Status and outlook for irradiation testing

... from a Halden Reactor perspective ... mostly

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Overview

- A look back on fuels and materials testing
- Importance of instrumentation and in-core measurements
- What is currently being investigated?
  - fuel
  - cladding
  - materials
  - operational issues
- Future needs

(few examples, would take 20h instead of 20min)

A look back on fuels and materials testing - general developments (HBWR) -

1966 first measurement of fuel pellet centre temperature with a thermocouple

1968 computerised data acquisition (IBM 1800). All data from HBWR experiments since 1972 can be processed in the same way as data obtained today.

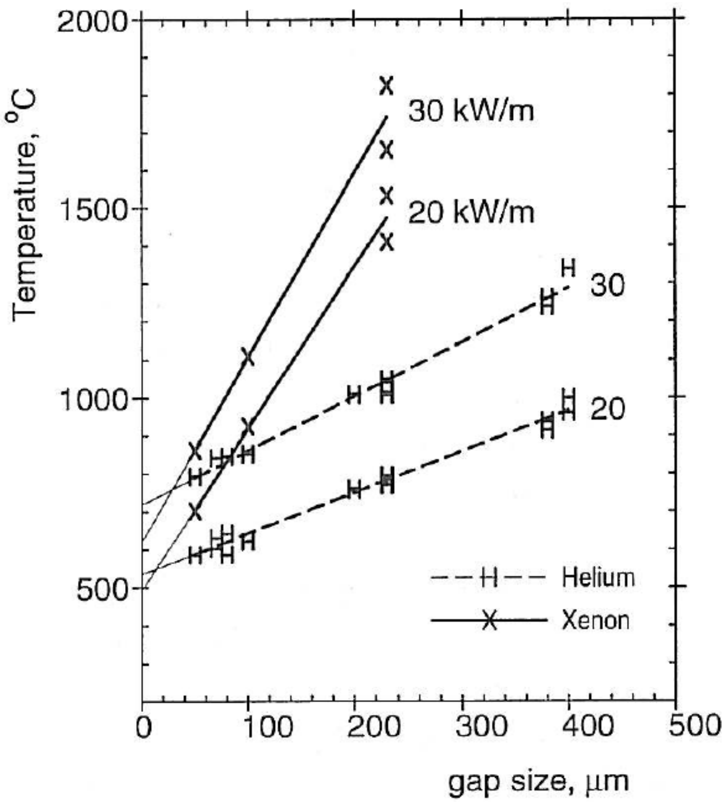
1970- development and application of ***instrumentation*** for measuring cladding elongation, diameter changes and rod pressure; ***fuels testing*** to generate performance data with respect to basic design and operational variables.

1980- loop systems to create representative LWR thermal-hydraulic and chemistry conditions; cladding corrosion investigations.

1990- investigations of core structure and RPV materials, crack growth (IASCC) measurements; high burn-up fuels testing

2000- operational issues; crud build-up and AOA (axial offset anomaly), activity transport, assembly bow, fretting, spacer relaxation etc.

Basic fuel behaviour experiments



Example of systematic variation of fill gas and gap size in early fuel behaviour studies

- Gap conductance
  - variation of pellet-cladding gap
  - fill gas type and composition (He/Xe/Ar)
  - pellet/clad surface roughness
  - concentric vs eccentric location of pellets
- Pellet-clad mechanical interaction
  - pellet end shape (flat, one or two-sided dishing, chamfer or not)
  - overall pellet shape (length to diameter ratio)
  - surface roughness, lubricants
- Fission gas release
  - Feedback on gap conductance
  - onset of significant FGR ≥1%
  - Influence of grain size

In-core instrumentation ...

... is essential for fuel performance studies and provides

- direct insight into phenomena while they are going on
- cross-correlations between interrelated phenomena

However, the conditions in the core of a (research) reactor are not conducive for instrument performance and the ability to survive for a long time. Factors contributing to failure are

- high neutron and gamma fluxes
- high temperatures
- high pressures

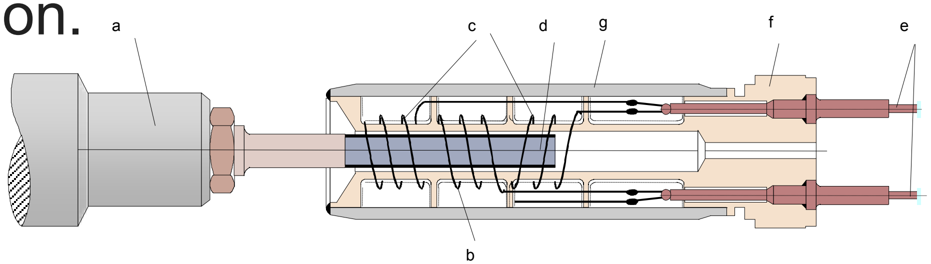
Temperatures, pressures, stresses, strains, dimensional changes, electrochemical potential and other important parameters can be measured in various ways, **but:**

Only robust methods will endure in-core conditions for longer times.

Linear Variable Differential Transformer (LVDT)

- a robust solution for measuring a number of phenomena -

- Many phenomena produce, or can be used to produce, length changes which in turn can be measured and converted into a measure of the phenomenon.
- The LVDT device has proved to be robust and versatile



- Important advantage: no cable penetration into the fuel rod
- Measurement applications are:
  - pressure transducer (fission gas release, densification)
  - fuel temperature (expansion thermometer)
  - fuel stack length (densification, swelling)
  - cladding elongation (axial PCMI)
  - cladding diameter (radial PCMI)
  - crack growth (crack mouth opening displacement)
  - stress relaxation

Typical fuel rod instrumentation

Fuel rods may be instrumented with

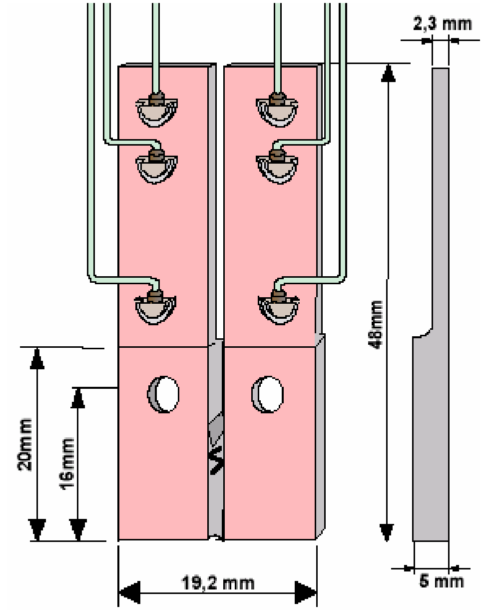
- fuel thermocouple
- rod pressure transducer for fission gas release assessment
- fuel stack elongation detector for measuring densification and swelling
- clad elongation detector for axial pellet-clad interaction (PCMI).

Crack growth in structural materials

Crack growth in structural materials, e.g. due to irradiation induced stress corrosion cracking (IASCC), is an important phenomenon being investigated. The most popular in-core measurement is the

Direct current potential drop method

- A DC is led through the arms of the CT and around the crack
- The small change of potential measure on the arms is converted to a change of crack length



Water chemistry parameters

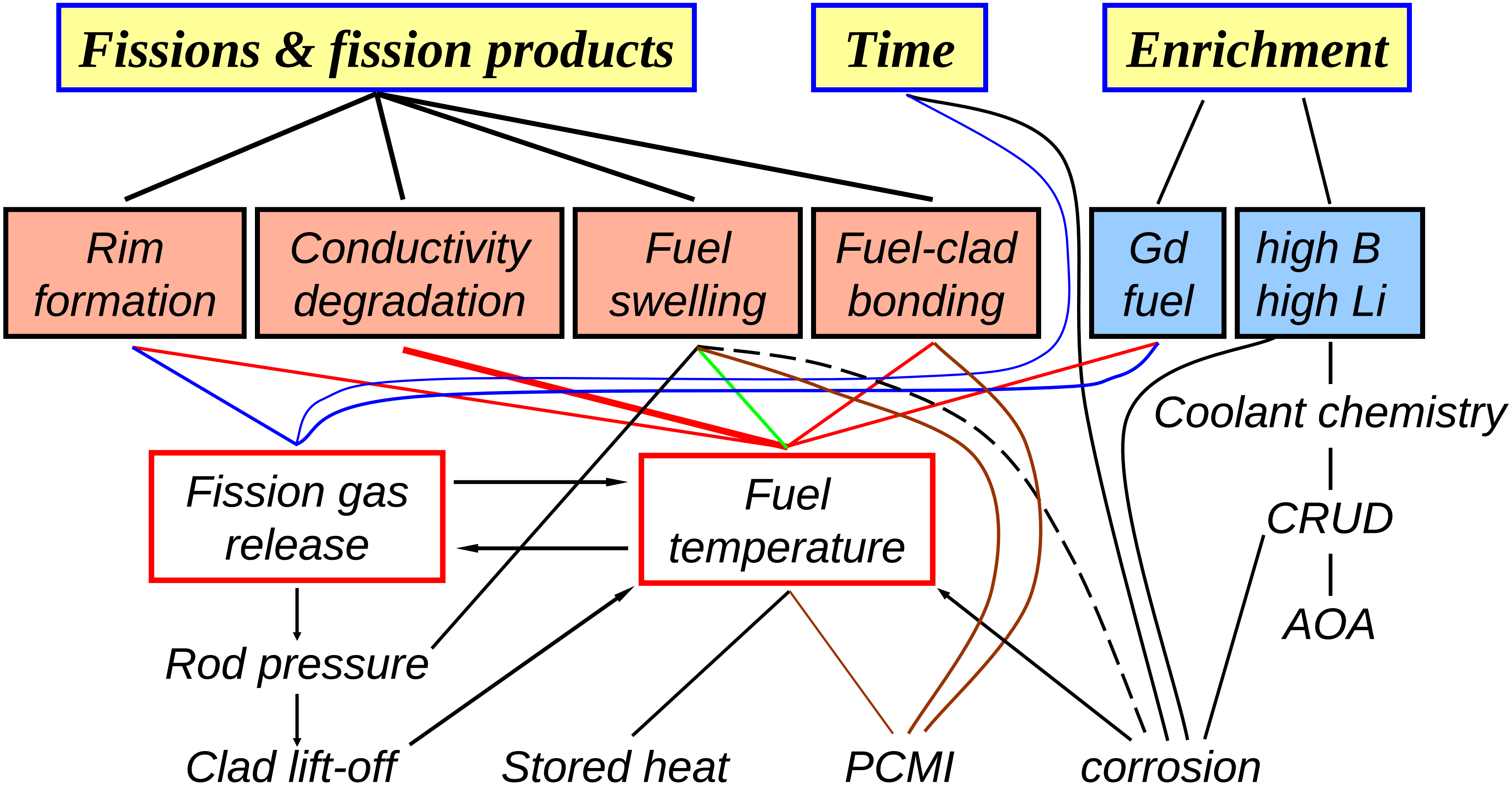
Water chemistry parameters are important for controlling the conditions of clad corrosion and materials studies (IASCC in PWR and BWR conditions). On-line measurements comprise:

- **Electrochemical potential (ECP).** Electrodes must withstand high temperatures, pressures and neutron and gamma fluxes in the reactor core. Platinum (Pt) and palladium (Pd) electrodes have been developed at Halden to improve performance and especially lifetime.
- **Coolant conductivity**. The sensor is a modification of the Halden platinum ECP electrode, in which the Pt sensing element is surrounded by a second Pt cylinder.
- **Electrochemical impedance spectroscopy (EIS)**. The technique can be used in low conductivity media, such as BWR type coolant, and is non-destructive.

Current needs for fuels & materials testing

- Many of the developments and research programs are driven by the nuclear industry's requirement to
  - increased burn-up as a means to improve fuel utilisation
  - decrease back end fuel cycle costs which may amount to a considerable fraction of the total fuel cycle costs
- The same requirements have led to the development of cladding alloys with improved properties
- Regarding core structural materials, research efforts are determined by ageing issues, i.e. the need to address cracking of components and to generate data for lifetime extension assessments

Experiments must address and untangle complex interactions – if possible ...



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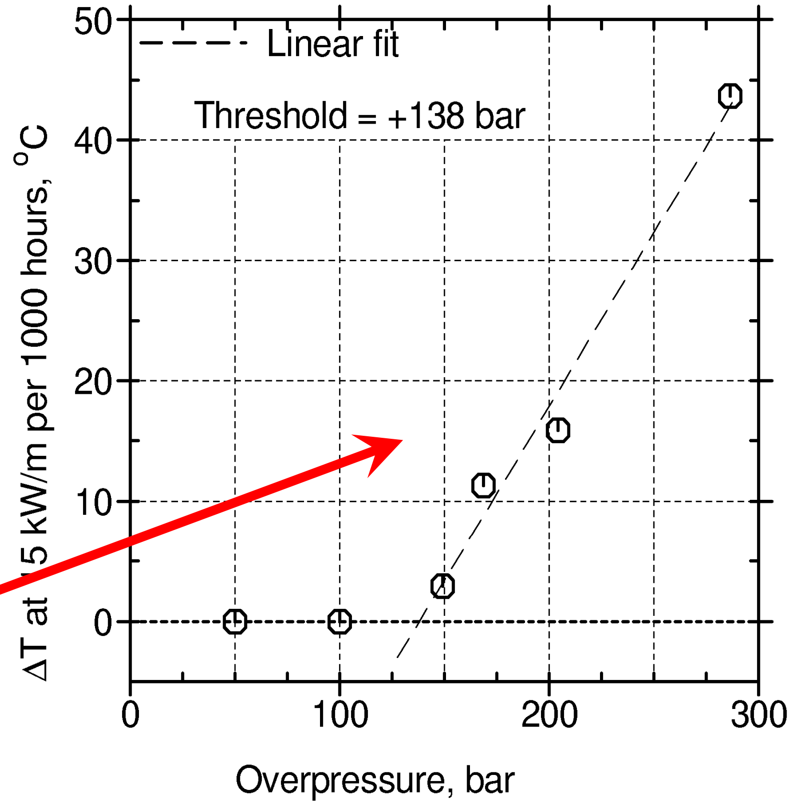
Fuel behaviour

- In order to cope with the consequences of high burnup, modified UO_2 fuels have been and are still being introduced
- Their properties must be thoroughly addressed by MTR testing to establish the necessary database for safety assessments:
  - impact of burnable neutron absorbers (Gd, Er) on fuel behaviour
  - additives to influence grain size and consequently fission gas release as well as mechanical properties
  - densification and swelling
  - high burn-up structure formation
  - fuel-clad bonding
- Also MOX (U-Pu) fuel is being developed further with the aim to reach parity with UO2 fuel.

Separate effects & integral fuel behaviour studies

- Thermal performance and degradation of fuel thermal conductivity with increasing burn-up
- Pellet-cladding interaction due to fuel swelling and pellet-clad bonding
- Fission gas release and its influence on thermal performance and rod pressure
- Rod overpressure / clad lift-off and tolerable rod pressure limits



Cladding behaviour studies

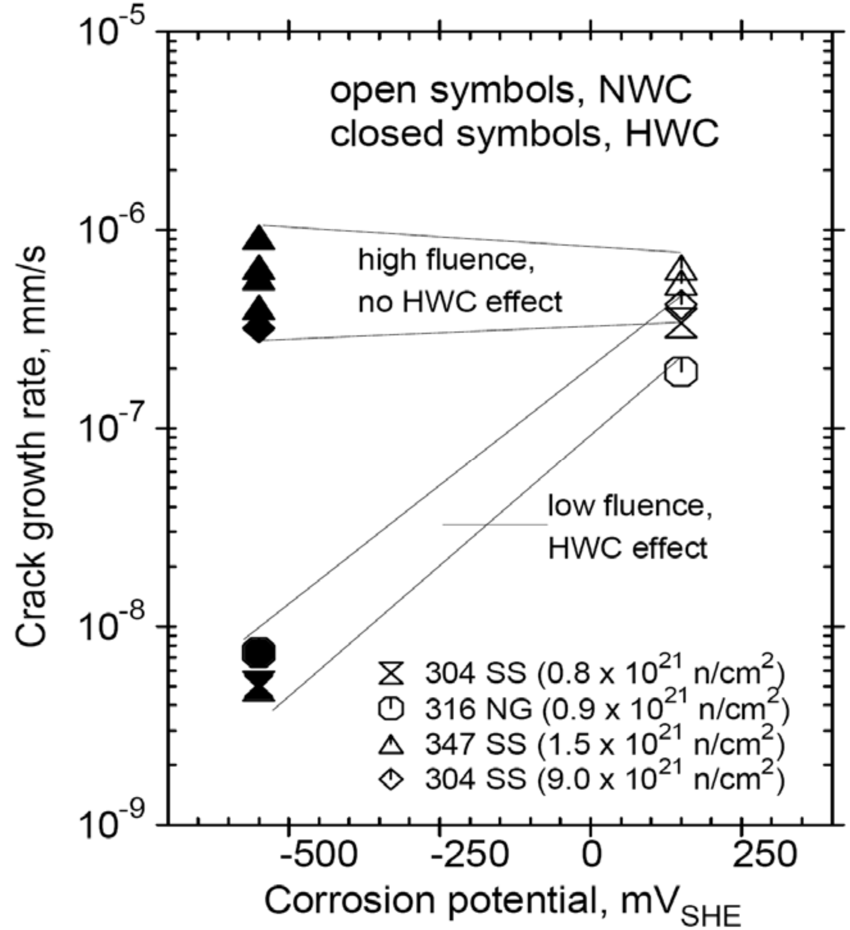
The cladding is the most important barrier that keeps the fission products confined. Understanding the mechanisms that challenge and weaken the cladding during exposure is essential for achieving zero failure. Testing addresses:

- Corrosion behaviour in demanding operational and water chemistry conditions
- Shadow corrosion (localised corrosion in BWRs)
- Mechanisms of secondary fuel failure degradation
- Screening of experimental cladding alloys
- Hydrogen pick-up
- Cladding creep under varying loading conditions
  - compressive stresses (the pressure in the cladding tube is lower than the (PWR) system pressure) and creep-down
  - tensile stresses (rod pressure exceeds system pressure) and creep-out

Materials testing

As the age of nuclear power plants increases, lifetime assessment programmes become more and more important. Halden reactor testing addresses:

- Irradiation assisted stress corrosion cracking (IASCC)
- Crack initiation (time to failure)
- Stress relaxation
- Irradiation of RPV materials, also subjected to annealing and re-irradiation



Operational issues

Many nuclear power plants are attempting to increase efficiency by operating at higher power and coolant temperatures than were common previously. This increases the probability of encountering problems. MTR/Halden reactor testing addresses:

- **Crud formation**
  - BWR: may cause a rise in clad temperature, increased cladding corrosion and higher probability of clad failure
  - PWR: incorporation of boron into crud can result in crud induced power shifts (CIPS), also known as “axial offset anomaly”, AOA
- **Guide tube and assembly bowing** caused by dimensional changes in zirconium base alloys under irradiation
  - often difficult to explain with conventional creep & growth models
  - testing of materials under compressive and tensile stress as well as low and high fast neutron flux

Future needs
- Water cooled reactor technology -

Developments are motivated by increasing demands on fuel utilisation, reliability, and operational flexibility to reduce operating costs while maintaining safety margins.

- Fuel performance experiments will continue to address modified UO_2 fuel (with additives, burnable poisons) and MOX fuel
- Erbium bearing fuel is a candidate in conjunction with >5% enrichment and burnups >100 MWd/kg
- Burnups >70 MWd/kg generate questions as to the consequences when larger fractions of the fuels are affected by high burnup structure formation
- Operational flexibility requires fuels that are able to withstand rapid power changes and the ensuing mechanical and chemical loads
- Silicon carbide and SS are candidates to cope with cladding corrosion in conjunction with hot plants and extended in-core residence time

Advanced reactor technologies

- Generation IV reactors and accelerator driven systems are very different in their thermal and nuclear characteristics compared to LWRs.
- It seems inevitable that research reactors or prototypes with material research capabilities be built to serve the special needs of Gen IV reactor development – not least regarding materials performance in conjunction with liquid metal cooling
- Instruments that work well in LWR conditions are not necessarily suitable for reliable measurements when exposed to Gen IV reactor conditions
- It can safely be assumed that considerable development work and testing will be needed in these areas in the future

No Summary

Let's go to work!

Thank you for your attention!