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.

end plug
plenum spring
Ø1 mm thermocouple
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% UO₂): 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
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
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 $T < T_{\text{threshold}}$
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:

- 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

Large PCMI but no failure
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

![Diagram of fuel rod system](image)

- Fuel rod pressure transducer
- Fuel rod elongation detector
- Outlet flow tube
- Pressure flask
- Extra free volume
- Coolant spray
- Upper cladding TC (TCC2 & TCC3)
- He-3 coil
- Electrical heater / Flow separator
- Neutron detector (Co)
- Lower cladding TC (TCC1)
- Neutron detector (V)
- Inlet TC
- Blow down/Inlet flow tube
## Making an overview from multiple tests: LOCA

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<thead>
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<th>test #</th>
<th>2</th>
<th>7</th>
<th>6</th>
<th>11</th>
<th>10</th>
<th>12</th>
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<th>3</th>
<th>5</th>
<th>9</th>
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<td>burnup, MWd/kg</td>
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<td>44.3</td>
<td>55.5</td>
<td>56</td>
<td>60</td>
<td>72.3</td>
<td>74.1</td>
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<td>90</td>
<td>92</td>
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<tr>
<td>balloon strain, %</td>
<td>54</td>
<td>23</td>
<td>49</td>
<td>25</td>
<td>15</td>
<td>40</td>
<td>45</td>
<td>8</td>
<td>15</td>
<td>61</td>
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### Radiography

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### Ceramography

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<tr>
<th>fragment size</th>
<th>coarse</th>
<th>coarse</th>
<th>coarse</th>
<th>coarse &amp; some fine</th>
<th>coarse &amp; fine</th>
<th>coarse (fine?)</th>
<th>medium &amp; fine</th>
<th>medium &amp; fine</th>
<th>medium &amp; fine</th>
<th>medium &amp; fine</th>
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</thead>
</table>

### VVER segments
Typical HRP Materials Tests

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

- **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

<table>
<thead>
<tr>
<th>FUEL</th>
<th>CLAD</th>
<th>Control Materials</th>
<th>Core Comp. Materials</th>
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<tbody>
<tr>
<td>Standard UO₂</td>
<td>Zirconium alloys, new ATF claddings</td>
<td>B₄C</td>
<td>Stainless steels Nickel based alloys</td>
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<td>UO₂ + additives MOX, inert matrix</td>
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<td>He release, pressure, swelling</td>
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<td>Zirconium alloys, new ATF claddings</td>
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</tr>
<tr>
<td>Fission gas release</td>
<td>Rod pressure, lift-off</td>
<td>Guide tube bowing</td>
<td>Crack initiation &amp; Time to failure</td>
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<tr>
<td>Fuel temperature</td>
<td>Gap conductance</td>
<td>IRI</td>
<td>Crack growth rate (IASCC)</td>
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<td>- conductivity</td>
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<td>Mechanical prop. changes</td>
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<tr>
<td>- stored energy</td>
<td>Creep &amp; Growth</td>
<td>Graphite</td>
<td>Embrittlement, annealing (RPV)</td>
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<tr>
<td>Fuel densification</td>
<td>Axial gaps (clad collapse, power peaks)</td>
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<tr>
<td>Fuel swelling</td>
<td>SCC/PCMI</td>
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**high burnup, operating conditions**  
**Water chemistry**