Access to irradiation capacity in the BR2 reactor
Irradiation devices and access procedures

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Presentation content

- General features of the BR2 reactor
- Irradiation device loading
- Generic devices for material irradiation
- Generic devices for fuel irradiation
- Administrative procedures
General features of the BR2 reactor

- **BR2 = high performance material test reactor**
  - 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 $6 \times 10^{14} \text{n/cm}^2\text{s}$

- Maximum rated power: 125MW cooling capacity of primary cooling system
  - Allowable heat flux in primary coolant
    - 470W/cm² for the driver fuel plates
      - Demineralised light water
      - Pressure to 1.2MPa, temperature 35-50°C
      - 10m/s flow velocity on fuel plate
    - Up to 600W/cm² can be allowed in experiments

- Compact core design with good access
  - Be + water moderated
  - Diverging core channels
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)
Flexible reactor configuration
Experiments can be loaded in full channel or inside central cavity of fuel element

Typical fluxes and dimensions are given below

<table>
<thead>
<tr>
<th>Channel type</th>
<th>Thermal flux range (10^{14}n/cm^2s)</th>
<th>Fast flux range (10^{14}n/cm^2s) ((E&gt;1\text{MeV}))</th>
<th>Gamma heating (W/g\ Al)</th>
<th>Diameter (mm)</th>
<th>Typical number available</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel1</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>Fuel2</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>Standard</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>Central large channel H1</td>
<td>up to 10</td>
<td>up to 1.8</td>
<td>3</td>
<td>200</td>
<td>1</td>
</tr>
<tr>
<td>Peripheral large channel Hi</td>
<td>3</td>
<td>1.3</td>
<td>0.1</td>
<td>200</td>
<td>4</td>
</tr>
<tr>
<td>Peripheral small channel P</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>
Experimental manipulation in BR2

- Tank in pool reactor
  - Irradiated materials can be inserted/retrieved during operation
  - Underwater transfer outside reactor building

- Pool connected to hot-cell for experiments mounting and dismantling
Generic devices for material irradiation

- SCK•CEN provides a full scope R&D capability on structure material research

- Qualification and safety studies of irradiation induced ageing effects on structure materials
  - Irradiation devices for high dose and low dose irradiation in representative conditions
  - Mechanical testing and corrosion studies in hot cell
  - Microstructure characterisation from atomic scale to full specimen size

- Scope
  - **Ageing** of current power reactors
  - **Development** of GEN4 & fusion
Ageing of pressure vessels: 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 required range of dose rates within cycle
  - >16 Charpy specimens in flux range >85% maximum
    - Alternative geometries (mini CT) also loadable
RECALL rig concept
The LIBERTY rig for material irradiation

- **Maximum flexibility irradiation rig**
  - 5 independent capsules in single rig in thimble tube: multiple temperatures
  - Very flexible irradiation time (minutes to weeks): multiple dose

- **Individual temperature control for each capsule**
  - Each capsule is designed for own temperature range
  - Active or passive capsules can be combined

- **Sample geometry very flexible**
  - Irradiation of large specimens, e.g. mini CT-Specimens (10 x 10 mm²) possible
  - Adaptive single use capsule design
Loading "LIBERTY" in the thimble

Loading the needle in "LIBERTY"

Temperature Control

Holder preparation

Specimens

Needle
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
BAMI capsules for screening irradiation

- Capsule irradiation in BAMI
  - Low temperature & high flux
  - Variable small specimens
  - Low cost, 8 capsules/position

<table>
<thead>
<tr>
<th>Device</th>
<th>BAMI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Environment</td>
<td>He or BR2 coolant</td>
</tr>
<tr>
<td>T [°C]</td>
<td>&lt;100</td>
</tr>
<tr>
<td>P [bar]</td>
<td>12.5</td>
</tr>
<tr>
<td>Fast flux* [10^{18} n/m^2/s]</td>
<td>1</td>
</tr>
<tr>
<td>Fast fluence* [10^{24} n/m^2]</td>
<td>2</td>
</tr>
<tr>
<td>Max. diameter [mm]</td>
<td>13</td>
</tr>
</tbody>
</table>

* Fast flux/fluence is the flux/fluence for E>1 MeV

Sample holder with specimens

X-ray of a BAMI capsule containing a sample holder
The MISTRAL device for database generation

- **Application:** material irradiation at high flux and moderate temperature
  - High dose rate: loading inside fuel element
  - Stable irradiation temperature before, during & after irradiation
  - Reusable rig with flexible loading position in reactor

- **Solution**
  - Pressurised water capsule inside element with electrical heating
  - Boiling water for **stable temperature**
  - Use 5 plate fuel element: **87 positions** for miniature specimens

- **Characteristics**
  - Temperature **150-350°C**
  - Up to **0.5 dpa** per reactor cycle of 3 weeks
MISTRAL cross section

Examples:
- Titanium specimens
- MIPS pressure tube
- ADS specimens

13 levels

BR2 Vn Fuel element

T/C: 8

Electrical heater

Instrumented Mini Charpy

Sample positions
7 x 13 = 91 (87)

Dummy sample: 4 (with T/C)

Thermocouple
T/C: 4 + 8 = 12

Water

Φ 25 mm

Φ 5 x 27 mm (OD: 7.8 mm)

Mini Charpy

Electrical heater (Φ 9 mm)

Tensile specimen

Pressure tube (Φ 34 mm)
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
Nuclear fuel irradiation experiments

- SCK•CEN provides a full scope R&D capability on fuel research

- Development of new fuels and safety testing of current fuels
  - Determine safe operational conditions for fuel in representative and under overpower conditions
  - Steady state irradiation: power and burn-up limits
  - Transient irradiation: test safety margins
  - Safety tests: experience in accident condition testing and PIE

- Scope
  - Power reactor fuels
  - Test reactor fuels
Power reactor fuel tools

- **Fuel fabrication:**
  - Oxide fuel laboratory
  - Sectioning and refabrication of irradiated fuel pins

- **Fuel irradiation:**
  - Pressurised water capsule for steady state/transient test
  - Dedicated rigs (also for fast neutron irradiation)

- **Fuel characterisation**
  - Full scale Non Destructive and Destructive Testing in hot cell
  - Radio-chemical laboratory
Fuel pin irradiation

- **Steady state** conditions or **transient** conditions
  - **Linear power** levels up to $q_{l_{\text{max}}}$ = 750 W/cm
  - Rod power variation by reactor power variation
  - Power increase rate $\Delta q_{l}/\Delta t_{\text{max}}$ = 100 W/cm/min
  - Accuracy of the rod power can be measured within 5%

- **Fuel pin dimensions**
  - Cladding diameters: 8 mm - 12.5 mm
  - Fuel stack length: 20 cm - 100 cm (core height BR-2 80 cm)

- **Capsule water pressure** from 1 to 160 bar
  - Heat transfer by natural convection at low power levels...
  - ... combined with boiling and condensation heat transfer at high rod power levels (depending on the pressure)

- Applicable for UO$_2$, MOX, ThoMOX, actinide bearing fuels
  - Thermal spectrum irradiation in PWC
  - Fast spectrum irradiation: see CIRCE device
Pressurised Water Capsule (PWC) & Calorimetric Device (CD)
Typical power transient

![Graph showing a power transient between 0% to 100% of peak power when date and time are taken into account. The graph indicates a peak of approximately 465 W/cm.](image-url)
Test reactor fuel programmes

- Research and development programmes for Low Enriched Uranium fuel
  - Screening and validation irradiation of LEU fuel plates for high performance reactors (heat flux 450 to 600W/cm²)
  - Burn up accumulation to average values >55% (local > 80%)
  - SCK•CEN remains major partner in conversion studies for High Performance Research Reactors and isotope production

- Validation of prototype fuel element design
  - Full scale simulation of thermal-hydraulic conditions of research reactors
  - Optimised neutronic conditions
  - Full PIE capability
  - SCK•CEN is capable of providing a full scale validation programme of RR fuel elements for licensing purpose
Test reactor fuel tools

- Fuel fabrication
  - Powder coating device
  - Pre-irradiation characterisation

- Fuel irradiation
  - Test baskets for plate irradiation
  - Instrumented test loops for full element irradiations
  - Advanced modelling of irradiation conditions

- Fuel characterisation
  - Inter cycle inspections
  - Non-destructive + destructive PIE
MTR fuel plate irradiation: FUTURE basket

- Qualification of representative full MTR plates up to 600W/cm²
- Non-instrumented basket for low lead time experiments
- Irradiation conditions determined by detailed modelling and validated by quantitative PIE
MTR fuel element irradiation

- Dedicated set-up for prototype elements
  - Full size elements/partial elements
  - Separate loop/basket for representative cooling conditions

- On-line monitoring
  - Power, temperature, flux

- Inter-cycle inspection
  - Under water observation
  - Failure detection
Access for experiments

- **Organisation**
  - Project responsible: applicant for experiment, owner of result
  - Technical responsible: project engineer, design & safety analysis owner
  - Operator: manipulation and operation of experiment and reactor, final safety responsible
  - Safety committee: evaluation of safety analysis, advisory to internal safety department
  - Internal safety department: reporting to national TSO

- **Project preparation**
  - Project responsible + Business development & support team SCK•CEN
  - Internal project approval
    - Financial criteria
    - Strategic criteria
    - Scientific criteria

- **Procedure of safety approval of experiments (CEE evaluation) described in technical “manual”**
  - 4 stage approval: conceptual design evaluation, detailed design evaluation, testing and commissioning evaluation + return of experience
  - Simplified procedure: “repetition” irradiation in qualified rig with similar experimental load
The experiment and rig flow

CAPABILITY
- Rig conceptual design
  - CEE-1
- Rig detailed design (mech, TH)
  - CEE-2
- Rig construction and licensing
  - CEE-3
- Rig qualification

EXPERIMENT
- Experimental requirements
  - CEE-1
- Experiment matrix First neutronics
  - CEE-2
- Fabrication/QC Detailed neutronics
  - CEE-3
- Core load optimization

- Irradiation
  - As-run neutronics
  - CEE REX
- Intercycle measurements

- Integral PIE
- Dismantling

- Non destructive PIE
- Destructive PIE

- Waste storage and handling
Collaboration models with SCK•CEN

- Education and training
  - Basic aspects of irradiation experiments inside BR2 are subject of *Practical Course on Irradiation Experiments*, hosted by the SCK•CEN academy

- Bilateral scientific and technological collaboration projects
  - Common interest and equitable sharing of efforts and results
  - BR2 and SCK•CEN hot labs are affiliate infrastructure of US NSUF

- Service contracts
  - Shared scientific results at marginal cost
  - Commercial basis at full cost with full ownership of result

- Strategic partnership
  - Long term commitment with guaranteed access to unique infrastructure
IAEA recognized International centre based on research reactor