Kraken

VTT's upcoming Serpent based reactor analysis framework

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Motivation – History

- VTT is conducting most of the independent deterministic safety analyses in Finland, commissioned by the Finnish safety authority.
- This is achieved with Finnish reactor analysis tools, developed by VTT.
- Most of our current production tools were developed in the 80's and 90's.
- The ageing of these tools leads to several challenges:
  - Lost and retiring expertise.
  - Applicability and state-of-the-art.
  - Extendability.
- At the same time, the writing of several next level tools has been underway at VTT.

Motivation – The next generation of Finnish tools

- Serpent Monte Carlo code (2004 –).
- FINIX fuel behavior module (2012 –)[1].
- Ants nodal neutronics code (2017 –)[2],[3].

These new tools have reminded VTT of the importance of

- Source code level expertise.
- Living code development.
- Conducting analyses with self developed tools.

Recently, a decision was made to renew the entire reactor analysis framework at VTT based on self developed tools.

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[1] T. Ikonen et al. "Module for thermomechanical modeling of LWR fuel in multiphysics simulations". In: *Annals of Nuclear Energy* 84 (2015), pp. 111–121. DOI: `10.1016/j.anucene.2014.11.004`.

[2] V. Sahlberg & A. Rintala. "Development and first results of a new rectangular nodal diffusion solver of Ants". In: *Proc. PHYSOR 2018*. Cancun, Mexico, Apr. 2018.

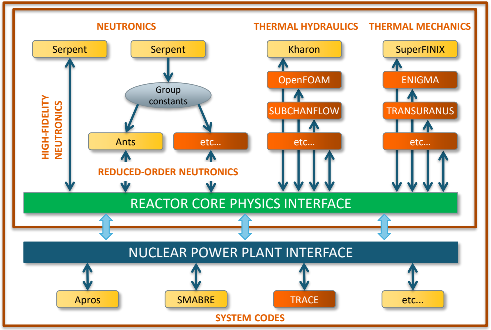
[3] A. Rintala & V. Sahlberg. "Extension of nodal diffusion solver of Ants to hexagonal geometry". In: *Kerntechnik* 84.4 (2019), pp. 252–261.

The Kraken framework

Motivation – Kraken

The development of the Kraken framework [4] has started in earnest in 2019:

- The Kraken framework couples together single physics solvers in a modular fashion.
- Coupling is designed to work both with self developed tools and state-of-the-art third-party codes.
- Core physics solvers are coupled together via a dedicated multi-physics driver module.
- The reactor core solver will be coupled with system codes in the future for the modelling of plant-level transients.



[4] V. Valtavirta et al. "Kraken – an Upcoming Finnish Reactor Analysis Framework". In: *Proc. ANS MC2019*. Portland, OR, USA, Aug. 2019.

Motivation – Long term plans

- The idea is that in the future, all of VTT's independent safety analyses will be conducted with Kraken.
- Focus on being able to evaluate fulfillment of design bases according to NUREG-0800 [5] and the corresponding Finnish regulations.
- A four year Finnish project started in the beginning of 2019 aiming to set up the basic capabilities.

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[5] *"Standard Review Plan for the Review of Safety Analysis Reports for Nuclear Power Plants: LWR Edition*. Technical report NUREG-0800, previously issued as NUREG/75-087. US-NRC, 1989.

Motivation – Long term plans

	2018	2019	2020	2021	2022
Single physics development	Steady state simulation	Fuel cycle simulation	Transient analyses	Transient analyses	
Multi-physics coupling		Steady state simulation	Fuel cycle simulation	Transient analyses	
Automating analyses		Steady state simulation	Fuel cycle simulation	Transient analyses	Transient analyses
Demonstrating and benchmarking		Steady state simulation	Steady state + fuel cycle	Fuel cycle + transients	Transient analyses

Figure: High-level timetable for the LONKERO project that focuses on Kraken development.

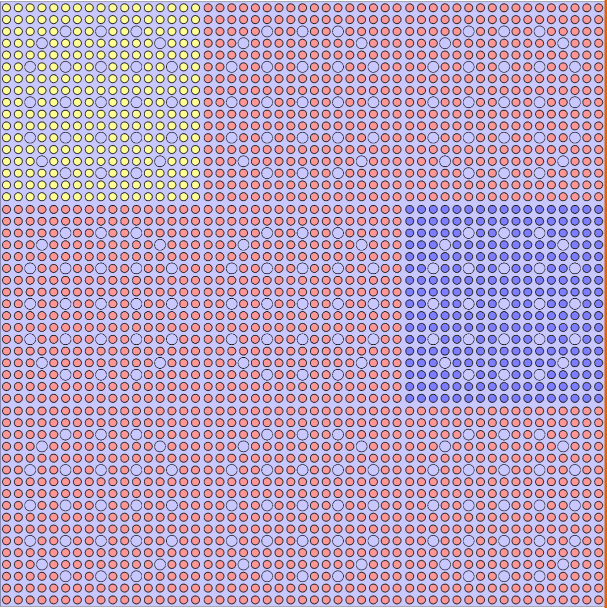
Recent work – code coupling

Code coupling in Kraken

- 2019 started with multiple separate solver modules each capable of solving their own set of physics.
- Need to couple the solvers, i.e. handle execution order, field transfers etc.
- Previous experience both on source code level internal coupling and external coupling with file-based data transfer.
- In Kraken, something in between: External coupling but socket based data transfer.
- Reduced development cost for coupling new solvers with reasonably fast data transfer.

Code coupling in Kraken

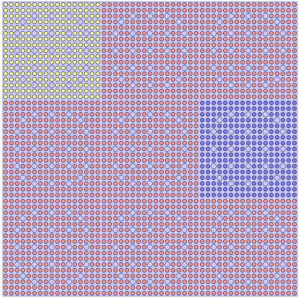
- A separate multi-physics driver module Cerberus handles the coupled solution.
- Common communications syntax between the solvers.
- Common syntax for mesh definitions.
- Solvers (or their wrappers) provide a standardized interface.
- Coupled sequence defined via Cerberus input.



Recent work – It’s alive!

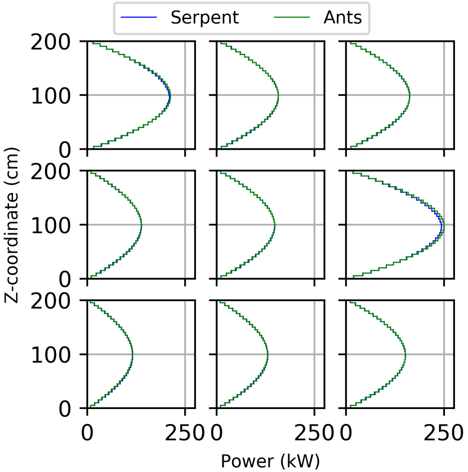
The first coupled problem[4]

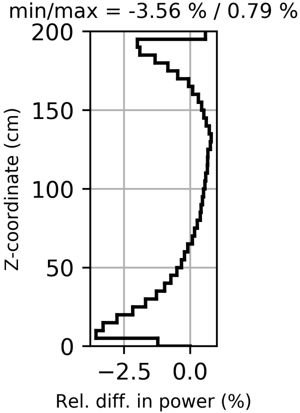
- The coupled calculation sequences were first tested in an asymmetric 3x3 assembly colorset problem.
  - Three different fuel assembly types.
  - Radially reflective BC.
  - Axially black BC (200 cm active height).
- Two coupled calculation sequences:
  - Monte Carlo: Serpent/Kharon/SuperFINIX
  - Nodal diffusion: Ants/Kharon/SuperFINIX
- Simple test problem to check that the couplings are working as intended.



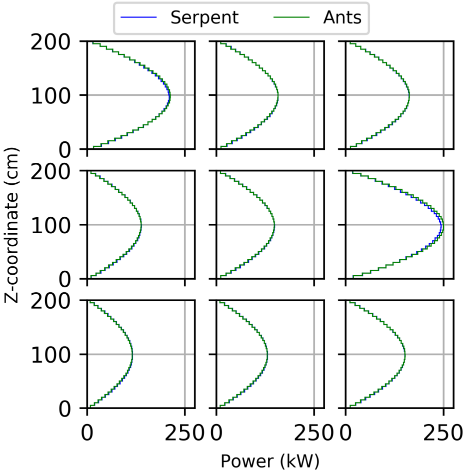
[4] V. Valtavirta et al. “Kraken – an Upcoming Finnish Reactor Analysis Framework”. In: *Proc. ANS MC2019*. Portland, OR, USA, Aug. 2019.

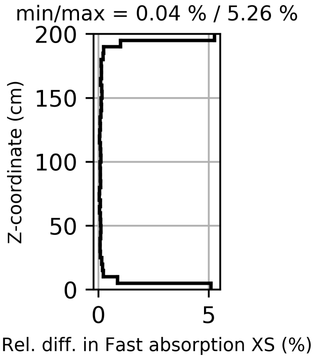
The first coupled problem

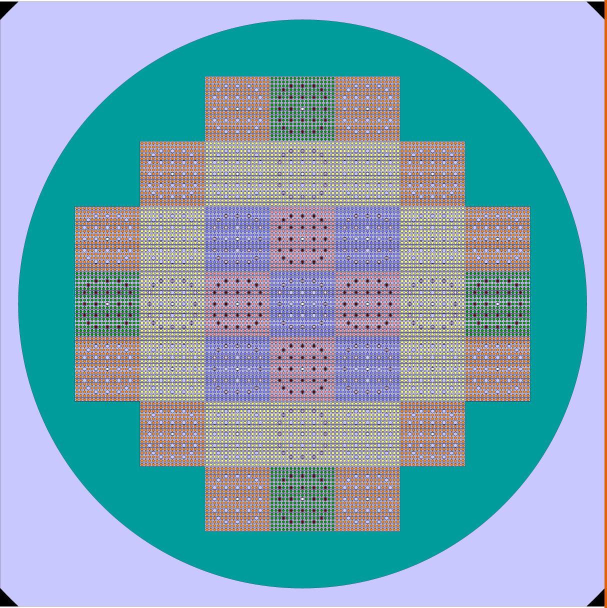




The first coupled problem

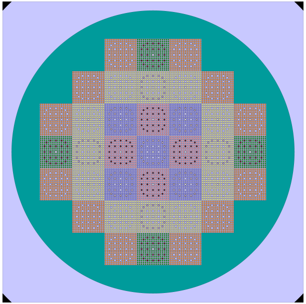


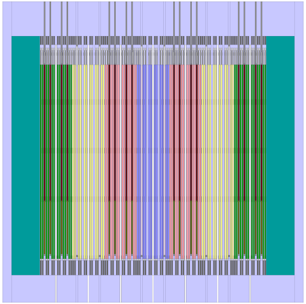




Recent work – It grows!

The second progression problem



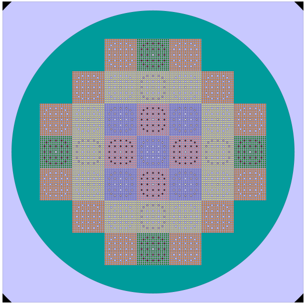


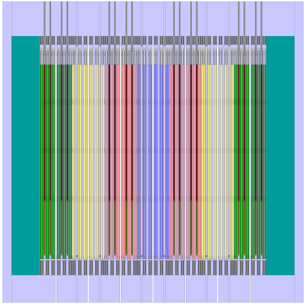
An SMR sized PWR core based on a combination of NuScale [6] and BEAVRS [7] data.

[6]NuScale Power LLC. *NuScale Standard Plant Design Certification Application, Part 2, Final Safety Analysis Report, Rev. 2, Chapter 4: Reactor*. 2018.

[7]N. Horelik et al. “Benchmark for Evaluation and Validation of Reactor Simulations (BEAVRS), v1.0.1”. In: *Proc. M&C 2013*. Sun Valley, ID, May 2013.

Second progression problem



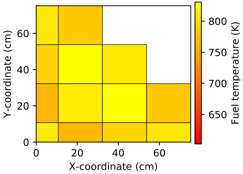


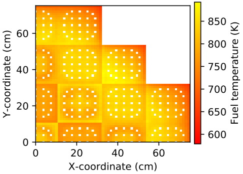
- 9768 fuel rods with a 200 cm active length.
- Core power of 160 MW_{th} (old NuScale core power) corresponding to an average linear power of 82 W/cm.

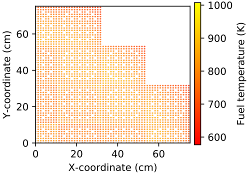
The second progression problem

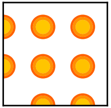
- Moving towards realistic reactor applications.
- Testing several new things:
  - Variable fidelity feedback.
  - Shutdown margin evaluation.
  - Reactivity coefficient evaluation.

Variable fidelity demonstration









- Serpent based calculation sequence.
- Fission power and fuel temperature exchanged at:
  - Assembly level.
  - Pin level.
  - Pin-radial level (3 equal volume radial regions).
- Estimate effects on:
  - Critical boron.
  - Assembly powers.
  - Pin powers.

Variable fidelity demonstration[8]

Coupled solution obtained with 50 iterations using 25 million active neutron histories per iteration.

Pin and pin-radial level cases used the exactly same core level fuel behavior input.

Assembly level case used only one representative fuel rod per assembly.

Running times:

	Assembly	Pin	Pin-radial
Neutronics	380 min	400 min	684 min
Fuel behavior	0.35 min	50 min	70 min
Thermal-hydraulics	0.25 min	0.60 min	0.25 min

Final coupled fields were used in a separate Serpent calculation with 4×10^{10} active neutron histories to tally assembly and pin powers and evaluate the critical borons.

[8] V. Valtavirta et al. "SuperFINIX – A Flexible-Fidelity Core Level Fuel Behavior Solver for Multi-Physics Applications". In: *NENE 2019*. Portorož, Slovenia, Sept. 2019.

Variable fidelity demonstration

Differences in pin power distribution (reference = pin-radial):

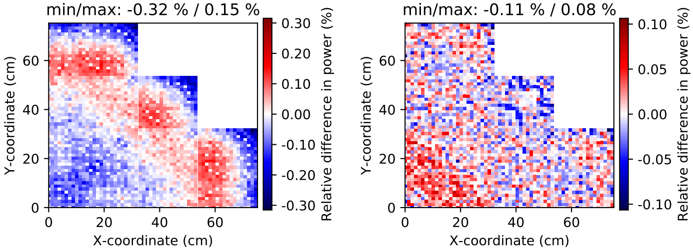


Figure: Differences in the pin power distribution due to a reduced fidelity discretization. **Left**: Assembly level discretization. **Right**: Pin level discretization.

Variable fidelity demonstration

Differences in pin power distribution (reference = pin-radial):

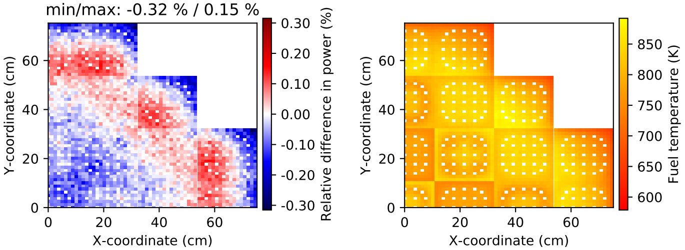


Figure: Assembly level discretization leads to errors in pin powers in assemblies that experience significant power/fuel temperature gradients.

Shutdown margin evaluation

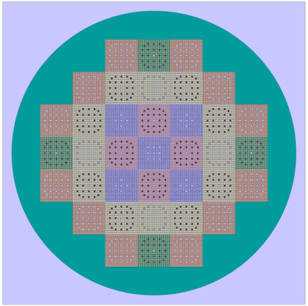
- Considering reactor operation at steady state with regulating banks at power dependent insertion limits (PDIL).
- Both short-term and long-term shutdown considered.
- Short term shutdown:
  - Control rods inserted.
  - Fission power dies out.
  - Core cools to inlet temperature.
  - Xenon does not decay.
- Long term shutdown:
  - Core cools to room temperature and ambient pressure.
  - Xenon decays.

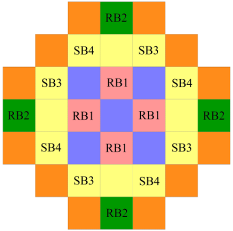
Capabilities required for shutdown margin evaluation

- Individually movable control assemblies (via Cerberus).
- Capability to set field values to e.g. HZP state.
- Capability to evaluate equilibrium xenon at HFP, store it and re-use it for HZP (short term shutdown).
- In general the fields from solvers can be stored to files and later used to initialize/set the values of a field.

Shutdown margin evaluation

Shutdown margin was evaluated for the SMR core using Ants[9].





[9] U. Lauranto. *Evaluating the fulfilment of control rod related nuclear design bases for an SMR core using Kraken.* Special Assignment, Aalto University, School of Science. 2019.

Shutdown margin evaluation

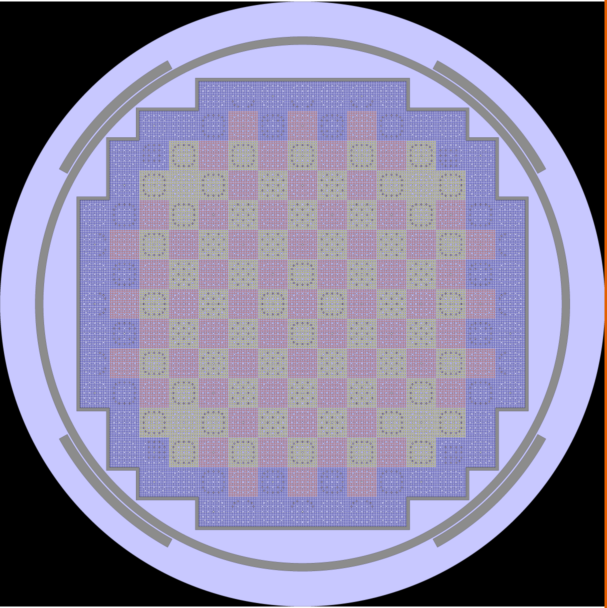
Shutdown margin was evaluated for the SMR core using Ants[9].

Parameter	(pcm)
1. Total Available CRA Worth:	
a. HFP Value	18187
b. HZP Value	18064
c. CZP Value	12453
2. Power Dependent Insertion Limits:	
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

[9] U. Lauranto. *Evaluating the fulfilment of control rod related nuclear design bases for an SMR core using Kraken.* Special Assignment, Aalto University, School of Science. 2019.

Reactivity coefficient evaluation

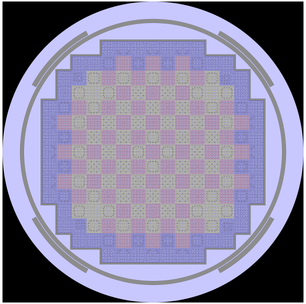
Requires perturbations to the different fields:
(see example...)

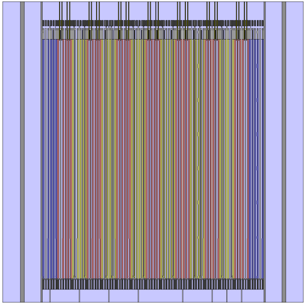


Future work – It feeds!

Future work

Kraken will be next applied to the BEAVRS benchmark:





- 9768 fuel rods $\Rightarrow$ 50952 fuel rods
- 200 cm active length $\Rightarrow$ 365.76 cm active length.

Steady state in 2019, fuel cycle simulation planned for 2020.

Conclusions and relevance to Serpent users

Conclusions and future work

- VTT has started building a new computational reactor analysis framework around Serpent.
- Serpent serves a dual role in the framework:
  - Group constant generation for reduced order solvers.
  - Direct high-fidelity coupled solutions.
- This will bring a new focus into Serpent development towards more routine group constant generation and multi-physics calculations.
  - Expect to see quality-of-life improvements on both sides.
- The Kraken framework as a whole is still very much in development.

Open questions

- Reactor simulator module.
- Generic field interpolation.
- Efficient MPI-parallelization.
- Output format for field and variable data (also for 3D plots).
- The whole burnup and time-dependent sequences are still to be implemented.
- System code coupling is envisioned but an open question.

Eventual distribution

Eventual distribution

- Kraken development is driven by VTT's needs.
- Our experiences regarding Serpent user community are extremely good.
- Distribution will still take some time.
- The idea is to distribute all of the modules under a single license (see e.g. SCALE).
- Non-commercial license most likely similar to that of Serpent 2.2.0.
- Will most likely also include a Python package (KrakenTools) for pre-/post-processing and (partly building on serpentTools).

beyond the obvious

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