Investigation of the structured control rods concept for flattening of the power distribution and reactivity swing in the HTGR core.

NATIONAL CENTRE FOR NUCLEAR RESEARCH ŚWIERK

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New reactor concepts and safety analyses for the Polish Nuclear Energy Program
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Outline

- Introduction
- Neutronic properties of HTGR
- Model of reactor core based on HTTR design
- Concept of radial division of control rod
- Methodology of distribution analyses
- Results of the implementation of control rod division
- Control rod worth analyses
- Results for optimal control rod stucture
- Conclusions

Introduction

- PhD topic:
  Development and validation of coupled neutronic and CFD calculations for HTR applications
- Supervisor
  prof. Dr hab. inż. Jerzy Cetnar
- HTGR
  - Reactor concept
  - High Temperature Gas-cooled Reactor
  - Helium as coolant
  - Graphite as moderator
  - Fuel in TRISO particles
- HTTR
  - Existing reactor
  - High Temperature engineering Test Reactor
  - The Oarai Research and Development Center, Japan
  - Thermal power 30 MW
  - Maximum outlet temperature 950 °C

Neutronic properties of HTGR

- Deep neutron thermalisation
- Vulnerability to Xe135 poisoning
- Large migration length
- Local neutron spectrum is strongly influenced by:
  - Control rods
  - Burnable poisons
  - Reflectors
- High neutron flux gradients
- Power peaks
- Double heterogeneity
  - Caused by fine structure of compacts filled with TRISO particles
  - Highly structured geometrical model is needed to account for neutron spectra effects that occur in the fuel due to resonant cross sections
- Neutronic cross section dependence on temperature

Model of reactor core based on HTTR design

Monte Carlo Continuous Energy Burn-up Code (MCB) is a general-purpose code dedicated to simulations of radiation transport and radiation-induced changes in matter. [...] The main competition to the Transmutation Trajectory Analysis (TTA) method implemented in MCB are the assorted variations of the exponential matrix method; e.g., the Chebyshev Rational Approximation Method (CRAM) implemented in SERPENT code. [2]

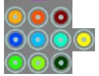
MCB is coupled with the POKE code that enables thermal-hydraulic calculations for prismatic HTGR cores models.

Model of reactor core based on HTTR design

Model made in MCB for economical analyses by team from the AGH University of Science and Technology.

Modified design of the HTTR, implementation of half-fuel blocks with control rod holes.

 - control rod

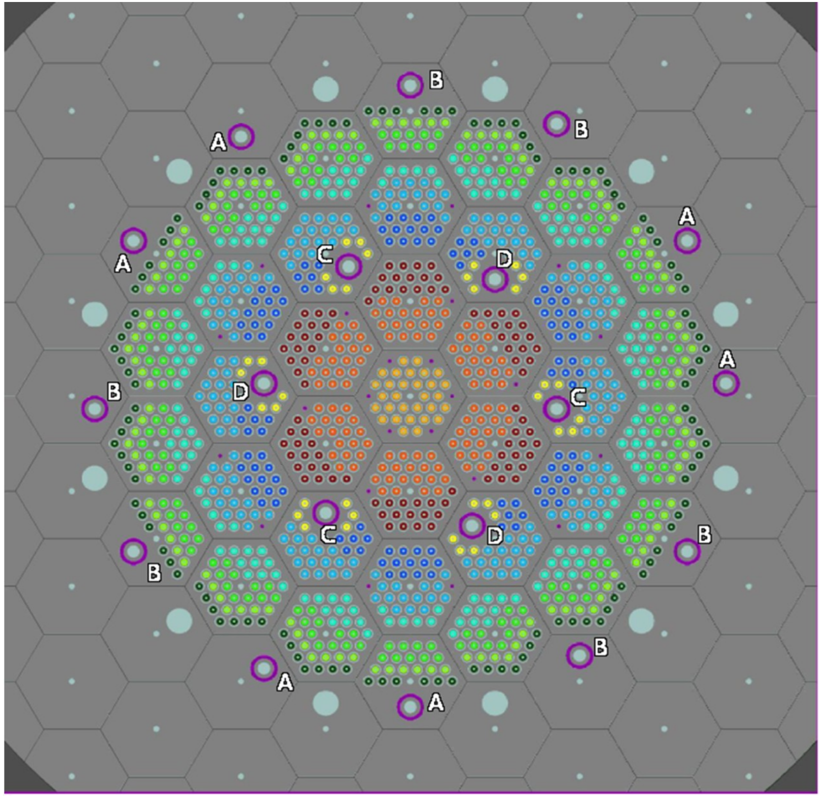
 - fuel compacts grouped into burnable zones

10 radial burnable zones

24 axial burnable zones in 8 layers of blocks

240 burnable zones total

Special burnable zone near contol rods.



Modelled core configuration. Source: [4]

Model of reactor core based on HTTR design

Parameters		Values
General	Power [MW]	180
	Fuel enrichment [%]	12
	Upper/lower reflector thickness [cm]	120.1
	Core radius [cm]	200
	Active core height [cm]	792.8
	Initial heavy metal mass [kg]	902.07
	Initial U235 mass [kg]	108.25
Fuel block	Apothem [cm]	18.1
	Height [cm]	99.1
	Fuel compacts pitch [cm]	5.15
	Control rod hole radius [cm]	5.08
	Graphite density [gcm^{-3}]	1.74
Fuel compact	Inner radius [cm]	0.5
	Graphite sleeve inner radius [cm]	1.3
	Graphite sleeve outer radius [cm]	1.7
	Radius of the coolant channel hole [cm]	2.05
	Packing fraction [%]	15

Compensation rods made of metallic tungsten due to its high temperature resistance.

Startup rods consists on B_4C microspheres in graphite matrix. [4]

Parameters			Values
TRISO capsules	Fuel kernel radius [μm]		250
	Fuel kernel density [gcm^{-3}]		10.65
	Porous carbon outer radius [μm]		345
	Porous carbon density [gcm^{-3}]		1.05
	Inner pyrocarbon (IpyC) outer radius [μm]		375
	Pyrocarbon density [gcm^{-3}]		1.9
	Silicon carbide (SiC): outer radius [μm]		420
	Silicon carbide density [gcm^{-3}]		3.18
	Outer radius of the outer pyrocarbon (OpyC) outer radius [μm]		460
Burnable poison	Burnable poison rod radius [cm]		0.7
	Burnable poison rod hole radius [cm]		0.71
	Eu_2O_3 density [gcm^{-3}]		7.42
	Burnable poison rod height [cm]		93.3
Control rods	Inner B_4C radius [cm]		1.97
	Inner tungsten radius [cm]		3.8
	Outer radius [cm]		4.3
	Length [cm]		800
	Tungsten isotope mass fraction [%]	W182	26.5
		W183	14.3
		W184	30.6
		W186	28.4
		He4	0.2
	Tungsten density [gcm^{-3}]		19.3
	B_4C-graphite matrix density [gcm^{-3}]		1.31
	B_4C-graphite matrix isotope mass fraction [%]	B10	3.35
		B11	13.35
		C12	83.3

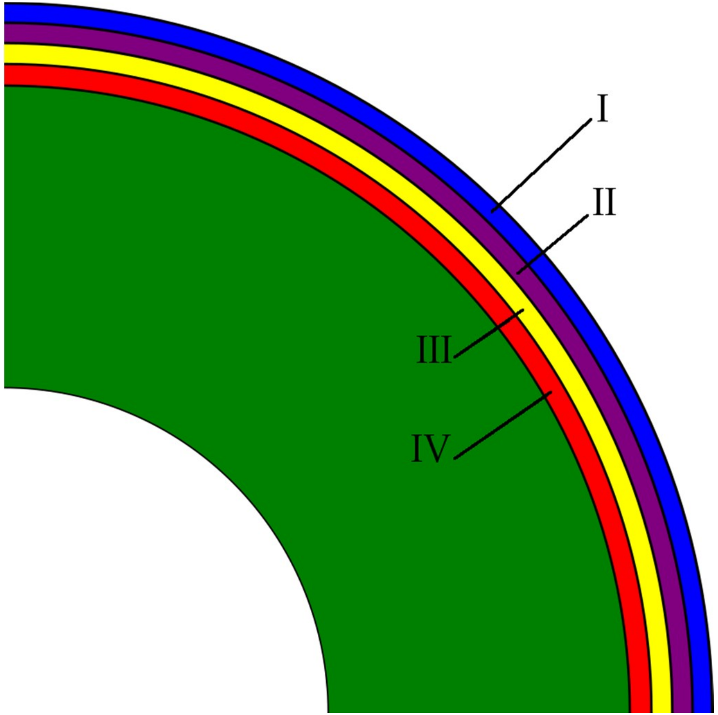
Concept of radial division of control rod

In order to reduce axial power oscillations, radial division of control rod into four radial layers was implemented.

Additionally, startup rod (green) is added to the rod structure.

Compensation rod operation starts from the outermost layer. When the outermost layer (I) is fully withdrawn, operation of the next layer can start. The innermost layer (IV) is withdrawn as the last.

Volume ratios between layers were modified without changing total volume of the absorber.



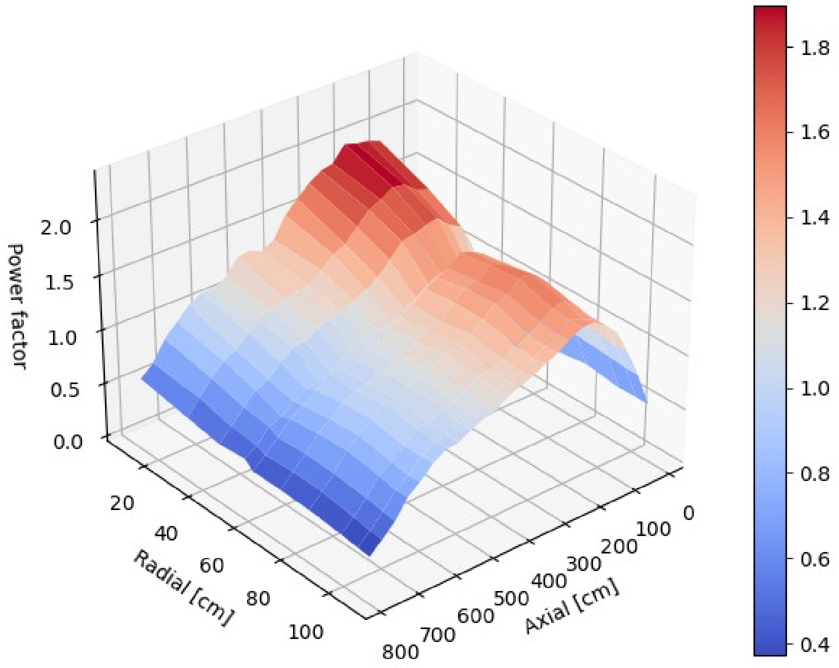
Configuration of control rod divided into four layers, each with equal volume.

Methodology of distribution analyses

$$O = \frac{\sum_{i=1}^{i_{max}} Q_i d_i}{\overline{Q} \sum_{i=1}^{i_{max}} d_i}$$

O – distribution parameter
d_i – average distance of burnable zone i
Q_i – average value in burnable zone i
Q – average value in the core

The parameter can be applied to power distribution or specific isotope concentration (i.e. Xe135) in radial or axial direction.



Examplary power profile.
Radial distribution parameter 1.01
Axial distribution parameter 0.91

Methodology of distribution analyses

d_i in axial direction is calculated as

$d_i = h_b(k\text{-}0.5)$, h_b – 1/3 block height

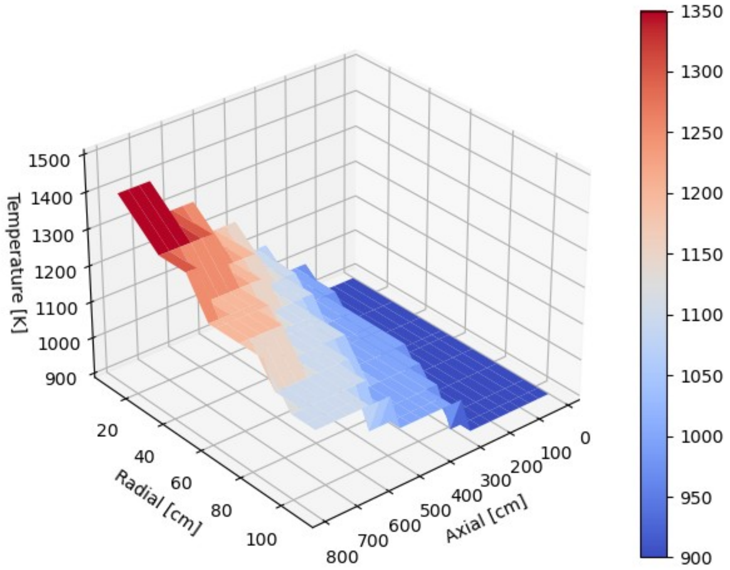
I	1	2	3	4	5	6	7	8	9	10	11	12
h_i [cm]	16.52	49.55	82.58	115.62	148.65	181.68	214.72	247.75	280.78	313.81	346.85	379.88
i	13	14	15	16	17	18	19	20	21	22	23	24
h_i [cm]	412.92	445.95	478.98	512.02	545.05	578.08	611.12	644.15	677.18	710.22	743.25	776.28

d_i in radial direction is average distance between all every fuel compact in i burnable zone to the center of the core.

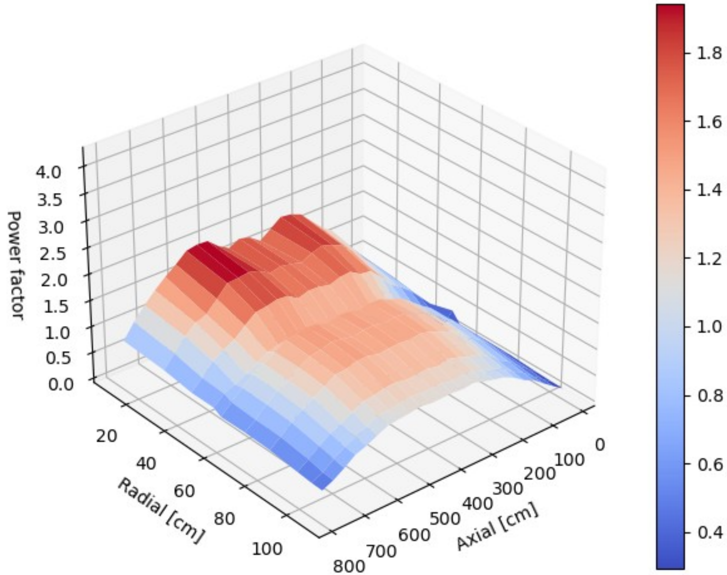
i	1	2	3	CR [1]	4	5	6	7	8	9
r_i [cm]	10	30.96	44.96	55.95	59.55	71.34	83.36	96.47	103.16	108.03

Results of the implementation of CR division

The coolant flows from top to bottom of the core. It has impact on the temperature profile and in consequence, also on the power profile.



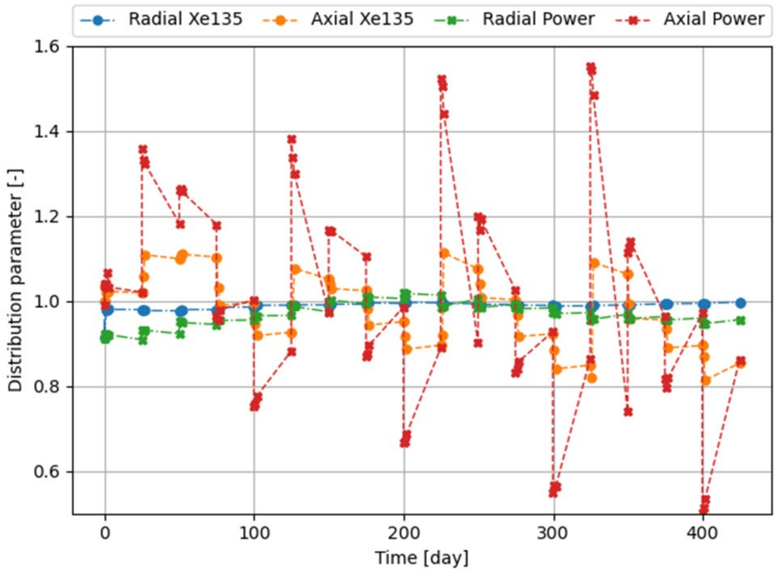
Power profile after initial timestep.



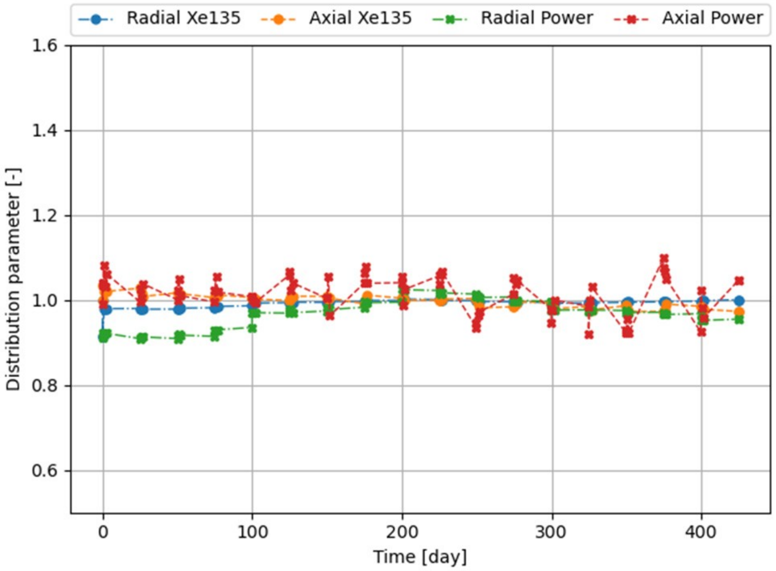
Temperature profile after initial timestep.

Results of the implementation of division of CRs

In both cases below the same amount of absorber was removed at the same times of operation – 25 days starting from day 20. After each operation, 2 additional 1 day long timesteps were conducted in order to prevent numerical oscillations.



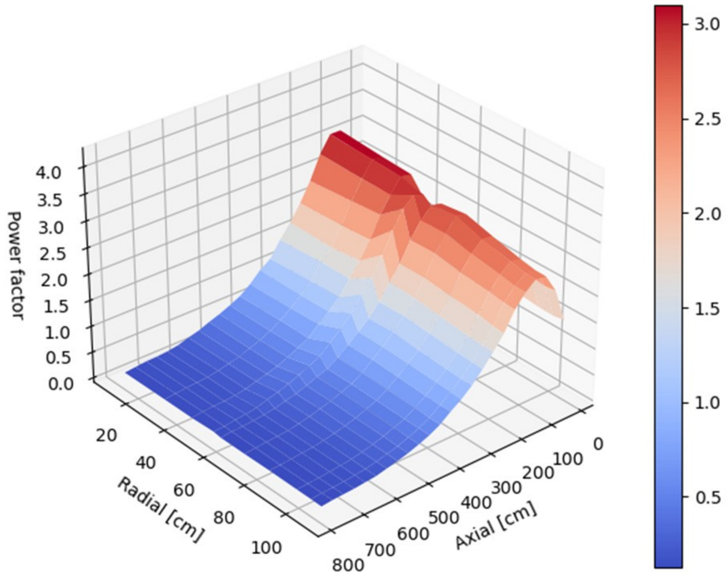
Distribution parameter without radial division of CRs, 1/4 of CR height of single CR group removed from the core at each operation



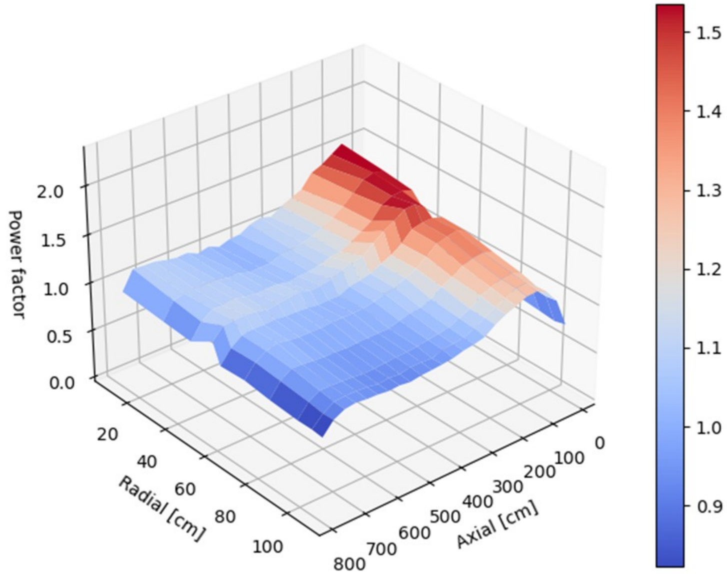
Distribution parameter with radial division of CRs, 1/ of CR thickness of single CR group removed from the core at each operation

Results of the implementation of division of CRs

Reorganization of the process of CR withdraval with implementation of radial CRs division significantly flattened the power profile.



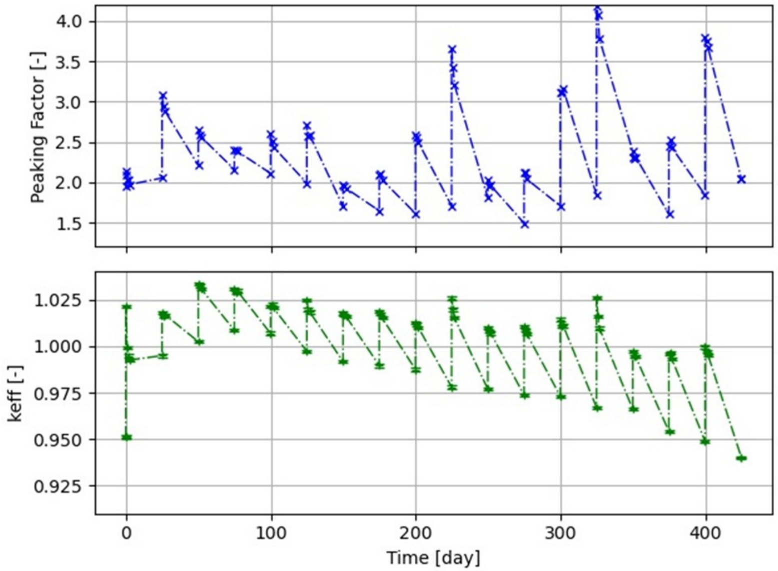
Power profile at day 300 without radial division of CRs. Axial distribution paremeter is 0.55.



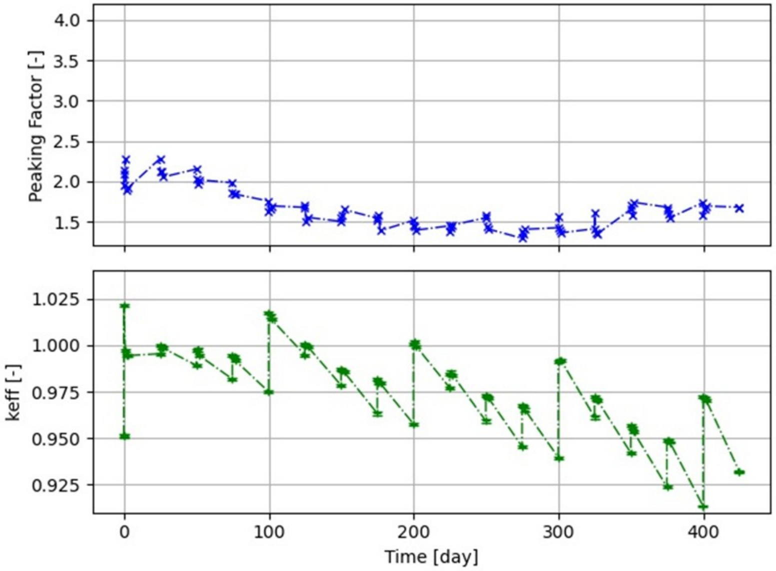
Power profile at day 300 with radial division of Crs. Axial distribution paremeter is 0.95.

Results of the implementation of division of CRs

However, it caused problem with keeping the reactor critical, since reactivity swings mostly decreased. Optimized control rods layers structre is needed.



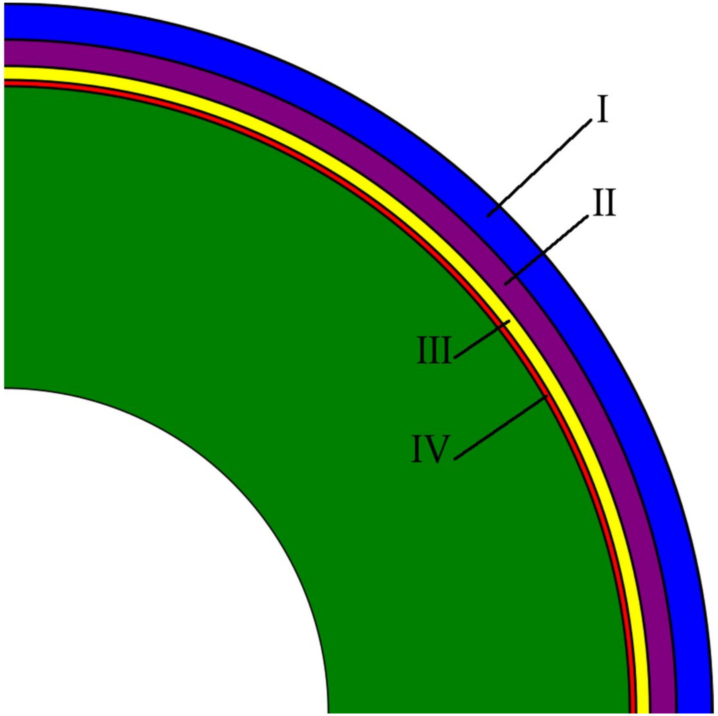
Power peaking factor and k_{eff} evolution without radial division of CRs.



Power peaking factor and k_{eff} evolution with radial division of CRs.

Control rod worth analyses

Due to the high number of parameters to set and their dependencies (volumetric fractions of control rod radial layers, times of operations), the search was carried out with a trial-and-error method. It was found that starting the operation from the outermost radial layer, the more inner layer of the control rod had a greater impact on the reactivity. Thus far, the structure of the radial layers of the control rod is most promising in terms of volumetric fraction, which is, starting from the outermost layer, 45%, 33.6%, 14.3%, and 7.1%.



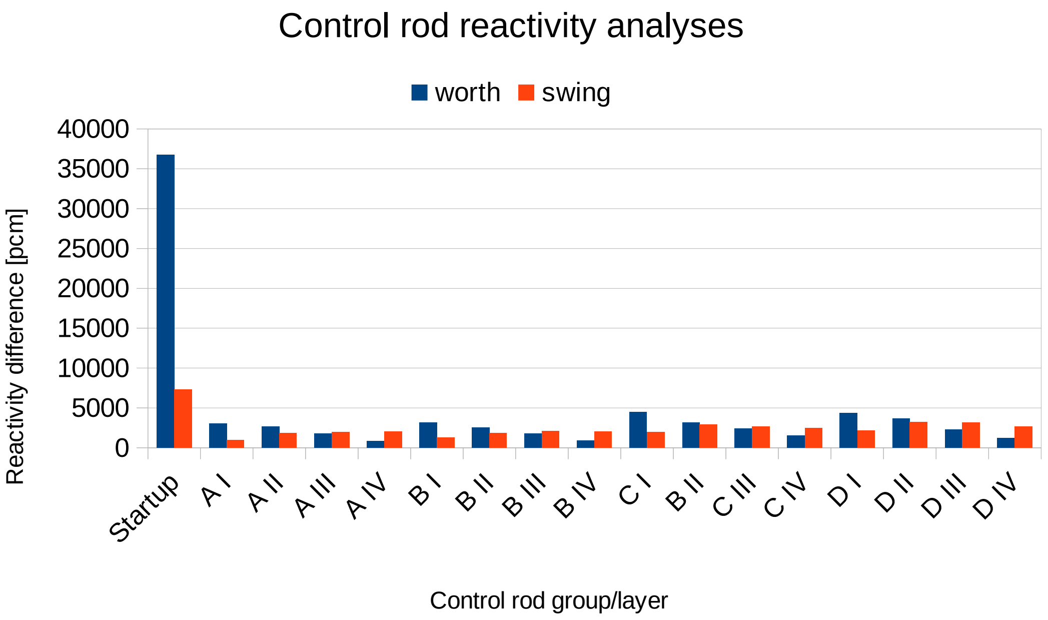
So-far optimal configuration of control rod.
Source: [4]

Control rod worth analyses

Every reactivity worth value is calculated as the difference in reactivity of the fresh core with all rods completely withdrawn and reactivity of the core with single specific rod parts inserted. [5]

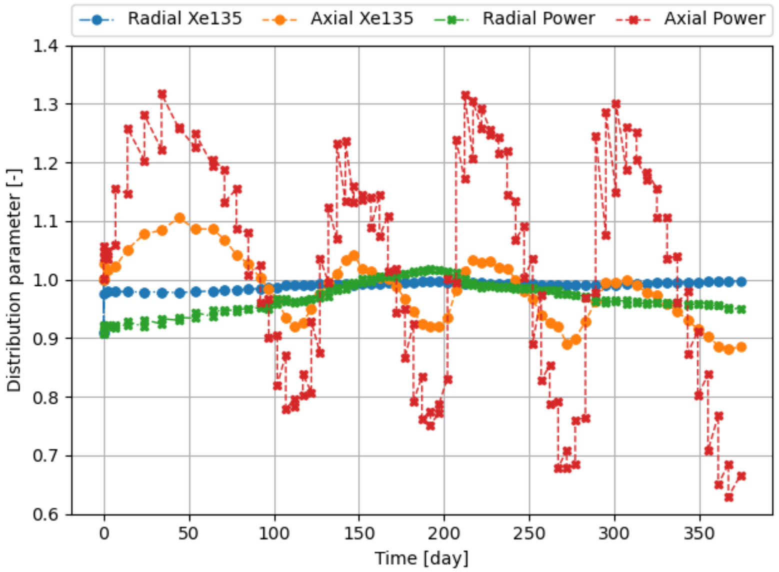
Reactivity swings are calculated as reactivity differences before and after specific rod layer operation.

The worth of tungsten radial layers decreases as the volumetric fraction of the radial layer decreases. Nevertheless, there is an almost opposite tendency in the case of reactivity swings.

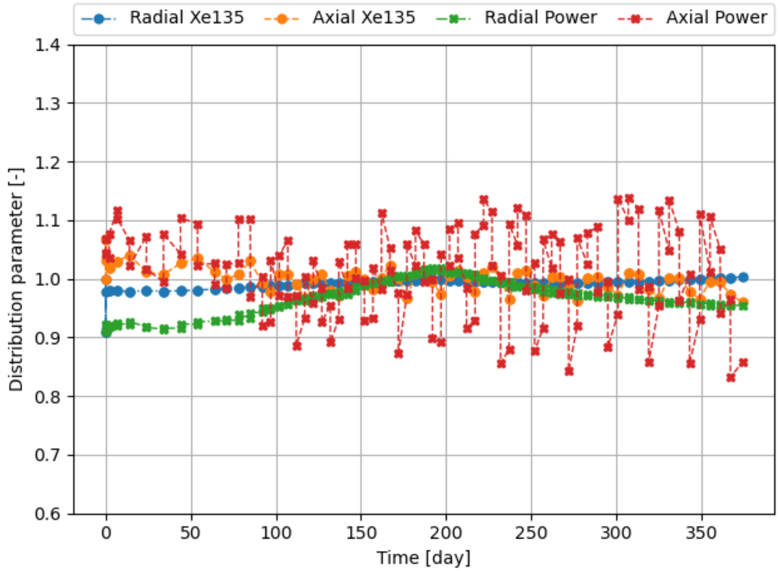


Results for optimal control rod stucture

A better timestep strategy was used to simulate situation when a CR layer is partially withdrown. Operations were perfomed roughly every 5 days. Additional 1 day long timesteps were still used after every operation.



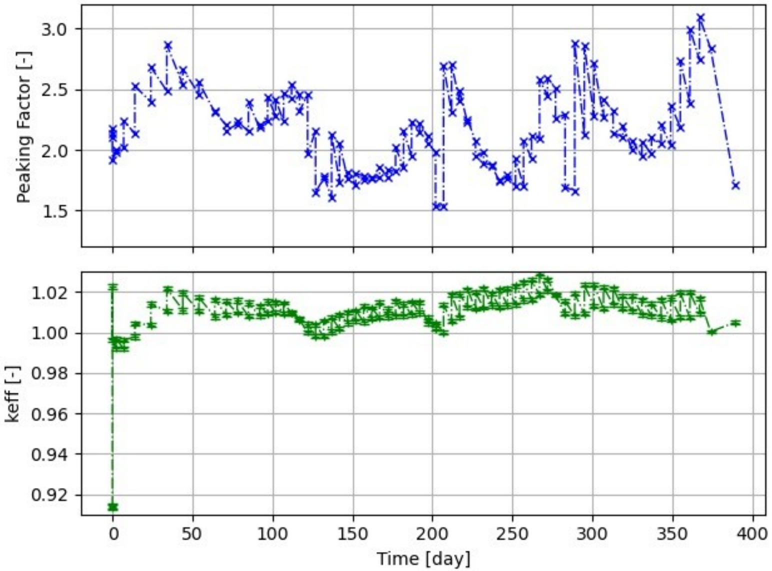
Distribution parameter without radial division of CRs, 1/16 of CR height of single CR group removed from the core at each operation



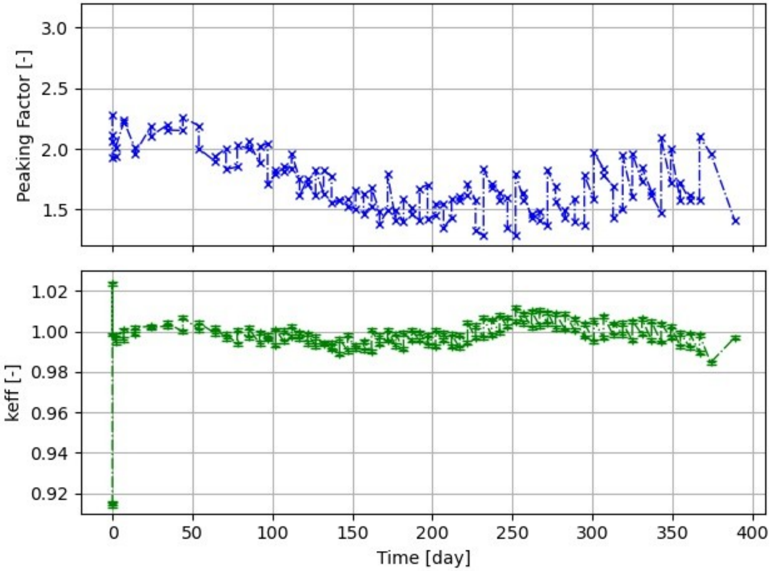
Distribution parameter with radial division of CRs, 1/4 of CR layer high of single CR group removed from the core at each operation

Results for optimal control rod stucture

More detailed calculations shows that the so-far optimized control rod structure not only still significantly improves the power profile, but also helps to keep the reactor critical.



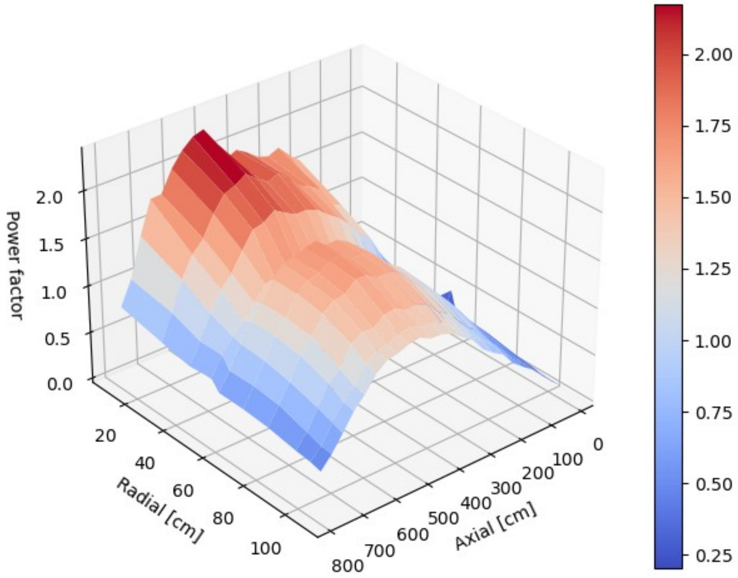
Power peaking factor and k_{eff} evolution without radial division of CRs



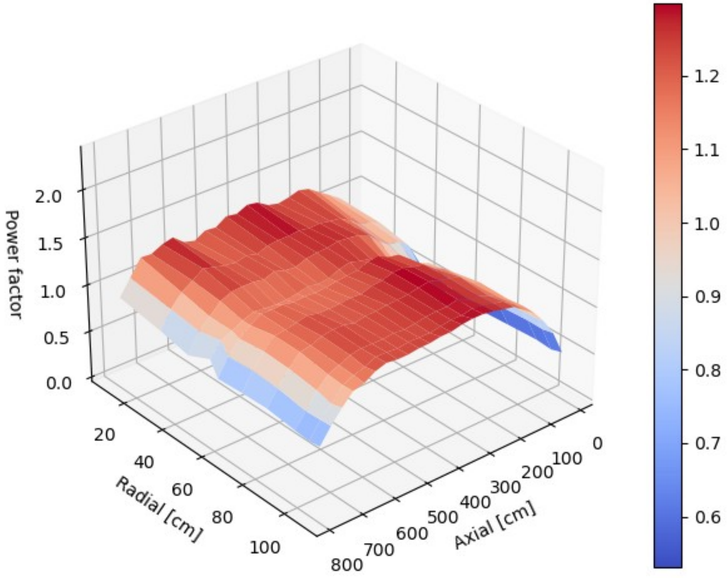
Power peaking factor and k_{eff} evolution with radial division of CRs.

Results for optimal control rod stucture

Even using refined timesteps the highest value of the power peaking factor appears at the beginning of the reactor operation.



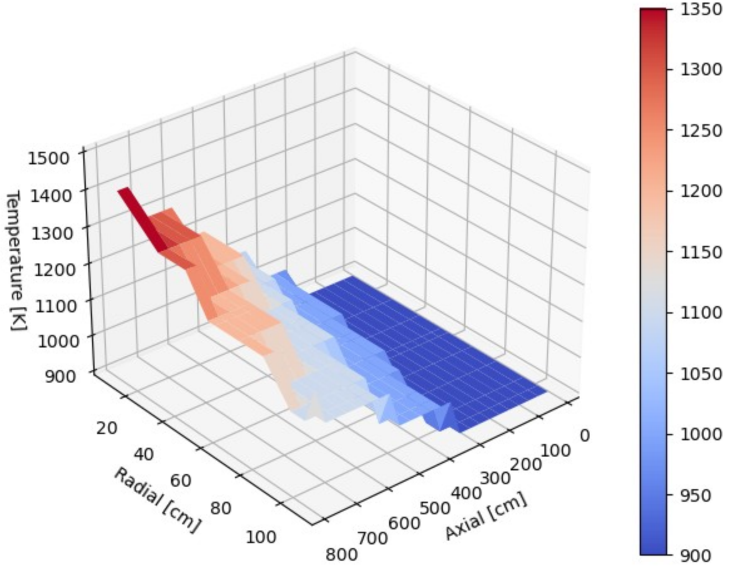
Power profile at day 7 with radial division of CRs – highest power peaking factor



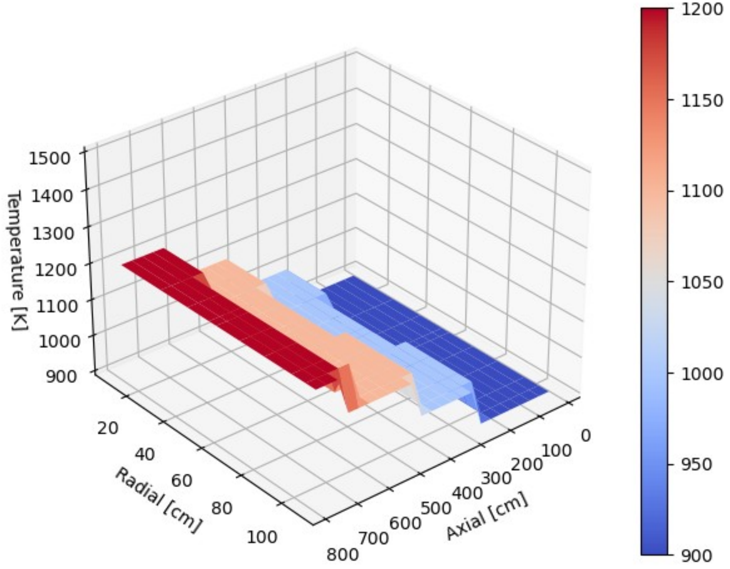
Power profile at day 227 with radial division of CRs. - lowest power peaking factor

Results for optimal control rod stucture

Although significant improvement of the power profile was achieved, there is still place to improve the temperature profile.



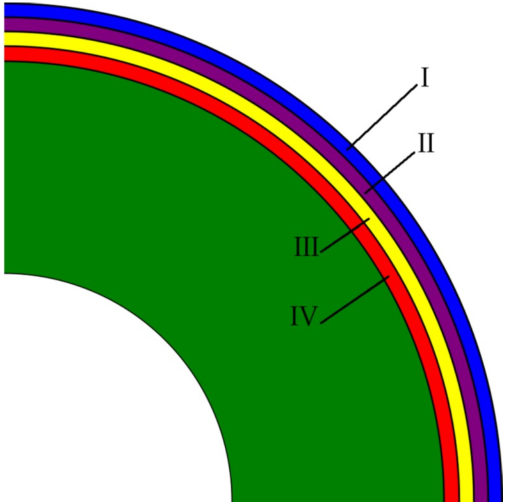
Temperature profile at day 7 with radial division of CRs.

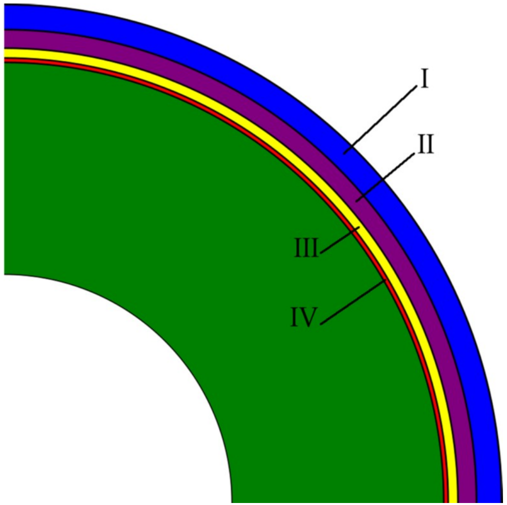


Temperature profile at day 227 with radial division of CRs.

Conclusions

- Radial division of control rods is effective way to reduce axial power oscillations if combined with division of control rods to sections
- Worth of the last removed control rod layer is significantly higher comparing to the other layers, thus the layer should contain small amount of absorber.
- At the end, the highest power peaking factor appeared at the beginning of the core operation. Since burnable poisons were used, further improvement can be achieved by introducing fuel with different enrichments.





Literature

1. Cetnar J. et. al.: *Advanced burnup assessments in prismatic HTR for Pu/MA/Th utilization using MCB system*, AGH, 2013
2. Cetnar J. et. al.: *The MCB Code for Numerical Modeling of Fourth Generation Nuclear Reactors*, Computer Science, vol. 16, p.329-350, 2015
3. Cetnar J. et. al.: *Przygotowanie różnych konfiguracji rdzenia pryzmatycznego reaktora HTGR na potrzeby analizy ekonomicznej*, AGH, 2020
4. Górkiewicz M., Cetnar J., *Flattening of the Power Distribution in the HTGR Core with Structured Control Rods*, Energies, 2021, 14, 7377
5. Savva, P.; Varvayanni, M.; Catsaros, N. Dependence of control rod worth on fuel burnup. Nucl. Eng. Des. 2011, 241, 492–497

Thank you for attention

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