Optimization of control rod design and operation strategy for reduction of power peaks in the HTTR-based core

NATIONAL CENTRE FOR NUCLEAR RESEARCH ŚWIERK

Michał Górkiewicz

Division of Nuclear Energy and Environmental Studies

Michal.Gorkiewicz@ncbj.gov.pl

Fundusze Europejskie
Wiedza Edukacja Rozwój

Rzeczpospolita Polska

Unia Europejska
Europejski Fundusz Społeczny

New reactor concepts and safety analyses for the Polish Nuclear Energy Program
POWR.03.02.00-00.I005/17

Outline

- Introduction
- Neutronic properties of HTGR
- Model of reactor core based on HTTR design
- Concept of radial division of control rod
- Methodology of oscillation analyses
- Results
- 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]

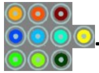
MCB is coupled with the POKE code that enables thermal-hydraulic calculations for prismatic HTGR cores models.

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 rods and section number

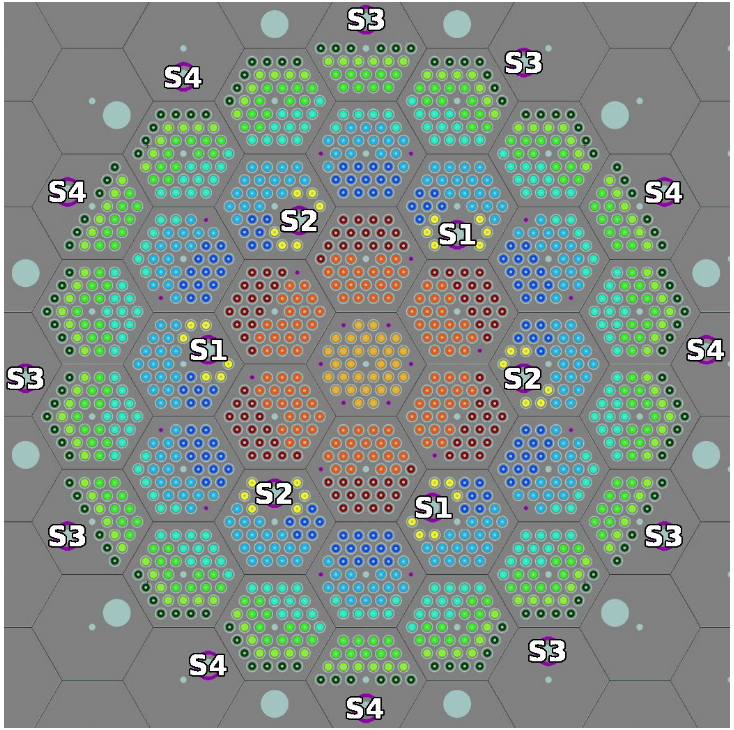
- fuel compacts grouped into burnable zones

10 radial burnable zones

24 axial burnable zones in 8 layers of blocks

240 burnable zones total

Special burnable zone near contol rods.



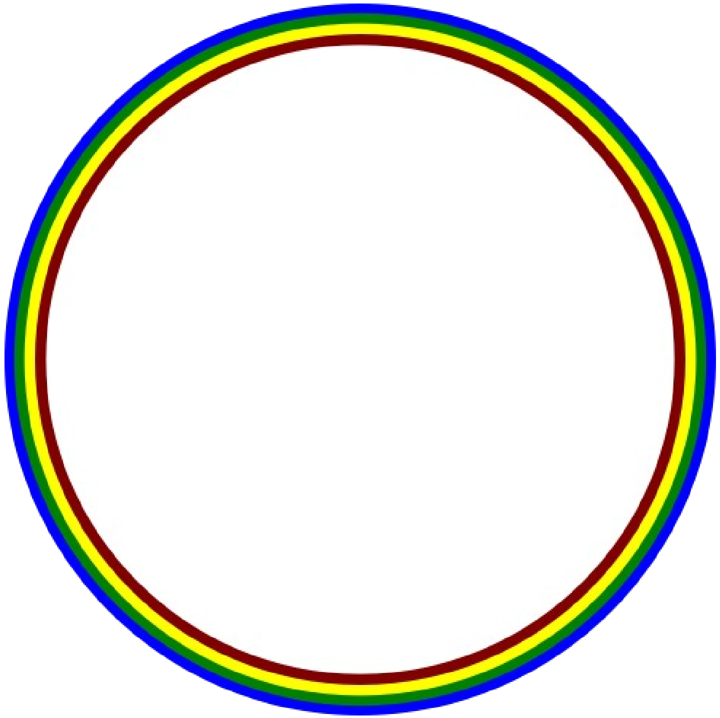
Modelled core configuration. Source: [2]

Concept of radial division of control rod

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

Contol rod operation starts from the outermost layer. When the outermost layer is fully withdrawn, operation of the next layer can start. The innermost layer is withdrawn as the last.

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

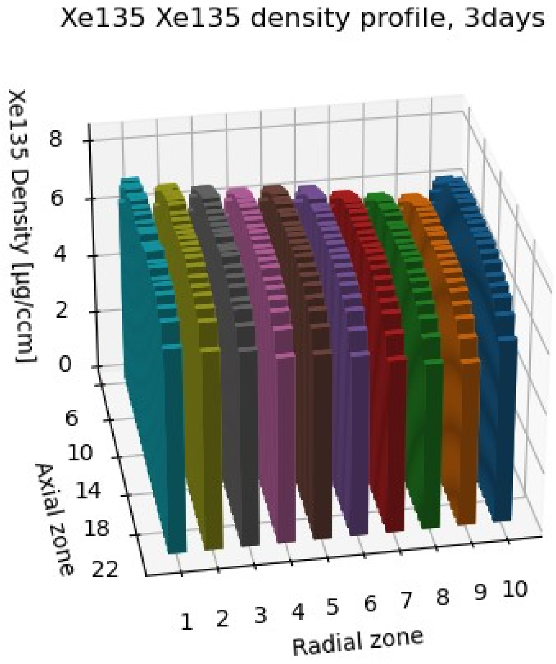


Configuration of control rod divided into four layers, each with equal volume.

Methodology of oscillation analyses

$$O_{i,j,t} = \frac{\sum_{k=1}^{k_{max}} Q_{i,j,k,t} d_k}{O_{i,j,0}} \cdot \frac{Q_{i,0}}{Q_{i,t}}$$

i – power or specific isotope concentration
j – direction (axial or radial)
t – number of timestep
k – number of burnable zone in direction j
$O_{i,j,t}$ – Oscillation parameter of i in direction j in timestep t
$d_{j,k}$ – average distance of burnable zone k in direction j
$Q_{i,j,k,t}$ – average value of i in direction j in burnable zone k
$O_{i,j,0}$ – Oscillation parameter in reference time step
$Q_{i,0}$ – total value of i in reference timestep
$Q_{i,t}$ – total value of i in timestep t

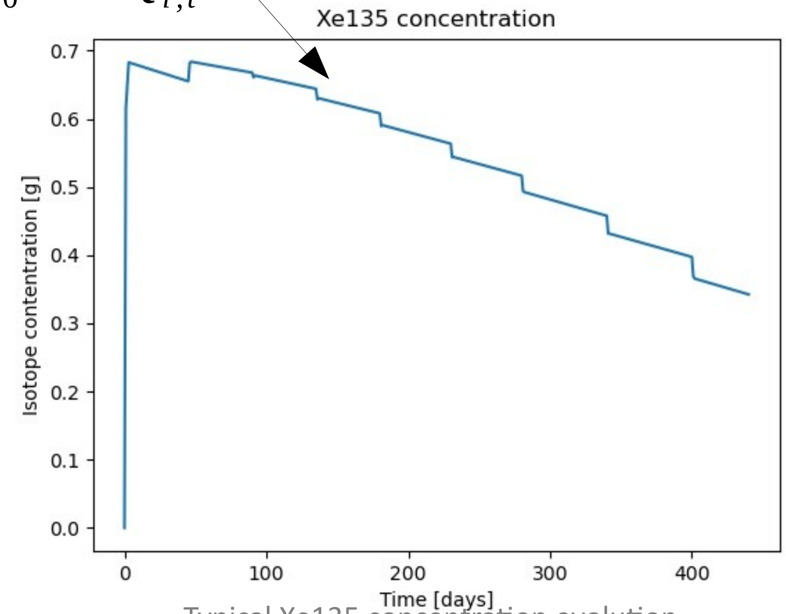


Typical Xe135 density distribution.

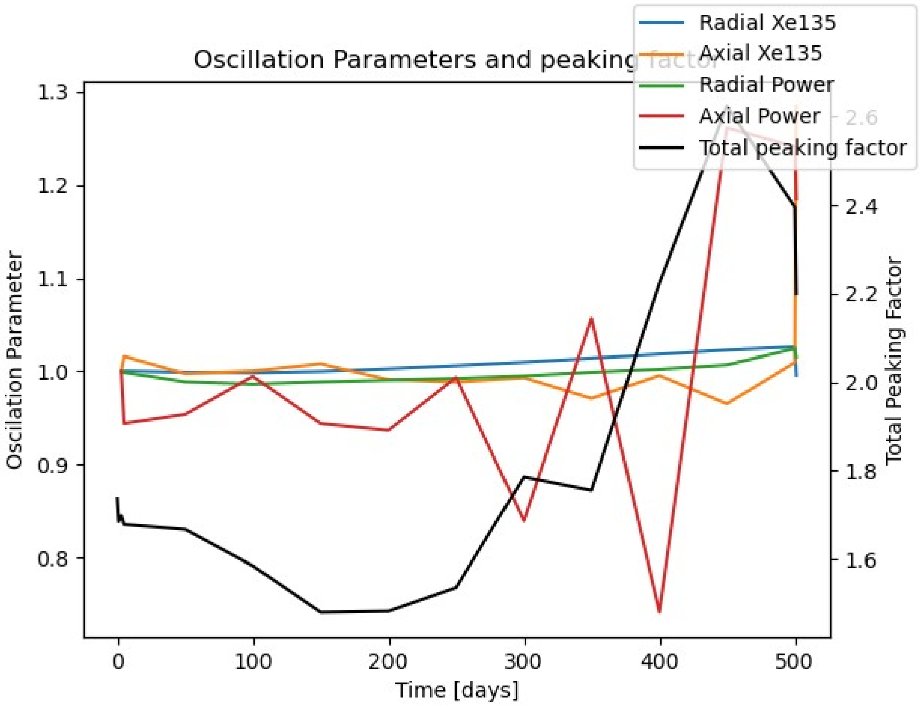
Methodology of oscillation analyses

$$O_{i,j,t} = \frac{\sum_{k=1}^{k_{max}} Q_{i,j,k,t} d_k}{O_{i,j,0}} \cdot \frac{Q_{i,0}}{Q_{i,t}}$$

Assumed 3 days as reference timestep.
d_k in axial direction is calculated as
$d_k = h_b(k\text{-}0.5)$
h_b – 1/3 block height
d_k in axial direction is average distance between all every fuel compact in k burnable zone to the center of the core.

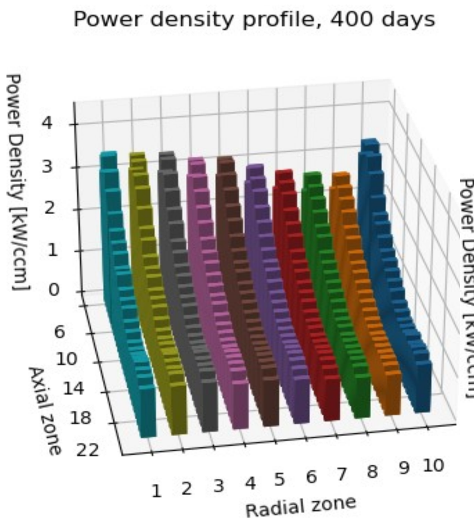


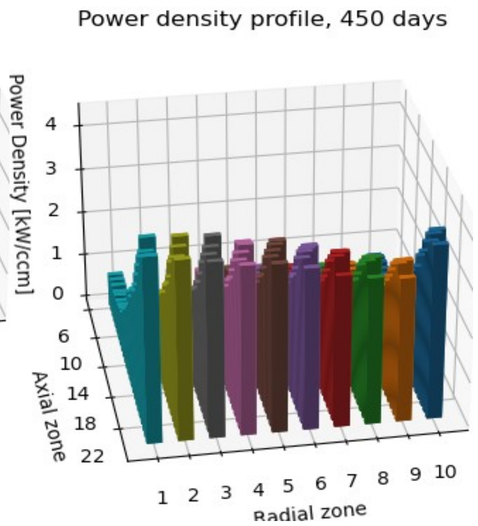
Typical Xe135 concentration evolution.



Oscillation parameters for control rods withdrawn for entire cycle.

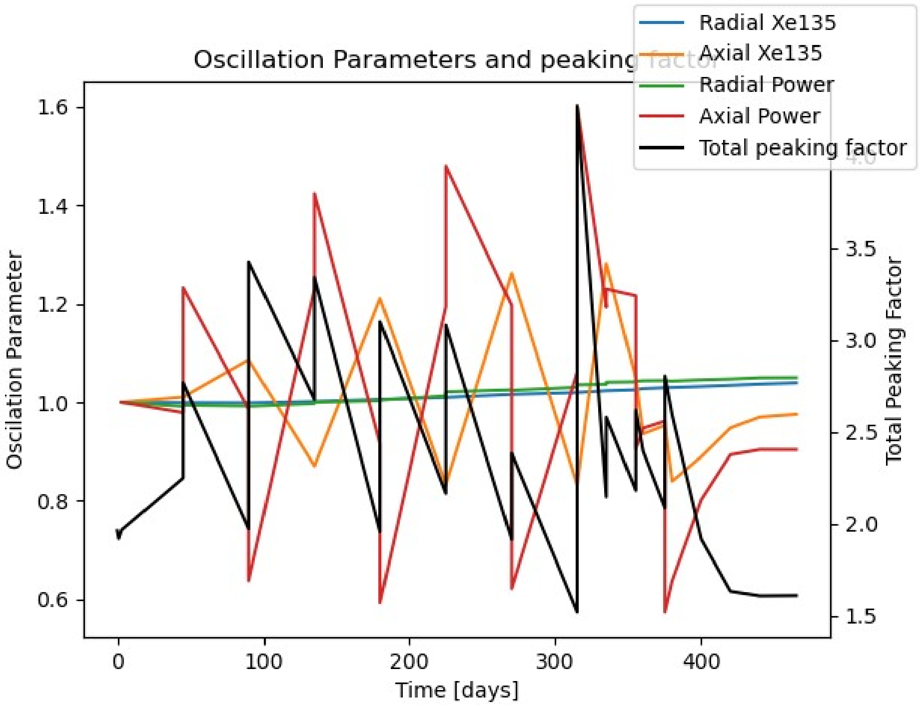
Power oscillations without control rods operations.



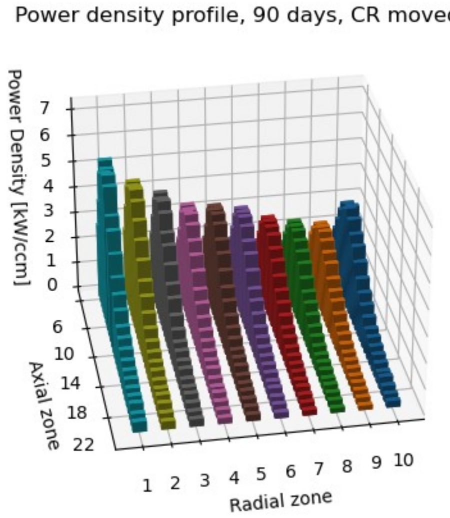


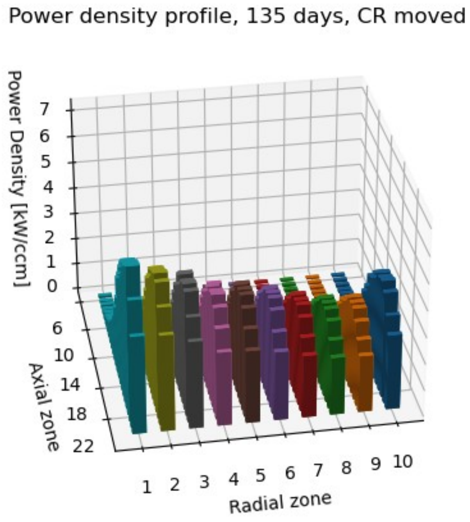
Results

Application of radial division of control rods.



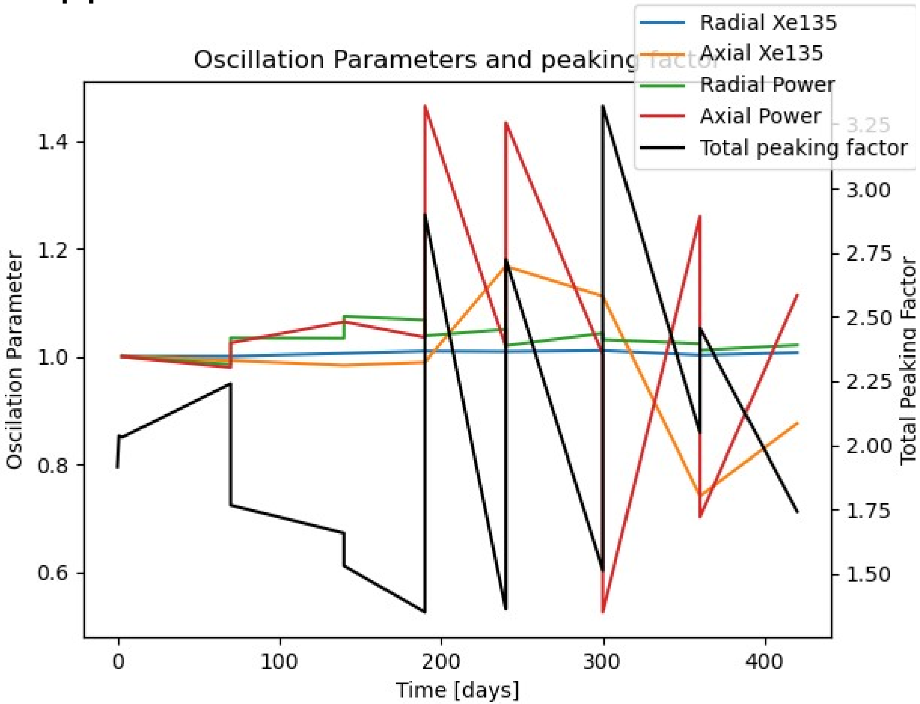
Oscillation parameters without division of control rods into sections. Operation strategy:
Axial halves of layers every 45 days;
Axial quarter of the innermost layer every 20 days.



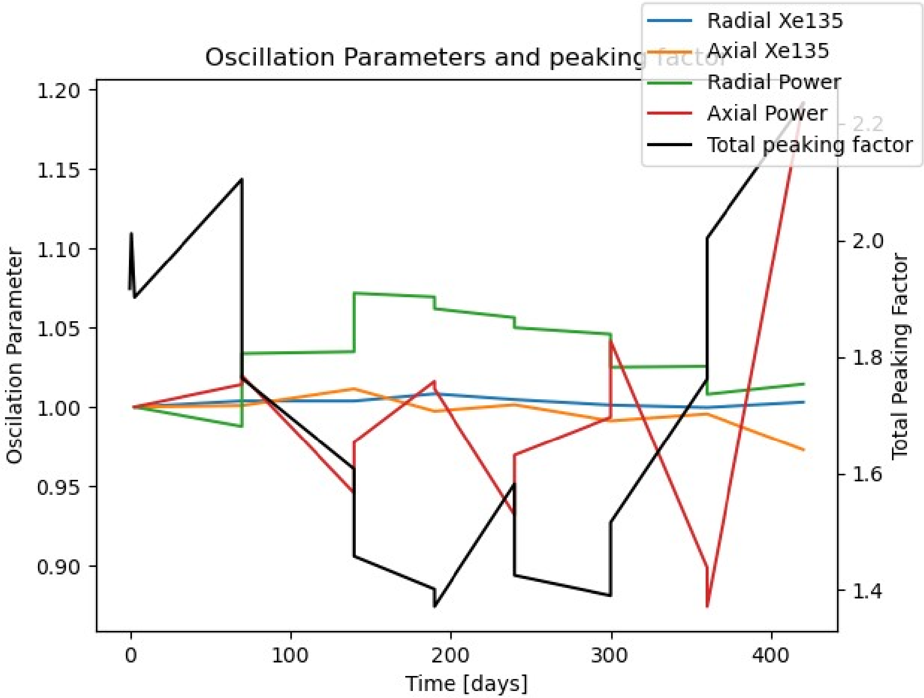


Results

Application of control rods division to sections.



Oscillation parameters. Operation strategy: 70d:S4-all; 140d:S3-all; 190d:S2-bottom halves; 240d:S2-inner halves; 300d:S1-bottom halves; 360d:S1-top halves



Oscillation parameters. Operation strategy: 70d:S4-all; 140d:S3-all; 190d:S2-outer halves; 240d:S2-inner halves; 300d:S1-outer halves; 360d:S1-inner halves

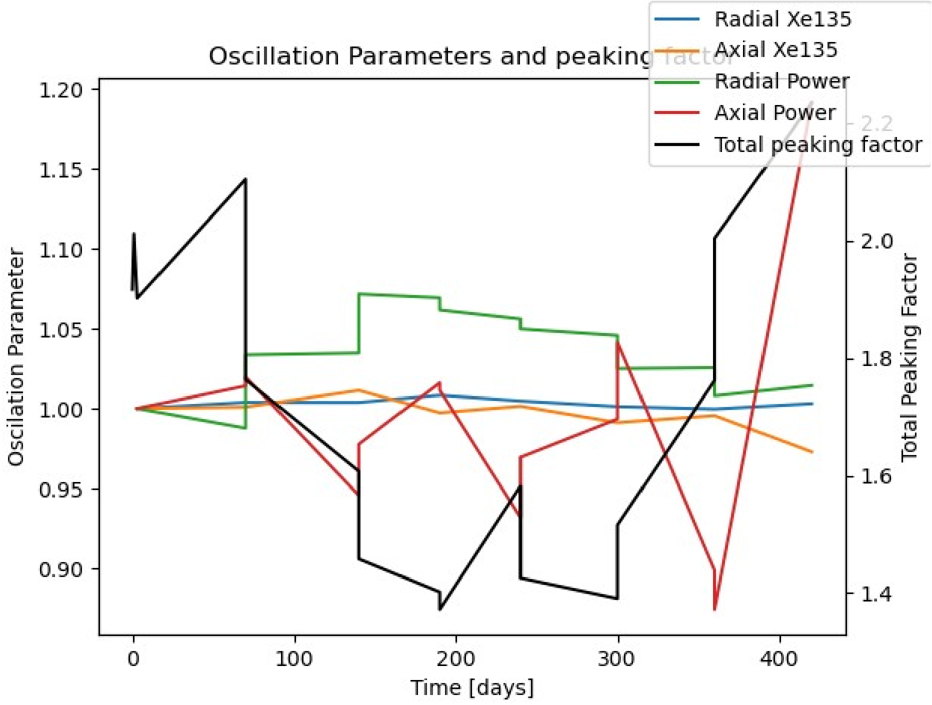
Xe135 Oscillations

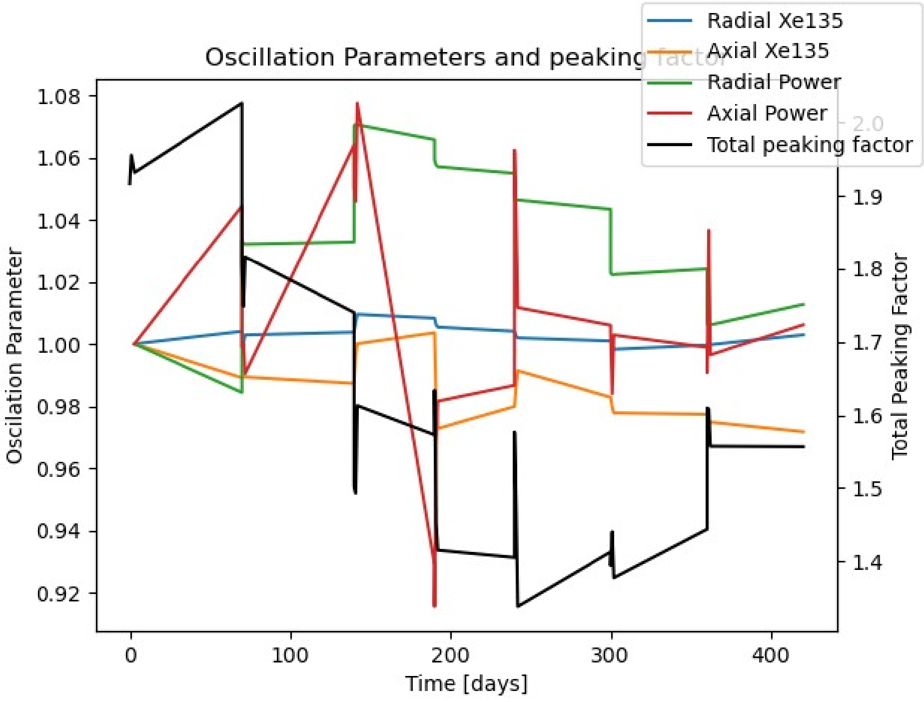
Does Xe135 really oscillate that much?

Numerical **O**scillations

Burnup calculations aiming to follow long term development use step lengths much longer than the timescale involved in physical xenon oscillations. Due to long steps 135I and 135Xe concentrations have time to reach saturation levels corresponding to the used flux at each step, making the physical xenon oscillation mechanism impossible. Instead, if the flux is tilted, the areas with high flux will get high xenon concentration during the following depletion step and the other way around. This in turn means that in the next neutronics solution the flux will tilt the other way, leading to an unphysical oscillation. [4]

Two additional 1 day long steps were applied after every operation.

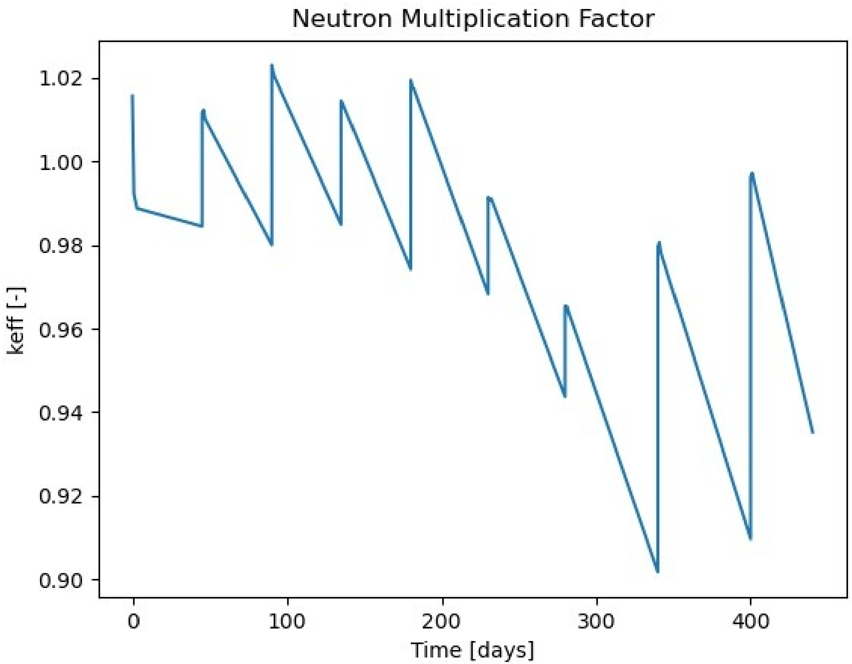


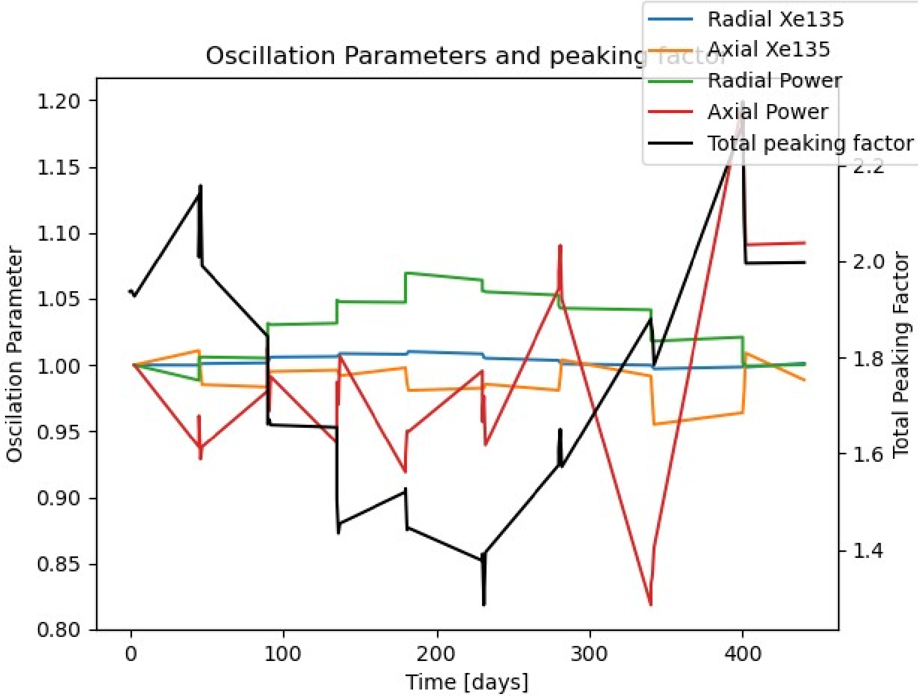


Oscillation parameters without (left) and with (right) additional steps. The same operation strategy in both cases: 70d:S4-All; 140d:S3-All; 190d:S2-Outer halves; 240d:S2-Inner halves; 300d:S1-Outer halves; 360d:S1-Inner halves

Results

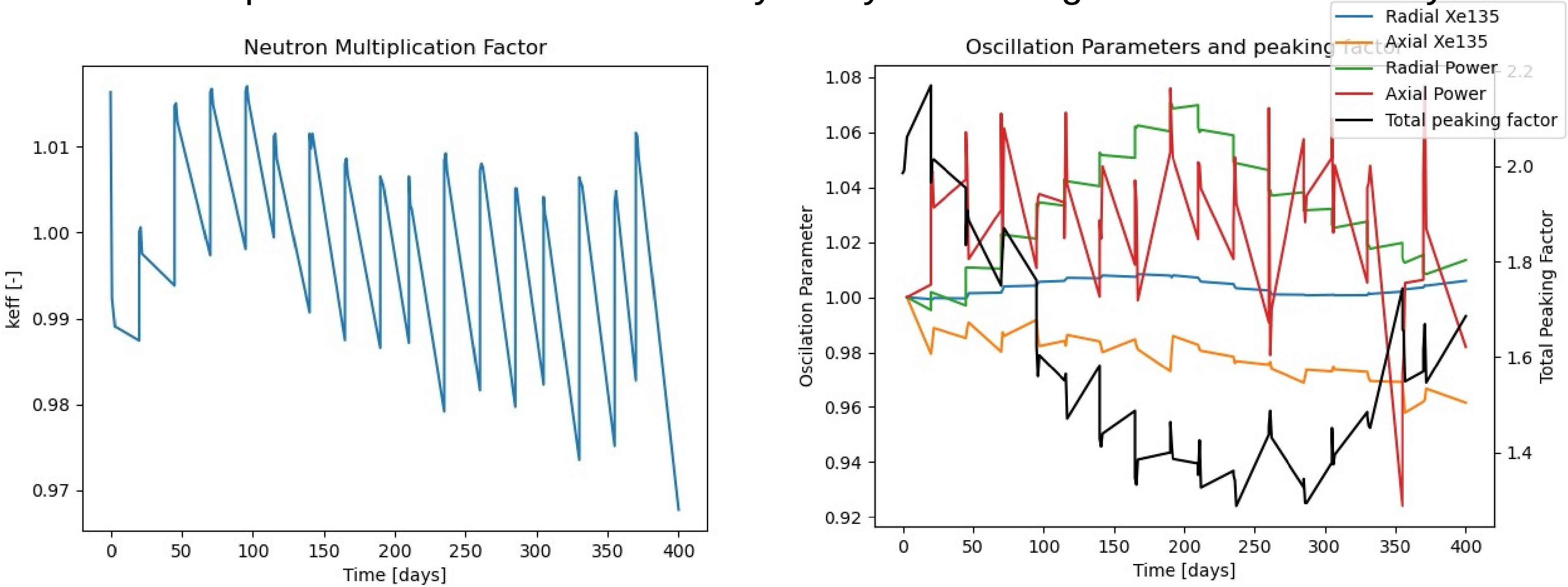
The innermost layers of control rods presents the highest control rod worth.





k-eff evolution (left) and Oscillation Parameters (right). Operation strategy:
45d:S4-3 outer layers; 90d:S4-innermost layer; 135d:S3-3 outer layers; 180d:S3-innermost layer;
230d:S2-outer halves; 280d:S1-outer halves; 340d:S2-inner halves; 400d:S1-inner halves

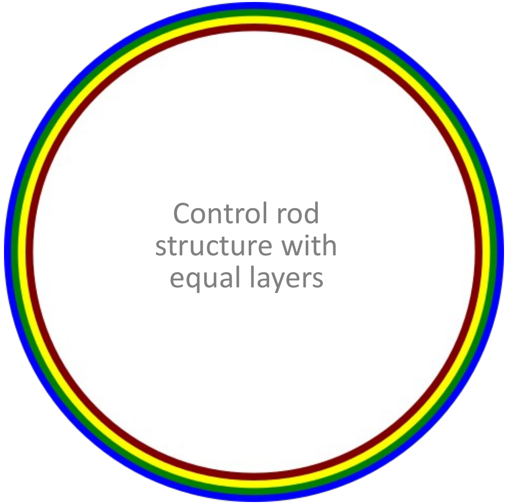
One can equalize worth of control rod layers by transfering material to outer layers.

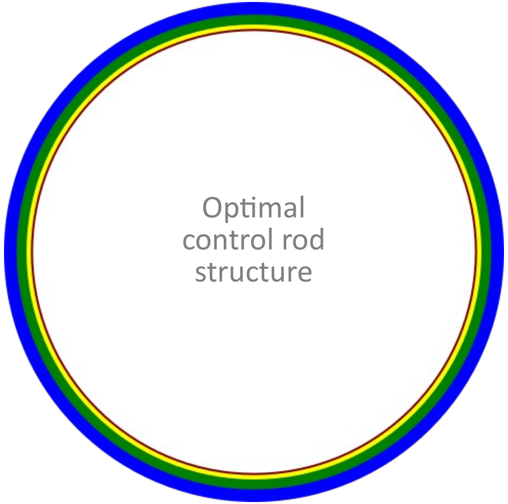


k-eff evolution (left) and Oscillation Parameters (right).
Operation strategy: One layer every 25 days.
Control rod volume distribution in layers (statring from outermost): 45%, 33.6%,14.3%, 7.1%

Conclusions

- Radial division of control rods is effective way to reduce axial power oscillations if combined with division of control rods to sections
- It is essential to reduce Xe135 numerical oscillations
- Worth of control rod layer is significantly higher for innermost layer, thus the layer should contain small amount of absorber – implementation may be highly unpractical in reality





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. Dufek J. et. al., Preventing xenon oscillations in Monte Carlo burnup calculations by equilibrium xenon distribution, Annals of Nuclear Energy, 2013, vol. 60, p. 78-85
5. Bogdanova E.V., Xenon instability study of large core Monte Carlo calculations, Kerntechnik, 2016, vol.81

Thank you for attention

Michał Górkiewicz

Division of Nuclear Energy and Environmental Studies

Michal.Gorkiewicz@ncbj.gov.pl

Fundusze Europejskie Wiedza Edukacja Rozwój

Rzeczpospolita Polska

Unia Europejska Europejski Fundusz Społeczny

New reactor concepts and safety analyses for the Polish Nuclear Energy Program
POWR.03.02.00-00.I005/17