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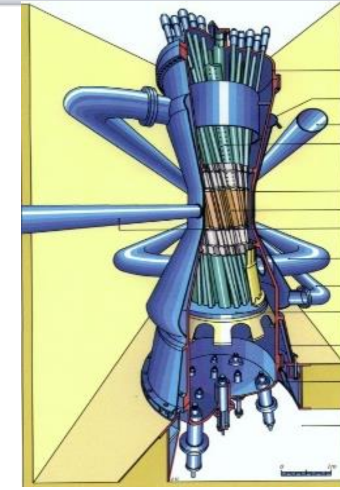

Feasibility Studies for Simultaneous Irradiation of NBSR & MITR Fuel Elements in the BR2 Reactor

S. Kalcheva, S. Van Dyck, S. Van den Berghe, G. Van den Branden

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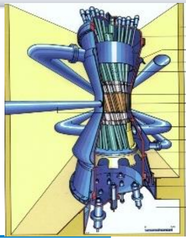
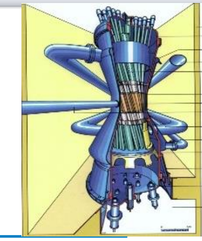


Outline

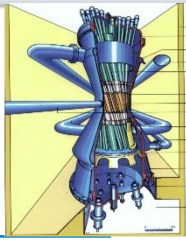
- Introduction
- Purpose of Design Demonstration Element tests
- Technical requirements for DDE
- MCNP calculation methodology
  - Full core 3-D MCNP modeling of BR2 reactor
  - 3-D modelling of DDE-MITR and DDE-NBSR
  - 3-D power and burn-up evolution simulation
- Calculation results
- Summary



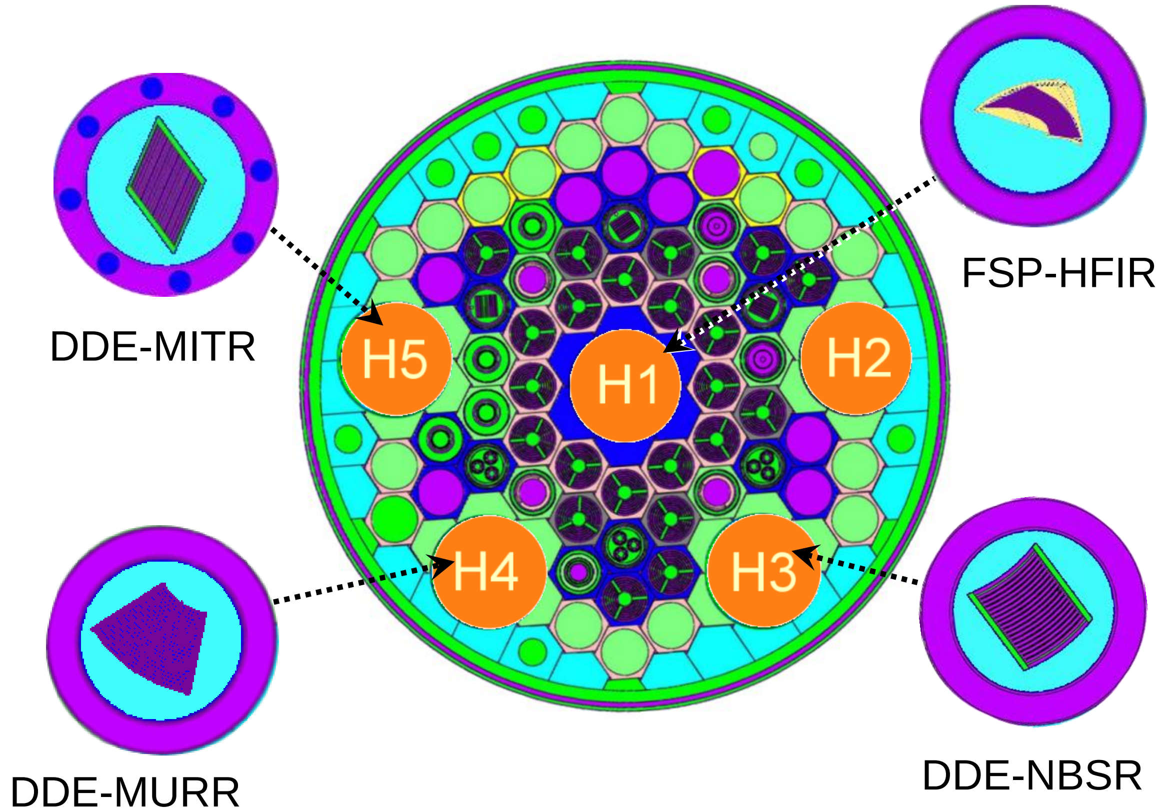
Introduction

- Four Design Demonstration Element (DDE) tests foreseen in the US High Performance Research Reactor (USHPRR) conversion program:
  - Missouri University Research Reactor (MURR),
  - Massachusetts Institute of Technology Reactor (MITR),
  - National Bureau of Standards Reactor (NBSR) and
  - High Flux Isotope Reactor (HFIR)
- BR2 Reactor along with other MTR (ATR) involved in preliminary feasibility studies

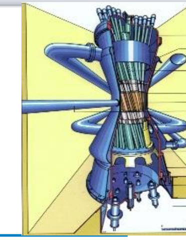
Purpose of DDE tests



- Qualification of the new LEU fuel for each DDE in the BR2 reactor at *conditions that are similar for reactor of origin*



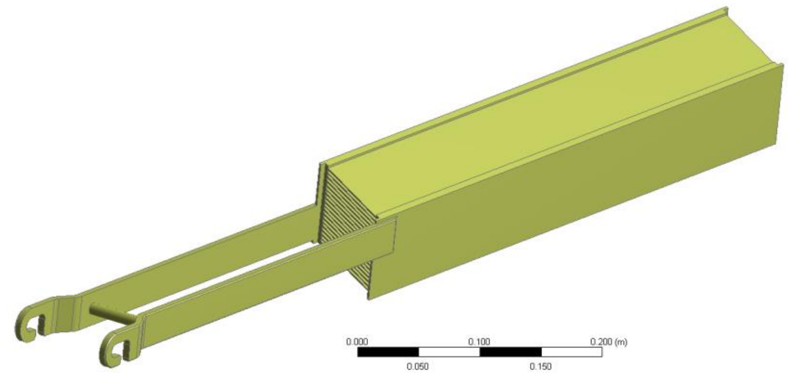
- Present study: scenarios for *simultaneous irradiation of MITR and NBSR Test Assemblies*



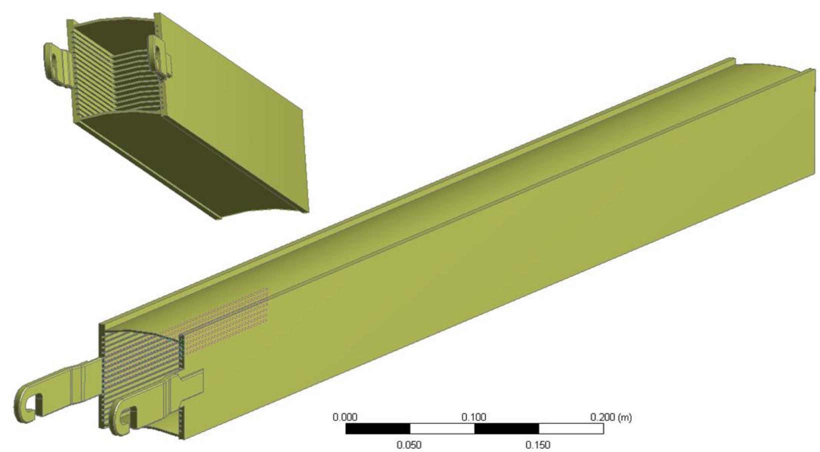
Technical requirements for DDE tests

- Simultaneous irradiation → challenge for core management

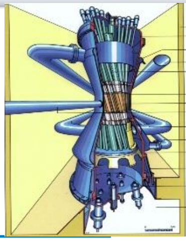
- DDE-MITR
  - Q_{max} (BOL)=**64** W/cm^2
  - F_{max} (EOL)=5.8E21 fiss/cm^3



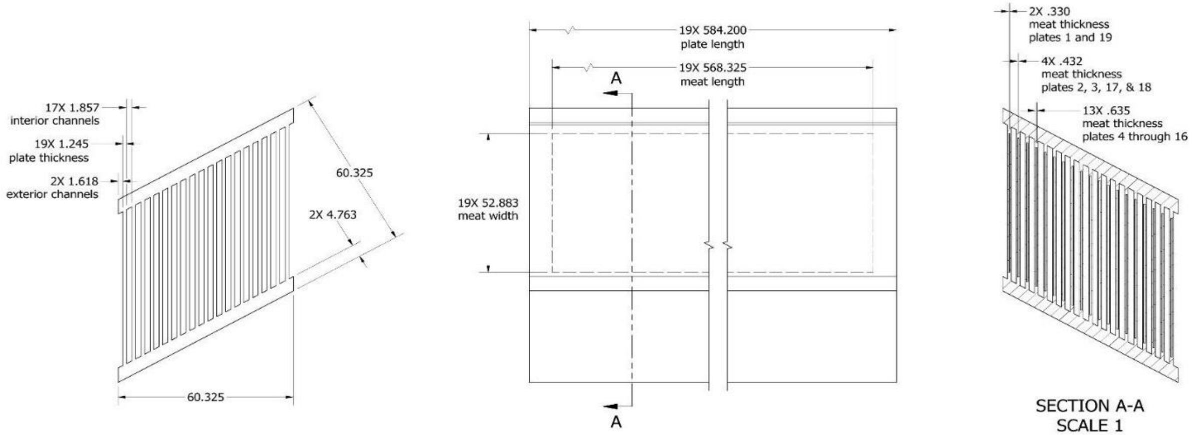
- DDE-NBSR
  - Q_{max} (BOL)=**160** W/cm^2
  - F_{max} (EOL)=7.9E21 fiss/cm^3



Geometry & dimensions of DDE's

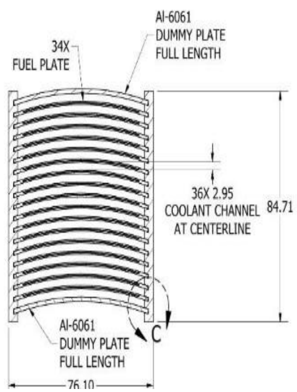


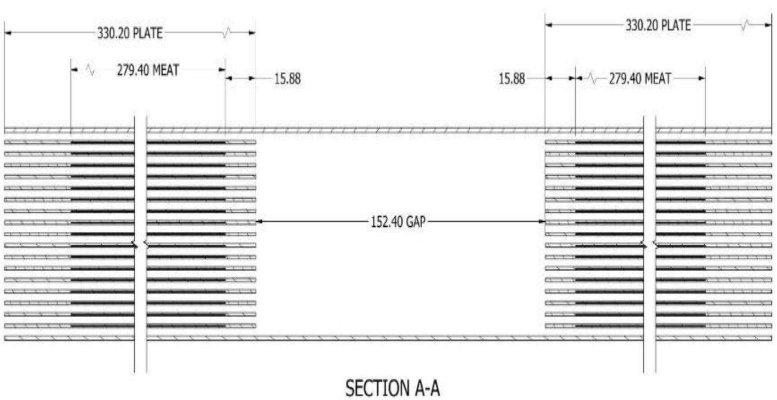
- **DDE-MITR**
  - rhomboid form
  - 19 plates
  - variable meat thickness

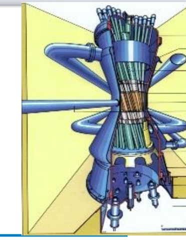


Dimensions in mm

- **DDE-NBSR**
  - Upper and lower sections
  - Divided by water gap
  - Total 2 x 17=34 plates

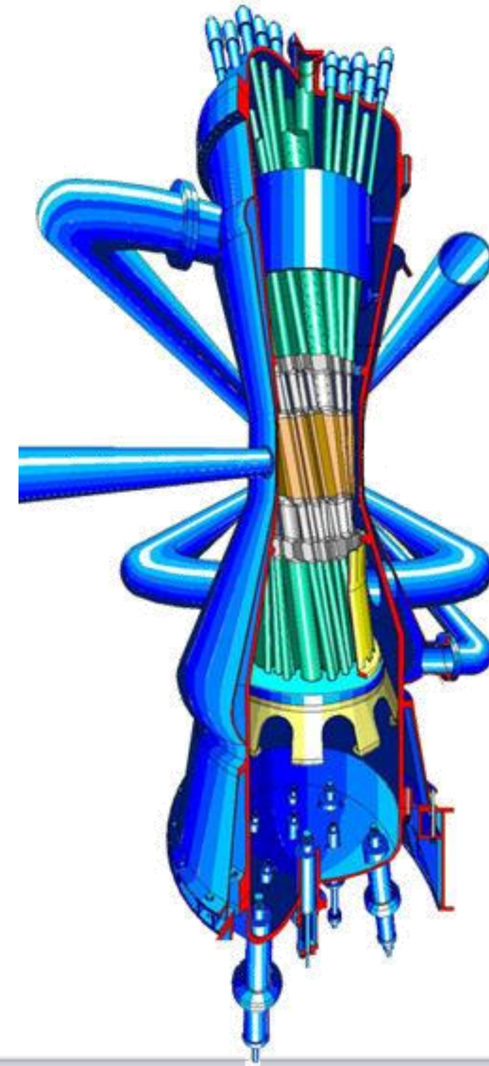




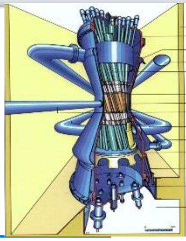


Description of BR2 reactor characteristics

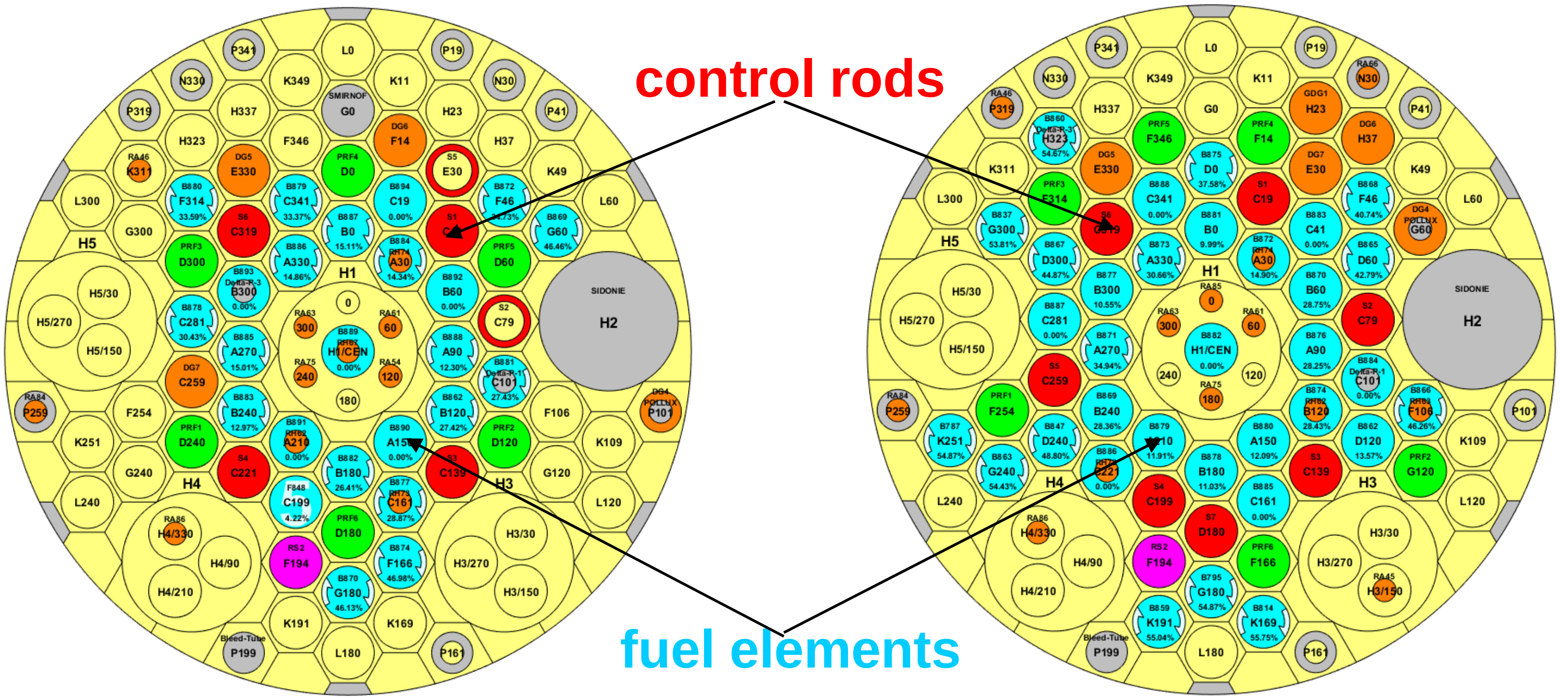
- Hyperboloid core composed of twisted and inclined reactor channels
- HEU core positioned inside and reflected by beryllium matrix
- Flexible BR2 power – 40 to 100 MW
- 6-8 operation cycles per year (each 3-4 weeks long)
- High power density
  - 470 W/cm^2 nominal
  - 600 W/cm^2 admissible
- Maximum neutron flux
  - 1,2 x 10^{15} n/cm^2/s thermal
  - 8,4 x 10^{14} n/cm^2/s fast



Flexible BR2 reactor core loadings

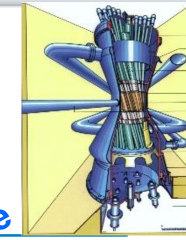


- Variable core configuration – variable number of CR's, FE's
- Fuel elements initial U5 burnup between 0% and 50%



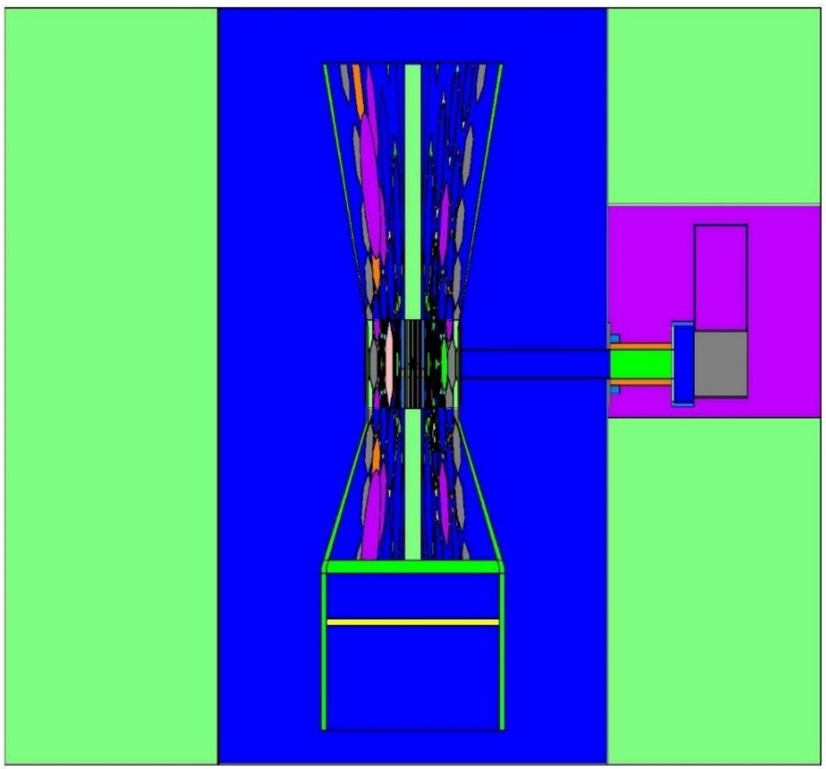
compact core
(4 CR, 20 FE, 40 MW)

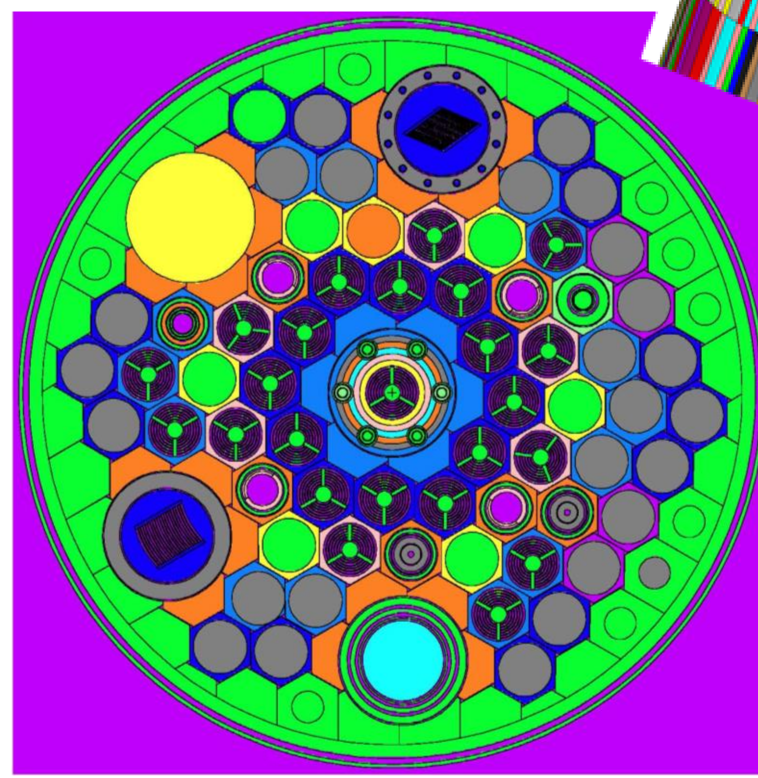
extended core
(6 CR, 30 FE, 60 MW)



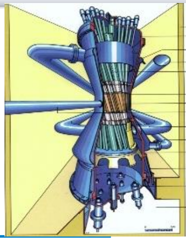
MCNP6 3-D full core modeling of BR2

- Automatic burn-up & criticality simulation
- 3-D whole core geometry & depletion
- Follow-up irradiation history of each FA

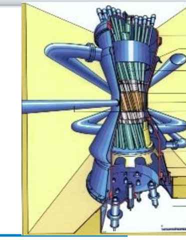




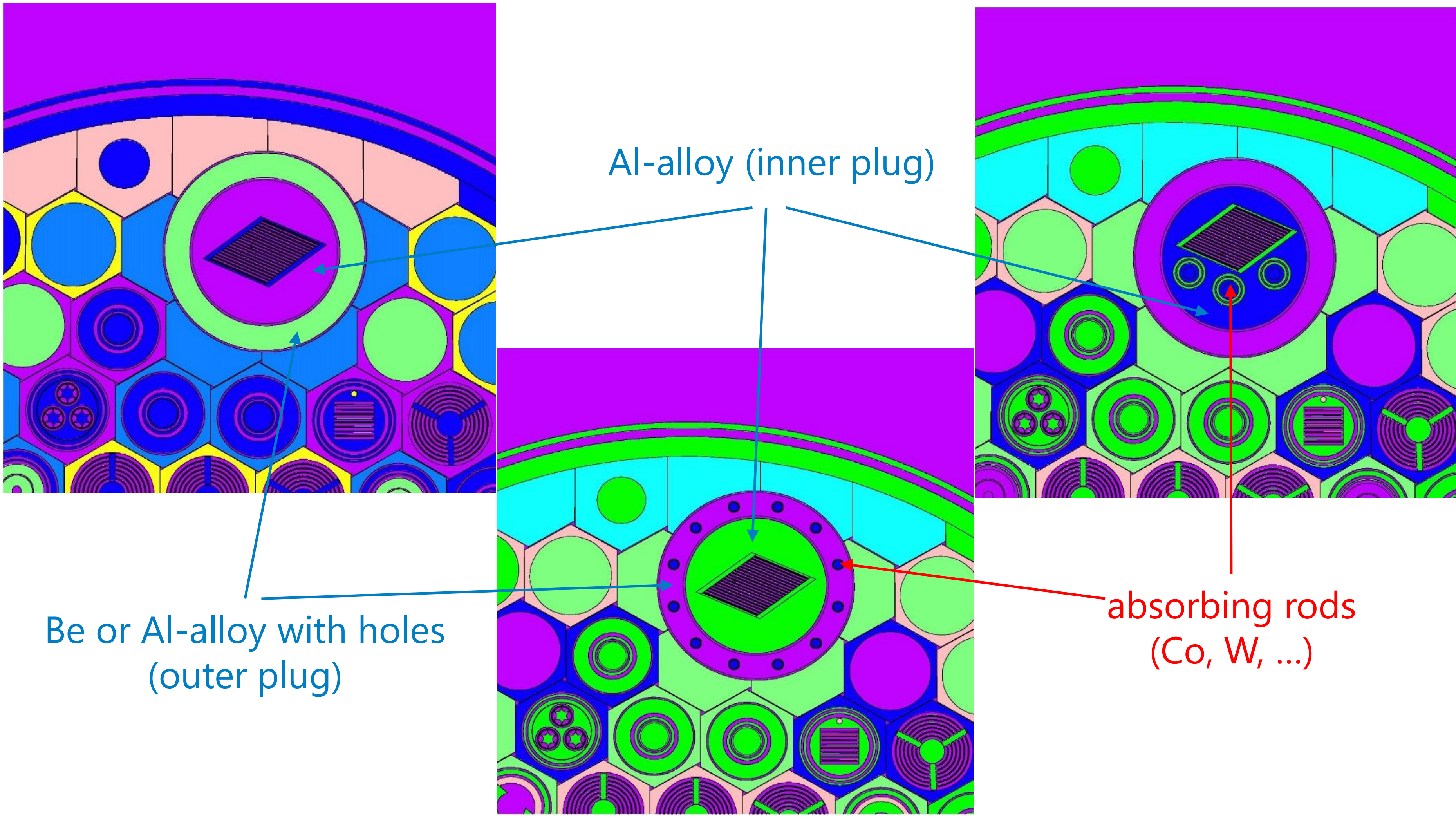
Modeling optimizations for DDE-MITR



- Chosen channel H5 (D=200 mm)
- Optimization of position needed for axial profile
  - Z= -15.28 cm to +43.17 cm
- Special loadings (DG's) in surrounding channels
- Choice of appropriate plug material (Al-alloy, Be)
  - 3 designs for outer plug proposed (Be, Al-alloy, Al-alloy with holes)
  - absorbing rods (Co, W, ..) in inner/outer plug

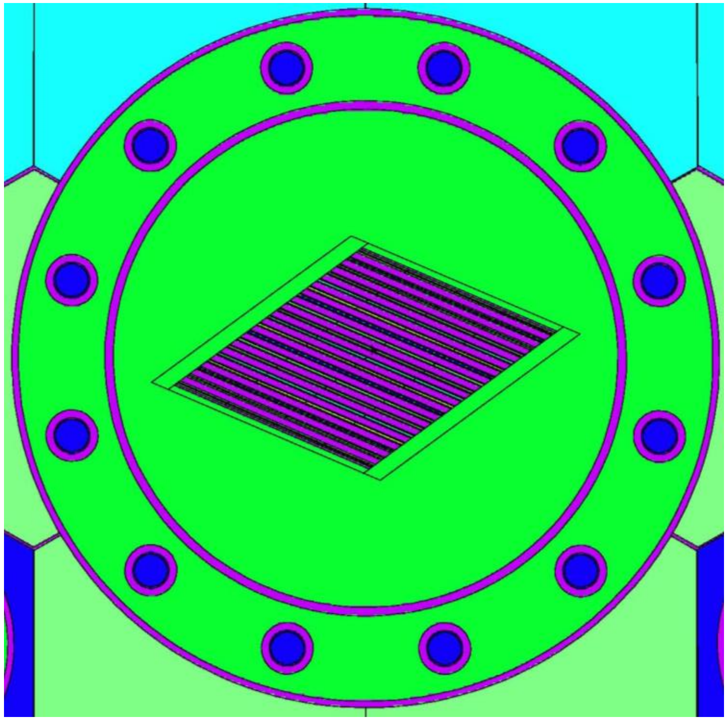


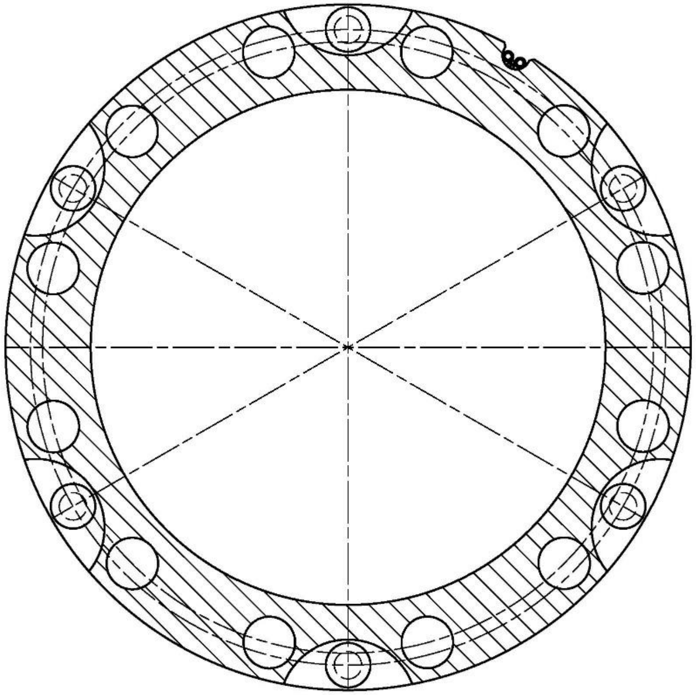
Modeling optimizations for DDE-MITR (cont'd)



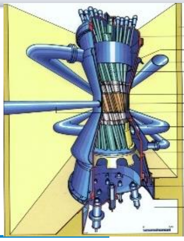
Final design PLUGS for DDE-MITR

- Inner plug: Al-alloy (to lower the heat flux)
- Outer plug:
  - Al-alloy with 12 holes filled with rods (Co, W, Al, etc.)

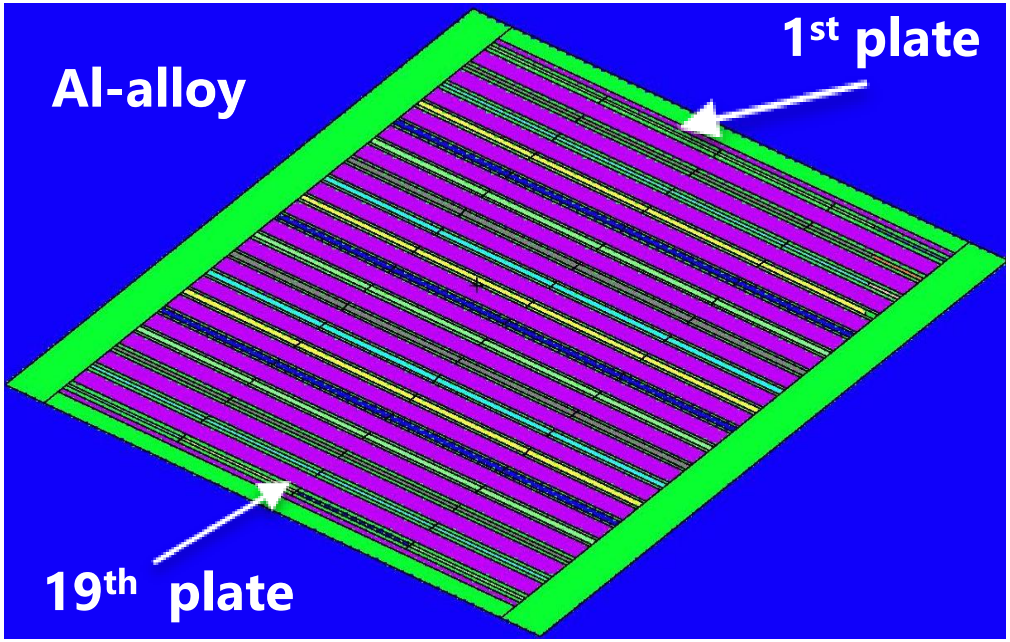


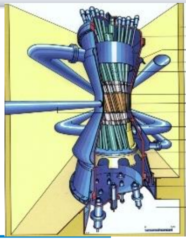


Calculation model of DDE-MITR



- MCNP model of the DDE-MITR-FE contain 19 plates
- Fuel meat thickness varies from 0.33 mm to 0.635 mm
- Each fuel plate modeled with uniform mesh
  - 4 in the transverse direction (13.2 mm wide)
  - 18 in the axial direction (31.6 mm long)
  - Total number of fuel zones: 19x4x18=**1368**

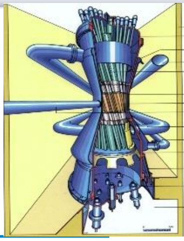




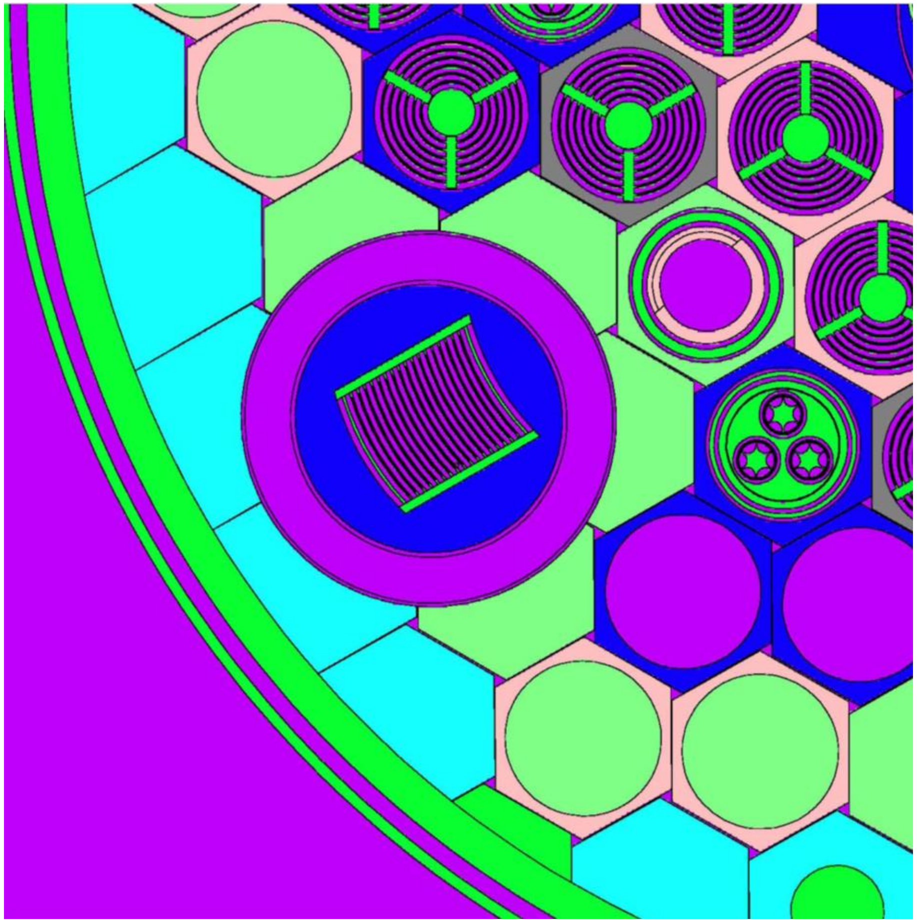
Summary of DDE-MITR-FE parameters

Parameter	value
Axial position in H5 channel relatively to reactor core mid-plane, mm	+123.8
Outer/inner radius of outer fresh Be-plug, mm	99.8/75.0
Radius of inner Al-plug, mm	72.50
U_{total} density, g/cm^3	15.3
U10Mo density, g/cm^3	17.0
^{235}U enrichment, %	19.75
^{236}U enrichment, %	0.24
Meat thickness of fuel plates 1 & 19, mm	0.33
Meat thickness of fuel plates 2, 3,17 & 18, mm	0.432
Meat thickness of fuel plates 4 to 16, mm	0.635
Plate thickness, mm	1.245
2 exterior water channels thickness, mm	1.618
Plate length, mm	584.200
Meat length, mm	568.325
Diameter of absorbing rods in outer/inner plug, mm	10/20

Modeling optimizations for DDE-NBSR

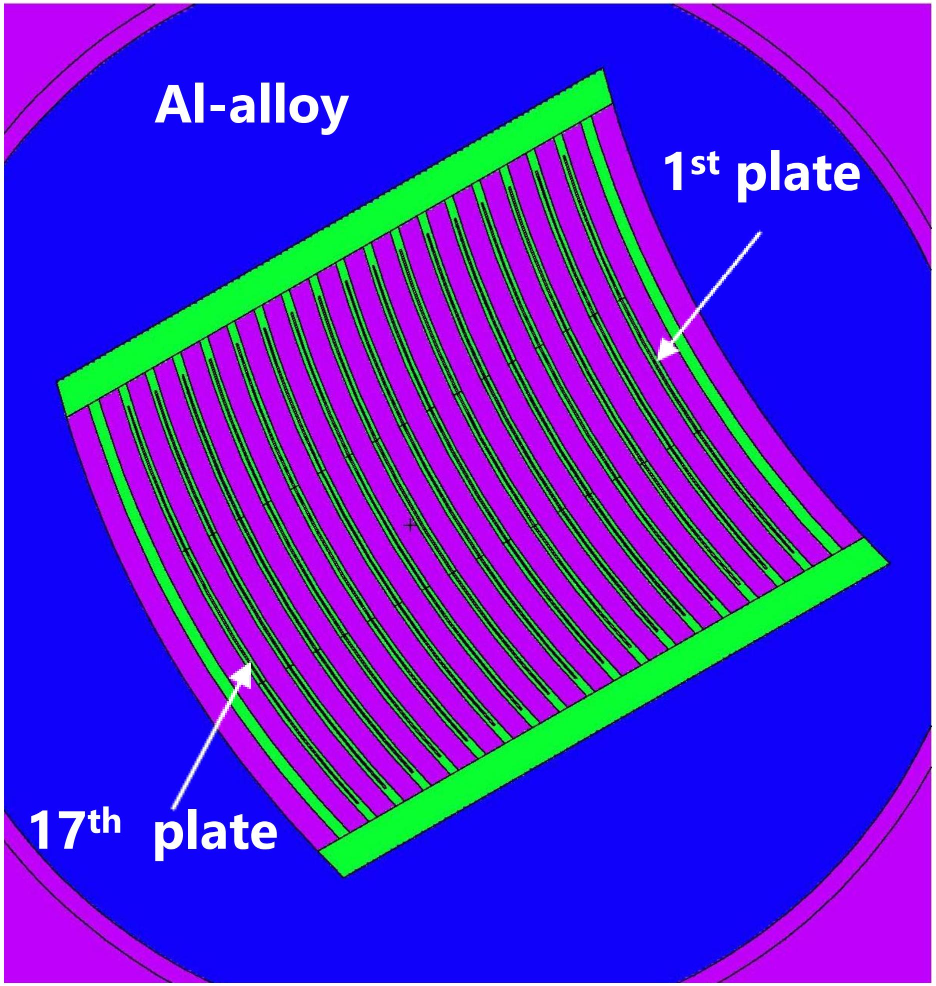


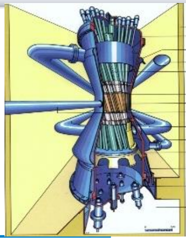
- Chosen channel H3 (D=200 mm)
- Inner plug (Al-alloy)
- Outer plug (Be)
- Optimization of water gap between upper and lower plate
  - water gap=15.24 cm (original design)
  - water gap= 5.24 cm & shift NBSR-FE UP by ΔZ=+5 cm (preferred scenario)
  - water gap= 5.24 cm & shift NBSR-FE DOWN ΔZ=-5 cm



Calculation model of DDE-NBSR

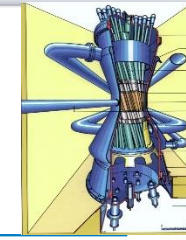
- All fuel plate dimensions not changed (original)
- 17 fuel plates in upper position
- 17 fuel plates in lower position
- 3 azimuth zones in each plate (each ~20 mm long)
- 14 axial zones (each ~20 mm long)
- Total number of fuel zones 2x17x3x14=**1428**





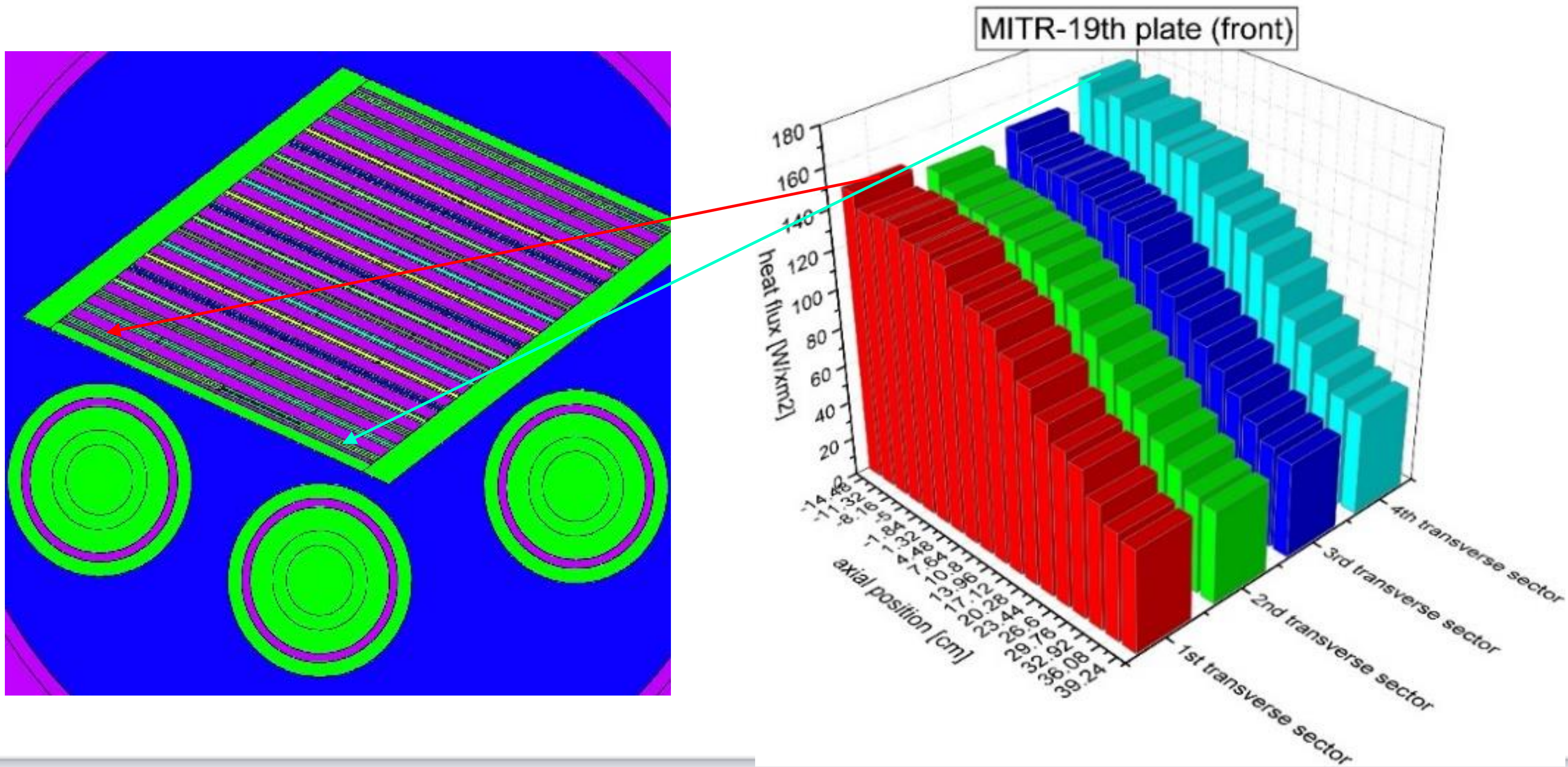
Summary of DDE-NBSR-FE parameters

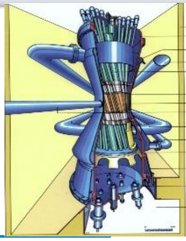
Parameter	value
Axial position in H3 channel relatively to reactor core mid-plane, mm	+100.0
Outer/inner radius of outer fresh Be-plug, mm	99.8/75.0
Radius of inner 60%Al+40%Be-plug, mm	72.50
U_{total} density, g/cm^3	15.3
U10Mo density, g/cm^3	17.0
^{235}U enrichment, %	19.75
^{236}U enrichment, %	0.24
Meat thickness of all (17 lower + 17 upper) fuel plates, mm	0.22
Plate thickness, mm	1.27
36 water channels thickness, mm	2.95
2 dummy exterior plates thickness, mm	1.65
Meat length (upper, lower plate), mm	279.4
Plate length (upper, lower plate), mm	330.2
Water gap between lower and upper plates, mm	52.4



DDE-MITR: Heat flux at BOL (Al rods inner plug)

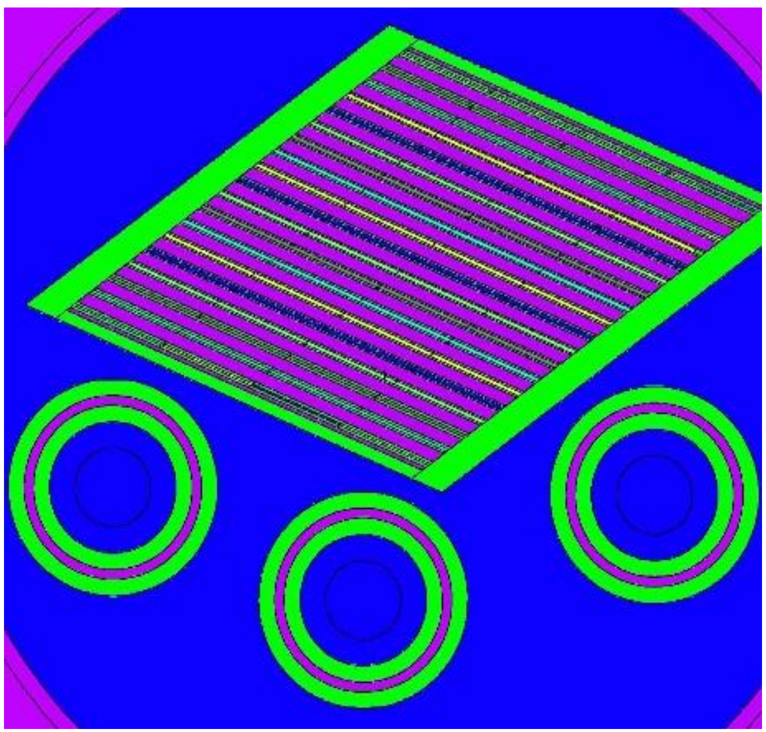
- Be (outer plug), Al-alloy (inner plug)
- Q_{max} =158 W/cm^2 ; Q_{min} =31 W/cm^2

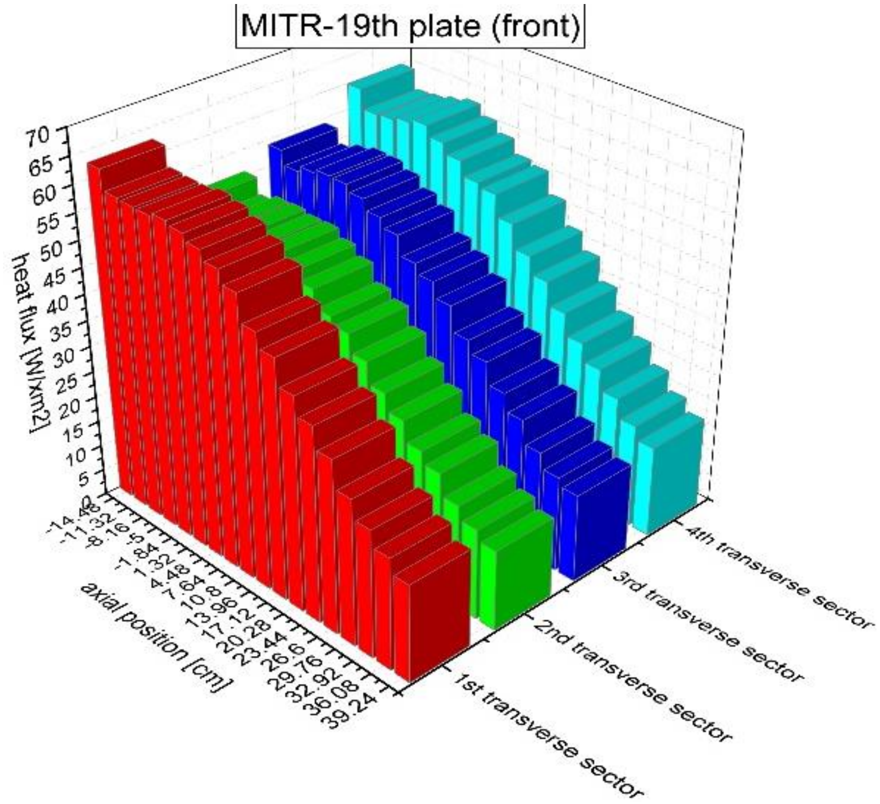




DDE-MITR: Heat flux at BOL (Co, W rods inner plug)

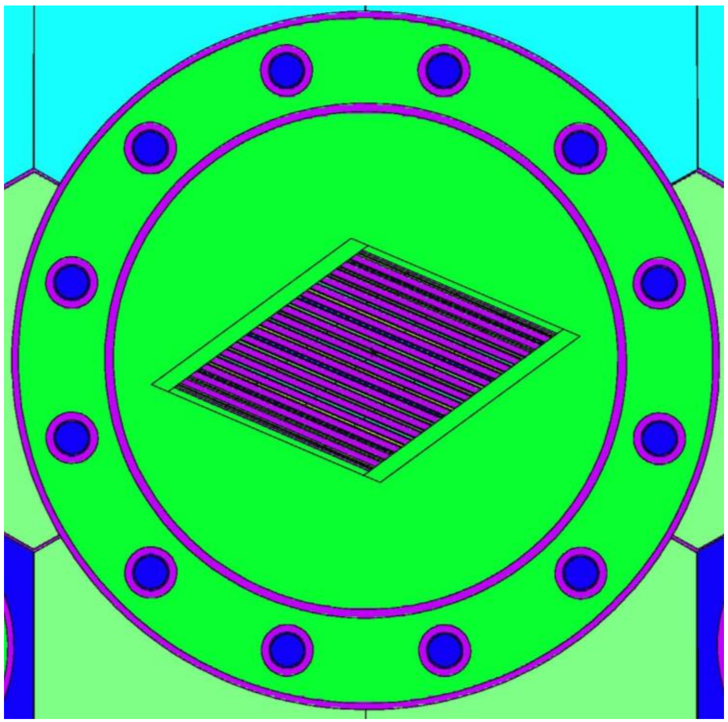
- Be (outer plug), Al-alloy (inner plug)
- Q_{max} =65 W/cm^2 ; Q_{min} =15 W/cm^2

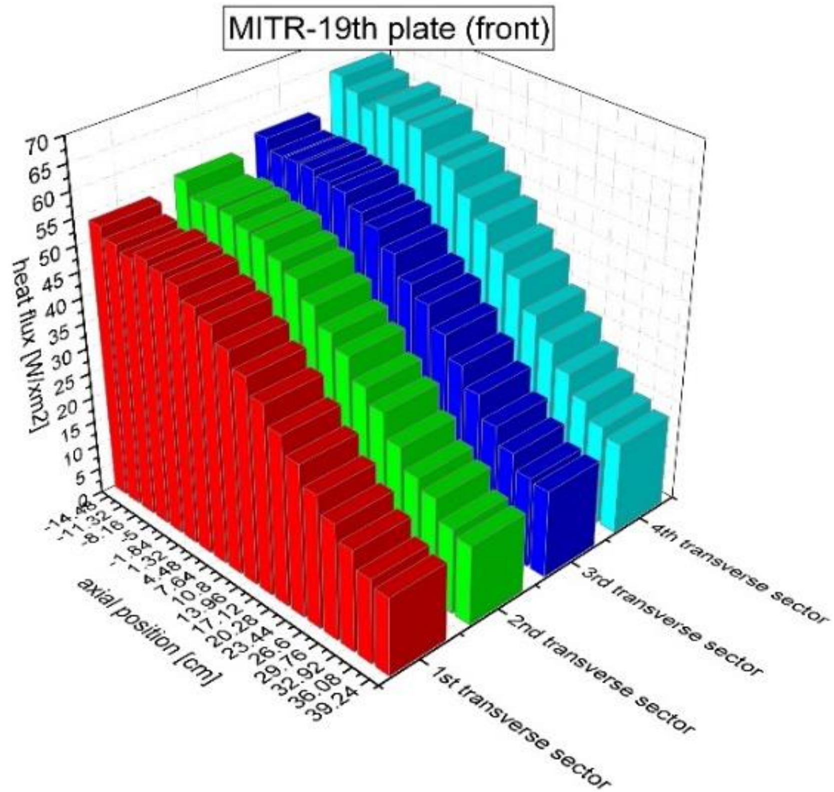




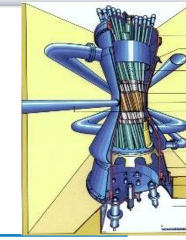
DDE-MITR: Heat flux at BOL (Co, W rods outer plug)

- Proposed geometry design: Al-alloy (inner & outer plug)
- Q_{max} =67 W/cm^2 ; Q_{min} =16 W/cm^2

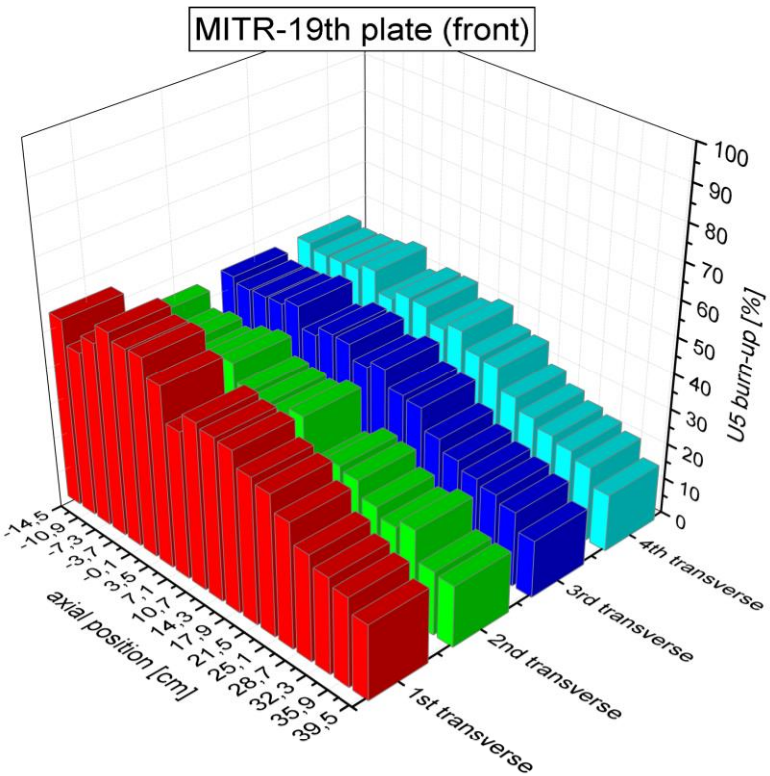


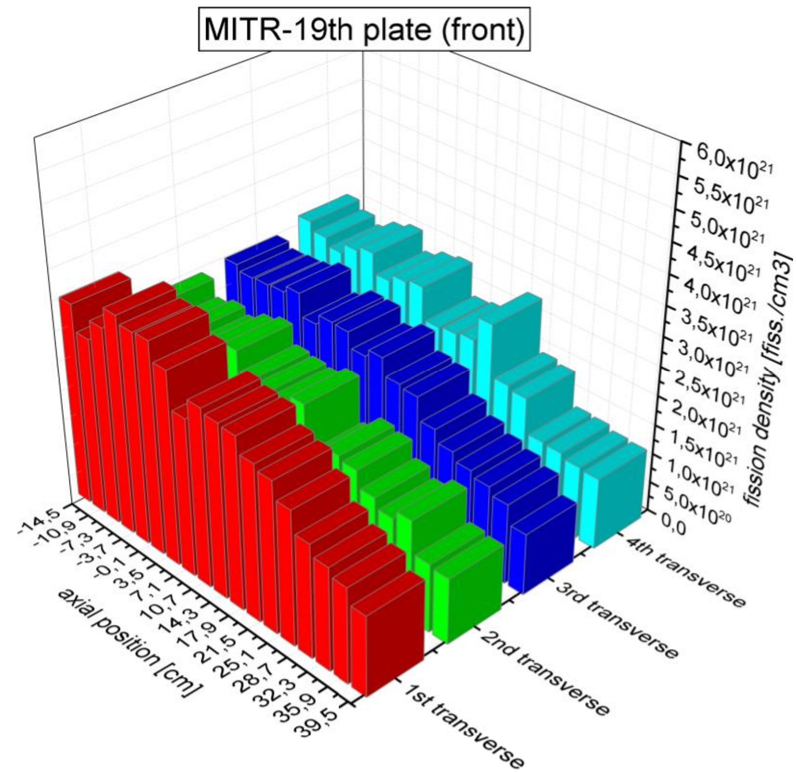


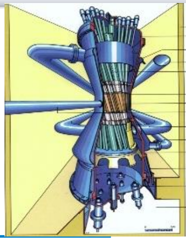
DDE-MITR: Burn-up at 250 F.P.D. ~ BR2 10 cycles



- Axial distributions at 250 days for proposed design
  - Maximum U5 burn-up: 55%
  - Maximum fission density: 3,5E21 fiss/cm^3

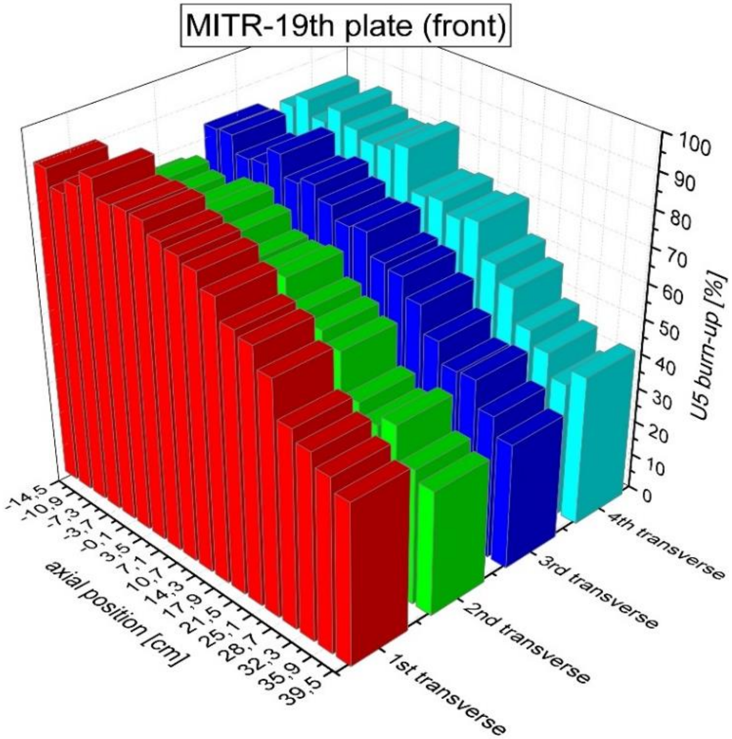


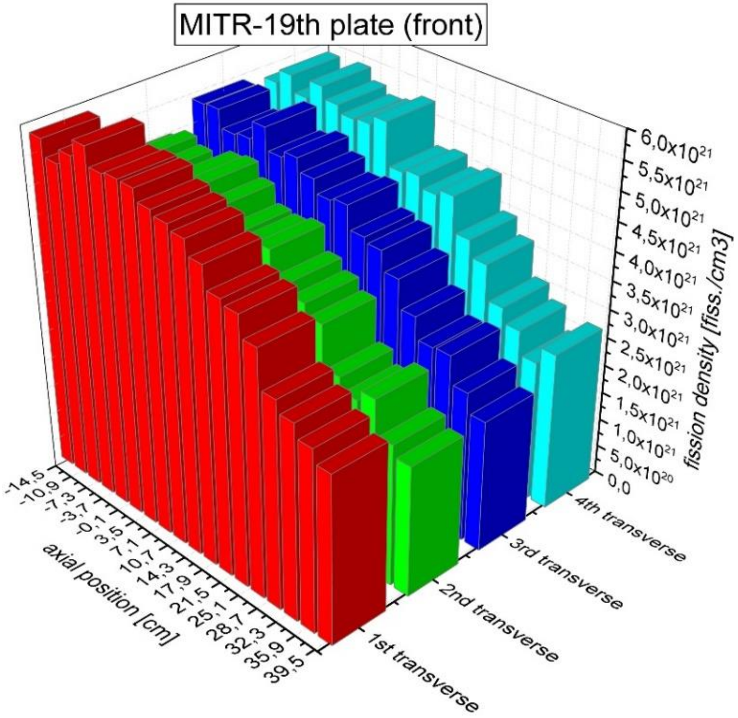




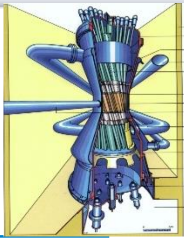
DDE-MITR: Burn-up at 630 F.P.D. ~ BR2 26 cycles

- Axial distributions at EOL for proposed design
  - Maximum U5 burn-up: 90%
  - Maximum fission density: 5,8E21 fiss/cm^3

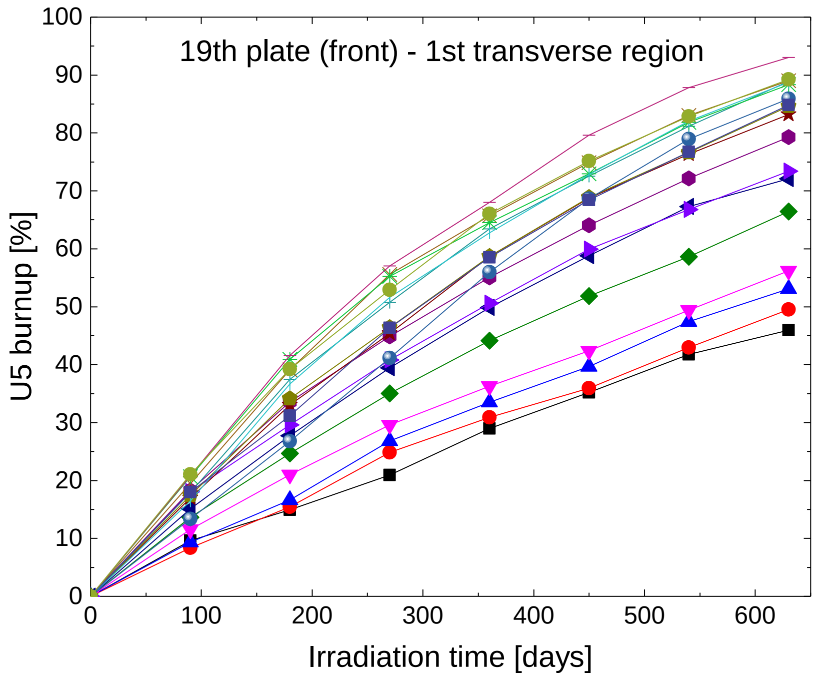


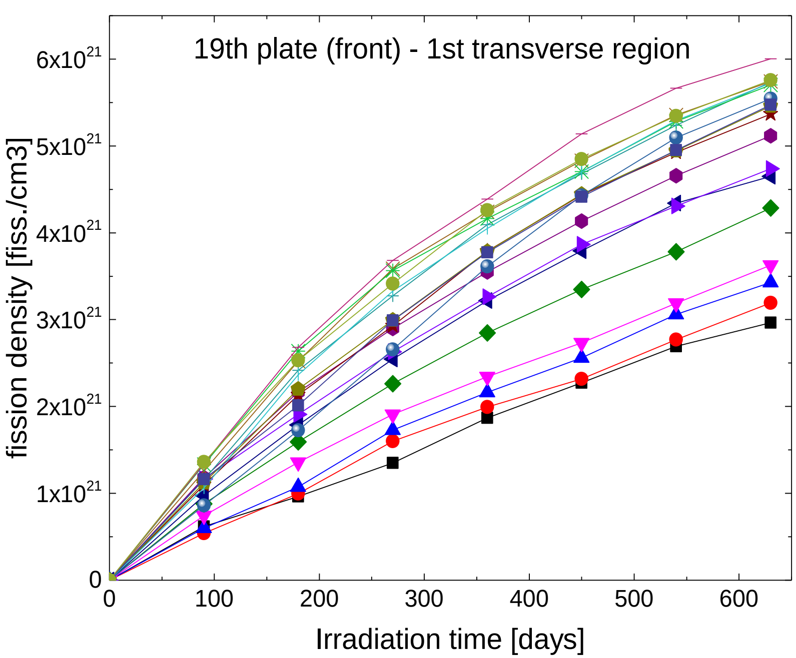


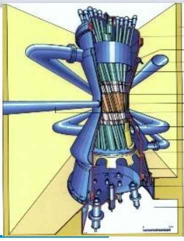
DDE-MITR: Burn-up evolution (proposed design)



- Time evolution of U5 burn-up (left) and fission density (right) during ~ 26 BR2 operation cycles:
  - scenario with cobalt rods inner/outer plug
  - for Q_{max} =67 W/cm² at BOL

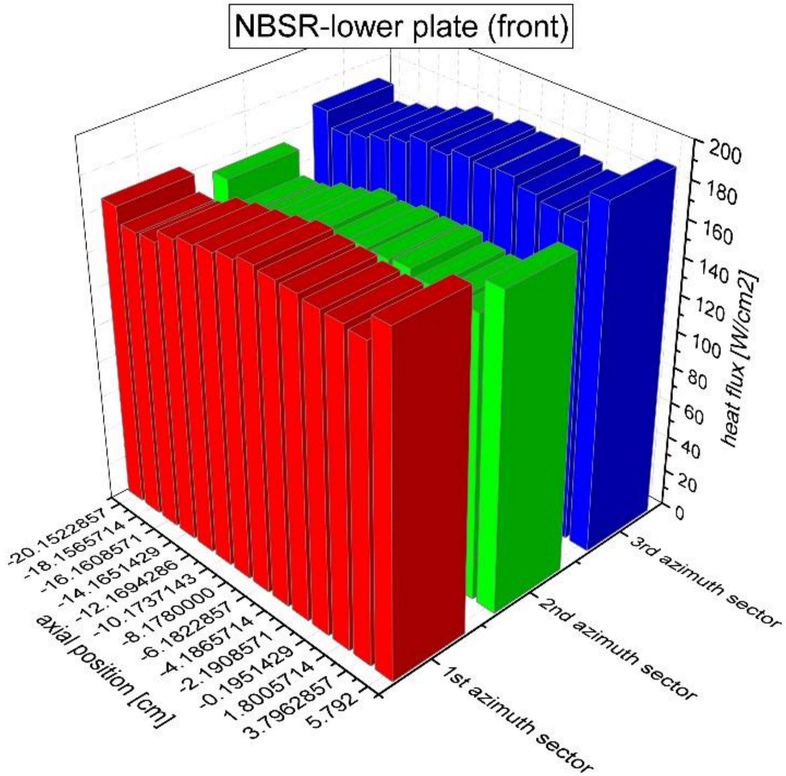


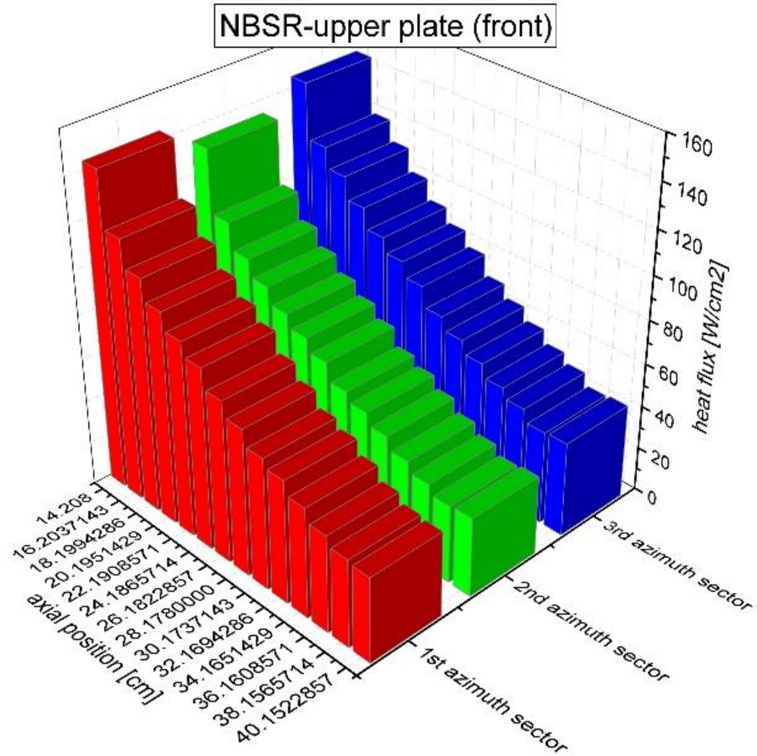




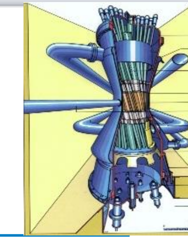
DDE-NBSR: Heat flux at BOL

- BOC #1
- Q_{max} =180 W/cm^2 ; Q_{min} =155 W/cm^2 (lower plate)
- Q_{max} =145 W/cm^2 ; Q_{min} =40 W/cm^2 (upper plate)

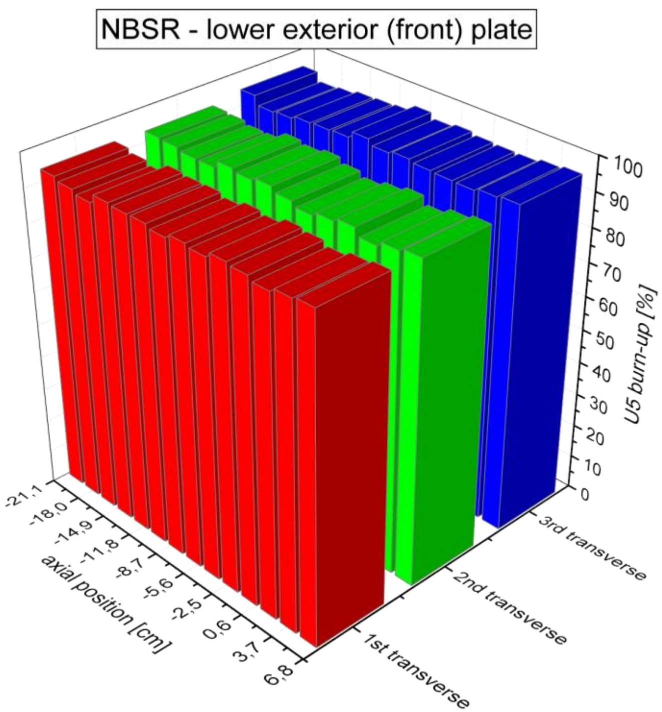


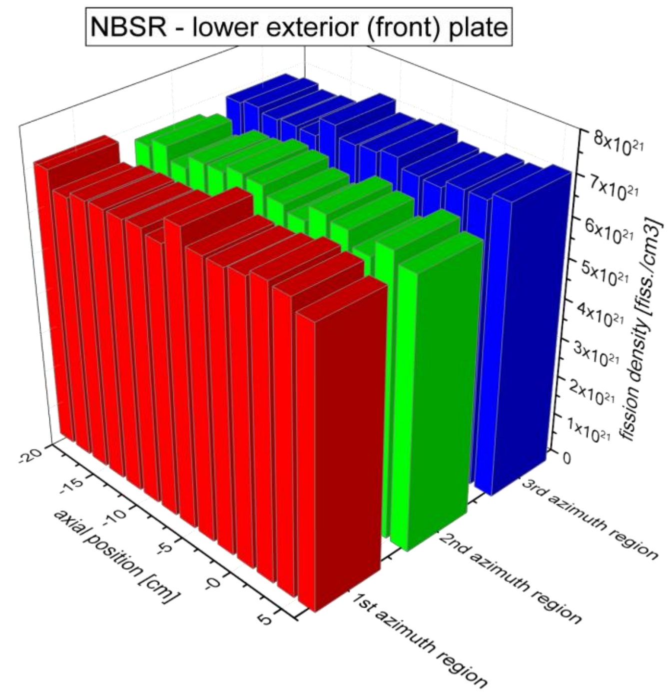


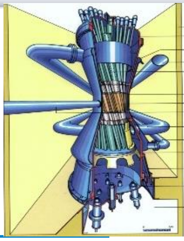
DDE-NBSR: Burn-up at 350 F.P.D. ~ BR2 15 cycles



- Axial distributions for proposed design
  - Maximum U5 burn-up: > 90%
  - Maximum fission density: 7,2E21 fiss/cm^3

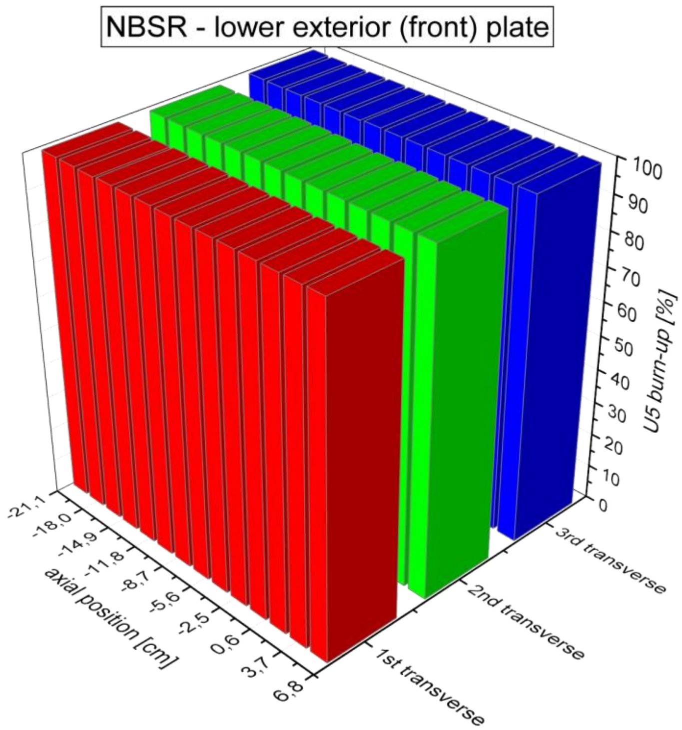


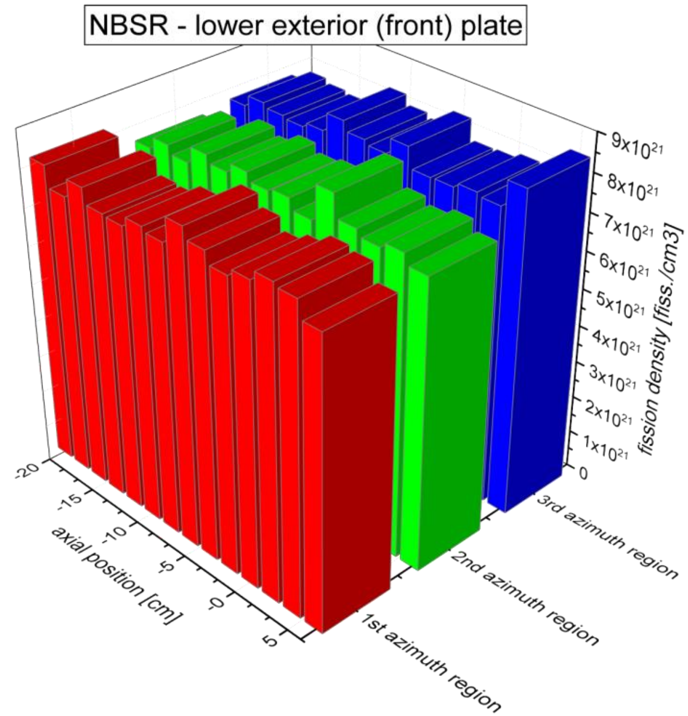




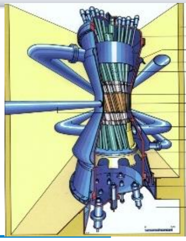
DDE-NBSR: Burn-up at 600 F.P.D. ~ BR2 25 cycles

- Axial distributions at EOL for proposed design
  - Maximum U5 burn-up: 100%
  - Maximum fission density: 8,4E21 fiss/cm^3

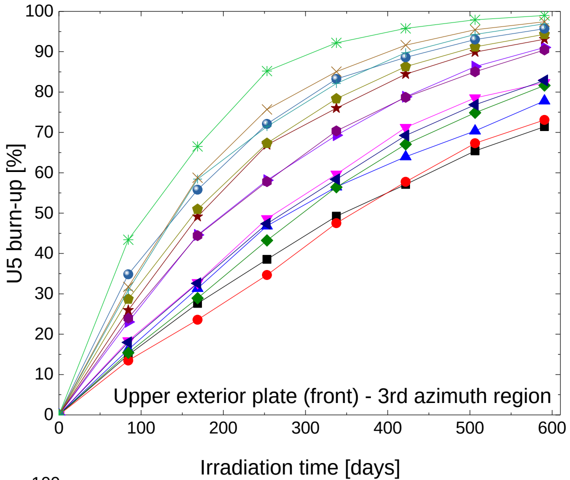


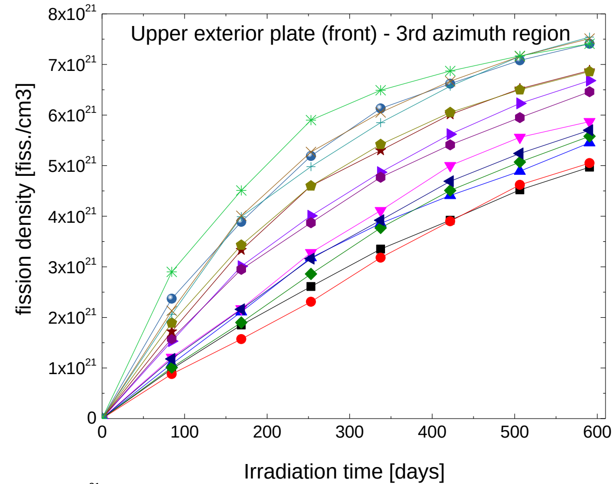


DDE-NBSR: Burn-up evolution during 25 cycles

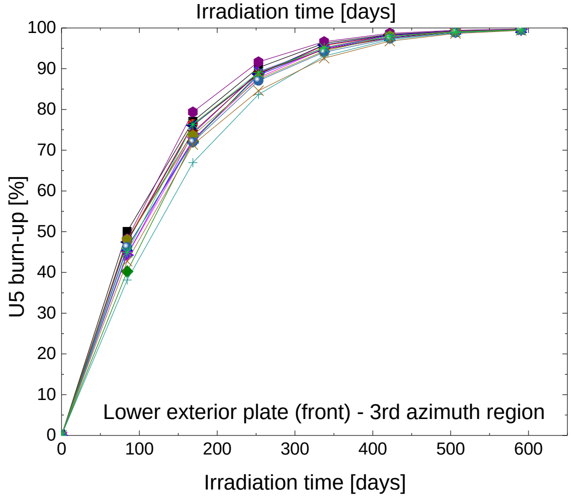


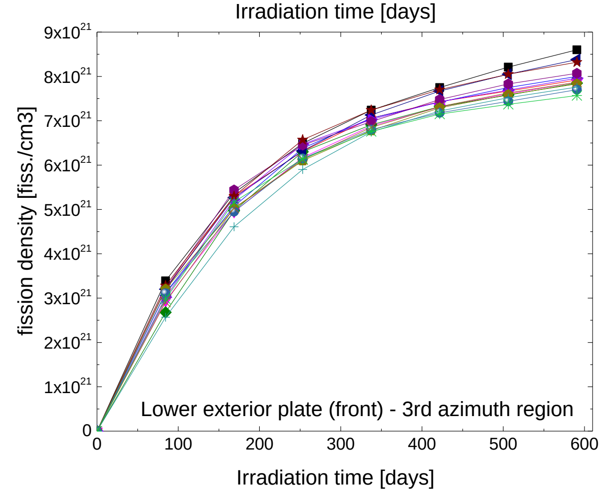
- Time evolution of U5 burn-up (left) and fission density (right)
  - upper plate

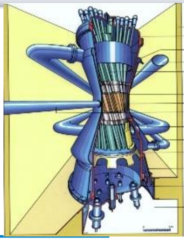




  - lower plate





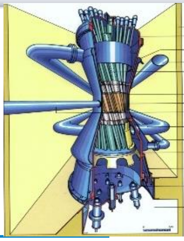


Summary

- **DDE-NBSR**
  - Location in one of the 200 mm diameter channels (H3, H4 or H5)
  - Reduced water gap between upper and lower fuel plates
  - Use of pure Be-outer plug and Al-alloy for inner plug
  - Negligible reactivity effect of DDE-NBSR vs. standard Be-plug
  - **Target performances (BOL) are met: Q_{max}=170 W/cm^2**
  - **Target performances (EOL)**
    - **~12-15 cycles > 90% U5 burn-up, 7,2E21 fiss/cm^3**
    - **~15-25 cycles saturation of U5 burn-up, 8,4E21 fiss/cm^3**

➡ **12 cycles sufficient for maximum fission density ≤ 7E21 fiss/cm^3**

Summary (cont'd)



- **DDE-MITR**
  - Location in one of the 200 mm diameter channels (H3, H4 or H5)
  - Negligible reactivity effect of DDE-MITR vs. standard Be-plug
  - Loading of absorbing devices in surrounding channels
  - Inner plug Al-alloy
  - Outer plug: Be or Al-alloy with holes for absorber rods (Co, W)
  - **Target performances (BOL) are met: Q_{max}=65 W/cm^2**
  - **Target performances (EOL) are met: F_{max}=5.8E21 fiss/cm^3**
    - **25-26 BR2 cycles for Q_{max}(BOC1)=65 W/cm^2**
    - **< 20 BR2 cycles if maintain Q_{max}(BOCi)=65 W/cm^2 in cycles 'i'**
    - **< 20 BR2 cycles if increase target heat flux**

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