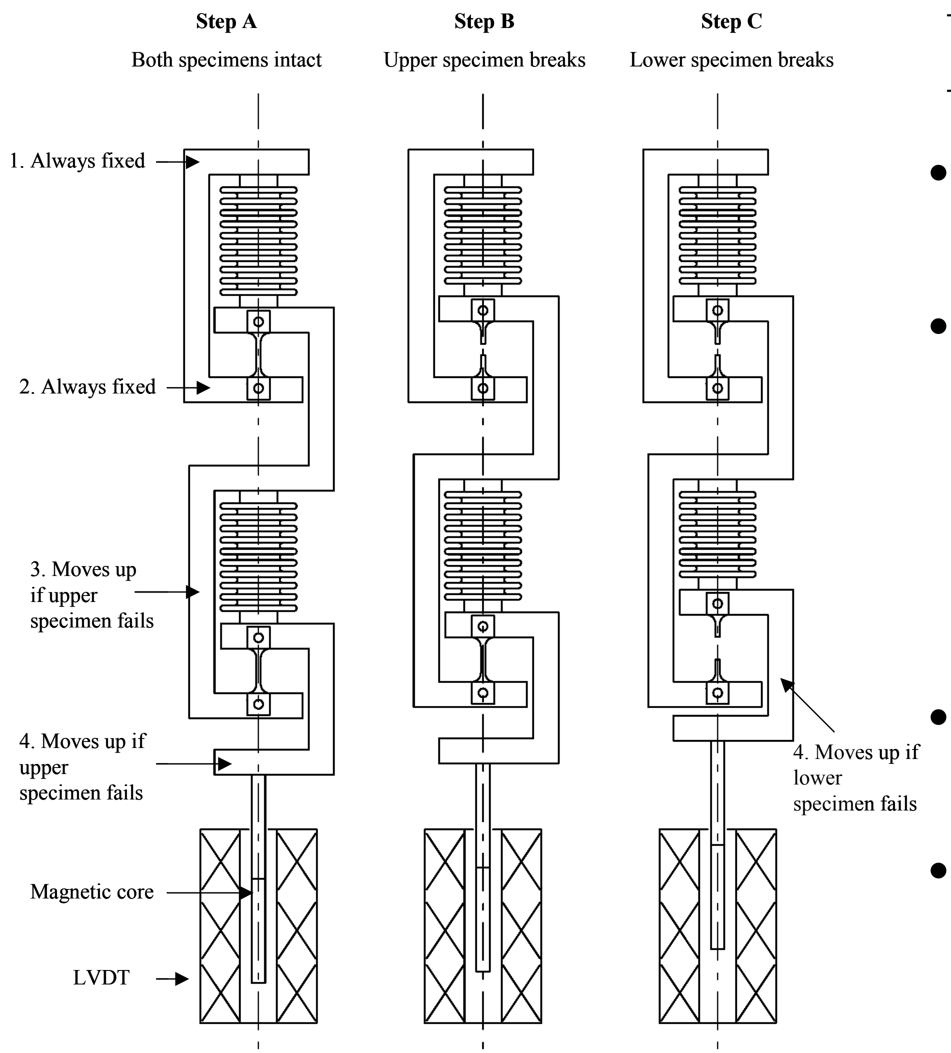
Miniature tensile specimen

- cylindrical, smooth, 1 mm diameter gage
- 30 specimens in rig

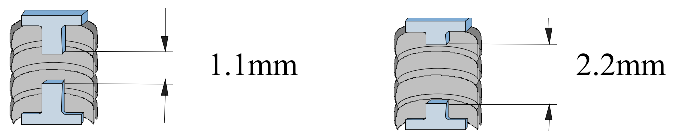
Material

- 304 L SS (~ 8 x 10^{21} n/cm^2) Barsebäck 1 NPP
- microstructure / mechanical properties saturated
- close to EOL fluence of e.g. top guide

Instrumentation

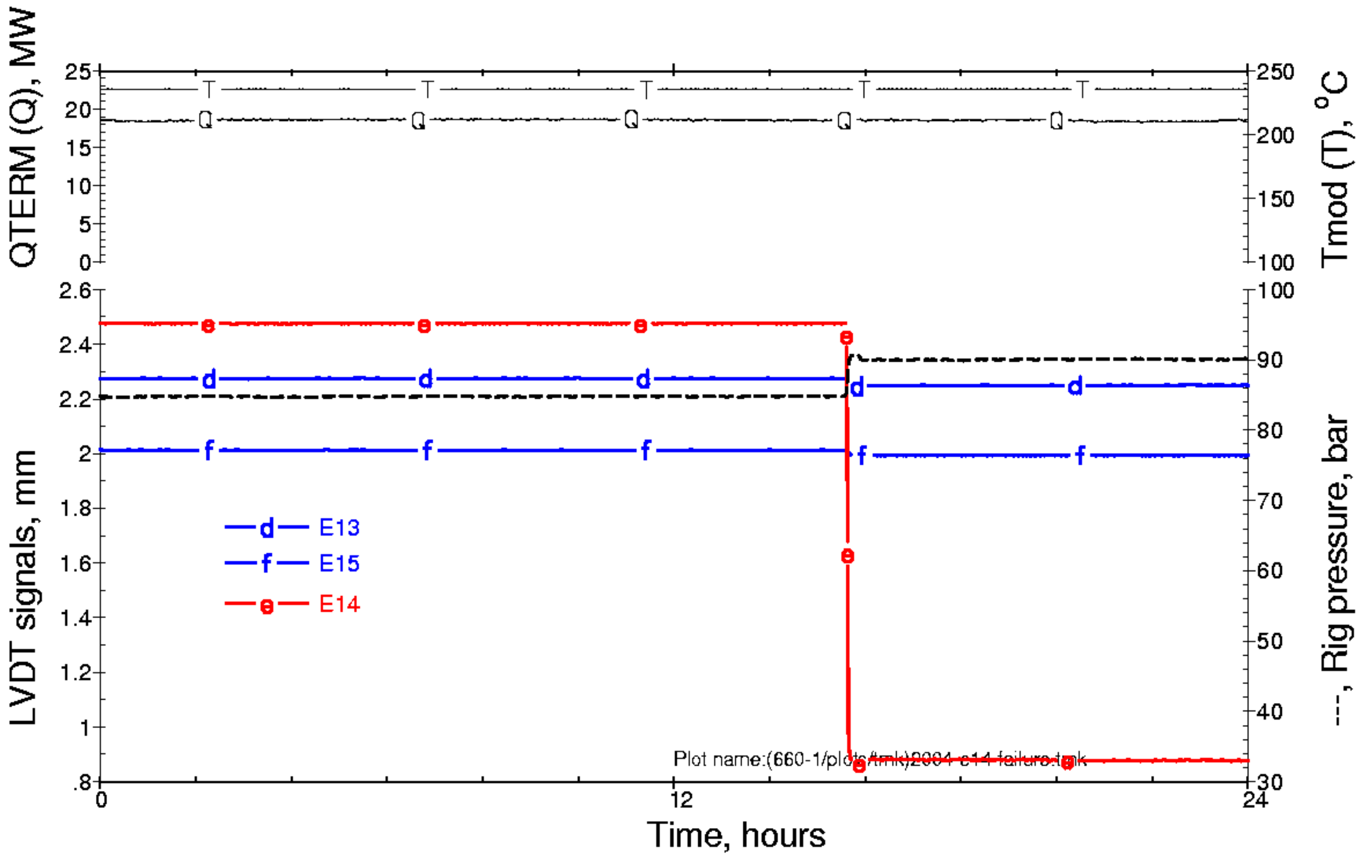


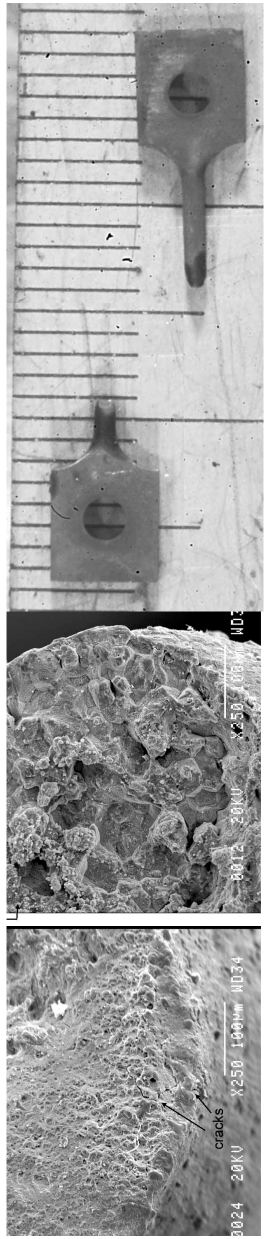
- Specimens arranged in pairs
- Identified by means of small and large gap spacers inside bellows



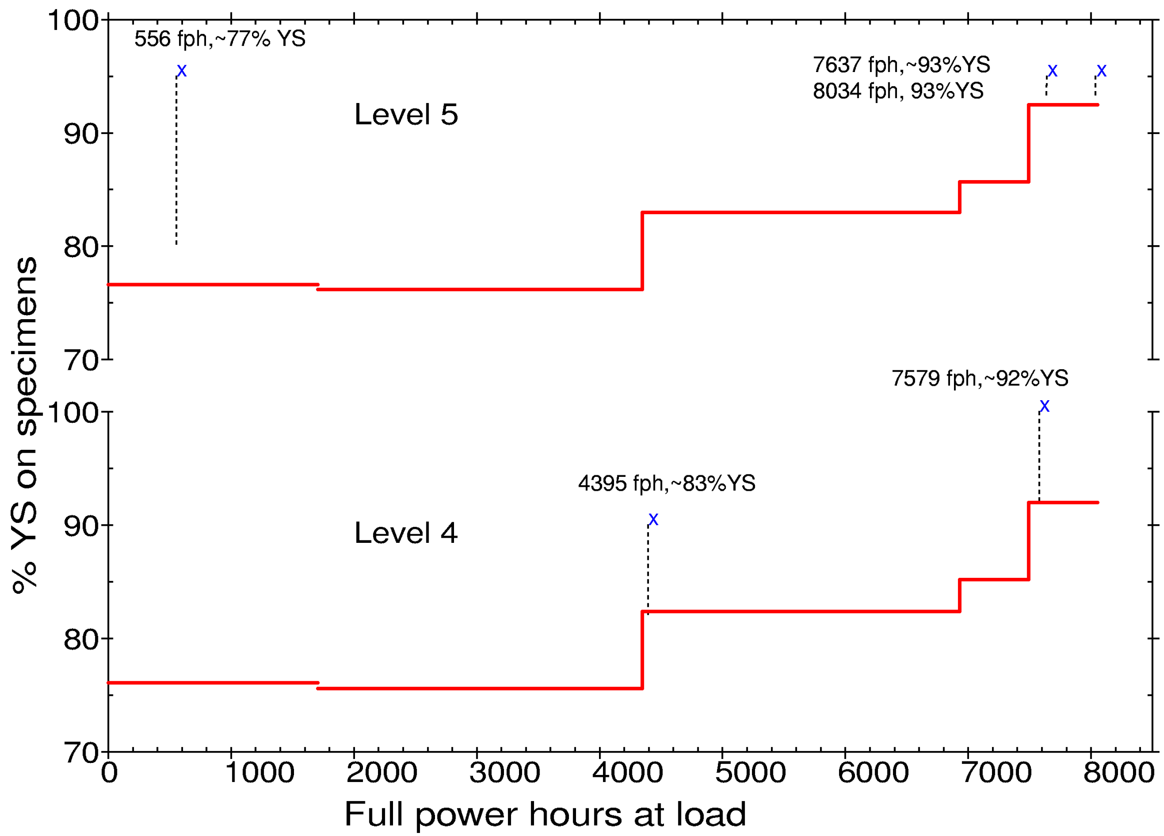
- Bellows collapse on specimen failure
- LVDT movement identifies failed specimen

Example of specimen failure recorded for crack initiation (integrated time-to-failure) study





Summary of specimen failures to date (NWC conditions)



Stress Relaxation Study

Objectives

- Establish the technical feasibility of on-line stress relaxation measurements during irradiation
- Measure the irradiation stress relaxation (& creep) of materials used in PWR and BWR plants
- Evaluate the applicability of the Halden stress relaxation data to other reactors (EBR II + commercial PWRs)

Stress Relaxation study

Specimens

- 30 tensile specimens (~2.5 mm, gauge length ~50 mm)
  - 12 samples in instrumented units
  - 18 samples in uninstrumented units

Materials

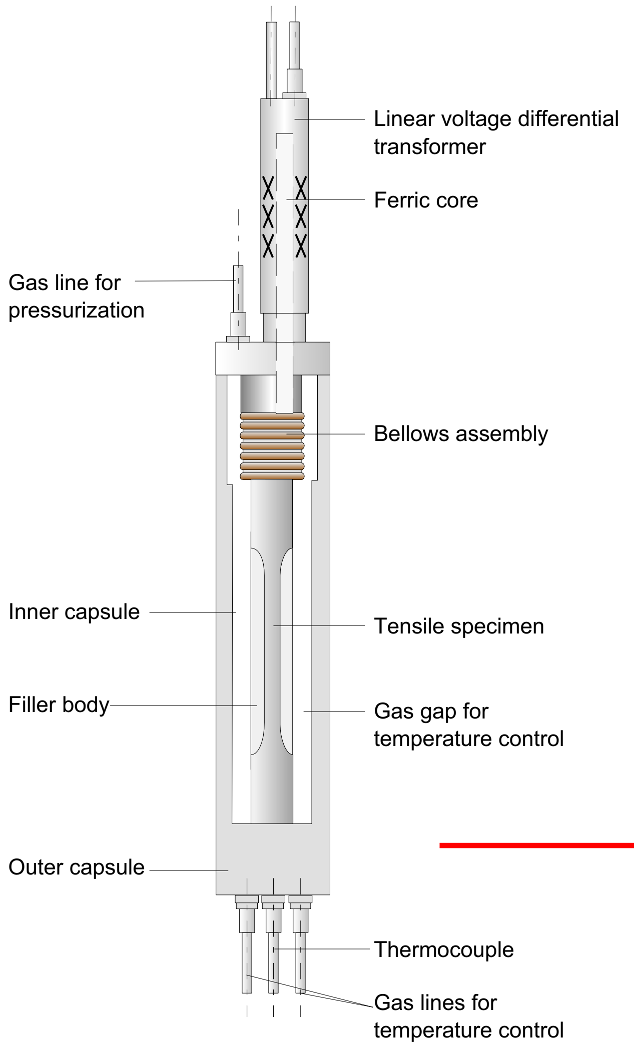
- CW 316, SA 304 SS; Aged Alloy 718

Test Conditions

• Stress Levels	70-345 MPa
• Temperatures	290, 330 and 370 °C
• Fluences	0.4, 1.6 + 2.0 dpa

Irradiation Arrangement

- Irradiation in inert (dry) irradiation conditions



- gas lines for on-line temperature control alter He-Ar gas mixture
- LVDTs monitor sample elongation
- stress applied with bellows
- constant displacement maintained by reducing applied stress on-line by bellows pressure
- 2 instrumented samples operated in "creep-mode" (stress constant + displacement measured continuously)