Evaluating the fulfilment of control rod related nuclear design bases for an SMR core using the Kraken computational framework

What is Kraken?

- Computational framework for reactor core physics.
- Developed at VTT Technical Research Centre of Finland Ltd.
- Kraken includes:
  - ***Serpent*** – high-fidelity neutronics
  - ***Ants*** – reduced-order neutronics
  - ***Kharon*** – thermal hydraulics
  - ***SuperFINIX*** – fuel behaviour
  - ***Cerberus*** – multi-physics driver

Putting Kraken to use

- Kraken has been tested with simple 3x3 assembly models.
- In this work, Kraken is applied to analyze a reactor core corresponding to an SMR.

Reactor module

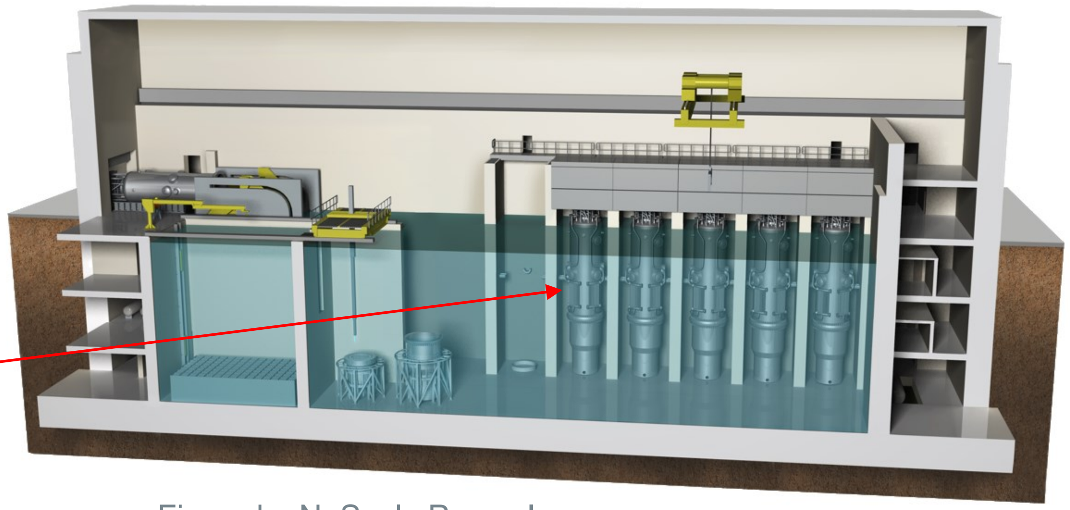
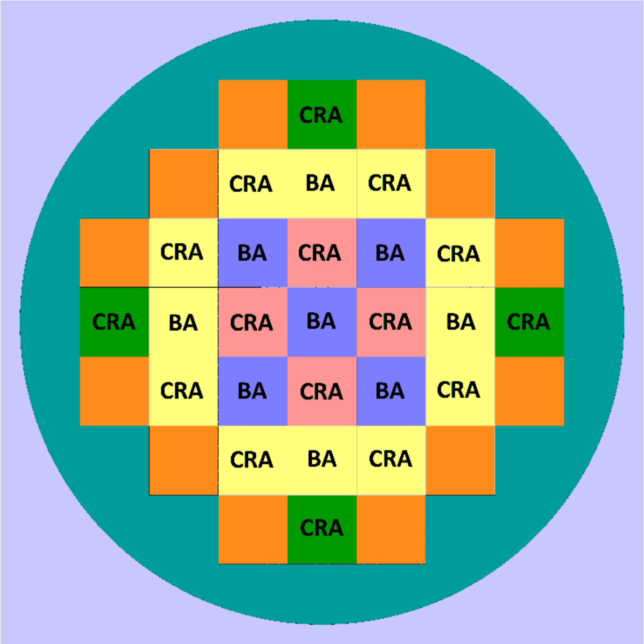


Figure by NuScale Power Inc.

Model for the reactor core

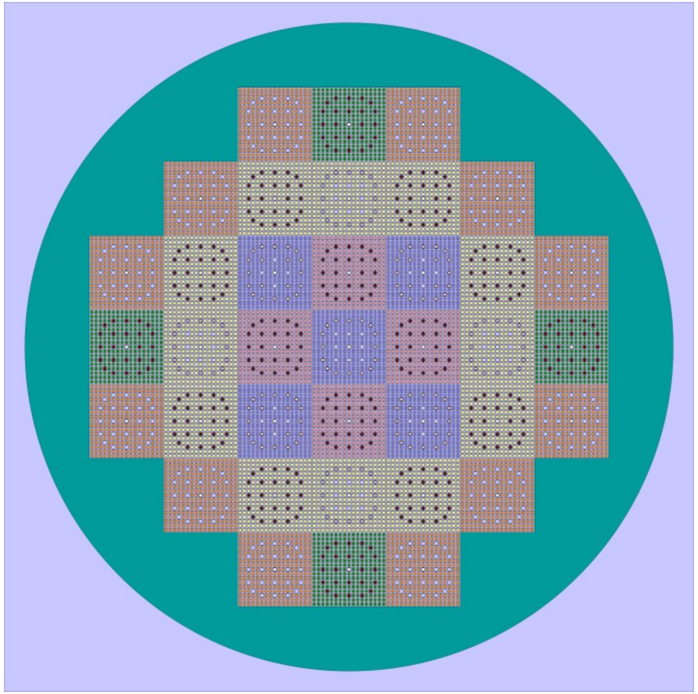
- SMR-scale PWR core.
- Data from the BEAVRS benchmark[1] and NuScale documents[2].
- The core consists of
  - 37 fuel assemblies with 264 fuel rods in each assembly
  - 16 Control Rod Assemblies (CRAs)
  - Borosilicate glass Burnable Absorbers (BA) in 9 assemblies



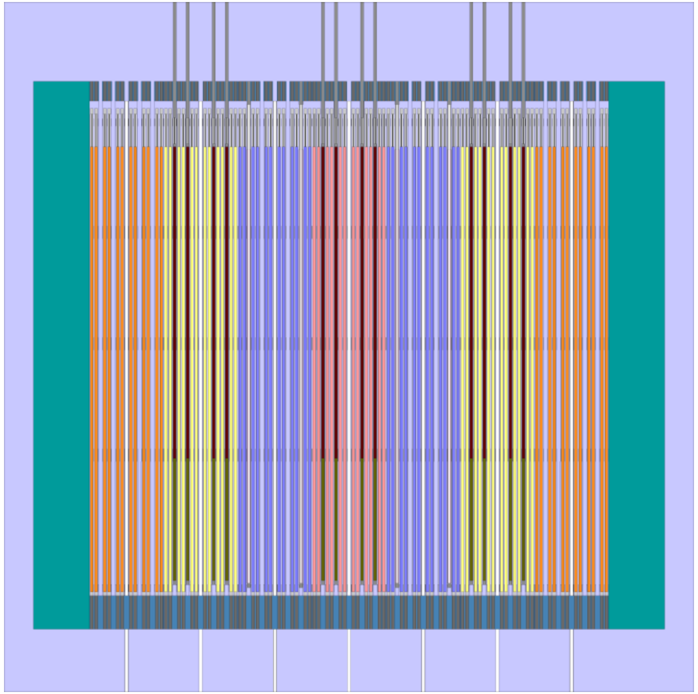
Fuel assemblies with different colors showing different fuel enrichments.

[1] N. Horelik, B. Herman, B. Forget, and K. Smith, “Benchmark for evaluation and validation of reactor simulations (BEAVRS), v2.0.2,” in Proc. Int. Conf. Mathematics and Computational Methods Applied to Nuc. Sci. & Eng, 2018.
[2] NuScale Power LLC, “NuScale Standard Plant Design Certification Application, Part 2, Chapter 4: Reactor, Rev. 2,” 2018.

Detailed geometry



Horizontal cut of the core.



Vertical cut of the core.

Requirements for control rods

- Reactivity Control Systems (RCSs) should be capable of providing a sufficient Shutdown Margin* (usually minimum of 1-5%).
- One of the RCSs should be capable of compensating for power defect, moderator cooling to cold conditions and xenon decay.
- Regulating banks may be inserted to Power Dependent Insertion Limits (PDILs), which should be accounted for.

- All these features can be studied with Kraken.

* The shutdown margin is defined as the instantaneous amount of reactivity by which the reactor is subcritical from the current condition assuming that the highest worth CRA is stuck out and all other CRAs are fully inserted.

Simplified model: Group constant generation

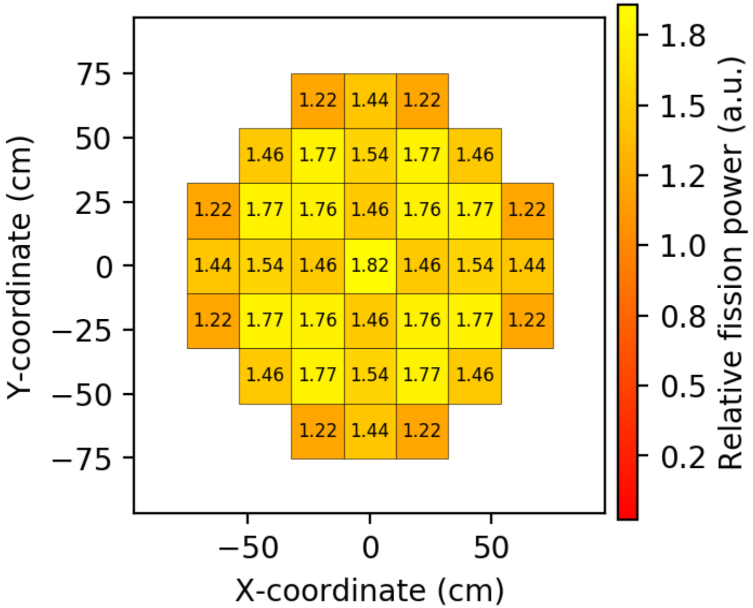
- High-fidelity calculations are computationally heavy
  → core-level calculations are run with reduced-order methods.
- Calculation nodes for the reduced-order neutronics solver Ants are produced by performing spatial homogenization
  → generating group constants for each assembly type.
- Vertical variation along the assembly is also accounted for.
- Group constants are generated with Serpent burnup calculation for each assembly type in Hot Full Power (HFP) and Cold Zero Power (CZP).
- The group constants were parameterized as a function fuel temperature, moderator temperature and boron concentration.
- Here, simulating a fresh core, only initial material compositions are calculated with xenon being accounted for in HFP.

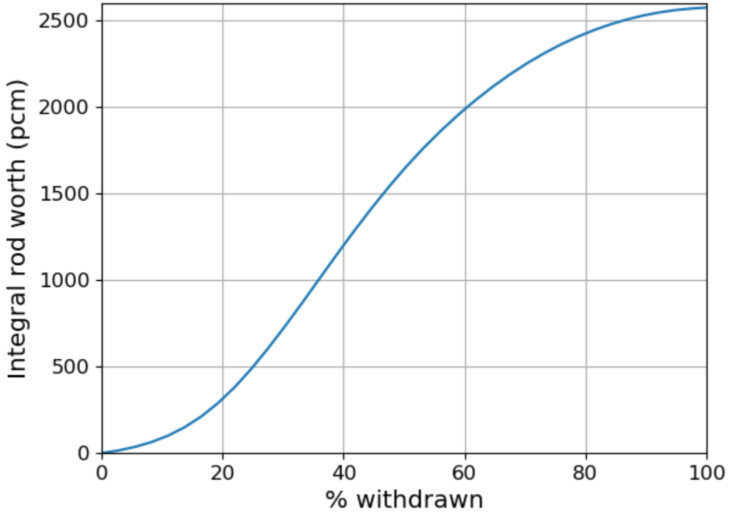
Full-core calculations

- Simulations are run with Ants (nodal diffusion) coupled with Kharon and SuperFINIX via Cerberus.
- Calculations are run in HFP, HZP and CZP with different CRA positions and boron concentration.
- Calculations give
  - CRA worths
  - Power defect
  - Shutdown margin
  - Moderator cooling
  - Xenon worth

Results

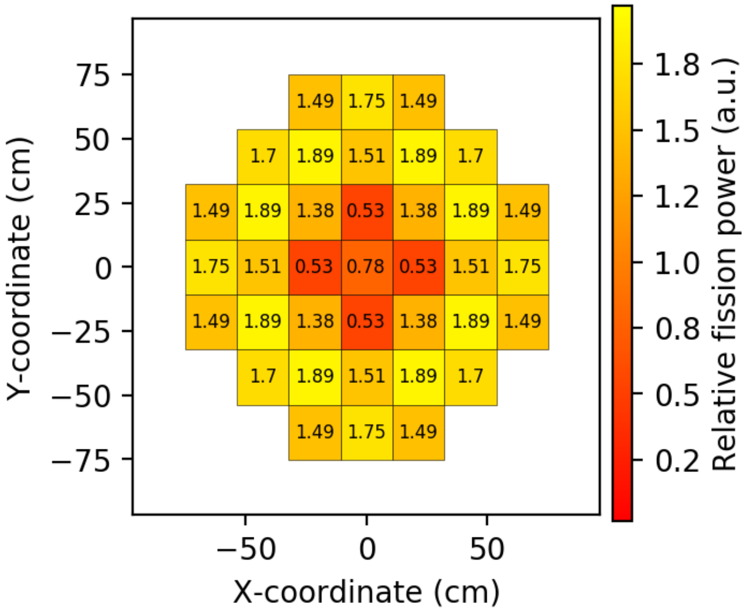
Control rod group insertion



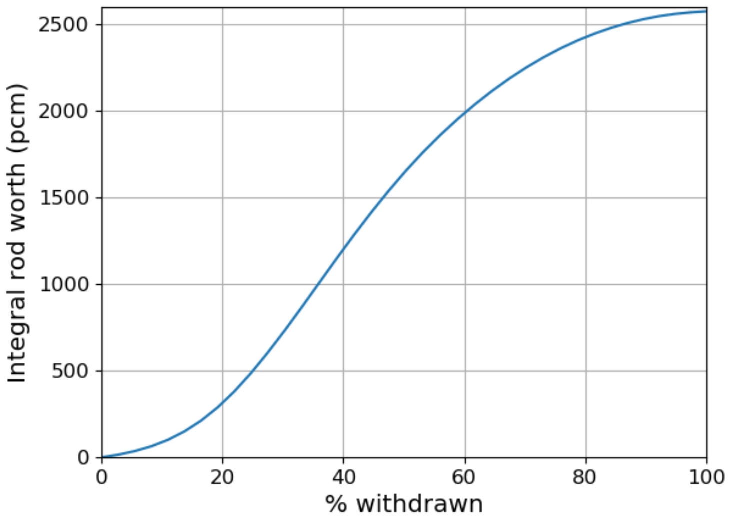


All CRAs withdrawn

Control rod group insertion



Regulating bank 1 inserted



Long term shutdown capability

- Net margin for hot shutdown takes into account one stuck CRA, the power defect and power dependent insertion limits.
- In the Net margin for long-term shutdown, the reactivity from moderator and fuel cooling, and xenon decay are accounted for.

Parameter	Reactivity (pcm)
1. Total Available CRA Worth:	
a. HFP Value	18187
b. HZP Value	18064
c. CZP Value	12453
2. PDILs	
a. HFP Value	332
b. HZP Value	929
3. Highest worth CRA stuck out	5317
4. Power Defect	662
5. Moderator cooling	924
6. Xenon Worth	2353
7. Net margin for hot shutdown (1.a. - 2.a. - 3. - 4.)	11876
8. Net margin for long-term shutdown (7. - 5. - 6.)	8599

Shutdown margin

State	SDM (pcm)
HFP with 931 ppm boron	12871
HFP with zero boron	2185
HZP with 931 ppm boron	9470
HZP with zero boron	-1421
CZP with 931 ppm boron	4190
CZP with zero boron	-10068

- Calculated in HFP, HZP and CZP with zero boron concentration and the critical boron concentration of the HFP state (931 ppm).
- Negative SDM in zero-power conditions with zero boron concentration → supercritical (fresh core).

Conclusions

- Kraken framework tested with an SMR-scale core.
- Control rod related quantities calculated.
- Control rods in the model provide sufficient shutdown capability.
- SDM within reasonable limits.
- A more detailed description in [3].

[3] U. Lauranto, *Evaluating the fulfilment of control rod related nuclear design bases for an SMR core using Kraken*, Aalto University, Espoo, Finland, 2019.

VTT

Thank you!