Fuels Research at the Halden Reactor Project
– Selected Results and Plans –

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Presented at
Regulatory Information Conference
March 10-12, 2009

The HRP Fuels & Materials Research ...

- Addresses safety and economy of power generation in present and future nuclear power plants and aims to
  - Demonstrate reliability and operational flexibility of current and new fuel designs, in particular for high burnup applications
  - Show compliance with safety criteria and assess safety margins
  - Assess measures for plant life extension and mitigation of core component ageing
- Is comprehensive with 10-15 experiments being executed concurrently within the joint HRP program
- Closely involves the participants in the definition and execution of experiments

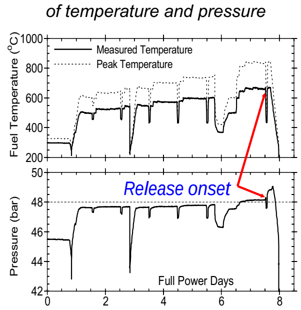
Instrumentation – a Key Factor in Halden Reactor Experimental Work

In-core instrumentation → **Fuel performance**

is essential for fuels & materials performance studies, providing
- direct insight into phenomena while they are going on
- cross-correlations between interrelated phenomena

Measurements comprise:
- Pressure in fuel rods
- Fuel temperature
- Elongation of cladding and fuel
- Change of cladding diameter
- Crack growth in materials
- Electrochemical potential, pH and other water chemistry-related variables
- Corrosion

Simultaneous measurement of temperature and pressure



When everything is in place . . .
Fuels & Materials Programme 2009 - 2011

Fuel High Burnup Capabilities in Normal Operating Conditions
- Long-term Fuel Performance
  - Comparative Integral Irradiation Test on Gadolinia Fuel
  - VVER Fuel Behaviour
  - Helium release from MOX fuel
  - Fission gas release mechanisms
- Integral Behaviour of LWR Fuel at High Burnup
- Tolerable Internal Rod Pressure in Normal Operation
- Fuel Creep
- Iodine Release and Gap Inventory
- Post Irradiation Examinations

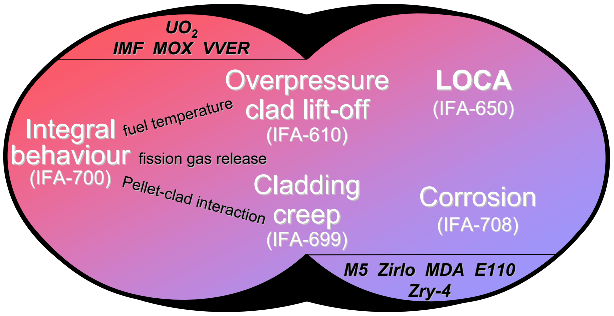
Fuel Response to Transients
- Rim Fuel Investigations
- Loss of Coolant

Cladding Creep / Corrosion & Water Chemistry Issues
- Cladding creep
- Cladding Corrosion and Hydriding
- BWR/PWR Crud Deposition

Plant Lifetime Extension
- Crack Growth Rate Investigations
  - PWR Crack Growth Studies
  - BWR Crack Growth Studies
- Crack Initiation Study (Integrated Time to Failure)
- Stress Relaxation Study
- Reactor Pressure Vessel Integrity
- Characterisation of IASCC Test Materials

Development of Instrumentation for Use in Materials Studies
- EIS, ECP, corrosion sensor, …

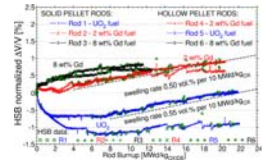
Integrated Fuels Testing Approach



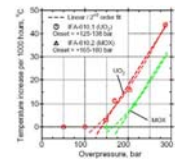
The same or similar fuel and cladding materials are employed in different types of experiments. The data provide a comprehensive picture of performance in different conditions.

Three examples

1. Integral behaviour *(fuel performance)*
   - Fuel temperature
   - Fission gas release
   - Dimensional changes



2. Rod overpressure *(safety margins)*
   - Temperature response
   - Hydraulic diameter
   - Fuel-clad contact



3. Loss-of-coolant *(safety criteria)*
   - Ballooning of irradiated fuel
   - Fuel fragment relocation
   - Code validation and development

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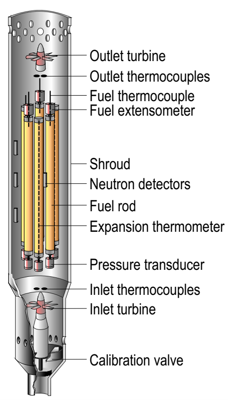
Performance of fuels with additives

- Typical fuels irradiation experiment with 6 instrumented fuel rods
  - 2 fuel thermocouples per rod *(pellet centre temperature)*
  - 1 fuel stack elongation detector *(densification, swelling)*
  - 1 rod pressure transducer *(fission gas release)*
- Several related experiments with similar design and objectives:
  - Fuel with gadolinia
  - VVER fuel
  - MOX fuel



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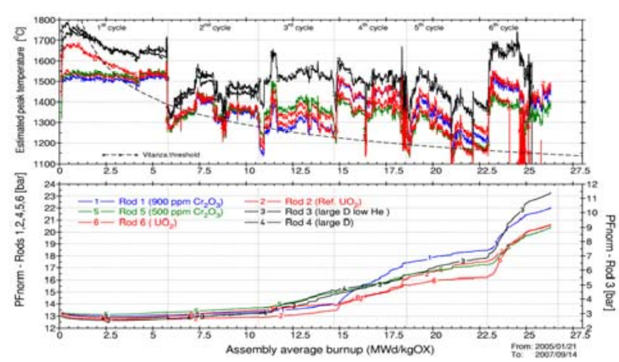
Measured: rod pressure and fuel temperature



Summary and plans – fuel performance

- Clear correlation between details of temperature history and development of pressure / fission gas release
- Similar fission gas release from all fuels despite differences in microstructure
  - Competition between (?)
    - increased grain size (impedes fission gas release)
    - diffusion enhancement due to additives
- Related plans
  - Experiment on fission gas release mechanisms
  - Helium release from MOX fuel
  - Fuel creep (UO_2, MOX)

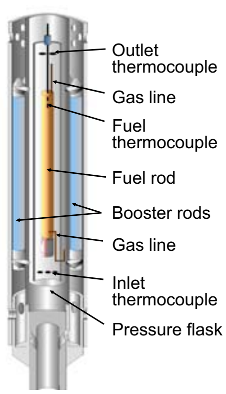
Fuel rod overpressure / clad lift-off

The potential for fission gas release increases with increasing burnup. Excessive fission gas release can cause the rod pressure to rise beyond system pressure. The consequences are investigated in the Halden Project's experimental series **IFA-610**:

- Establish the overpressure leading to onset of increasing fuel temperature
- Investigate the temperature response at different overpressure levels
- Assess different combinations of fuel and cladding

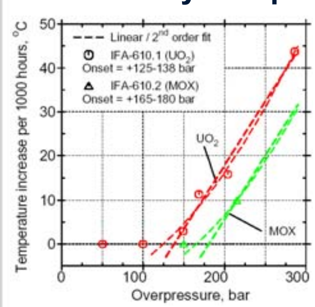
High burnup instrumented fuel segments are used for these investigations.

Measurement possibilities



- Fuel centreline temperature and its change (primary clad lift-off indicator)
- Temperature response to fill gas change (argon versus helium) during operation
- Fission gas release by means of gamma-spectroscopy
- PCMI and fuel swelling by means of clad elongation measurements
- Hydraulic diameter
- Coherence between fast response neutron detector (power) and clad elongation

Summary and plans – rod overpressure



Typical temperature response to over-pressure (system pres. 155bar). None of the tests (6) has shown a temperature in-crease with less than 100bar overpressure.

Observations

- The rate of temperature increase is correlated with the overpressure
- Thermal feedback occurs only at considerable overpressure (>100 bar), depending on the particular combination of fuel and cladding utilised in the test
- Below this threshold, clad creep-out is sufficiently compensated by fuel swelling, and no net thermal feedback becomes apparent

Plans

- On-going test with BWR fuel
- Thereafter, VVER fuel

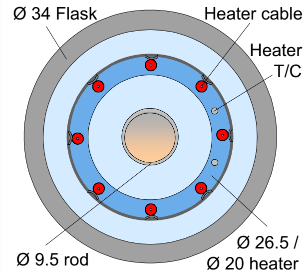
HRP Loss of Coolant Studies

The Halden reactor IFA-650 test series on LOCA fuel behaviour focuses on in-reactor effects that are different from those obtained in out-of-reactor tests. In particular, the heating from within the fuel rod, in contrast to the external heating of out-of-pile setups, may affect a number of phenomena.

Primary objectives:

- Measure the extent of fuel (fragment) relocation into the ballooned region and evaluate its possible effect on cladding temperature and oxidation
- Investigate the extent (if any) of "secondary transient hydriding" of the cladding above and below the burst region

HRP LOCA Experiment design



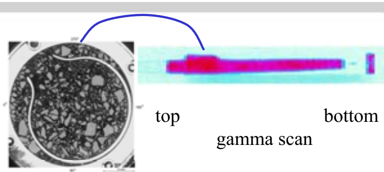
Cross section of fuel pin, flow separator and pressure tube used in HRP LOCA studies

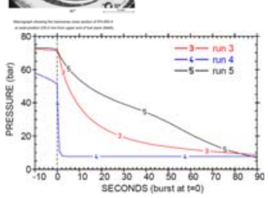
Design Features

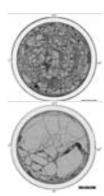
- Single rod experiment using high burnup fuel
- Heating provided from within the rod by low level nuclear power simulating decay heat
- Simulation of the thermal boundary conditions with an insulating channel and heated shroud
- Spray system for steam supply
- Possibility for both depressurisation and reflooding
- BWR and PWR conditions
- Instrumentation
  - 2-3 cladding thermocouples
  - rod pressure sensor
  - cladding elongation detector

Some results

- High burnup fuel can fragment, relocate into the ballooning volume and be blown out of the cladding
- Rod depressurisation after failure strongly influences fragmentation, relocation and expulsion of fuel
- The data are being used by HRP participants for code validation and development (NEA working group WGFS)







Icare-Cathare Fraptran-Genflo
Athlet-Tespa/CD Trace-Falcon
Transuranus Trac_PF1 Meteor

Summary and plans – LOCA testing

- The Halden LOCA program has investigated the behaviour of high burnup fuel (82-92 MWd/kg)
- Various extents of fuel fragmentation and relocation have been observed, depending on the type of fuel and experimental conditions
- The fuel can be a plug between the ballooning spot and the gas plenum, limiting
  - the ability to supply sufficient gas for driving the ballooning
  - the driving force for axial fuel relocation and expulsion
- The series will continue with high burnup PWR fuel (April 2009), followed by further BWR and VVER fuel behaviour studies under LOCA conditions