NUCLIC Nuclear Innovation Consultancy

GEMINI+ HTGR Neutronics

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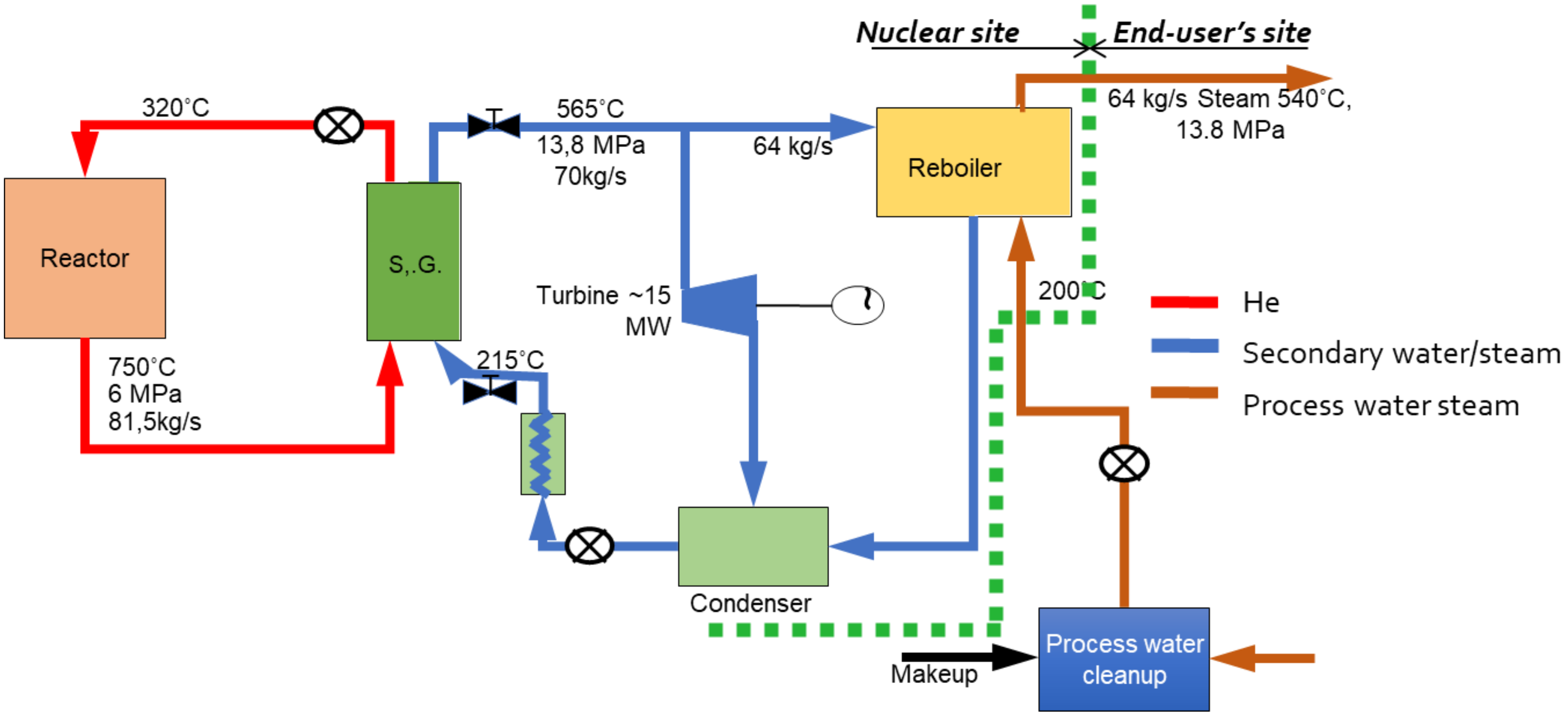
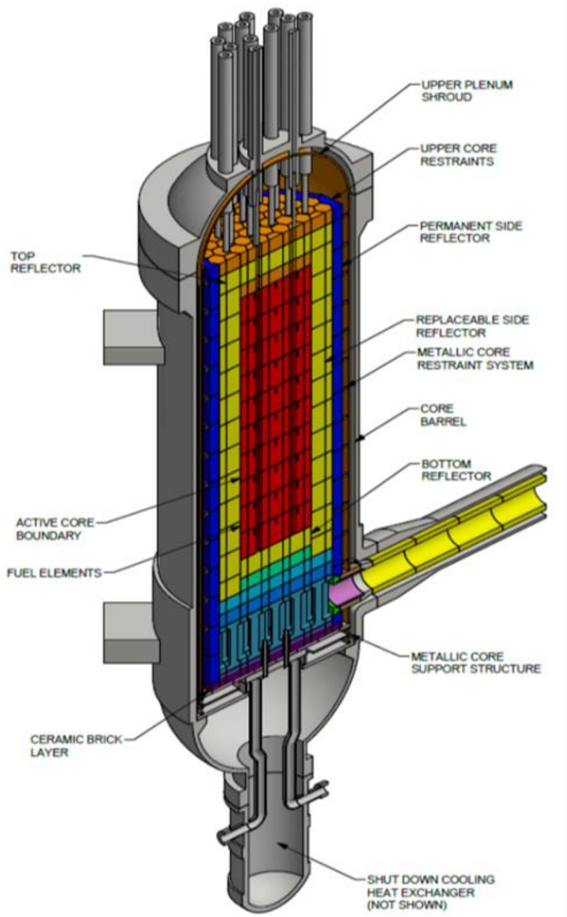
Outline

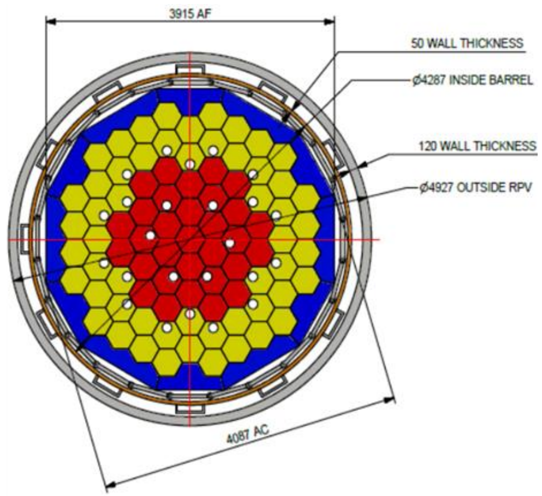
- ***General configuration of the GEMINI+ HTGR system***
- ***Core design ➔ Core neutronics design***
- ***SERPENT model - Evolution***
- ***Results***
  - *K_{eff}-history*
  - *Control rods*
  - *(Evolution of) power and burn-up distribution*
  - *Temperature coefficients of reactivity*
  - *Axial offset / Xe-oscillations?*
  - *Steam ingress reactivity*
- ***Concluding remarks***

General configuration of the GEMINI+ HTGR system



GEMINI+ Core Neutronics Design





Prismatic HTR – Core configuration

180 MW_{th} reactor (165 for customer, 15 for internal needs + losses)

3.5 rings of fuel blocks; 2 rings of reflectors

Power density of 5.9 MW/m^3

Core diameter of 3.915 m and core height of 8.8 m

SERPENT monte carlo neutronics code

- *SERPENT continuous energy monte carlo neutron (and photon) transport code (VTT, Finland)*
- *Version 2.3.31 with JEFF 3.1.1 nuclear data*
- *Explicit random particle distribution to simulate coated particles in compacts ➔ Double heterogeneity is intrinsically taken into account*
- *Multi-physics input to accommodate input of general temperature distributions (e.g. generated by the SPECTRA thermal hydraulics code) ➔ Converged Power- and Temperature distribution at BOL after just a few (~ 4) iterations between netronics and core thermal hydraulics. Fixed temperature distribution until EOL*
- *Statistical uncertainties determined by neutron population parameters: 100000 ("fine mode") – 400000 ("extra fine mode") neutrons per cycle, 1000 cycles with 100 inactive cycles.*
- *The high precision monte carlo calculations, using around 350 cores, and a hybrid MPI/OpenMP parallelization, were carried out on the HPC cluster of the Swierk Computing Centre (CIS), National Centre for Nuclear Research (NCBJ), Poland.*

Configuration characteristics of SERPENT model

Parameter	Value	Unit
Reactor/core configuration	-	-
# Radial rings of fuel blocks (ring around centre column is first ring)	3	-
# Fuel block columns	25	-
# Control block columns	6	-
# Axial fuel/control block layers	11	-
Distance between side faces of adjacent blocks	0.2	cm
Core height	800 / 880 10 layers / 11 layers of blocks	cm
# Replaceable reflector rings	2	-
# Replaceable reflector columns	54	-
Bottom reflector (with coolant holes)	-	-
Reflector material	NBG-17 graphite [7]	
Reflector thickness	160	cm
Top reflector (with coolant and control rod holes)	-	-
Reflector material	NBG-17 graphite [7]	-
Reflector thickness	120	cm
Core barrel	-	-
Core barrel inner diameter	199.1	cm
Core barrel effective outer diameter	207.1	cm
Core barrel material	Alloy 800H	-
Core barrel height (in SERPENT neutronics model)	1080 / 1160 (10 / 11 layer core)	cm
Reactor Pressure Vessel	-	-
RPV inner diameter	234.1	cm
RPV outer diameter	244.05	cm
RPV material	Alloy SA508	-
RPV height (in SERPENT neutronics model)	1080 / 1160 (10 / 11 layer core)	cm
Fuel block configuration	-	-
Block height	80	cm
Hexagon flat-to-flat distance	36	cm
Block material	NBG-17 graphite [7]	-
Triangular pitch	1.9	cm
# channels with fuel compacts	216 (w/o BP) 210 (with BP)	-
Compact channel diameter	1.27	cm
# small coolant channels	6	-
Small coolant channel diameter	1.27	cm
# large coolant channels	102	-
Large coolant channel diameter	1.6	cm
Control block configuration	-	-
Block height	80	cm
Hexagon flat-to-flat distance	36	cm
Block material	NBG-17 graphite [7]	-
Triangular pitch	1.9	cm
# channels with fuel compacts	174 (w/o BP) 170 (with BP)	-
Compact channel diameter	1.27	cm
# small coolant channels	5	-
Small coolant channel diameter	1.27	cm
# large coolant channels	102	-
Large coolant channel diameter	1.6	cm
Control rod channel diameter	13	cm

N.B. The (effective) inner and outer diameter of the core barrel and the pressure vessel as stated here may slightly deviate from what is stated in [2]. This, however, does not influence the neutronic characteristics of the *core*.

Parameter	Value	Unit
Control rod configuration (model - simplified)	-	-
# core rods	6	-
# reflector rods	18	-
Rod geometry	Annular	-
Rod length	800 / 880 (10 layer core / 11 layer core)	cm
Inner radius	3.75	cm
Outer radius	5.25	cm
Absorber material	B_4C	-
Absorber material density	2.52	g/cm^3
Fuel compact configuration	-	
Matrix material	C	-
Matrix material density	1.75	g/cm^3
# coated particles per compact	2500 *)	-
Compact cylinder height	5.0	cm
Compact cylinder radius	0.625	cm
Coated particle configuration	-	-
Kernel diameter	500	micron
Kernel material	UO_2	-
Kernel density	10.4	g/cm^3
Buffer layer thickness	95	micron
Buffer layer material	C	-
Buffer layer density	1.05	g/cm^3
Inner PyC layer thickness	40	micron
Inner PyC material	C	-
Inner PyC density	1.90	g/cm^3
SiC layer thickness	35	micron
SiC material	SiC	-
SiC density	3.18	g/cm^3
Outer PyC layer thickness	40	micron
Outer PyC material	C	-
Outer PyC density	1.90	g/cm^3
Burnable poison (BP) configuration (see Figs. 3 and 4 for locations of the burnable poison cylinders in the fuel blocks).		
Height	75.0	cm
Outer diameter of annular graphite cylinder	0.625	cm
Material of annular cylinder	C	-
Density of annular cylinder	1.75	g/cm^3
Burnable poison (BP) material mixture	B_4C in graphite	-
Fraction f_{BP} of B_4C in graphite	0.0 - 1.0*)	-
Density of B_4C in mixture	2.52	g/cm^3
Density of C in mixture	1.75	
Outer radius R_{BP} of BP material mixture	0.2 - 0.525*)	cm
Subdivision of BP material for accurate depletion calculation - # concentric rings	10	-
^{10}B content of boron in BP	20 (natural boron)	%

*) The number of coated particles per compact, as well as the fuel enrichment and the parameters of the burnable poison cylinders have been/are being varied in the neutronics studies, in order to arrive at an acceptable / optimised configuration (ongoing in August/September 2020).

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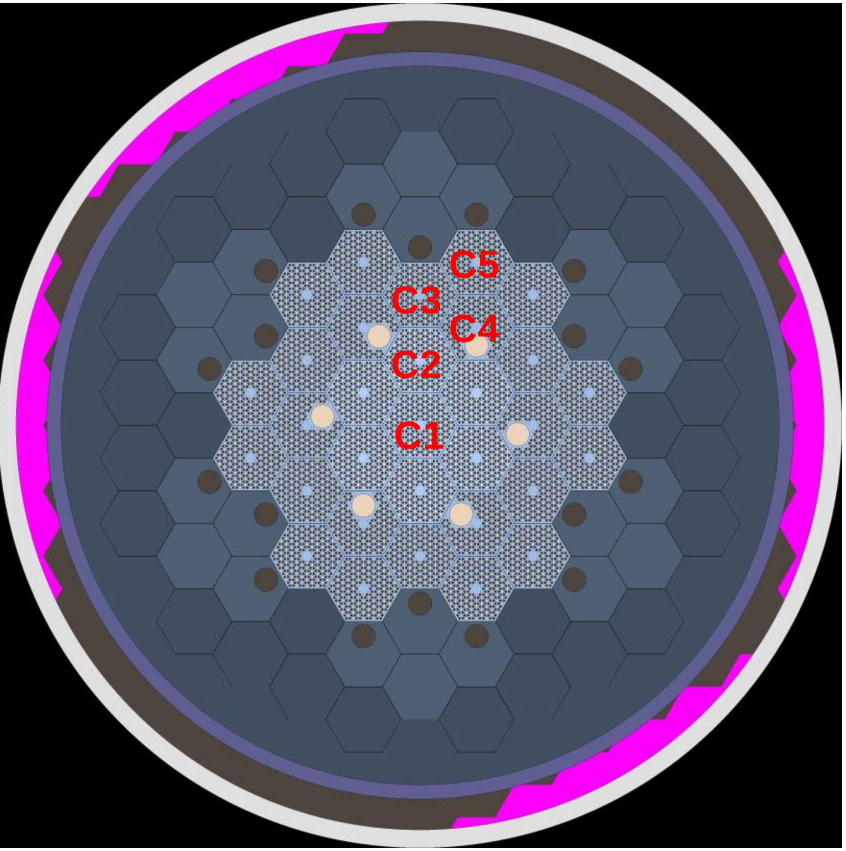
SERPENT reactor model cross sections (1)



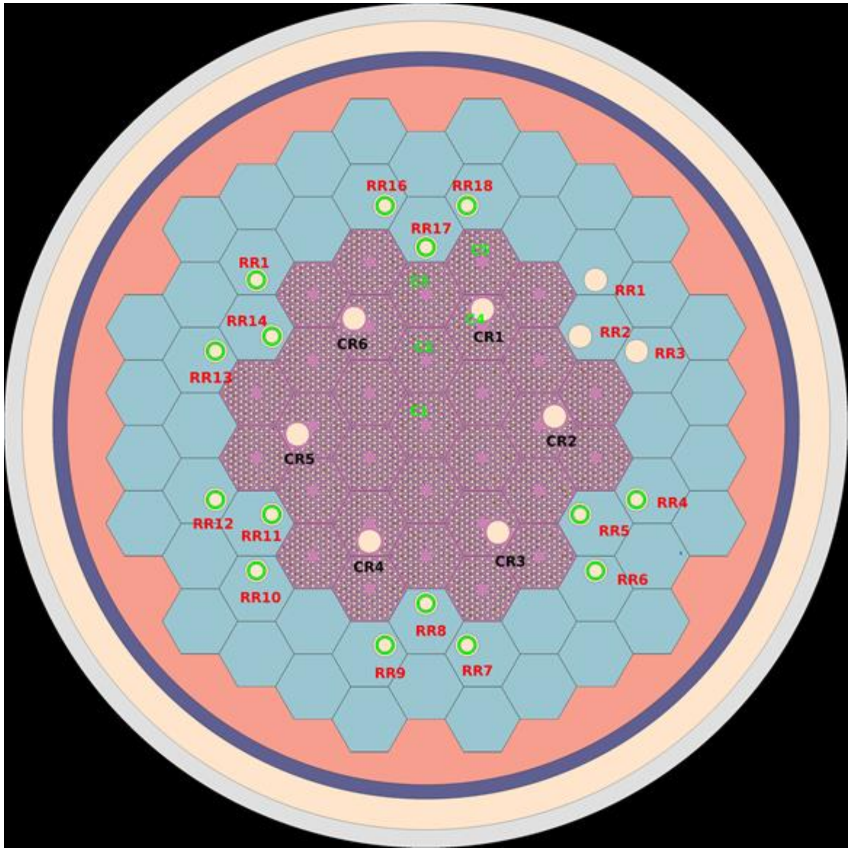


Fig. 1 Horizonal cross section (z = 1000 cm plane; near the top of the core) of the SERPENT neutronics model for the current (June 2020) version of the GEMINI+ reactor. Control rod identifiers are given. The outer (light grey) section is the pressure vessel. Dimensions are given in Table 1. Also indicated (in green) are 5 representative (due to symmetry; for C4 this is not exact, but in rather good approximation) core columns (C1 - C5).

SERPENT reactor model cross sections (2)

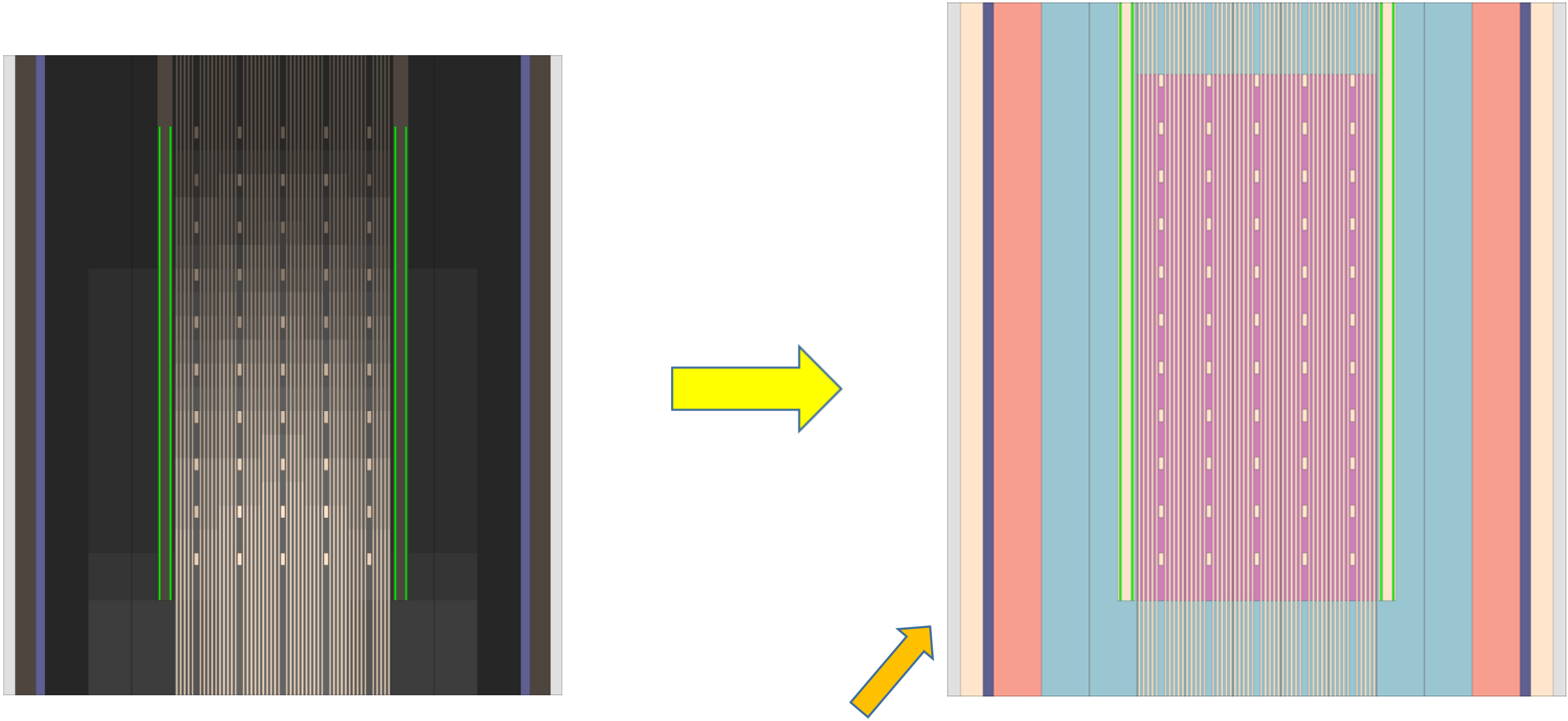


Fig. 2 Vertical cross section (x = 0 cm plane) of the SERPENT neutronics model for the current (June 2020) version of the GEMINI+ reactor (11 layers of fuel blocks in the core). Note that the visible reflector control rods (RR8 and RR17, in green) have been fully inserted in this case. Further note that the aspect ratio shown in the drawing is not entirely realistic. Actual dimensions are given in Table 1.

Core elements: full fuel block

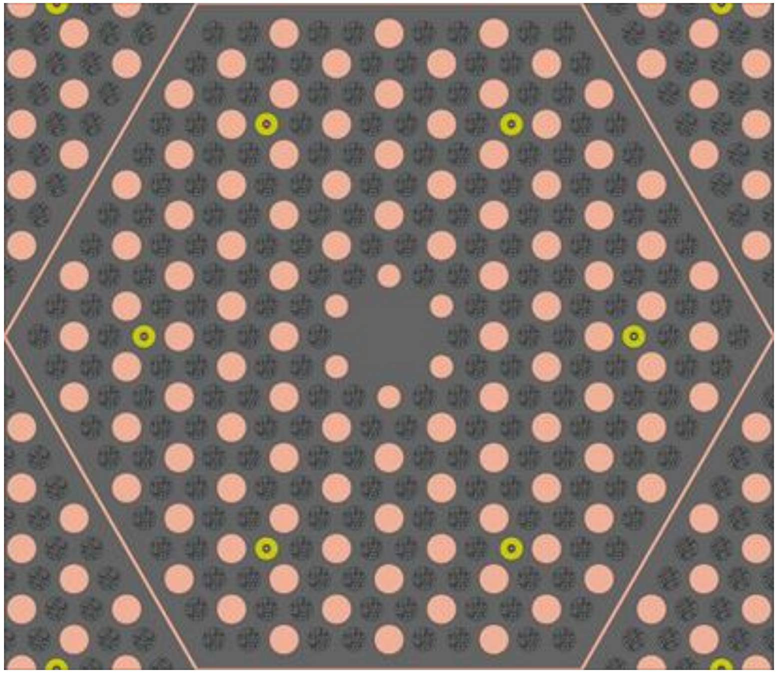


Fig. 3. Full fuel block without control rod channel. 6 compact stacks have been replaced by burnable poison cylinders.

Core elements: fuel block with control rod channel

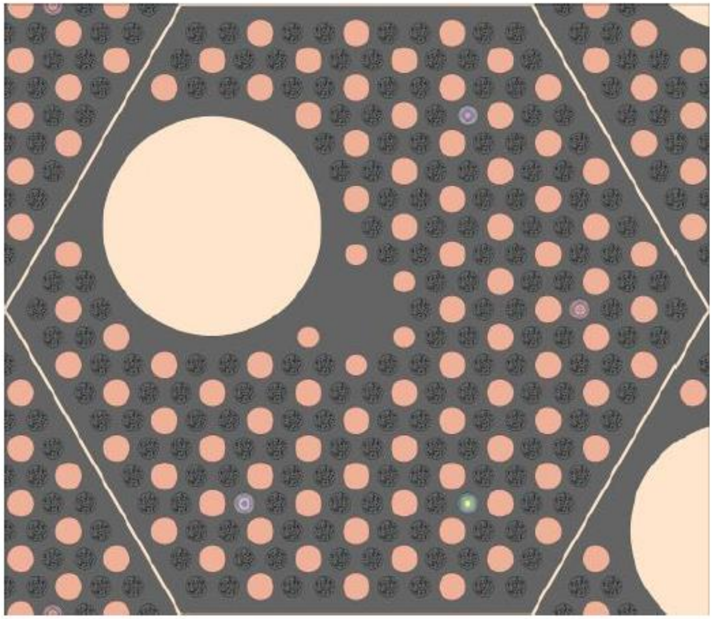


Fig. 4. Fuel block with control rod channel. 4 compact stacks have been replaced by burnable poison cylinders.

Burnable poison cylinders

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- ***To tailor the history of the (uncontrolled) keff from Beginning-of-Life (BOL; start of operation; ^{135}Xe-free) to End-of-Life (EOL; 550 full power days; equilibrium ^{135}Xe and ^{149}Sm). The main purpose of this is to ensure that the uncontrolled keff (i.e. the value for all rods out) is within the range that can actually be compensated by the control/shutdown rods in the reflector and the core, for all operational states of the reactor. See Sections V and VI.***
- ***To improve the (radial) power distribution over the core, as additional measure in response to the too high maximum fuel temperature in the earlier design version with 10 layers of fuel blocks in the core, without BP.***
- ***Graphite cylinder of 1.25 cm diameter (same as compact) with a central hole (radius R_{BP} to be optimised) filled with graphite and B_4C (initial fraction f_{BP} to be optimised).***

Some results

- *K_{eff}-history (different initial spatial distributions of BP parameters)*
- *Control rods*
- *(Evolution of) power and burn-up distribution (different initial spatial distributions of BP parameters)*
- *Temperature coefficients of reactivity (at BOL, MOL, EOL)*
- *Axial offset / Xe-oscillations?*
- *Steam ingress reactivity*

Fixed spatial temperature distribution (at BOL, as calculated by SPECTRA Thermal- Hydraulics code, NRG, NLD) was used for the entire operation cycle from 0 to 550 days.

N.B. More results are presented in GEMINI+ deliverable D2.8, e.g. simultaneous convergence of power- and temperature distribution at BOL, fast flux/fluence, activation, required start-up source strength, etc.

k_{eff} – history - “Uniform” BP distribution

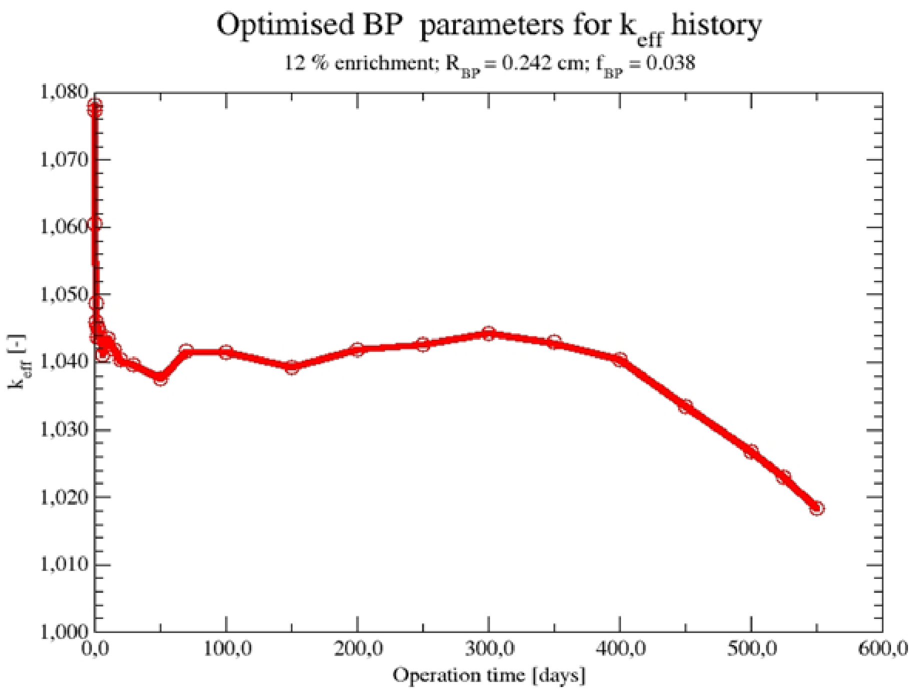

Fig. 6. Uncontrolled (i.e. all control rods out) k_{eff} versus operation time for a uniform enrichment of 12%, burnable poison cylinder radius R_{BP} = 0.242 cm and burnable poison fraction (B_4C in graphite) f_{BP} = 0.038. Note the equilibrium reactivity worth of ^{135}Xe is approximately -2840 pcm. k_{eff} varies between 1.078 (BOL, no Xe) and 1.018 (EOL, Xe-eq.). The relative standard deviation in k_{eff} is 12 to 13 pcm, which is consistent with the neutron population parameters: 100000 neutrons per cycle and 1000 cycles per point in time. In the calculation 26 non-equidistant time steps were used.

k_{eff} – history – “Optimized” BP distribution

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Current optimization goal:
Uniform <u>radial</u> power distribution

Future optimization goal:
Uniform radial and <u>axial</u> power distribution

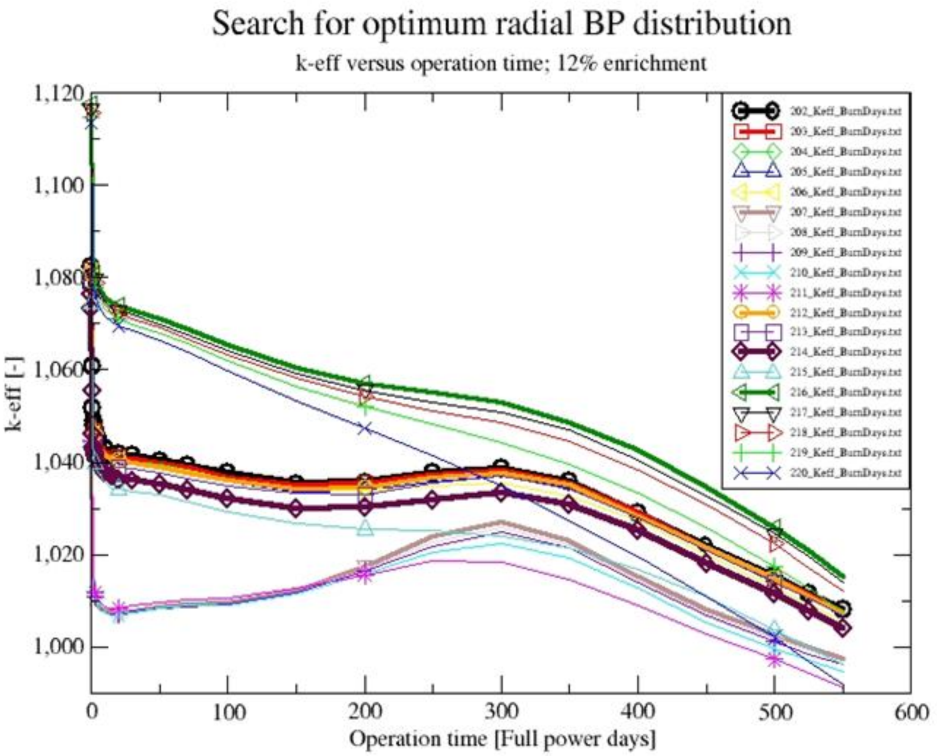

Fig. 7. Uncontrolled k_{eff} histories from calculations to improve the radial power distribution (see Section VI), by applying different burnable poison parameters for columns C1 and C2 on the one hand and C3, C4 and C5 on the other. Case 202 (bold “black circles”) is the same as shown in Fig. 6 (uniform BP parameters). Case 214 (bold “purple diamonds”) is the most favourable configuration so far. Neutron population parameters are the same as in Fig. 6, again yielding a relative standard deviation in k_{eff} of 12 to 13 pcm.

Table 2. Burnable poison parameters for case 214.

BP parameter	Columns C1, C2		Columns C3, C4, C5	Units
f_{BP}	0.038		0.038	[-]
R_{BP}	0.290		0.227	[cm]

Control rods

- ***Control rods modeled as annular B_4C cylinders***
- ***Influence of control rod insertion on k_{eff}***
- ***At BOL (0 days), MOL (250 days) and EOL (525 days)***
- ***At CZP, HZP and HFP states, i.e. corresponding temperature (distributions)***

Control rod reactivity - BOL

Table 3a. k_{eff} for characteristic control rod configurations at CZP, BOL, Xe-free for 11 layer core, uniform 12 % initial enrichment and uniform burnable poison parameters (case 202). CR = Core Rods, RR = Reflector Rods.

Rod positions	k_{eff}	Remarks
All CR in; all RR in	9.14812E-01 (0.012%)	CZP state is subcritical with all rods in: OK
All CR in; all RR out	1.00170E+00 (0.58%)	Core rods in only are not sufficient in this configuration in CZP state: **not OK** (at BOL)
All CR in; RR1/2/3 in; RR10/11/12 in	9.65733E-01 (0.012%)	Core rods + some reflector rods are sufficient at BOL. This **could be OK**, as most RR are in anyway during first days of operation (see below).
CR1 out; RR1, RR2, RR3 out; other rods in	9.77099E-01 (0.012%)	Approximately 60 degr. sector free of rods, to accommodate (re-) load: OK
CR1 out; RR1, RR2, RR3, RR16, RR17, RR18 out; other rods in	1.018760E+00 (0.012%)	Slightly over 60 degr. sector free of rods, to accommodate (re-load): **not OK**

All 6 core control rods are assumed to be fully withdrawn at HFP (full power operation) state.

Reflector rods are assumed to be withdrawn one at the time.

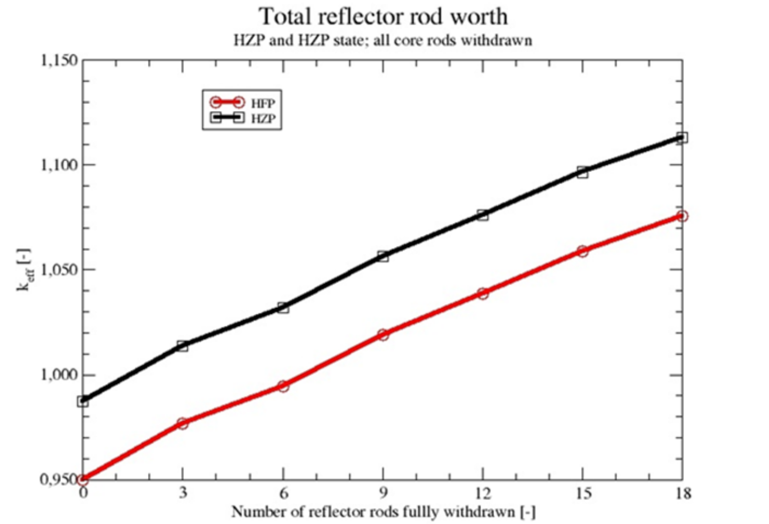

Fig.8. k_{eff} as function of the number of withdrawn control rods in the reflector for case 202 at BOL. All control rod in the core are out. The value for all rods out at HFP corresponds to the initial value in Fig. 6. Relative standard deviation in k_{eff} is 12 to 13 pcm.

Control rod reactivity - MOL

Table 3b. k_{eff} for characteristic control rod configurations at HZP and HFP, MOL, for 11 layer core, uniform 12 % initial enrichment and uniform burnable poison parameters (case 202). CR = Core Rods, RR = Reflector Rods. Standard deviation 0.012%

Configuration	**State**	**k-eff (no Xe)**	**k-eff (eq. Xe)**	**Remarks**
All CR in; all RR in	CZP	0.87920	0.85508	CZP state at MOL is subcritical with all rods in: OK
All rods in except CR4 and RR2	CZP	0.91520	0.88982	CZP state at MOL can be kept subcritical with one stuck core rod and one stuck reflector rod: OK
CR1 out; RR1, RR2, RR3 out, other rods in	CZP	0.93998	0.91387	Approximately 60 degr. Sector free of rods at MOL, to accommodate (re-) load: OK
All core rods out; all reflector rods in except RR2	HFP	0.95256	0.92740	HFP state at MOL can be kept subcritical with one stuck reflector rod: OK
All CR out; all RR in	HFP	0.94233	0.91770	HFP state at MOL can be kept subcritical by reflector rods only: OK
All rods out	HFP	1.06624	1.03752	HFP state at MOL; full power operation
All core rods out; all reflector rods in except RR2	HZP	0.97574	0.94836	HZP state at MOL can be kept subcritical with one stuck reflector rod: OK
All CR in; all RR in	HZP	0.81942	0.79819	HZP state at MOL is subcritical with all rods in: OK
All CR out; all RR in	HZP	0.96561	0.93868	HZP state at MOL can be kept subcritical by reflector rods only: OK
All rods out	HZP	1.08945	1.05751	HZP state at MOL; start of full power operation

Control rod reactivity - EOL

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Table 3c. k_{eff} for characteristic control rod configurations at HZP and HFP, EOL, for 11 layer core, uniform 12 % initial enrichment and uniform burnable poison parameters (case 202). CR = Core Rods, RR = Reflector Rods.

Configuration	State	k-eff (no Xe)	k-eff (eq. Xe)	Remarks
All CR in; all RR in	CZP	0.84782	0.81578	CZP state at EOL is subcritical with all rods in: OK
All rods in except CR4 and RR3	CZP	0.88318	0.84979	CZP state at EOL can be kept subcritical with one stuck core rod and one stuck reflector rod: OK
CR1 out; RR1, RR2, RR3 out, other rods in	CZP	0.90680	0.87252	Approximately 60 degr. Sector free of rods at EOL, to accommodate (re-) load: OK
All core rods out; all reflector rods in except RR3	HFP	0.91958	0.89552	HFP state at EOL can be kept subcritical with one stuck reflector rod: OK
All CR out; all RR in	HFP	0.90909	0.88540	HFP state at EOL can be kept subcritical by reflector rods only: OK
All rods out	HFP	1.03971	1.01130	HFP state at EOL; full power operation
All core rods out; all reflector rods in except RR2	HZP	0.95553	0.92163	HZP state at EOL can be kept subcritical with one stuck reflector rod: OK
All CR in; all RR in	HZP	0.79776	0.77117	HZP state at EOL is subcritical with all rods in: OK
All CR out; all RR in	HZP	0.94512	0.91186	HZP state at EOL can be kept subcritical by reflector rods only: OK
All rods out	HZP	1.07177	1.03301	HZP state at EOL; start of full power operation

Power distribution – “Uniform” BP distribution

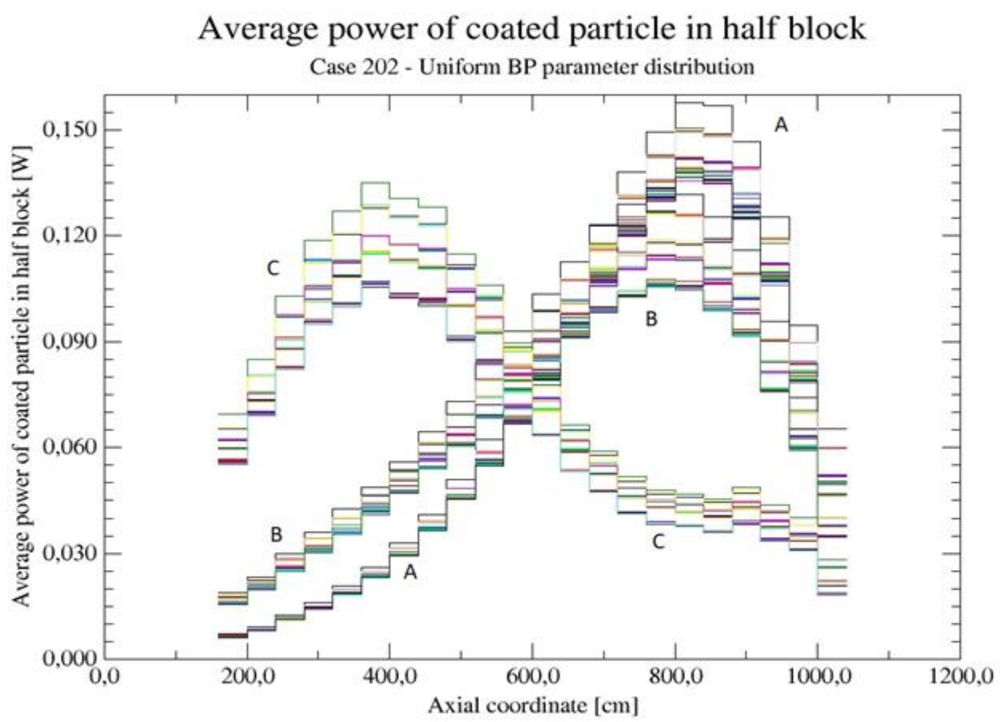


Fig. 9. Axial distribution of power per coated particle (average over half block) for all (31) fuel columns in the core for case 202 (uniform BP parameter distribution) at BOL/Xe-free (“A”), 250 days (“B”) and 525 days (“C”). The highest power per coated particle (158 mW) occurs at BOL in column C1 (820 cm). The relative standard deviation of the power in the results shown is 0.22% for the peak values.

Power distribution – "Optimized" BP distribution

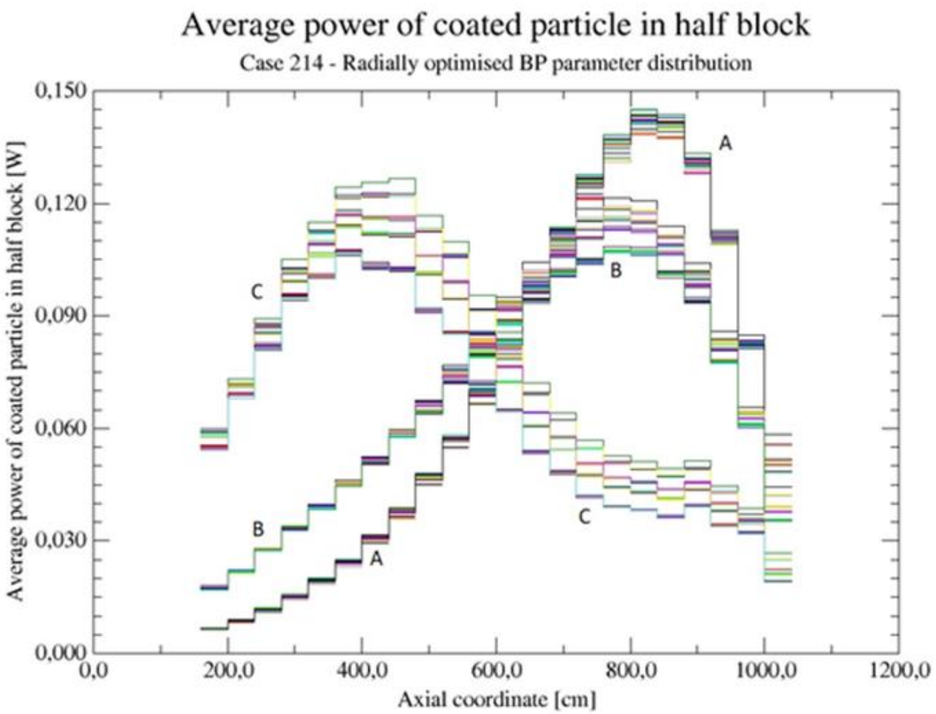


Fig. 10. Axial distribution of power per coated particle (average over half block) for all (31) fuel columns in the core for case 214 (radially "optimised" BP parameter distribution; Table 2) at BOL/Xe-free ("A"), 250 days ("B") and 525 days ("C"). The highest power per coated particle (145 mW) occurs at BOL ("A") in a peripheral column of type C5 (820 cm). Note that the lowest power per coated particle at the same elevation is 138 mW, occurring in a central column of type C2. The relative standard deviation of the power in the results shown is 0.22% for the peak values.

N.B. The radial power profile is almost "flat" in state "A" (BOL) of case 214, which is a requirement for acceptable behaviour in case of DLOFC (SPECTRA transient thermal hydraulics calculations).

Burn-up distribution (EOL)

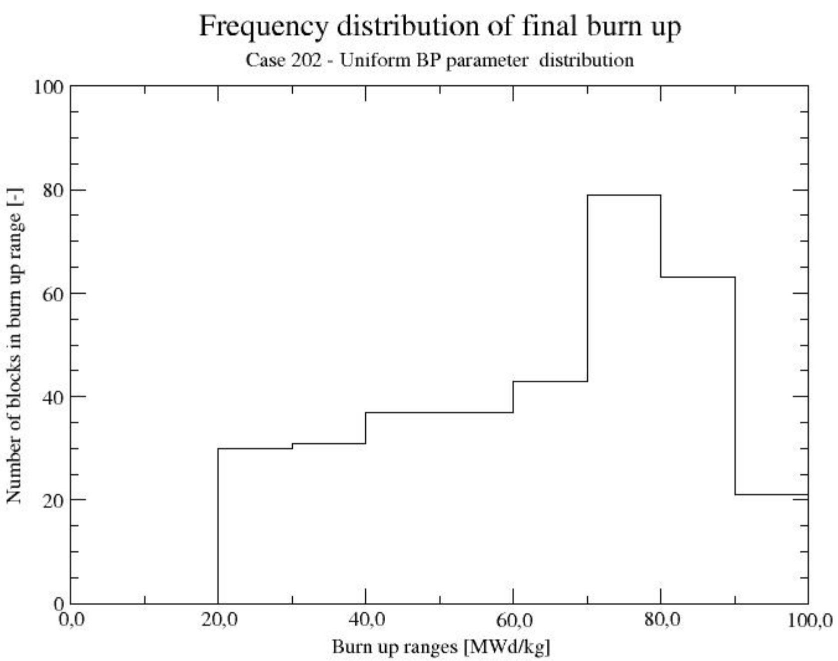


Fig. 11. Frequency distribution of the final burn up (per block) for case 202, i.e. the number of blocks containing fuel in the indicated burn up range. The maximum burn up is 98.5 MWd/kg. The average burn up is 63.8 MWd/kg.

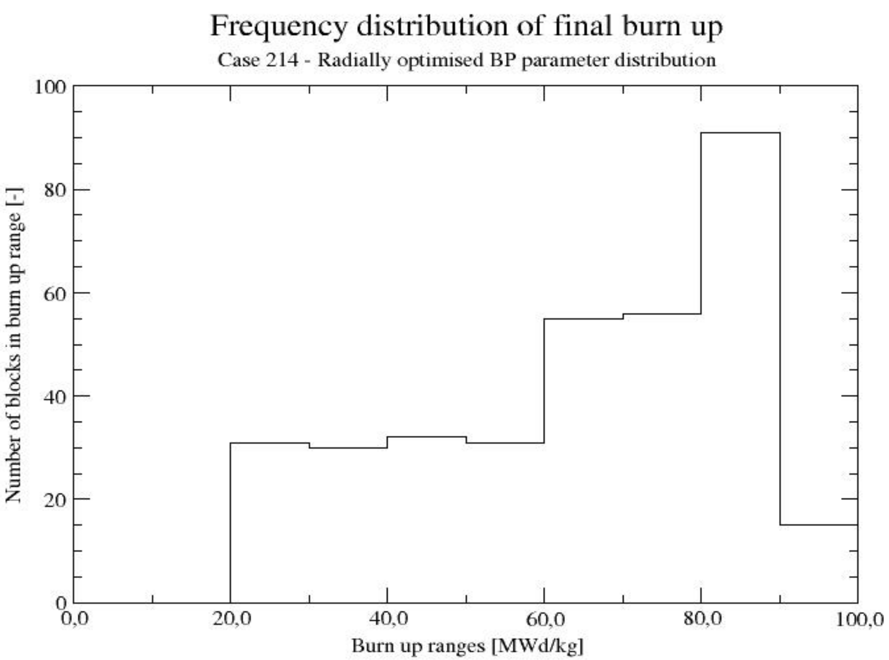


Fig. 12. Frequency distribution of the final burn up (per block) for case 202, i.e. the number of blocks containing fuel in the indicated burn up range. The maximum burn up is 94.6 MWd/kg. The average burn up is 63.8 MWd/kg.

Temperature coefficients of reactivity - BOL

Definition: $\alpha_x = [(1/k_{eff,ref}) - (1/k_{eff,x})] / \Delta T_x$ $\Delta T_x = 30$ K

X = F (Fuel), M (Moderator), R (Reflector), A (All)

Table 4. Temperature coefficients of reactivity (fuel, moderator, reflector) for case 202, BOL (Xe-free), in pcm/K. The uncertainty in the calculated values of the temperature coefficients is 0.3 pcm/K.

Configuration/State	α_F (Fuel)	α_M (Moderator)	α_R (Reflector)	Sum	α_A
CZP, all rods in	-10.0	-38.1	-162.0	-210.1	-48.7
HZP, all rods in	-6.8	-4.0	-0.8	-21.6	-20.2
HZP, core rods out, reflector rods in	-4.6	-10.2	0.4	-14.4	-15.1
HZP, all rods out	-4.1	-8.6	1.2	-11.5	-11.3
HFP, core rods out, reflector rods in	-5.3	-9.7	0.3	-14.7	-14.4
HFP, all rods out	-3.1	-7.4	1.9	-8.6	-9.7

Temperature coefficient of reactivity – MOL/EOL

Table 5. Temperature coefficients of reactivity (fuel, moderator, reflector) for case 202, MOL (250 full power days) and EOL (525 full power days), in pcm/K. The uncertainty in the calculated values of the temperature coefficients is 0.3 pcm/K.

MOL

State	Coefficient	Eq. Xe	No Xe
CZP	α_A	-42.1	-40.9
CZP	α_F (Fuel)	-11.4	-11.0
CZP	α_M (Moderator)	-30.4	-29.6
CZP	α_R (Reflector)	-86.7	-83.3
CZP	Sum	-128.5	-123.9
HZP	α_F (Fuel)	-7.5	-6.7

EOL

State	Coefficient	Eq. Xe	No Xe
CZP	α_A	-46.9	-45.6
CZP	α_F (Fuel)	-10.2	-11.2
CZP	α_M (Moderator)	-36.3	-34.6
CZP	α_R (Reflector)	-113.9	-114.6
CZP	Sum	-160.4	-160.4
HZP	α_F (Fuel)	-6.3	-6.7

Axial offset

Definition: FAO = (Pupper - Plower) / (Pupper + Plower)

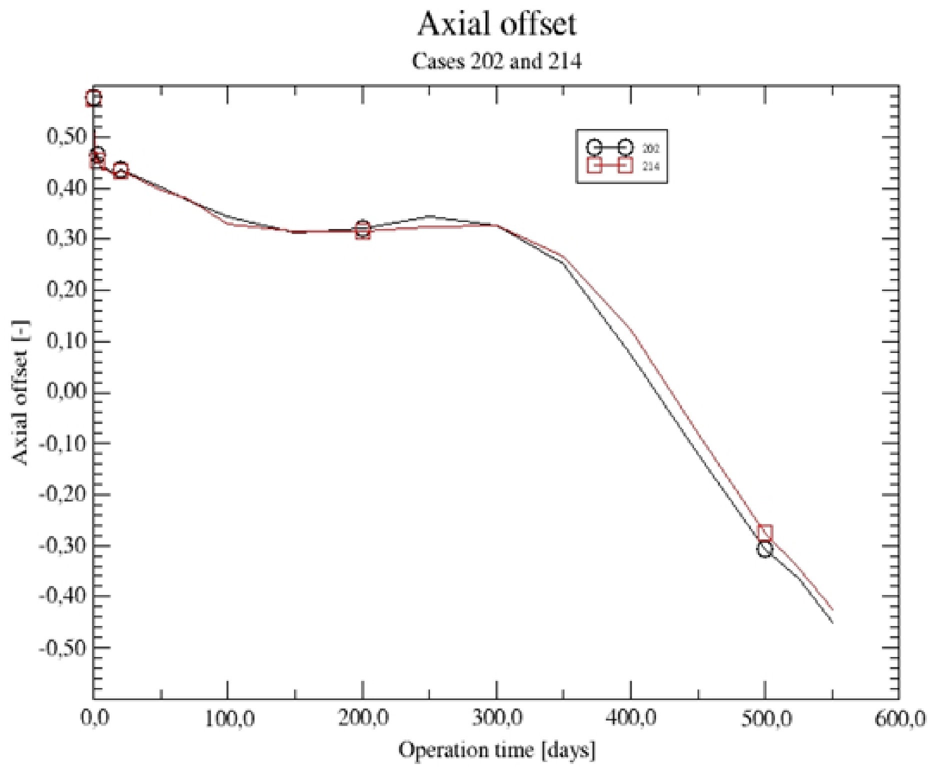


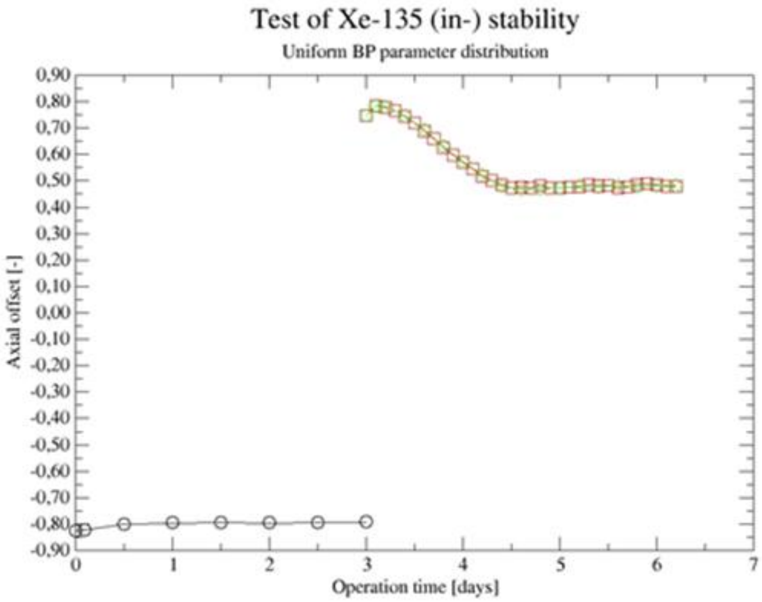
Fig. 13. Axial offset as function of operation time for cases 202 and 214.

Axial Xe-oscillation test

Scenario:

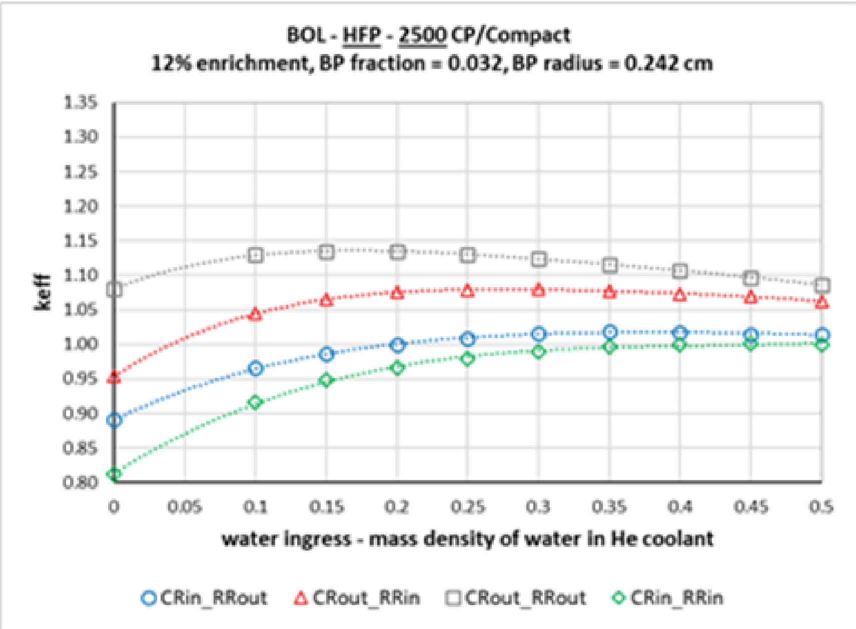
- ***From BOL to t = 3 days (Xe-equilibrium) reflector rods 50% inserted. Core rods fully out.***
- ***At t = 3 days reflector rods are fully withdrawn***

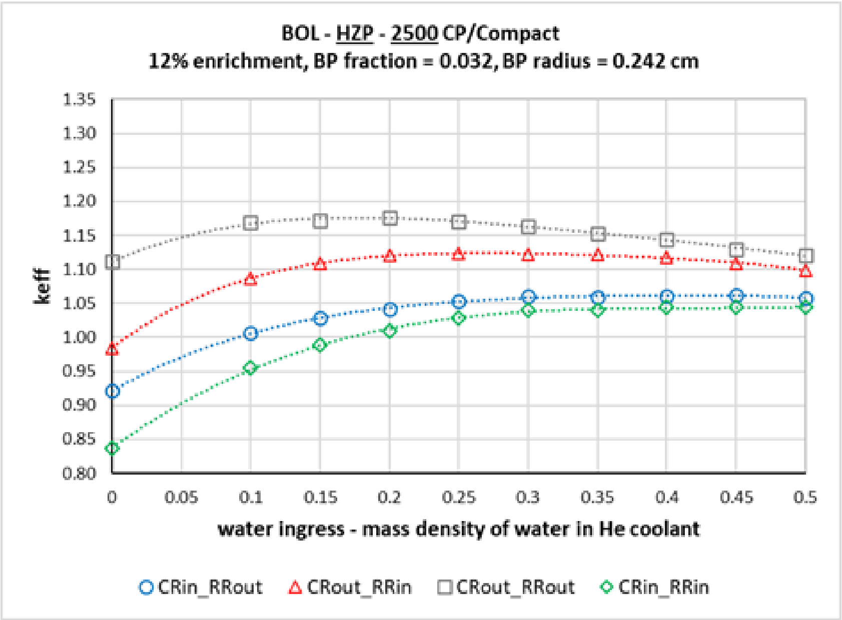
Axial offset as function of time. No "oscillations"



However, partially inserted rods should be avoided as much as possible

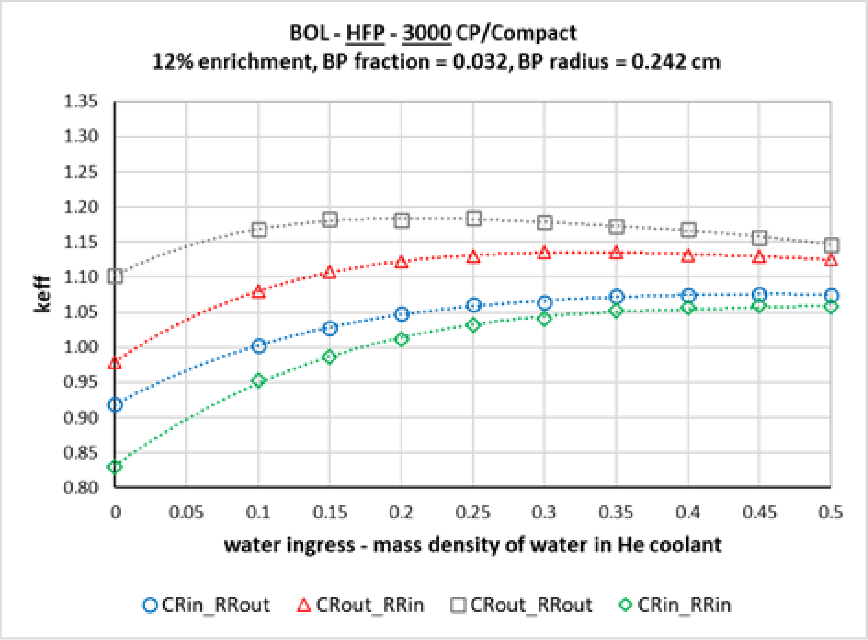
Steam ingress reactivity – 2500 CP/compact

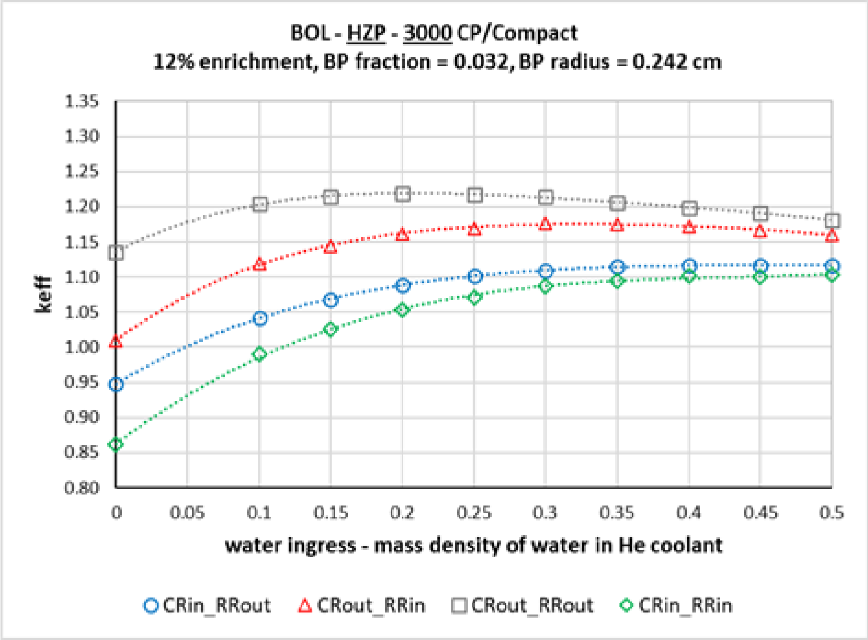




Reactor can be kept subcritical at 0.15 g/cm³ (HZP/HFP) using all control rods

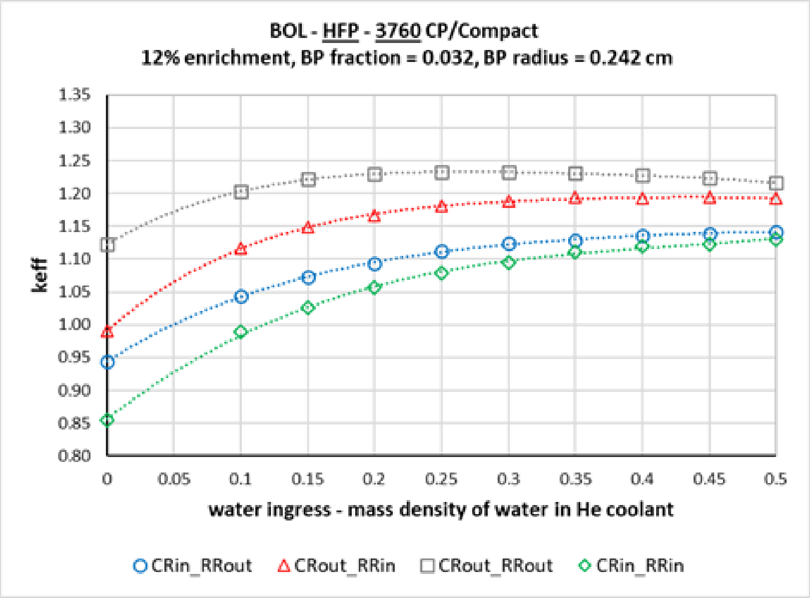
Steam ingress reactivity – 3000 CP/compact

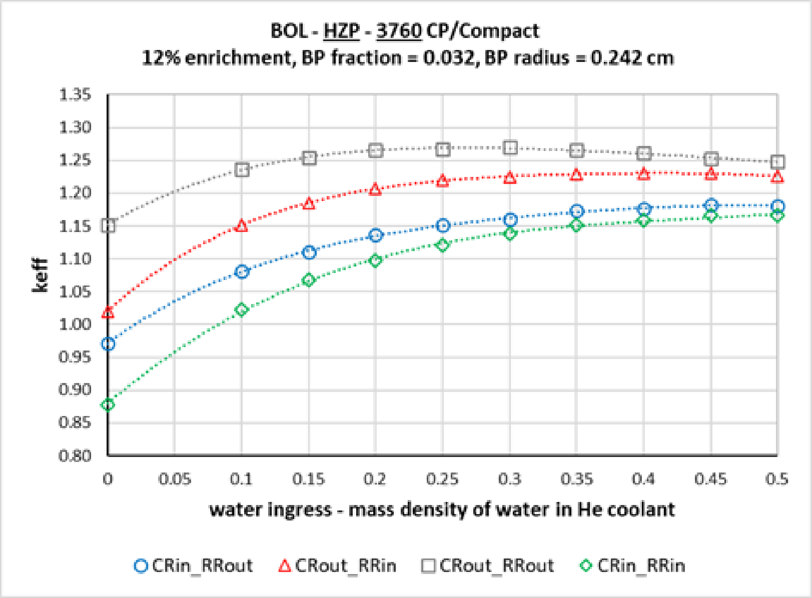




Lower M/F-ratio at higher #CP/compact ➔ Higher reactivity increase due to steam ingress

Steam ingress reactivity – 3760 CP/compact





Control rod worth decreases with increasing steam ingress!
➔ Measures necessary to limit steam ingress into the core

Conclusions

Extensive neutronics calculations have been performed on the current (June 2020) design of the 180 MWth GEMINI+ HTGR. Neutronics features seem quite promising, but further improvements and therefore further investigations would be desirable, especially concerning:

- ***Temperature coefficients of reactivity, control rod worths, etc. beyond BOL, also for further optimised configurations of the BP parameter distribution.***
- ***Thermal hydraulic feedback, reflecting the considerable change axial power profile during the operation cycle. In the current calculations, the temperature distribution has been kept constant throughout the operation cycle, as was initially envisaged. Adapting this to the actual power distribution at each point in time would be desirable. A simplified (HTR, etc.) thermal hydraulic model for integration with SERPENT is being developed.***
- ***Further reduction of the axial power peaking, thereby reducing the maximum power per coated particle and also improving the fuel utilisation. Possible methods are axial profiling of BP parameters, axial profiling of enrichment and/or a multi-batch loading scheme.***

The End… Questions?

It's up to you now!!!

Thank you
for your attention!

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