Experimental irradiations of materials and fuels in the BR2 reactor

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BR2 reactor

- Main tool in support of development of nuclear technology at SCK•CEN
  - Material and fuel testing for different reactor types
  - Integrated system and safety tests

- Scope of research
  - Light Water Reactors
  - Fast reactors (gas and sodium cooled)
  - High temperature gas reactor
  - Accelerator Driven Systems

- Irradiation services towards industry
  - Radio-isotopes for medical and industrial applications
  - NTD Silicon

- Current irradiation programmes
  - Studies in support of PWR development and life management
  - Studies in support of ADS development
  - Studies in support of material test reactor fuel development
  - Studies in support of fusion development (ITER, IFMIF)
General features of BR2

- Light water cooled tank in pool type reactor
  - Primary circuit cooling capacity: design rating 100MW
  - 1.2 MPa pressure, average temperature 40°C
Core configuration

- Beryllium + water moderated core
  - 79 reactor core channels, some accessible during reactor operation
  - Thermal flux: $10^{15} \text{n/cm}^2\text{s}$
  - Fast flux ($>0.1\text{MeV}$) $6 \times 10^{14} \text{n/cm}^2\text{s}$

- Flexible configuration
  - No “fixed” position of fuel and control rods
  - Possibility to install through reactor loops
A variable core configuration with customized irradiation conditions in the experimental positions

Full-scale 3D BR2 model used with MCNP 4C
beryllium-matrix

inclined beryllium hexagons arranged in a form of a twisted hyperboloid bundle around the central vertical channel

every channel is materialized by a hexagonal beryllium prism with central circular bore
Pool-type reactor

Easy access to irradiation channels with possibility to install large experiments
BR2 fuel characteristics

- Metallic fuel, U-Alx dispersion in cilindric plates
  - Standard element 80mm outer diameter, 24mm inner diameter, 6 plates, 76mm active length
  - 470W/cm² on fuel elements in normal conditions
  - Up to 600W/cm² in experiments
  - Burnable poisons, Maximum fission density : $1.6 \times 10^{21}/\text{cm}^3$
First criticality 1961
- License: no calendar limit, but decennial safety reassessments

Start-up: early 1963 $\Rightarrow$ 224,000 MWd
- 1\textsuperscript{st} major shutdown: Be-matrix replacement 1979
- Operation resumed with 2\textsuperscript{nd} Be-matrix: 1980 $\Rightarrow$ 180,000 MWd
- 2\textsuperscript{nd} major shutdown: major refurbishment 1996
- Operation resumed with 3\textsuperscript{rd} Be-matrix in 1997

Present decennial safety review valid up to 2016
- Technically to be qualified beyond 2020 (another 180,000 MWd)
Neutron Modelling of BR2

- Objective: support safety and quality of experiments:
  - Detailed information on neutron and photon flux distributions, fission and gamma heating in any part of the reactor core and over the duration of the reactor cycle

- Method:
  - 3-D Monte Carlo Modelling of BR2 with detailed geometrical description of the reactor and its experimental load
  - Axial and radial burn-up distribution in fuel elements
  - Full irradiation history recalculated with actual durations of operation cycles and shut down periods

- Validation:
  - Comparison of calculation with post-irradiation measurements
  - Comparison of calculation with on-line and in-pile measurements
Procedures for preparation of experiments

- Partner contact – request for offer
- Feasibility study – contract preparation phase
- Safety evaluation of experiment (CEE) phase 1 to 3:
  - Independent expert committee examines safety aspects of experiment
  - Advises internal safety department
- Authorisation for irradiation
  - Granted by TSO upon advice by internal safety department, as part of permission to start reactor cycle
- Safety evaluation of experiment (CEE) phase 4:
  - Return of experience
  - If positive, repetition of experiment can be permitted with short procedure
Safety Evaluation of Experiments

- **Phase 1: Conceptual design**
  - Compatibility between experiment concept and limits in reactor safety assessment report
  - Upon positive evaluation, detailed engineering design starts
  - Can be result of feasibility study for large projects
- **Phase 2: Detailed design**
  - Evaluation of detailed engineering design: mechanics, thermohydraulics, nuclear effects, corrosion, instrumentation, back-end of experiment
  - Upon positive evaluation, assembly of experiment is done
- **Phase 3: Reception tests**
  - Evaluation of experiment reception tests
  - Operation and accident procedures
  - Upon positive evaluation, permission to load experiment
- **Phase 4: return of experience**
  - Obligatory if repetition is applicable in future
  - For example, PWR loop irradiations are mostly considered as repetitions
Dedicated PWR facilities in BR2 have been developed:
- CALLISTO loop: full simulation of PWR in 3 in-pile sections
- PWC-CCD fuel pin testing capsule

Irradiation programmes for PWR applications
- Study of commercial fuel types:
  - MOX and evolutionary UO$_2$ fuels
  - Burn-up extension beyond licensed limit
  - Preconditioning and power transient testing

Innovative LWR fuels:
- Inert matrix fuels
- Th based MOX
- High TU loaded fuels
- Screening tests to low and medium burn-up

Structural materials
- Reactor pressure vessel steel: radiation embrittlement studies
- Reactor internals: radiation effects on mechanical and stress corrosion behaviour
Characteristics of CALLISTO IPS
Positioning of CALLISTO
# Irradiation conditions

## BR2 Configuration

| Nominal Power: | 20 | 55 MW |

### Neutron flux \(10^{14} \text{n/cm}^2.s\)

<table>
<thead>
<tr>
<th>Channel</th>
<th>Thermal</th>
<th>Fast (&gt;1 Mev)</th>
<th>(\gamma) heating [W/gr(_{Al})]</th>
</tr>
</thead>
<tbody>
<tr>
<td>D180</td>
<td>4.1</td>
<td>0.9</td>
<td>6.0</td>
</tr>
<tr>
<td>K49</td>
<td>1.2</td>
<td>0.1</td>
<td>1.0</td>
</tr>
<tr>
<td>K311</td>
<td>1.5</td>
<td>0.2</td>
<td>1.3</td>
</tr>
</tbody>
</table>

### Parameter

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Typical value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Linear power at hot plane</td>
<td>350 \text{W/cm}</td>
</tr>
<tr>
<td>Axial shape factor (max/avg)</td>
<td>1.6</td>
</tr>
<tr>
<td>Coolant pressure</td>
<td>155 \text{bar}</td>
</tr>
<tr>
<td>Coolant mass flow rate (in IPS)</td>
<td>2.1 \text{kg/s}</td>
</tr>
<tr>
<td>Av. coolant velocity along rods</td>
<td>3 \text{m/s}</td>
</tr>
<tr>
<td>Coolant temperature</td>
<td></td>
</tr>
<tr>
<td>at fuel bundle inlet</td>
<td>294 \text{°C}</td>
</tr>
<tr>
<td>at fuel bundle outlet</td>
<td>313 \text{°C}</td>
</tr>
</tbody>
</table>
Fuel pin power evolution during reactor cycle
In-pile behaviour studies

- Instrumented rods:
  - central temperature
  - gas pressure in rod plenum
  - Length dilatation
- Benchmarking of codes for fuel behaviour
  - Thermo-Mechanical behaviour
  - Microstructure development
  - Fission products

[Graphs showing data for OMICO Rod II and Axial Burnup profiles of the Instrumented rods]
Fission gas release studies

- Model of fuel microstructure is coupled to nuclear modelling: MACROS code
- Prediction of fission gas behaviour as function of irradiation history

Burn-up distribution

FP distribution
PWC-CCD device for transient testing

- Pressurised water capsule with calibration and cycling device (PWC-CCD)
  - PWC provides specified irradiation temperature and barrier for fission products in case of fuel pin failure.
  - CCD device allows for precise thermal balance: fission power and nuclear heating (latter calibrated by irradiation of stainless steel dummy rod).
Material irradiations

- Volume of CALLISTO allows for large number for specimens to be irradiated in PWR relevant conditions to low and medium dose
- Reactor pressure vessel materials
  - IPS3 for irradiation of materials to support-extend RPV surveillance programmes
  - IPS2 to evaluate flux effects
- Reactor internals: IPS2 for study of irradiation effects on mechanical behaviour, microstructure and stress corrosion behaviour
  - Comparison of alloys, irradiated under well controlled conditions for screening of metallurgical factors controlling mechanical and corrosion behaviour
  - PWR chemistry allows in-pile crack nucleation tests
Example: IASCC of stainless steels with tailored stacking fault energy

- Irradiation of tensile specimens to 1 dpa in CALLISTO IPS2
- PIE testing in PWR environment in hot-cell
- Fractography and TEM to identify mechanical and corrosion correlation to SFE

![Image of LSFE, Ref SFE, and HSFE samples]

![Graph showing correlation between SFE and IASCC]

<table>
<thead>
<tr>
<th>LSFE</th>
<th>Ref SFE</th>
<th>HSFE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>64mJ/m²</td>
</tr>
<tr>
<td>23</td>
<td>38</td>
<td></td>
</tr>
</tbody>
</table>
Correlation between IASCC and channel density

Low SFE: larger channels on several slip systems – high strain concentration

High SFE: small channels, parallel, low strain concentration
Crack nucleation in stainless steel swelling mandrels

- Threshold combination of strain and dose:
  - 3% strain: provided by swelling of B$_4$C in Al$_2$O$_3$
  - 2.2 dpa, accumulated in 220 days
Summary PWR irradiations

- “Standardised” irradiations in well validated conditions
- Service activity for commercial materials and (mainly) fuels with strong scientific backing
- Research activity for development of better understanding of underlying phenomena and screening of new materials
- Flexible use of facility from technical and organisational point of view.
Development of Accellerator Driven Systems - ADS

- MYRRHA project of pilot scale ADS test reactor at SCK•CEN
- Supportive R&D for qualification of materials, fuels and irradiation technology.
- Main issues:
  - Material degradation at expected MYRRHA irradiation conditions: validation of preliminary material selection.
  - Compatibility of materials with liquid metal coolant before and after irradiation
Simulation of ADS: the ASTIR experiments

- Simulation of ADS conditions: irradiation in molten PbBi at 450°C
- Irradiation of structure materials
- Cooling by primary coolant BR2
- Irradiation temperature control by thermal barrier gap
- Control of atmosphere to prevent Po release.
ASTIR Capsule design

- Double wall construction with a thin gap filled with He
  - Irradiation temperature control:
    - Axial flux distribution: a variable gap width from 0.08mm to 0.5mm for a constant temperature
    - Active He pressure control to achieve 450°C in the capsule.
  - 8 thermocouples and 2 heating elements
- Safety:
  - Retention of Po
  - Controlled freezing and melting between reactor cycles
Capsule load

Charpy

CT

Pressurized tubes filled with 102 bar Ar at 20°C

Tensile
Out of pile equipment

- **Function**
  - Helium pressure control
    - From 1mbar to 1200mbar in the gap
  - Temperature control
    - Cascade control with pressure control as slave and temperature as master
    - Process is very slow
    - Process is non-linear
  - Check of integrity of instrumentation penetrations and in-pile section seals

- **Safety considerations:**
  - From 1200mbar to 1mbar in less then 15 minutes to prevent freezing of PbBi during a reactor scram or reverse
  - Prevention of Po release in normal and accident conditions
Summary of ADS irradiations

- Challenging application due to new irradiation environment requested
- Development of PIE capabilities in parallel with irradiation technique development
- Opportunity for (re)new(ed) irradiation technology for using maximum fast flux irradiation positions
- Preparation of research and development programmes for future ADS and fast reactors
MTR fuel development

- Qualification of LEU based fuel for high performance MTRs
  - High density dispersion type U-Mo as prime candidate
- Stepped irradiation programme
  - *Miniature plates for screening (ATR)*
  - Full size plates for optimal production parameter selection
  - Mixed element irradiation
  - *Qualification of burnable absorbers in element structure*
  - *Lead Test Assembly irradiation with burnable absorbers*
U-Mo fuel plate test: E-FUTURE

- 4 plate test irradiation
- 3 sets of dosimeters in central plate
- Average heat flux 245-255W/cm²
- Maximum heat flux 460-470W/cm²
Thermal-hydraulic design

- Input: mechanical design, inlet water temperature, pressure drop along the core, MCNP power distribution

- Output: flow distribution, temperature distribution on plate surface

- Verification of acceptance criteria for experiment is OK
MTR fuel development II
Simulation of Jules Horowitz Reactor: the EVITA loop

- Full scale RJH element qualification
- Representative thermal hydraulic simulation
- Open cooling system
Irradiation Objectives

- Qualification of the fuel element for RJH, including:
  - Irradiation beyond the maximal burn-up at elements unloading
  - Representative power generation (mean power, peak power and power gradients between plates)
  - Representative thermal-hydraulic conditions:
    - cladding temperature
    - coolant velocity
  - 109 to 146 irradiation days per element (in function of required burn-up).
8 plates fuel element, 96.2 mm O.D. fuel element
   - BR2 is 80 mm O.D.
- $\text{U}_3\text{Si}_2$ 4.8 g/cc fuel enriched at 27% with 0.61mm meat thickness (first phase)
- 516 W/cm$^2$ at the hot spot including fuel density uncertainty (10%>BR2 fuel spec.)
- Up to 60 % burnup to be reached in 5 BR2 cycles
- Distance between plates: 1.95 mm
  - 3.0 mm in BR2
- 15 m/s average coolant velocity
  - 10 m/s in BR2
- No burnable poison.
Implementation of test objectives

- Particular features with impact on BR2 operation:
  - A full size fuel element must be irradiated at high power level
  - Larger size and pressure drop than standard BR2 element: open loop in BR2 with enhanced flow from booster pump
  - EVITA uses a modified H1 channel (200mm) with 98mm central hole & 2 aspiration plugs in periphery

- Strong interaction between RJH element and BR2:
  - Deterministic influence on reactor power in order to achieve specified power level; perturbation of some isotopes productions (Ir) and impact on other experiments
  - Reactivity evolution in function of burn-up: 70% Aluminium / 30% water environment in the beginning, solid Beryllium at the end
First element has been irradiated for 8 weeks (2 cycles) in 2009
- Accumulated burn-up 38%
- First, non destructive PIE reveals no defects

Irradiation of second element is ongoing
- 2 reactor cycles (3 weeks each) completed
- Switch to Be plug has been done after evaluation of reactivity effect
- 2 more reactor cycles (4 weeks each) planned to reach target burn-up
Test results: power density over first irradiation cycle
Temperature measurement

Average delta T used for total power determination and calculation of maximum power
Maximum power to be corrected for “hot channel”
Test results: flux measurements over first irradiation cycle
Unloading of the RJH element after its first irradiation cycle
Intermediate results

- RJH fuel element behaves as expected
- Deviation of about 10% between expected and measured power:
  - Gamma heating in structure contribution was revised: deviation of 5%
- Analysis of thermal balance requires high degree of detail: temperature distribution at outlet may cause 5% of deviation of power determination based on thermal balance from average temperature increase.
Summary MTR fuel irradiation

- Unique features of BR2 reactor are used to full extent.
- Due to high performance of reactor, wide range of MTR fuels can be tested.
- U-Mo qualification programme is first step in conversion process of BR2 and partner reactors.
In-core testing

- Easy access of BR2 core allows for the installation of in-pile instruments and active mechanical components
  - Nuclear instrumentation
  - Environment monitoring
  - Mechanical testing
  - Irradiation testing of mechanical and electronic sensors

- Environment of testing
  - Primary BR2 water – reactor pool water
  - PWR water – CALLISTO loop
  - Vacuum – liquid metal capsules
In-pile mechanical testing

- Uni-axial tensile testing and fatigue studies

- Objective: study of competition between radiation damage accumulation and dynamic recovery and its effect on mechanical behaviour

- Technology: loading with gass filled bellows; LVDT and strain gauges for force-displacement control

- Test environment:
  - Water (up to 100°C) or liquid metal (up to 450°C)
Objective:
- Improved quality by on-line monitoring of experiments
- Qualification of instruments for use in other facilities

Typical applications
- Flux monitoring: gamma and neutrons
- Environment monitoring: ECP measurement, hydrogen sensor for LWR environment
- Qualification of instruments: fibre optics and sensors for on-line monitoring of large installations (e.g. ITER)
Summary in-pile testing

- Targetted to both internal as external users
- Both internal development as well as international partnership
- Relying on large experience in instrumentation of complex irradiation experiments
- Often small scale experiments – piggy back irradiations
Typical loading of the BR2 core anno 2010

- Control rods
- Mo production devices
- Short irradiation activation isotopes production devices
- PWR test loop
- Si doping device
- JHR simulation loop
- U-Mo test capsule
- Standard irradiation capsules for materials and activation isotopes
“Commercial” strategy for irradiation projects

- Strategic importance of scope of irradiation project:
  - Fit in “core” business of institute
  - Valorisation and validation of previous experience and knowledge: e.g. PWR irradiations, in-pile testing of instrumentation, “repetitive” experiments
  - Opportunity to develop expertise relevant for future strategy: MTR fuel development, GEN IV & ADS material testing

- Compatibility of all irradiation projects:
  - Impact on reactor operation
  - Priority setting

- Implementation of partnership
  - “Pure” service vs joint development
  - Construction of balanced user community including research institutes, utilities, nuclear suppliers, authorities, other industries
  - Create added value for all partners
Summary of the possibilities of BR2

- **Fluxes and dpa:**
  - Up to $10^{15}$ n/cm$^2$/s thermal and $6 \times 10^{14}$ n/cm$^2$/s fast (>0.1 MeV)
  - Up to 0.5 dpa/cycle, 5 cycles per year $\Rightarrow$ **2.5 dpa/year**

- **Available irradiation volumes (with \~ cosm flux profile):**
  - standard channel: 80 mm diameter, 900 mm height
  - large channel: 200 mm diameter, 900 mm height

- **Environment determined by irradiation devices**
  - PWR loop conditions, water pool conditions, stagnant water, stagnant inert gas, liquid metal, vacuum, air cooling flow
  - Temperature ranges from 50 to 600°C, depending on the irradiation device used

- **High flexibility**
  - Accommodation of experiments with conflicting requirements due to large gradients
  - Accessibility during reactor operation for short irradiations
  - Short lead time for repetitive irradiation experiments
  - Safety related experiments supported by inherent safety of BR2
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