STUDIECENTRUM VOOR KERNENERGIE
CENTRE D'ETUDE DE L'ENERGIE NUCLEAIRE

Introduction to the BR2 reactor

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BNS | ENGIE |SCK•CEN Technical Workshop on BR2 past and future

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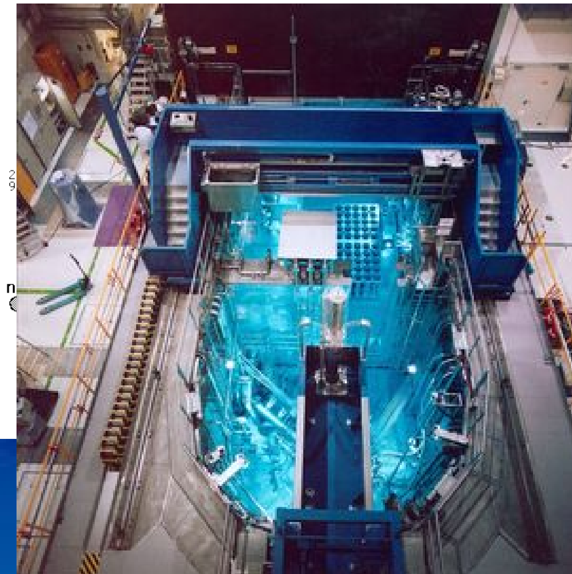
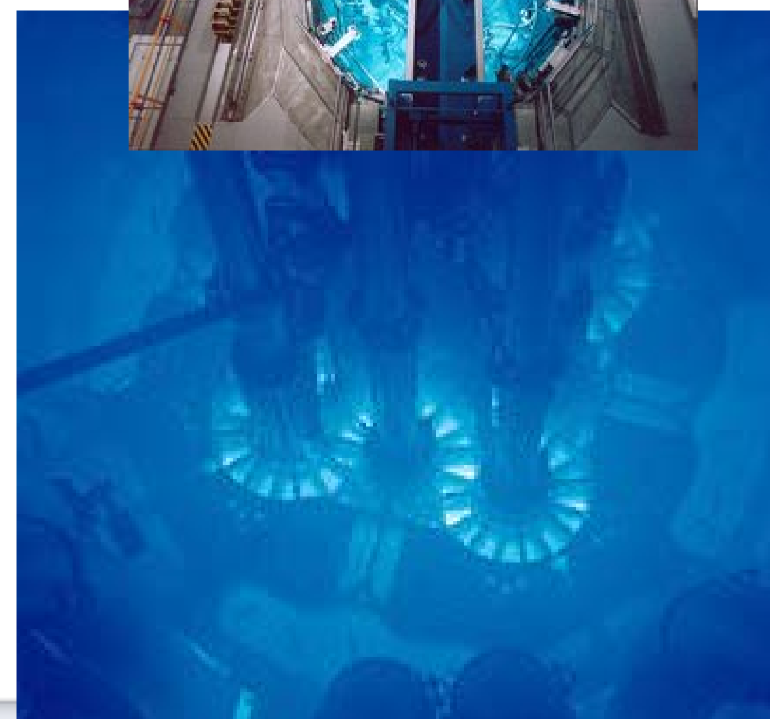
Research reactor characteristics

- A research reactor is primarily a source of (neutron) radiation
  - Sustain nuclear fission chain reaction
    - Fissile material
    - Moderator & reflector
    - Absorber
    - Coolant
  - Provide access for experimental facilities
- Main differences with power reactors
  - Smaller thermal output
  - Lower temperature and pressure
  - Higher power density
  - Simpler installations





The Unique features of the BR2 reactor

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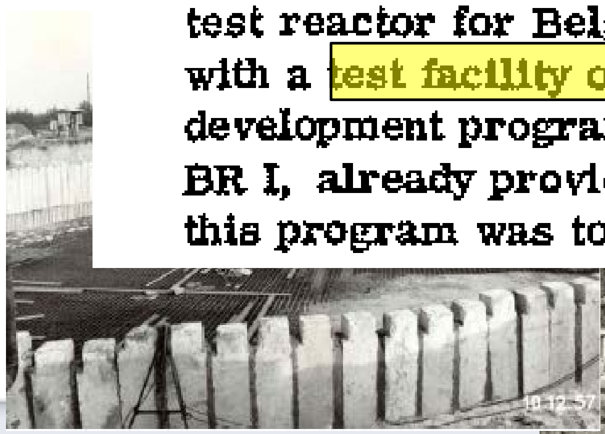
BR2 design goal

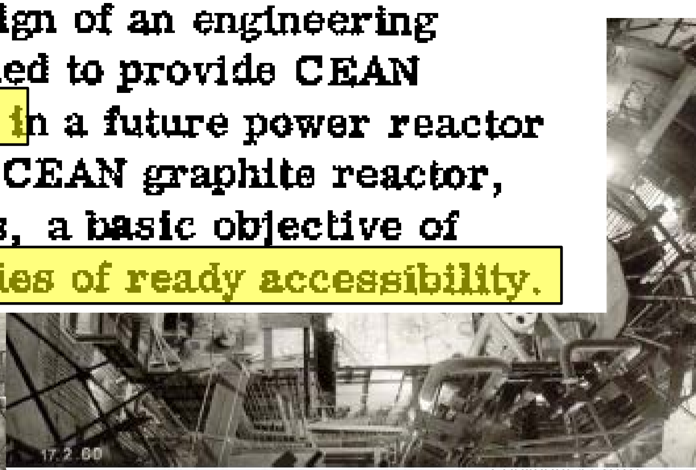
NDA

III. INTRODUCTION

A. PURPOSE OF PROJECT AND PHASE I

Under terms of a contract with the Centre d'Etudes pour les Applications de l'Energie Nucleaire (CEAN), the Nuclear Development Corporation of America (NDA) undertook the design of an engineering test reactor for Belgium. This reactor is intended to provide CEAN with a test facility of greatest overall usefulness in a future power reactor development program. Inasmuch as the present CEAN graphite reactor, BR I, already provides low neutron flux facilities, a basic objective of this program was to provide high flux test facilities of ready accessibility.





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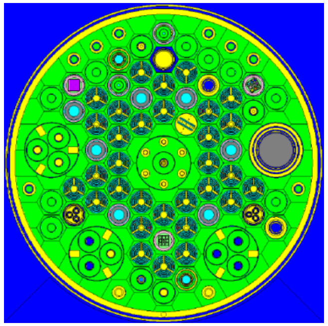
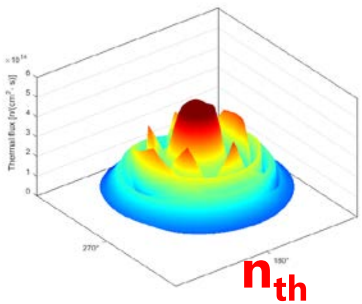
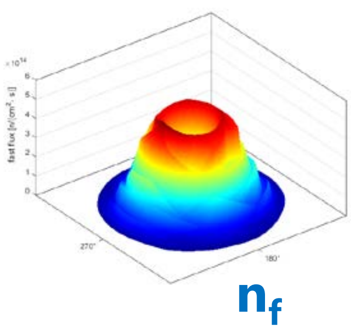
Reactor core performance of BR2







- Design goal: thermal neutron flux up to 10^{15} n/cm^{2}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)
- Achievable flux levels (at mid plane in vessel)
  - Thermal flux: 7 10^{13} n/cm^{2}s to 10^{15} n/cm^{2}s
  - Fast flux (E>0.1MeV): 1 10^{13} n/cm^{2}s to 6 10^{14} n/cm^{2}s
- Allowable heat flux in primary coolant
  - 470W/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 600W/cm^2 can be allowed in experiments

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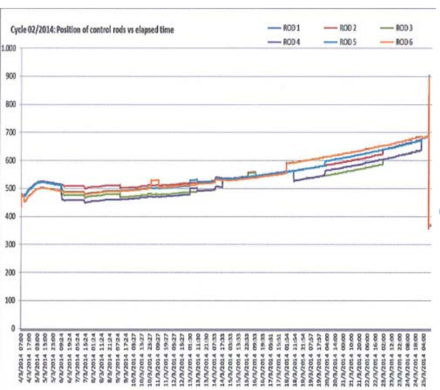
BR2 driver fuel



- Fuel: neutron source of the reactor
  - Fissile isotope: ^{235}U
  - High enrichment: up to 93%
    - High density of fissile atoms
    - Low absorption by ^{238}U
    - Low doppler effect
  - Metallic MTR fuel: dispersed UAl alloy in Al matrix
    - High thermal conductivity – high heat flux possible
    - Low fission product mobility – limited impact of cladding failure
  - Addition of burnable absorbers
    - Fuel cycle efficiency
    - Compensation of burn-up with shim rods
- Fuel geometry
  - Standard: 5-6 concentric plates
    - inner space for irradiation capsules (34 or 26mm)
  - Non standard elements in 200mm channels
    - inner space adapted to experiment

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Reactor core geometry

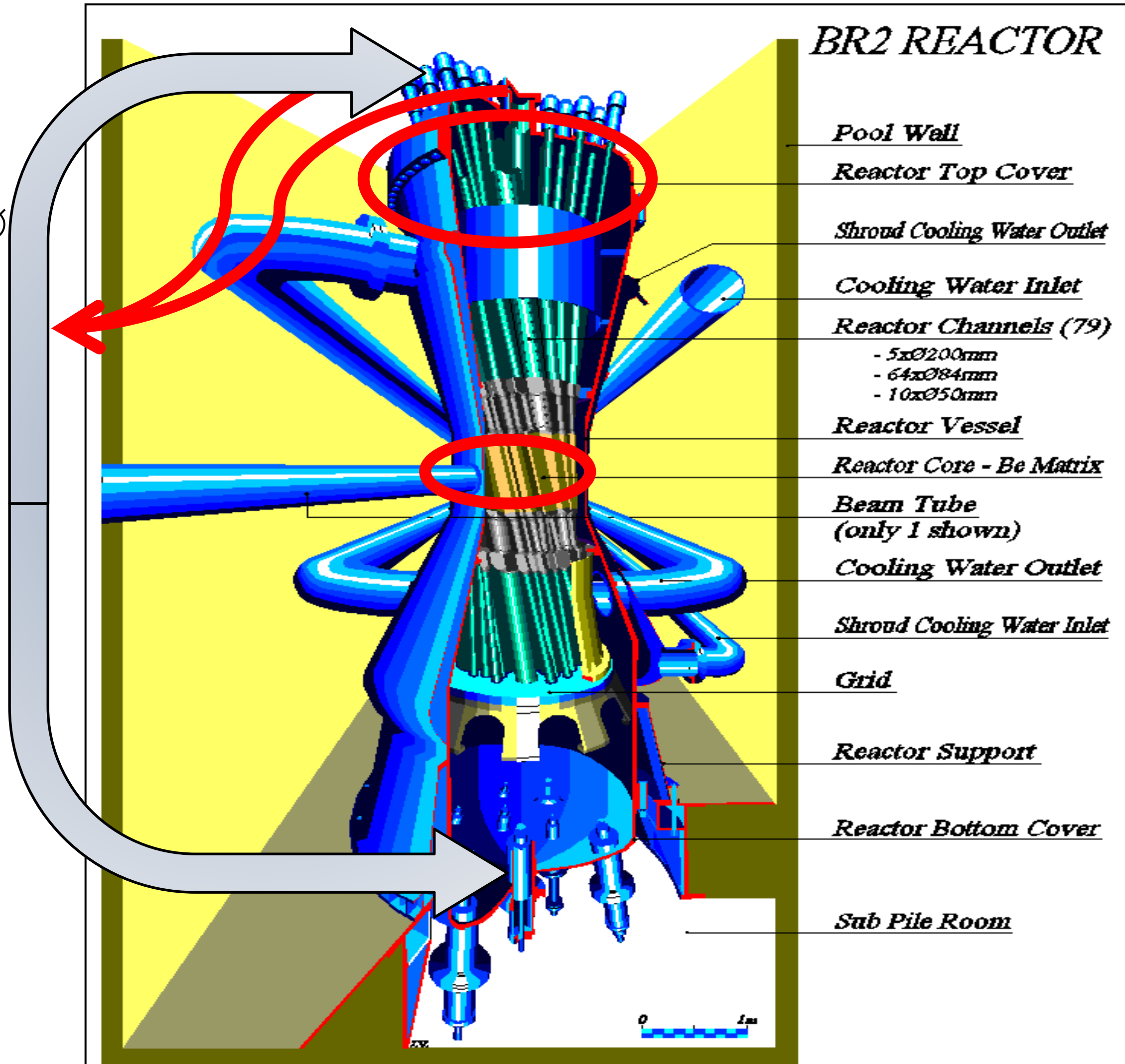
Diverging reactor channels for compact core and good access: core 1m, cover 2m ∅

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



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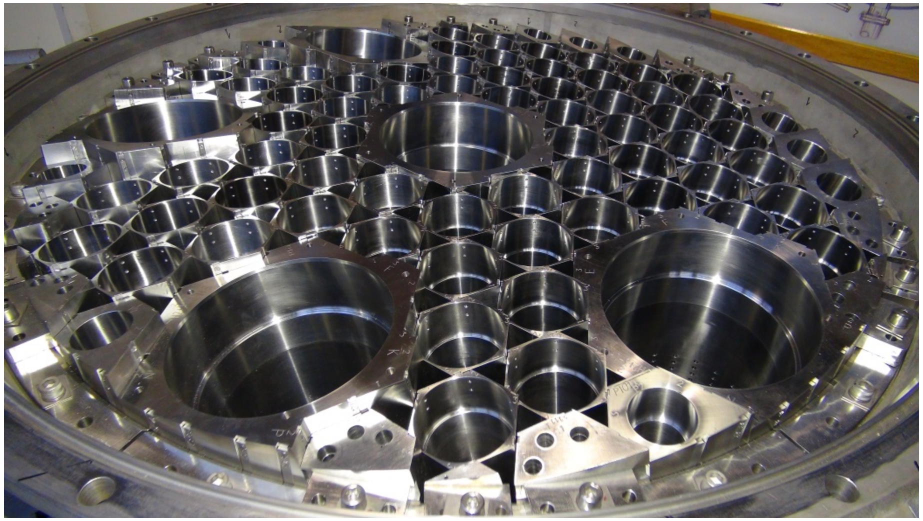
Reactor core channels

- Total channel length >9m
- Central 1m part: Be metal block
  - Single piece 84mm bore (64)
  - Single piece 50mm bore (10)
  - 6 piece 200 mm bore (5)
- Beryllium is mounted between stainless steel extension pieces
- Top-down water flow with common top & bottom plenum



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Be as neutron moderator

	H_2O	D_2O	He	Li	Be	B	C	Na	Pb
N $[10^{24} cm^{-3}]$	0,0334 vloeistof	0,0332 vloeistof	0,0017 70bar,300K	0,0460	0,124 metaal	0,128	0,0802 grafiet	0,0254 metaal	0,0330
A [-]	1	2	4	6.9	9	10.8	12	23	207.2
ξ [-]	1,000	0,725	0,425	0,262	0,206	0,1741	0,158	0,0846	0,00962
σ_s [barn]	103	13,6	1,34	1,37	7,63	5,24	5,55	3,28	11,1
σ_a [barn]	0,664	0,00133	0,00747	70,5	0,0076	767	0,0035	0,53	0,171
$\xi\,\sigma_s/\sigma_a$ [-]	155	7410	76,2	0,005	207	0,001	250	0,524	0,62
$1/(N\sigma_s\xi^{1/2})$ [cm]	0,28	2,48	673	NA	2,36	NA	5,65	41,3	27,8

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BR2 main thermal-hydraulic characteristics compared to commercial power plant

	BR2	PWR
reactor type	tank-in-pool	pressure vessel
containment building	steel-concrete (single) circular – dome	steel-concrete (double) circular – dome
pressure vessel	aluminium	steel
coolant	light water <60°C, 1.5MPa	light water up to 325°C, 15.5MPa
primary flow	water in closed loop (1)	water in closed loop (1 to 4)
secondary flow	water in open loop (cooling towers)	water/steam in closed loop + ternary circuit in open loop
heat exchangers	coil-wound heat exchangers	steam generators

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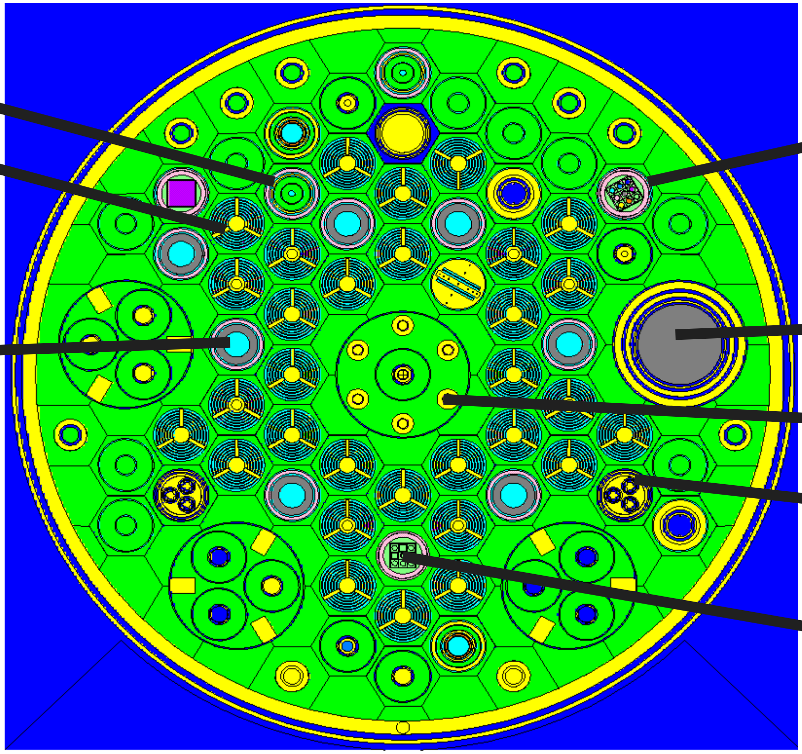
BR2 = Multipurpose Reactor



Mid-plane cross section of a typical BR2 core

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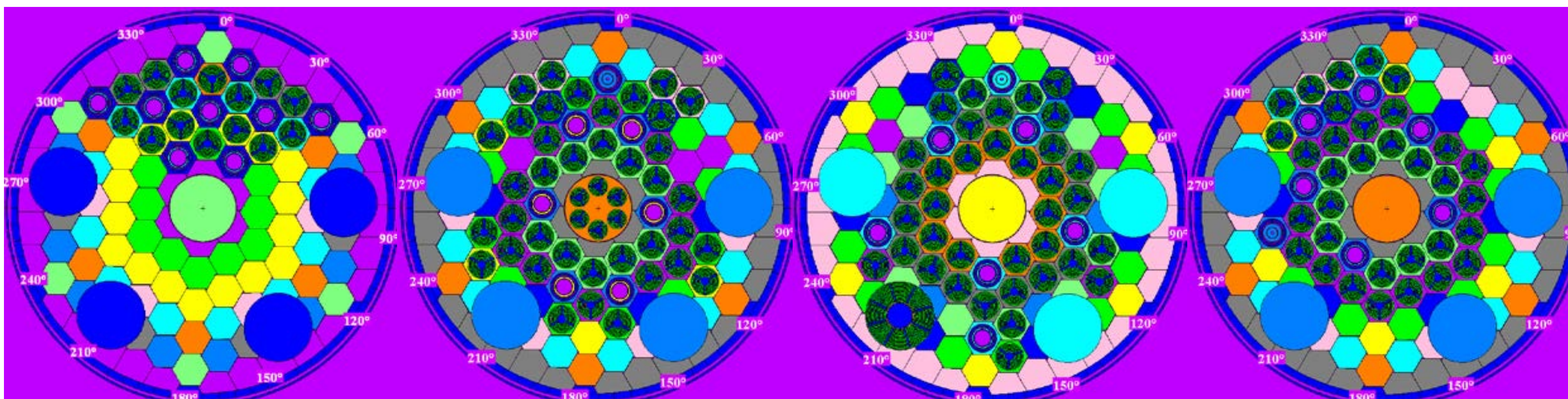
Flexible reactor configuration

- 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



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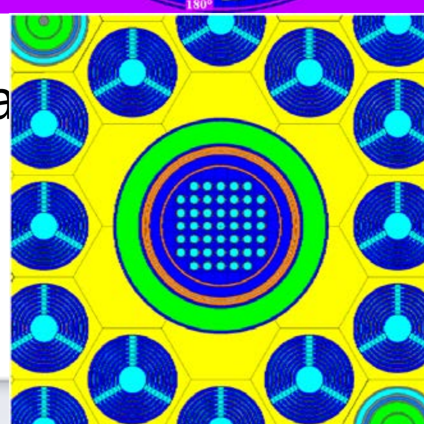

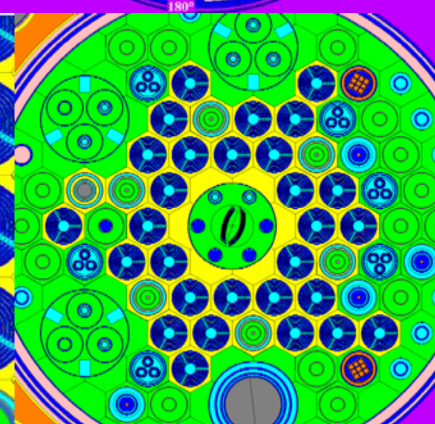

- BR2 reactor ma ncluding irradiations)

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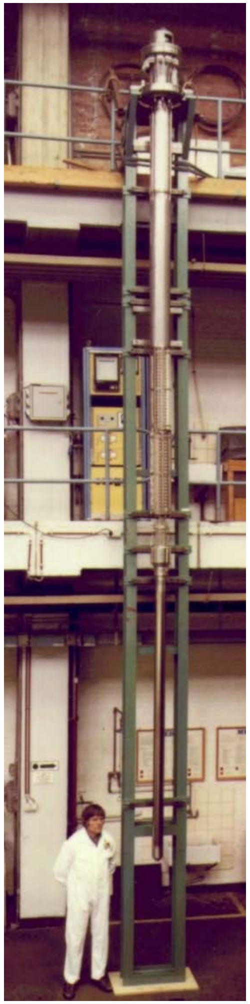
Experimental accessibility BR2

- Experiments can be loaded in full channel or inside central cavity of fuel element
- Experimental content is loaded from reactor top cover
- Channels through vessel allow for installation of experimental loops
- Irradiations can be loaded for single or multiple cycles
- On-line unloading from thimble tube devices or rigs with pressure locks



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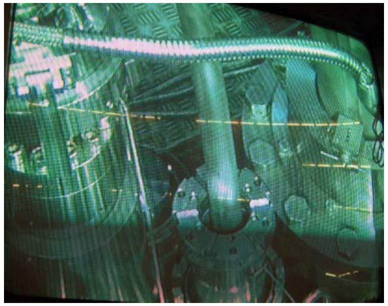
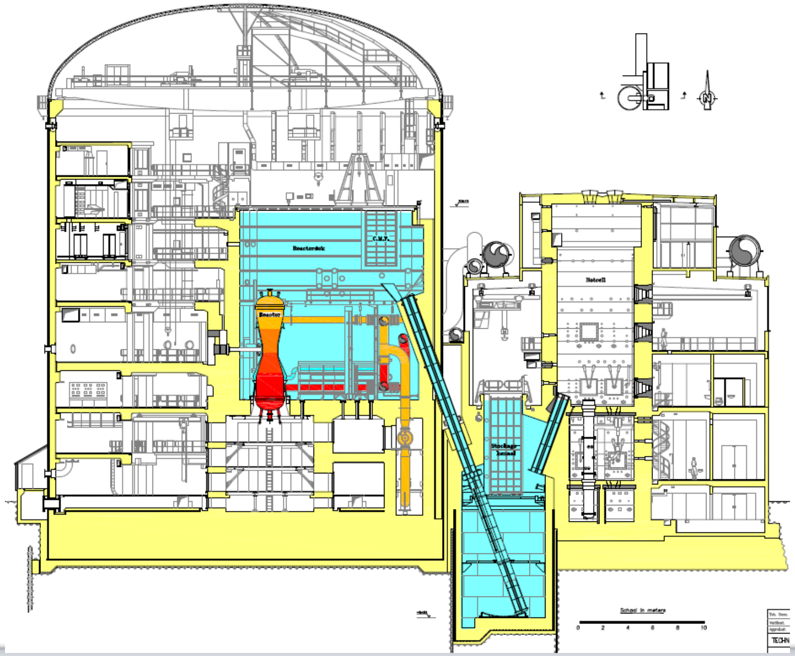
Experimental manipulation in BR2

- 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





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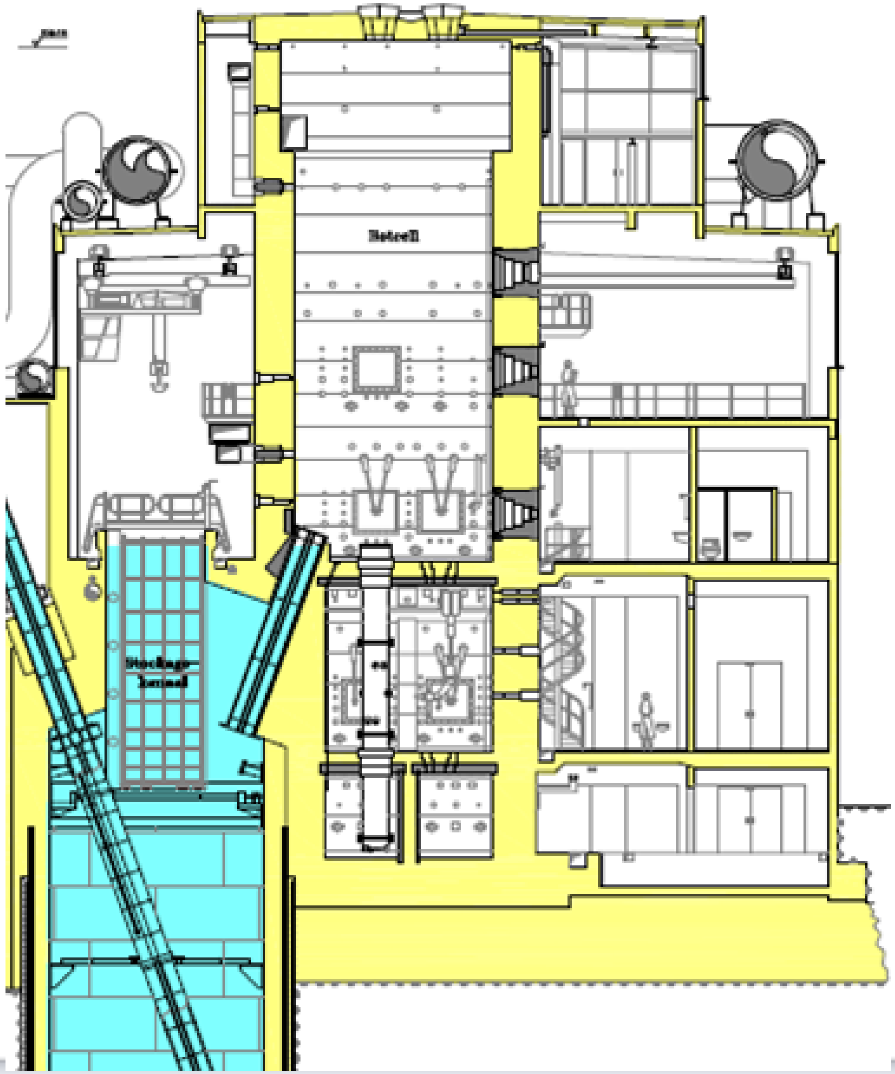
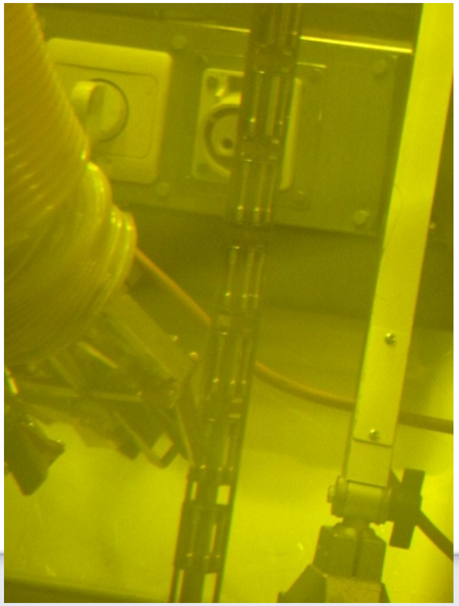
The BR2 hot cell



- 16m high, shielding designed for 60000Ci (2.5MeV)
- Used for dismantling, conditioning and shipping of irradiated materials
- Connected to transfer chute
- Equipped with own storage facility



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The third BR2 refurbishment

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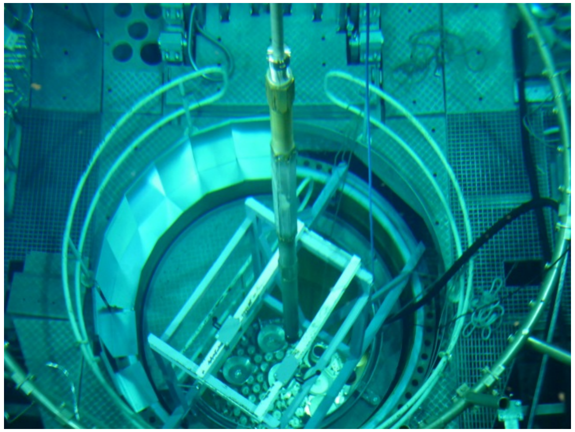
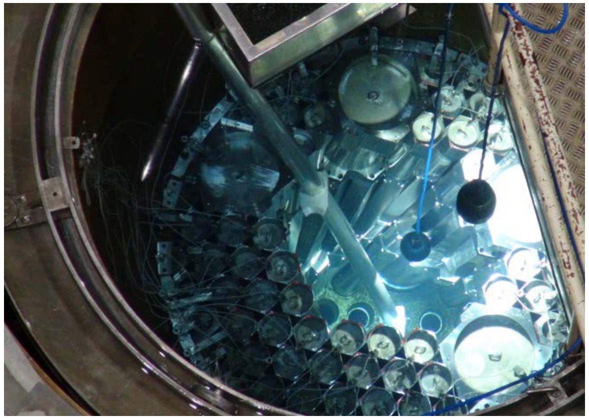
BR2 refurbishment history

- Belgian Reactor 2 : in operation since 1963
  - Upgraded in 1968 to 100MW
  - Refurbishment in 1977-1980
  - Subject to decennial license review since 1986
  - Refurbished in 1995-1997



- Third refurbishment 2015-2016 – back in operation for the 4th era
  - Replacing Beryllium matrix
  - Perform major maintenance operations and inspections
  - Updated instrumentation to conform to future challenges
  - Potential for improved operational regime (higher up-time)



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Framework of the third refurbishment

- Decennial licensing review period: 2016-2026
  - Review content
    - Conformity of safety studies to modern standards
    - Compliance of critical components to licensed limits
    - Ageing management programme for Long Term Operation (new for 2016)
  - Plant asset management project
    - Start 2010
    - Review of all systems, structures and components
      - Safety, availability and economy impact
    - Definition and implementation of mitigating measures
- Evolution in international MTR community
  - Shut down of facilities (OSIRIS: 2015) or end of activity (^{99}Mo at NRU: 2016)
  - Start of new facilities (RJH>2020)

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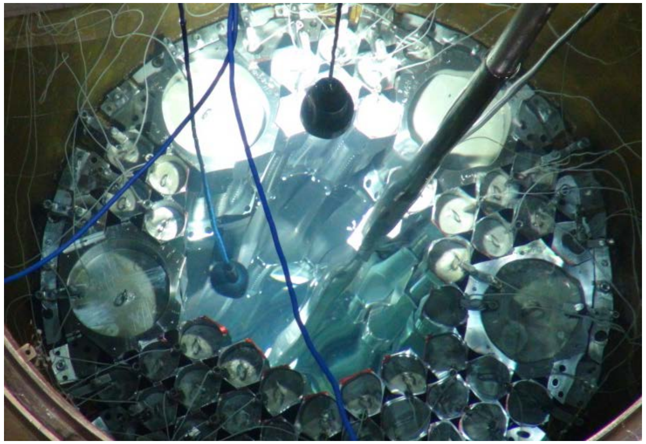
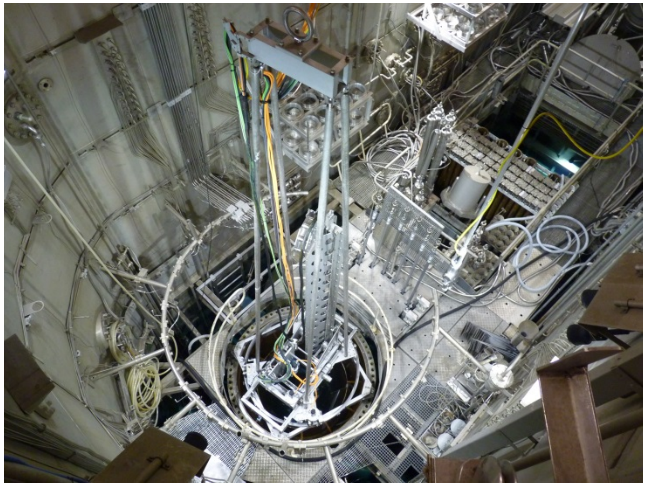
Highlights of the 2015 – 2016 refurbishment

- Reactor key components with licensed limitations: core components and vessel
  - Be matrix: max fluence value will be reached before 2026
    - Proactive replacement in 2015-2016
    - New matrix life >10 years



  - Reactor vessel: minimum fracture toughness will not be reached before 2026
    - Inspection performed during refurbishment
    - Surveillance programme continues to generate data for period 2026-2036
    - End of Life BR2 vessel certainly >2026



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Investing in the future

- *A major investment plan for sustained BR2 safety and availability for the next operational period*
  - *Secure licensing period of 2016-2026*
  - *Open perspective towards 2026-2036*

- Cooling tower renovation
  - Replacement of fans, building refurbishment
- Renovation of underground piping
  - Securing reliability for comming decades
- Modernisation of electrical grid
  - Conforming to modern standards and ensuring maintenance

- *Enhanced annual up-time potential technically feasible, pending economical conditions*

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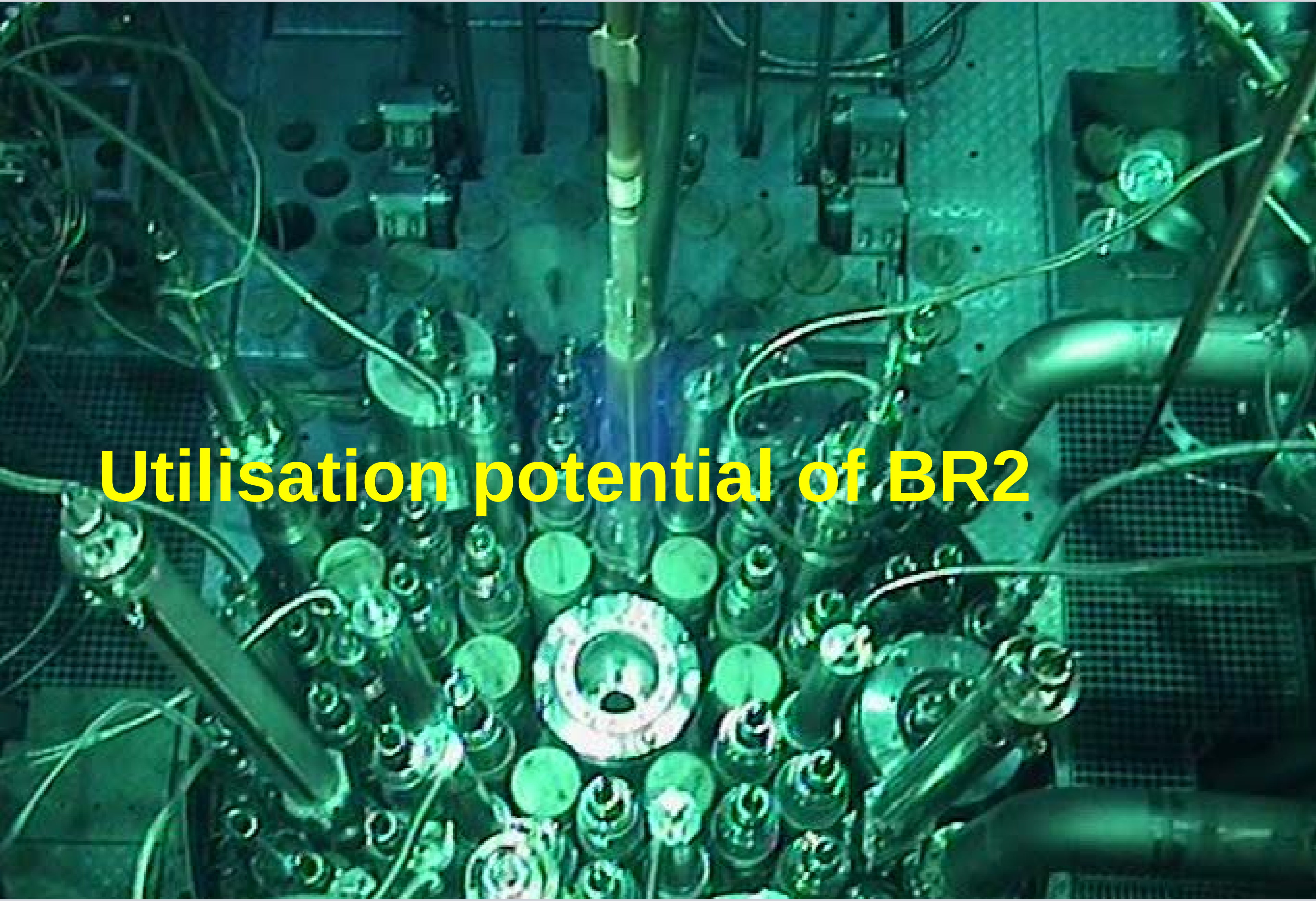
Utilisation potential of BR2



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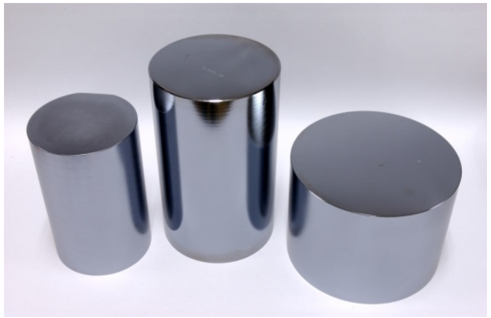
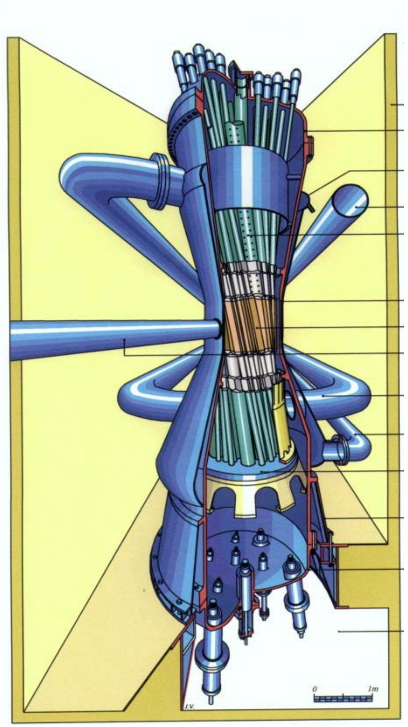
Radio-isotopes and NTD silicon



SCK•CEN has capacity to produce up to 65% of the weekly worldwide needs for medical radioisotopes

SCK•CEN produces on average 25% of worldwide demand of semiconductors for renewable energy applications



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Radio-isotopes from fission

- Irradiation of (HE) Uranium metallic (dispersed) targets
  - Irradiation capacity: 75 targets, 6 irradiation facilities
  - Maximum production rate ^{99}Mo: 7800 Ci/week (6 day calibrated)
  - Annual production: 20% of global demand (17-20 weeks production)
  - *Enhanced availability in future may increase this capacity to 210000Ci annually*

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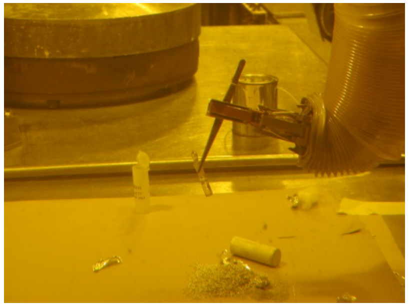
Radio-isotopes from activation

- Irradiation in thimble tubes:
  - ^{177}Lu, ^{186}Re, ^{153}Sm, ^{169}Er, ^{90}Y, ^{32}P, ^{125}I,…
  - “Small” quantities and low heat generation
  - Flexible loading/unloading
  - Low to medium flux ($4 \times 10^{14} n/cm^2s$)

- Irradiation in baskets (primary water flow)
  - ^{192}Ir, ^{84}Sr, ^{188}W, ^{117m}Sn, ^{67}Cu, ^{14}C,…
  - “Large” quantities, high heat generation
  - Full cycle irradiation
  - Up to maximum neutron flux available in BR2



- Decanning and packaging in BR2 hot-cell

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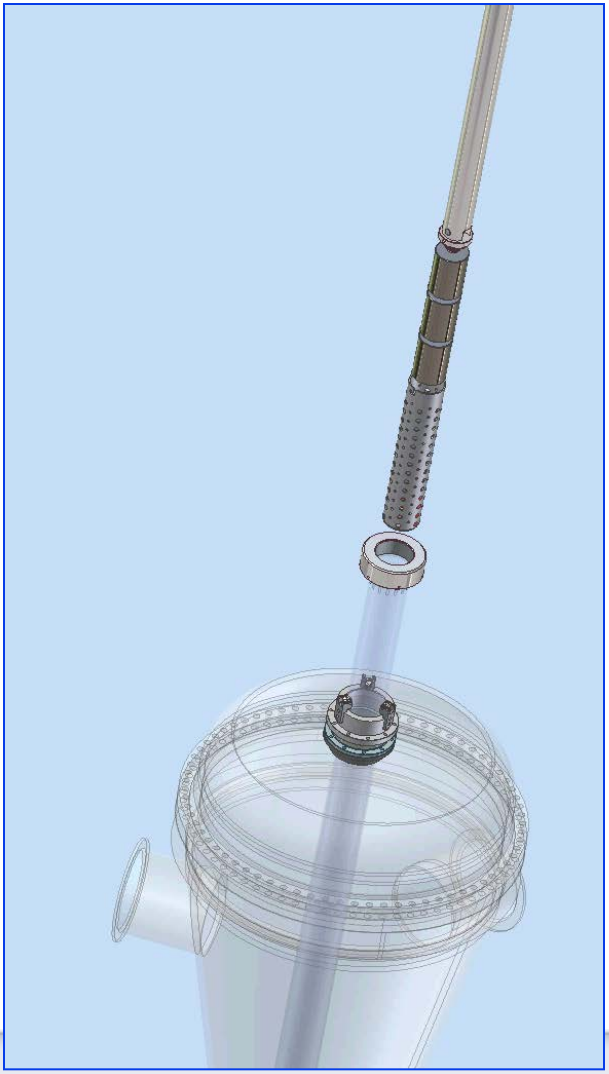
Production of high grade semiconductors by neutron transmutation



- **$^{30}Si(n,\gamma)^{31}Si\beta\text{-}^{31}P$** creates semiconduction silicon crystals with high quality.
- 2 installation in BR2:
  - SIDONIE: inside vessel for 4-5″ diameter crystals
  - POSEIDON pool side facility for 6-8″ crystals
- Total capacity of 15 and 18 tonnes/year respectively
- Application of NTD Si: transport (electric-hybrid vehicles), energy (solar & wind)

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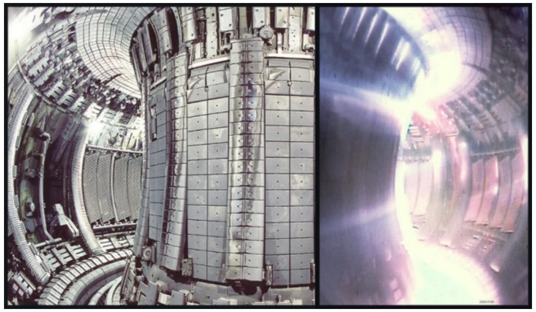
Material irradiation testing

- 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



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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

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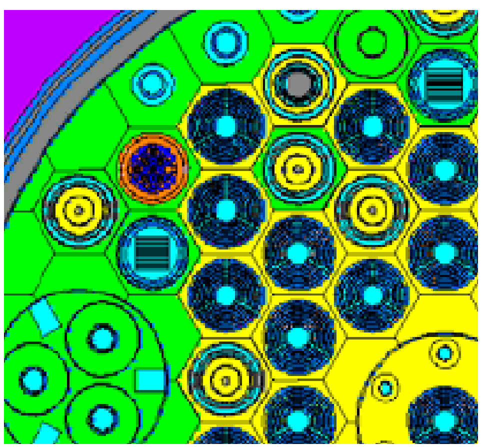
Neutronic conditions for LWR vessel irradiations

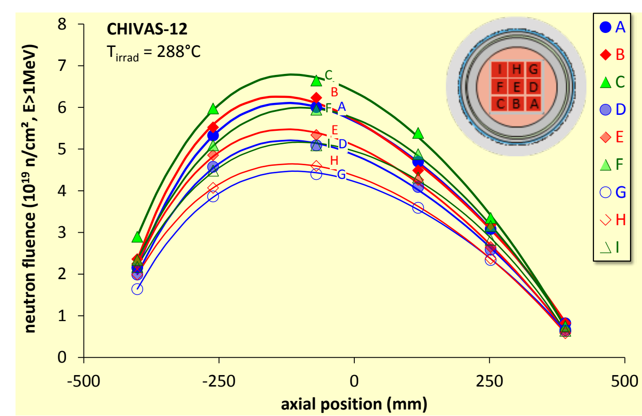
- Past: fixed channel, variable environment
  - Tailored flux level by changing total power and number of fuel elements next to IPS

	0FE	1FE	2FE	
typical flux max (in needle E)	8.0 10^{+12}	1.4 10^{+13}	2.3 10^{+13}	n/cm².s

  - Flux distribution is calculated by MCNP model and verified with dosimetry



A 1.12	B 1.22	C 1.36
D 0.87	E 0.98	F 1.10
G 0.69	H 0.78	I 0.89



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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

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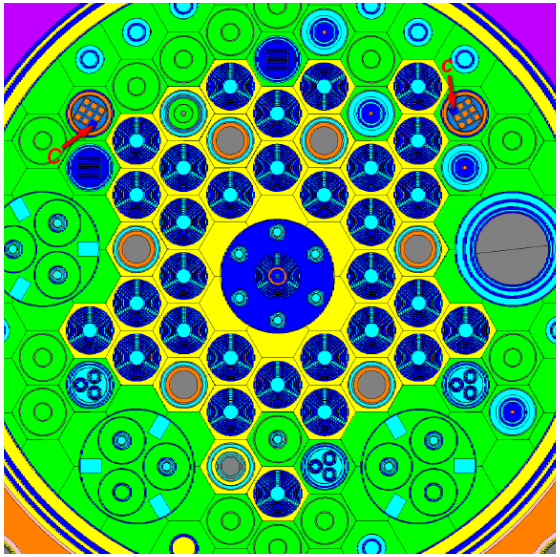
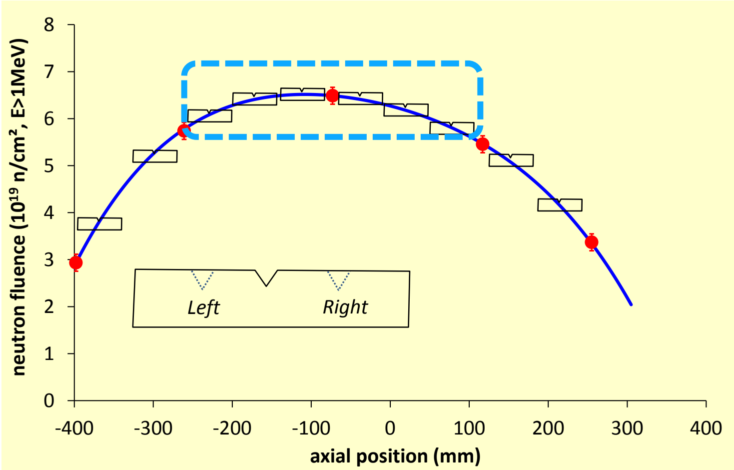
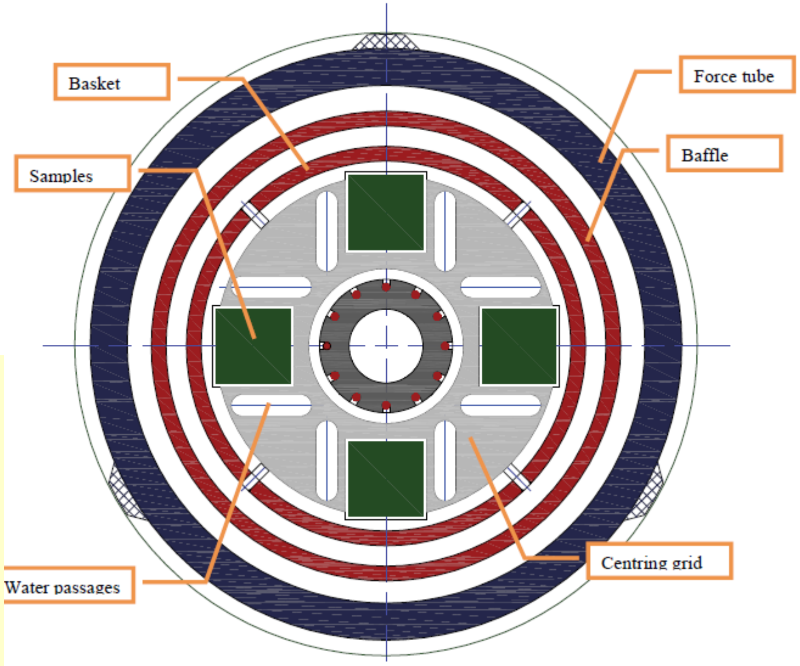
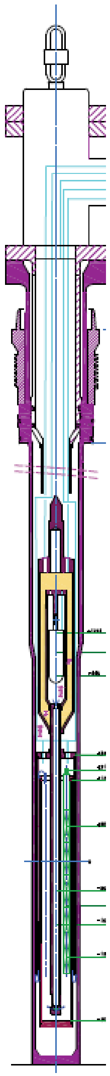
RECALL rig concept









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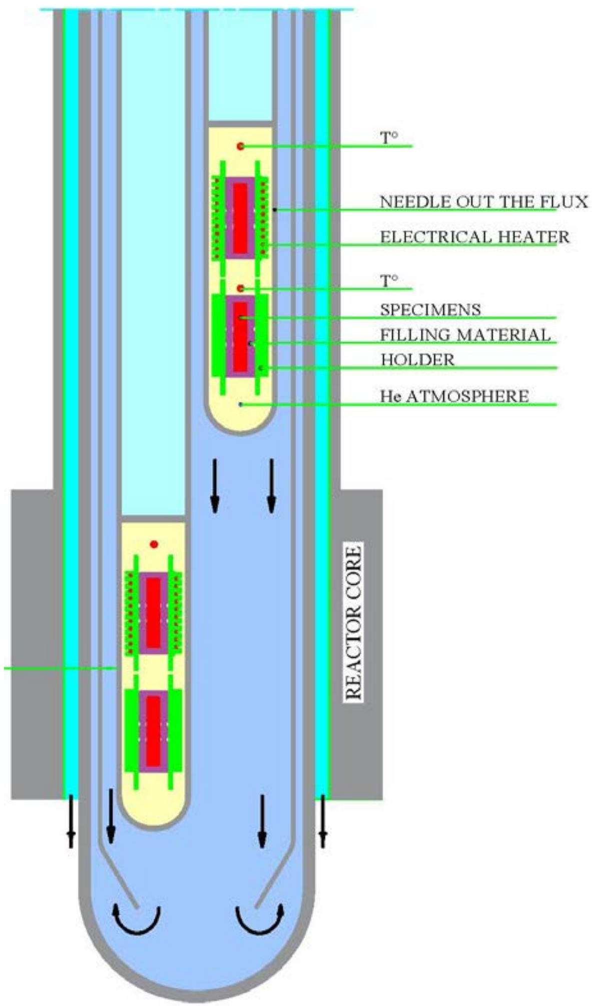
The LIBERTY rig for material irradiation

- 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 mm^2) possible
  - Adaptive single use capsule design



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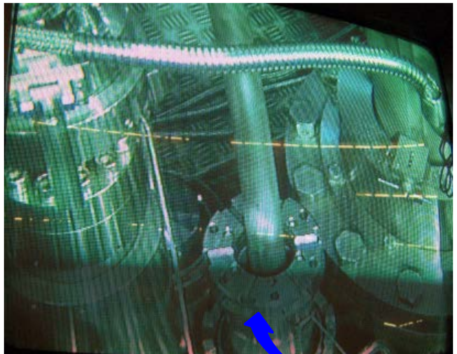
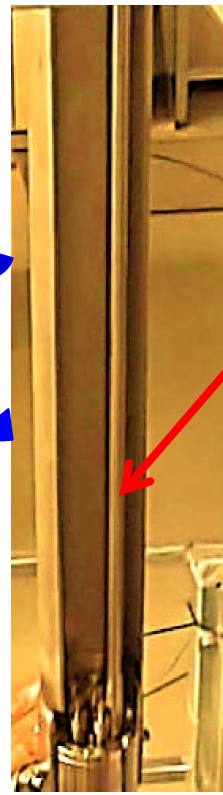
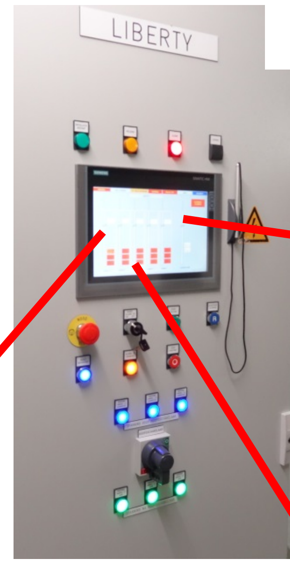
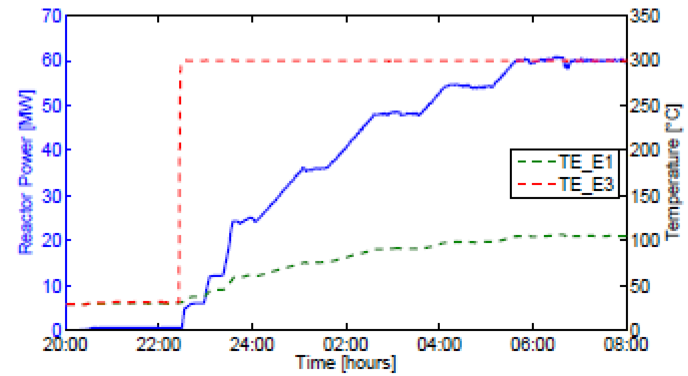


Loading “LIBERTY” in the thimble

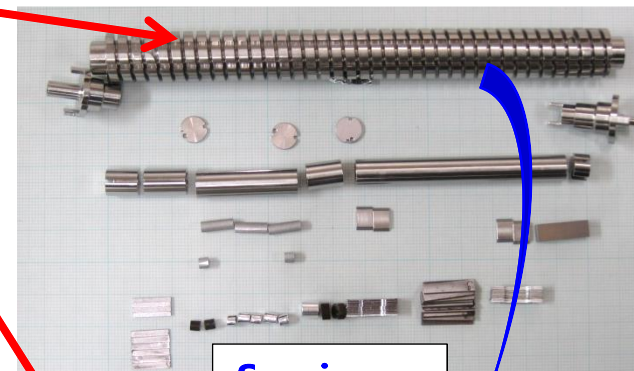


Temperature Control





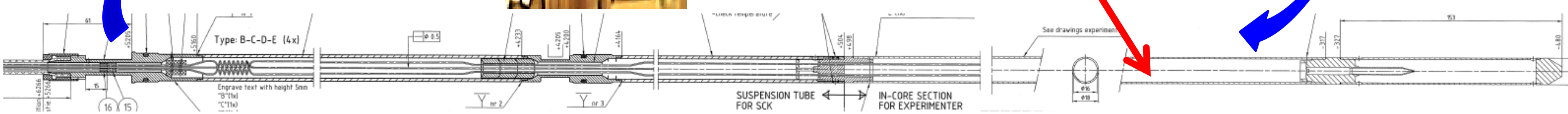
Holder preparation



Specimens

Loading the needle in “LIBERTY”

Needle



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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

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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

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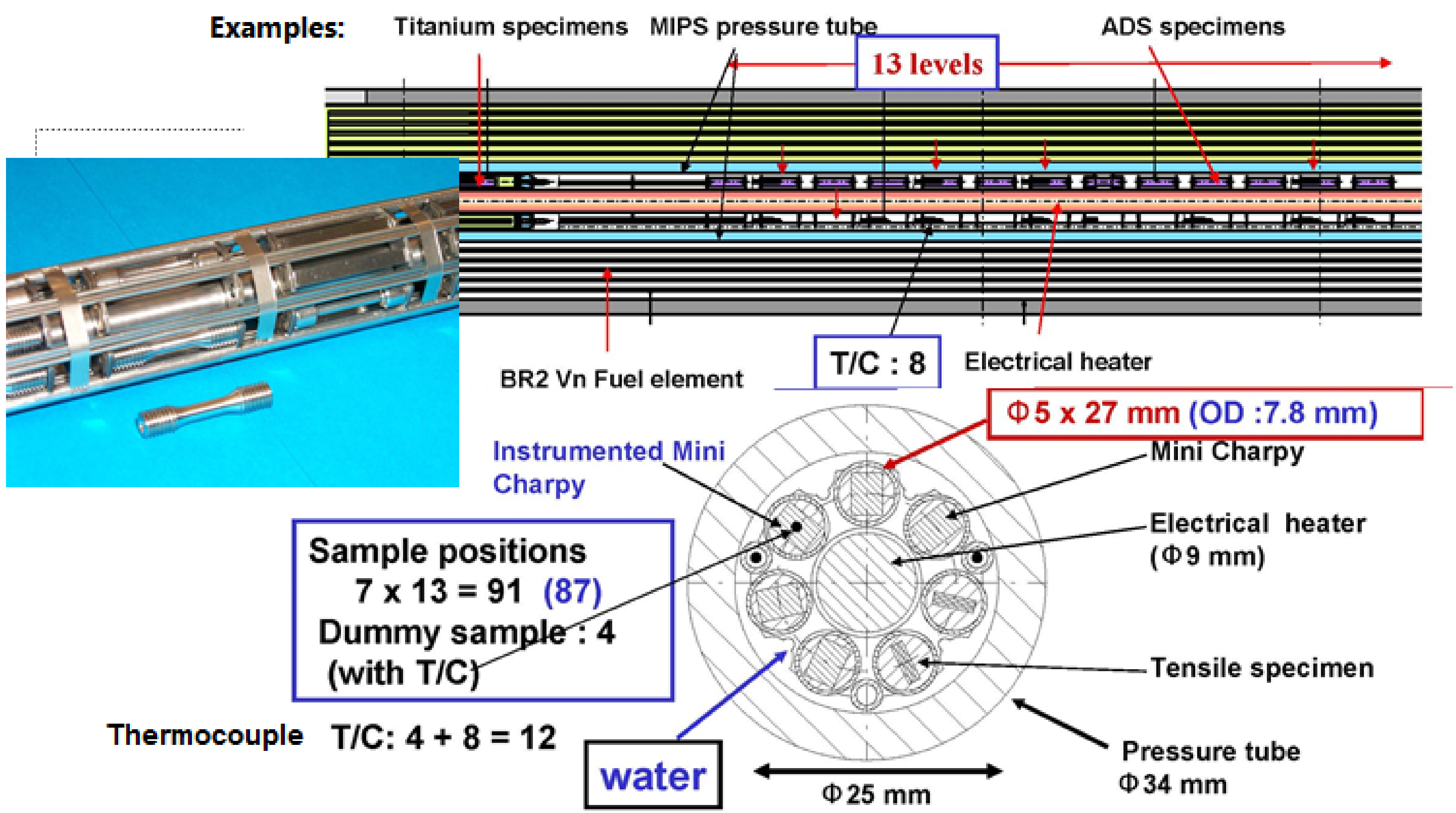
MISTRAL cross section



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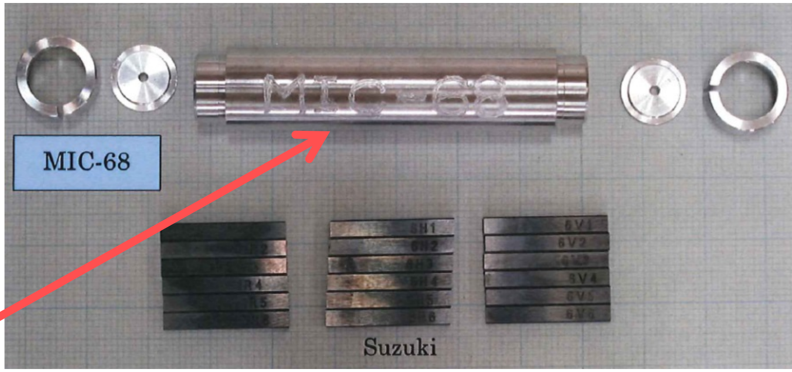
BAMI capsules for screening irradiation

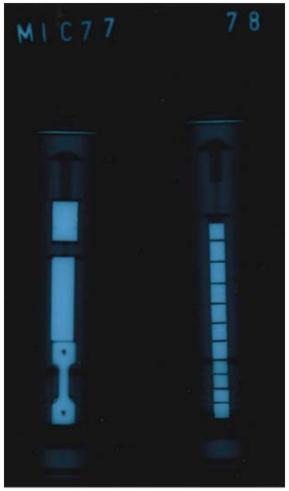
- Capsule irradiation in BAMI
  - Low temperature & high flux
  - Variable small specimens
  - Low cost, 8 capsules/position

Device	BAMI
Environment	He or BR2 coolant
T [°C]	<100
P [bar]	12.5
Fast flux* [10^{18} n/m^2/s]	1
Fast fluence* [10^{24} n/m^2]	2
Max. diameter [mm]	13

*** 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

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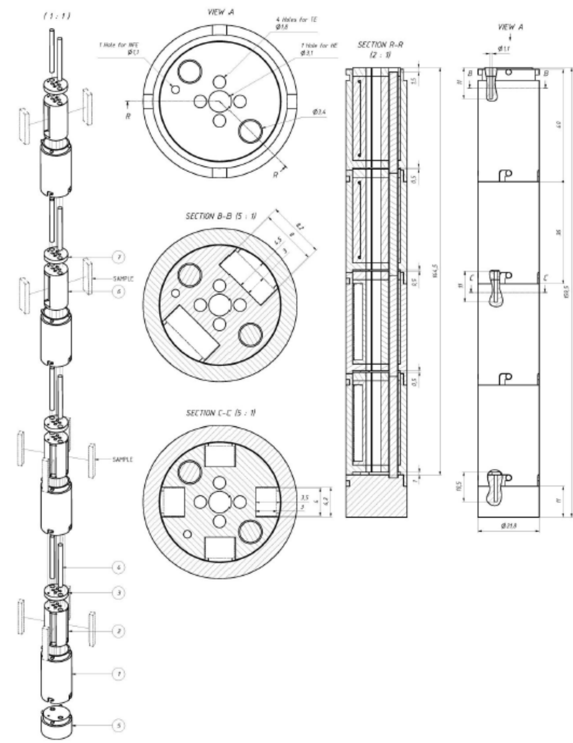
The High Temperature High Flux device

- 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
  - 0.6 dpa per reactor cycle of 3 weeks



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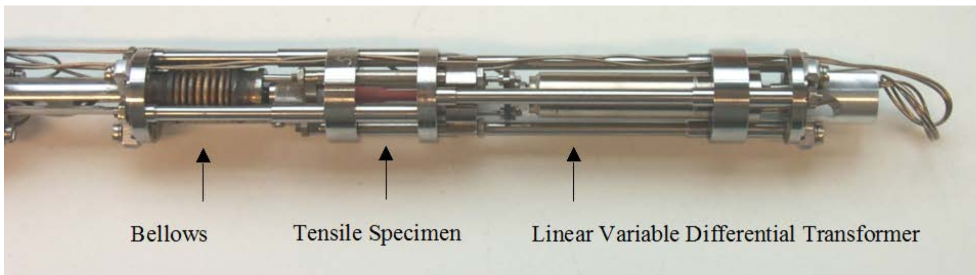
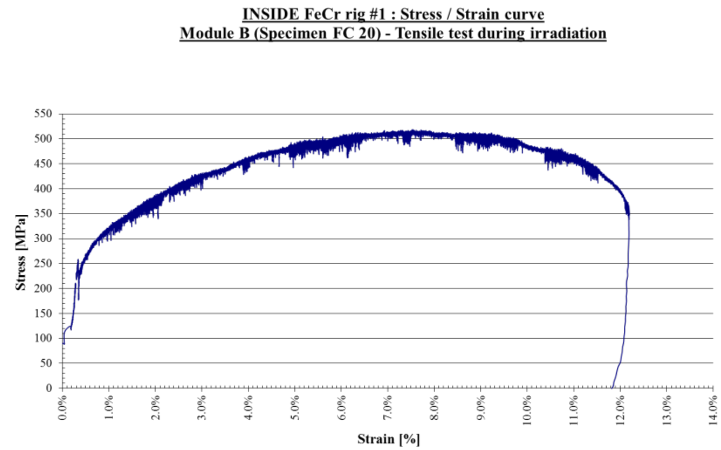
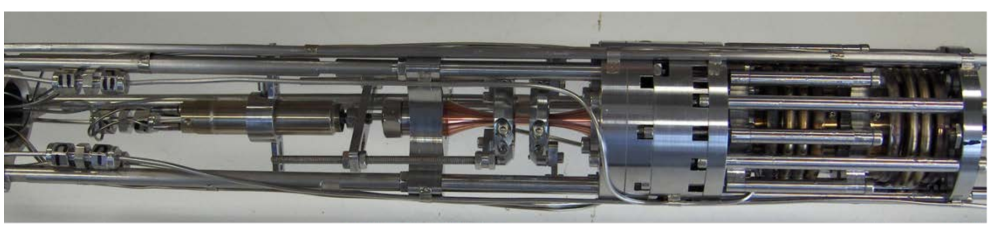
Special Devices: In-situ Testing

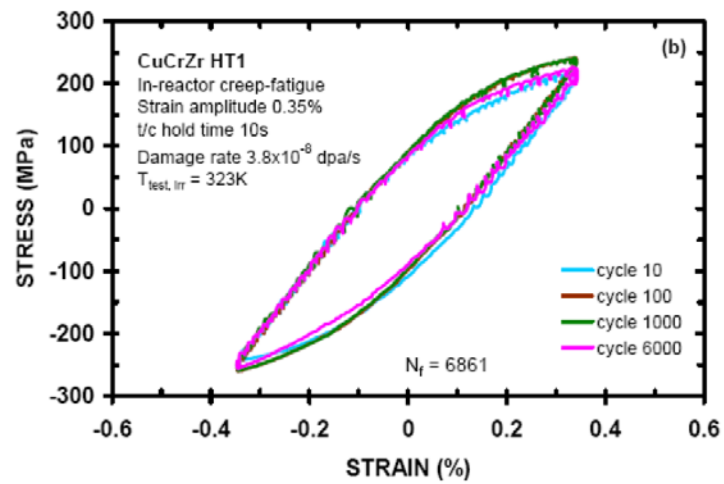
In-situ Tensile Test





In-situ Fatigue Test





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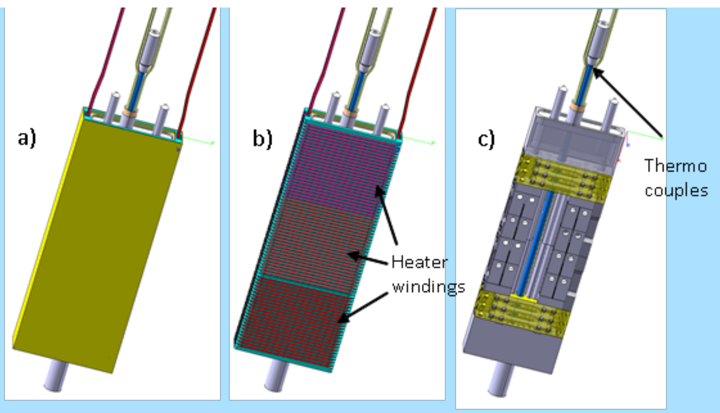
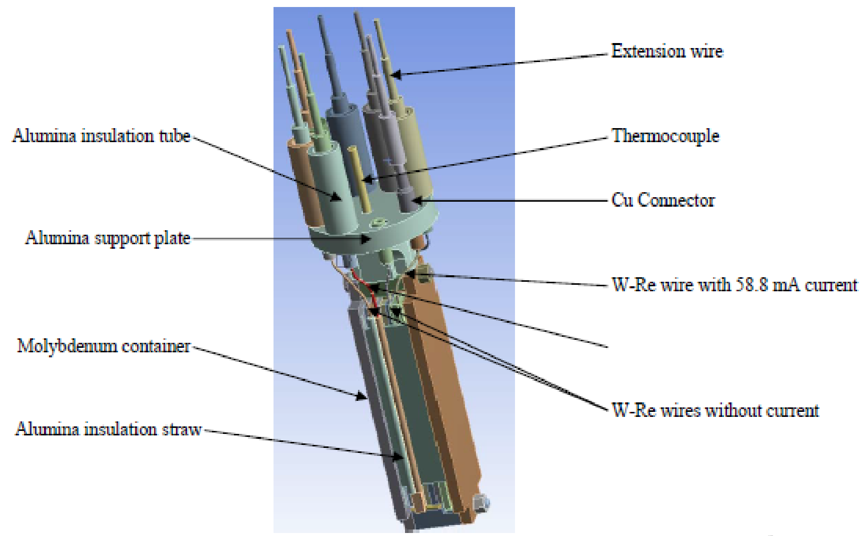
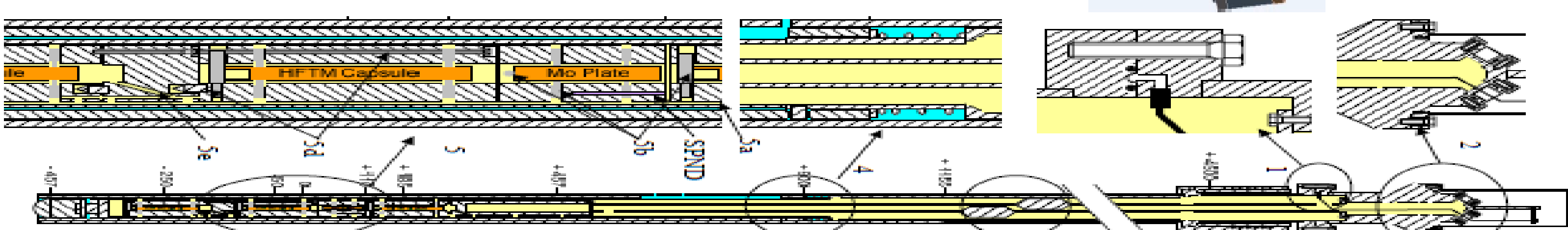
Special Devices: integrated instrument and material testing

- Example: LIBIDO device with He and NaK filled capsules
  - Accomodation of advanced irradiation devices in the BR2 core
  - Extreme environmental conditions in terms of environment and irradiation temperature (250-500°C in Nak & 1000°C in He)



a) complete capsule, b) capsule stripped of external brazing cap,
c) specimen stack with upper and lower caps





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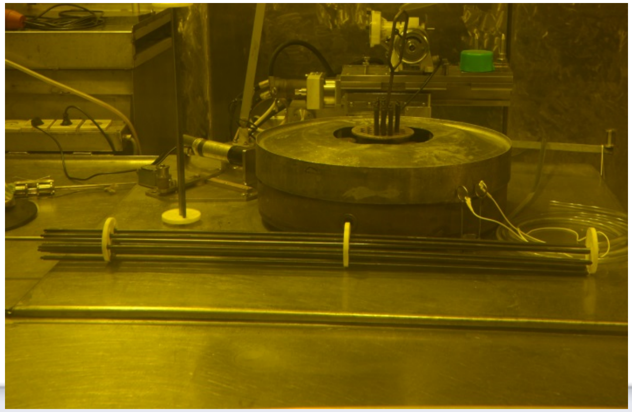
Nuclear fuel irradiation experiments

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

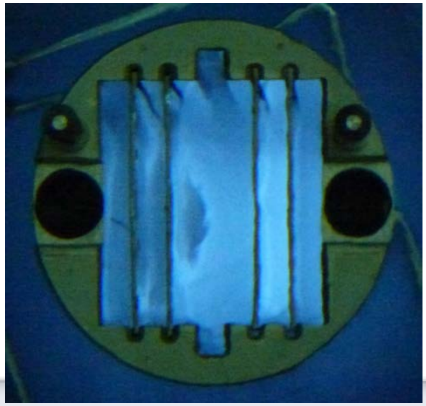
- Development of new fuels and safety testing of current fuels
  - Determine safe operational conditions for fuel in representative and under overpower conditions
  - Steady state irradiation: power and burn-up limits
  - Transient irradiation: test safety margins
  - Safety tests: experience in accident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

- Scope

Power reactor fuels



Test reactor fuels



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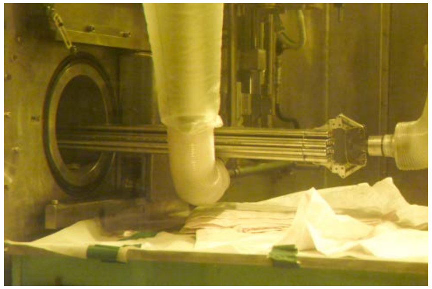
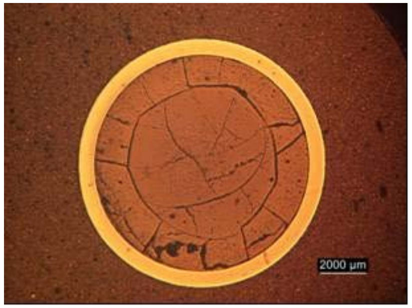
Power reactor fuel tools

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



- Fuel irradiation:
  - Pressurised water capsule for steady state/transient test
  - Dedicated rigs

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



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Fuel pin irradiation

- Steady state conditions or transient conditions
  - Linear power levels up to $q_{l,max}$ = 750 W/cm
  - Rod power variation by reactor power variation
  - Power increase rate $\Delta q_l/\Delta t_{max}$ = 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

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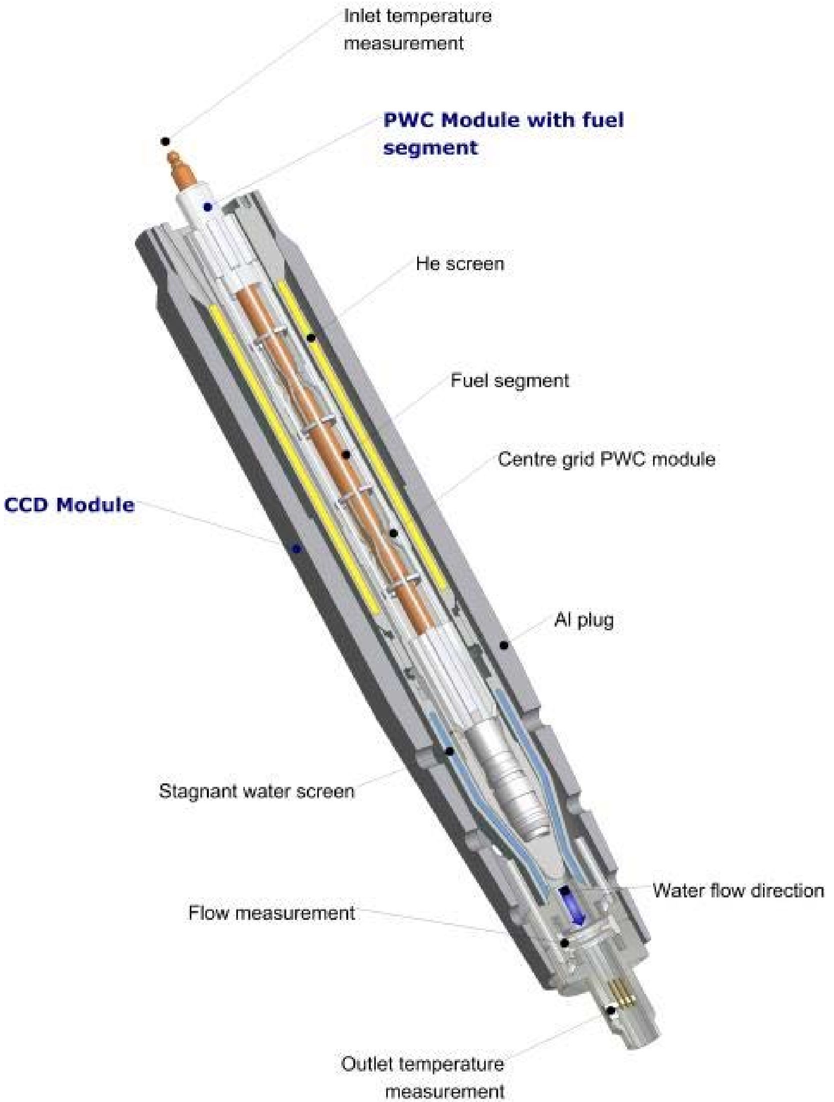
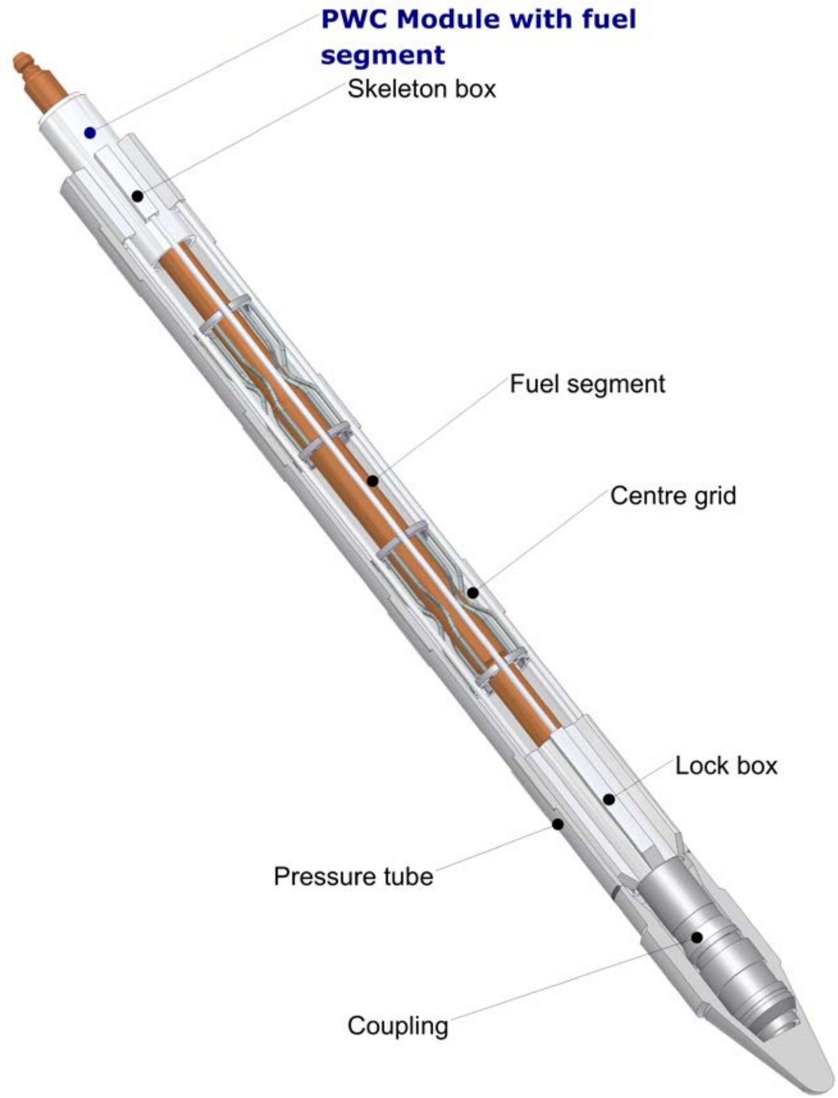
Pressurised Water Capsule (PWC) & Calorimetric Device (CD)





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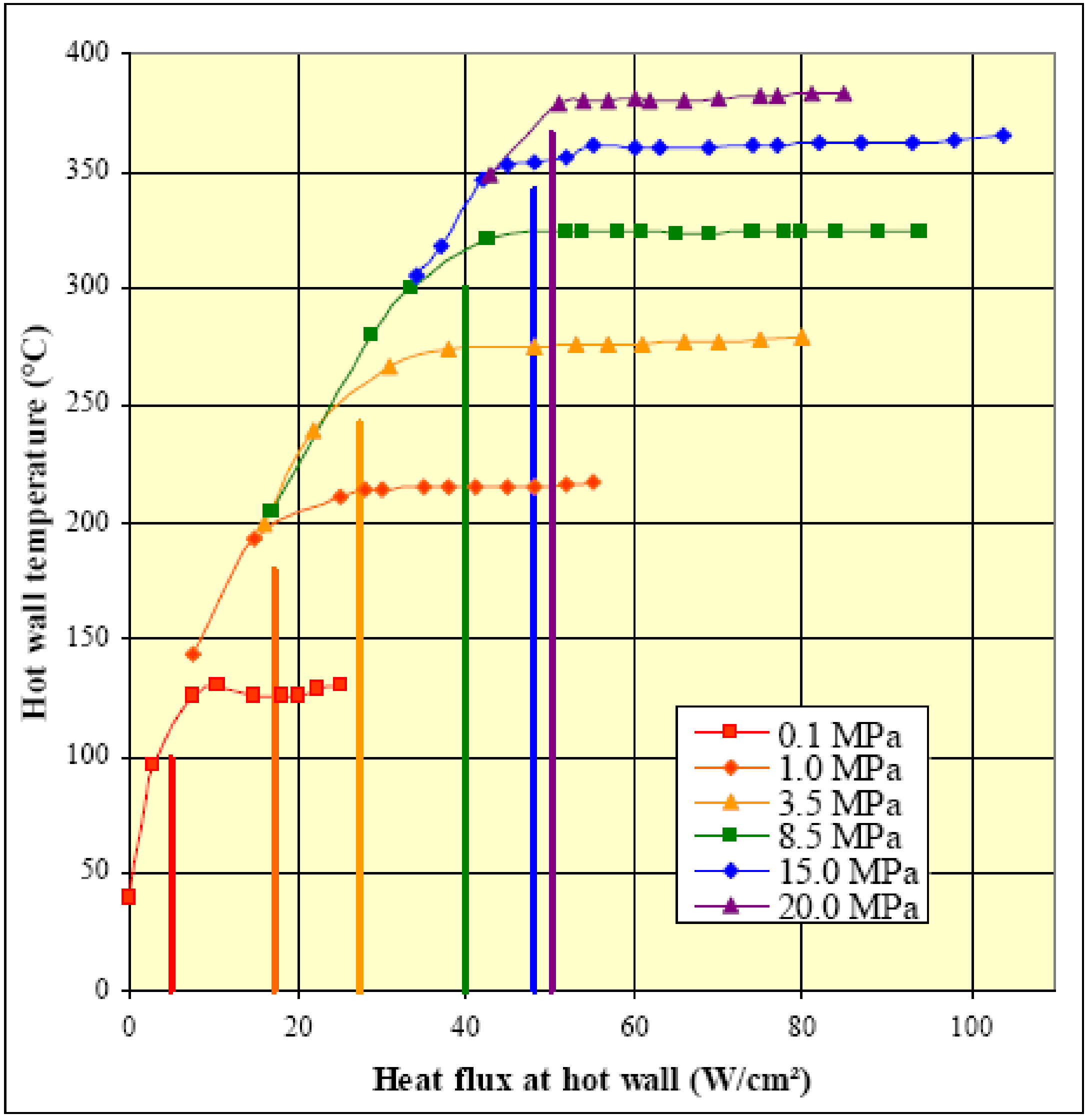
PWC capsule temperature control
$T_{clad}(P_{rod}, p_{PWC})$



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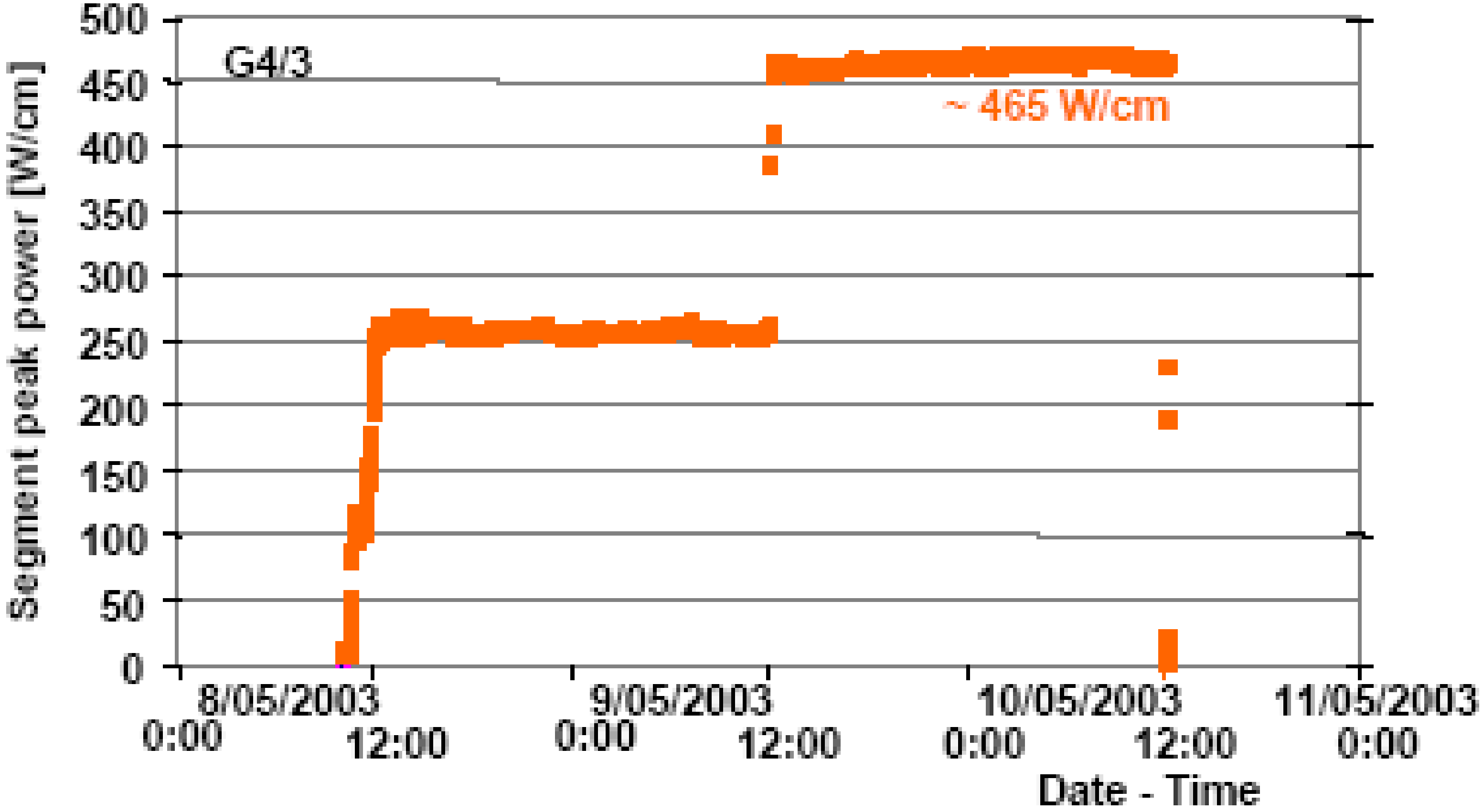
Typical power transient



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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/cm^2)
  - 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

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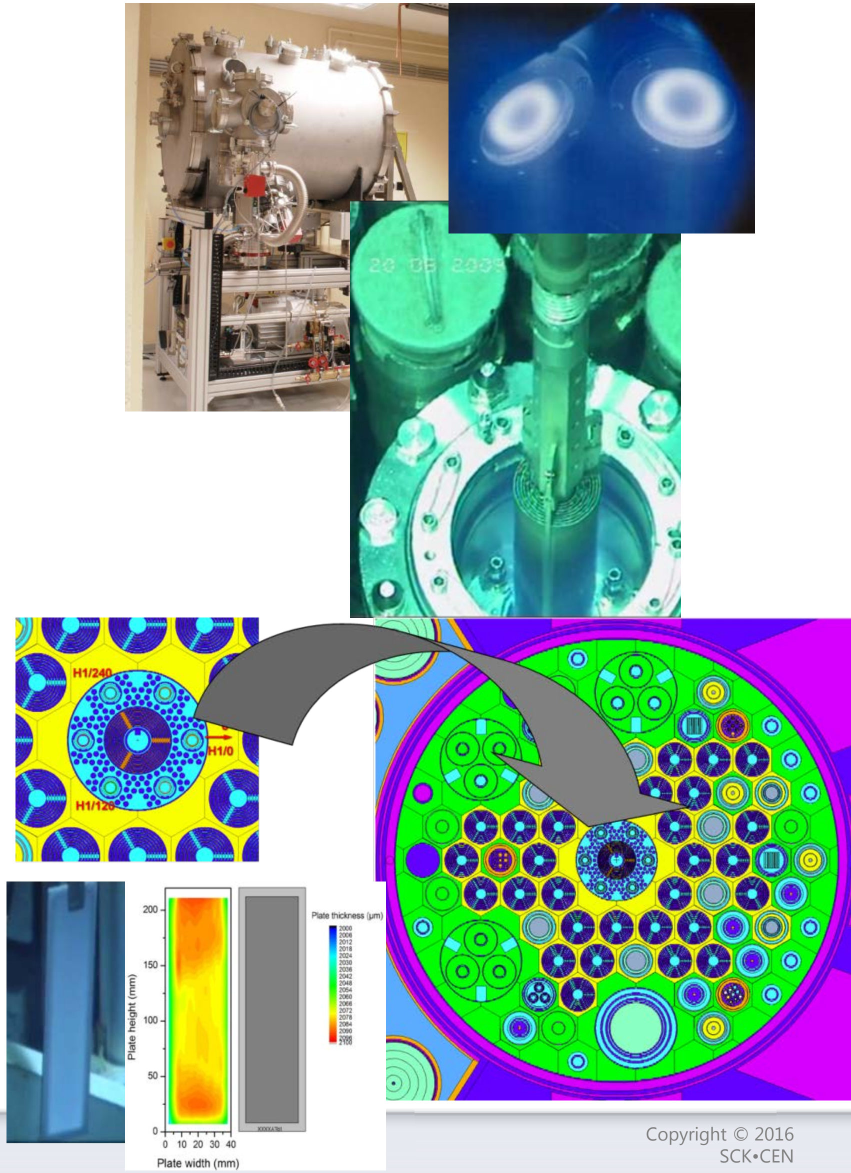
Test reactor fuel tools

- 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



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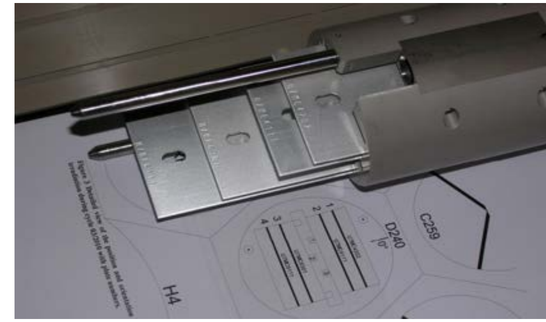
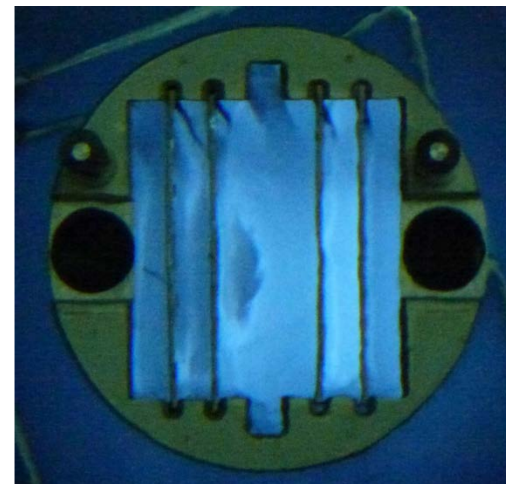
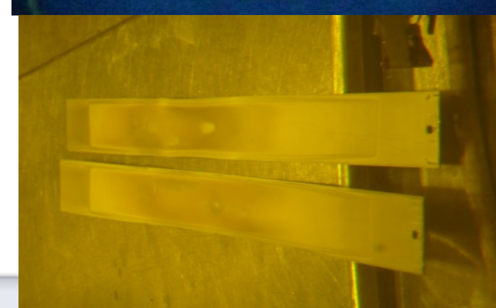
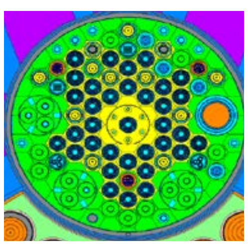
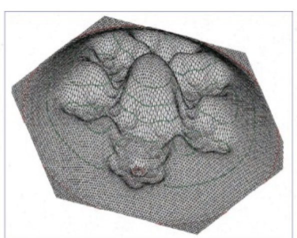
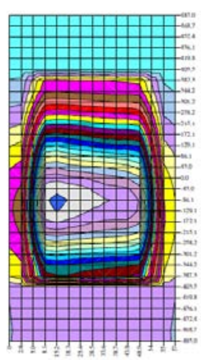
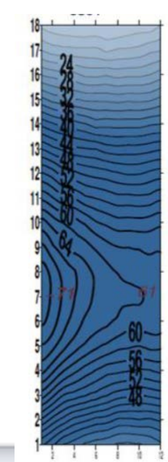
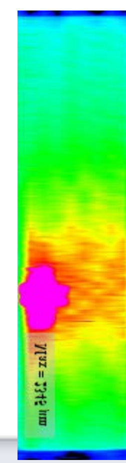
MTR fuel plate irradiation: FUTURE basket

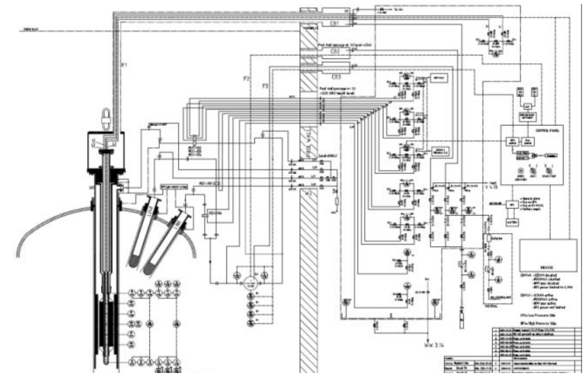
- Qualification of representative full MTR plates up to 600W/cm^2
- Non-instrumented basket for low lead time experiments
- Irradiation conditions determined by detailed modelling and validated by quantitative PIE

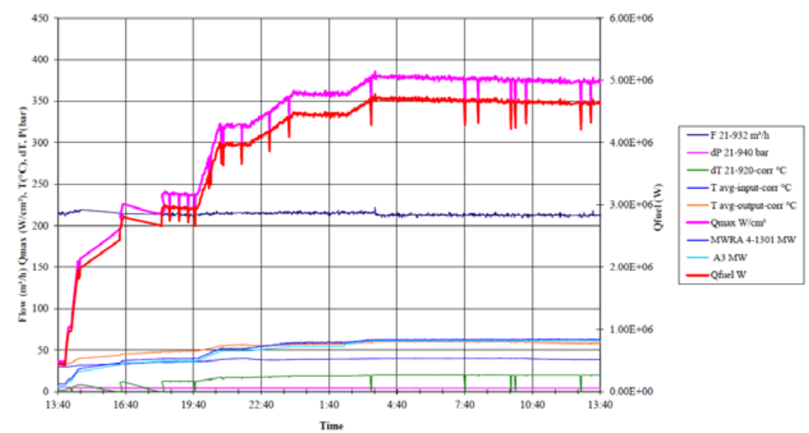


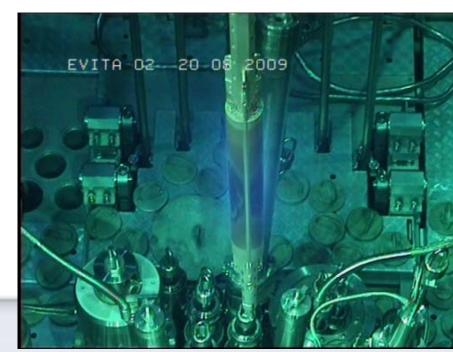








MTR fuel element irradiation

- 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







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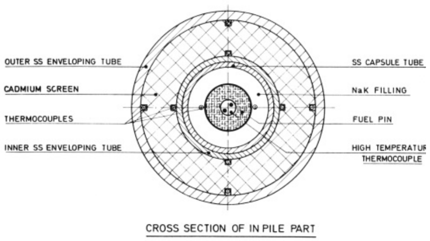
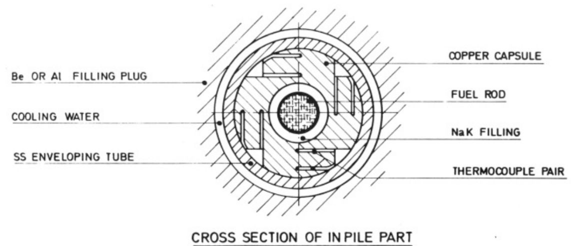
Fast reactor activity experience

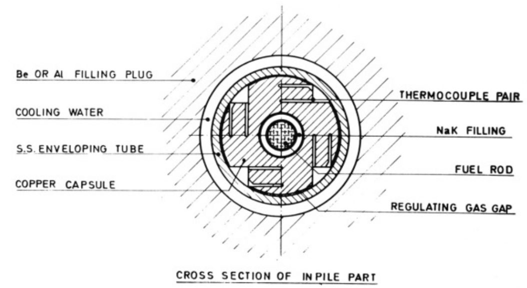
- Pioneering work
  - Capsule irradiation of materials and fuel pins in Na-K capsules
    - Screening irradiations and BOL phenomena



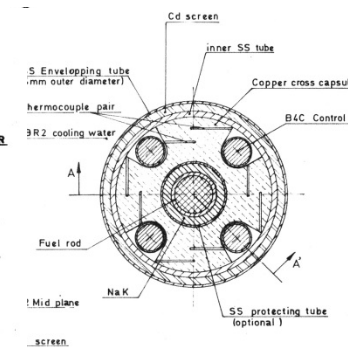
FAFNIR (Fuel Array Fast Neutron Irradiation Rig)



CIRCE (Calorimetric Irradiation Capsule Experiment.)

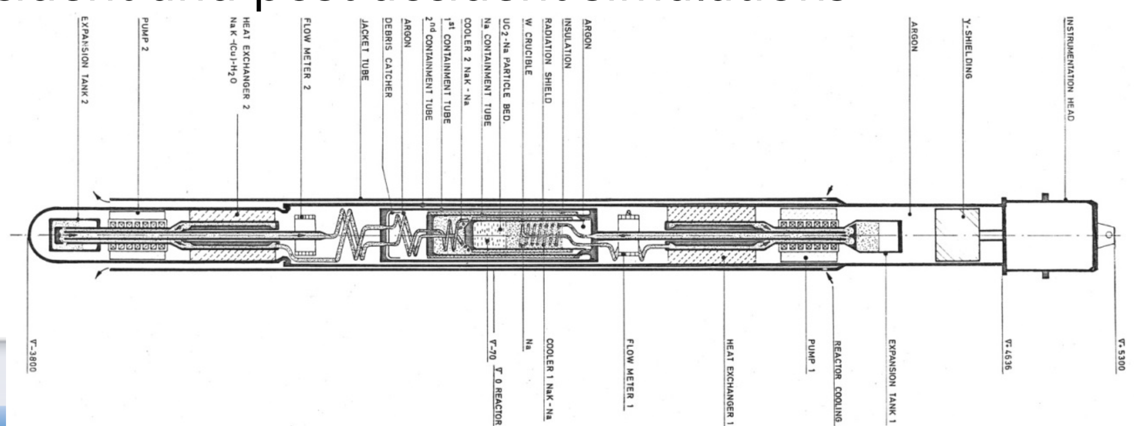


CFC (Compatibility Fuel Cladding)



PCF IRRADIATION DEVICE

- Advanced studies
  - Loop tests for SFR and GFR fuels in nominal conditions
  - Accident and post accident simulations



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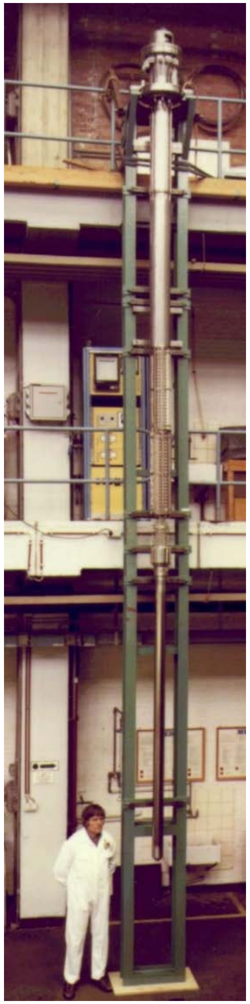
Typical Sodium integrated loop: IPSL-500

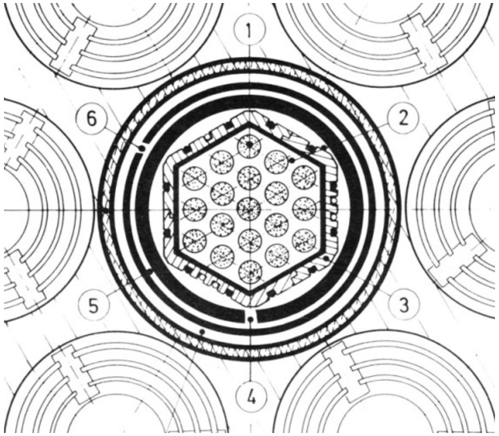
Operating characteristics

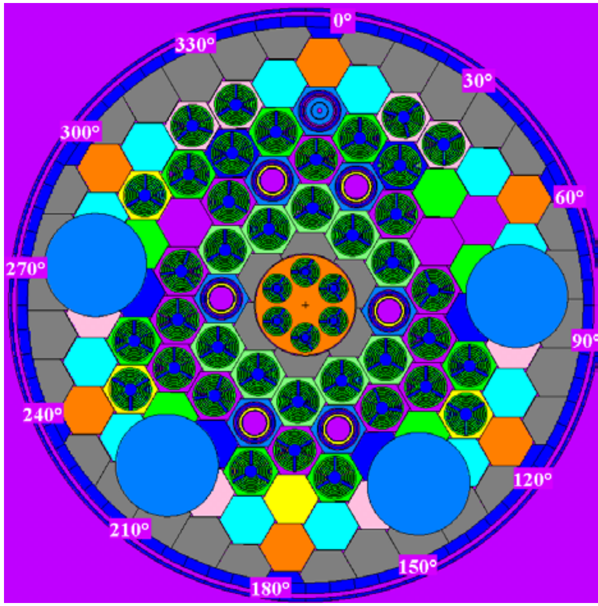
- Fuel rod power 500 W/cm
- Fuel pin diameter 6 to 7 mm
- Active fissile length 500 mm
- Total length 1080 mm
- Number of parallel pins: 19

Loop design

- Maximum working temperature 700 °C
- Maximum working pressure at 6 Kg/cm^2
- Design pressure 40 Kg/cm^2
- Flow and pressure head 2,5 l/s
- Total power output 500 kW
- Material AISI 316
- Sodium volume 19 l







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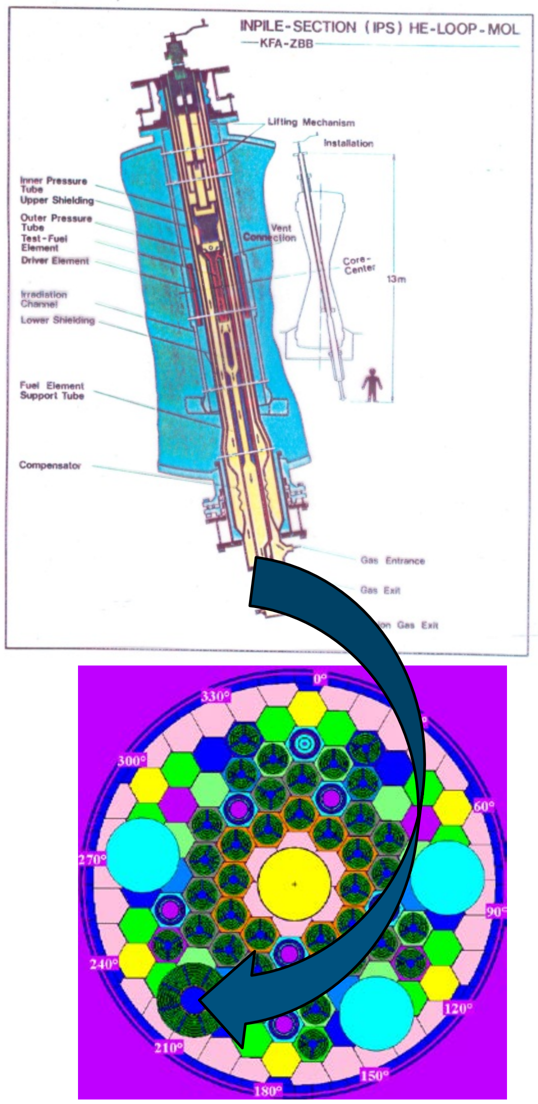
Gas cooled fast reactor

- Helium cooled loop
- Fuel pin power up to 500W/cm
- Cladding temperature up to 680°C

- Burn up accumulation 3GWd/t for each irradiation cycle
- Accumulated burn up to about 100GWd/t



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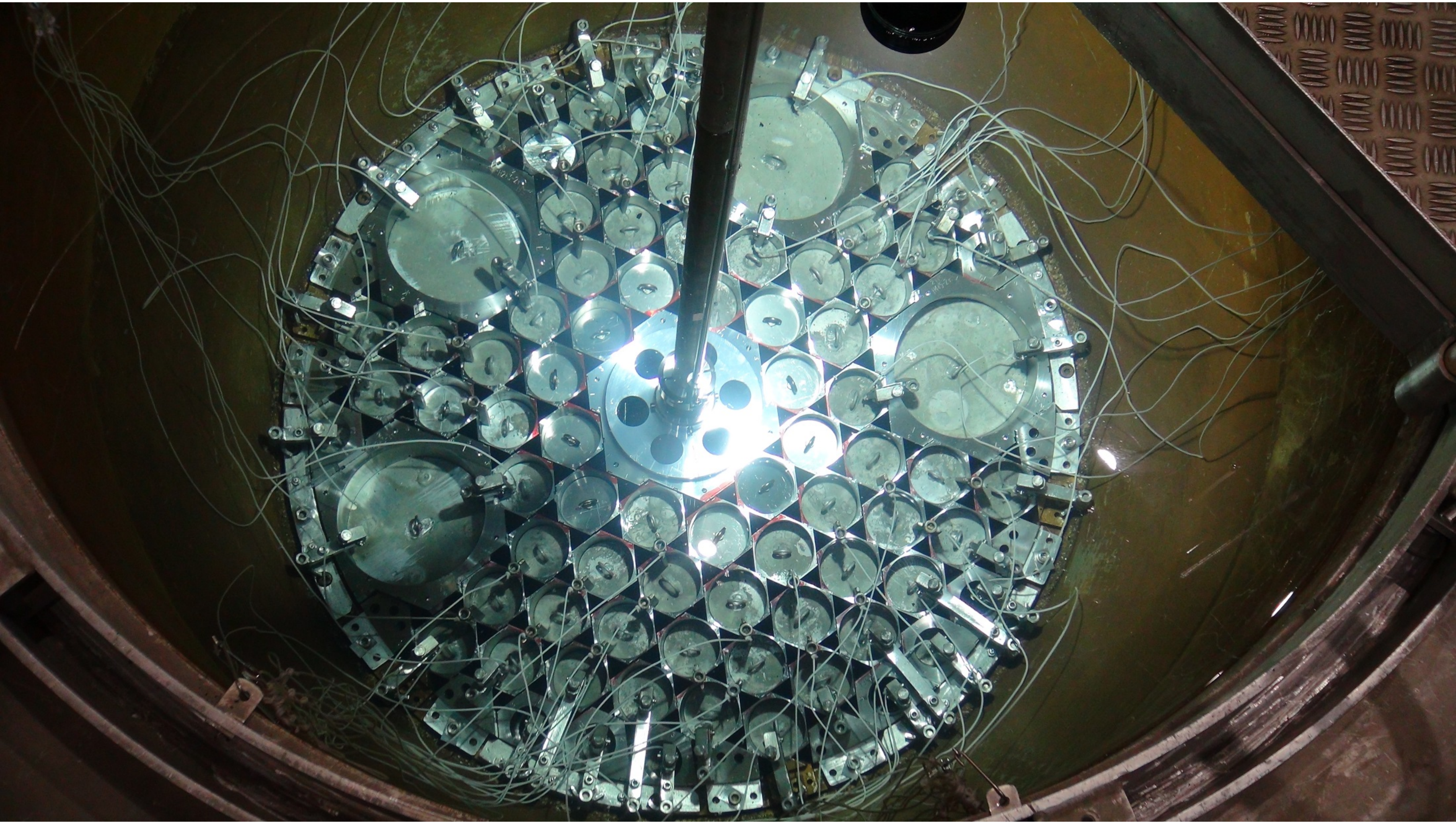
Summary BR2



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