sck cen

Belgian Nuclear Research Centre

J. Van den Bosch - 02/06/2022

Possibilities of the BR2 reactor for materials and fuel R&D

BR2 reactor design and conditions

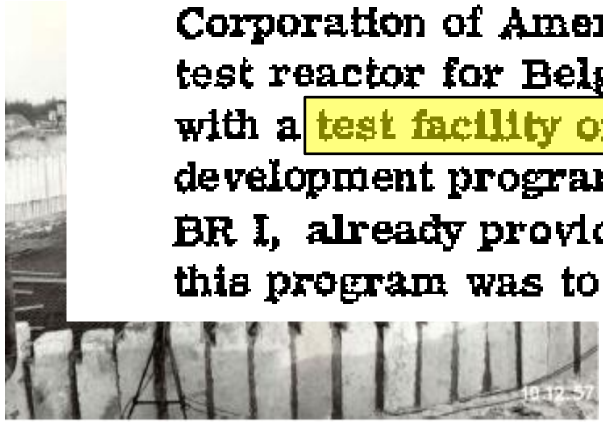
BR2 design goal

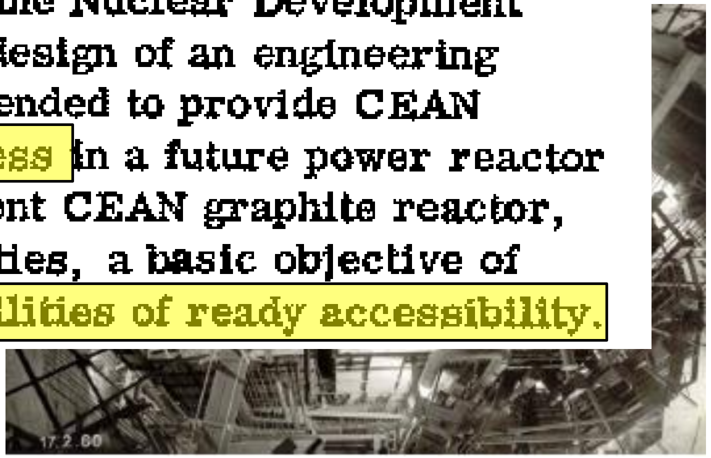
NDA

III. INTRODUCTION

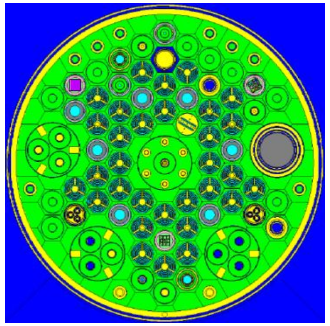
A. PURPOSE OF PROJECT AND PHASE I

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.

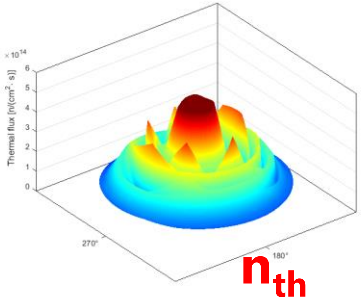




Reactor core performance of BR2

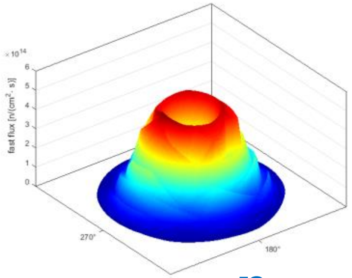


- Design goal: thermal neutron flux up to 10^{15} n/cm^{2}s
  - Compact core arrangement with central flux trap
  - Material choice: Be moderator and metallic uranium fuel
  - High overall core power (upgraded from 50 to 100MW in 1968)
    - 25MW additional cooling capacity for experiments



n_{th}

- 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



n_f

- 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

Reactor core geometry

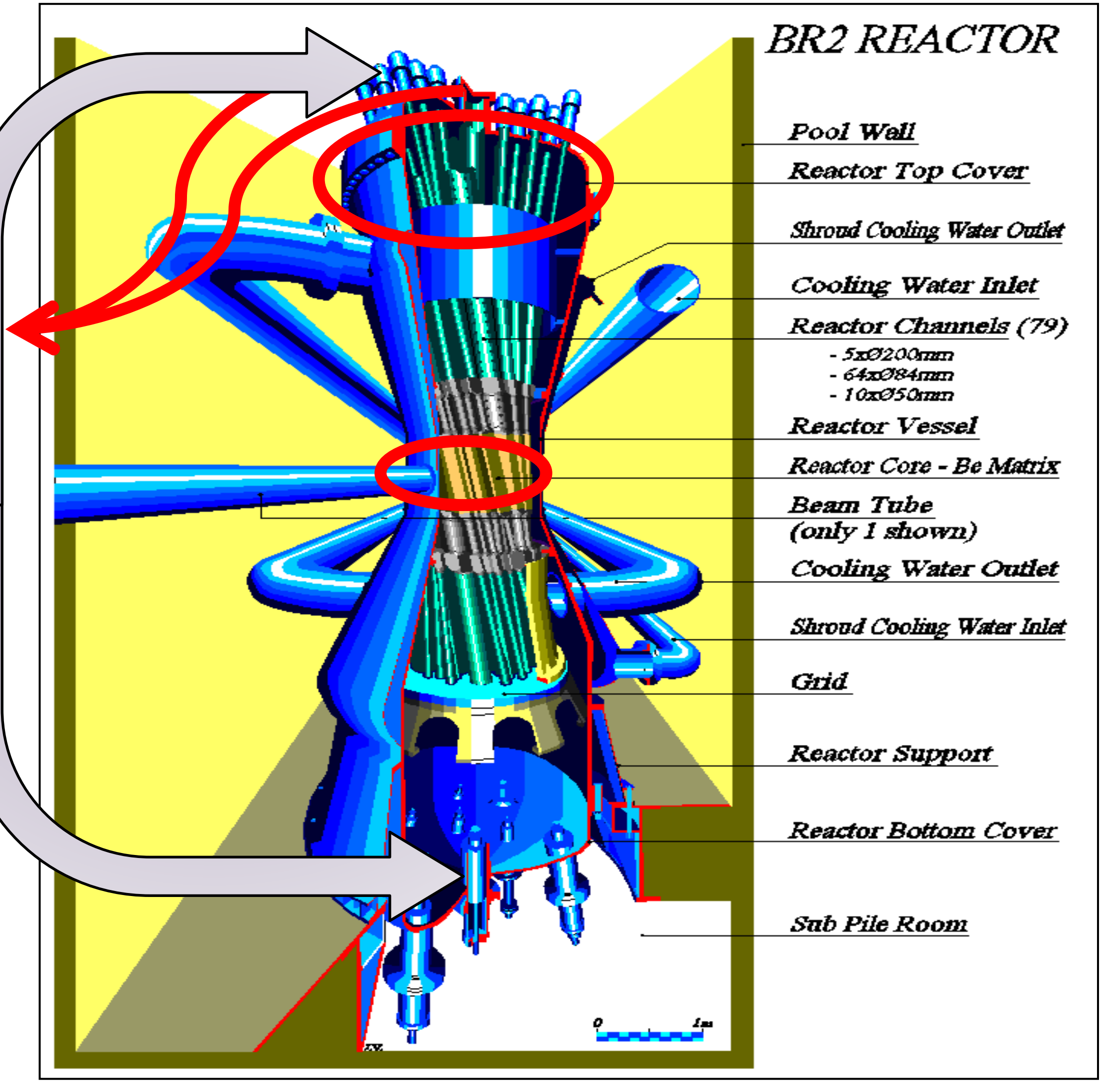
Diverging reactor channels for compact core and good access: core 1m, cover 2m ∅

Angle of channels from 0 to 27°

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

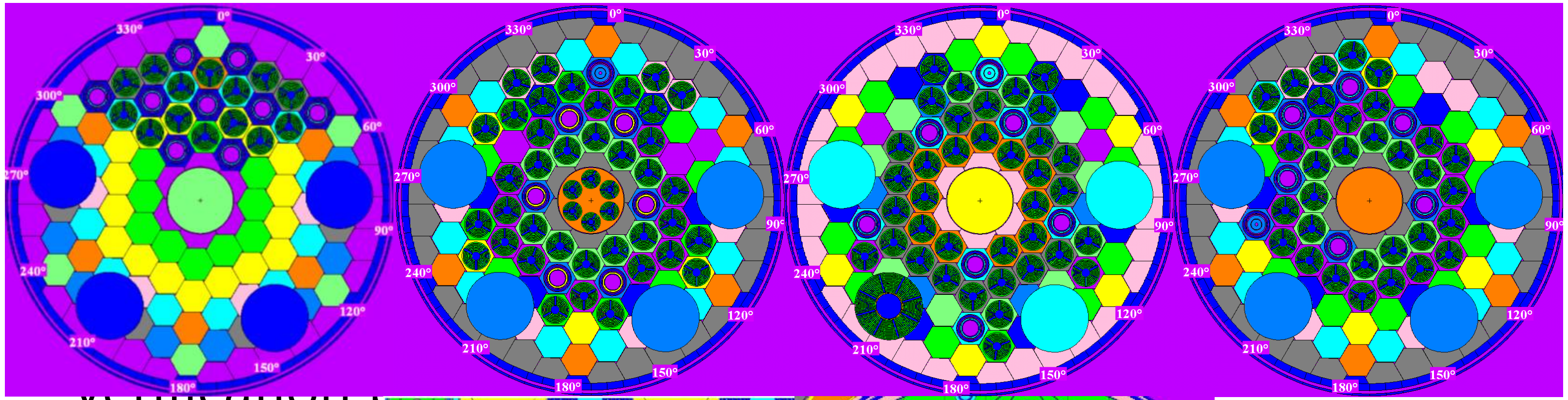
Irradiation inside rigs in reactor channel or in axis of fuel element

Loading elements hang on top cover

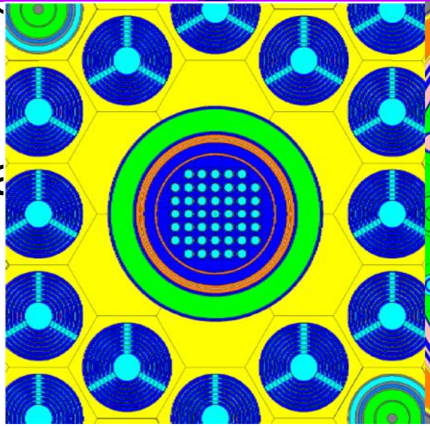


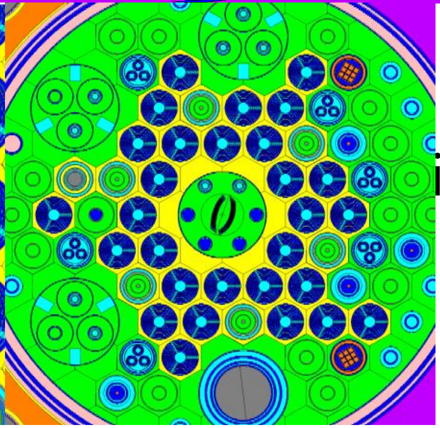
Flexible reactor configuration

- 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



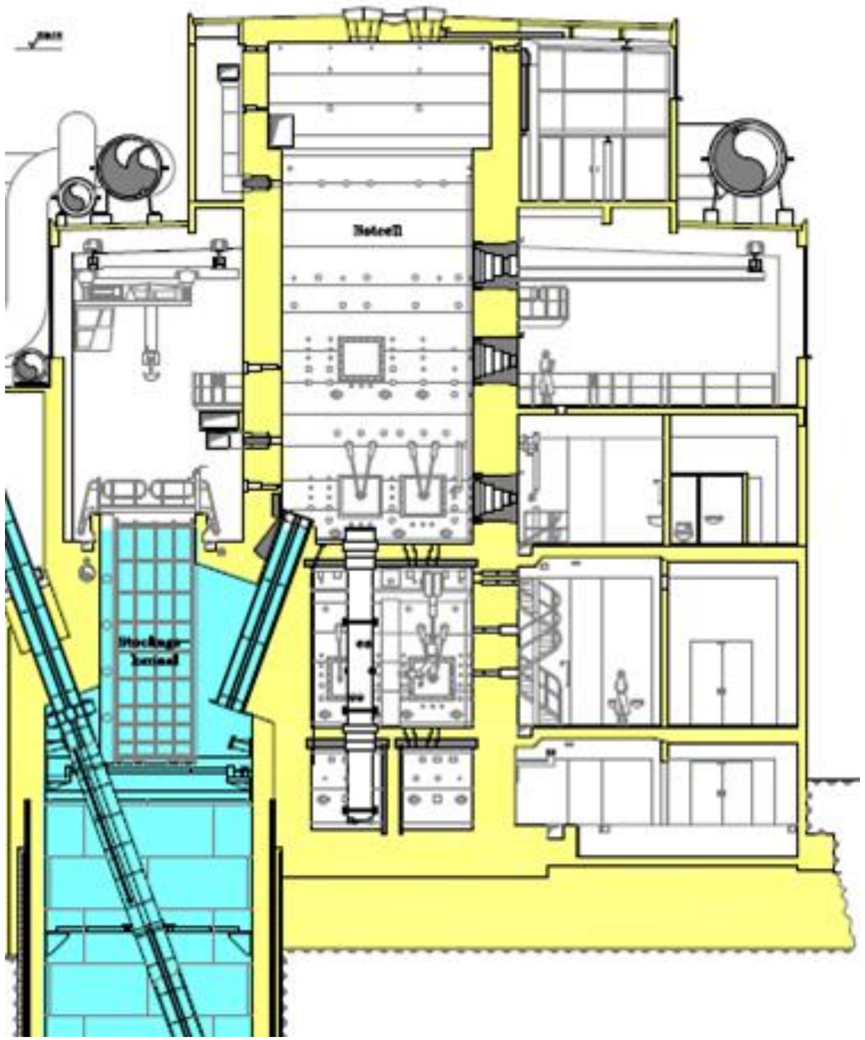
- verification t



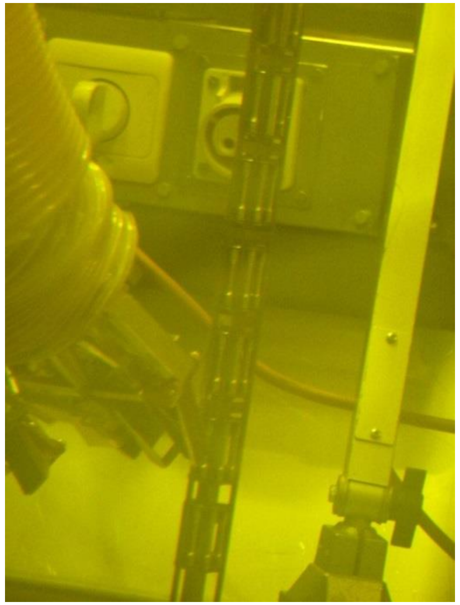


- BR2 reactor ma … including irradiations)

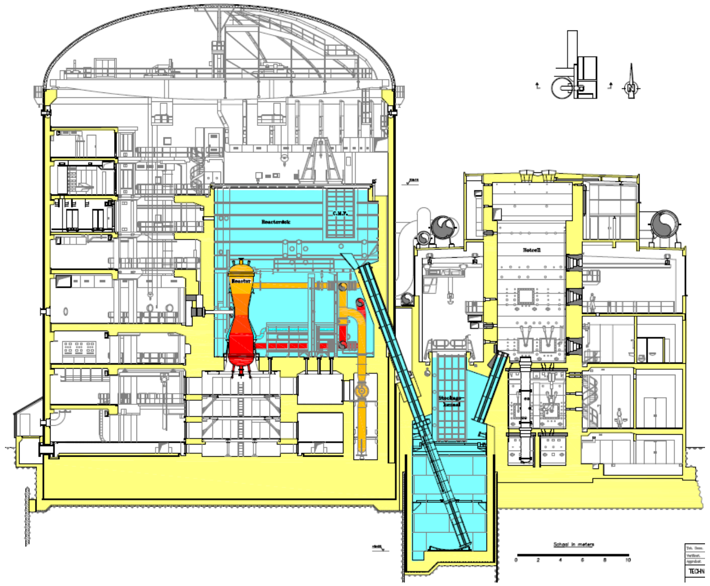
The BR2 hot cell



- 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



Proximity of PIE facilities



LHMA Hot Cells

Dosimetry

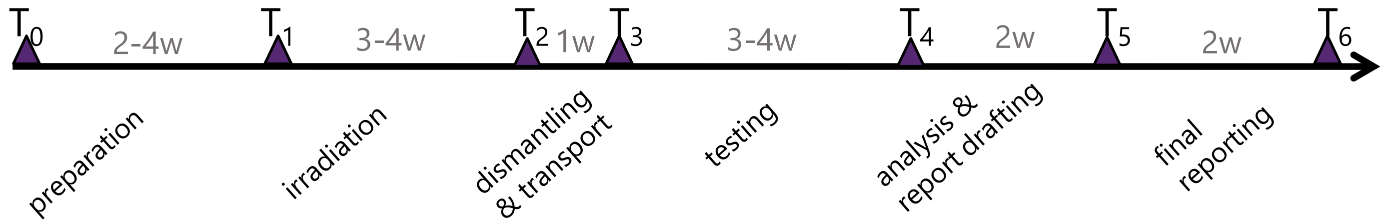
Tensile testing

Charpy impact testing

Fracture toughness testing

Microstructure

Total : **3 – 4 months**



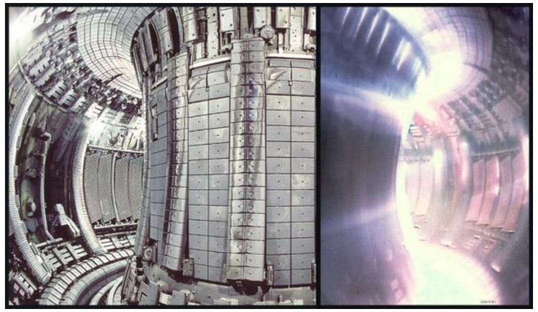
Structural Materials Irradiation Devices

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 SMR, GENIV & Fusion

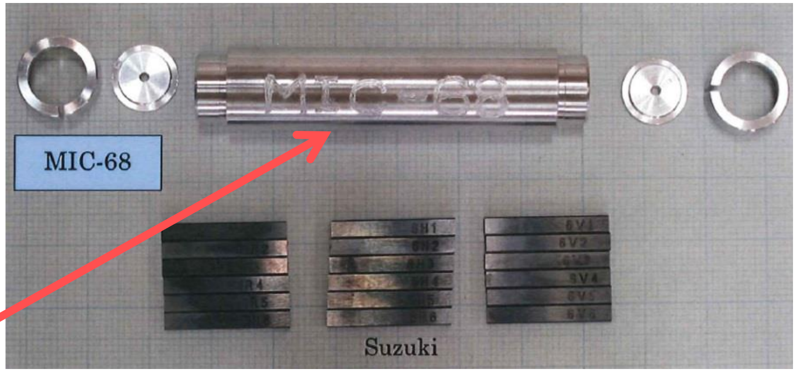


BAMI capsules for screening irradiation

- Capsule irradiation in BAMI
  - Low temperature & high flux
  - Variable small

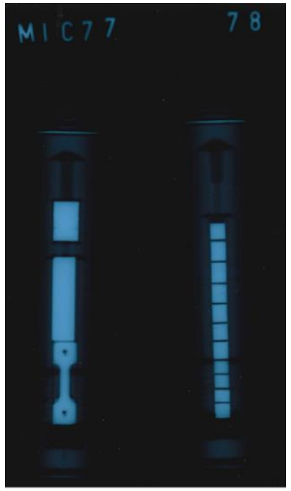
Device	BAMI
Environment	He or BR2 coolant
T [°C]	<100
P [bar]	12.5
Fast flux* $[10^{18}\ n/m^2/s]$	1
Fast fluence* $[10^{24}\ n/m^2]$	2
Max. diameter [mm]	13

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



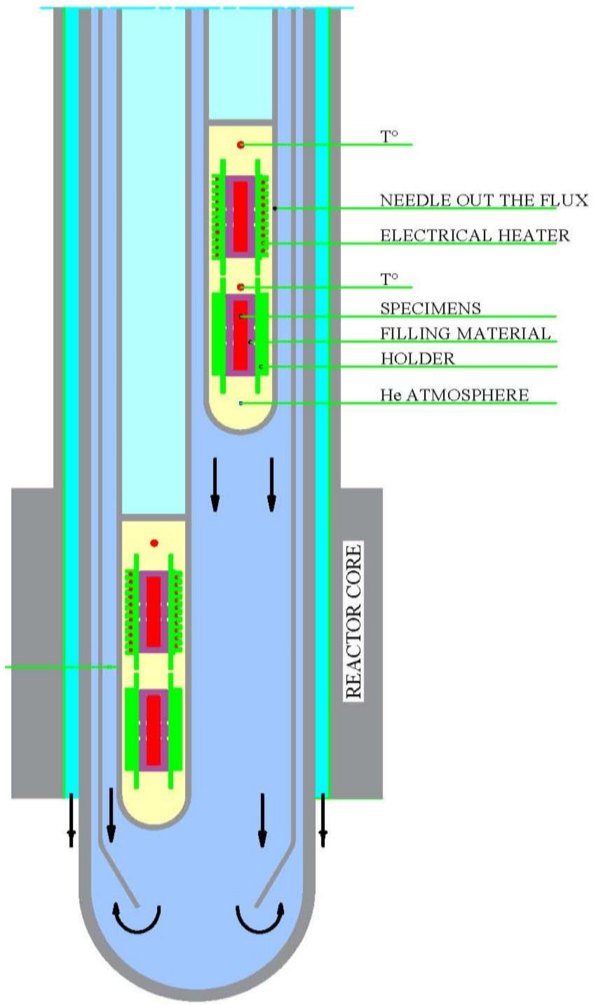
Sample holder with specimens

X-ray of a BAMI capsule containing a sample holder



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



LIBERTY application range

Irradiation conditions	max	min
Temperature range	50 – 1000 ºC	
Specimen environment	Gas (He), vacuum, pool water	
BR2 channel	E30	L300
Fast flux (E>1Mev) [10^{13} n/cm2/s]	3.2-4.8	0.6-1.3
Irradiation time	21 (28) days	2 hours
Fast fluence [n/cm2]	8.7 (11.6) x10^{18}	4.3x10^{16}

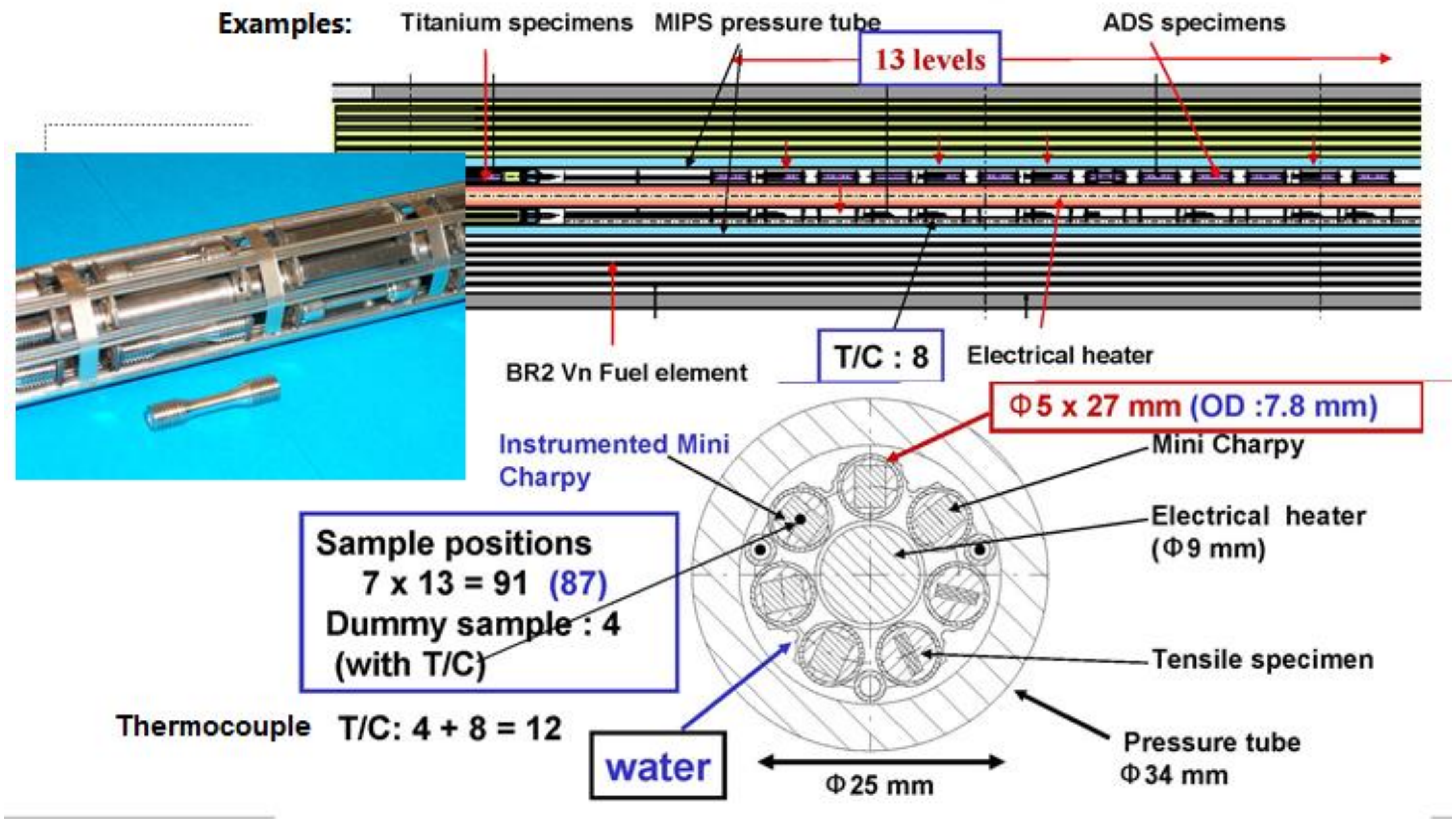
The MISTRAL device for database generation

- 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

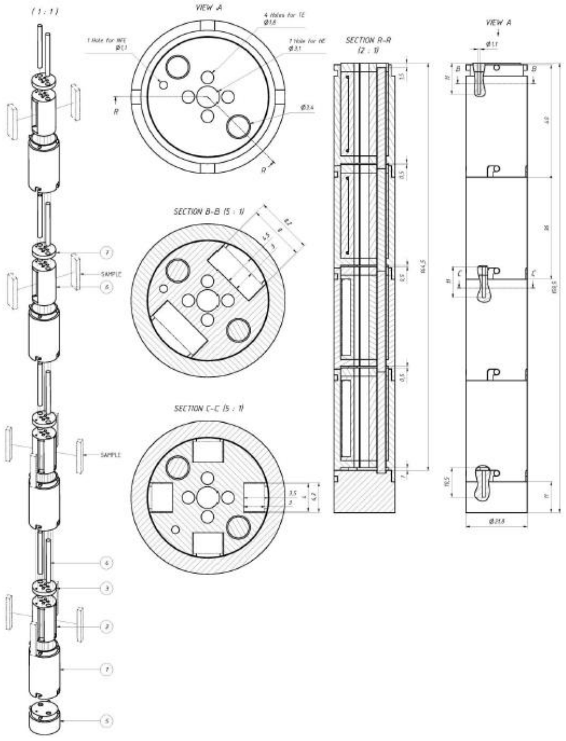
- Characteristics
  - Temperature 150-350°C
  - Up to 0.5 dpa per reactor cycle of 3 weeks

MISTRAL cross section



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/cm^2 (E>1MeV) in hottest channel

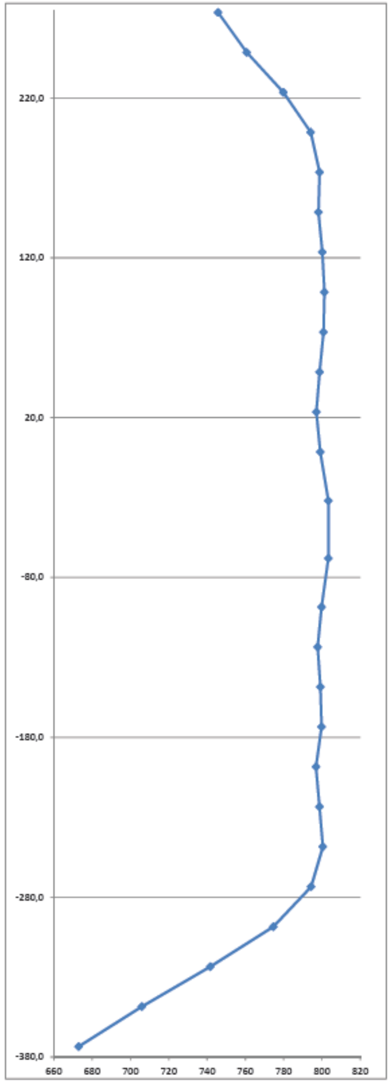


HTHF – High Temperature High Flux

- Purpose of the device
  - Specimens (not fuel) irradiation at
    - High temperature : 300 → 1000 °C (measured and controlled)
    - High flux: in a VIn fuel element (dose up to 10 dpa)
    - Nuclear Heating from 8 up to 14 W/g
  - Specimens:
    - Type: flat tensile, mini-Charpy & simple geometries (like cylinders)
    - Material: High temperature resistant: W, Mo, SiC, … Fe (300 °C)
  - No requirement to preheat specimens at irradiation temperature before the first neutron.
  - Environment: gas (Helium) or vacuum

HTHF – Calculation results

Pos ---	Diameter mm	Insulation?	Position mm	Flux Shape [%]	Temp °C
1	20,40		273,5	58%	745,7
2	20,40		248,5	63%	760,7
3	20,40		223,5	68%	779,9
4	20,50		198,5	73%	794,1
5	20,80	TK	173,5	78%	798,8
6	21,10		148,5	82%	798,2
7	21,20		123,5	86%	800,2
8	21,30		98,5	90%	801,3
9	21,40		73,5	93%	800,8
10	21,50		48,5	95%	798,8
11	21,60		23,5	97%	797,1
12	21,60		-1,5	99%	799,1
13	21,70	TK	-32,0	100%	803,3
14	21,70	TK	-68,0	100%	803,4
15	21,60		-98,5	99%	799,8
16	21,60		-123,5	98%	797,8
17	21,50		-148,5	96%	799,2
18	21,40		-173,5	93%	799,8
19	21,40		-198,5	90%	796,9
20	21,20		-223,5	86%	798,7
21	20,90	TK + IMR	-248,5	81%	800,5
22	20,60		-273,5	76%	794,3
23	20,40		-298,5	70%	774,6
24	20,40		-323,5	63%	741,7
25	20,40		-348,5	57%	706,0
26	20,40		-373,5	52%	672,9

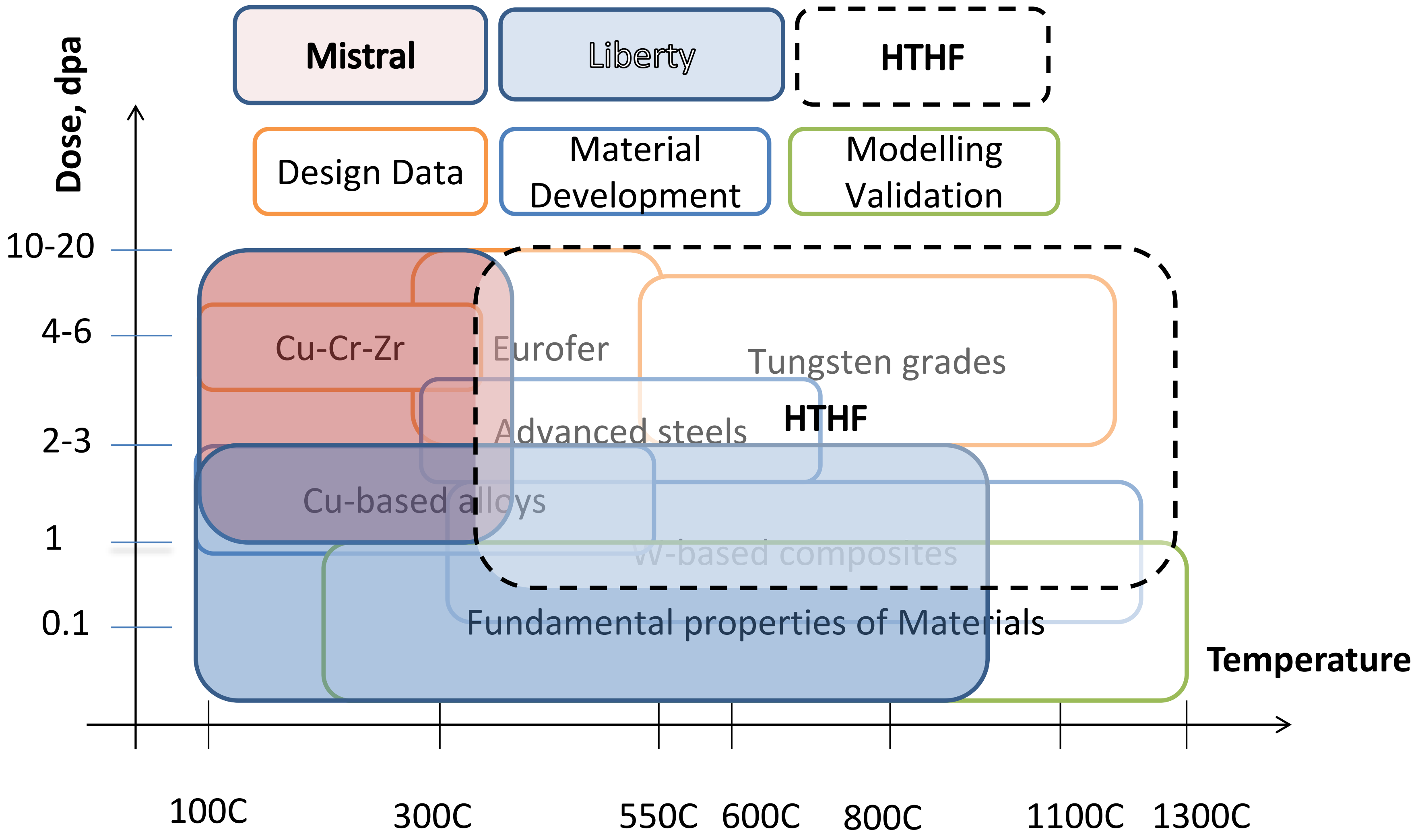


Temperature profile +/- flat over predefined range.

(+/- 1% at calculated pressure)

Measurements of temperature at max 4 levels.

Material Irradiation needs vs BR2 capability



Fuel Irradiation Capabilities of BR2

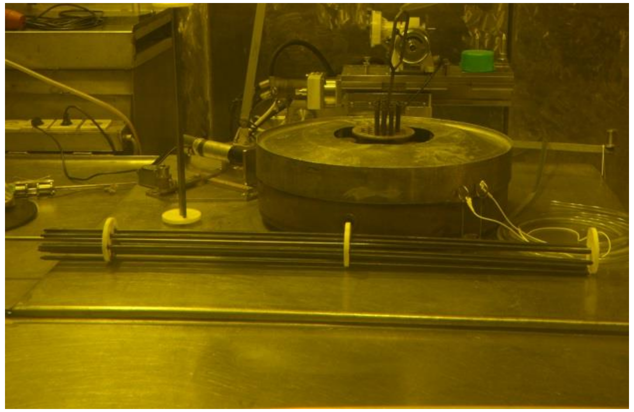
Nuclear fuel irradiation experiments

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

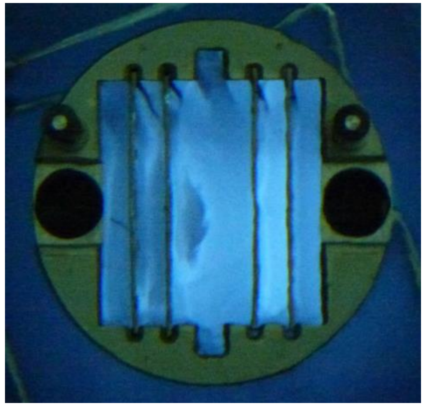
- Development of new fuels and safety testing of current fuels
  - Determine safe operational conditions for fuel in representative and under overpower conditions
  - Steady state irradiation: power and burn-up limits
  - Transient irradiation: test safety margins
  - Safety tests: experience in accident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

- Scope

Power reactor fuels

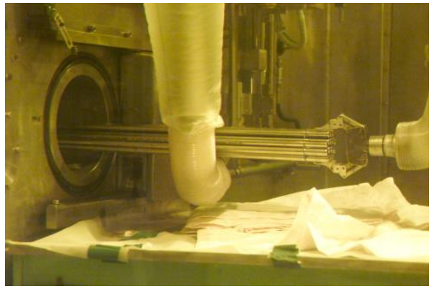


Test reactor fuels



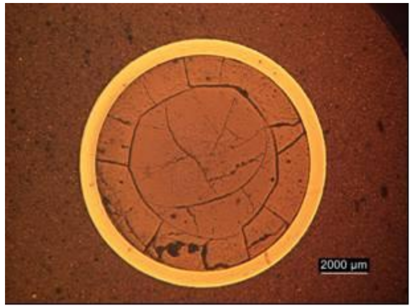
Power reactor fuel tools

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



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

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



Fuel pin irradiation

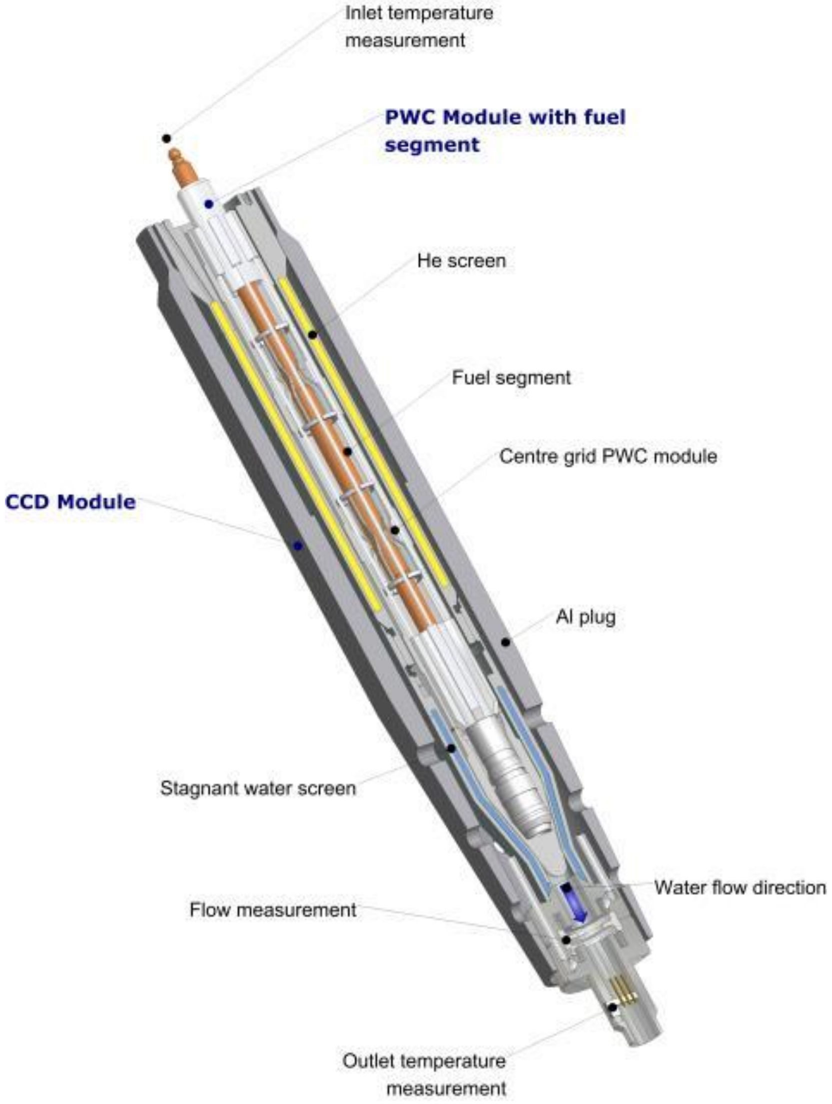
- Steady state conditions or transient conditions
  - Linear power levels up to $q_{l,max}$ = 750 W/cm
  - Rod power variation by reactor power variation
  - Power increase rate $\Delta q_l/\Delta t_{max}$ = 100 W/cm/min
  - Accuracy of the rod power can be measured within 5%

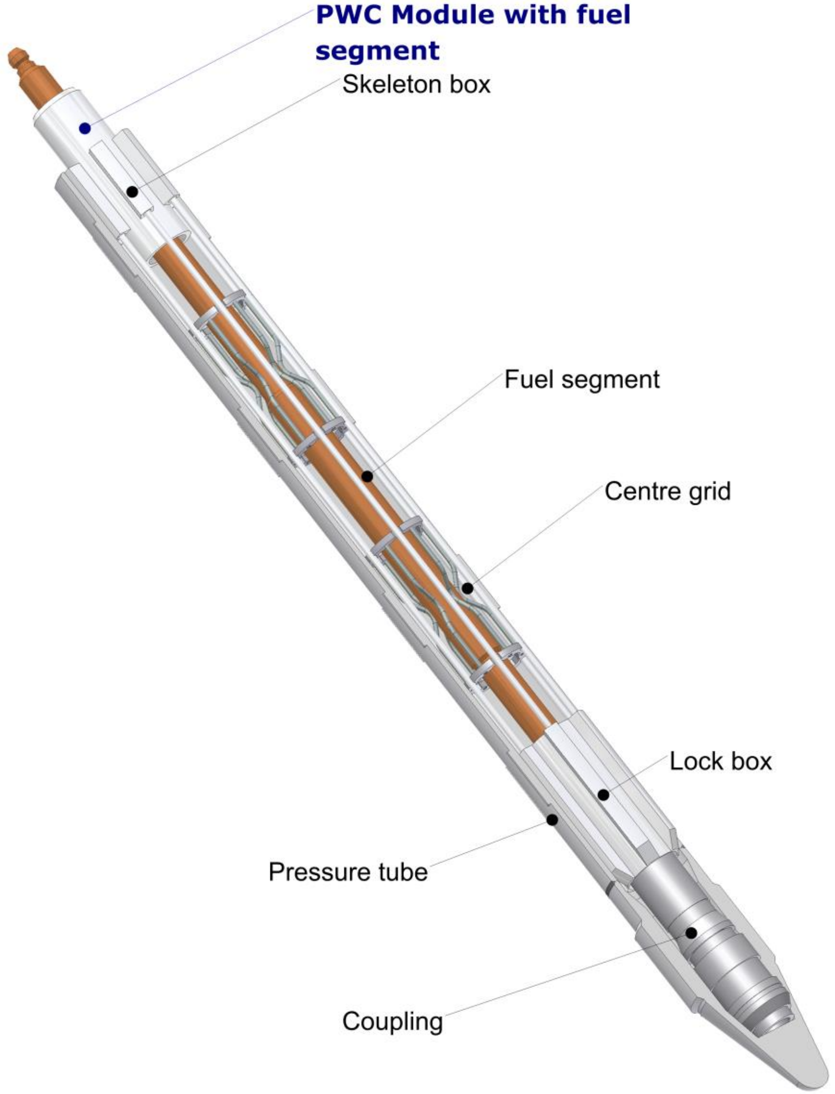
- Fuel pin dimensions
  - Cladding diameters: 8 mm - 12.5 mm
  - Fuel stack length: 20 cm - 100 cm (core height BR-2 80 cm)

- 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

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





POM irradiation capsule

- Developed in the 1960's and 1970's
  - Fast reactor fuel development
  - Collaboration with ITU Karlsruhe

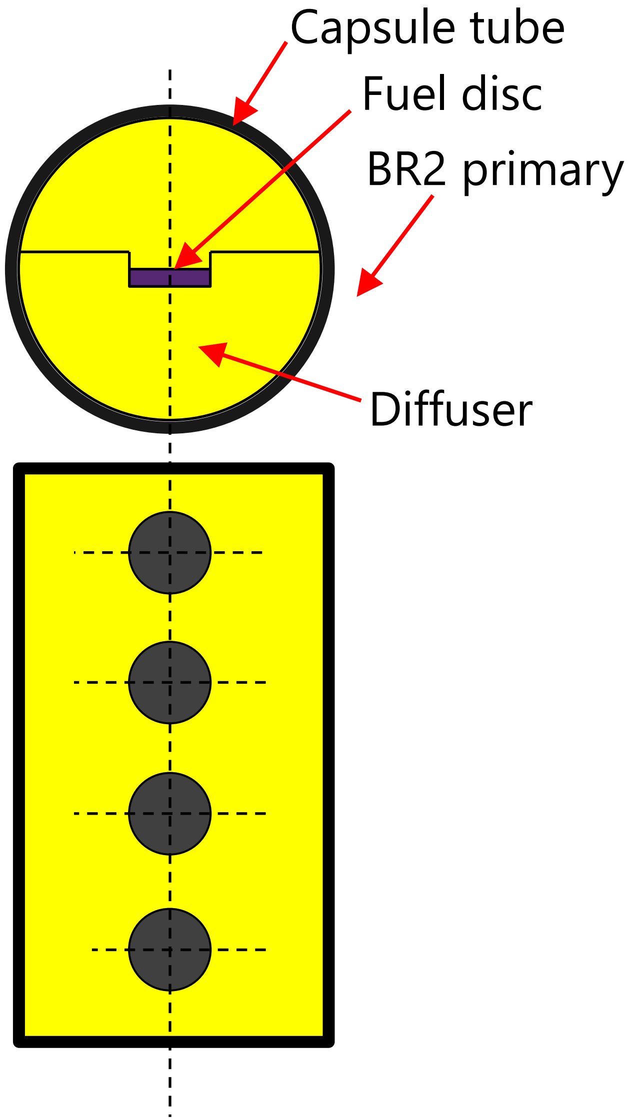
- Various fuel types were studied (MOX, carbides, nitrides)
  - **POM-II**: 13 pellets UO_2/PuO_2
  - **POM-III**: 7 pellets UO_2 and 10 pellets UO_2/PuO_2. Movable capsule to adjust the neutron flux. Pellet holders in Zircalloy2.
  - **POM-IV**: 17 pellets (U,Pu)C. The capsule can moved 200 mm in the axial direction in order to adjust the neutron flux.
  - **POM-V**: 17 pellets UO_2/PuO_2. with SAP pellet holder.
  - **POM-VI,VIII**:17 pellets (U,Pu) Carbide, Nitride.
  - **POM-IX**: 17 cladded (stainless steel) pellets UO2/PuO2.

Campana et. al.:

https://www.osti.gov/servlets/purl/4284660

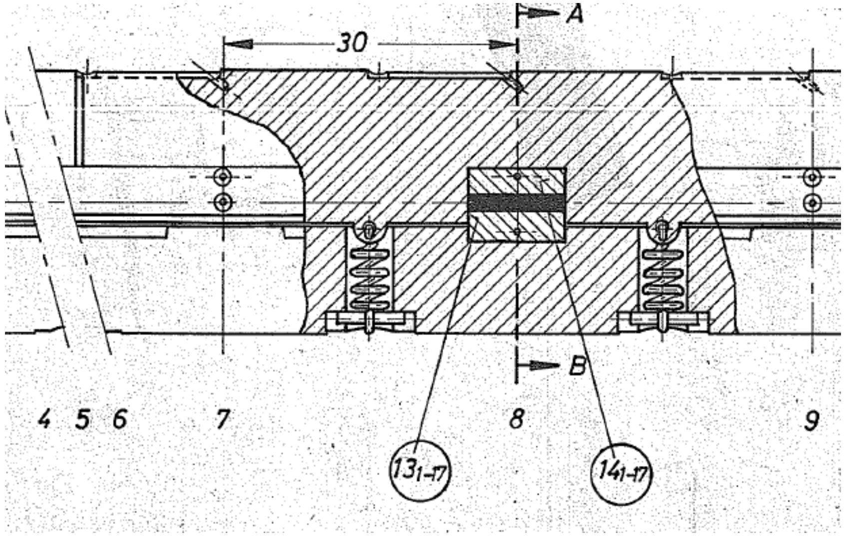
POM-II design

- Pellets
  - 1.5 mm thickness, 10 mm dia, 1.2 gram
  - 10-25 discs per capsule in vertical arrangement
- Diffuser
  - Sintered Aluminum oxide dispersed matrix (SAP) or Zircalloy
- Capsule tube
  - Stainless steel 26/30 mm ID/OD
  - Small plenum for fission gases
- Gas filling
  - 16 bar Helium



POM-II design

- Suspension piece of several meters long
- Lower capsule piece of about 1 m



POM-II: Conditions and Instrumentation

- Power and burnup POM-II irradiation
  - Typically loaded in core periphery with φ_{th}=2.7 x10^{14} $cm^{-2}s^{-1}$
  - Power levels up to 1000 W/cm^2 (20 kW/cm^3) on the fuel surfaces
  - Possible to achieve 100 GWd/t_{HM} in 80 days of irradiation
  - Fuel temperatures: 600 °C surface and 1800 °C center

- Thermo-couples
  - Individual TC for each disc
  - Additional TCs inside diffuser

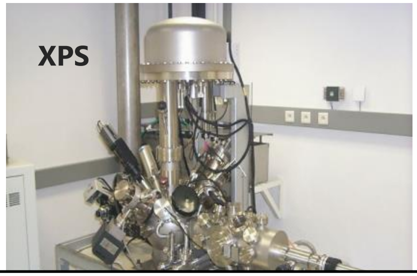
- Flux detectors

Post irradiation examinations on fuel

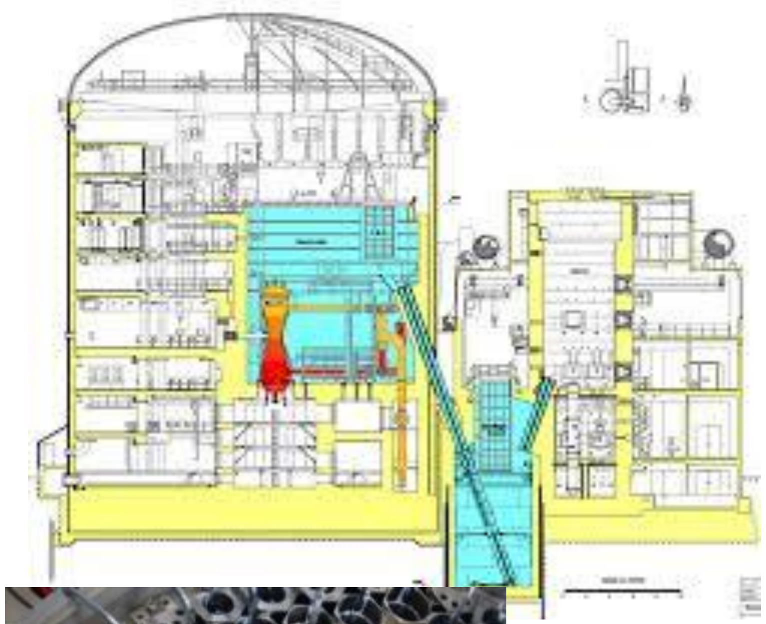
__Non-destructive__:
- Visual Inspection
- Clad Integrity
- Oxide thickness
- Rod length
- Profilometry
- X-ray radiography
- Gamma scanning
- Gamma spectrometry
    - ^{85}Kr
    - ^{137}Cs
    - ^{140}Ba/^{140}La ^{106}Ru

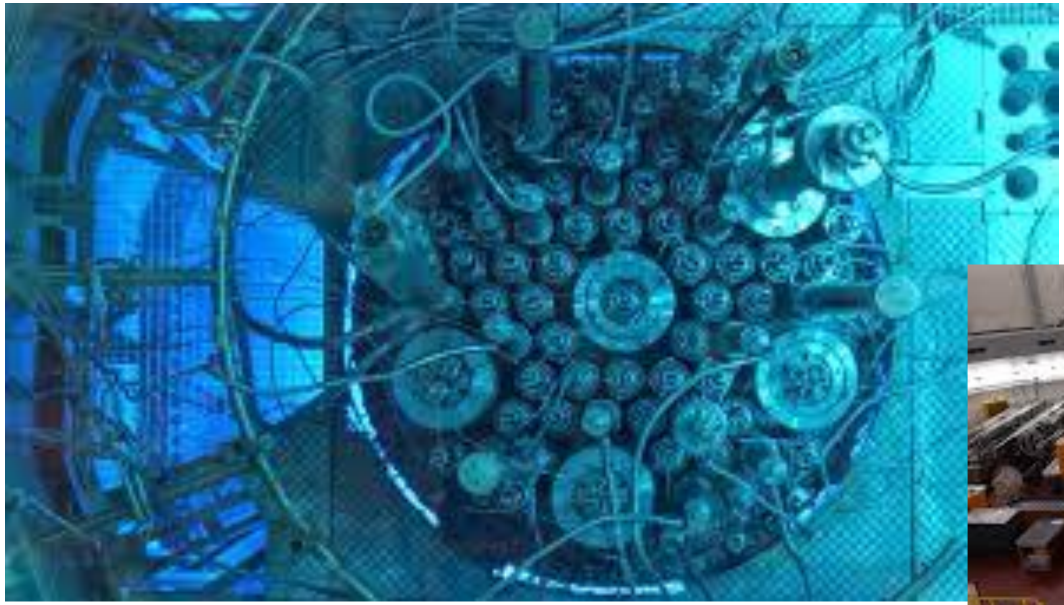
EPMA

__Destructive__:
- Rod punction
- Mass spectrometry
- Fuel density
- Hydrogen content (clad)
- Optical microscopy
- Radiography
- μ-hardness
- SEM
- EPMA
- XRD (unirradiated fuel)
- TEM (clad)
- XPS (clad)



__Radiochemistry__:
- Base actinides (U, Pu)
- Minor actinides (Np, Am, Cm)
- Fission products
    - Cs, I
    - Sr, Mo, Tc, Ru, Rh, Ag, Sb
    - Ce, Gd, Pm, Nd, Sm, Eu





BR2 @ your service

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