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Original Article

Definition of the neutronics benchmark of the NuScale-like core

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ABSTRACT

This paper defines a 3D full core neutronics benchmark which is based on the NuScale small modular reactor (SMR) concept. The paper provides a detailed description of the NuScale-like core, a list of expected outputs, and a reference solution to the benchmark exercises obtained with the Monte Carlo code Serpent.

The benchmark was developed in the framework of the Euratom McSAFER project and can be used for verification of computational chains dedicated to 3D full-core neutronics simulations of water cooled SMRs.

The paper is supplemented with a digital data set to ease the modeling process.

1. Introduction

Nowadays, there is growing interest in small modular reactors (SMRs) as a potential source of low-carbon energy.

The McSAFER is a 3-year H2020 Euratom project launched in September 2020. The project aims at improving safety analysis methodologies for SMRs by employing high-fidelity Monte Carlo (MC) based multi-physics reactor analysis tools developed in the preceding European projects NURESAFE [1], HPMC [2] and McSAFE [3]. One of the important tasks of McSAFER is to compare the performance of these high-fidelity tools and "traditional" diffusion-based methods as applied to transient analysis of different light water-cooled SMRs.

The comparison between different computational chains is performed in a stepwise manner by gradually increasing the complexity of the simulated cases. The performance assessment comprises static neutronic calculations, steady-state coupled neutronics/TH analyses, and finally, coupled neutron-kinetics/thermal-hydraulic (TH) simulations of selected reactivity-initiated transients (RIA).

In order to conduct fair comparisons between various computational chains and different partners of the project, fairly detailed and fixed specifications must be provided for each of the reactor concepts. Since all reactor concepts considered in McSAFER are developed as commercial enterprises, not all relevant information is publicly available. From the point of view of the goals of the McSAFER project, the existence of fixed specifications is more important than the exact details of the specifications, meaning that expert judgement can well be applied in determining suitable values for missing data.

One of the SMR concepts considered in McSAFER is the NuScale design developed by NuScale Power LLC. It is one of the most mature SMR designs and is the first one to be certified for use in the United States by the U.S. Nuclear Regulatory Commission [4]. In a nutshell, NuScale is an integrated Pressurized Water Reactor (PWR) concept with reactor vessel, pressurizer, and helical steam generators placed inside a compact containment vessel. The primary coolant system is pump-free with a coolant flow driven by natural circulation. The expected power output is equal to 160 MWth or 50 MWe. Nevertheless, the future license applications foresee power uprates up to 250 MWth or 77 MWe.

This document presents an exhaustive description of the NuScale-like core which is used for the benchmarking of the static neutronic methods within the McSAFER project. The description comprises detailed fuel and core geometries, explicit material compositions, and imposed operating conditions. A list of the benchmark exercises used is also included. The provided data is sufficient to reproduce the calculations performed within the relevant tasks of the McSAFER projects.

The presented benchmark can be used for code-to-code

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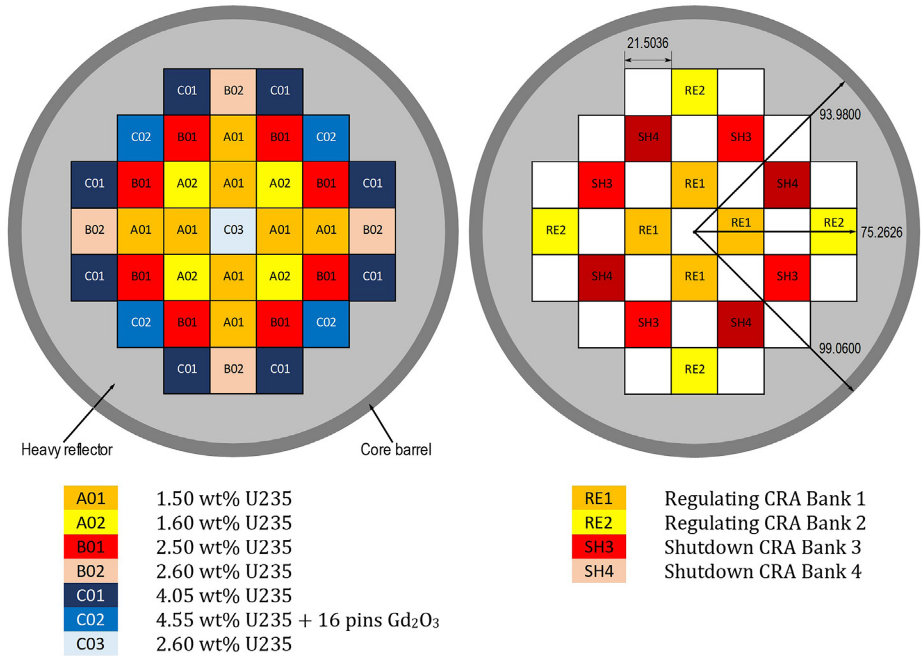


Fig. 1. Core loading pattern and control rod assembly locations. All dimensions are in cm.

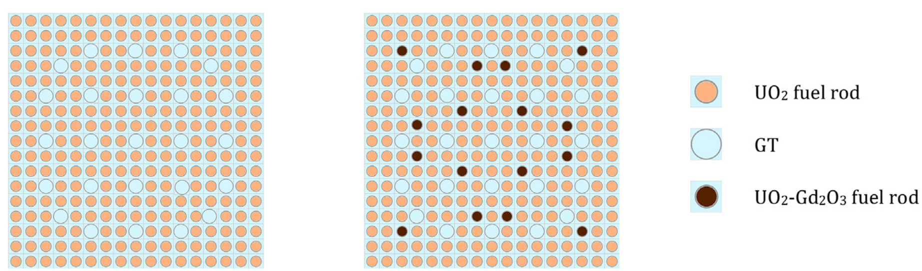


Fig. 2. Radial layouts of fuel assemblies: un-poisoned (left) and poisoned (right).

comparison verification of the neutronic tools and computational procedures intended for SMR applications. To facilitate the comparison, the paper provides a reference solution to the benchmark exercises obtained using the Monte Carlo code Serpent.

To ease the modeling process, this paper is supplemented with a digital data set hosted online at the HZDR data repository website [5].[1] The digital data includes:

– Spreadsheet with operational data and material compositions,
– Spreadsheet with the reference Serpent solution

2. Benchmark specifications

This benchmark is devoted to static neutronics calculations of the NuScale core in its initial Beginning of Life (BOL) state. Depletion analysis and Xe/Sm poisoning modeling are not foreseen. The following sub-sections contain all necessary information required for the neutronic modeling including:

– Fuel loading pattern and location of control rod assemblies (CRAs) within the core
– Radial and axial layouts of all core components and their relevant dimensions
– Imposed operating temperatures required to select appropriate temperature dependent cross section data or to activate suitable temperature treatment
– Description of materials comprising the core and their detailed isotopic compositions

The provided NuScale core specifications are primarily derived from a public version of the Final Safety Analysis Report (FSAR) submitted to the US Nuclear Regulatory Commission (NRC) as a part of the Design Certification Application [6].

It should be noted, however, that several important design parameters are not provided in the public FSAR version and required making educated guesses and introducing simplifications for their determination. Among others this includes mimicking the equilibrium core loading by fresh fuel with variable U-235 enrichment, arbitrary positioning of poisoned fuel assemblies, and simplification of the radial heavy reflector design. Dimensions are not adjusted for thermal expansion in this benchmark.

2.1. Radial core layout

The radial layout of the initial NuScale core is shown in Fig. 1. The core is loaded with 37 all-fresh no-Xe UO_2 fuel assemblies at six

[1] http://doi.org/10.14278/rodare.2024

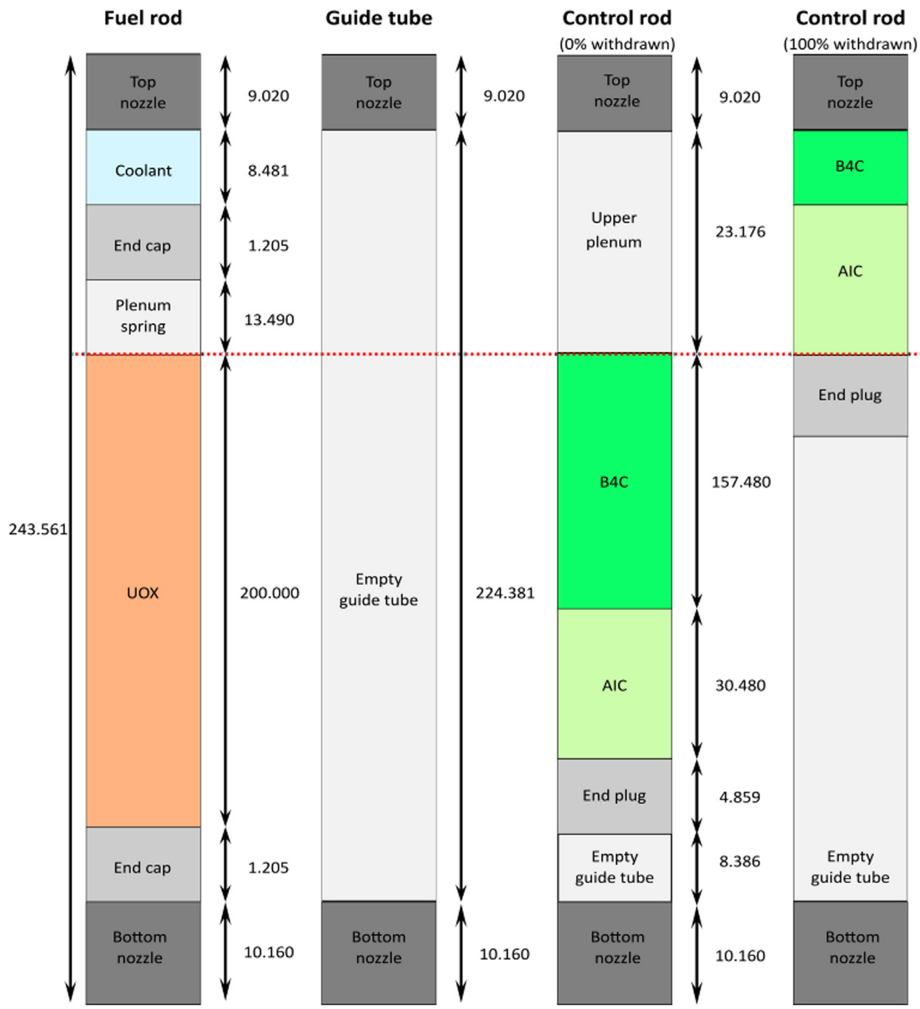
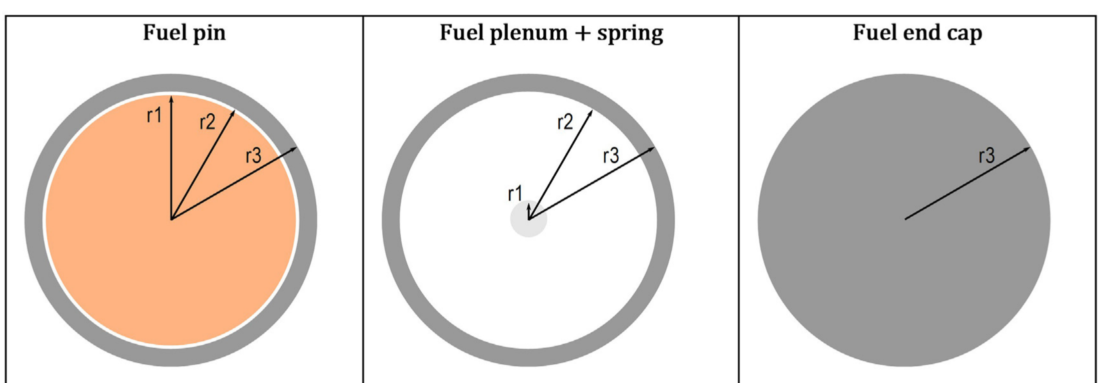
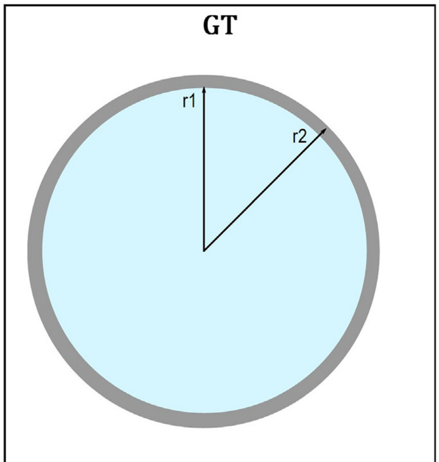


Fig. 3. Axial structure and axial alignment of the different components of the NuScale core. All dimensions are in “cm”.



Region	Material	r, cm	Material	r, cm	Material	r, cm
r1	Fuel	0.4058	Inconel	0.0646	-	-
r2	He	0.4140	He	0.4140	-	-
r3	Zr-4	0.4750	Zr-4	0.4750	Zr-4	0.4750

Fig. 4. Radial pin-cells forming up the fuel rod.



Region	Material	r, cm
r1	Coolant	0.5715
r2	Zr-4	0.6121

Fig. 5. Radial pin-cell forming up the empty GT.

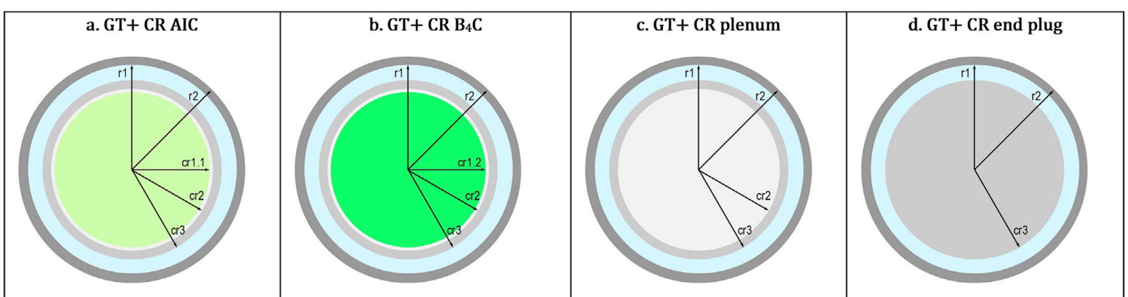
Table 1
Axial positions of spacer grids.

SG	Type	Position	H, cm
SG5	HTP	Top	223.581
		Bottom	219.136
SG4	HTP	Top	172.527
		Bottom	168.082
SG3	HTP	Top	121.473
		Bottom	117.028
SG2	HTP	Top	70.419
		Bottom	65.974
SG1	HMP	Top	19.365
		Bottom	14.920

different U-235 enrichment levels, which were adjusted to approximate batch-wise U-235 content at the beginning of the equilibrium fuel cycle. Four fuel assemblies contain 16 fuel pins with Gd_2O_3 burnable poison (Fig. 1, left). In total, there are 7 different fuel assembly types.

The core is regulated and controlled by 16 control rod assemblies (CRA) divided into two regulating (RE) and two shutdown (SH) banks as shown in the right panel of Fig. 1.

The core is surrounded by a heavy steel reflector and bounded by a cylindrical core barrel. The inner and outer radii of the core barrel are shown in Fig. 1, right. In reality, the heavy reflector



Region	Material	r, cm	Material	r, cm	Material	r, cm	Material	r, cm
r1	Coolant	0.5715	Coolant	0.5715	Coolant	0.5715	Coolant	0.5715
r2	Zr-4	0.6121	Zr-4	0.6121	Zr-4	0.6121	Zr-4	0.6121
cr1.1	AIC	0.4267	-	-	-	-	-	-
cr1.2	-	-	B_4C	0.4229	-	-	-	-
cr2	He	0.4369	He	0.4369	He	0.4369	-	-
cr3	304 SS	0.4839	304 SS	0.4839	304 SS	0.4839	304 SS	0.4839

Fig. 6. Radial pin-cells forming up the CR: a) GT filled with AIC absorber, b) GT filled with B_4C absorber, c) GT filled with CR plenum d) GT filled with CR end plug.

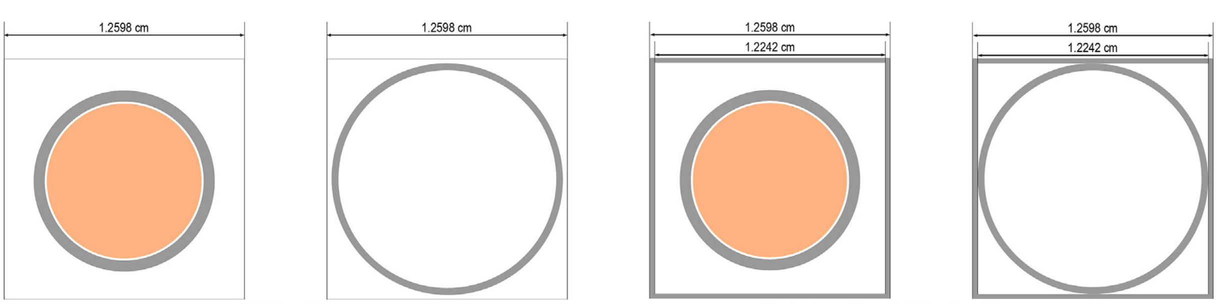


Fig. 7. Modification to be made to pin cells when spacer grid is present.

Table 2
Materials to be used for different parts of the NuScale core model.

Part	Material
Fuel pellets	UO_2 or UO_2+$Gd2O_3$
Fuel rod cladding	Zr-4 (replaces M5®)
Fuel rod plenum springs	Inconel
Fuel rod lower end cap	Zr-4
Fuel rod upper end cap	Zr-4
Coolant	H_2O with 1000 ppm boron
Guide tube	Zr-4
HMP™ spacer grid	Inconel
HTP™ spacer grid	Zr-4
Control rod absorber	AIC or B_4C
Control rod cladding	304L stainless steel (SS)
Control rod upper end plug	304L SS
Control rod bottom plug	304L SS
Core barrel	304L SS

comprises coolant channels required to cope with gamma heating. However, actual dimensions and locations of the coolant channels are not available in the FSAR. Therefore, the radial heavy reflector is modelled in a simplified manner as a homogeneous mixture of steel and water.

2.2. Radial layouts of fuel assemblies

All fuel assemblies, utilized in NuScale, have a typical 17×17 lattice. The fuel rod pitch inside the assembly is 1.2598 cm. The fuel assembly pitch inside the core is 21.5036 cm. It should be noted that the resulting inter-assembly gap is explicitly modeled.

All fuel assemblies listed in the left panel of Fig. 1, except the C02 type, do not contain any burnable poison (BP). These fuel assemblies comprise 264 fuel rods and 24 guide tubes (GT) into which control rods can be inserted. In addition, the assemblies contain a central instrumentation tube, which is modelled as an empty guide tube in this benchmark. The locations of fuel rods and GTs is shown in Fig. 2, left.

To cope with initial excess reactivity, some fuel assemblies are loaded with integral burnable poison (BP) in the form of a homogeneous mixture of UO_2 and gadolinia (Gd_2O_3). However, the actual BP configuration is not publicly available (e.g. amount of gadolinia, number of BP pins per fuel assembly, BP location within fuel assembly, etc.). In this benchmark, it was assumed that the fuel assemblies with the highest U-235 enrichment (the C02 type) contain 16 gadolinia BP rods. The placement of BP in fuel assemblies of the C02 type is shown in Fig. 2, right.

Table 4
Nuclide compositions of coolant with 1000 ppm boron. Units: 1/(barn·cm).

Nuclide	ND
H-1	5.02932E-02
O-16	2.51573E-02
B-10	8.33778E-06
B-11	3.35608E-05

2.3. Axial and radial structures of fuel rods, guide tubes, and control rods

Axial structure and axial dimensions of fuel rods, GTs, and CRs are presented in Fig. 3. In this figure, the fuel rod and CR are also aligned axially, showing their axial positions relative to each other at fully withdrawn and fully inserted states. The following assumptions and simplifications should be taken into account:

- The fuel rod is constructed as a combination of three different heterogeneous pin-cells: the fuel, the plenum, and the end cap. These pin cells are defined in Fig. 4 including radial dimensions and comprising materials. A detailed isotopic composition of every material is provided in Section 2.5.
- In Fig. 3, the “coolant” region above the end cap of the fuel rod contains homogeneous coolant only as specified in Section 2.5.
- The bottom and top nozzle parts of fuel assemblies are modelled as homogeneous mixtures of steel and coolant as specified in Table 7.
- The bottom and top nozzles constitute axial boundaries of the core.
- According to the FSAR, the active fuel region is surrounded by lower and upper blankets. Due to lacking data on exact fuel and blanket enrichment and absorber fuel gadolinia content, suitable fuel compositions had to be designed manually. To simplify this process, the upper and lower blanket regions of the fuel stacks are replaced with the normal fuel composition. In effect, the whole fuel stack height of 200 cm is composed of a single material for a specific fuel rod type.
- In reality, the lower region of the guide tubes has a narrower structure (dashpot) intended for slowing down the CR. This dashpot region has been removed from this specification. Instead, the same (above dashpot) width is used for the guide tubes throughout their whole length. In effect, the guide tube diameter stays constant throughout its axial length. The radial pin-cell geometry of the empty GT is specified in Fig. 5.

Table 3
Nuclide compositions of all fuel types. Units: 1/(barn·cm).

Nuclide	Fuel type					
	A01	A02	B01	B02/C03	C01	C02
	ND	ND	ND	ND	ND	ND
U-235	3.56456E-04	3.80219E-04	5.94084E-04	6.17846E-04	9.62391E-04	9.61347E-04
U-238	2.31116E-02	2.30881E-02	2.28766E-02	2.28531E-02	2.25123E-02	1.99124E-02
O-16	4.69361E-02	4.69367E-02	4.69414E-02	4.69419E-02	4.69495E-02	4.58016E-02
Gd-152						5.40541E-06
Gd-154						5.89189E-05
Gd-155						4.00000E-04
Gd-156						5.53243E-04
Gd-157						4.22973E-04
Gd-158						6.71352E-04
Gd-160						5.90811E-04

Table 5
Nuclide compositions of Zr-4, Inconel, and stainless steel 340L SS. Units: 1/(barn·cm).

Zr-4		Inconel		304L SS	
Nuclide	ND	Nuclide	ND	Nuclide	ND
Cr-50	3.29620E-06	Cr-50	7.82390E-04	Cr-50	7.67780E-04
Cr-52	6.35640E-05	Cr-52	1.50880E-02	Cr-52	1.48060E-02
Cr-53	7.20760E-06	Cr-53	1.71080E-03	Cr-53	1.67890E-03
Cr-54	1.79410E-06	Cr-54	4.25860E-04	Cr-54	4.17910E-04
Fe-54	8.66980E-06	Fe-54	1.47970E-03	Fe-54	3.46200E-03
Fe-56	1.36100E-04	Fe-56	2.32290E-02	Fe-56	5.43450E-02
Fe-57	3.14310E-06	Fe-57	5.36450E-04	Fe-57	1.25510E-03
Fe-58	4.18290E-07	Fe-58	7.13920E-05	Fe-58	1.67030E-04
O-16	3.07440E-04	Mn-55	7.82010E-04	Mn-55	1.76040E-03
O-17	1.16800E-07	Ni-58	2.93200E-02	Ni-58	5.60890E-03
Sn-112	4.67350E-06	Ni-60	1.12940E-02	Ni-60	2.16050E-03
Sn-114	3.17990E-06	Ni-61	4.90940E-04	Ni-61	9.39170E-05
Sn-115	1.63810E-06	Ni-62	1.56530E-03	Ni-62	2.99450E-04
Sn-116	7.00550E-05	Ni-64	3.98640E-04	Ni-64	7.62610E-05
Sn-117	3.70030E-05	Si-28	5.67570E-04	Si-28	9.52810E-04
Sn-118	1.16690E-04	Si-29	2.88200E-05	Si-29	4.83810E-05
Sn-119	4.13870E-05	Si-30	1.89980E-05	Si-30	3.18930E-05
Sn-120	1.56970E-04				
Sn-122	2.23080E-05				
Sn-124	2.78970E-05				
Zr-90	2.18280E-02				
Zr-91	4.76010E-03				
Zr-92	7.27590E-03				
Zr-94	7.37340E-03				
Zr-96	1.18790E-03				

Table 6
Nuclide compositions of control rod absorber materials and of fill gas. Units: 1/(barn·cm).

AIC (80-15-5)		B4C		Helium	
Nuclide	ND	Nuclide	ND	Nuclide	ND
Ag-107	2.35230E-02	B-10	1.52060E-02	He-3	4.80890E-10
Ag-109	2.18540E-02	B-11	6.15140E-02	He-4	2.40440E-04
Cd-106	3.38820E-05	C-12	1.89720E-02		
Cd-108	2.41660E-05	C-13	2.12520E-04		
Cd-110	3.39360E-04				
Cd-111	3.48210E-04				
Cd-112	6.56110E-04				
Cd-113	3.32750E-04				
Cd-114	7.82520E-04				
Cd-116	2.04430E-04				
In-113	3.42190E-04				
In-115	7.65110E-03				

Table 7
Compositions of homogeneous mixtures.

Homogeneous mixture	Constituents	Volume fraction
Heavy reflector	304L SS	0.956
	Coolant	0.044
Bottom nozzle	304L SS	0.172
	Coolant	0.828
Top nozzle	304L SS	0.177
	Coolant	0.823

Table 8
Operating conditions applied to neutronics benchmark.

Parameter	Value	Comments
Power	160 MW	
Uniform fuel temperature	900 K	
Uniform coolant temperature	600 K	
Soluble boron content	1000 ppm	Composition: see Table 4
Uniform structures temperature	600 K	
Initial CR position	100% withdrawal	Axial layouts: see Fig. 3

– Axially, the CRs comprise B_4C and Ag-In-Cd (AIC) absorber regions as well as a plenum part and end plug part. In reality, the lower AIC region of the CRs is further divided into a solid AIC part and an annular AIC tip. Due to the lack of publicly available information on the exact geometry of the annular AIC tip, the annular part is replaced with a solid AIC part. The four pin cells forming up the CR are defined in Fig. 6.

2.4. Grid spacers

The fuel assemblies have two different spacer grid (SG) types, the more numerous HTP^{TM} spacer made of Zircaloy 4 and the bottommost HMP^{TM} spacer grid made of Alloy 718 (Inconel). The exact grid spacer mass and geometry are not publicly known so a simplified approach is used in the benchmark. In particular, each pin-cell in the fuel assembly lattice (Fig. 2) is replaced with a spacer grid pin-cell shown in Fig. 7. In this benchmark the height of the SGs is equal to 4.445 cm. The axial positions of spacer grids are listed in Table 1.

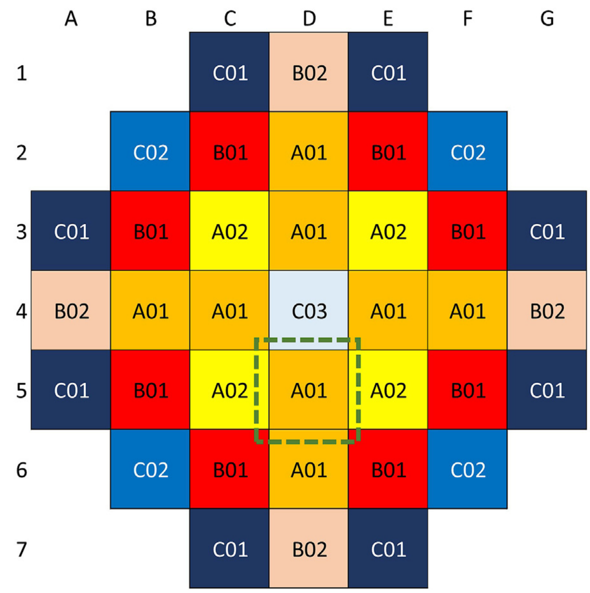


Fig. 8. Location of the asymmetrically inserted RE1 CR.

Table 9
Summary of the integral core parameters.

Core state	k-eff	$\sigma_{k\text{-eff}}$	CRW, pcm	σ_{CRW}, pcm
Reference (all rods out)	1.02768	0.00001	n/a	n/a
RE1 in	1.00723	0.00001	-1975	2
RE2 in	1.00313	0.00001	-2381	2
SH3 in	0.98978	0.00001	-3726	2
SH4 in	0.98971	0.00001	-3733	2
All rods in (SCRAM)	0.85791	0.00002	-19255	2

2.5. Materials

A summary of the materials to be used for the different parts of the NuScale model is given in Table 2. The volume fractions for regions modelled as homogeneous mixtures are listed in Table 7. The compositions for different materials are listed in Table 3.

Table 4, Table 5, and Table 6. All material compositions are provided as number densities (ND) to facilitate the modeling and to avoid any misinterpretations.

It worth mentioning that isotopic compositions of Zr-4, Inconel, AIC, B_4C, and 304L SS were adopted from the BEAVRS benchmark specifications [7].

2.6. Operating conditions

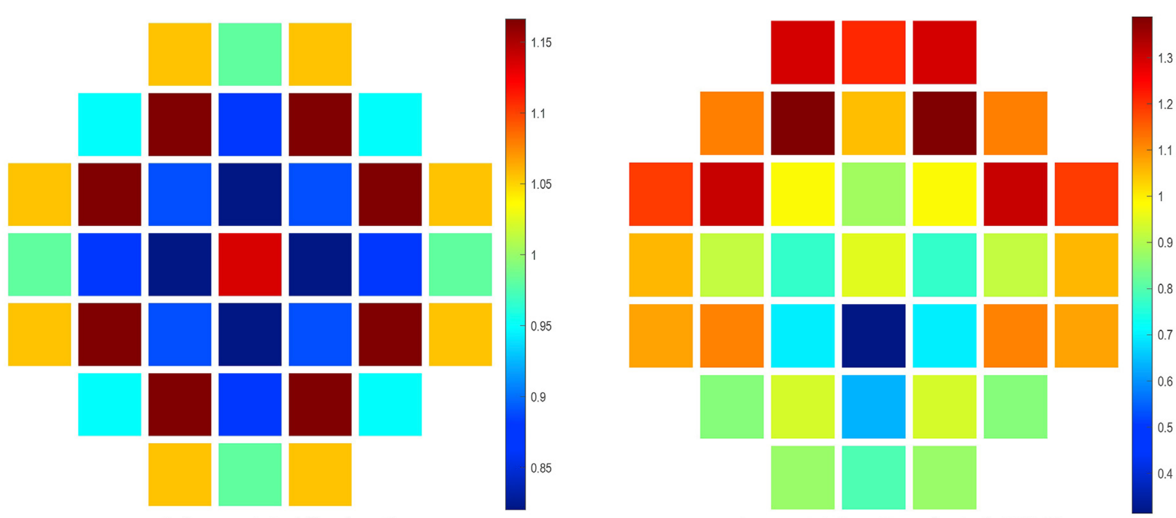
Table 8 summarizes fixed operating conditions used in this benchmark.

3. Expected results and reference Serpent Monte Carlo solution

3.1. Expected results

The following outputs are suggested for a consistent comparison of various computational approaches:

– K-eff
– CRA reactivity worth
  o Separate CRA banks (i.e. RE1, RE2, SH3, and SH4)
  o Reactivity worth of all CRA banks combined (SCRAM)
– Normalized radial power distribution
  o Reference case
  o Asymmetric insertion of a single RE1 CR at location D5 as shown in Fig. 8.
– Radial pin power distribution in Watts
  o Reference case



Reference state (all rods out) Asymmetric insertion of a single RE1 CR

Fig. 9. Normalized radial power distribution.

Table 10
Normalized radial power distribution values.

–	Reference state (all rods out)							–	Asymmetric insertion of a single RE1 CR						
	A	**B**	**C**	**D**	**E**	**F**	**G**		**A**	**B**	**C**	**D**	**E**	**F**	**G**
1			1.0561	0.9810	1.0561			**1**			1.2977	1.2093	1.2977		
2		0.9507	1.1662	0.8803	1.1662	0.9507		**2**		1.1187	1.3869	1.0481	1.3869	1.1187	
3	1.0561	1.1662	0.8893	0.8200	0.8893	1.1662	1.0561	**3**	1.1907	1.3098	0.9766	0.8798	0.9766	1.3098	1.1907
4	0.9810	0.8803	0.8200	1.1362	0.8200	0.8803	0.9810	**4**	1.0575	0.9152	0.7681	0.9498	0.7681	0.9152	1.0575
5	1.0561	1.1662	0.8893	0.8200	0.8893	1.1662	1.0561	**5**	1.0807	1.1152	0.6995	0.3138	0.6995	1.1152	1.0807
6		0.9507	1.1662	0.8803	1.1662	0.9507		**6**		0.8544	0.9380	0.6363	0.9380	0.8544	
7			1.0561	0.9810	1.0561			**7**			0.8742	0.7962	0.8742		

Table 11
Axial power profile.

Lower boundary, cm	Upper boundary, cm	Power, MW
11.365	14.920	0.6553
14.920	19.365	0.9182
19.365	31.017	4.1540
31.017	42.670	6.3682
42.670	54.322	8.3573
54.322	65.974	10.0322
65.974	70.419	4.0497
70.419	82.071	11.9449
82.071	93.724	12.9909
93.724	105.376	13.5872
105.376	117.028	13.7097
117.028	121.473	4.9838
121.473	133.125	13.3353
133.125	144.778	12.6828
144.778	156.430	11.5780
156.430	168.082	10.0769
168.082	172.527	3.2594
172.527	182.236	6.4714
182.236	191.946	5.1145
191.946	201.656	3.6038
201.656	211.365	2.1263
Total:		**160.000**

o Asymmetric insertion of a single RE1 CR at location D5 as shown in Fig. 8.
– Axial power profile in MW units for the reference case

3.2. Reference Serpent Monte Carlo solution

This sub-section summarizes the results of the neutronics benchmark of the NuScale-like core obtained with the Serpent Monte Carlo. These results can be used for verification of deterministic computational chains applied and for cross comparisons with other Monte Carlo codes. These results are also available as digital data set at the HZDR data repository website [5]. The full-core Serpent simulation were executed using the following options:

– Serpent version 2.2.0
– ENDF/B-VII.1 based nuclear data library
– Enabled unresolved resonance probability table sampling
– Application of the thermal scattering law (i.e. S(α,β)) to hydrogen in coolant
– Disabled Doppler-broadening rejection correction (DBRC)
– No gamma-smearing i.e. fission energy is deposited locally at fission sites
– 200 inactive cycles, 2500 active cycles, and 1,000,000 neutron histories per cycle

All radial power distributions and the radially averaged axial power profile were obtained by the averaging the results of the 10 independent Serpent calculations. The integral core parameters including k-eff, control rod worth (CRW) of separate CRA banks, and total SCRAM worth are summarized in Table 9. The normalized radial power distributions in the "all rods out" case and in the case of asymmetric insertion of a single RE1 CR shown are visualized in Fig. 9. The corresponding numerical values are provided in Table 10. The axial power values are provided in Table 11 along with the recommended axial meshing accounting for the locations of SGs. Every axial power value is calculated as a sum over all radial nodes in a corresponding axial layer. The axial power profile is shown in Fig. 10. The pin-power distributions in the reference and rodded cases are visualized in Fig. 11. Due to the space considerations, the corresponding numerical values are provided in the digital data set only.

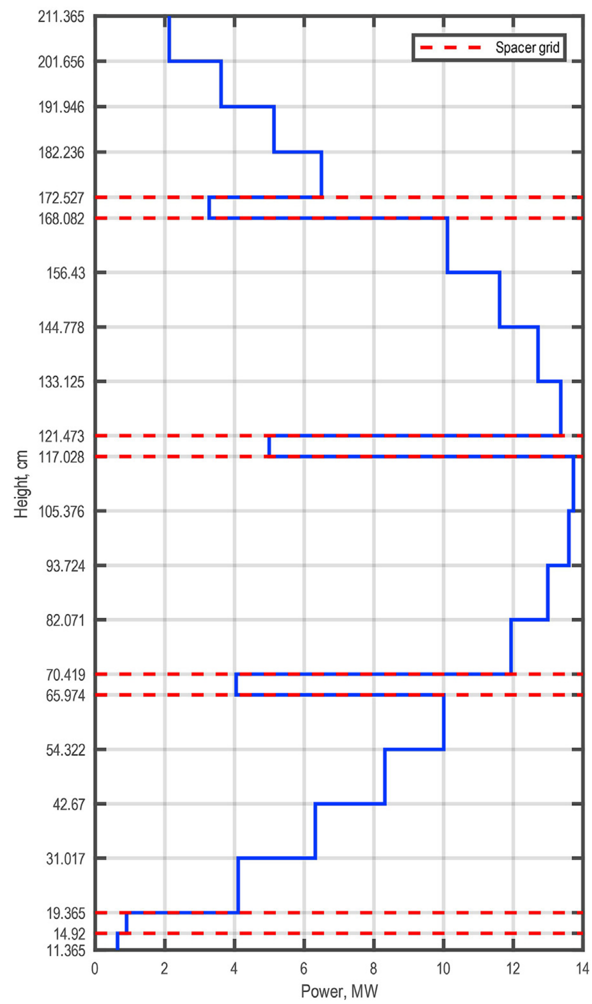
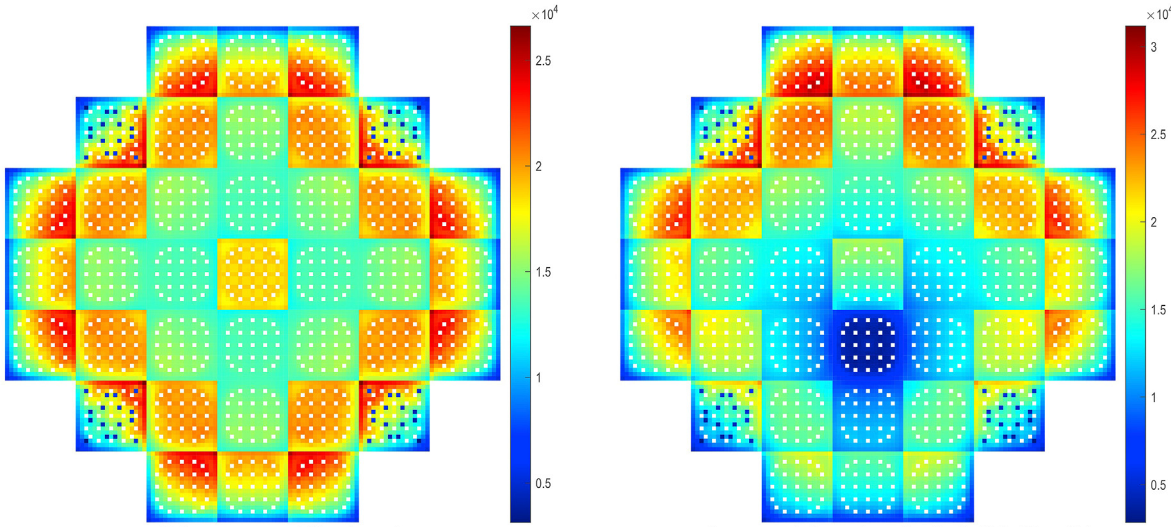


Fig. 10. Radially average axial power distribution in MW.



Reference state (all rods out) Asymmetric insertion of a single RE1 CR at D5

Fig. 11. Radial pin-power distribution in Watts.

4. Summary and conclusions

This paper presented a 3D full core neutronics benchmark which is based on the NuScale SMR concept. The paper included a detail description of the NuScale-like core, a list of expected outputs, and a reference solution to the benchmark exercises obtained with the Monte Carlo code Serpent. The proposed benchmark can be used for verification of the computational chains dedicated to 3D full-core neutronics simulations of water cooled SMRs. The benchmark is already being employed at HZDR and VTT for verification of the in-house 3D deterministic core simulators, namely DYN3D at HZDR [8] and Ants [9] at VTT. A dedicated publication, summarizing these activities, is currently under preparation.

The proposed neutronics benchmark will serve as a starting point in development of more sophisticated computational exercises dedicated to steady-state and transient coupled neutronics/TH analyses of the NuScale-like cores.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Emil Fridman reports that the project has received funding from the European Union's Horizon 2020 research and innovation program under grant agreement No 945063.

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