The new material irradiation infrastructure at the BR2 reactor
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Characteristics of the BR2 reactor
Reactor core performance of BR2

- Design goal: thermal neutron flux up to $10^{15} \text{ n/cm}^2\text{s}$
  - Achievement by
    - Compact core arrangement with central flux trap
    - Material choice: Be moderator and metallic uranium fuel
    - High overall core power (upgraded from 50 to 100MW in 1968)
      - 25MW additional cooling capacity for experiments

- Achievable flux levels (at mid plane in vessel)
  - Thermal flux: $7 \times 10^{13} \text{ n/cm}^2\text{s}$ to $10^{15} \text{ n/cm}^2\text{s}$
  - Fast flux ($E > 0.1 \text{MeV}$): $1 \times 10^{13} \text{ n/cm}^2\text{s}$ to $6 \times 10^{14} \text{ n/cm}^2\text{s}$

- Allowable heat flux in primary coolant
  - $470 \text{W/cm}^2$ for the driver fuel plates
    - Demineralised water
    - Pressure to 1.2MPa, temperature 35-50°C
    - 10m/s flow velocity on fuel plate
  - Up to $600 \text{W/cm}^2$ can be allowed in experiments
Spectral tailoring in BR2 experiments

Objective
- Simulation of fast reactor conditions
- Separation between transmutation and lattice damage

Method
- Selection of irradiation position in reflector or fuel element
- Addition of absorbing materials

![Graph showing neutron flux vs. neutron energy with and without Cd-screen](image-url)
Diverging reactor channels for compact core and good access: core 1m, cover 2m Ø

Angle of channels from 0 to 27°

Reactor channels accessible from top (all) and bottom (17)

Irradiation inside rigs in reactor channel or in axis of fuel element

Loading elements hang on top cover
## Overview of typical irradiation positions

<table>
<thead>
<tr>
<th>Channel type</th>
<th>thermal flux range ((10^{14} \text{n/cm}^2\text{s}))</th>
<th>fast flux range ((10^{14} \text{n/cm}^2\text{s})) ((E&gt;1\text{MeV}))</th>
<th>Gamma heating ((\text{W/g Al}))</th>
<th>diameter ((\text{mm}))</th>
<th>typical number available</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>F1</strong></td>
<td>1 to 3.5</td>
<td>0.5 to 2.8</td>
<td>1.7 to 8.8</td>
<td>25.4</td>
<td>30</td>
</tr>
<tr>
<td><strong>F2</strong></td>
<td>up to 2.5</td>
<td>up to 2.5</td>
<td>up to 6.8</td>
<td>32</td>
<td>2*</td>
</tr>
<tr>
<td><strong>S</strong></td>
<td>1 to 3.5</td>
<td>0.1 to 0.7</td>
<td>0.9 to 2.3</td>
<td>84</td>
<td>24**</td>
</tr>
<tr>
<td><strong>Central large channel H1</strong></td>
<td>up to 10</td>
<td>up to 1.8</td>
<td>3</td>
<td>200</td>
<td>1***</td>
</tr>
<tr>
<td><strong>Peripheral large channel Hi</strong></td>
<td>3</td>
<td>1.3</td>
<td>0.1</td>
<td>200</td>
<td>4****</td>
</tr>
<tr>
<td><strong>Peripheral small channel P</strong></td>
<td>0.7 to 1.5</td>
<td>0.05 to 0.1</td>
<td>0.4 to 1</td>
<td>50</td>
<td>9</td>
</tr>
</tbody>
</table>
Flexible reactor configuration

- Combination of multiple experiments in core load
  - Position of fuel, control rods and experiments are optimised
  - Choice of type of fuel elements
  - Adapted reactor power and cycle length

- Reactor load is optimised for each operating cycle
  - 3D MCNP model with burn-up evolution of entire core
  - Detailed model of experiment if required
  - Verification by measurement before start

- BR2 reactor management is ISO 9001 certified (including irradiations)
Typical configuration variants in BR2
BR2 = Multipurpose Reactor

Mid-plane cross section of a typical BR2 core
New material irradiation devices
Material irradiation for selection and qualification

- New applications of nuclear energy
  - Issue: application target is beyond current database
    - Higher temperatures
    - Higher (fast neutron) fluence
    - Different environments

- Materials: wide variation for screening
  - Stainless & high chromium steels: GEN 3&4
  - Ceramics & cermets: ATF claddings & fusion
  - Copper, tungsten, steel: fusion

- Solutions
  - Provide rigs with high flexibility in irradiation conditions
  - Select high fast flux positions: ≥0.5 dpa / cycle
  - Provide cost effective solutions for irradiation of many samples
Purpose of the device

- Specimens (not fuel) irradiation at
  - High temperature: 300 → 1000 °C (measured and controlled)
  - High flux: in a VIn fuel element (dose up to 10 dpa)
  - Nuclear Heating from 8 up to 14 W/g

Specimens:
- Type: flat tensile, mini-Charpy & simple geometries (like cylinders)
- Material: High temperature resistant: W, Mo, SiC, ... Fe (300 °C)

No requirement to preheat specimens at irradiation temperature before the first neutron.

Environment: gas (Helium) or vacuum
The High Temperature High Flux device

- Material irradiation for GEN 4/fusion conditions
  - High dose rate (>0.5 dpa per reactor cycle)
  - Stable irradiation temperature during irradiation
  - Low cost rig with flexible loading position in reactor

- Solution
  - Gas filled capsule inside 6 plate fuel element and electrical heating
  - Control of temperature by gas gap design and gas pressure
  - Miniature specimens

- Characteristics
  - Temperature 300-1000°C
  - Single use capsule
  - Up to 0.75 dpa per reactor cycle of 3 weeks
    - fluence 4.7 to 5.2E20 n/cm² (E>1MeV) in hottest channel
1 - Graphite sheath
2 – Graphite matrix for mini-Charpy
3 – Graphite cover
4 – Graphite pen
5 – Graphite centering plug
6 – Graphite matrix for flat tensile
7 – Graphite cover
Temperature profile +/- flat over predefined range.
(+/- 1% at calculated pressure)

Measurements of temperature at max 4 levels.

<table>
<thead>
<tr>
<th>Pos</th>
<th>Diameter mm</th>
<th>Insulation?</th>
<th>Position mm</th>
<th>Flux Shape [%]</th>
<th>Temp °C</th>
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<tbody>
<tr>
<td>1</td>
<td>20.40</td>
<td></td>
<td>273.5</td>
<td>50%</td>
<td>745.7</td>
</tr>
<tr>
<td>2</td>
<td>20.40</td>
<td></td>
<td>268.5</td>
<td>62%</td>
<td>760.7</td>
</tr>
<tr>
<td>3</td>
<td>20.40</td>
<td></td>
<td>223.5</td>
<td>88%</td>
<td>779.0</td>
</tr>
<tr>
<td>4</td>
<td>20.50</td>
<td></td>
<td>198.5</td>
<td>73%</td>
<td>784.1</td>
</tr>
<tr>
<td>5</td>
<td>20.80</td>
<td>TK</td>
<td>173.5</td>
<td>70%</td>
<td>785.8</td>
</tr>
<tr>
<td>6</td>
<td>21.10</td>
<td></td>
<td>148.5</td>
<td>89%</td>
<td>788.2</td>
</tr>
<tr>
<td>7</td>
<td>21.20</td>
<td></td>
<td>133.5</td>
<td>86%</td>
<td>800.2</td>
</tr>
<tr>
<td>8</td>
<td>21.30</td>
<td></td>
<td>98.5</td>
<td>90%</td>
<td>803.3</td>
</tr>
<tr>
<td>9</td>
<td>21.40</td>
<td></td>
<td>79.5</td>
<td>93%</td>
<td>800.8</td>
</tr>
<tr>
<td>10</td>
<td>21.50</td>
<td></td>
<td>48.5</td>
<td>95%</td>
<td>788.8</td>
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<tr>
<td>11</td>
<td>21.60</td>
<td></td>
<td>23.5</td>
<td>97%</td>
<td>797.1</td>
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<tr>
<td>12</td>
<td>21.60</td>
<td></td>
<td>-1.5</td>
<td>99%</td>
<td>799.1</td>
</tr>
<tr>
<td>13</td>
<td>21.70</td>
<td>TK</td>
<td>-32.0</td>
<td>100%</td>
<td>803.3</td>
</tr>
<tr>
<td>14</td>
<td>21.50</td>
<td>TK</td>
<td>-66.0</td>
<td>100%</td>
<td>803.4</td>
</tr>
<tr>
<td>15</td>
<td>21.60</td>
<td></td>
<td>-91.5</td>
<td>99%</td>
<td>799.8</td>
</tr>
<tr>
<td>16</td>
<td>21.80</td>
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<td>-123.5</td>
<td>98%</td>
<td>787.8</td>
</tr>
<tr>
<td>17</td>
<td>21.80</td>
<td></td>
<td>-148.5</td>
<td>96%</td>
<td>789.3</td>
</tr>
<tr>
<td>18</td>
<td>21.90</td>
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<td>-173.5</td>
<td>95%</td>
<td>780.8</td>
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<tr>
<td>19</td>
<td>21.40</td>
<td></td>
<td>-186.5</td>
<td>90%</td>
<td>788.0</td>
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<tr>
<td>20</td>
<td>21.20</td>
<td></td>
<td>-238.5</td>
<td>80%</td>
<td>788.7</td>
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<tr>
<td>21</td>
<td>20.00</td>
<td>TK + 10%</td>
<td>-248.5</td>
<td>81%</td>
<td>800.5</td>
</tr>
<tr>
<td>22</td>
<td>20.00</td>
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<td>-373.5</td>
<td>76%</td>
<td>784.3</td>
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<tr>
<td>23</td>
<td>20.40</td>
<td></td>
<td>-298.5</td>
<td>70%</td>
<td>774.6</td>
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<tr>
<td>24</td>
<td>20.40</td>
<td></td>
<td>-323.5</td>
<td>65%</td>
<td>741.7</td>
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<tr>
<td>25</td>
<td>20.40</td>
<td></td>
<td>-348.5</td>
<td>57%</td>
<td>706.0</td>
</tr>
<tr>
<td>26</td>
<td>20.40</td>
<td></td>
<td>-373.5</td>
<td>52%</td>
<td>672.9</td>
</tr>
</tbody>
</table>
Irradiation behavior

- Strong temperature dependence on nuclear heating
- Optimisation of temperature feedback on temperature control
- Strong gradient between W samples and C matrix
Optimised control: irradiation cycle 2
Irradiation conditions

- Fast flux at mid plane during first 2 cycles
  - $1.7 \times 10^{14} \text{n/cm}^2\text{s}$ and $1.4 \times 10^{14} \text{n/cm}^2\text{s}$
- Accumulated damage after 2 cycles
  - 0.42 dpa in W
- Neutron spectrum

![Neutron spectrum graph](HTHF Cycle 05/2017)
Material irradiation in support of long term operation

- Irradiation induced ageing of reactor pressure vessel steels
  - Issue: current files from surveillance programmes insufficient for LTO
    - Insufficient material
    - Low lead factor
  - Challenge
    - Provide validated datasets compatible with existing surveillance programmes
      - Relevant dose levels for Long Term Operation
      - Sufficient volume/ numerous specimens
      - Representative and controlled temperature
  - Solution
    - Provide a rig with stable temperature control in low to moderate flux position (0.X dpa in one or 2 reactor cycles)
    - Validate data on standardised specimen type against surveillance data from plant
    - Generate new data beyond database on newly irradiated samples
The new RECALL device

- Requirement: material irradiation in typical LWR conditions
  - Loading of full size Charpy specimens (>10)
  - Stable irradiation temperature before, during & after irradiation (250-320°C)
  - Flux levels relevant for LWR plant life management: 0.05 to 0.15 dpa per reactor cycle of 3 weeks

- Solution
  - Reusable rig with flexible loading position in reactor
    - Short lead times
    - Limited impact on other experiments
    - Variable position in reactor yields wider range of dose rates
  - >16 Charpy specimens in flux range >85% maximum
RECALL operation

- Pressurised water is injected at low temperature in IPS
  - Saturation pressure set to stabilize irradiation temperature
- Preheating to irradiation temperature
  - Heating of samples before start of irradiation
- Evacuation of nuclear heating by nucleate boiling
  - Stable irradiation temperature independent of heat flux
- Injection of cold water
  - Control of steam fraction and reactivity effect (void factor)
Temperature distribution

Sample center line temperature profile

- Vertical coordinates
- Temperature

- Without boiling
- With boiling
Steam fraction as function of cold water injection
Expected fast flux distribution in needles & structure
Conclusions

- 2 new devices are presented for material irradiation
  - High fast flux device for multi-cycle dpa accumulation: HTHF
  - Low fast flux device for ageing studies with strict temperature control: RECALL

- Utilisation of flexibility of reactor
  - Selection of fuel element with similar heating over cycles: HTHF
  - Creation of reflector position with desired fluence over 2 cycles and rotation at mid experiment: RECALL

- Cost effectiveness and short lead times
  - Generic design method and re-use of OPE: HTHF
  - Reloadable device in reactor pool or hot-cell: RECALL