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A Direct Comparison of High-Order and Low-Order Neutronics Calculations of the 165 MWth Xe-100 Reactor

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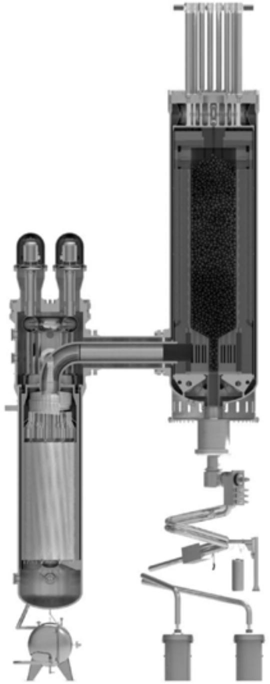
Background

(Wikipedia)

~ 60 years



(x-energy.com)

AVR reactor
World's first pebble-bed reactor
Jülich Research Centre, West Germany
46 MWt (15MWe)
Operated from 1967 - 1988

In 2020, Xe-100 reactor was awarded ARDP
World's first commercial scale advanced nuclear reactor
Washington state, U. S.
200 MWt (82.5MWe)
Delivered by 2027

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Objective

Currently, the Xe-100 design has only been modeled with X-Energy's in-house code VSOP-A [2], which is a lower-order diffusion code. In this study, we are building a high-order Serpent [3] Monte Carlo neutronics model to investigate the neutronics characteristics of the Xe-100 design and to perform a code-to-code verification of the results obtained.

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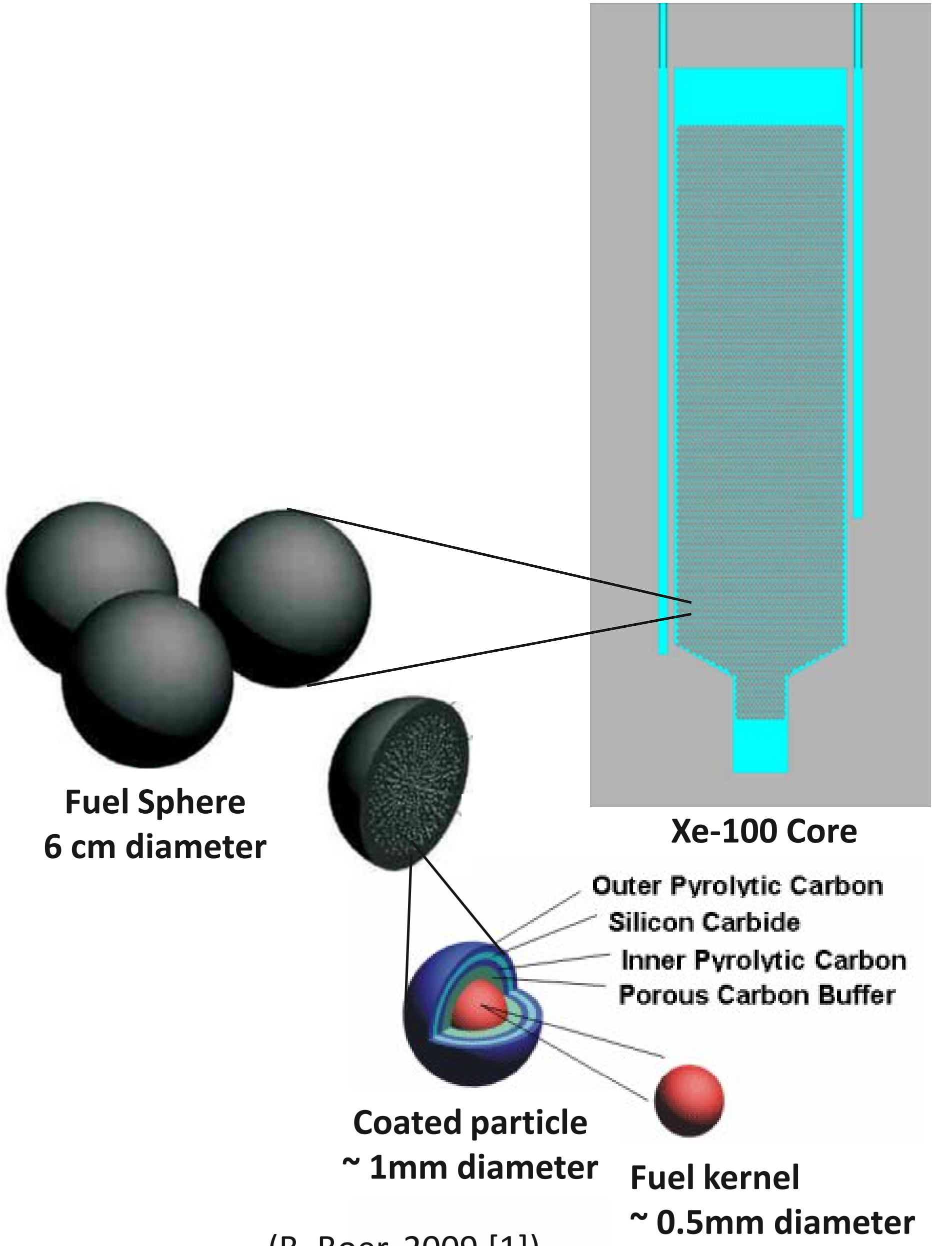
Xe-100 design (1)

- Features
  - Helium-cooled;
  - graphite-moderated;
- TRistructural-ISOtropic (TRISO) fuel
  - Microencapsulated coated fuel particles;
  - Fuel kernel;
  - Four layers of three isotropic materials;
  - Vessel for fission product gases;
- Advantages
  - online refueling scheme;
  - low excess reactivity;
  - high outlet coolant temperature;
  - capability of the load-following mode;
  - Etc.



(B. Boer, 2009 [1])

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Xe-100 design (2)

Xe-100 (X Energy, LLC, United States of America)

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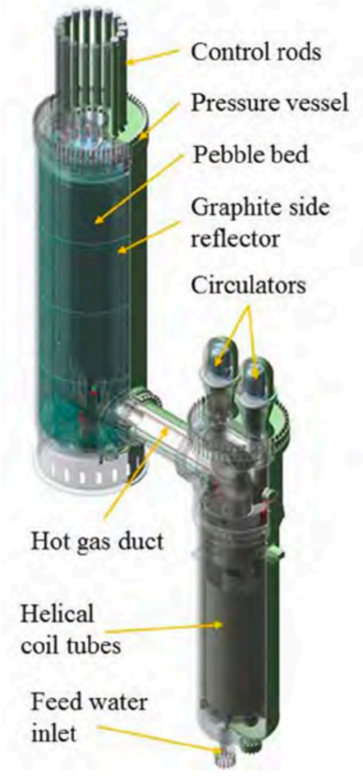
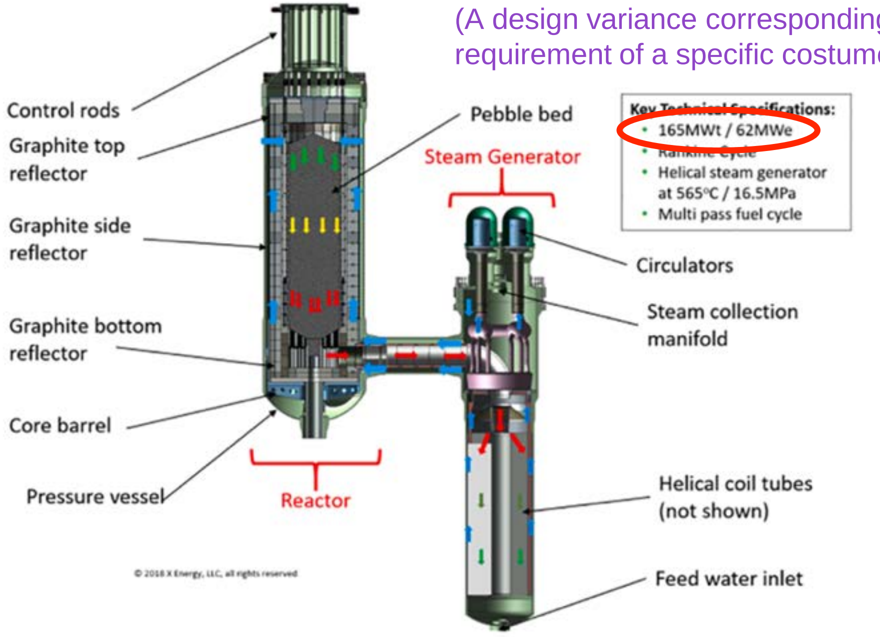
Nominal design [4]



MAJOR TECHNICAL PARAMETERS	
Parameter	**Value**
Technology developer, country of origin	X Energy, LLC, United States of America
Reactor type	Modular HTGR
Coolant/moderator	Helium/graphite
Thermal/electrical capacity, MW(t)/MW(e)	200 / 82.5
Primary circulation	Forced helium circulation
NSSS Operating Pressure (primary/secondary), MPa	6.0 / 16.5
Core Inlet/Outlet Coolant Temperature (°C)	260 / 750
Fuel type/assembly array	UCO TRISO/pebbles
Number of fuel assemblies in the core	220 000 pebbles per reactor
Fuel enrichment (%)	15.5
Core Discharge Burnup (GWd/ton)	165
Refuelling Cycle (months)	Online fuel loading
Reactivity control mechanism	Thermal feedback & control rods
Approach to safety systems	Passive
Design life (years)	60
Plant footprint (m²)	340m x 385m (4 reactor modules with 4 turbines)
RPV height/diameter (m)	16.4 / 4.88
RPV weight (metric ton)	274
Seismic Design (SSE)	0.5g
Fuel cycle requirements / Approach	Uranium once through (initially)
Distinguishing features	Online refuelling, core cannot melt and fuel damage minimized by design, independent radionuclide barriers, potential for advanced fuel cycles
Design status	Basic design development

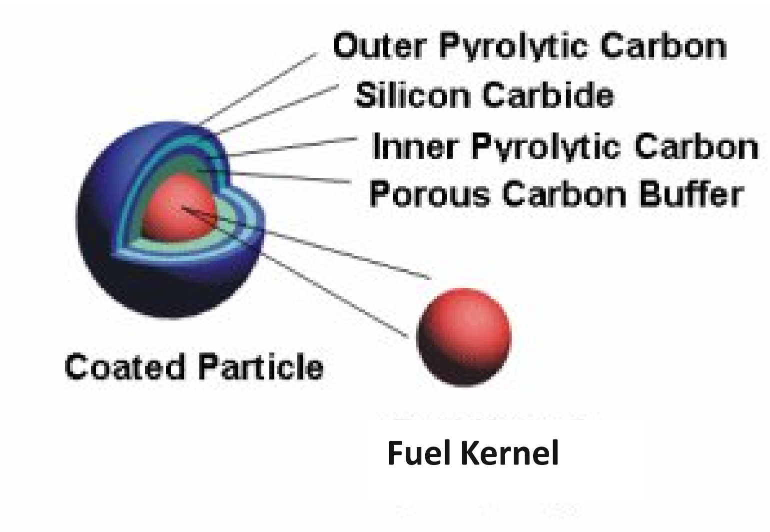
Design considered in this study [5]

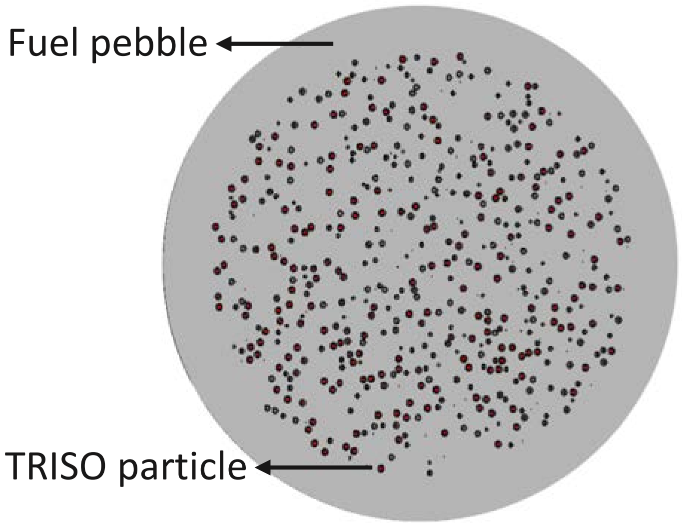
(A design variance corresponding to the requirement of a specific costumer)



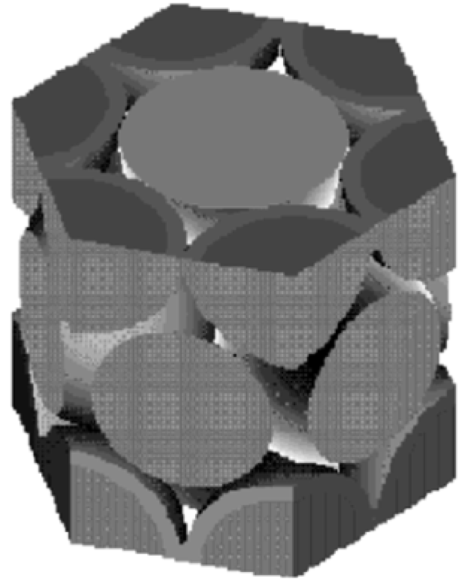
- 200MWt/82.5MWe (nominal design)
- 165MWt/62.0MWe (this study)
- At this preliminary stage, only public data were employed.

Xe-100 Serpent model (fuel pebble)





TRISO distribution in a fuel pebble



HCP unit cell of the fuel pebbles [6]

- Kernel material: $UC_{0.5}O_{1.5}$
- ^{235}U enrichment: 15.5 wt.%
- Kernel diameter: 0.425 mm
- Buffer layer thickness: 100 µm
- IPyC layer thickness: 40 µm
- SiC layer thickness: 35 µm
- OPyC layer thickness: 40 µm

- TRISO particles per pebble: 19,542
- Uranium loading per pebble: 7 g
- TRISO particles randomly distributed
- outer fuel-free zone thickness: 5 mm

- Pebbles in the core: 219,503
- Same TRISO distribution
- Hexagonal Closest Packing (HCP)
- Discrete Element Method (DEM)

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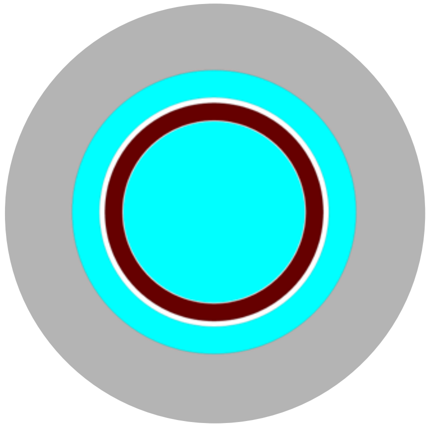
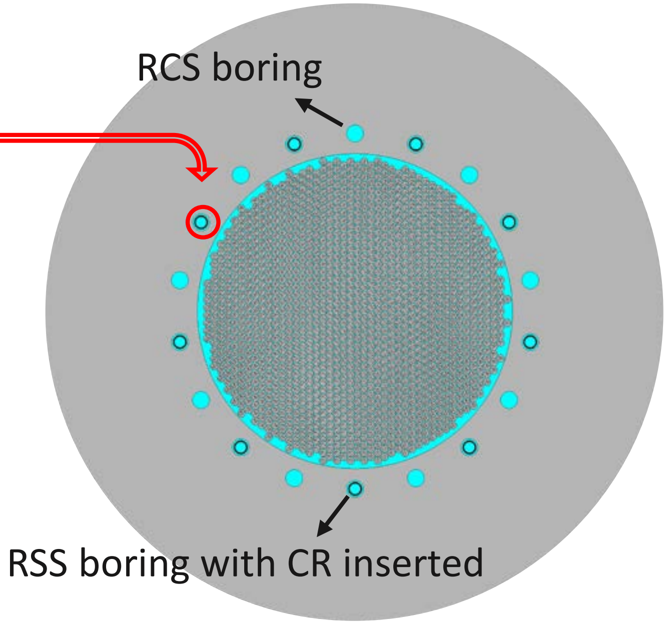
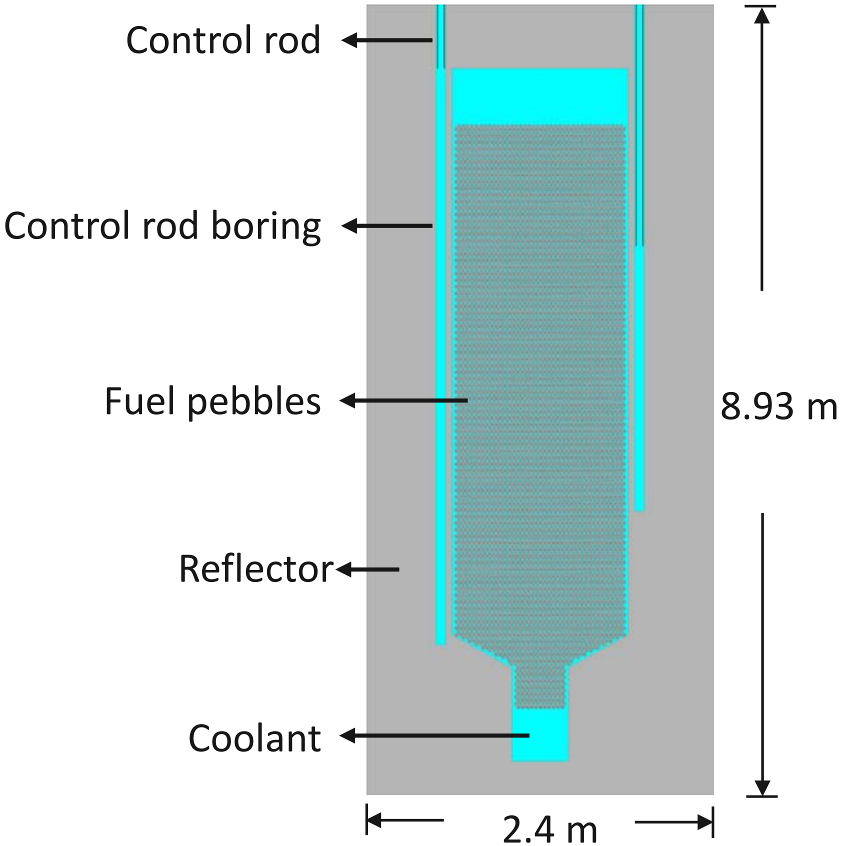
Xe-100 Serpent model (core)



Top view of the CR



Top view of the core



Side view of the core

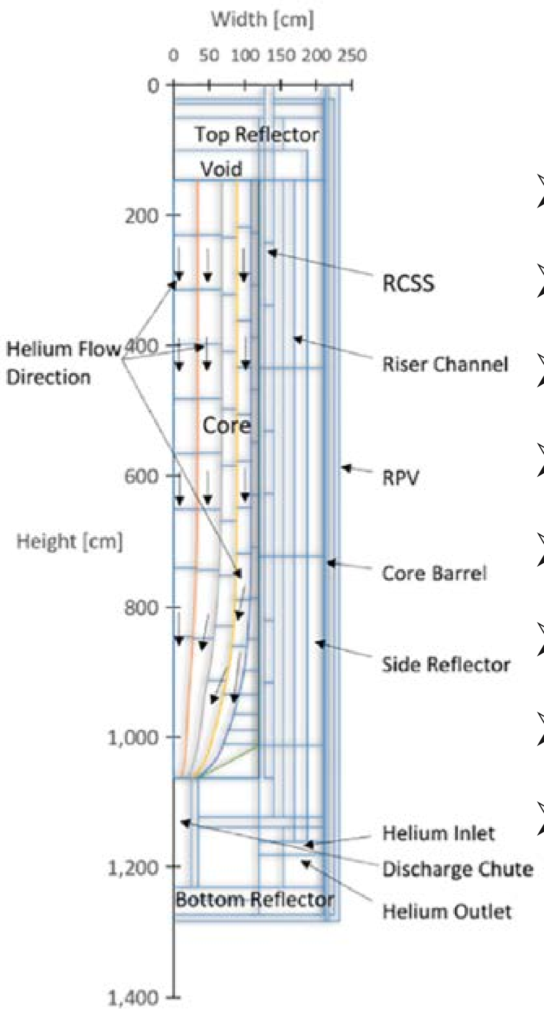
- B_4C compacts (8 mm thickness)
- Incoloy-800H canisters
- inner radius: 41.5 mm
- inner wall thickness: 0.5 mm
- outer wall thickness: 2.5 mm

- Borings are 10 cm from active core
- Diameters: 13 cm
- Active length: 660 cm
- Reactivity Control System (RCS)
  - CR x 9; max. insertion 660 cm
- Reserve Shutdown System (RSS)
  - CR x 9; max. insertion 860 cm

- ENDF/B-VII.0
- 1,000,000 realizations per cycle
- 500 active cycles
- $\pm k_{eff} < 10$ pcm
- 13 hours with 40 processor cores

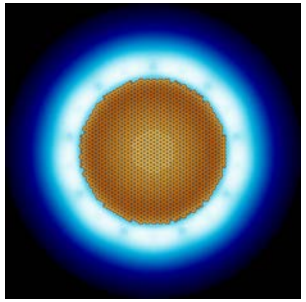
Differences between the models (VSOP-A ⇔ Serpent)

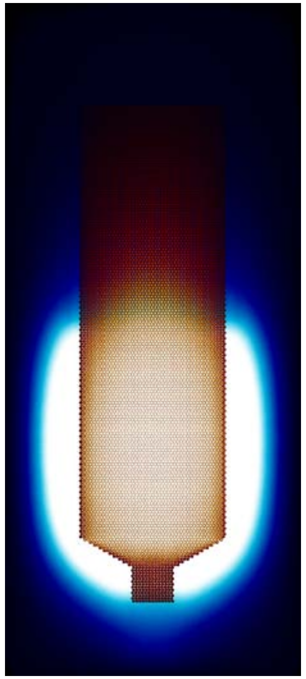
VSOP-A model



- Deterministic (diffusion)
- XS generation: difficult
- Flux structure: 4 groups
- Fuel: incompressible flow
- BU phases: all (run-in, etc.)
- TH feedbacks: yes
- Status: mature
- Geometric details: complete

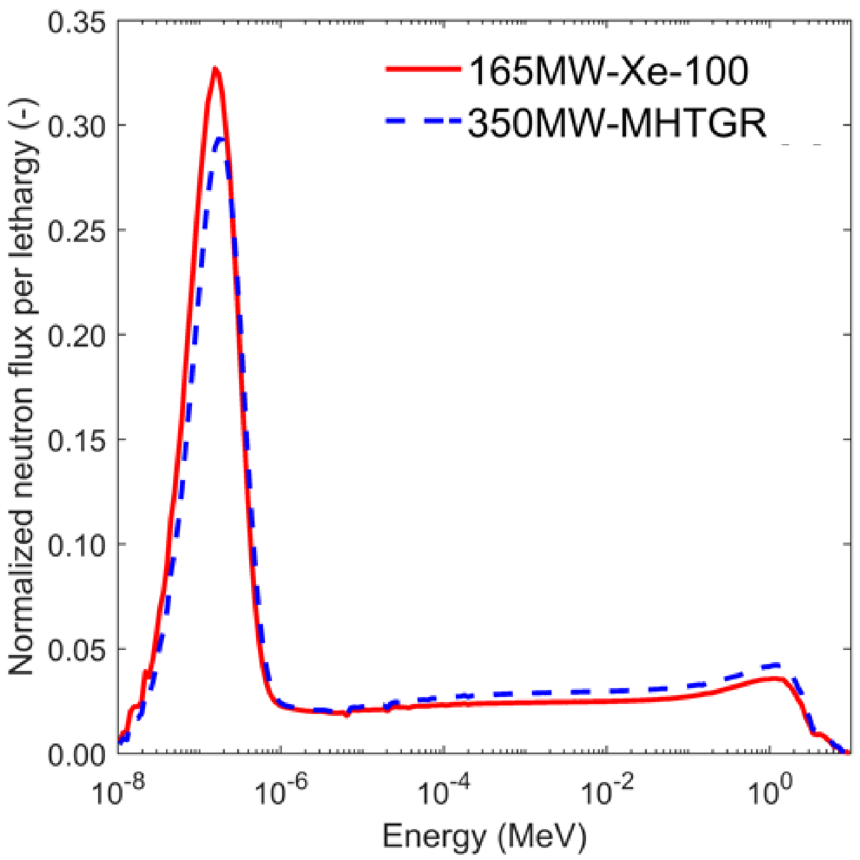
Serpent model

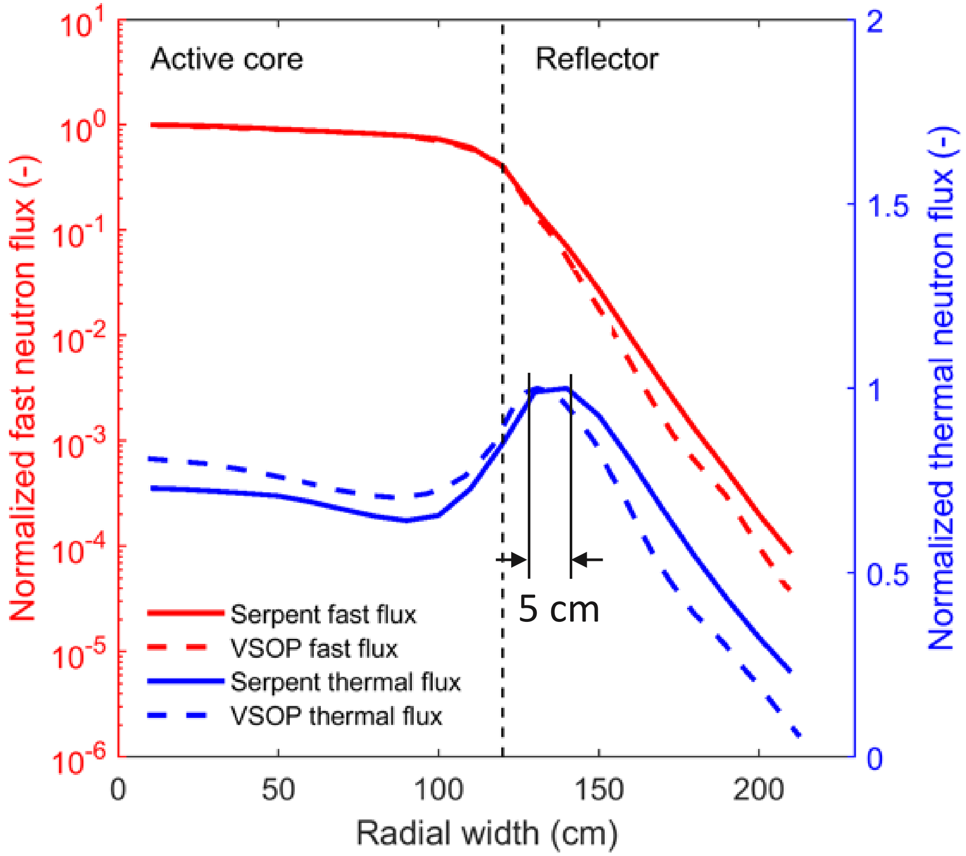




- Monte Carlo (5×10^8 histories)
- XS generation: naturally solved
- Flux structure: continuous
- Fuel: single pebble resolved
- BU phases: fresh core
- TH feedbacks: no (900K/600K)
- Status: preliminary
- Geometric details: in progress

Results comparisons (spectra and flux distributions)





- Neutron spectra
- 165MW Xe-100 ⇔ GA's 350MW MHTGR
- Similar hardness

- Radial neutron flux distributions
- 4-group structure
- Normalized based on max. flux

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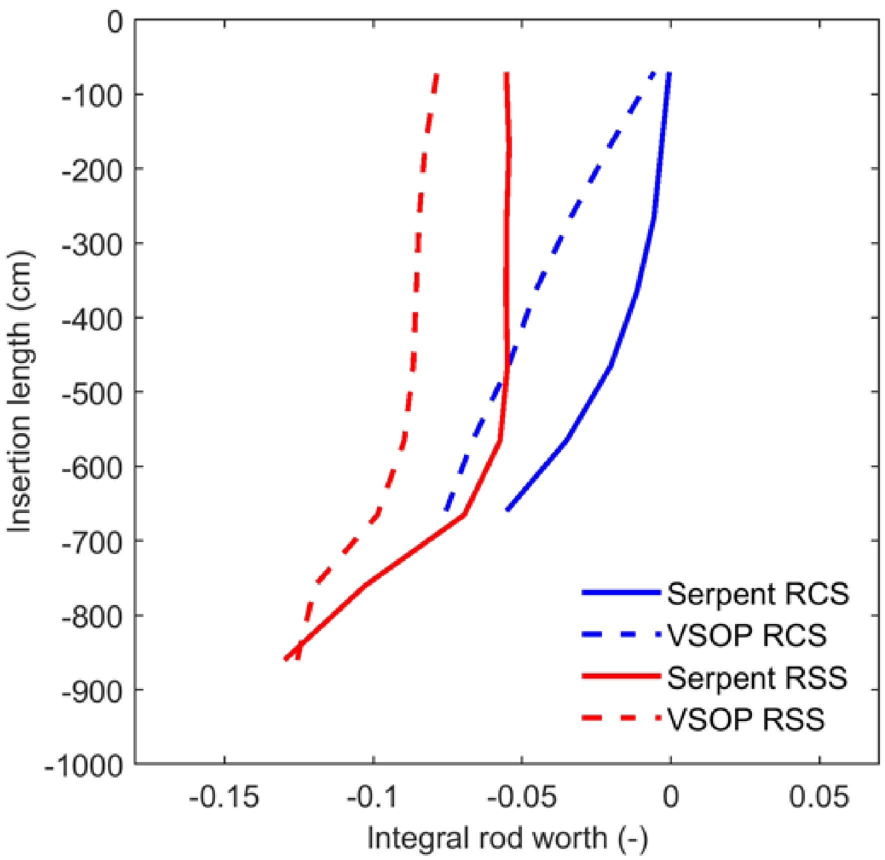
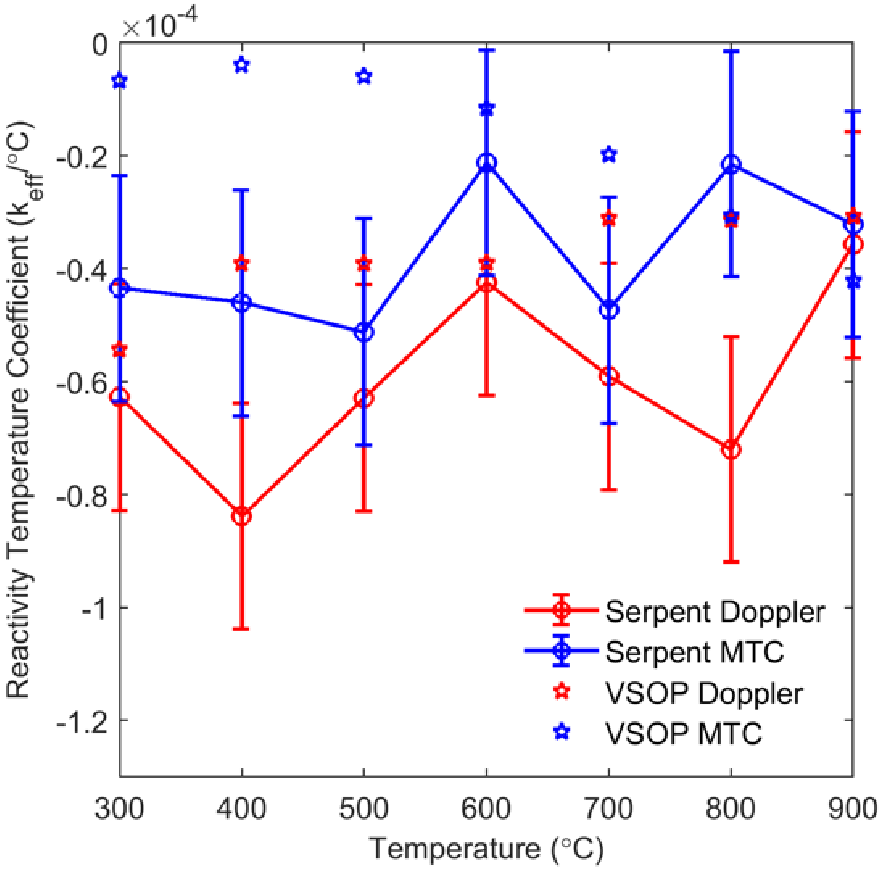
Results comparisons (CR worth and RTC)





- Difference w.r.t. the k_{eff} with all CR withdrawn
- Worth of the RSS was minor in the overlap region
- Similar trend
- Max. discrepancy ~ 3400 pcm

- $RTC(T) = \frac{k_{eff}(T+50℃)-k_{eff}(T-50℃)}{100℃}$
- Doppler Coef. (moderator temp. at 600K)
- MTC (fuel temp. at 900K)

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Summary and …

- A preliminary Serpent model of the 165MWth Xe-100 design was built
- Neutronics characteristics were investigated
- Comparative studies demonstrated the Serpent model to be reasonable

Future work

- Extension of the current Serpent model
- Modeling of more geometric details (e.g., coolant channels)
- Implementation of the discrete element method (DEM)

References

- [1] B. BOER, “Optimized Core Design and Fuel Management of a Pebble-Bed Type Nuclear Reactor,” ISBN 978-1-58603-966-0 (2009).
- [2] E. J. MULDER, “VSOP-A: Code System for Simulating Aspects of the Reactor Physics and Fuel Cycle,” MulTech Report MTR-001 (Jul 2019).
- [3] J. LEPPÄNEN, “The Serpent Monte Carlo Code: Status, Development and Applications in 2013,” Ann. Nucl. Energy, 82, 142–150 (2015).
- [4] IAEA, “Advances in Small Modular Reactor Technology Developments,” Technical report (2020).
- [5] E. J. MULDER and W. A. BOYES, “Neutronics characteristics of a 165MWth Xe-100 reactor,” *Nucl. Eng. Des.*, **357**, 110415 (2020).
- [6] F. C. DIFILIPPO, “Monte Carlo calculations of pebble bed benchmark configurations of the PROTEUS facility,” *Nucl. Sci. Eng.*, **143**, 240–253 (2003).