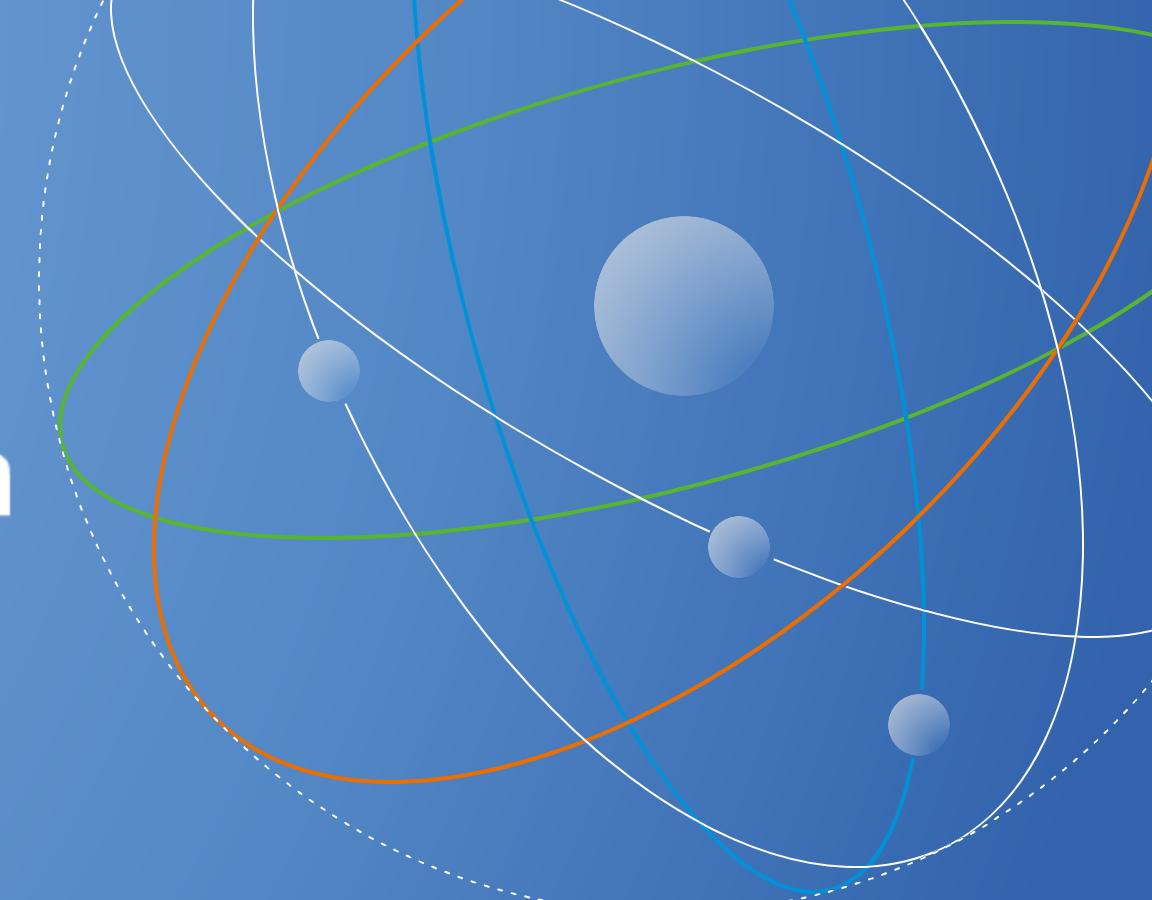


OpenMC Application on IAEA CRP

– Neutronic Benchmark on CEFR Start-up Tests

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September 23, 2025



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OpenMC Application on IAEA CRP –
Neutronic Benchmark on CEFR Start-up Tests

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- 02** V&V with CEFR Experimental Data
- 03** How to utilize or apply

OpenMC in the CEFR CRP

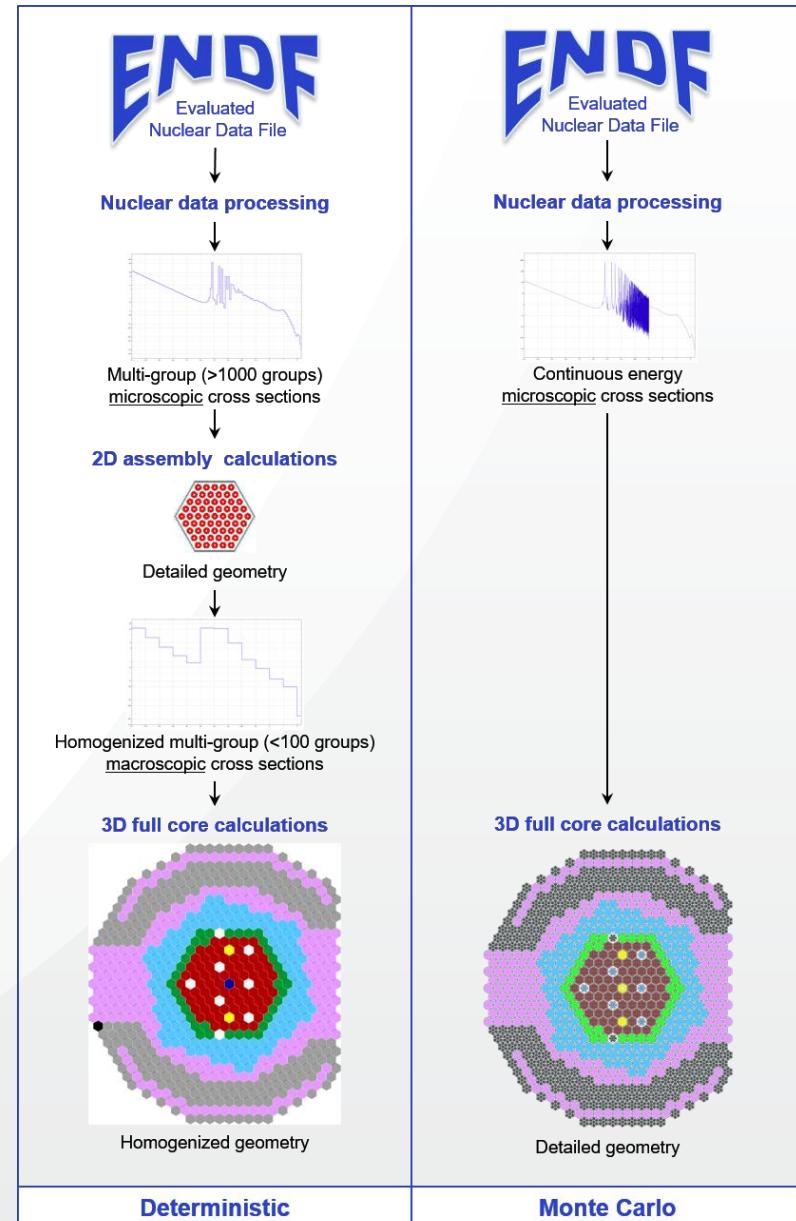
Advantages to use the MC method

- Direct use of the CE XS data for the modelling of neutron interactions instead of the MG approximation
- Accurate treatment of resonances and associated self-shielding effects
- No need for homogenization
- Direct treatment of complex 3D geometries without the need for the “intermediate” 2D assembly calculations

Neutronics Benchmark of CEFR Start-up Tests

- Stochastic analysis 10 codes in 20 Organizations
 - 3 organizations used OpenMC
- Deterministic analysis 15 codes in 17 organizations
 - Most of organizations used two-step approach
 - 4 organization adopted XS generated by stochastic codes

Gen-IV reactors have various shapes



Roles of Monte Carlo Solutions

- MC solutions can be considered as a “reference” for deterministic codes
- Some noticeable drawbacks
 - Compared to deterministic methods, full core Monte Carlo calculations are significantly more time consuming.
 - The accuracy of the results depends on the number of simulated particles or number of particles arriving at the region of interest.
 - In contrast to integral parameters such as k-eff, it is difficult to obtain accurate estimates of localized quantities such as, for example, pin-wise power distribution.
 - Monte Carlo codes will also struggle to accurately predict low-worth reactivity effect.

Why CEFR Start-up Tests Matter

CEFR Start-up Tests Data

- Rare measurement data at the clean core for non-light water reactor
- Various kinds of experiments before operating the reactor core
- Start-up tests at the clean core
- Importance for code validation

Distributed OpenMC Input files cover

- Criticality
- Control rod worth
- Sodium void reactivity

Basic Input Structure

Model

Geometry

Materials

Settings

Dimension

Range of model

Density

Thermal exp. coef.

Temp.

Cal. options

Post-processing

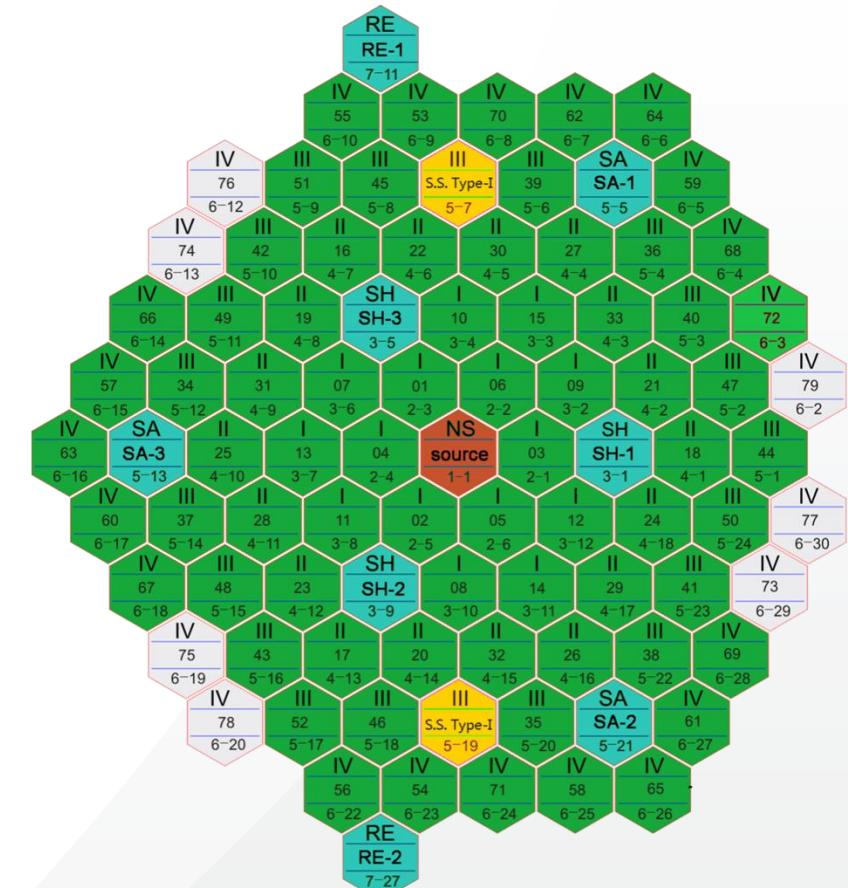
Benchmark Specification Overview

China Experimental Fast Reactor (CEFR)

- China Institute of Atomic Energy (CIAE)
- 65 MWt (20 MWe) Pool-type Sodium Cooled Fast Reactor
- Start-up tests at 250 deg-C
 - Criticality, control rod worth, temperature coefficient, void reactivity, subassembly swap reactivity, reaction rates

Key specifications

- Fuel region of 450 mm with 64.4 wt.% ^{235}U of UO_2 fuel
- Blanket region of 350 mm with 0.3 wt.% ^{235}U of UO_2 fuel
- B_4C with different ^{10}B enrichment
 - Boron shielding subassemblies
 - Control rod subassemblies: regulating, shim and safety



The layout of the core loading operation

type of nozzle
Sequence number of loading
identifier of position (the 22nd in 6th ring)
fuel SA
neutron source SA
control SA

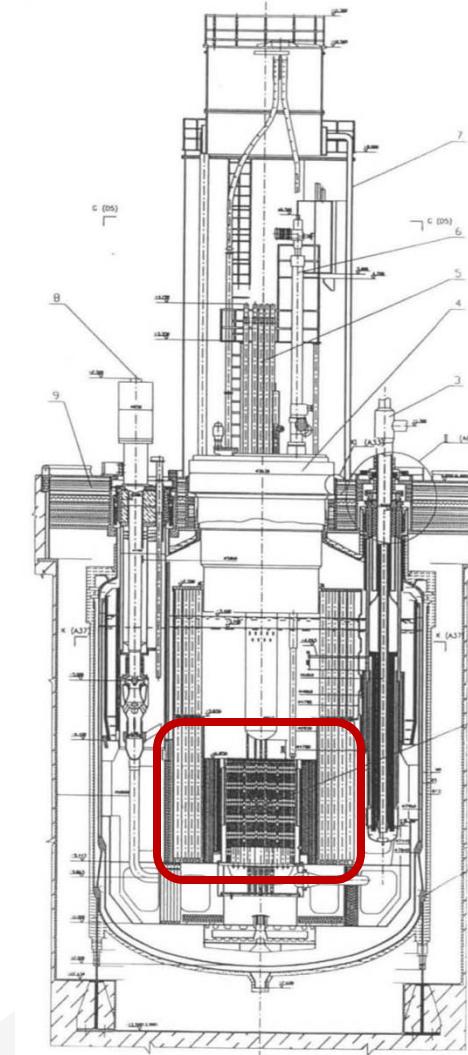
SH: shim rod SA
SA: safety rod SA
RE: regulating rod SA

mock-up fuel SA
SS SA Type-I

Benchmark Specification Overview

Main Parameters of CEFR

Parameter	Value
Thermal power [MW]	65
Electric power [MW]	20
Designed life [year]	30
Maximum burn-up [MWd/t]	60,000
Maximum neutron flux [$\text{cm}^{-2}\text{s}^{-1}$]	3.2×10^{15}
Refueling period [day]	80
Diameter of main vessel [m]	8.0
Height of main vessel [m]	12.2
Covering gas pressure [MPa]	0.005
Core inlet temperature (full power) [$^{\circ}\text{C}$]	360
Core outlet temperature (full power) [$^{\circ}\text{C}$]	530
SA lattice pitch [mm]	61.0
SA outer flat-to-flat dimension [mm]	59.0
SA inner flat-to-flat dimension [mm]	56.6
Wrapper thickness [mm]	1.2



Double-layer vessels
Sodium surface covers the argon gas

1. Main Vessel
2. Reactor Core
3. Intermediate heat exchanger
4. Rotating plug
5. Control Rod Driving Mechanism
6. Fuelling Machine
7. Protective Cover
8. Main Pump
9. Fixed Shielding

* All the parameters are given for first loading, at installation temperature of 20 °C, and in nominal value or design value.



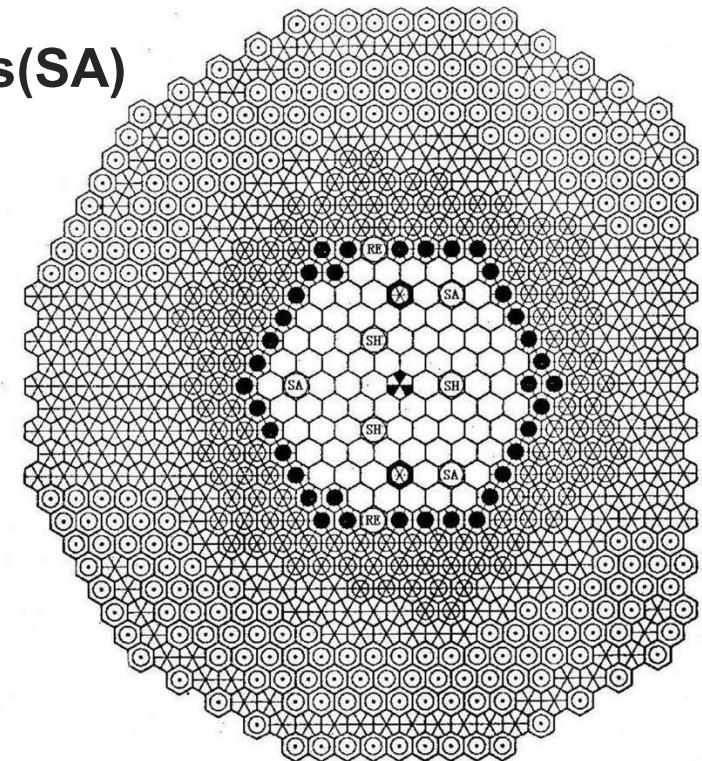
Benchmark Specification Overview

Core layout of the first loading with 7 different subassemblies(SA)

- 79 Fuel SAs
- 8 control SAs
 - 2 regulating CRs with natural B10 for fine power control
 - 3 shim CRs with 92% enriched B10 for large reactivity control
 - 3 safety CRs with 92% enriched B10 for emergency shutdown
- 1 Neutron source SA
- 230 boron shielding SAs
- 394 stainless steel (SS) SAs of 4 types
 - Type I & Type II are the same shape
 - Type III & Type IV are the same shape

■ External shape and dimension of all SAs are almost the same, inner structure varies

■ Due to the long mean free path, which is a characteristic of fast reactors, a wide range of non-fuel regions should be modelled.



Legend	Assembly Type	Number
○	Fuel Assembly	79
◎	1-Steel Shielding Assembly	2
●	2-Steel Shielding Assembly	37
◆	3-Steel Shielding Assembly	132
◆	4-Steel Shielding Assembly	223
◇	Boron Shielding Assembly	230
□	Safety Rod Assembly	3
△	Regulating Rod Assembly	2
◆	Shim Rod Assembly	3
◆	Neutron Source Assembly	1

Material & Cross Section Data

- ☒ Conversion from Gram density to Atomic density
 - Mass, Volume or Gram density
 - Atom fractions or weight fractions
 - Enrichment or Natural Abundance
 - Temperature and Thermal Expansion Coefficient
- ☒ Cold Zero Power conditions with 250 °C in CEFR Start-up Tests
 - To update material compositions and core dimensions due to thermal expansions
- ☒ Cross-section libraries
 - ENDF/B, JEFF, JENDL...
 - Pre-generated ENDF/B-VII.1 cross-section library at 250 deg-C
- ☒ Impurities, Simplification

Processing of Material Data

8 Materials in the CEFR Core

Material	Used in	$\alpha_L^\dagger, 1/^\circ\text{C}$	Alias*
Enriched UO ₂	Fuel	1.1E-05	UOF
Depleted UO ₂	Blanket	1.0E-05	UOB
⁺ SS 15-15Ti	Cladding, spacer wires, central tubes of CR and neutron source SA	1.8E-05	Ti1515
⁺ SS 316Ti	SS structures not mentioned above	1.8E-05	Ti316
92.0% B ₄ C	Safety and shim CR	4.2E-06	B4Cenr
19.6% B ₄ C	Regulating CR	4.2E-06	B4Cnat
19.8% B ₄ C	Boron shielding	4.2E-06	B4Cnat2
He	Gap	-	He
Sodium	Coolant	Eq.	Na

⁺SS - stainless steel [†] α_L - linear expansion coefficient *Alias - material name used in the input

- ▣ To match the operating temperature of 250 °C, material densities given at 20 °C should be adjusted using corresponding linear expansion coefficients, α_L according to below Eqs:
- ▣ Care must be taken to assure that the input material densities correspond to actual conditions

$$\varepsilon(T) = \frac{L(T)}{L(T_0)} = 1 + \alpha_L \cdot [T - T_0]$$

$$\rho(T) = \frac{\rho(T_0)}{\varepsilon(T)^3} \quad \text{where} \quad T_0 = \text{the reference temperature}$$

T = operating temperature

L(T) = the temperature dependent linear dimension

$\varepsilon(T)$ = linear relative expansion

$\rho(T)$ = mass density.

Material – Fuel and Absorbers

Fuel/Blanket in fuel SAs

		Design value	Measured value				Total Number*
			Average	Standard Deviation	Minimum	Maximum	
Fuel	Mass of UO ₂ [kg]	5.30±0.13	5.28127	0.01295	5.2570	5.3421	89
	Mass of U [kg]	4.66±0.12	4.64602	0.01167	4.6246	4.6979	
	Mass of ²³⁵ U [kg]	N/A	2.98197 ⁽¹⁾	0.00852	2.9667	3.0156	
	Enrichment of ²³⁵ U [wt%]	64.4±0.5	64.18315	0.09761	64.08	64.41	
Blanket	Mass of UO ₂ [kg]	4.51±0.30	4.56629	0.01548	4.5345	4.6079	89
	Mass of U [kg]	3.97±0.28	4.01855	0.01418	3.9940	4.0587	
	Mass of ²³⁵ U [kg]	N/A	0.0179 ⁽¹⁾	3.1403E-04	0.0172	0.0183	
	Enrichment of ²³⁵ U [wt%]	0.3~0.72	0.44532	0.00719	0.42924	0.45646	

Absorber in control SAs

		Design Value	Measured value					Total Number
			Average	Standard Deviation	MIN	MAX		
	Mass of B ₄ C [kg]	0.87±0.07	0.86545	0.00522	0.86	0.87	11	
Mass of ¹⁰ B [kg]	Shim & Safety SAs	0.59±0.05	0.58625 ⁽²⁾	0.00518	0.58	0.59	8	
	Regulating SAs	0.119±0.04	0.11733 ⁽²⁾	0.00057735	0.117	0.118	3	

Isotopic Compositions of the fuel and blanket

>Total masses of fuel and blanket components in a fuel SA

Component	Mass, kg/SA	
	Fuel	Blanket
UO ₂	5.28127	4.56629
U	4.64602	4.01855
U-235	2.98197	0.01790

Dimensions of fuel and blanket regions at 20 °C

Parameter	Fuel	Blanket
Inner pellet radius (r_i), cm	0.08000	0.00000
Outer pellet radius (r_o), cm	0.25500	0.25500
Total region height (h), cm	45.00000	35.00000
Number of fuel pins (n)	61	61
Total volume (V), cm ³ /SA	505.56276	436.14220

Total volume

$$V = (r_o^2 - r_i^2) \cdot \pi \cdot h \cdot n$$

where r_i = the inner pellet radius

r_o = the outer pellet radius

h = the region height

n = the total number of fuel rods per SA

Isotopic Compositions of the fuel and blanket

- For the fuel region the following mass densities were obtained:

$$\rho_{U235} = \frac{m_{U235}}{V} = \frac{2.98197}{505.56276} \cdot 1000 \frac{g}{kg} = 5.89832 \frac{g}{cm^3}$$

$$\rho_{U238} = \frac{m_{U238}}{V} = \frac{m_U - m_{U235}}{V} = \frac{4.64602 - 2.98197}{505.56276} \cdot 1000 \frac{g}{kg} = 3.29148 \frac{g}{cm^3}$$

$$\rho_O = \frac{m_O}{V} = \frac{m_{UO_2} - m_U}{V} = \frac{5.28127 - 4.64602}{505.56276} \cdot 1000 \frac{g}{kg} = 1.25652 \frac{g}{cm^3}$$

$$\rho_{UO_2} = \rho_{U235} + \rho_{U238} + \rho_O = 5.89832 + 3.29148 + 1.25652 = 10.44632 \frac{g}{cm^3}$$

Isotopic Compositions of the fuel and blanket

- For the blanket region the following mass densities were obtained:

$$\rho_{U235} = \frac{m_{U235}}{V} = \frac{0.0179}{436.14220} \cdot 1000 \frac{g}{kg} = 0.04104 \frac{g}{cm^3}$$

$$\rho_{U238} = \frac{m_{U238}}{V} = \frac{m_U - m_{U235}}{V} = \frac{4.01855 - 0.01790}{436.14220} \cdot 1000 \frac{g}{kg} = 9.17281 \frac{g}{cm^3}$$

$$\rho_O = \frac{m_O}{V} = \frac{m_{UO_2} - m_U}{V} = \frac{4.56629 - 4.01855}{436.14220} \cdot 1000 \frac{g}{kg} = 1.25587 \frac{g}{cm^3}$$

$$\rho_{UO_2} = \rho_{U235} + \rho_{U238} + \rho_O = 0.04104 + 9.17281 + 1.25587 = 10.46973 \frac{g}{cm^3}$$

Isotopic Compositions of the fuel and blanket

- Adjustment to match the actual operating temperature of 250 °C
- U-234 is ignored in this benchmark
- Isotopic composition of fuel

Isotope	Mass density, g/cm ³		ND, #/barn·cm	
	20 °C	250 °C	20 °C	250 °C
U-235	5.89832	5.85378	1.51123E-02	1.49981E-02
U-238	3.29148	3.26662	8.32669E-03	8.26381E-03
O-16	1.25652	1.24703	4.73084E-02	4.69512E-02
Total	10.44632	10.36743	7.07474E-02	7.02131E-02

- Isotopic composition of blanket

Isotope	Mass density, g/cm ³		ND, #/barn·cm	
	20 °C	250 °C	20 °C	250 °C
U-235	0.04104	0.04076	1.05154E-04	1.04432E-04
U-238	9.17281	9.10981	2.32051E-02	2.30457E-02
O-16	1.25587	1.24725	4.72841E-02	4.69594E-02
Total	10.46973	10.39782	7.05944E-02	7.01095E-02

Isotopic Composition of B_4C

- ☒ Three different B_4C were used
 - 92.0% enriched B_4C in safety (SA) and shim (SH) CRs
 - 19.6% natural B_4C in regulating (RE) CRs
 - 19.8% natural B_4C in boron shielding
- ☒ Mass of B-10 is significant than Mass of B_4C

- ☒ B_4C in control rods: B-10 total masses and isotopic enrichment

	SA+SH	RE
Mass of B-10, kg/SA	0.58625	0.11733
Enrich. B-10, at%	92.0%	19.6%

- ☒ B_4C in Control Rods: Dimensions at 20 °C

Parameter	SA+SH
Outer pellet radius (r_o), cm	0.61000
Total region height (h), cm	51.00000
Number of CR pins (n)	7
Total volume (V), cm^3/SA	417.32823

Isotopic Composition of B₄C

Material density of B-10

$$\rho_{B10} = \frac{m_{B10}}{V}$$

SH+SA CR:

$$\rho_{B10} = \frac{0.58625}{417.32823} \cdot 1000 \frac{g}{kg} = 1.40477 \frac{g}{cm^3}$$

RE CR:

$$\rho_{B10} = \frac{0.11733}{417.32823} \cdot 1000 \frac{g}{kg} = 0.28115 \frac{g}{cm^3}$$

Converting into number density

$$ND_{B10} = \frac{\rho_{B10}}{A_{B10}} N_{Avogadro}$$

SH+SA CR:

$$ND_{B10} = \frac{1.40477}{10.01294} \cdot 0.60221408 = 8.44879E-02 \frac{1}{barn \cdot cm}$$

RE CR:

$$ND_{B10} = \frac{0.28115}{10.01294} \cdot 0.60221408 = 1.69091E-02 \frac{1}{barn \cdot cm}$$

where A = atomic mass

N_{Avo} = Avogadro constant × 10⁻²⁴

Atomic mass is obtained from

https://physics.nist.gov/cgi-bin/Compositions/stand_alone.pl?ele=&all=all&ascii=ascii

Isotopic Composition of B_4C

- The ND of B-11 is calculated using atomic weight (at%) and the ND of B-10 as follows:

$$ND_{B11} = ND_{B10} \cdot \frac{100 - \text{at\%}}{\text{at\%}}$$

SH+SA CR:

$$ND_{B11} = 8.44879E-02 \cdot \frac{100 - 92.0}{92.0} = 7.34677E-02 \frac{1}{\text{barn}\cdot\text{cm}}$$

RE CR:

$$ND_{B11} = 1.69091E-02 \cdot \frac{100 - 19.6}{19.6} = 6.93619E-02 \frac{1}{\text{barn}\cdot\text{cm}}$$

- The ND of C is calculated:

$$ND_{C12} = \frac{(ND_{B10} + ND_{B11})}{4}$$

SH+SA CR:

$$ND_{C12} = 2.29587E-02 \frac{1}{\text{barn}\cdot\text{cm}}$$

RE CR:

$$ND_{C12} = 2.15677E-02 \frac{1}{\text{barn}\cdot\text{cm}}$$

- The total ND of B_4C is

$$ND_{B_4C} = ND_{B10} + ND_{B11} + ND_C$$

SH+SA CR:

$$ND_{B_4C} = 1.14793E-01 \frac{1}{\text{barn}\cdot\text{cm}}$$

RE CR:

$$ND_{B_4C} = 1.07839E-01 \frac{1}{\text{barn}\cdot\text{cm}}$$

Isotopic Composition of B_4C

Isotopic composition of B_4C in SH, SA and RE CR

Isotope	ND, #/barn·cm			
	SH + SA CR		RE	
	20 °C	250 °C	20 °C	250 °C
B-10	8.44879E-02	8.42435E-02	1.69091E-02	1.68602E-02
B-11	7.34677E-03	7.32552E-03	6.93619E-02	6.91612E-02
C-12	2.29587E-02	2.28923E-02	2.15677E-02	2.15054E-02
Total	1.14793E-01	1.14461E-01	1.07839E-01	1.07527E-01

Isotopic Composition of natural B_4C

- Natural B_4C is used in boron shielding SAs
- B_4C in shielding SA: B_4C Total Mass and Isotopic Enrichment

B_4C in Shielding SA	Value
Mass of B_4C , kg/SA	2.43000
Enrich. B-10, at%	19.8%

- B_4C in Shielding SA: Dimensions at 20 °C

Parameter	Value
Outer pellet radius (r_o), cm	0.81000
Total region height (h), cm	80.00000
Number of CR pins (n)	7
Total volume (V), cm^3/SA	1154.27141

Isotopic Composition of natural B_4C

- The mass density of B_4C can be calculated by the total volume:

$$\rho_{B_4C} = \frac{m_{B_4C}}{V}$$

$$\rho_{B_4C} = \frac{2.43000}{1154.27141} \cdot 1000 \frac{g}{kg} = 2.10522 \frac{g}{cm^3}$$

- Atomic mass of B_4C is calculated as follows:

$$A_{B_4C} = A_C + 4 \cdot \left[\frac{at\%}{100} \cdot A_{B10} + \frac{100-at\%}{100} A_{B11} \right]$$

$$A_{B_4C} = 12.00000 + 4 \cdot \left[\frac{19.8}{100} \cdot 10.01294 + \frac{100-19.8}{100} 11.00931 \right] = 55.24810 \frac{g}{cm^3}$$

- The ND of B_4C is calculated

$$ND_{B_4C} = \frac{\rho_{B_4C}}{A_{B_4C}} N_{Avogadro}$$

$$ND_{B_4C} = \frac{2.10522}{55.24810} \cdot 0.60221408 = 2.29473E-02 \frac{1}{barn \cdot cm}$$

Isotopic Composition of natural B_4C

- The ND of the separate isotopes is obtained from the ND of B_4C as follows:

$$ND_C = ND_{B_4C} = 2.29473E - 02 \frac{1}{\text{barn}\cdot\text{cm}}$$

$$ND_{B10} = 4 \cdot \frac{at\%}{100} \cdot ND_{B_4C} = 4 \cdot \frac{19.8}{100} \cdot 2.29473E - 02 = 1.81743E - 02 \frac{1}{\text{barn}\cdot\text{cm}}$$

$$ND_{B11} = 4 \cdot \frac{100 - at\%}{100} \cdot ND_{B_4C} = 4 \cdot \frac{100 - 19.8}{100} \cdot 2.29473E - 02 = 7.36150E - 02 \frac{1}{\text{barn}\cdot\text{cm}}$$

- Isotopic composition of B_4C in shielding SA

Isotope	ND, #/barn·cm	
	20 °C	250 °C
B-10	1.81743E-02	1.81217E-02
B-11	7.36150E-02	7.34021E-02
C-12	2.29473E-02	2.28809E-02
Total	1.14737E-01	1.14405E-01

Material – Stainless Steel

Components made of 15-15 Ti

SA type	Components made of 15-15Ti
Fuel SA	rod cladding, spacer wire
Control SA	rod cladding, spacer wire, cylinder tube (D=49 mm)
Neutron Source SA	central tube (D=20 mm), spacer wire

Composition of Stainless Steel

Element	Relative Mass [%]	
	15-15Ti	316Ti
C	0.06	0.06
Si	0.45	0.60
Ti	0.35	0.40
V	0.20	0
Cr	16.25	17.00
Mn	1.50	1.75
Fe	64.24	65.19
Ni	14.75	12.50
Mo	2.20	2.50
Density [g/cm ³]	7.97	7.98

Some nuclear data libraries contain XS data for natural elements, it is strongly recommended to decompose them into the isotopic constituents

Isotopic Composition of Stainless Steels

Example to demonstrate to get atomic density for the Fe element in the 316 Ti SS

Step 1 $A_{Fe} = A_{Fe54} \cdot f_{Fe54} + A_{Fe56} \cdot f_{Fe56} + A_{Fe57} \cdot f_{Fe57} + A_{Fe58} \cdot f_{Fe58}$

where f is a relative natural abundance

Step 2 $\rho_{Fe} = \rho_{316Ti} \cdot w\%_{Fe}$

where w% is a relative mass of the element

Step 3 $ND_{Fe} = \frac{\rho_{Fe}}{A_{Fe}} \cdot N_{Avogadro}$

Step 4 $ND_{Fe54} = ND_{Fe} \cdot f_{Fe54}$

$$ND_{Fe56} = ND_{Fe} \cdot f_{Fe56}$$

$$ND_{Fe57} = ND_{Fe} \cdot f_{Fe57}$$

$$ND_{Fe58} = ND_{Fe} \cdot f_{Fe58}$$

Isotopic Composition of SS: 15-15Ti

Element	Relative mass, w%	Isotope	A, g/mol	Natural abundance, %	ND, #/barn·cm	
					20 °C	250 °C
Fe	64.24%	Fe-54	53.93962	5.8450%	3.22711E-03	3.18736E-03
		Fe-56	55.93491	91.7540%	5.06588E-02	5.00347E-02
		Fe-57	56.93541	2.1190%	1.16993E-03	1.15552E-03
		Fe-58	57.93329	0.2820%	1.55696E-04	1.53779E-04
Cr	16.25%	Cr-50	49.94606	4.35%	6.51756E-04	6.43727E-04
		Cr-52	51.93999	83.79%	1.25685E-02	1.24136E-02
		Cr-53	52.94079	9.50%	1.42516E-03	1.40761E-03
		Cr-54	53.93937	2.37%	3.54753E-04	3.50383E-04
Ni	14.75%	Ni-58	57.9357	68.08%	8.21128E-03	8.11014E-03
		Ni-60	59.93079	26.22%	3.16295E-03	3.12399E-03
		Ni-61	60.93143	1.14%	1.37492E-04	1.35798E-04
		Ni-62	61.92799	3.63%	4.38397E-04	4.32997E-04
Mo	2.20%	Ni-64	63.92818	0.93%	1.11632E-04	1.10257E-04
		Mo-92	91.90683	14.53%	1.59885E-04	1.57916E-04
		Mo-94	93.90509	9.15%	1.00685E-04	9.94445E-05
		Mo-95	94.90589	15.84%	1.74300E-04	1.72153E-04
Mo	2.20%	Mo-96	95.90467	16.67%	1.83433E-04	1.81174E-04
		Mo-97	96.90598	9.60%	1.05636E-04	1.04335E-04
		Mo-98	97.90536	24.39%	2.68383E-04	2.65077E-04
		Mo-100	99.90746	9.82%	1.08057E-04	1.06726E-04
Mn	1.50%	Mn-55	54.93805	100.00%	1.31047E-03	1.29433E-03
C	0.06%	C-12	11.99999	98.93%	2.39983E-04	2.37026E-04
Ti	0.35%	Ti-46	45.95276	8.25%	2.89533E-05	2.85966E-05
		Ti-47	46.95134	7.44%	2.61106E-05	2.57889E-05
		Ti-48	47.94795	73.72%	2.58719E-04	2.55532E-04
		Ti-49	48.94788	5.41%	1.89863E-05	1.87524E-05
Si	0.45%	Ti-50	49.9448	5.18%	1.81791E-05	1.79552E-05
		Si-28	27.97734	92.22%	7.09186E-04	7.00451E-04
		Si-29	28.97652	4.69%	3.60272E-05	3.55834E-05
		Si-30	30.00002	3.09%	2.37772E-05	2.34843E-05
				Total:	8.60442E-02	8.49843E-02

Isotopic Composition of SS: 316Ti

Element	Relative mass, w%	Isotope	A, g/mol	Natural abundance, %	ND, #/barn·cm	
					20 °C	250 °C
Fe	65.19%	Fe-54	53.93962	5.8450%	3.27894E-03	3.23855E-03
		Fe-56	55.93491	91.7540%	5.14724E-02	5.08384E-02
		Fe-57	56.93541	2.1190%	1.18872E-03	1.17408E-03
		Fe-58	57.93329	0.2820%	1.58197E-04	1.56248E-04
Cr	17.00%	Cr-50	49.94606	4.35%	6.82692E-04	6.74283E-04
		Cr-52	51.93999	83.79%	1.31650E-02	1.30029E-02
		Cr-53	52.94079	9.50%	1.49281E-03	1.47442E-03
		Cr-54	53.93937	2.37%	3.71592E-04	3.67015E-04
Ni	12.50%	Ni-58	57.9357	68.08%	6.96745E-03	6.88162E-03
		Ni-60	59.93079	26.22%	2.68383E-03	2.65077E-03
		Ni-61	60.93143	1.14%	1.16665E-04	1.15228E-04
		Ni-62	61.92799	3.63%	3.71989E-04	3.67407E-04
Mo	2.50%	Ni-64	63.92818	0.93%	9.47217E-05	9.35550E-05
		Mo-92	91.90683	14.53%	1.81916E-04	1.79675E-04
		Mo-94	93.90509	9.15%	1.14558E-04	1.13147E-04
		Mo-95	94.90589	15.84%	1.98317E-04	1.95874E-04
Mo	2.50%	Mo-96	95.90467	16.67%	2.08709E-04	2.06138E-04
		Mo-97	96.90598	9.60%	1.20192E-04	1.18712E-04
		Mo-98	97.90536	24.39%	3.05363E-04	3.01602E-04
		Mo-100	99.90746	9.82%	1.22946E-04	1.21432E-04
Mn	1.75%	Mn-55	54.93805	100.00%	1.53080E-03	1.51194E-03
C	0.06%	C-12	11.99999	98.93%	2.40284E-04	2.37324E-04
Ti	0.40%	Ti-46	45.95276	8.25%	3.31310E-05	3.27229E-05
		Ti-47	46.95134	7.44%	2.98781E-05	2.95101E-05
		Ti-48	47.94795	73.72%	2.96050E-04	2.92403E-04
		Ti-49	48.94788	5.41%	2.17259E-05	2.14583E-05
Si	0.60%	Ti-50	49.94448	5.18%	2.08022E-05	2.05460E-05
		Si-28	27.97734	92.22%	9.46768E-04	9.35106E-04
		Si-29	28.97652	4.69%	4.80966E-05	4.75041E-05
		Si-30	30.00002	3.09%	3.17427E-05	3.13517E-05
				Total:	8.64963E-02	8.54309E-02

Material – Sodium

- ▣ The impurity content is quite low (< 200 µg/g after the cleaning), it is recommended to use pure ^{23}Na in neutronics modelling.
 - ▣ In addition, by use of cold trap, the impurities are extracted and filtered constantly.
 - ▣ In nature, sodium has only one isotope, ^{23}Na
 - Due to the activation in the core, ^{24}Na and ^{22}Na are produced; however, both nuclides are of minor amount and won't cause significant influence to neutronics behaviour.
 - The major impurities in sodium are C, O, N, Ca, K, Fe, etc, which mainly come from the raw sodium from factory, the surface of metallic equipment in primary system, the corrosion products, refilling of covering gas, etc.

- ▣ The density of liquid sodium varies with temperature according to following Eq.

$$\rho_{\text{Na}} = 950.0483 - 0.2298 T - 14.6045 \times 10^{-6}T^2 + 5.6377 \times 10^{-9}T^3$$

where ρ_{Na} = the sodium density in g/cm³

T = the sodium temperature in °C

Substituting T= 250 °C into the equation will give $\rho_{\text{Na}} = 0.89177 \text{ g/cm}^3$

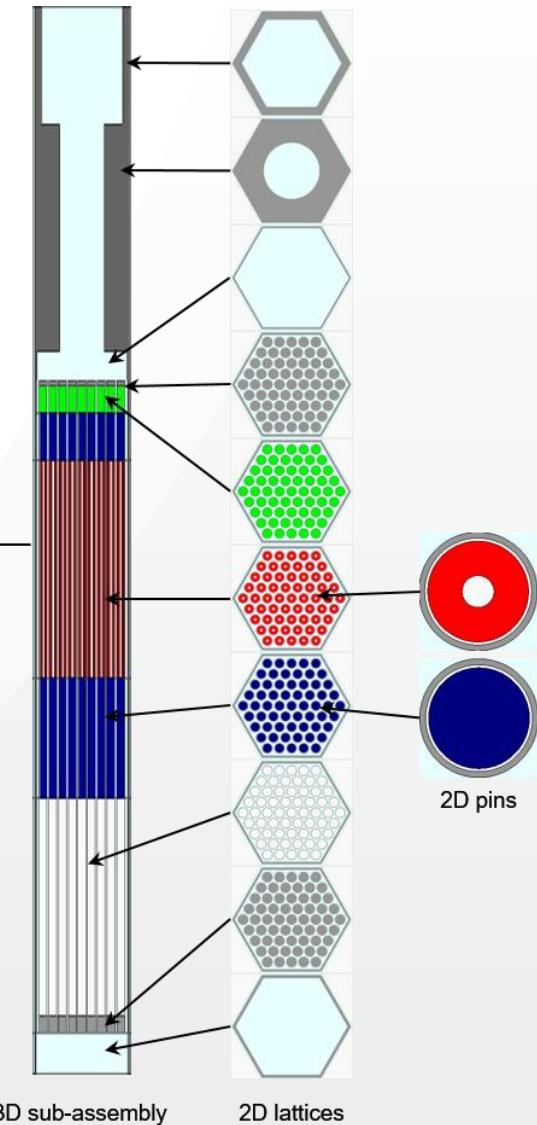
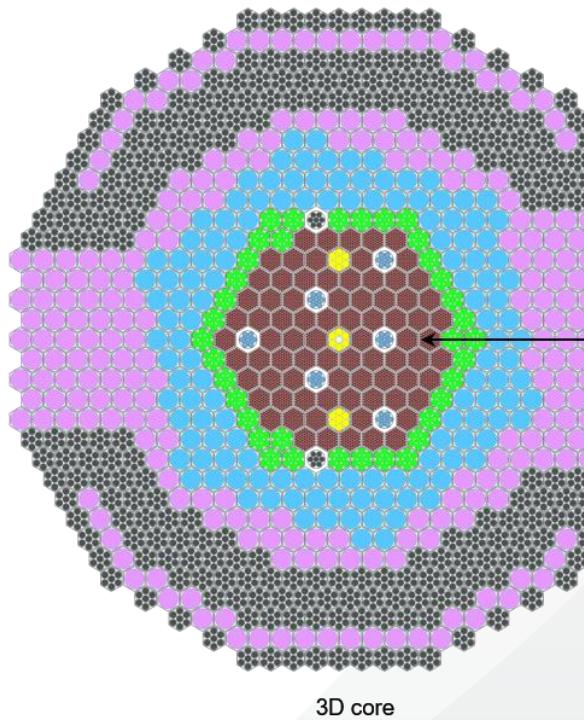
Processing of Geometry Data

- ☒ The decomposition of the core model into 4 hierarchical levels:

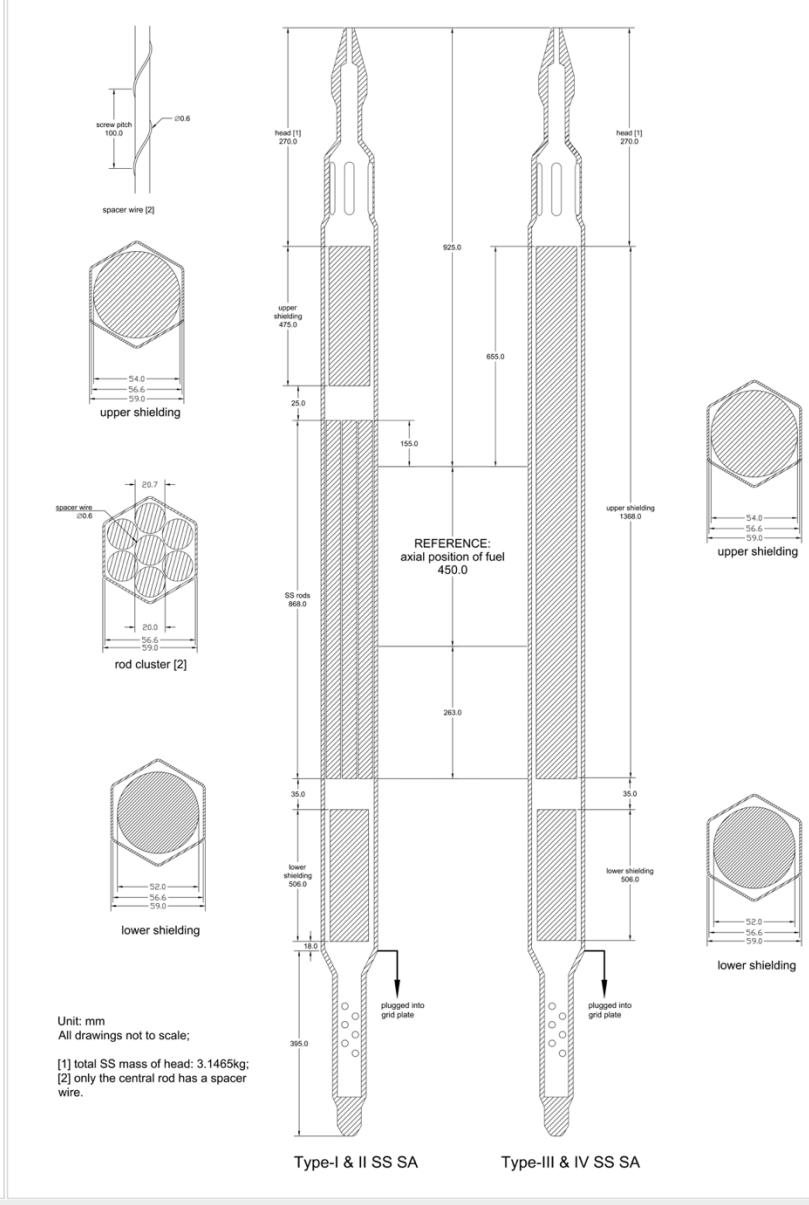
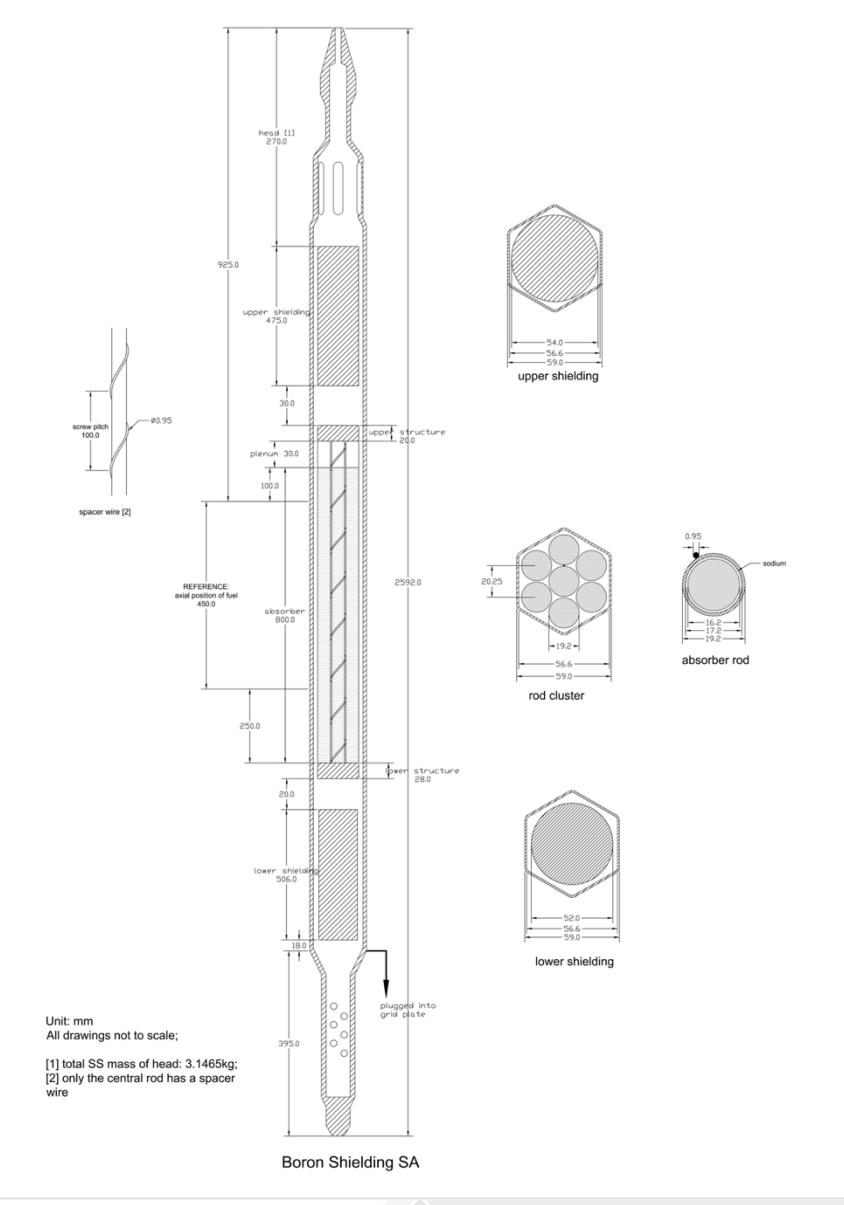
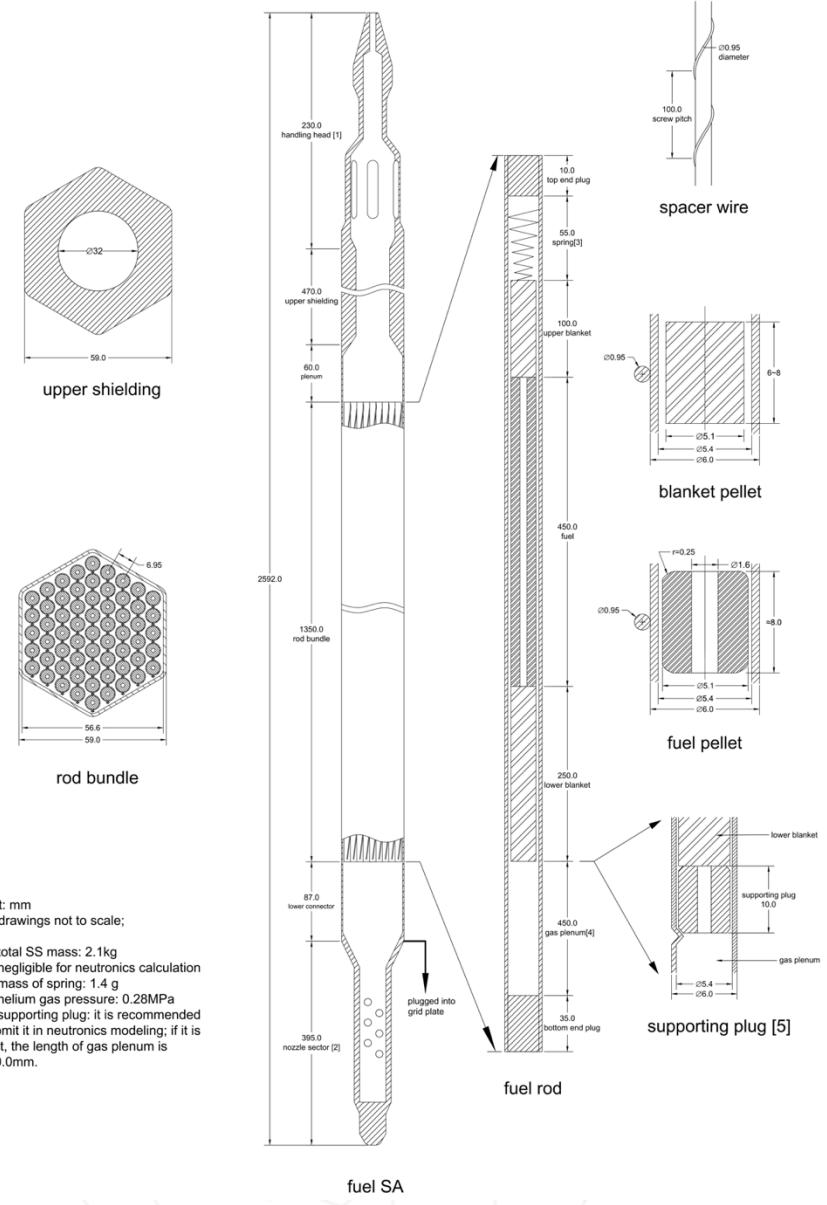
- ☐ 3D reactor core
- ☐ 3D SAs
- ☐ 2D lattices or cells
X-Y slices of each axial region of 3D SAs
- ☐ 2D pins

- ☒ The geometry modelling in 2-stage:

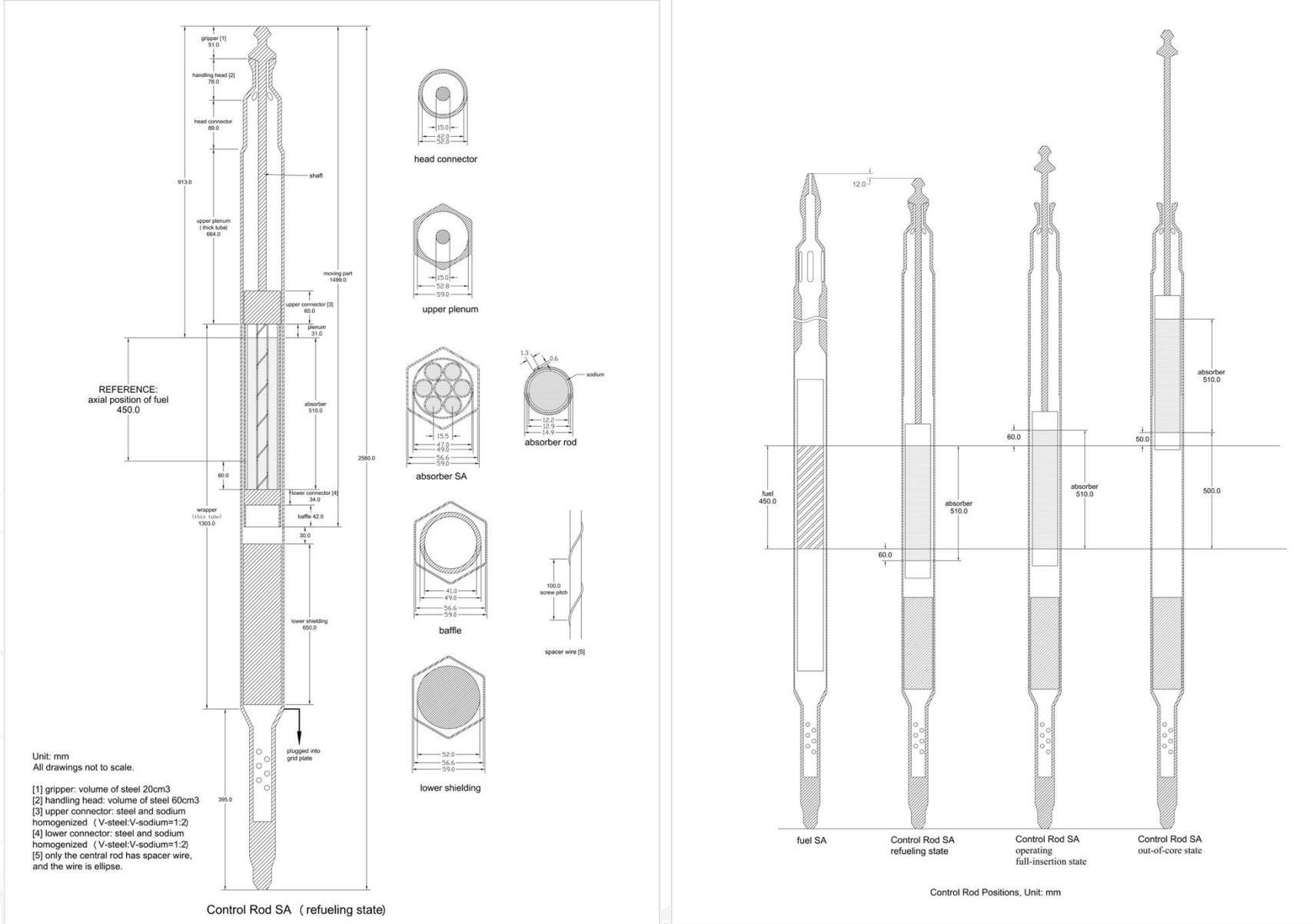
- ☐ Decomposition of the geometry into “building” blocks using the hierarchical levels
(i.e. from the 3D core level to the 2D pin level)
- ☐ Defining the building blocks and building the geometry using the “inverted” hierarchical levels
(i.e. from the 2D pin level to the 3D core level)



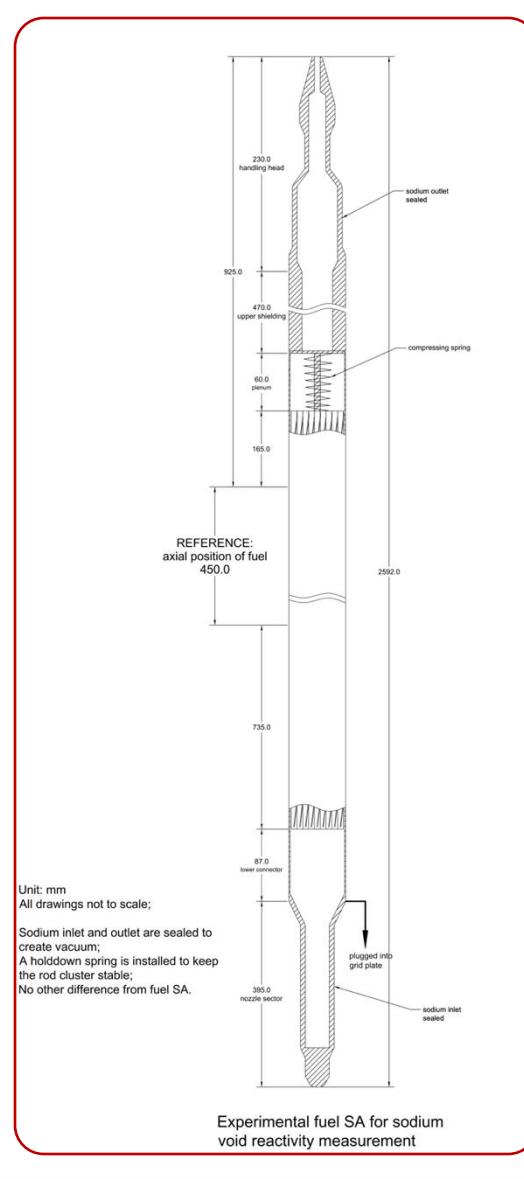
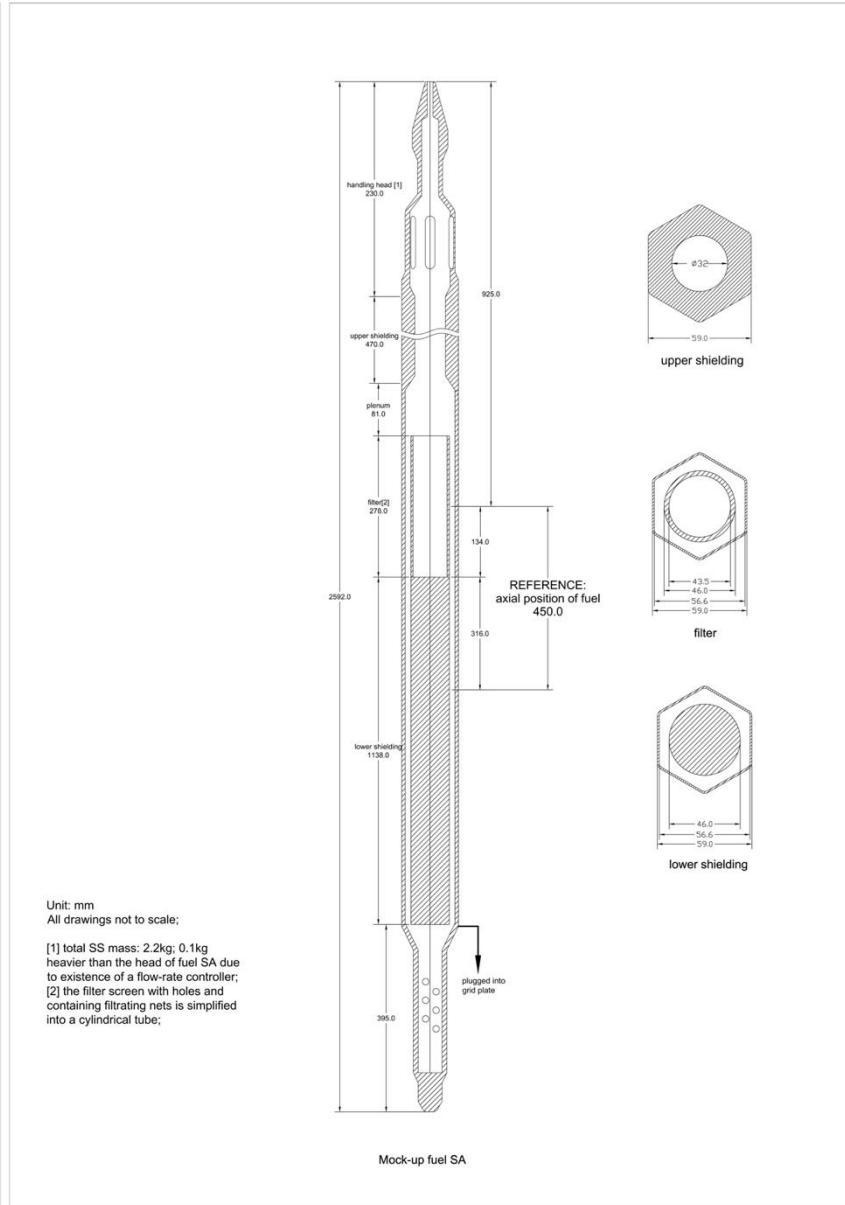
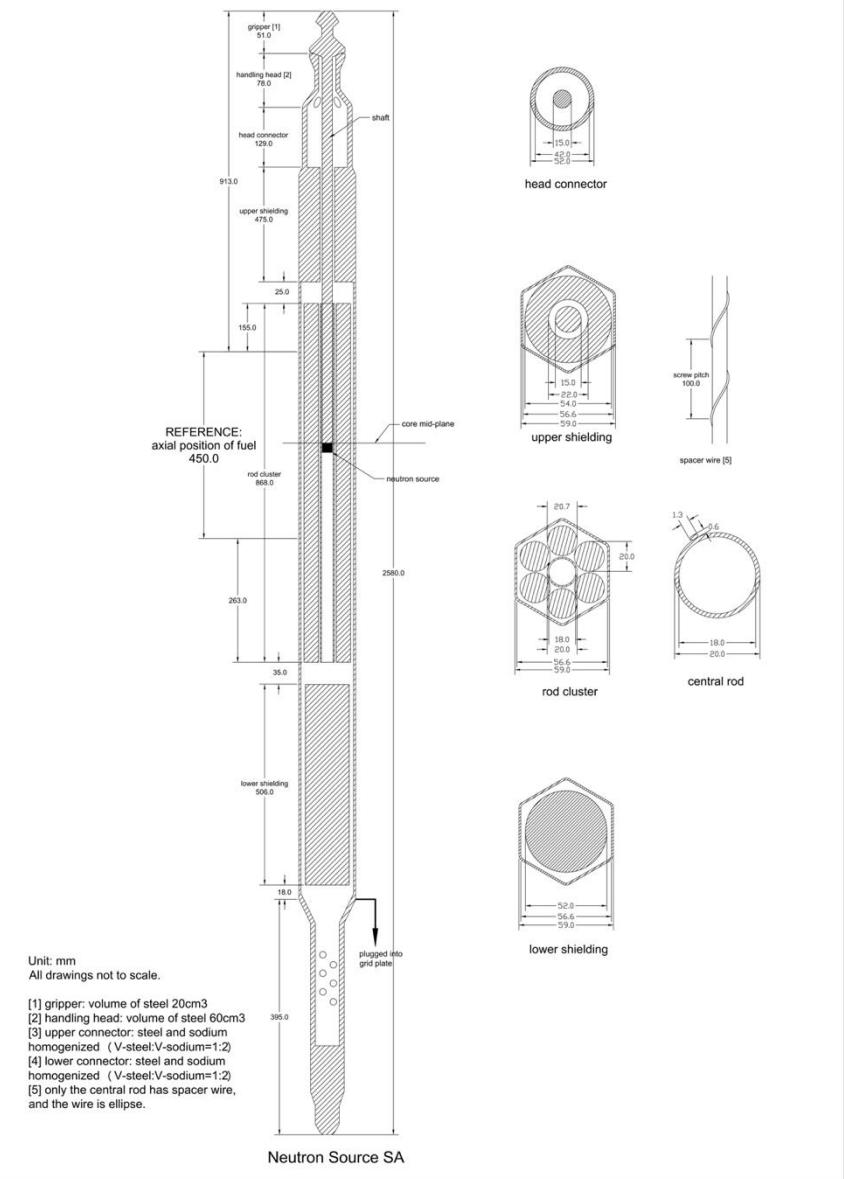
Detailed Geometry of Each SA



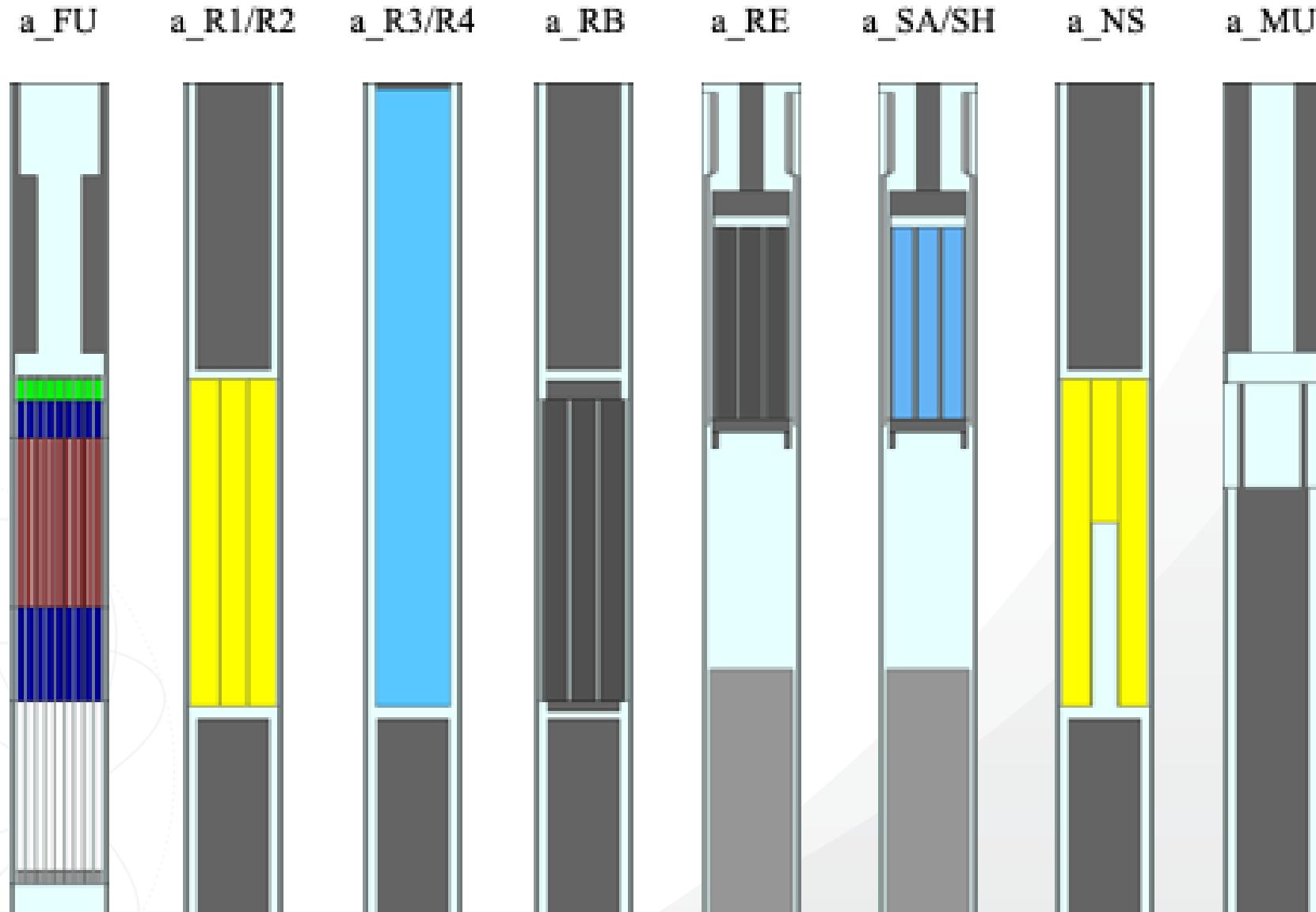
Detailed Geometry of Each SA



Detailed Geometry of Each SA



Axial Layout of the CEFR SAs by OpenMC



Description of Axial SA regions

#	a_FU	a_R1/R2	a_R3/R4	a_RB	a_RE/SA/SH	a_NS	a_MU
1	Head	Upper shield	Upper shield	Upper shield	Head+gripper	Upper shield	Upper shield
2	Upper shield	Na plenum	Na plenum	Na plenum	Head connector	Na plenum	Na plenum
3	Upper connector	SS rods cluster	Lower shield	Upper shield	Transition	SS rods cluster	Filter
4	Top end plug	Na plenum	-	Rod cluster	Upper plenum	NS rods cluster	Lower shield
5	Spring	Lower shield	-	Lower shield	Normal wrapper	Na plenum	-
6	Upper blanket	-	-	Na plenum	Lower shield	Lower shield	-
7	Fuel	-	-	Lower shield	-	-	-
8	Lower blanket	-	-	-	-	-	-
9	Lower gas plenum	-	-	-	-	-	-
10	Bottom end plug	-	-	-	-	-	-
11	Lower connector	-	-	-	-	-	-

Dimensions of Axial SA regions

Upper region boundary at 20 °C, cm

#	<u>a_FU</u>	<u>a_R1/R2</u>	<u>a_R3/R4</u>	<u>a_RB</u>	<u>a_RE/SA/SH</u>	<u>a_NS</u>	<u>a_MU</u>
1	219.700	219.700	219.700	219.700	218.500	219.700	219.700
2	196.700	145.200	55.900	145.200	205.600	145.200	149.700
3	149.700	142.700	52.400	142.200	197.700	142.700	141.600
4	143.700	55.900	-	137.200	196.700	104.700	113.800
5	142.700	52.400	-	57.200	130.300	55.900	-
6	137.200	-	-	54.400	65.600	52.400	-
7	127.200	-	-	52.400	-	-	-
8	82.200	-	-	0.000	-	-	-
9	57.200	-	-	-	-	-	-
10	12.200	-	-	-	-	-	-
11	8.700	-	-	-	-	-	-

Upper region boundary at 20 °C, cm

#	<u>a_FU</u>	<u>a_R1/R2</u>	<u>a_R3/R4</u>	<u>a_RB</u>	<u>a_RE/SA/SH</u>	<u>a_NS</u>	<u>a_MU</u>
1	220.473	220.610	220.610	220.610	219.405	220.610	220.610
2	197.377	145.801	56.131	145.801	206.451	145.801	150.320
3	150.183	143.291	52.617	142.789	198.518	143.291	142.186
4	144.158	56.131	-	137.768	197.514	105.133	114.271
5	143.154	52.617	-	57.437	130.839	56.131	-
6	137.631	-	-	54.625	65.872	52.617	-
7	127.608	-	-	52.617	-	-	-
8	82.494	-	-	0.000	-	-	-
9	57.437	-	-	-	-	-	-
10	12.251	-	-	-	-	-	-
11	8.736	-	-	-	-	-	-

Simplifications and Approximations

☒ How close the geometry specifications should be reflected in the MC model?

- ☐ A general approach is to model all important regions from neutronic perspective as closely as possible to the available specifications, in particular at the active core level.
- ☐ Only peripheral regions, with reduced neutronic importance such as handling heads, are treated in an approximately.

☒ Description of Geometry-related simplifications

Object	Affected region	Simplification
Space wire	Fuel rod	Mixed with cladding
Spring	Fuel rod	Modelled as a homogeneous mixture of steel and He
Supporting plug	Fuel rod	Not modelled
Rounded corners	Fuel pellet	Not modelled
Handling head	Fuel SA	Modelled as hexagonal wrappers of different thickness
	Other SAs	Modelled as an extension of the upper shield
Nozzle sector	All SAs	Not modelled

Structure of OpenMC input for the CEFR core

Category	File name
Main input	E71_CEFR_main_79assy_250C_ARO/input
Surfaces	CEFR-01-surf-250C.omc
Materials	CEFR-02-mat-1-all-250C.omc
Pins	CEFR-03-pin-1-FU.omc CEFR-03-pin-2-CR.omc CEFR-03-pin-3-RR.omc
Lattices	CEFR-04-lat-1-FU.omc CEFR-04-lat-2-CR.omc CEFR-04-lat-3-RR.omc CEFR-04-lat-4-RB.omc CEFR-04-lat-5-NS.omc
Sub-assemblies	CEFR-05-asy-1-FU.omc CEFR-05-asy-3-RR.omc CEFR-05-asy-4-RB.omc CEFR-05-asy-5-NS.omc
Control rod SAs	CEFR-07-rod-position-0-AR0.omc
Core	CEFR-06-core-lat-79assy-250C.omc
Settings	SET-01-BASIC.omc SET-02-PLOT.omc SET-03-TALLY.omc

Example: Building the fuel SA geometry

• Definition of the surfaces used to construct radial region of fuel pins

```
#-----  
# --- Pin surfaces - fuel  
#-----  
# --- 61 pin lattices (same inner/outer clad)  
# --- Fuel fissile  
# Fissile fuel pellet inner hole radius (cm)  
cyl_FI_hole = openmc.ZCylinder( x0=0, y0=0, r=0.08020, name='cyl_FI_hole')  
# Fissile fuel pellet radius (cm)  
cyl_FI_fuel = openmc.ZCylinder( x0=0, y0=0, r=0.25565, name='cyl_FI_fuel')  
# --- Fuel fertile  
# Fertile fuel pellet radius (cm)  
cyl_FE_fuel = openmc.ZCylinder( x0=0, y0=0, r=0.25559, name='cyl_FE_fuel')  
# --- Cladding  
# Inner clad radius (cm)  
cyl_Clad61_IN = openmc.ZCylinder( x0=0, y0=0, r=0.27112, name='cyl_Clad61_IN')  
# Outer clad radius (cm)  
cyl_Clad61_OU = openmc.ZCylinder( x0=0, y0=0, r=0.30499, name='cyl_Clad61_OU')
```

• Definition of the surfaces used to construct radial region of fuel SA

```
#-----  
# --- Radial surfaces - Fuel assembly  
#-----  
# --- SA wrapper hexagons  
# pitch=2.84172, Wrapper tube inner flat-to-flat/2 (cm)  
hex_WR_IN = openmc.hexagonal_prism(orientation='x', origin=(0,0), edge_length= 3.281335614)  
# pitch=2.96221, Wrapper tube outer flat-to-flat/2 (cm)  
hex_WR_OU = openmc.hexagonal_prism(orientation='x', origin=(0,0), edge_length= 3.420465482)  
# pitch=3.06260, S/A Pitch flat-to-flat/2 (cm)  
hex_SA_PITCH = openmc.hexagonal_prism(orientation='x', origin=(0,0), edge_length= 3.536385869)
```

Example: Building the fuel SA geometry

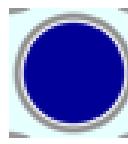
Surfaces defining the upper boundaries of axial region of fuel SA

```
#-----  
# --- Axial surfaces - Fuel assembly  
#-----  
  
# --- fuel - axial s/a regions - upper boundary  
pz_FUEL_HEA = openmc.ZPlane( z0= 220.473 ,name='pz_FUEL_HEA') # 01 - Head  
pz_FUEL_USH = openmc.ZPlane( z0= 197.377 ,name='pz_FUEL_USH') # 02 - Upper shield  
pz_FUEL_UCN = openmc.ZPlane( z0= 150.183 ,name='pz_FUEL_UCN') # 03 - Upper connector  
pz_FUEL_TEP = openmc.ZPlane( z0= 144.158 ,name='pz_FUEL_TEP') # 04 - Top end plug  
pz_FUEL_SPR = openmc.ZPlane( z0= 143.154 ,name='pz_FUEL_SPR') # 05 - Spring  
pz_FUEL_UBL = openmc.ZPlane( z0= 137.631 ,name='pz_FUEL_UBL') # 06 - Upper blanket  
pz_FUEL_FIS = openmc.ZPlane( z0= 127.608 ,name='pz_FUEL_FIS') # 07 - Fissile  
pz_FUEL_LBL = openmc.ZPlane( z0= 82.494 ,name='pz_FUEL_LBL') # 08 - Lower blanket  
pz_FUEL_LGP = openmc.ZPlane( z0= 57.437 ,name='pz_FUEL_LGP') # 09 - Lower gas plenum  
pz_FUEL_BEP = openmc.ZPlane( z0= 12.251 ,name='pz_FUEL_BEP') # 10 - Bottom end plug  
pz_FUEL_LCN = openmc.ZPlane( z0= 8.736 ,name='pz_FUEL_LCN') # 11 - Lower connector
```

Example: Building the fuel SA geometry

Building 2D pins of the fuel

- Defining cells
- Setting regions
- Filling materials
- Making universes

#	2D pin		OpenMC input
	Content	Snapshot	
3	Upper blanket		<pre># ---- Upper fuel fertile/blanket (UBL) c_FU_UBL_1 = openmc.Cell(name='c_FU_UBL_1') c_FU_UBL_2 = openmc.Cell(name='c_FU_UBL_2') c_FU_UBL_3 = openmc.Cell(name='c_FU_UBL_3') c_FU_UBL_4 = openmc.Cell(name='c_FU_UBL_4') c_FU_UBL_1.region = -cyl_FE_fuel c_FU_UBL_2.region = +cyl_FE_fuel & -cyl_Clad61_IN c_FU_UBL_3.region = +cyl_Clad61_IN & -cyl_Clad61_OU c_FU_UBL_4.region = +cyl_Clad61_OU c_FU_UBL_1.fill = UOB c_FU_UBL_2.fill = He c_FU_UBL_3.fill = SS c_FU_UBL_4.fill = Na_FU_FE p_FU_UBL = openmc.Universe(cells=[c_FU_UBL_1,c_FU_UBL_2,c_FU_UBL_3,c_FU_UBL_4])</pre>
4	Fuel		<pre># ---- Fuel fissile (FIS) c_FU_FIS_0 = openmc.Cell(name='c_FU_FIS_0') c_FU_FIS_1 = openmc.Cell(name='c_FU_FIS_1') c_FU_FIS_2 = openmc.Cell(name='c_FU_FIS_2') c_FU_FIS_3 = openmc.Cell(name='c_FU_FIS_3') c_FU_FIS_4 = openmc.Cell(name='c_FU_FIS_4') c_FU_FIS_0.region = -cyl_FI_hole c_FU_FIS_1.region = +cyl_FI_hole & -cyl_FI_fuel c_FU_FIS_2.region = +cyl_FI_fuel & -cyl_Clad61_IN c_FU_FIS_3.region = +cyl_Clad61_IN & -cyl_Clad61_OU c_FU_FIS_4.region = +cyl_Clad61_OU c_FU_FIS_0.fill = He c_FU_FIS_1.fill = UOF c_FU_FIS_2.fill = He c_FU_FIS_3.fill = SS c_FU_FIS_4.fill = Na_FU_FI p_FU_FIS = openmc.Universe(cells=[c_FU_FIS_0,c_FU_FIS_1,c_FU_FIS_2,c_FU_FIS_3,c_FU_FIS_4])</pre>

Example: Building the fuel SA geometry

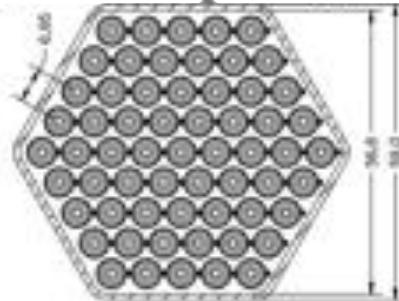
Building 2D pins of the fuel SA

2D pin		OpenMC input	2D pin		OpenMC input
Content	Snapshot		Content	Snapshot	
Spring		<pre># --- Spring (SPR) c_FU_SPR1 = openmc.Cell(name='c_FU_SPR1') c_FU_SPR2 = openmc.Cell(name='c_FU_SPR2') c_FU_SPR3 = openmc.Cell(name='c_FU_SPR3') c_FU_SPR1.region = -cyl_Clad61_IN c_FU_SPR2.region = +cyl_Clad61_IN & -cyl_Clad61_OU c_FU_SPR3.region = +cyl_Clad61_OU c_FU_SPR1.fill = BOMOG_SPR_FU c_FU_SPR2.fill = SS c_FU_SPR3.fill = Na_FU_Out p_FU_SPR = openmc.Universe(cells=[c_FU_SPR1,c_FU_SPR2,c_FU_SPR3])</pre>	Lower blanket		<pre># --- Lower fuel fertile/blanket (LBL) c_FU_LBL_1 = openmc.Cell(name='c_FU_LBL_1') c_FU_LBL_2 = openmc.Cell(name='c_FU_LBL_2') c_FU_LBL_3 = openmc.Cell(name='c_FU_LBL_3') c_FU_LBL_4 = openmc.Cell(name='c_FU_LBL_4') c_FU_LBL_1.region = -cyl_FE_fuel c_FU_LBL_2.region = +cyl_FE_fuel & -cyl_Clad61_IN c_FU_LBL_3.region = +cyl_Clad61_IN & -cyl_Clad61_OU c_FU_LBL_4.region = +cyl_Clad61_OU c_FU_LBL_1.fill = DOB c_FU_LBL_2.fill = Be c_FU_LBL_3.fill = SS c_FU_LBL_4.fill = Na_FU_FE p_FU_LBL = openmc.Universe(cells=[c_FU_LBL_1,c_FU_LBL_2,c_FU_LBL_3,c_FU_LBL_4])</pre>
Upper blanket		<pre># --- Upper fuel fertile/blanket (UBL) c_FU_UBL_1 = openmc.Cell(name='c_FU_UBL_1') c_FU_UBL_2 = openmc.Cell(name='c_FU_UBL_2') c_FU_UBL_3 = openmc.Cell(name='c_FU_UBL_3') c_FU_UBL_4 = openmc.Cell(name='c_FU_UBL_4') c_FU_UBL_1.region = -cyl_FE_fuel c_FU_UBL_2.region = +cyl_FE_fuel & -cyl_Clad61_IN c_FU_UBL_3.region = +cyl_Clad61_IN & -cyl_Clad61_OU c_FU_UBL_4.region = +cyl_Clad61_OU c_FU_UBL_1.fill = DOB c_FU_UBL_2.fill = Be c_FU_UBL_3.fill = SS c_FU_UBL_4.fill = Na_FU_FE p_FU_UBL = openmc.Universe(cells=[c_FU_UBL_1,c_FU_UBL_2,c_FU_UBL_3,c_FU_UBL_4])</pre>	Lower gas plenum		<pre># --- Lower gas plenum (LGP) c_FU_LGP1 = openmc.Cell(name='c_FU_LGP1') c_FU_LGP2 = openmc.Cell(name='c_FU_LGP2') c_FU_LGP3 = openmc.Cell(name='c_FU_LGP3') c_FU_LGP1.region = -cyl_Clad61_IN c_FU_LGP2.region = +cyl_Clad61_IN & -cyl_Clad61_OU c_FU_LGP3.region = +cyl_Clad61_OU c_FU_LGP1.fill = Be c_FU_LGP2.fill = SS c_FU_LGP3.fill = Na_FU_In p_FU_LGP = openmc.Universe(cells=[c_FU_LGP1,c_FU_LGP2,c_FU_LGP3])</pre>
Fuel		<pre># --- Fuel fissile (FIS) c_FU_FIS_0 = openmc.Cell(name='c_FU_FIS_0') c_FU_FIS_1 = openmc.Cell(name='c_FU_FIS_1') c_FU_FIS_2 = openmc.Cell(name='c_FU_FIS_2') c_FU_FIS_3 = openmc.Cell(name='c_FU_FIS_3') c_FU_FIS_4 = openmc.Cell(name='c_FU_FIS_4') c_FU_FIS_0.region = -cyl_FI_hole c_FU_FIS_1.region = +cyl_FI_hole & -cyl_FI_fuel c_FU_FIS_2.region = +cyl_FI_fuel & -cyl_Clad61_IN c_FU_FIS_3.region = +cyl_Clad61_IN & -cyl_Clad61_OU c_FU_FIS_4.region = +cyl_Clad61_OU c_FU_FIS_0.fill = Be c_FU_FIS_1.fill = DOF c_FU_FIS_2.fill = Be c_FU_FIS_3.fill = SS c_FU_FIS_4.fill = Na_FU_FI p_FU_FIS = openmc.Universe(cells=[c_FU_FIS_0,c_FU_FIS_1,c_FU_FIS_2,c_FU_FIS_3,c_FU_FIS_4])</pre>	Bottom end plug		<pre># --- Bottom end plug (BEP) c_FU_BEP1 = openmc.Cell(name='c_FU_BEP1') c_FU_BEP2 = openmc.Cell(name='c_FU_BEP2') c_FU_BEP1.region = -cyl_Clad61_OU c_FU_BEP2.region = +cyl_Clad61_OU c_FU_BEP1.fill = SS c_FU_BEP2.fill = Na_FU_In p_FU_BEP = openmc.Universe(cells=[c_FU_BEP1,c_FU_BEP2])</pre>
			Top end plug		<pre># --- Top end plug (TEP) c_FU_TEP1 = openmc.Cell(name='c_FU_TEP1') c_FU_TEP2 = openmc.Cell(name='c_FU_TEP2') c_FU_TEP1.region = -cyl_Clad61_OU c_FU_TEP2.region = +cyl_Clad61_OU c_FU_TEP1.fill = SS c_FU_TEP2.fill = Na_FU_Out p_FU_TEP = openmc.Universe(cells=[c_FU_TEP1,c_FU_TEP2])</pre>

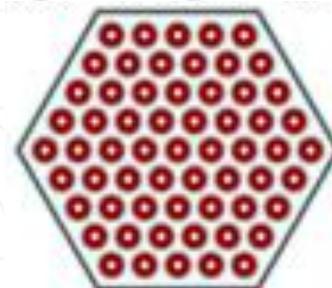
Example: Building the fuel SA geometry

Definition of the pin lattice

Benchmark specifications



OpenMC geometry



```
# -----
# --- Fuel fissile (FIS)
#
l_FU_FIS = openmc.HexLattice()
l_FU_FIS.orientation='x'
l_FU_FIS.center = [0., 0.]
l_FU_FIS.pitch  = [ 0.695]
l_FU_FIS.universes = \
    [ [p_FU_FIS]*24, [p_FU_FIS]*18, [p_FU_FIS]*12, [p_FU_FIS]*6, [p_FU_FIS] ]
l_FU_FIS.outer  = p_FU_NFI

c_l_FU_FIS_01 = openmc.Cell( name='c_l_FU_FIS_01')
c_l_FU_FIS_02 = openmc.Cell( name='c_l_FU_FIS_02')
c_l_FU_FIS_03 = openmc.Cell( name='c_l_FU_FIS_03')

c_l_FU_FIS_01.region = hex_WR_IN
c_l_FU_FIS_02.region = hex_WR_OU & ~hex_WR_IN
c_l_FU_FIS_03.region = ~hex_WR_OU

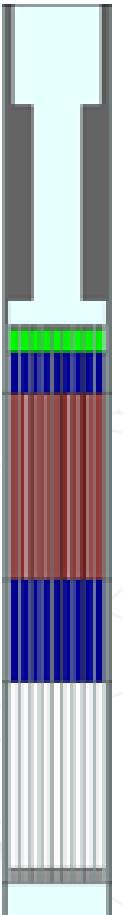
c_l_FU_FIS_01.fill = l_FU_FIS
c_l_FU_FIS_02.fill = Ti316
c_l_FU_FIS_03.fill = Na_FU_FI_bypass

u_FU_FIS = openmc.Universe()
u_FU_FIS.add_cells([c_l_FU_FIS_01, c_l_FU_FIS_02, c_l_FU_FIS_03])
```

Example: Building the fuel SA geometry

Building 3D fuel SA from 2D axial regions

a_FU



#	2D axial region		OpenMC input
	Content	Snapshot	
0	Outside		<pre>c_FU_OUT = openmc.Cell(name='c_FU_OUT') c_FU_OUT.region = +px_FUEL_HEA c_FU_OUT.fill = u_FU_HEA</pre>
1	Head		<pre>c_FU_HEA = openmc.Cell(name='c_FU_HEA') c_FU_HEA.region = -px_FUEL_HEA & +px_FUEL_USH c_FU_HEA.fill = u_FU_HEA</pre>
2	Upper shield		<pre>c_FU_USH = openmc.Cell(name='c_FU_USH') c_FU_USH.region = -px_FUEL_USH & +px_FUEL_UCN c_FU_USH.fill = u_FU_USH</pre>
3	Upper connector		<pre>c_FU_UCN = openmc.Cell(name='c_FU_UCN') c_FU_UCN.region = -px_FUEL_UCN & +px_FUEL_TEP c_FU_UCN.fill = u_FU_UCN</pre>
4	Top end plug		<pre>c_FU_TEP = openmc.Cell(name='c_FU_TEP') c_FU_TEP.region = -px_FUEL_TEP & +px_FUEL_SPR c_FU_TEP.fill = u_FU_TEP</pre>

#	2D axial region		OpenMC input
	Content	Snapshot	
5	Spring		<pre>c_FU_SPR = openmc.Cell(name='c_FU_SPR') c_FU_SPR.region = -px_FUEL_SPR & +px_FUEL_UBL c_FU_SPR.fill = u_FU_SPR</pre>
6	Upper blanket		<pre>c_FU_UBL = openmc.Cell(name='c_FU_UBL') c_FU_UBL.region = -px_FUEL_UBL & +px_FUEL_FIS c_FU_UBL.fill = u_FU_UBL</pre>
7	Fuel		<pre>c_FU_FIS = openmc.Cell(name='c_FU_FIS') c_FU_FIS.region = -px_FUEL_FIS & +px_FUEL_LBL c_FU_FIS.fill = u_FU_FIS</pre>
8	Lower blanket		<pre>c_FU_LBL = openmc.Cell(name='c_FU_LBL') c_FU_LBL.region = -px_FUEL_LBL & +px_FUEL_LGP c_FU_LBL.fill = u_FU_LBL</pre>
9	Lower gas plenum		<pre>c_FU_LGP = openmc.Cell(name='c_FU_LGP') c_FU_LGP.region = -px_FUEL_LGP & +px_FUEL_BEP c_FU_LGP.fill = u_FU_LGP</pre>
10	Bottom end plug		<pre>c_FU_BEP = openmc.Cell(name='c_FU_BEP') c_FU_BEP.region = -px_FUEL_BEP & +px_FUEL_LCN c_FU_BEP.fill = u_FU_BEP</pre>
11	Lower connector		<pre>c_FU_LCN = openmc.Cell(name='c_FU_LCN') c_FU_LCN.region = -px_FUEL_LCN c_FU_LCN.fill = u_FU_LCN</pre>
Merge			<pre>a_FU = openmc.Universe() a_FU.add_cells([c_FU_OUT,c_FU_HEA,c_FU_USH,c_FU_UCN,c_FU_TEP,c_FU_SPR c_FU_UBL,c_FU_FIS,c_FU_LBL,c_FU_LGP,c_FU_BEP,c_FU_LCN])</pre>

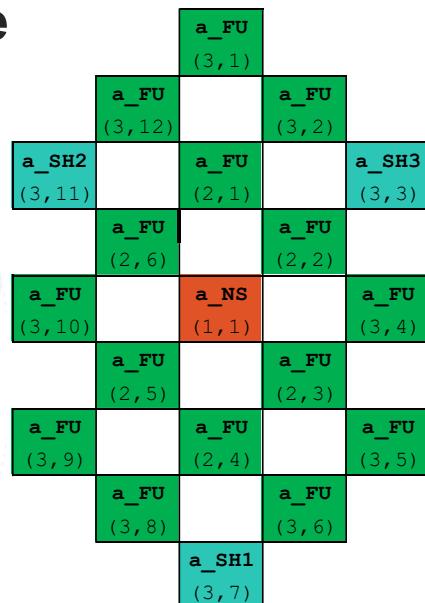
Example: Building the core

2 ways for a core arrangement

- SA in the same ring connect with '+', another ring are distinguished with ','
- Both are the same expression

Example 1)	<pre>l_core.universes = \ [[[a_FU]+[a_FU]+[a_SH3]+[a_FU]+[a_FU]+[a_FU]+[a_SH1]+[a_FU]+[a_FU]+[a_FU]+[a_SH2]+[a_FU],\n[a_FU]+[a_FU]+[a_FU] + [a_FU]+[a_FU]+[a_FU],\n[a_NS]]]</pre>
Example 2)	<pre>l_core.universes = \ [[[a_FU]*2 +[a_SH3] +[a_FU]*3 +[a_SH1] +[a_FU]*3 +[a_SH2] +[a_FU],\n[a_FU]*6,\n[a_NS]]]</pre>

Mini-core example



Run Parameters

- Inactive cycles**
- Active cycles**
- Neutron histories**

Start-up Tests I – Fuel Loading and Criticality

State of core

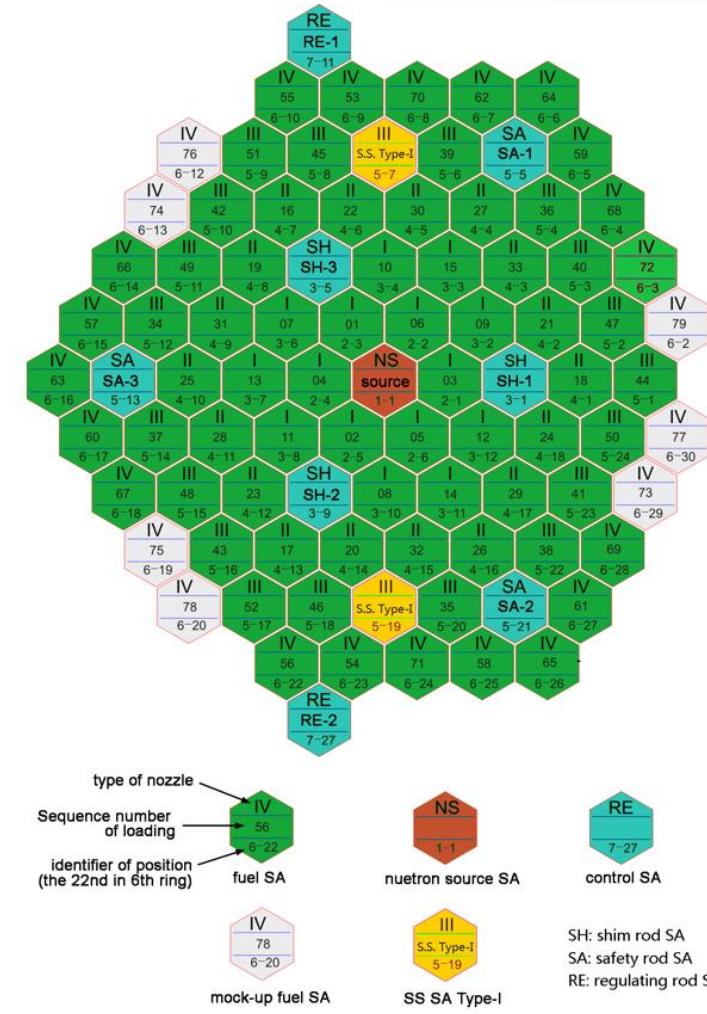
Target temperature	Cold state (250 °C)
Basic core layout	Clean core (72 fuel SAs + 2 SS SAs + 7 mock-up fuel SAs)
Control rod positions	RE2: variable RE1+3*SH+3*SA: out-of-core

Experimental process

- RE2 insertion to reach the criticality ($k_{\text{eff}} = 1.00000$)

Expected output

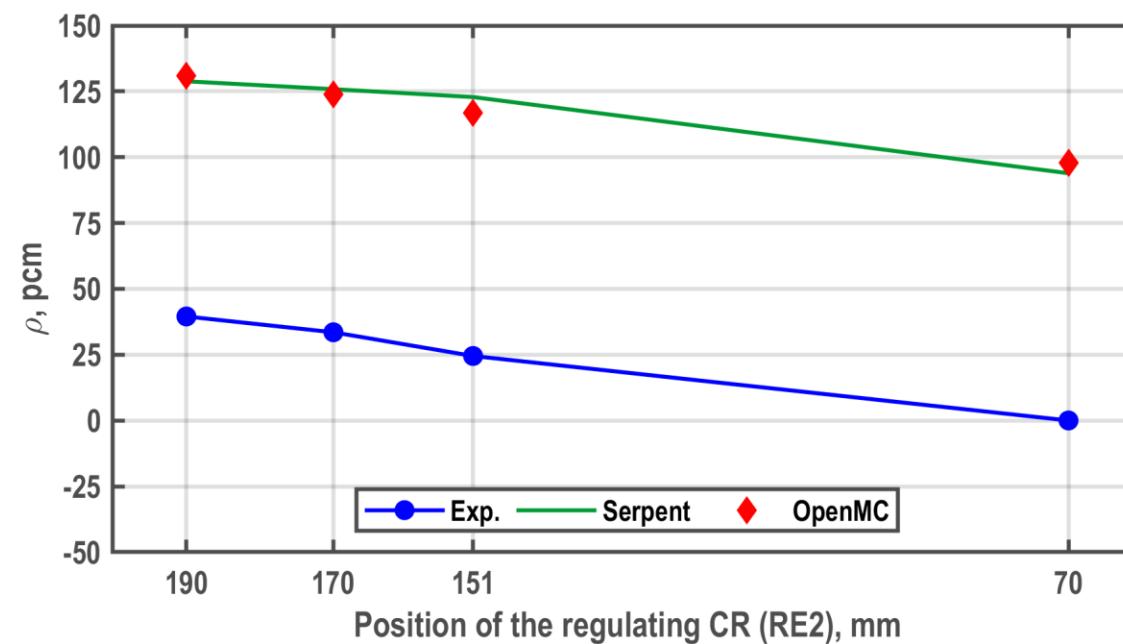
# of fuel SAs loaded	Rod position [mm]	Core state	k_{eff} (+std)
	Other 7 control rods	RE2	
72	Out-of-core	190	Supercritical
72	Out-of-core	170	Supercritical
72	Out-of-core	151	Supercritical
72	Out-of-core	70	Critical (Predicted)



Start-up Tests I – Fuel Loading and Criticality

First Criticality

RE2 position, mm	EXP		Serpent		OpenMC	
	ρ , pcm	ρ , pcm	1σ , pcm	ρ , pcm	1σ , pcm	
190	40	129	3	131	8	
170	34	126	3	124	8	
151	25	123	2	117	8	
70	0	94	3	98	8	



Start-up Tests II – Control rod Worth

State of core

Target temperature	Cold state (250 °C)
Basic core layout	Operation layout (79 fuel SAs)
Control rod positions	All: variable

Expected output – Integral Rod Worth

Rod	Control rod positions [mm]							
	RE1	RE2	SH1	SH2	SH3	SA1	SA2	SA3
RE1	Before	501	106	240	240	239	498	500
	After	-1	106	240	240	239	498	500
RE2	Before	106	499	240	240	239	498	500
	After	106	5	240	240	239	498	500
SH1	Before	240	240	501	141	141	498	499
	After	240	240	4	141	141	498	499
SH2	Before	239	240	151	498	151	498	500
	After	239	240	151	-1	151	498	500
SH3	Before	240	239	148	150	498	498	500
	After	240	239	148	150	7	498	500
SA1	Before	240	239	240	240	241	498	499
	After	240	239	240	240	241	46	499
SA2	Before	240	240	240	240	240	498	499
	After	240	239	240	240	240	498	55
SA3	Before	240	239	240	240	240	498	499
	After	240	239	240	240	240	498	40

$$\rho_{\text{rod}} = \frac{|k_{\text{eff}}^{\text{after}} - k_{\text{eff}}^{\text{before}}|}{k_{\text{eff}}^{\text{before}} \times k_{\text{eff}}^{\text{after}}} \times 10^5 [\text{pcm}]$$

where

ρ_{rod} : the integral rod worth

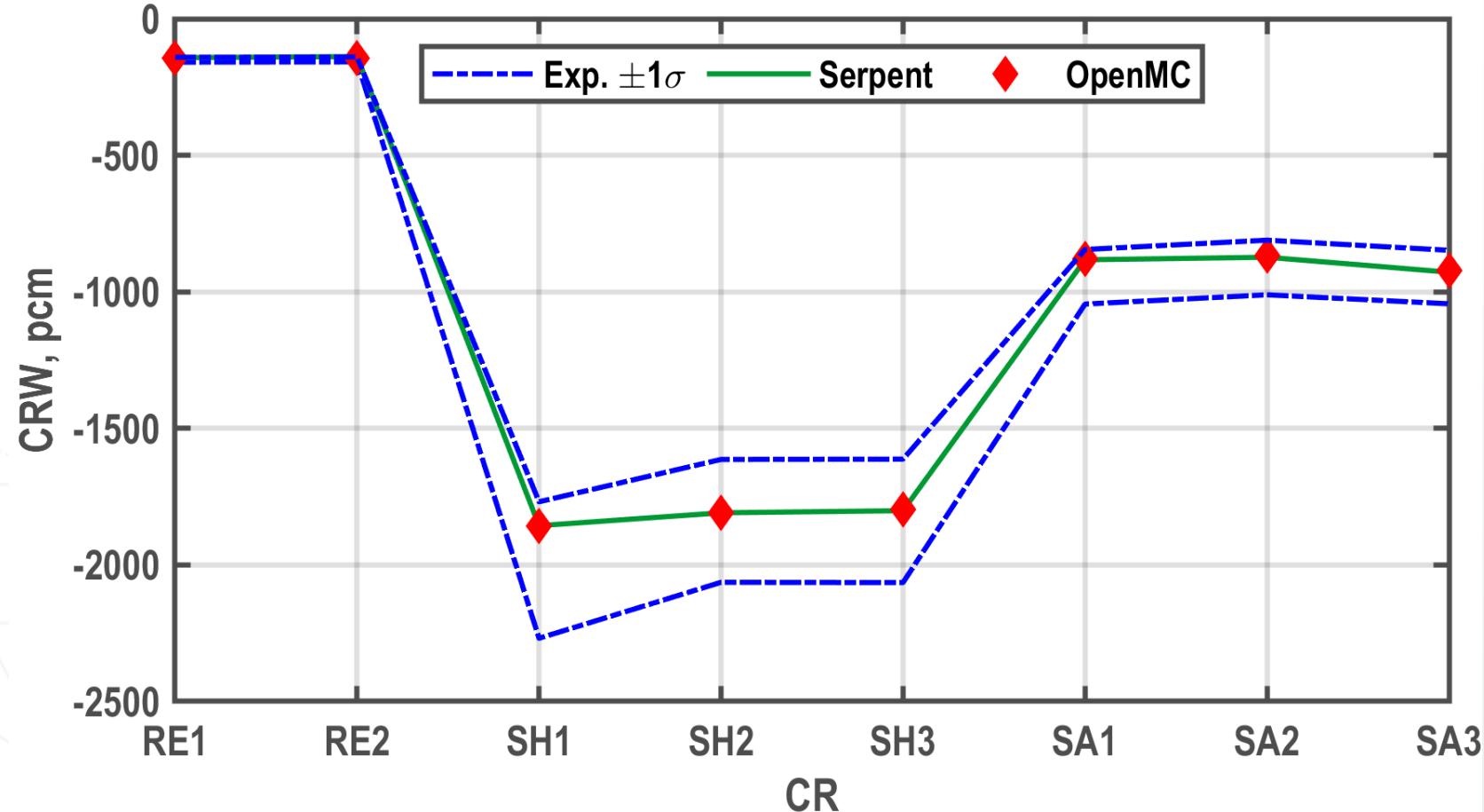
$k_{\text{eff}}^{\text{before}}$: k-eff before the rod drop

$k_{\text{eff}}^{\text{after}}$: k-eff after the rod drop

Start-up Tests II – Control rod Worth

CR	Position	Serpent		OpenMC		Serpent		OpenMC		EXP	
		k-eff	1σ	k-eff	1σ	CRW	1σ, pcm	CRW	1σ, pcm	CRW	1σ, pcm
RE1	OUT	1.00264	0.00002	1.00264	0.00008	-142	3	-144	11	-150	9
	IN	1.00121	0.00002	1.00119	0.00008	-	-	-	-	-	-
RE2	OUT	1.00263	0.00002	1.00265	0.00008	-138	3	-144	11	-149	9
	IN	1.00124	0.00002	1.00120	0.00008	-	-	-	-	-	-
SH1	OUT	1.00158	0.00002	1.00158	0.00008	-1857	3	-1859	11	-2019	250
	IN	0.98330	0.00002	0.98327	0.00008	-	-	-	-	-	-
SH2	OUT	1.00210	0.00002	1.00215	0.00008	-1809	3	-1810	11	-1839	225
	IN	0.98425	0.00002	0.98430	0.00008	-	-	-	-	-	-
SH3	OUT	1.00194	0.00002	1.00201	0.00008	-1802	3	-1798	11	-1839	226
	IN	0.98417	0.00002	0.98428	0.00008	-	-	-	-	-	-
SA1	OUT	1.00253	0.00002	1.00259	0.00008	-883	3	-880	11	-945	100
	IN	0.99374	0.00002	0.99382	0.00008	-	-	-	-	-	-
SA2	OUT	1.00250	0.00002	1.00252	0.00008	-873	3	-868	11	-911	100
	IN	0.99380	0.00002	0.99387	0.00008	-	-	-	-	-	-
SA3	OUT	1.00248	0.00002	1.00246	0.00008	-928	3	-923	11	-946	98
	IN	0.99324	0.00002	0.99327	0.00008	-	-	-	-	-	-

Start-up Tests II – Control rod Worth



Start-up Tests III – Sodium Void Reactivity

State of core

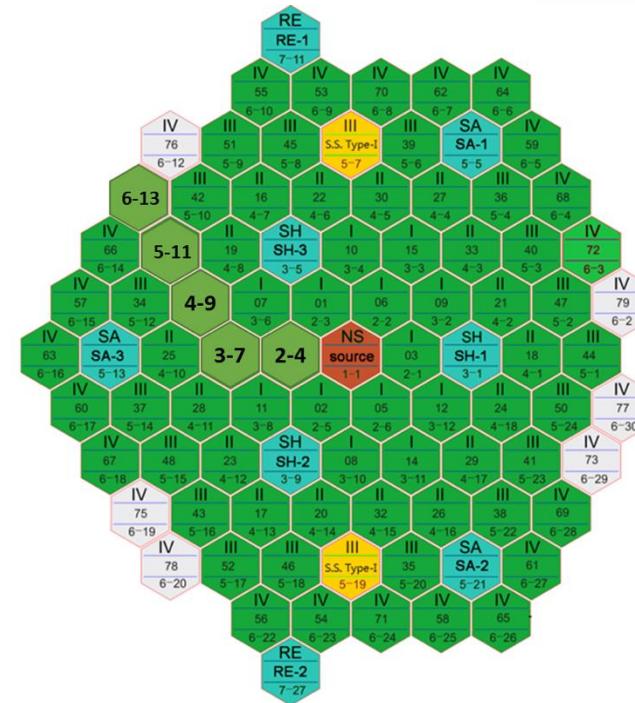
Target temperature	Cold state (250 °C)
Basic core layout	Operation layout (79 fuel SAs)
Control rod positions	All rods out (2*RE+3*SA+3* SH: out of core)

Experiment process

- Replacing a fuel SA with a ‘voided’ SA, which is vacuum sealed by welding

Expected output – Sodium void worth

Measurement position in core	Expected output	
	k-eff	Void reactivity
Operation State		
(2-4)		
(3-7)		
(4-9)		
(5-11)		
(6-13)		



where

$$\rho_{sv} = \frac{k_{eff}^{voided} - k_{eff}^{original}}{k_{eff}^{original} \times k_{eff}^{voided}} \times 10^5 \text{ [pcm]}$$

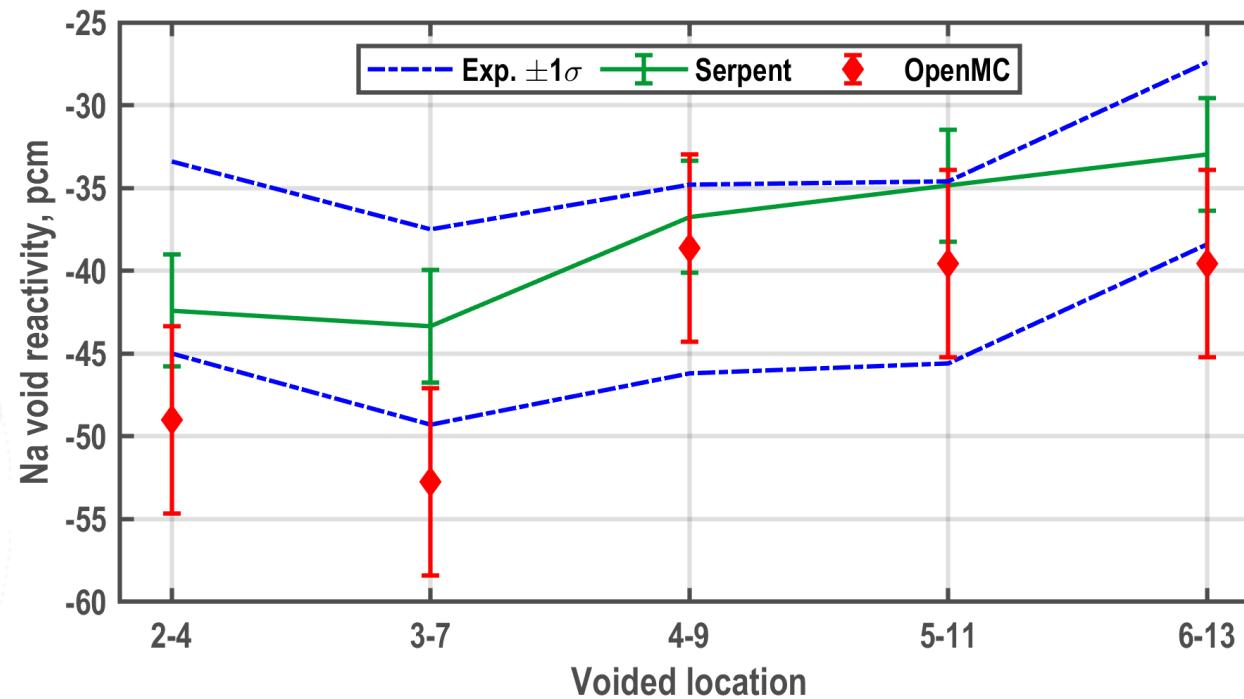
ρ_{sv} : the sodium void reactivity

$k_{eff}^{original}$: k-eff at the original core

k_{eff}^{voided} : k-eff by replacing the voided fuel SA

Start-up Tests III – Sodium Void Reactivity

Case	Serpent		OpenMC		Serpent		OpenMC		EXP	
	k-eff	1σ	k-eff	1σ	ρ, pcm	1σ, pcm	ρ, pcm	1σ, pcm	ρ, pcm	1σ, pcm
Ref	1.03043	0.00002	1.03046	0.00004	-	-	-	-	-	-
C2-4	1.02998	0.00002	1.02994	0.00004	-42.4	3.4	-49.0	5.7	-39.2	5.8
C3-7	1.02997	0.00002	1.02990	0.00004	-43.3	3.4	-52.8	5.7	-43.4	5.9
C4-9	1.03004	0.00002	1.03005	0.00004	-36.7	3.4	-38.6	5.7	-40.5	5.7
C5-11	1.03006	0.00002	1.03004	0.00004	-34.9	3.4	-39.6	5.7	-40.1	5.5
C6-13	1.03008	0.00002	1.03004	0.00004	-33.0	3.4	-39.6	5.7	-32.9	5.5



Application and Expansions

☒ TECDOC I - Start-up Tests

- ❑ Fuel loading and first criticality
- ❑ Calibration at cold state in operation loading
- ❑ Sodium void reactivity
- ❑ Rod swap reactivity
- ❑ Temperature coefficient
- ❑ Distribution of reaction rate

☒ TECDOC II – Extension Phase

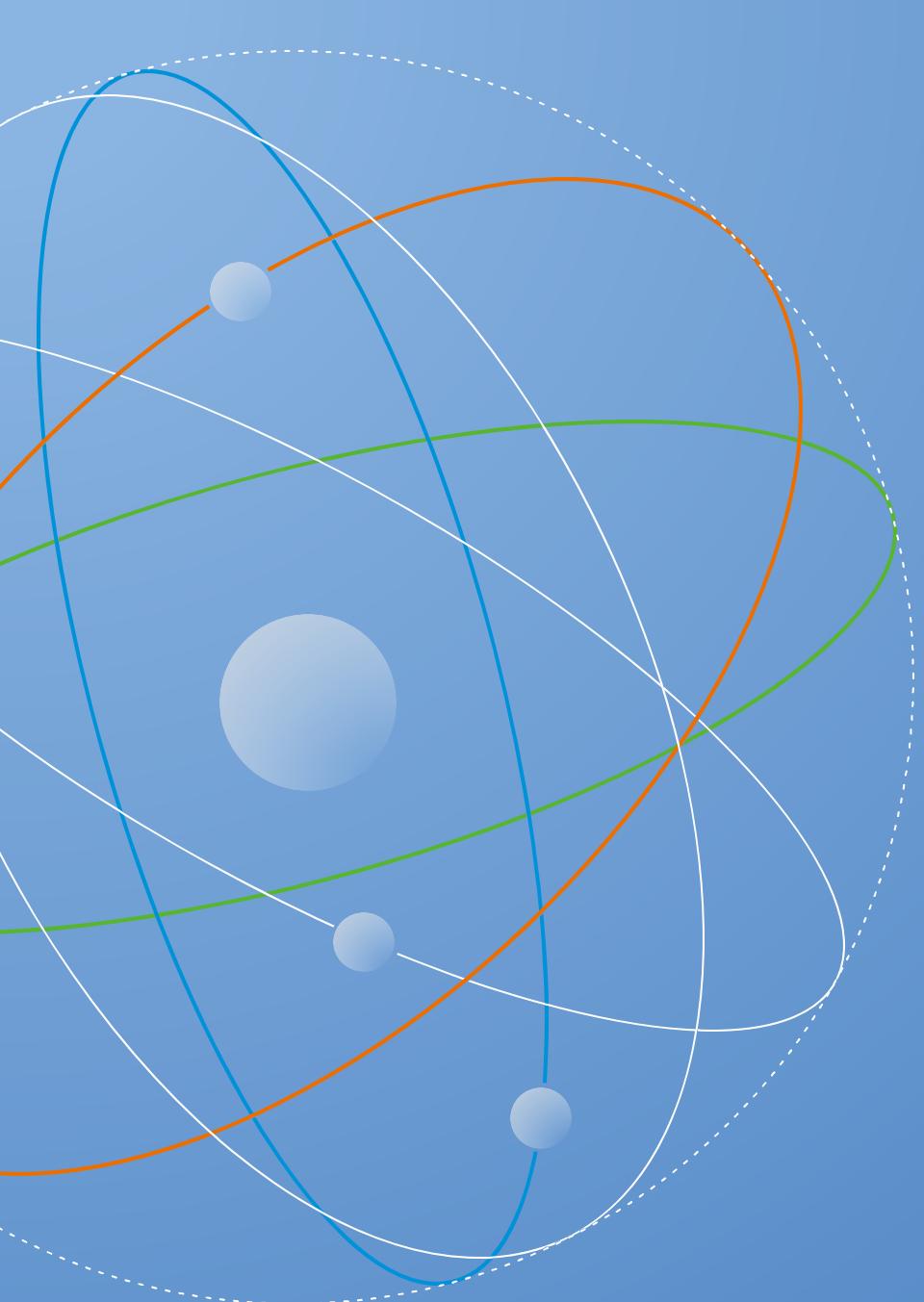
- ❑ Burn-up
- ❑ Deep Penetration
- ❑ Neutron Dynamics

☒ TCS

- ❑ Comparison or sensitivity test with your own modeling way

☒ Group Activity I

- ❑ <https://github.com/JIWONC-CORE/ictp-workshop>



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THANK YOU