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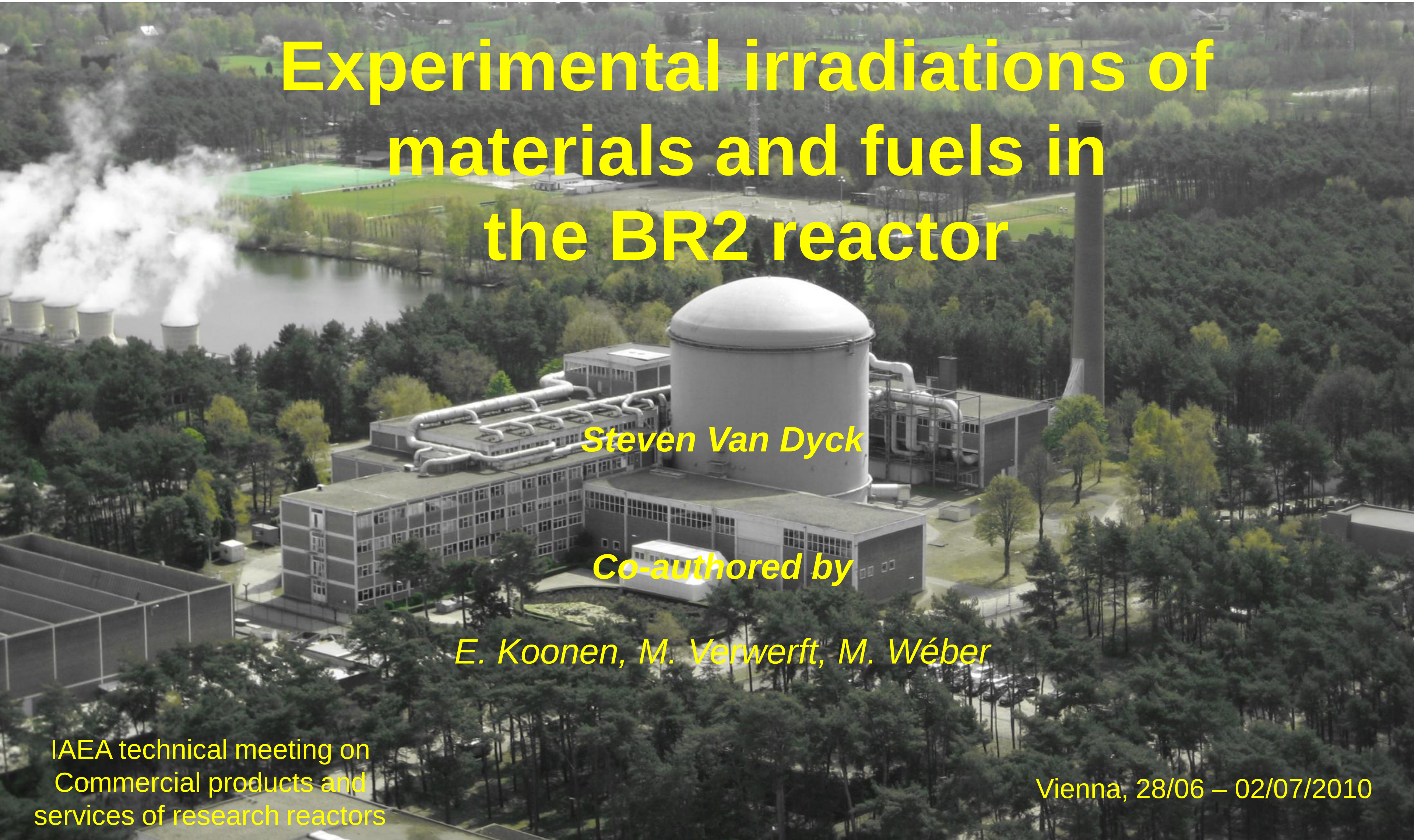
CENTRE D'ETUDE DE L'ENERGIE NUCLEAIRE



Experimental irradiations of materials and fuels in the BR2 reactor

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Co-authored by

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IAEA technical meeting on Commercial products and services of research reactors

Vienna, 28/06 – 02/07/2010

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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)

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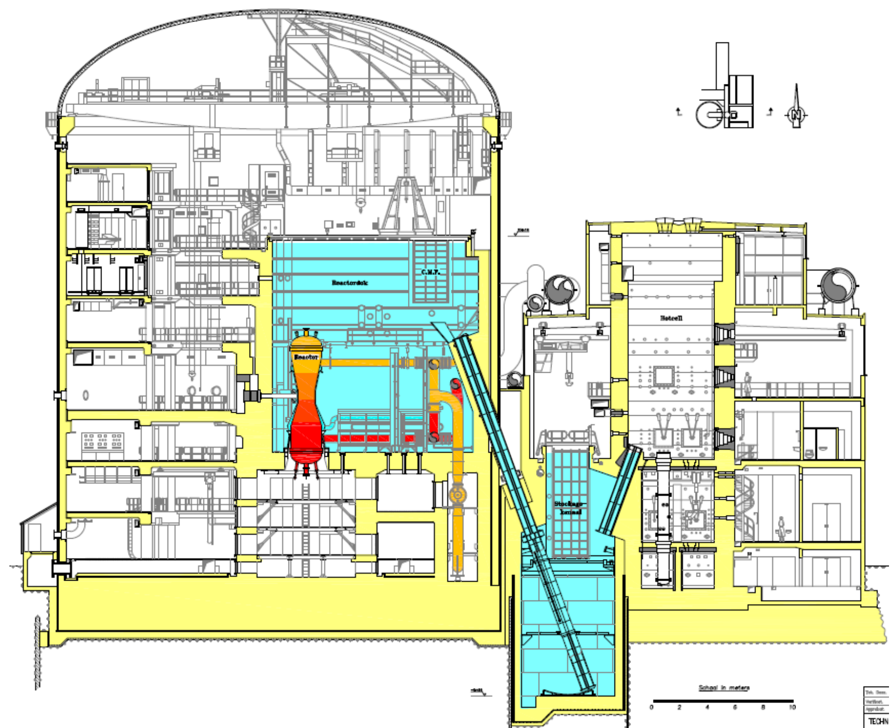
General features of BR2

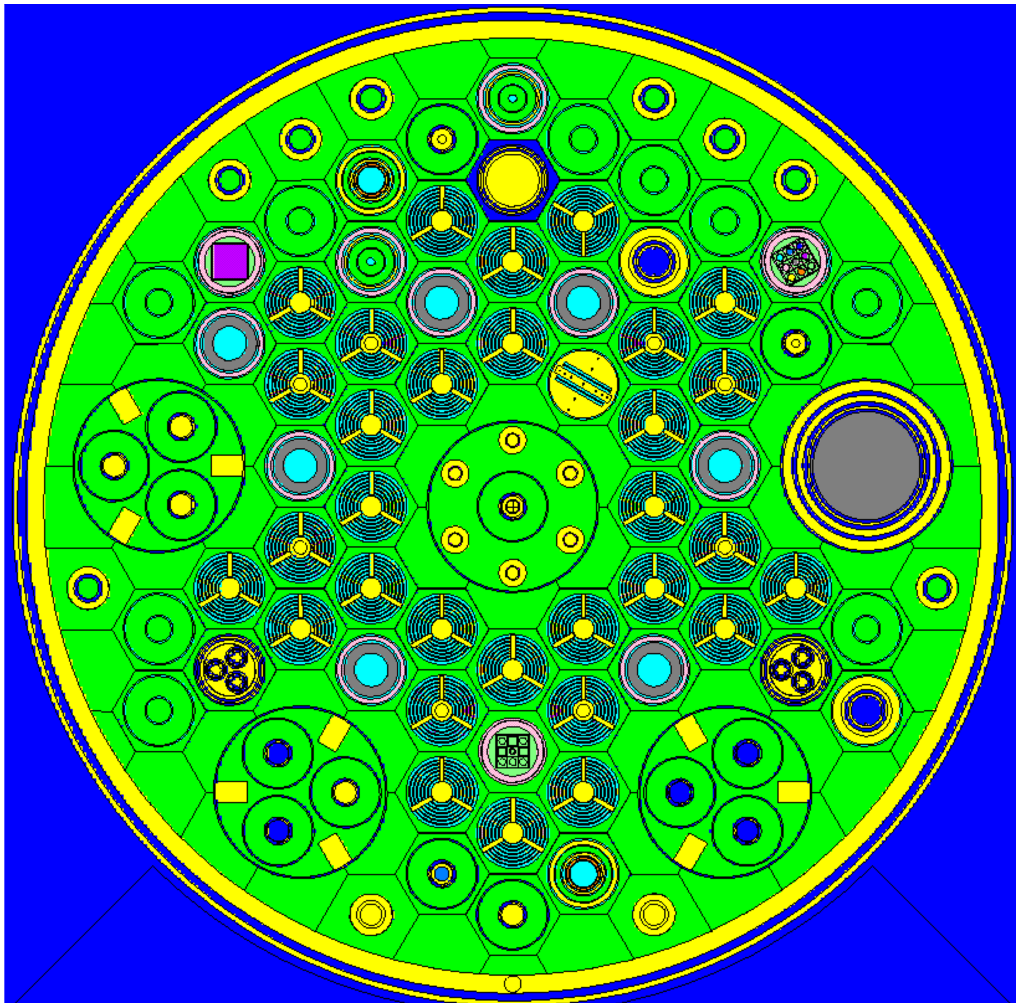
- Light water cooled tank in pool type reactor
  - Primary circuit cooling capacity: design rating 100MW
  - 1.2 MPa pressure, average temperature 40°C



Core configuration

- Beryllium + water moderated core
  - 79 reactor core channels, some accessible during reactor operation
  - Thermal flux: 10^{15}n/cm²s
  - Fast flux (>0.1MeV) 6 10^{14}n/cm²s)
- Flexible configuration
  - No “fixed” position of fuel and control rods
  - Possibility to install through reactor loops

BR2 core: cross section in the mid-plane



A variable core configuration with customized irradiation conditions in the experimental positions

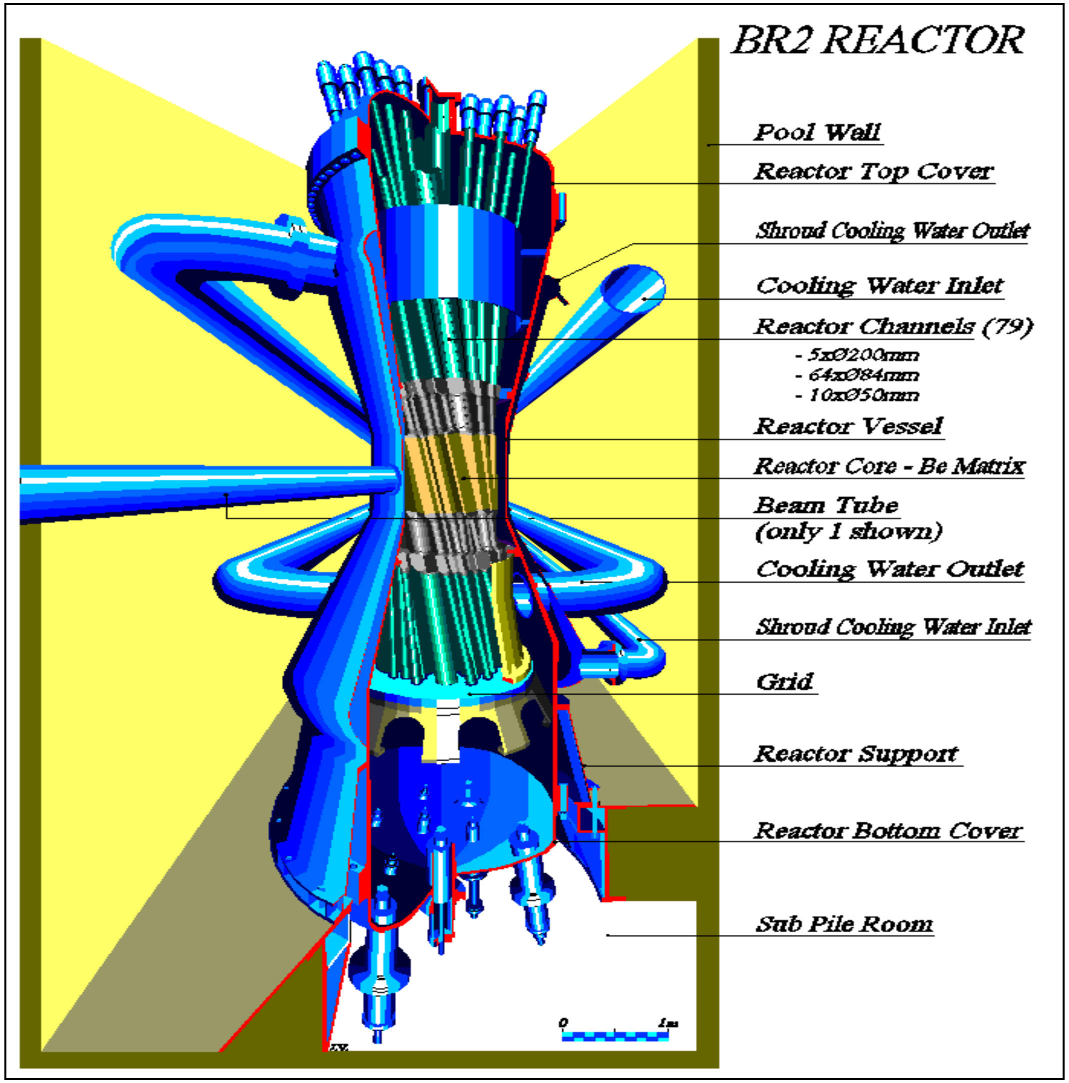
Full-scale 3D BR2 model used with MCNP 4C

BR2 reactor layout of core positioned in pressurised vessel

beryllium-matrix

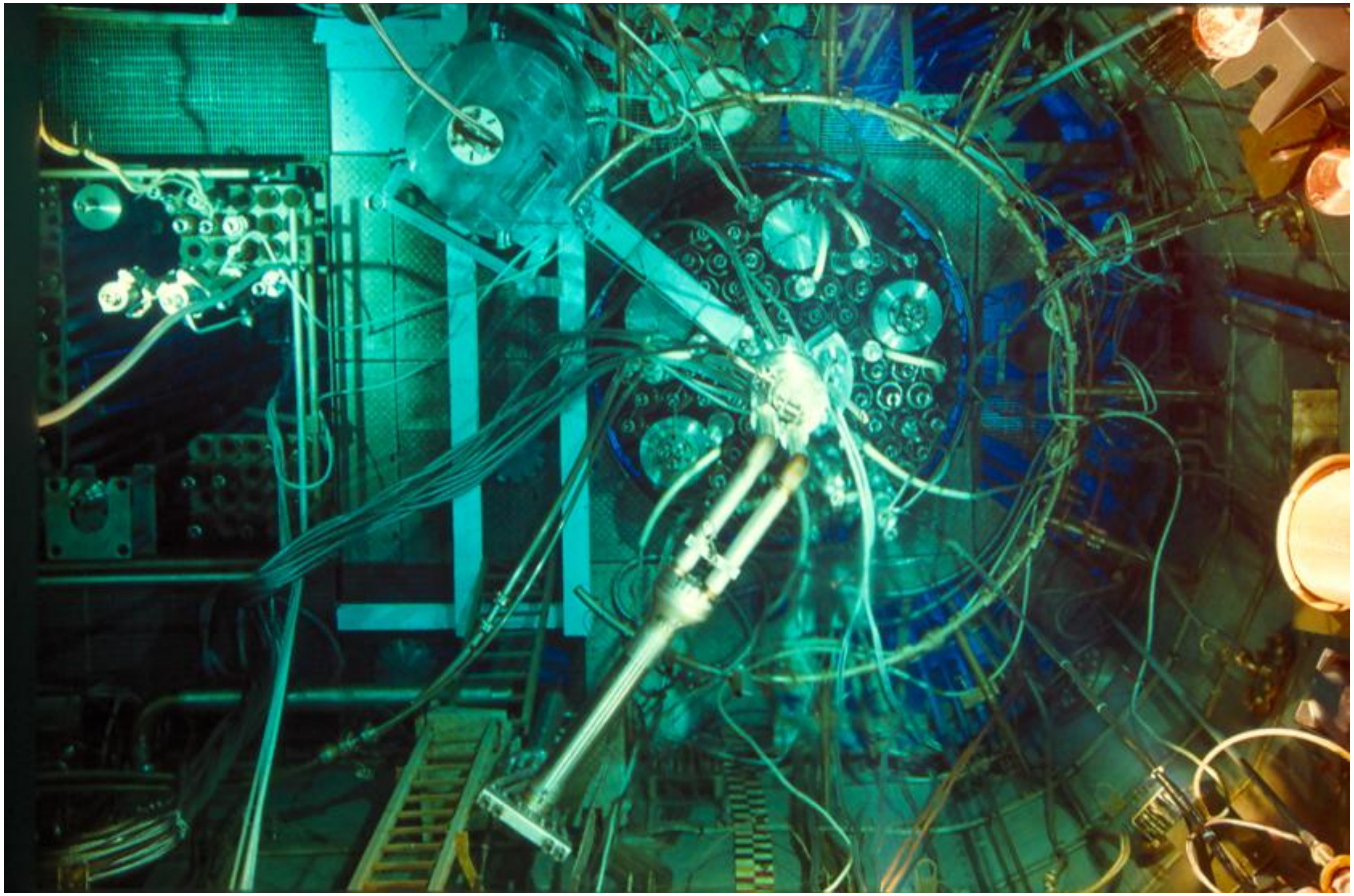
inclined beryllium hexagons arranged in a form of a twisted hyperboloid bundle around the central vertical channel

every channel is materialized by a hexagonal beryllium prism with central circular bore



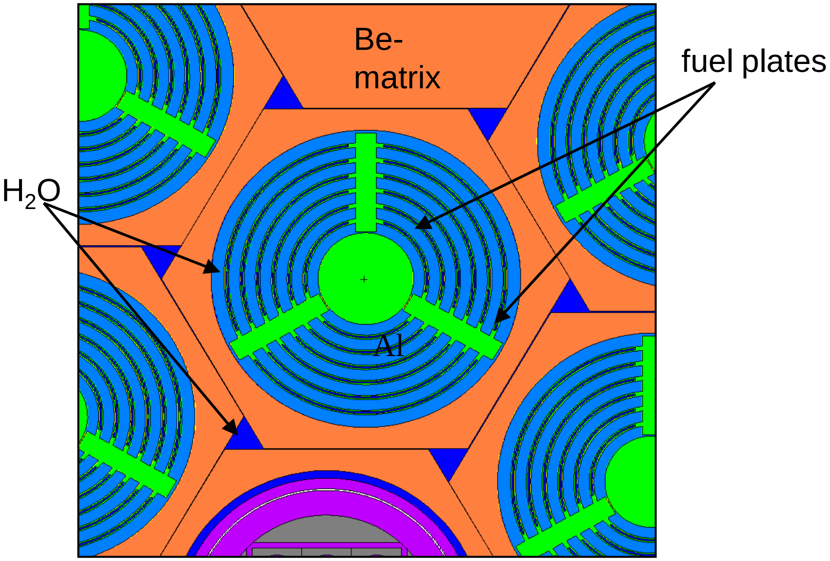
Pool-type reactor

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 10^{21}/cm³



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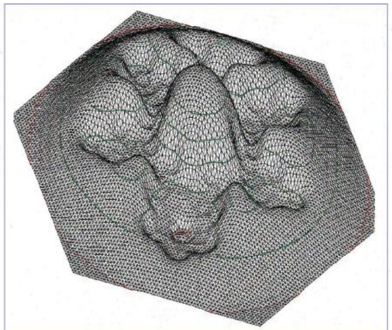
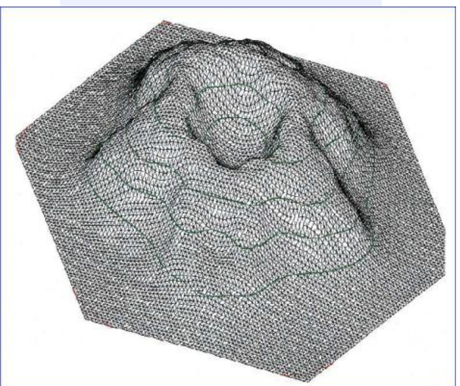
BR2 history & future perspectives

- First criticality 1961
  - ➲ License: no calendar limit, but decennial safety reassessments
- Start-up: early 1963 ⇨ 224.000 MWd
  - 1st major shutdown: Be-matrix replacement 1979
  - Operation resumed with 2nd Be-matrix: 1980 ⇨ 180.000 MWd
  - 2nd major shutdown: major refurbishment 1996
  - Operation resumed with 3rd 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

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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

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Safety Evaluation of Experiments

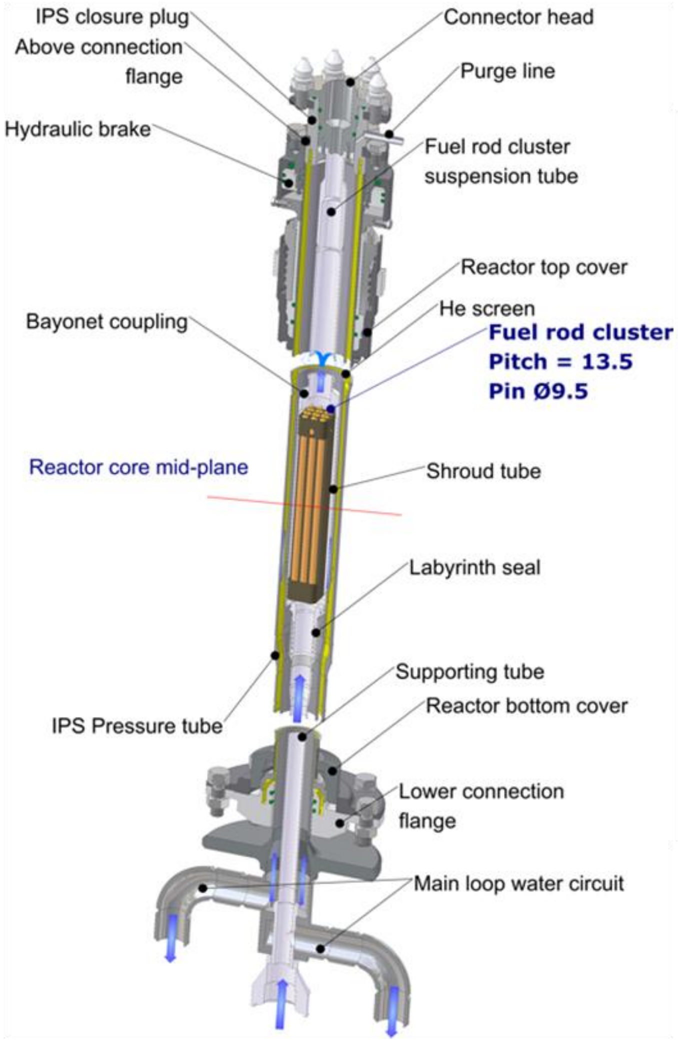
- Phase 1: Conceptual design
  - Compatibility between experiment concept and limits in reactor safety assessment report
  - Upon positive evaluation, detailed engineering design starts
  - Can be result of feasibility study for large projects
- Phase 2: Detailed design
  - Evaluation of detailed engineering 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

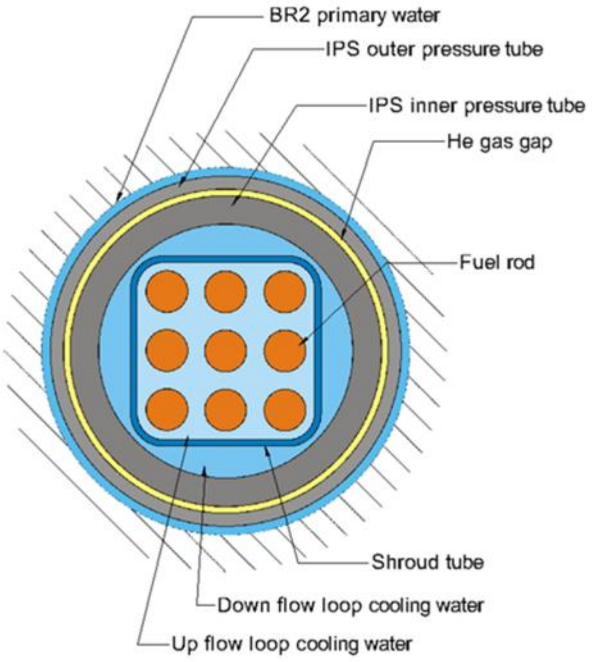
PWR irradiations at the BR2

- 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

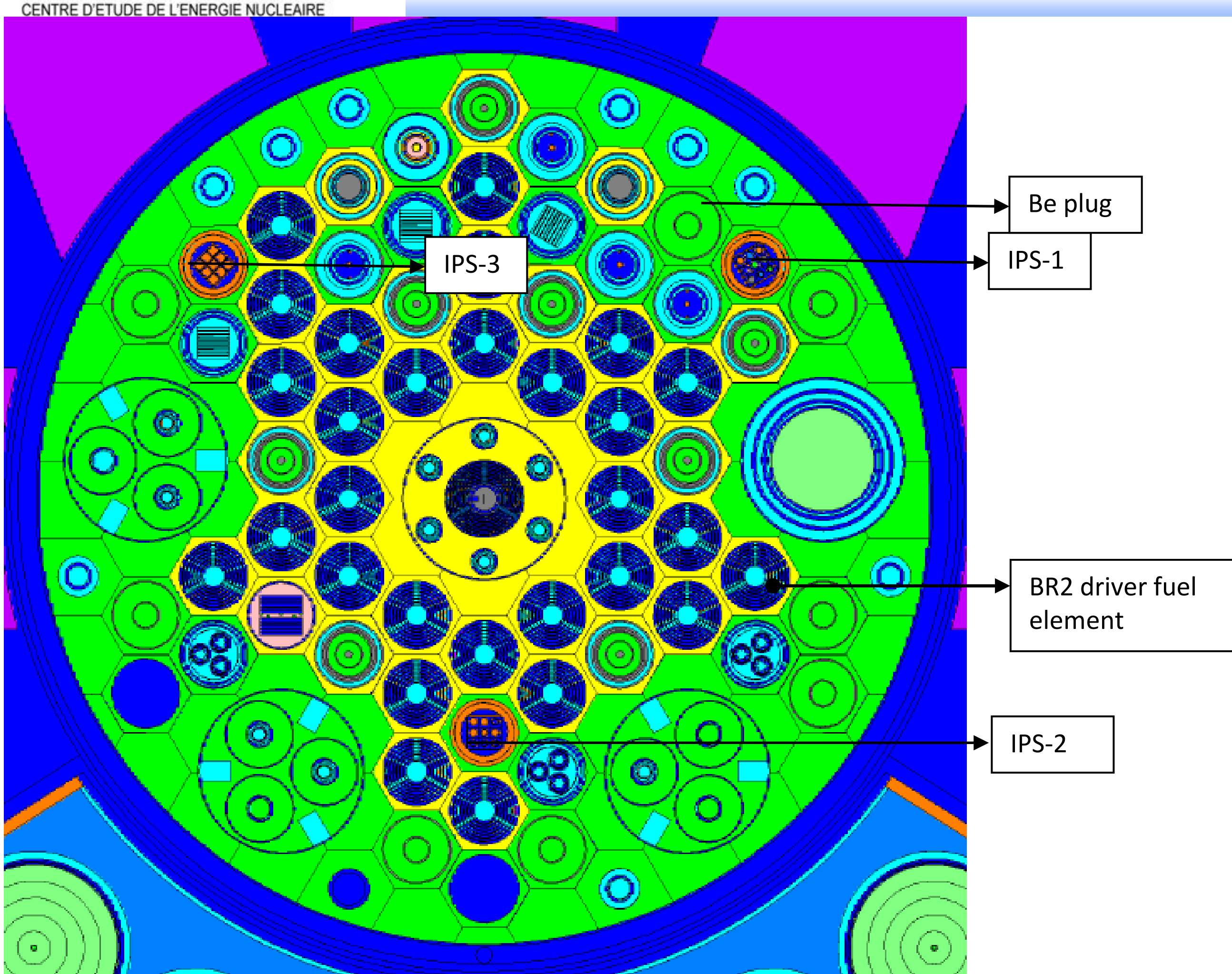
- Irradiation programmes for PWR applications
  - Study of commercial fuel types:
    - MOX and evolutionary UO_2 fuels
    - Burn-up extension beyond licensed limit
    - Preconditioning and power transient testing
  - Innovative LWR fuels:
    - Inert matrix fuels
    - Th based MOX
    - High TU loaded 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

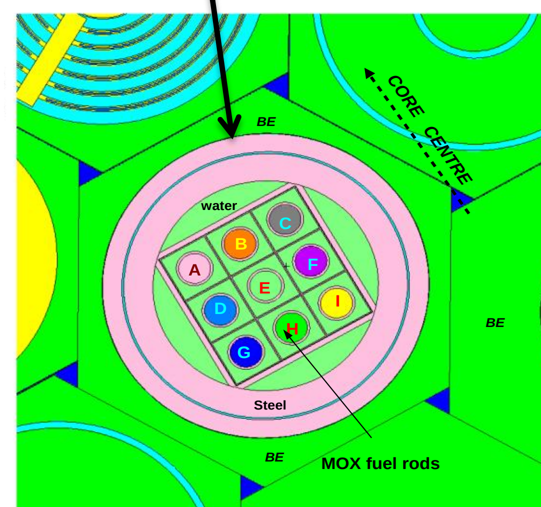
Characteristics of CALLISTO IPS





Positioning of CALLISTO





Irradiation conditions

BR2 Configuration **20**

Nominal Power: **55 MW**

Channel	Neutron flux [10^{14} n/cm².s]		γ heating
	Thermal	Fast (>1 Mev)	[W/gr_{Al}]
D180	4.1	0.9	6.0
K49	1.2	0.1	1.0
K311	1.5	0.2	1.3

Parameter	Typical value	
Linear power at hot plane	350	W/cm
Axial shape factor (max/avg)	1.6	
Coolant pressure	155	bar
Coolant mass flow rate (in IPS)	2.1	kg/s
Av. coolant velocity along rods	3	m/s
Coolant temperature		
at fuel bundle inlet	294	°C
at fuel bundle outlet	313	°C

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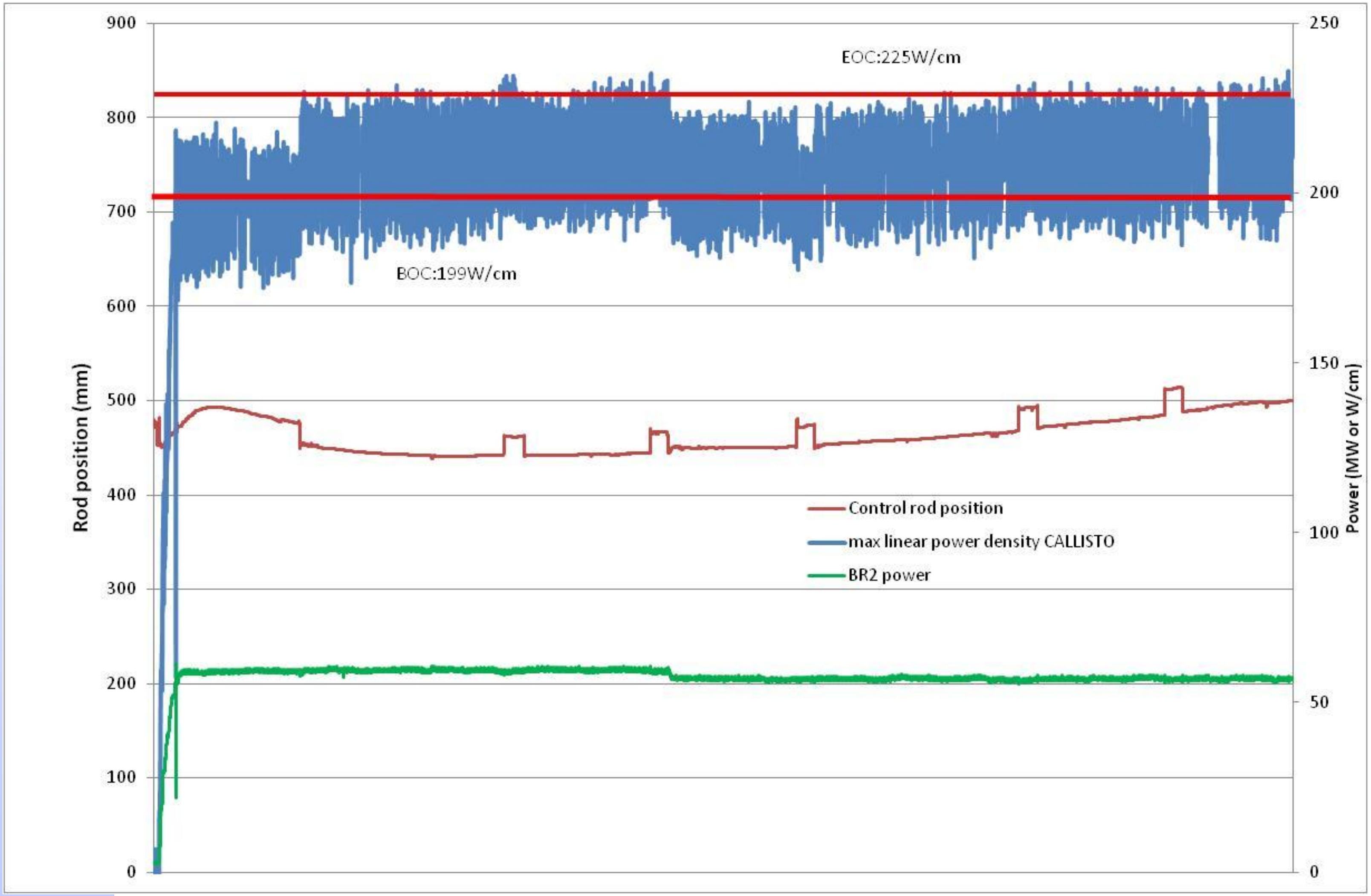
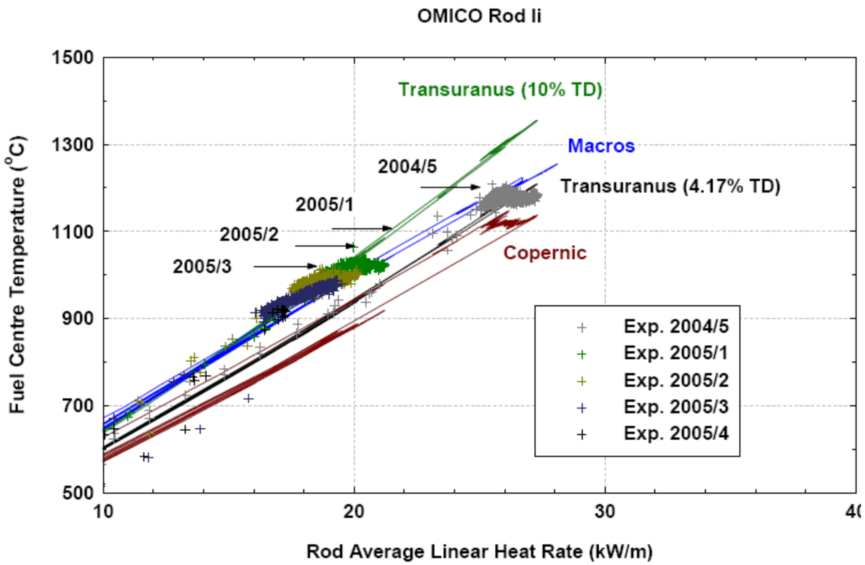
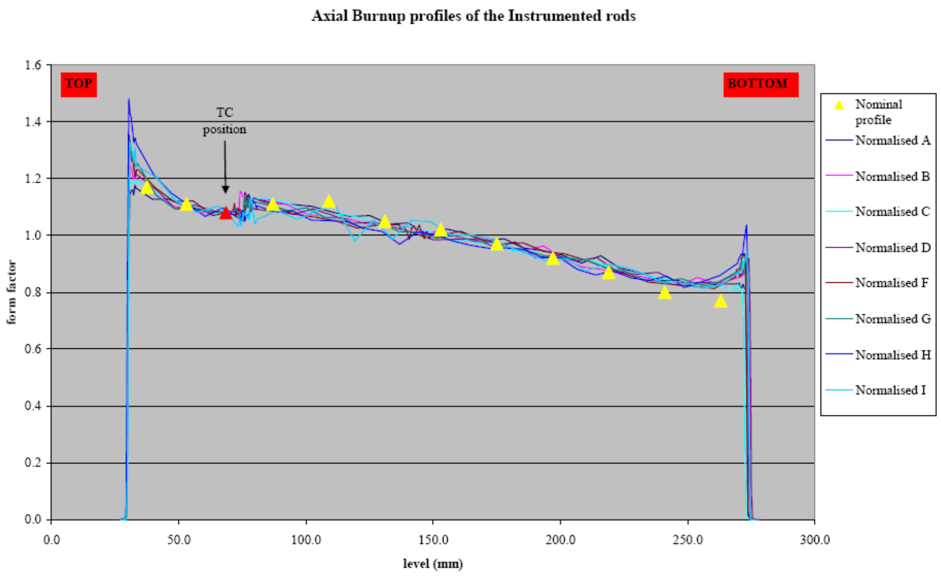
Fuel pin power evolution during reactor cycle



In-pile behaviour studies

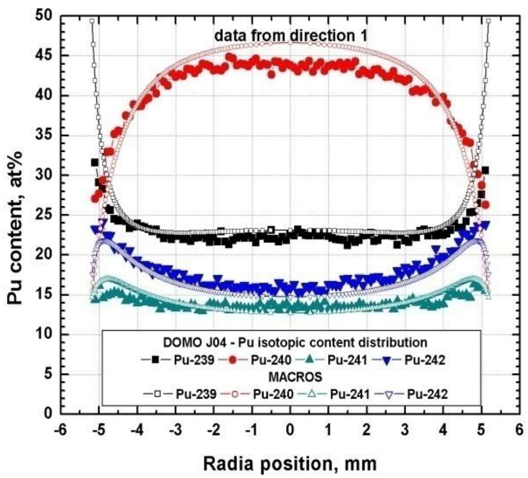
- Instrumented rods:
  - central temperature
  - gas pressure in rod plenum
  - Length dilatation
- Benchmarking of codes for fuel behaviour
  - Thermo-Mechanical behaviour
  - Microstructure development
  - Fission products



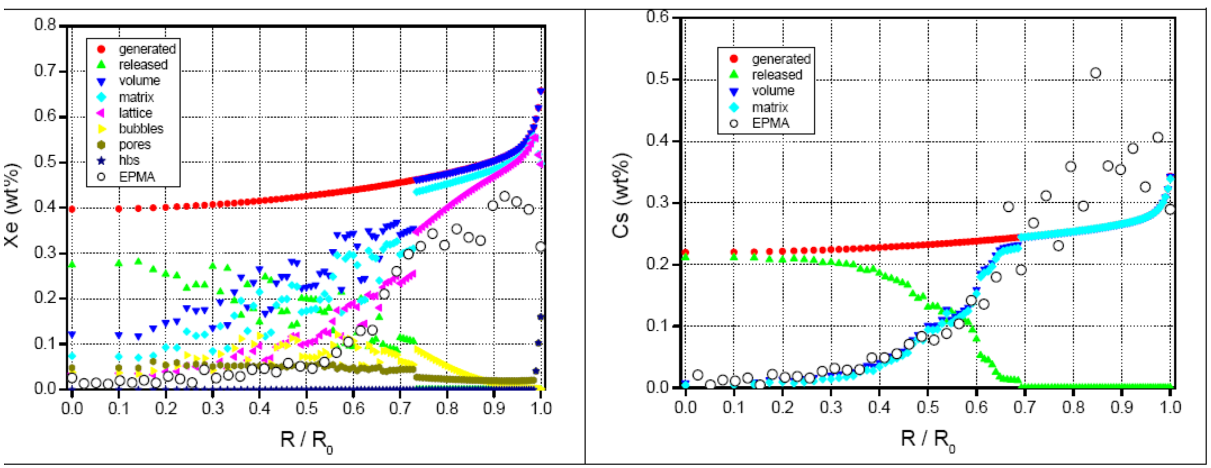


Fission gas release studies

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

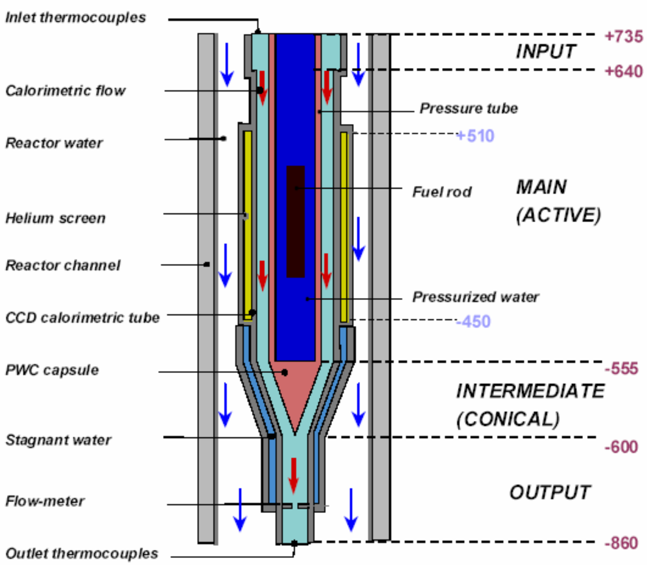


Burn-up distribution

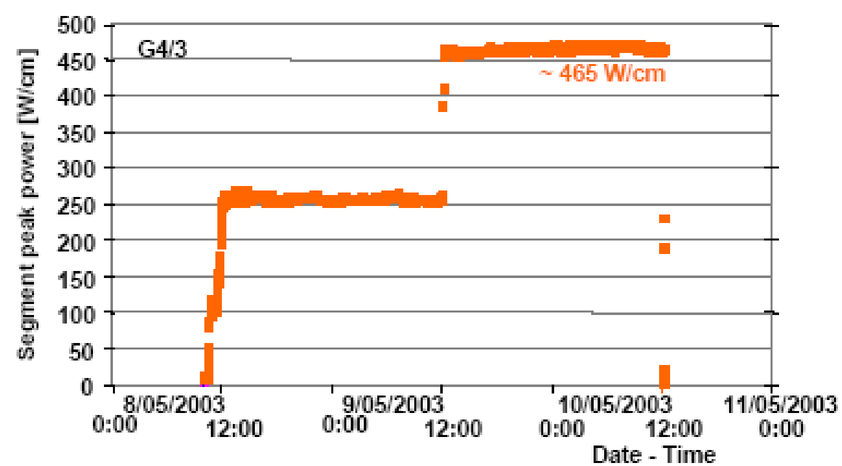


FP distribution

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).



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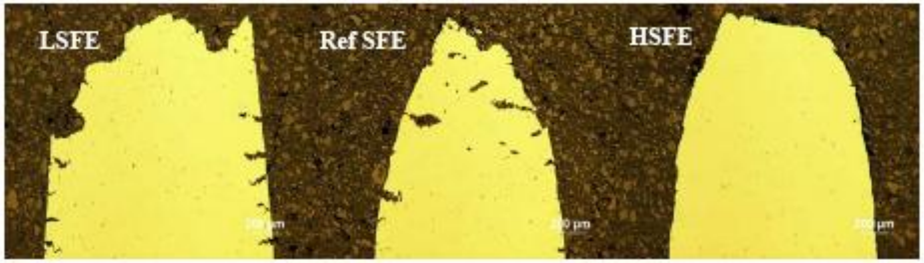
Material irradiations

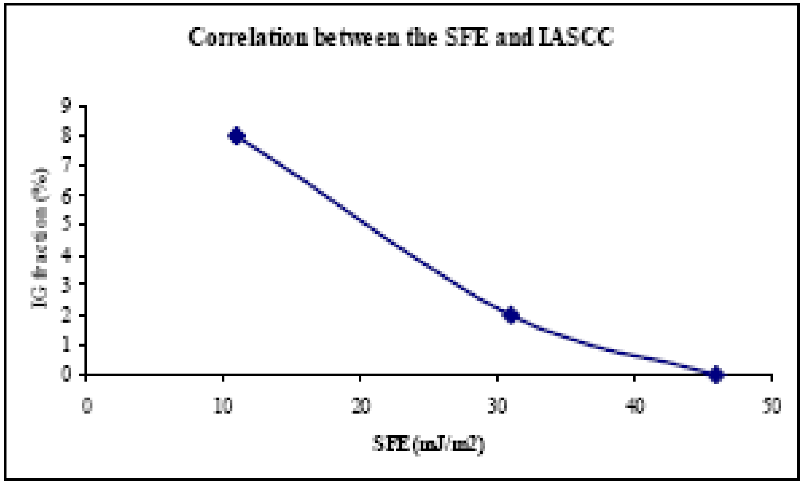
- Volume of CALLISTO allows for large number for specimens to be irradiated in PWR relevant conditions to low and medium dose
- Reactor pressure vessel materials
  - IPS3 for irradiation of materials to support-extend RPV surveillance programmes
  - IPS2 to evaluate flux effects
- Reactor internals: 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 mechancial and corrosion correlation to SFE



23 38 64mJ/m²



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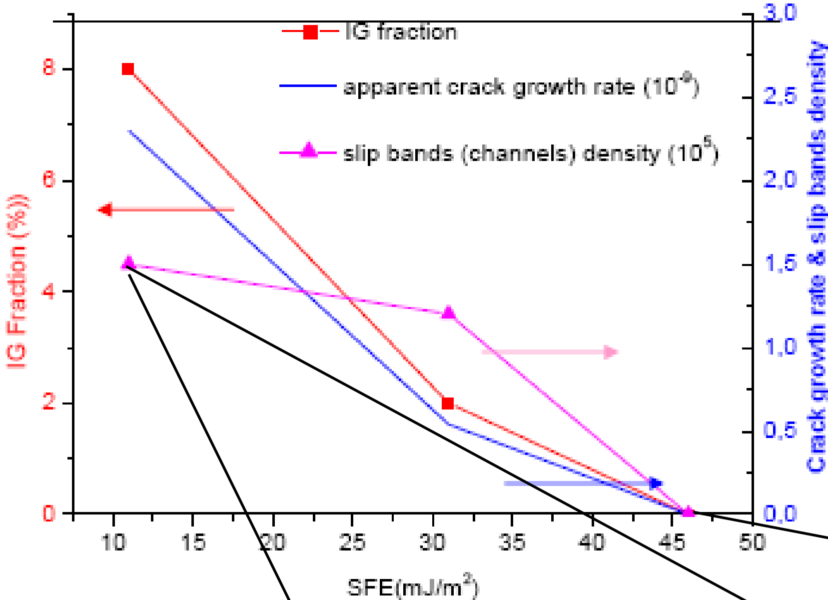
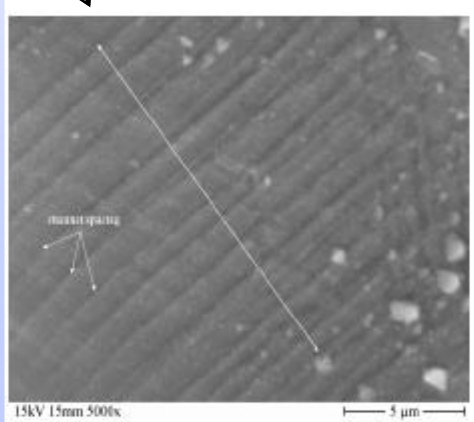
IASCC & deformation mode f(SFE)

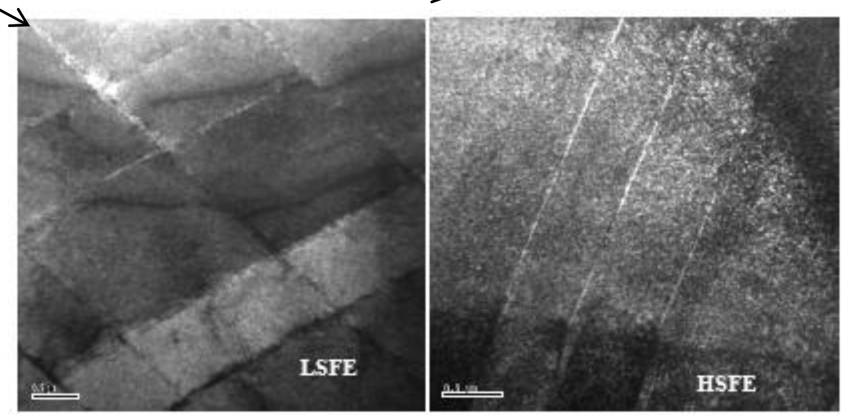


Correlation between IASCC and channel density

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

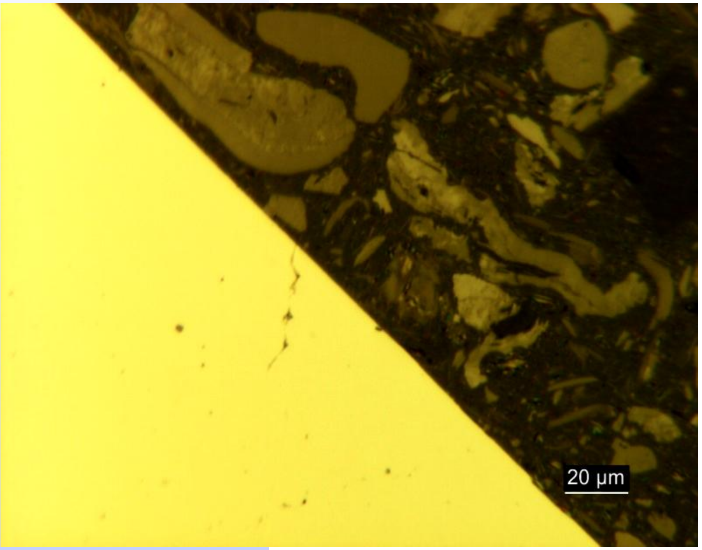
High SFE: small channels, parallel, low strain concentration

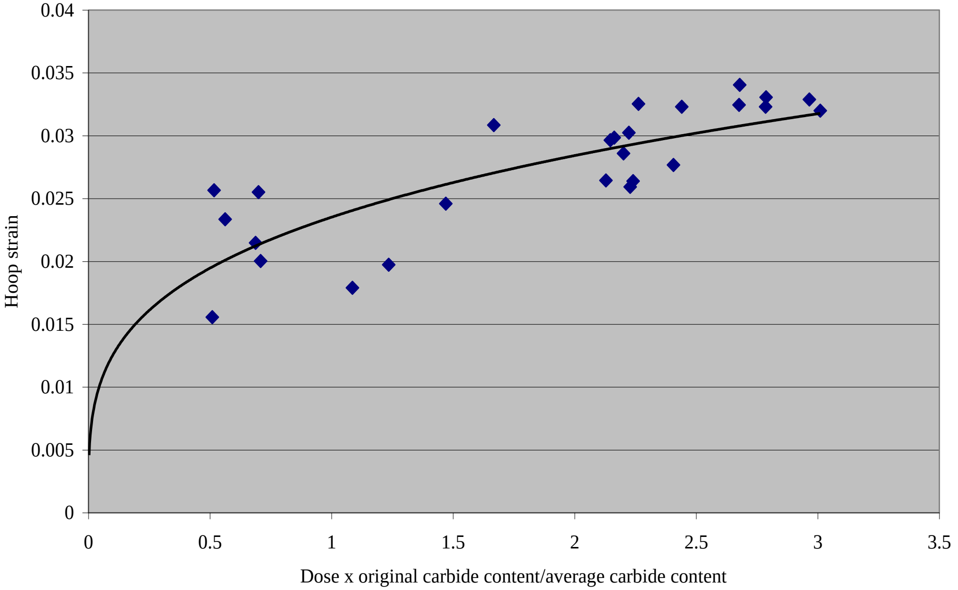




Crack nucleation in stainless steel swelling mandrels

- Threshold combination of strain and dose:
  - 3% strain: provided by swelling of B_4C in Al_2O_3
  - 2.2 dpa, accumulated in 220 days





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Summary PWR irradiations

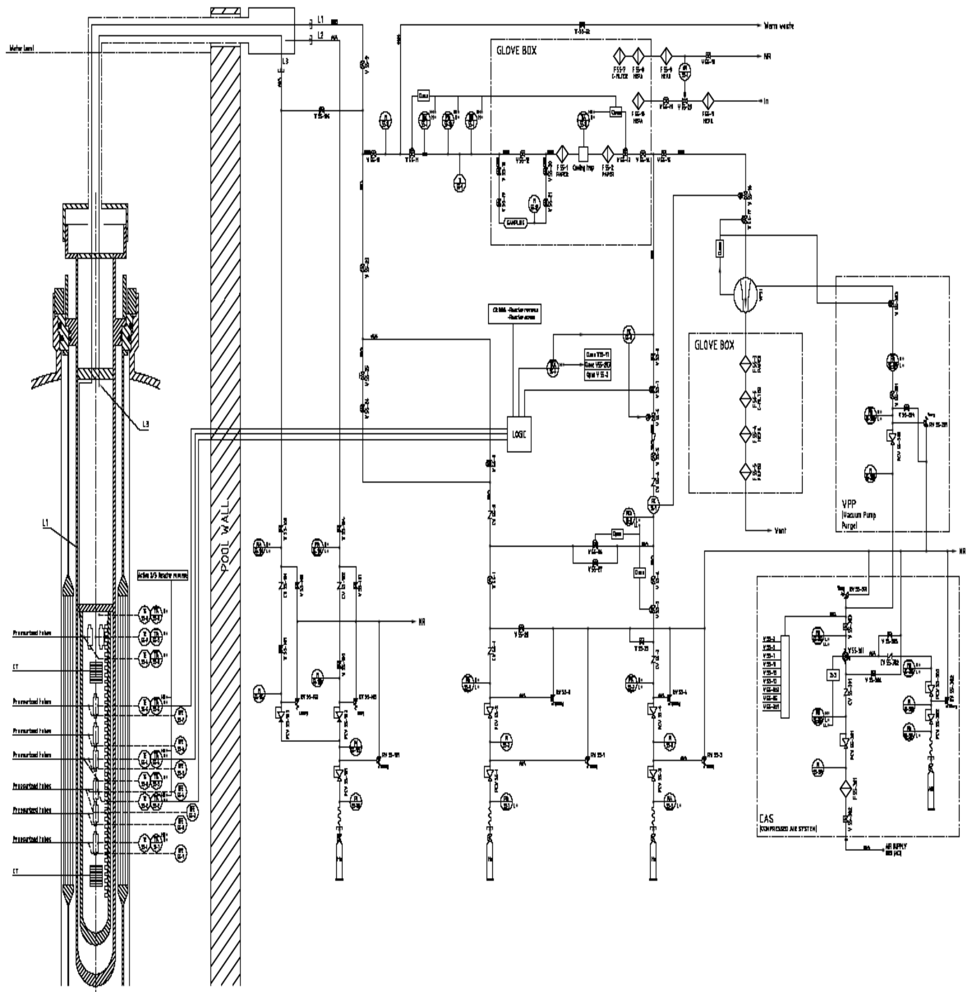
- “Standardised” irradiations in well validated conditions
- Service activity for commercial materials and (mainly) fuels with strong scientific backing
- Research activity for development of better understanding of underlying phenomena and screening of new materials
- Flexible use of facility from technical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

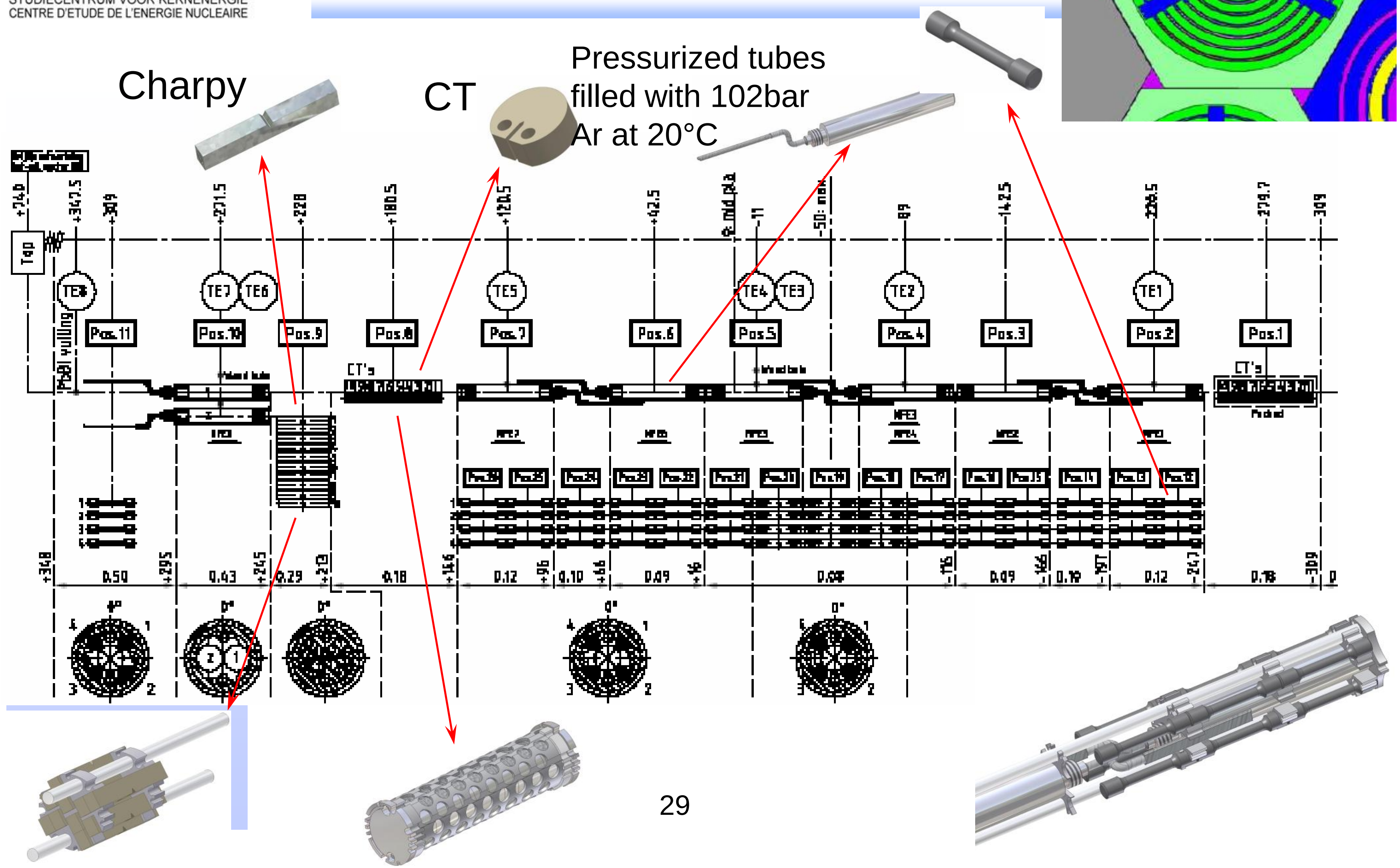
- Simulation of ADS conditions: irradiation in molten PbBi at 450°C
- Irradiation of structure materials
- Cooling by primary coolant BR2
- Irradiation temperature control by thermal barrier gap
- Control of atmosphere to prevent Po release.

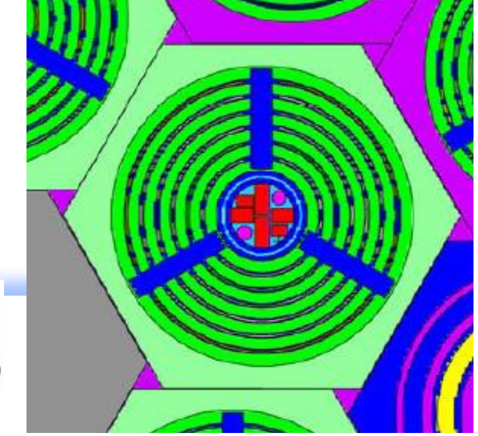


ASTIR Capsule design

- 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

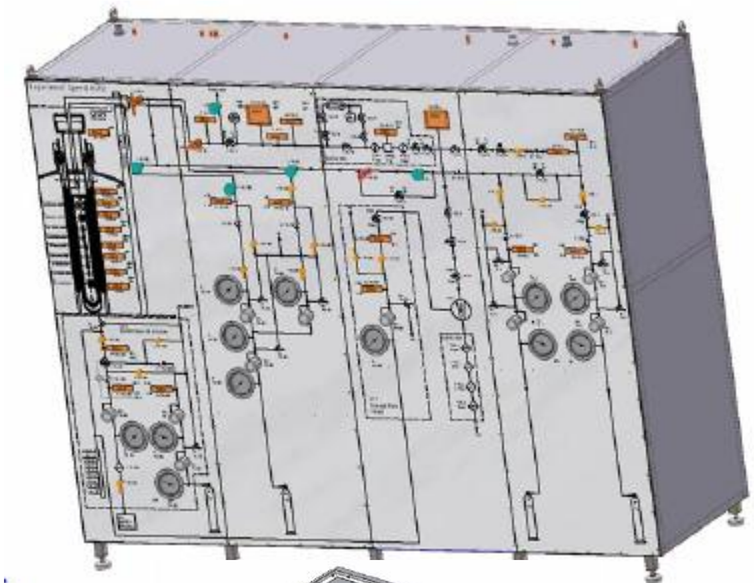
Capsule load

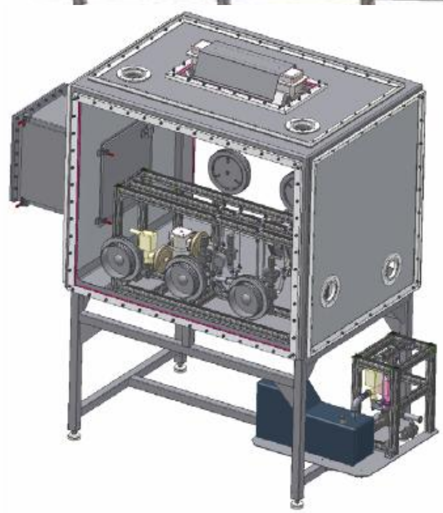




Out of pile equipment

- 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





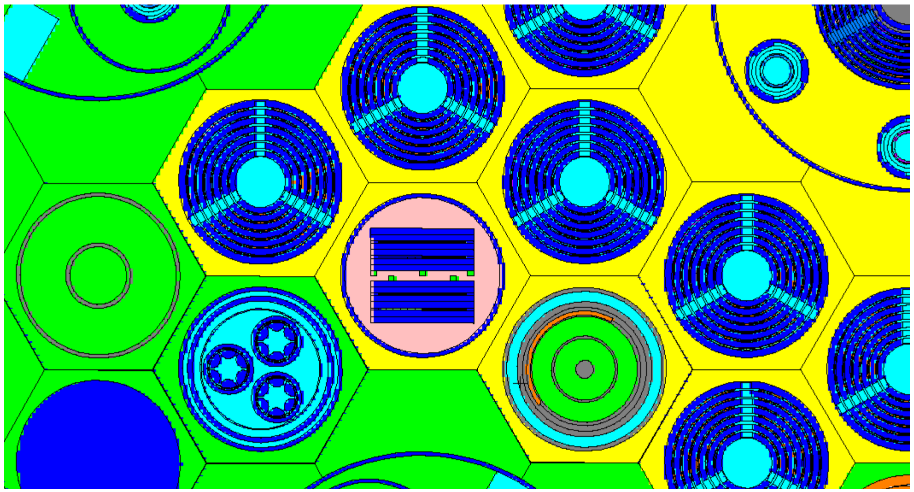
Summary of ADS irradiations

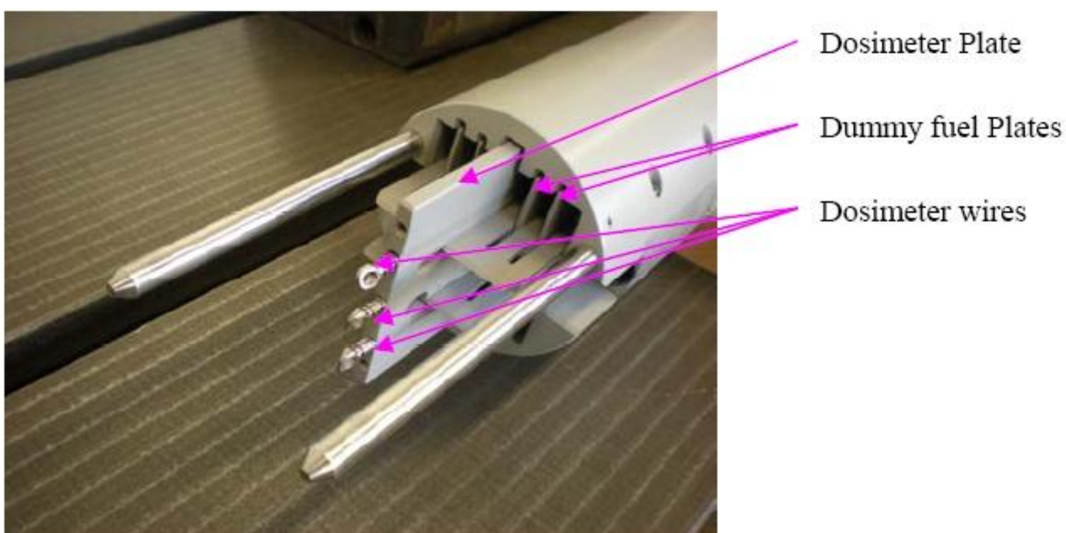
- Challenging application due to new irradiation environment requested
- Development of PIE capabilities in parallel with irradiation technique development
- Opportunity for (re)new(ed) irradiation technology for using maximum fast flux irradiation positions
- Preparation of research and development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

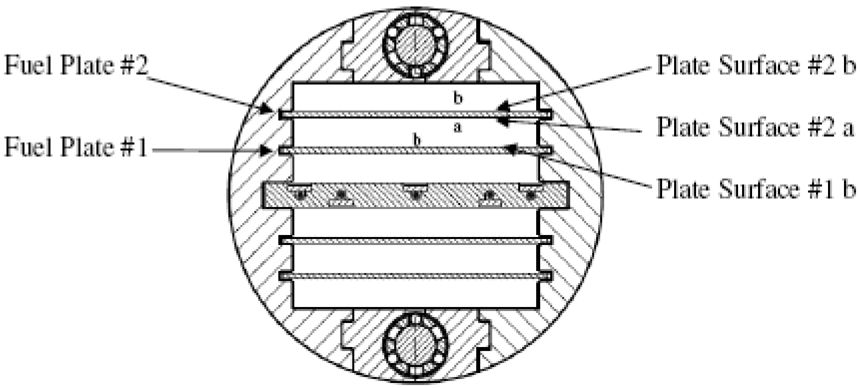
U-Mo fuel plate test: E-FUTURE

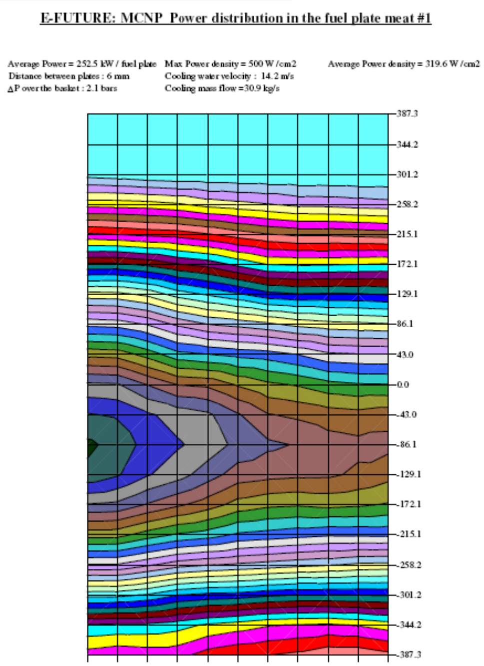


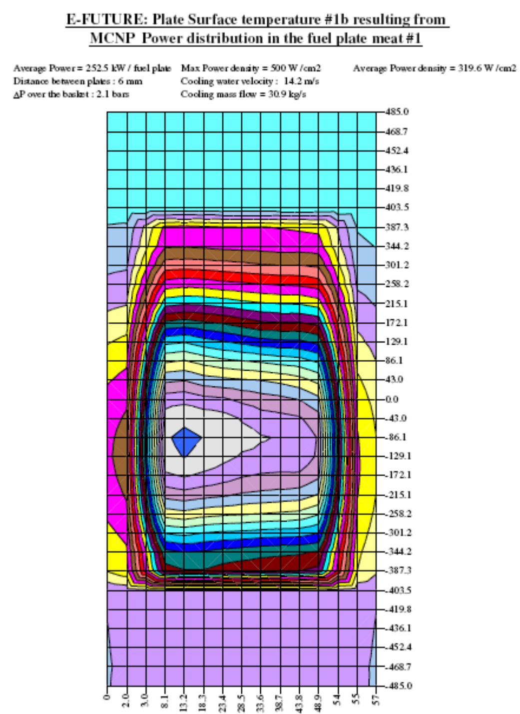


- 4 plate test irradiation
- 3 sets of dosimeters in central plate
- Average heat flux 245-255W/cm²
- Maximum heat flux 460-470W/cm²

Thermal-hydraulic design



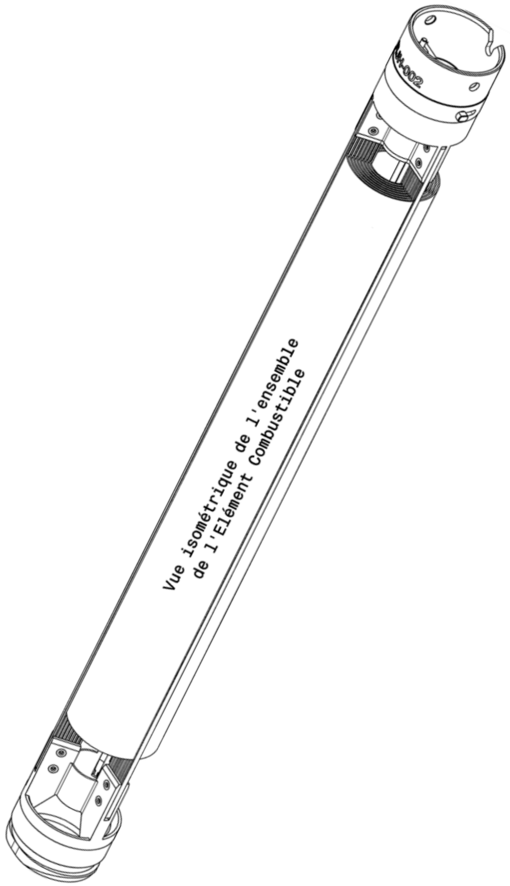


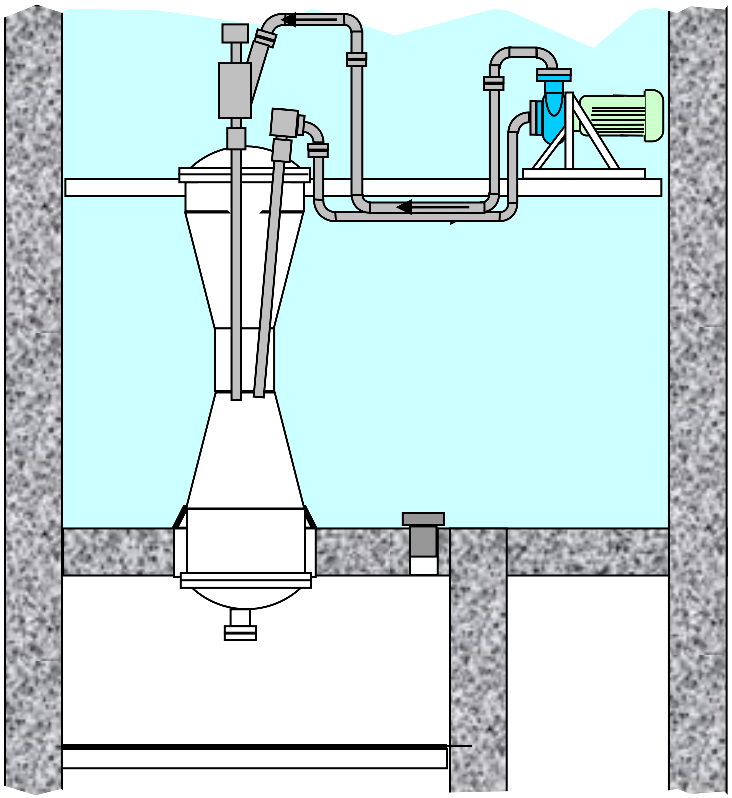


- Input: mechanical design, inlet water temperature, pressure drop along the core, MCNP power distribution
- Output: flow distribution, temperature distribution on plate surface
- Verification of acceptance criteria for experiment is OK

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).

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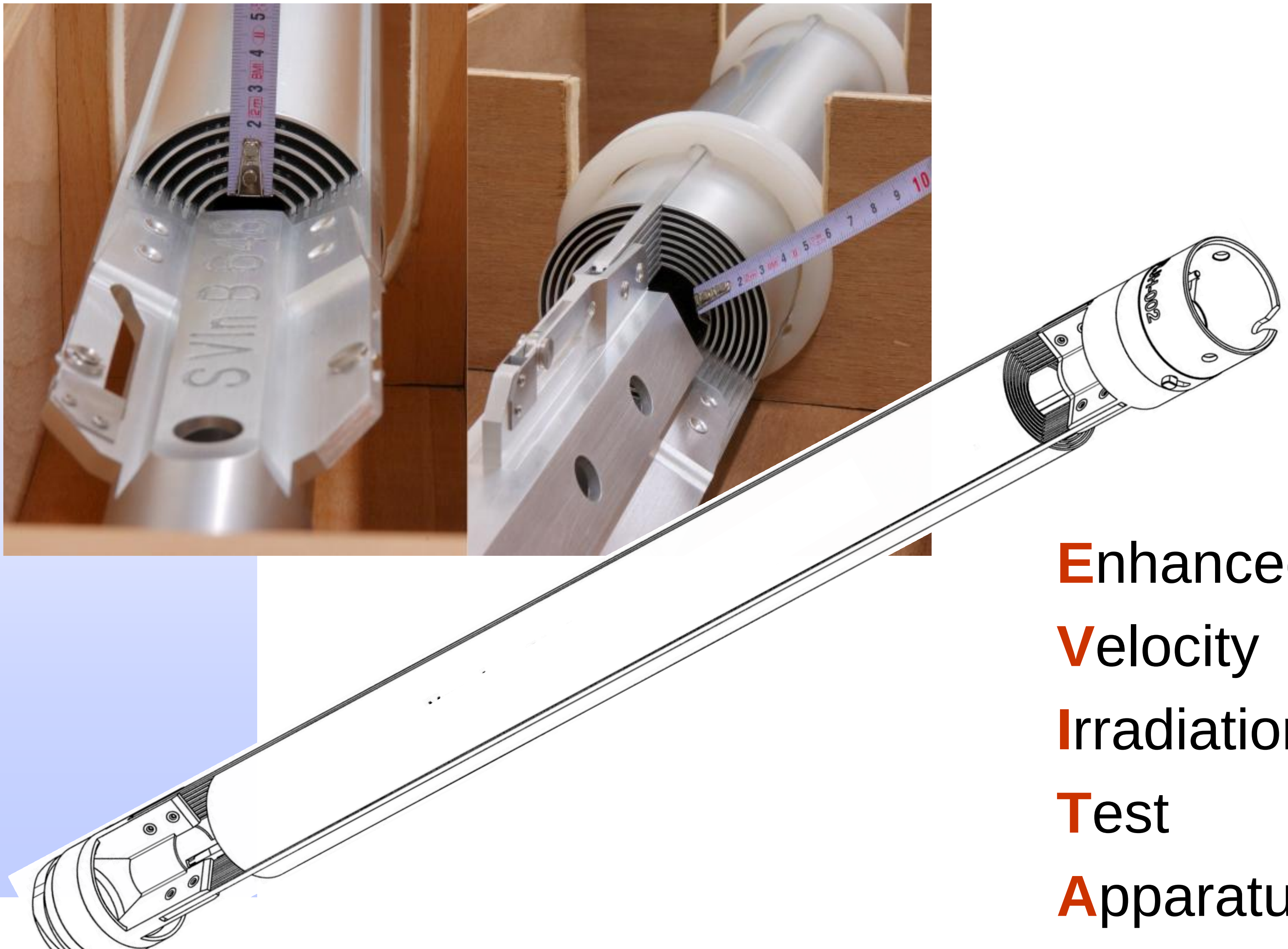
RJH fuel design



Enhanced
Velocity
Irradiation
Test
Apparatus

Fuel specifications

- 8 plates fuel element, 96.2 mm O.D. fuel element
  - BR2 is 80 mm O.D.
- U_3Si_2 4.8 g/cc fuel enriched at 27% with 0,61mm meat thickness (first phase)
- 516 W/cm² 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.

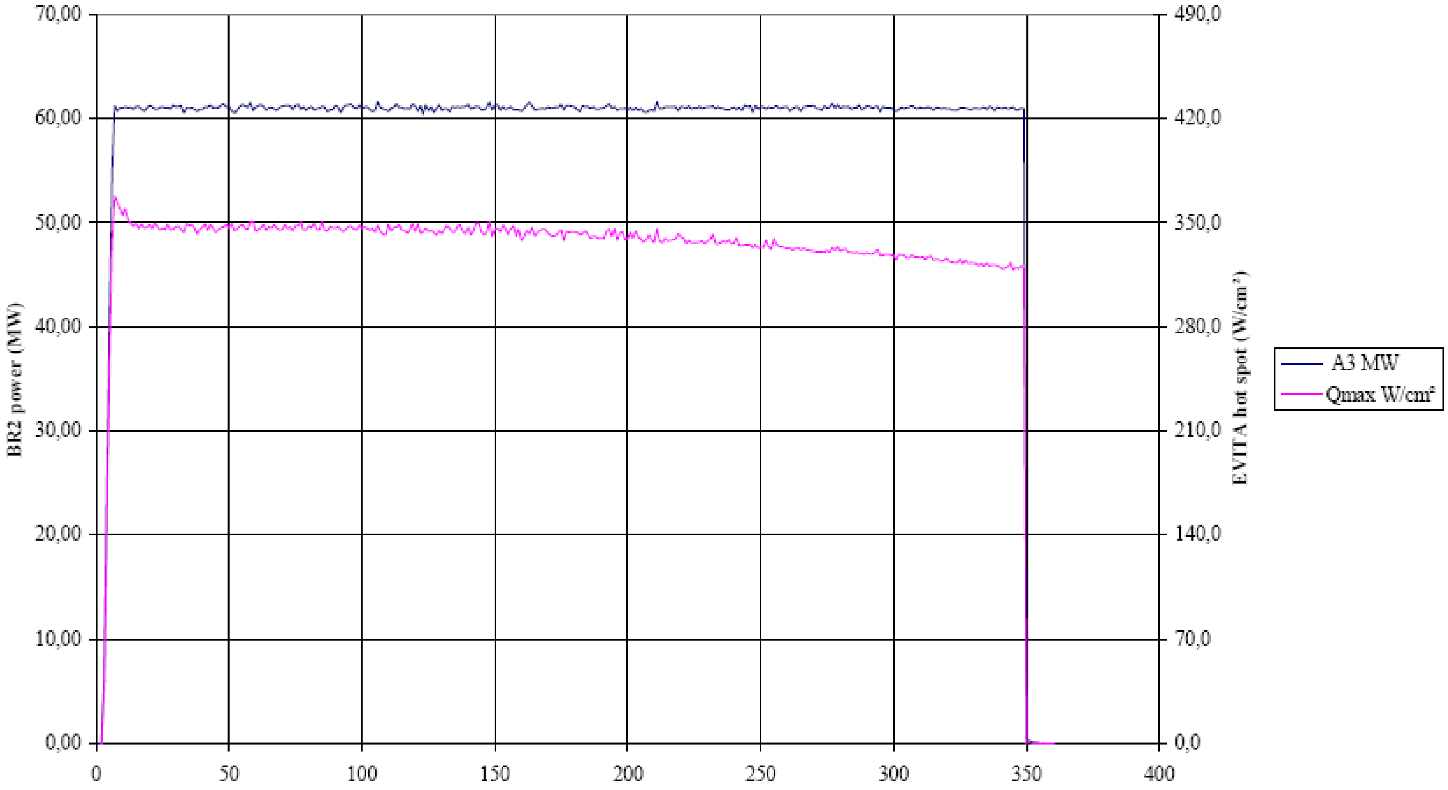
Implementation of test objectives

- 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

Test status

- 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



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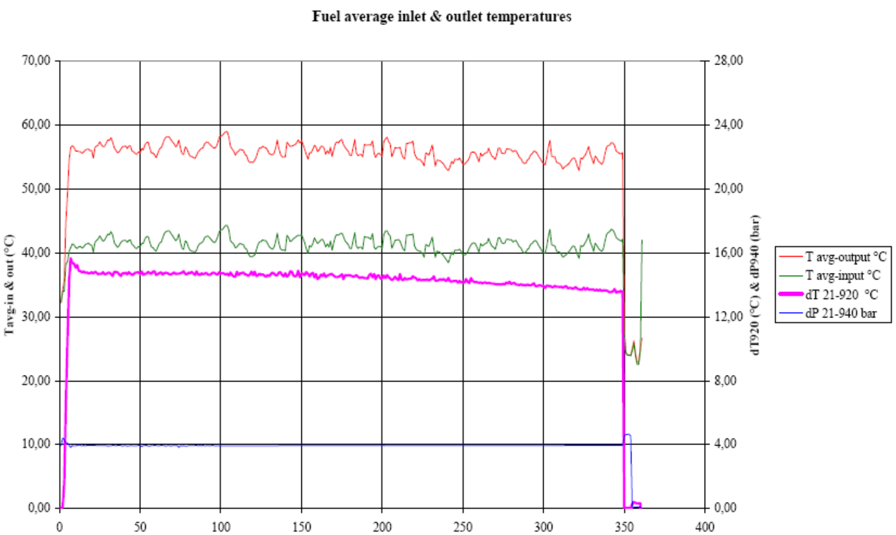
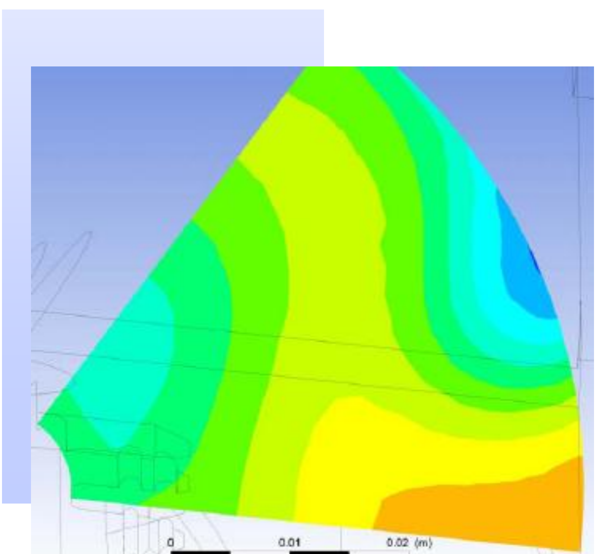
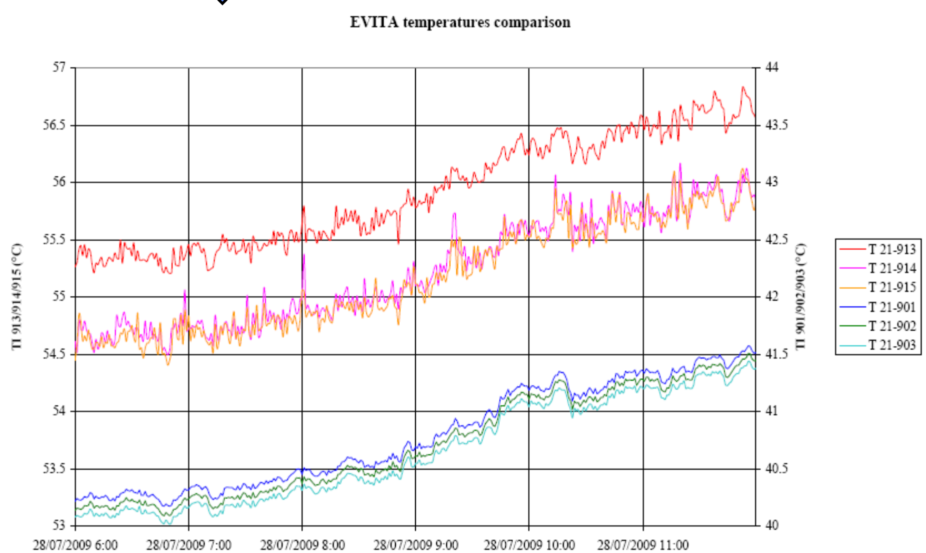
Temperature measurement



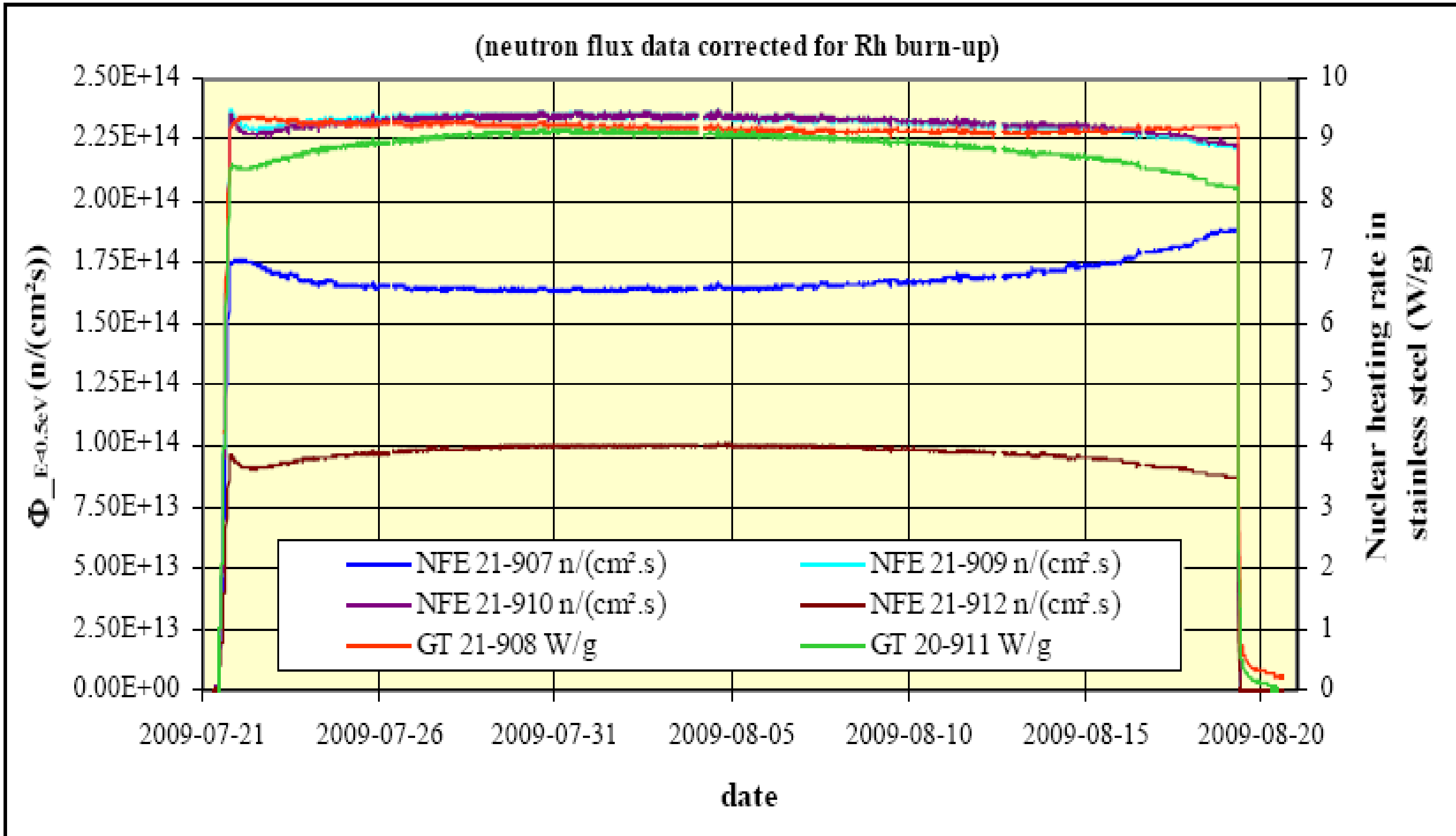


Average delta T used for total power determination and calculation of maximum power

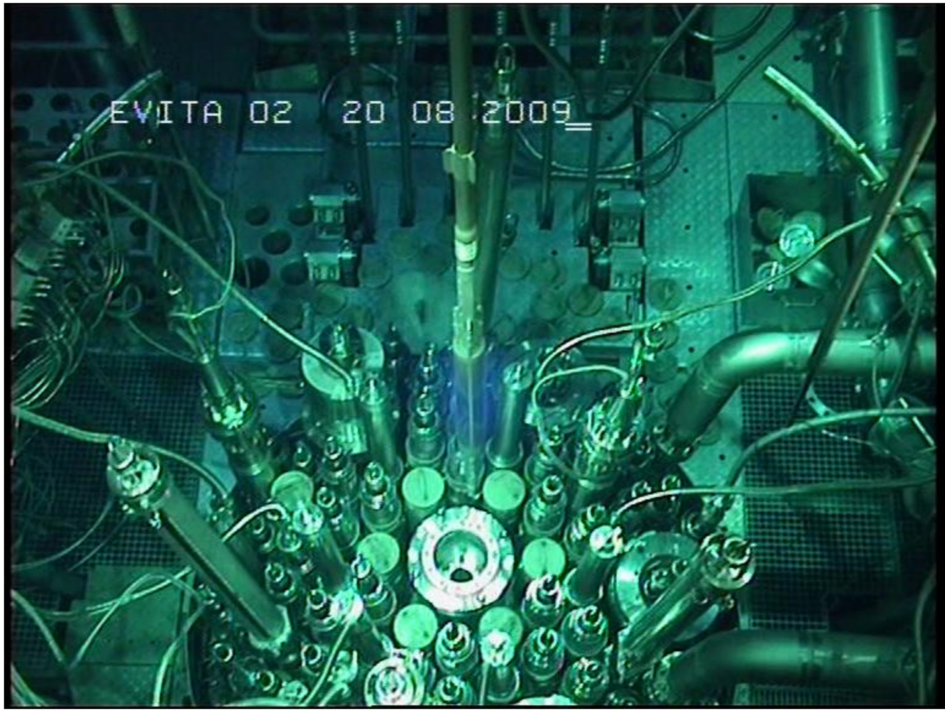
Maximum power to be corrected for “hot channel”

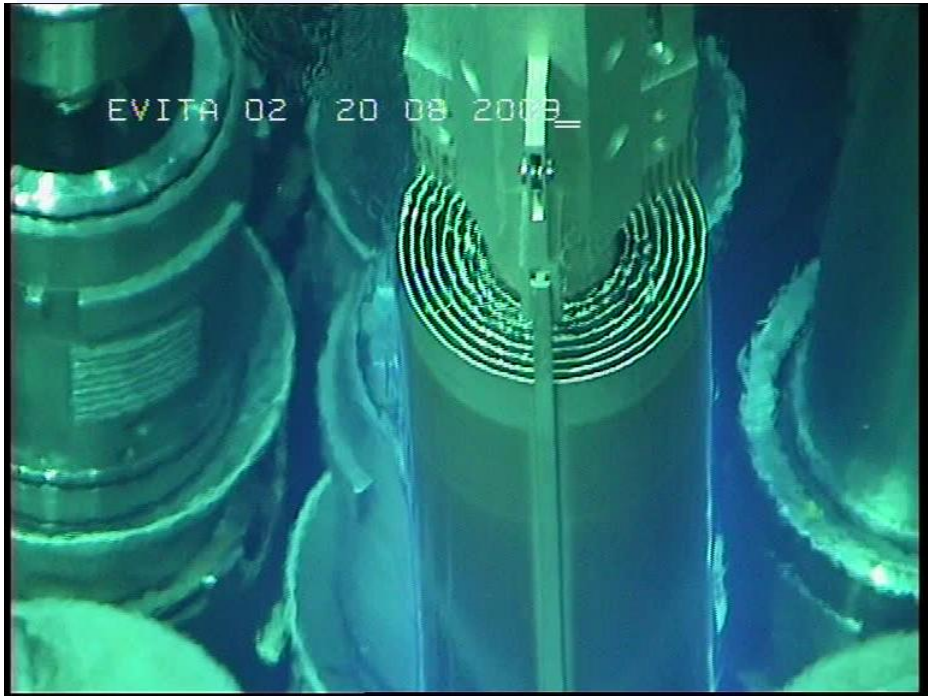


Test results: flux measurements over first irradiation cycle



Unloading of the RJH element after its first irradiation cycle





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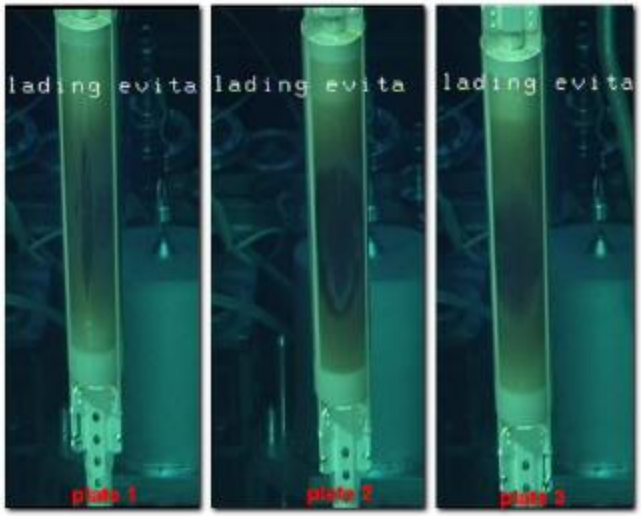
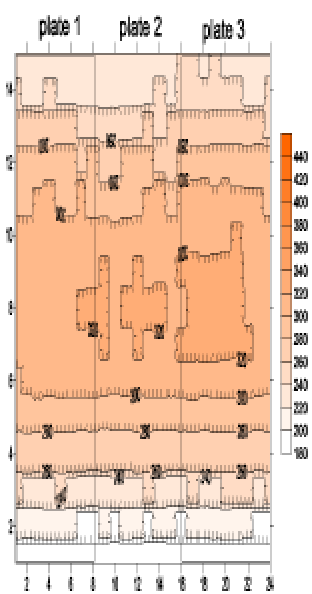
Intermediate results





- 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.

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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.

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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
  - Vaccuum – liquid metal capsules

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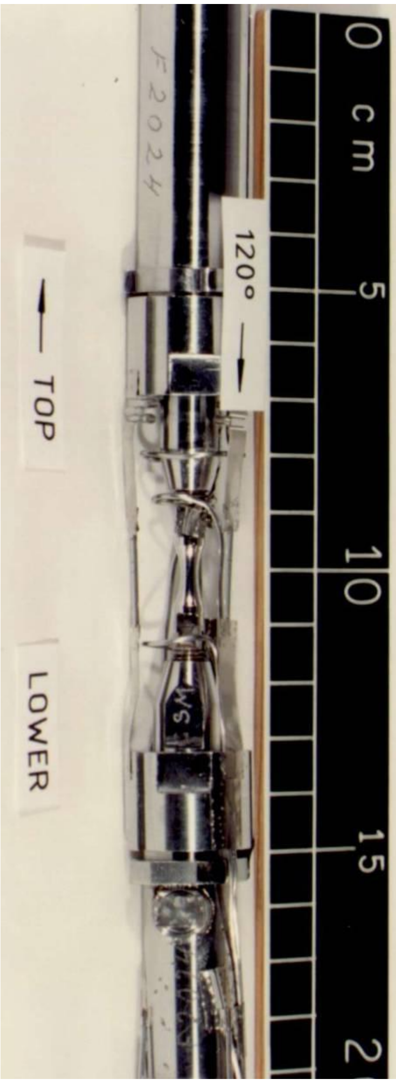
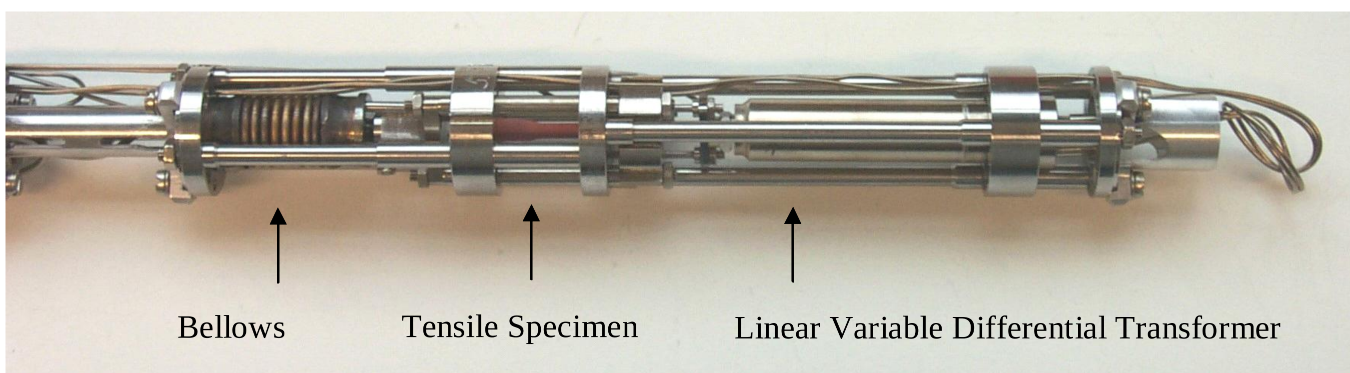
In-pile mechanical testing



- 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)



In-pile instrumentation

- 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)

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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 edvices

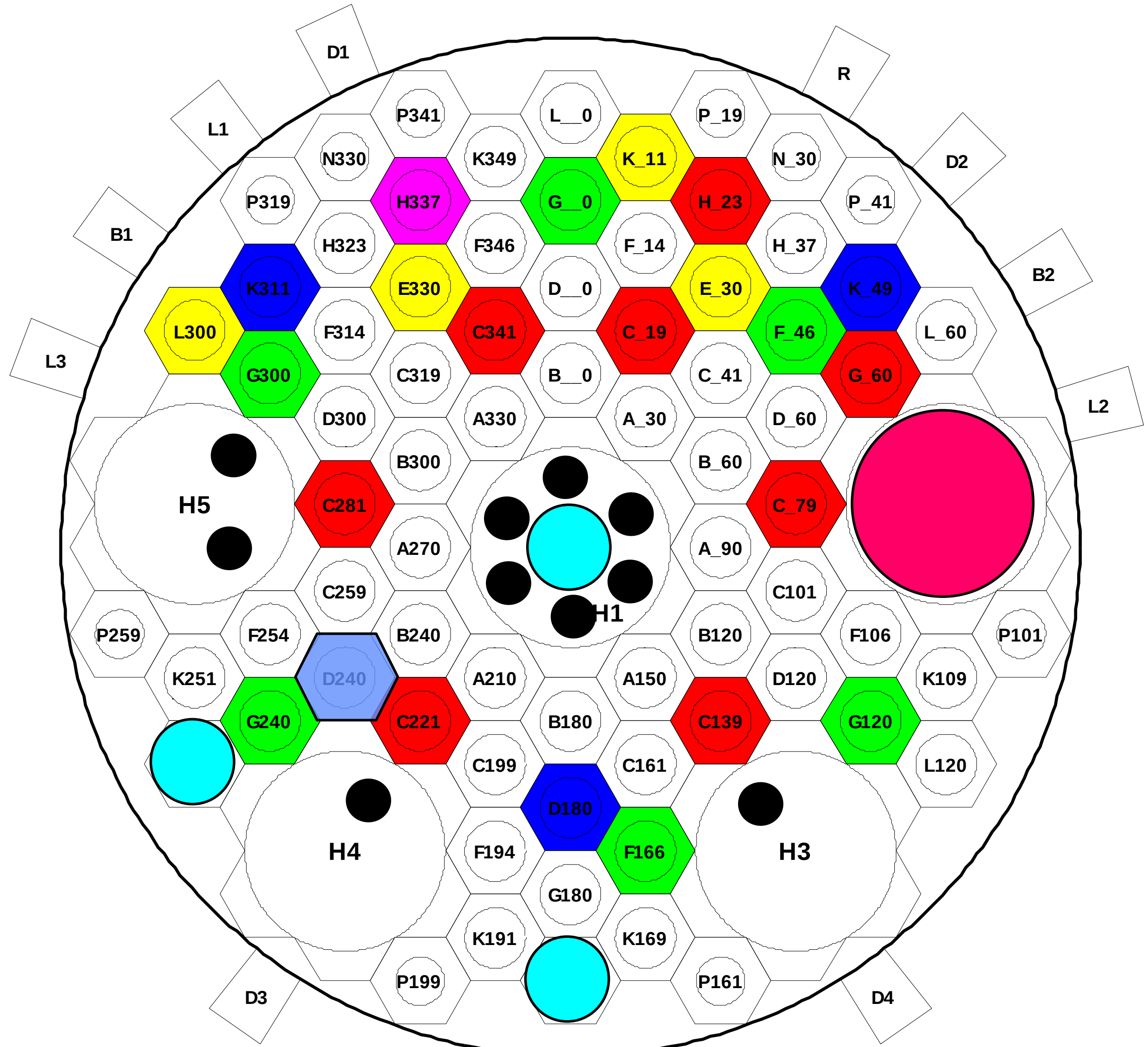
PWR test loop

Si doping device

JHR simulation loop

U-Mo test capsule

Standard irradiation capsules for materials and activation isotopes



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"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

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Summary of the possibilities of BR2

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

- **Available irradiation volumes (with ~ cosine 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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