Kraken workshop

Introduction to the Kraken framework

Ville Valtavirta

Outline

- Kraken on one slide

- Coupling scheme in Kraken
- Physics solvers involved

- Current status and future plans
- Licensing and distribution

Kraken on one slide

VTT is replacing its legacy reactor analysis toolchains (HEXTRAN, TRAB-3D) with a new set, **Kraken**, building largely on VTT's own modern solvers.

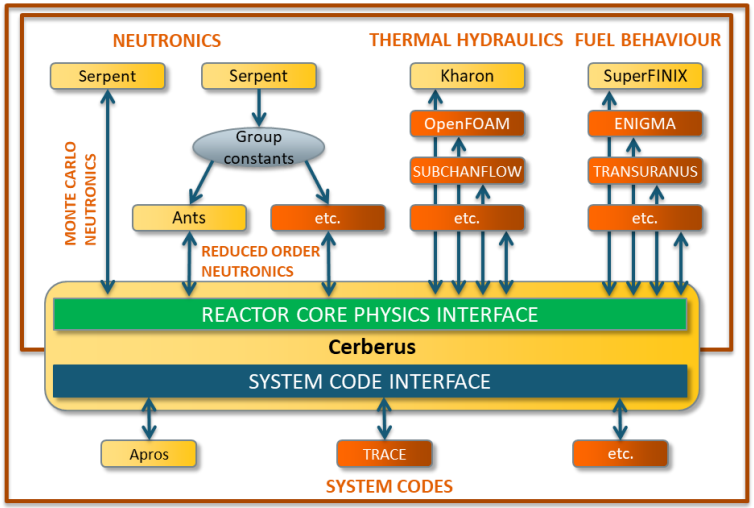
Kraken will provide VTT with the **tools** required for future safety analyses and the **expertise** to use those tools in a proper manner.

Kraken is designed both for **independent determinist safety analyses**, **evaluation of new reactor concepts** and as a **general research tool**.

Basic capabilities for **steady state**, **fuel cycle** and **transient** analyses implemented during 2019-2021.

Validation effort ongoing with focus on demonstrating capabilities required for deterministic safety analyses.

A **non-commercial user license** is being drafted with **international distribution** planned through OECD/NEA data bank and RSICC later in 2022.



A schematic representation of the plans for the completed Kraken framework. Finnish solver modules developed at VTT are shown in yellow, while potential state-of-the-art third party solvers to be coupled are shown in orange.

Code coupling approach in Kraken

Couplings for coupled calculations

Codes can be coupled in many ways:

- Memory level coupling:

Codes compiled together or linked as libraries. Executed as a single process.

- MPI or socket based coupling:

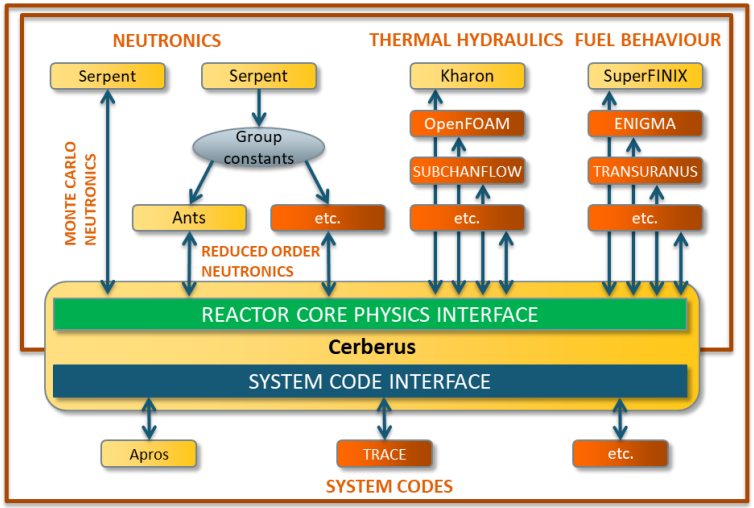
Data exchanged between separate processes using common protocols.

- Input/file based coupling:

External driver updates code inputs based on the outputs of others.

Kraken is intended to bring together solvers from various sources:

- Those developed at VTT specifically for Kraken.
- Those already developed at VTT, not specifically for Kraken.
- Externally developed codes, for which source code may be available.
- Externally developed codes, for which source code is not available.



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Couplings for coupled calculations

A central multi-physics driver Cerberus:

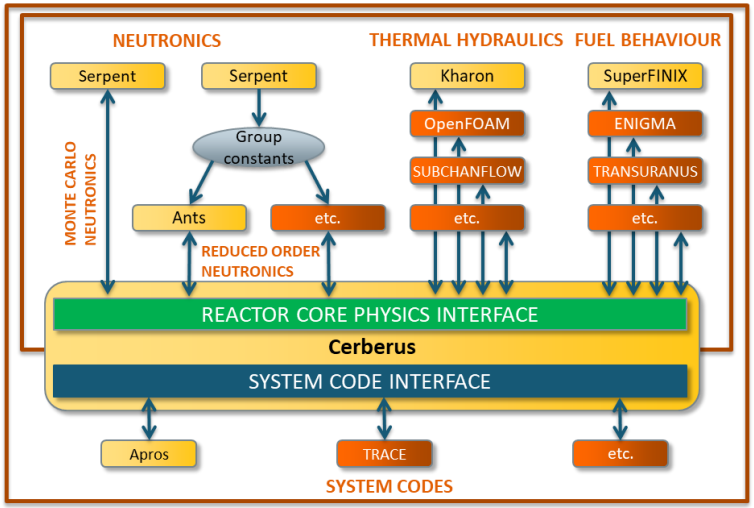
- Each solver only needs to communicate with Cerberus.

Data transfer through sockets:

- Native Kraken solvers support socket communication automatically.
- Others utilize wrapper programs. SCFWrap, TUWrap, TRACEWrap.

Code agnostic and modular coupling approach:

- Cerberus does not know which solver is which.
- All solvers look similar through Cerberus.
- Can exchange solver modules to a higher or lower fidelity easily without changes to other solvers or simulation model as a whole.



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Physics solvers

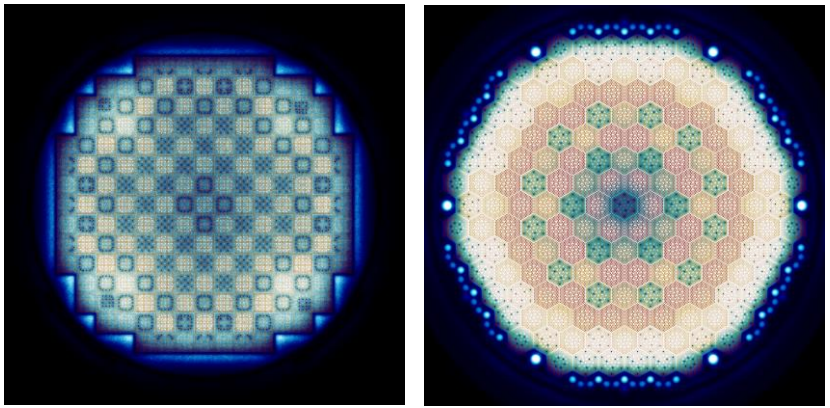
Physics solvers related to Kraken

- **Neutronics solvers**
  - Serpent
  - Ants
- **Thermal hydraulics solvers**
  - Kharon
  - OpenFOAM
  - SUBCHANFLOW
- **Fuel behavior solvers**
  - FINIX
  - SuperFINIX
  - TRANSURANUS
  - Goose
- **System codes**
  - Apros
  - TRACE

Neutronics

Serpent Monte Carlo code

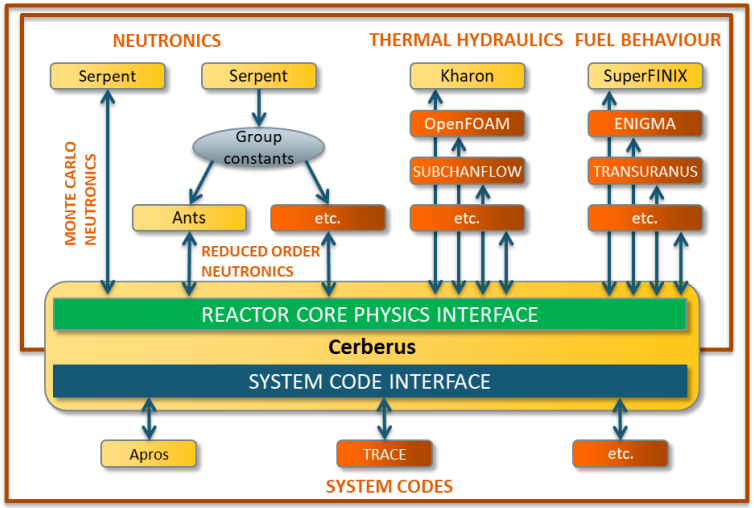
- Continuous-energy Monte Carlo transport calculation code developed at VTT since 2004.
- Neutron, photon and coupled neutron / photon transport modes.
- Originally developed for reactor physics, but scope of applications not limited to reactor modelling
- Advanced features and capabilities:
  - Automated procedures for burnup calculation and group constant generation
  - Multi-physics interface for thermal hydraulics and fuel performance code coupling
  - Domain decomposition enabling core-level burnup calculations
  - Transient simulation mode with delayed neutron physics
  - Methods for sensitivity and uncertainty analysis
  - Support for CAD- and unstructured mesh-based geometries
  - Weight-window based variance reduction techniques with built-in importance solver
  - ...



Serpent meshplots for BEAVRS (left) and Khmelnitsky 2 (right) initial core. Warm colors indicate fission power and cold colors indicate thermal flux.

Serpent Monte Carlo code

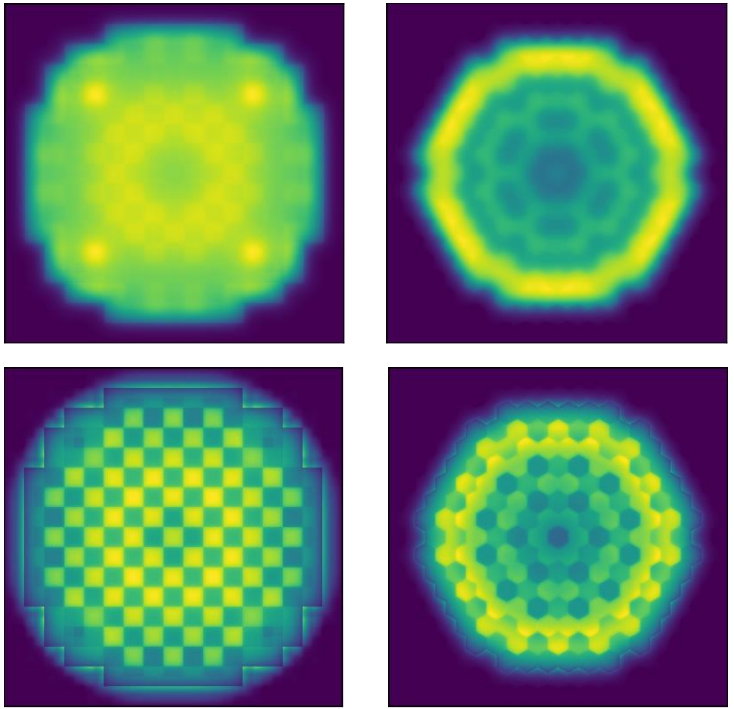
- Dual role in the Kraken framework:
  1) Group constant generation for the Ants nodal neutronics code (reduced-order sequence)
  2) Direct coupling to other physics solvers (high-fidelity sequence)
- The Serpent-based high-fidelity sequence can be used for best-estimate analyses or verification of reduced-order calculations without major modifications in the configuration
- New base version 2.2.0 released in May 2022, three licensing options:
  - Single-user licenses from OECD/NEA Data Bank and RSICC – free of charge for non-commercial research and educational use
  - Commercial license – agreement with VTT, license fees applied
  - Reduced academic license for unlimited number of users ("professor license") – agreement with VTT, one-time processing fee applied
- Serpent has currently more than 1000 users in 250 organizations in 44 countries around the world



Serpent serves a dual role in the Kraken framework.

Ants nodal neutronics program

- Multi-group nodal neutronics code developed at VTT since 2017.
- Currently solves nodal diffusion equation.
- Combines AFEN and FENM approaches for flux solution.
- Rectangular, hexagonal and triangular nodal models.
- Steady state, burnup and transient.
- Supports e.g. pin power reconstruction, predictor-corrector methods in depletion, microscopic depletion with CRAM.
- Ants serves as the reduced order neutronics solver in Kraken providing solutions to stationary, depletion and transient neutronics problems in a reasonable time.
- Development and validation work ongoing.



Thermal hydraulics

Kharon thermal hydraulics solver

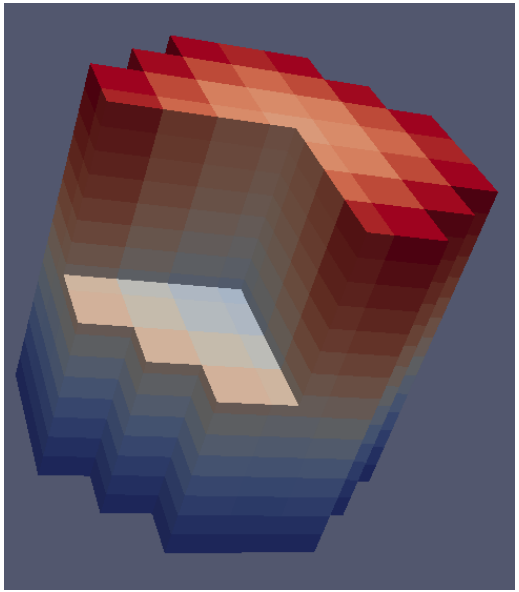
A simple core level thermal hydraulics solver developed at VTT:

- Two phase.
- Time-independent.
- Closed channel.
- Porous medium.

Models flow based on channel inlet and outlet boundary conditions and basic geometry.

Also models heat transfer from fuel rod cladding to coolant providing boundary condition for fuel behaviour codes.

Utilized in stationary and fuel cycle simulations. Transient simulations need another tool.



OpenFOAM computational fluid dynamics code

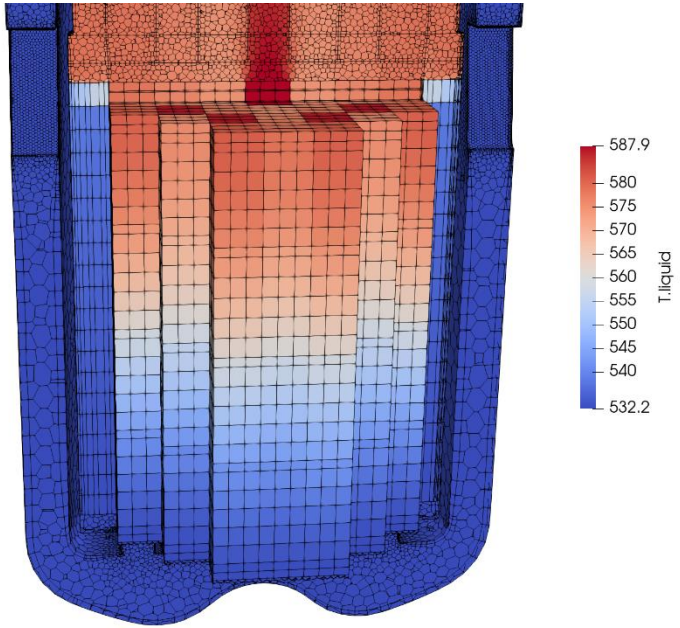
Open source software for CFD modelling and other purposes: https://openfoam.org/

VTT is a contributor in the project.

Past history in coupling Serpent and OpenFOAM in many ways.

Kraken applications will mostly use the multiphase porous medium solver (*multiphaseEulerFoam*).

- Stationary and transient coarse mesh solutions inside the reactor core.
- Mixing, natural circulation etc. inside the reactor pressure vessel.



SUBCHANFLOW thermal hydraulics solver

Subchannel level TH-solver developed by KIT.

https://www.inr.kit.edu/english/1008.php

Long history in coupling Serpent and SUBCHANFLOW using various approaches.

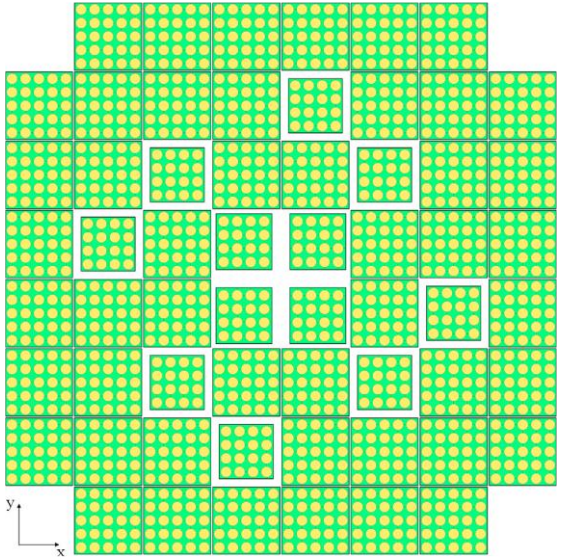
Most recently in the McSAFE project:

- ICoCo coupling.
- Master-slave coupling: sss-scf-tu and sss-scf.

Kraken coupling utilizes the pre-existing C API and a Kraken-specific wrapper layer (SCFWrap) to handle communications to/from Cerberus.

Applied in stationary, depletion and transient analyses.

Python preprocessor created in McSAFE utilized in generation of calculation mesh and interpolations.



Plot of the SCF model for the SPERT-IIIE core.

D. Ferraro *et al.*, " Serpent/SUBCHANFLOW pin-by-pin coupled transient calculations for the SPERT-IIIE hot full power tests", Annals of Nuclear Energy 142 (2020)

Fuel behaviour

FINIX fuel behaviour module

The FINIX fuel behaviour module has been developed at VTT since 2012.

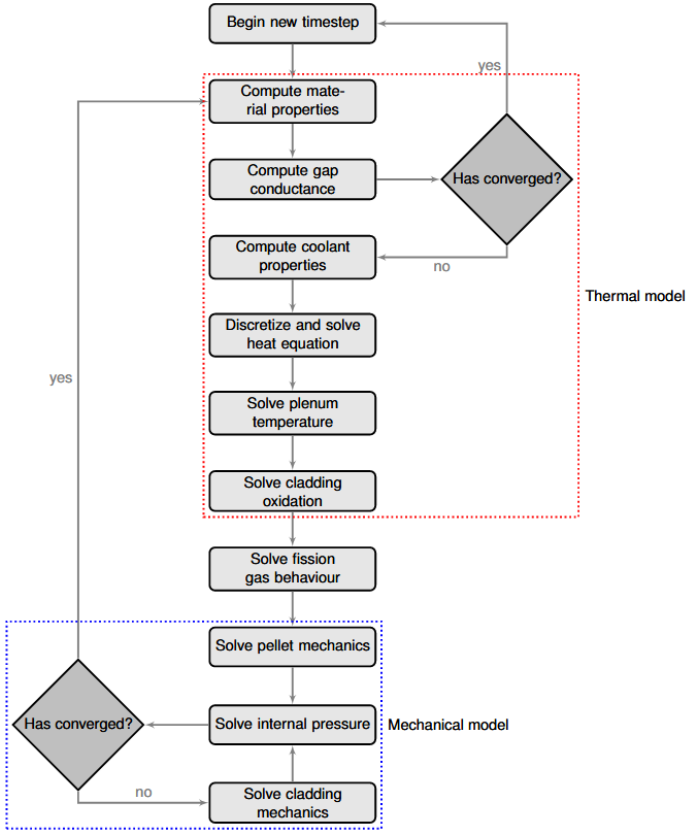
FINIX is a traditional 1.5 dimensional single rod fuel performance code.

Originally developed as a simple fuel behaviour solver module that could be coupled to reactor analysis codes at the source code level.

Developed for LWR applications.

Verified against FRAPTRAN and FRAPCON in RIA and steady state scenarios and compared against experimental Halden reactor data.

In the Kraken framework, FINIX is used through SuperFINIX, the core level fuel behaviour solver.



Overview of the FINIX solution model.

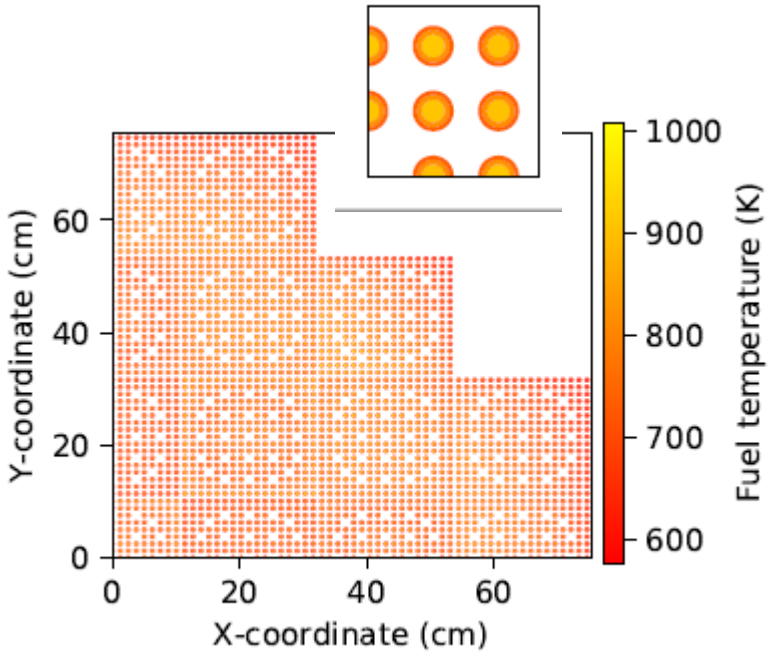
SuperFINIX core level fuel behaviour solver

The SuperFINIX core level fuel behaviour solver was written in 2019.

FINIX models a single fuel rod. LWR cores contain hundreds of fuel assemblies, tens of thousands of fuel rods.

Flexible fidelity for field input and output:

- Nodal codes, such as Ants require one fuel temperature value per node.
- Monte Carlo codes, such as Serpent can utilize individual rod radial distributions for fuel temperatures.
- Conversely power distribution may be evaluated at assembly, quarter assembly, rod or sub-rod level.
- SuperFINIX accepts input fields and provides output fields at multiple levels of discretization for the same model.



High fidelity fuel temperature fields taken from SuperFINIX.

TRANSURANUS fuel performance code

European fuel performance code developed by the JRC.

https://data.jrc.ec.europa.eu/collection/transuranus

Coupled with Serpent in the McSAFE project:

- ICoCo coupling.
- Master-slave coupling: sss-scf-tu and sss-tu.

Single rod solver, but Kraken coupling utilizes pre-existing C and C++ layers and a Kraken-specific wrapper layer (TUWrap) to handle communications to/from Cerberus.

To be applied in stationary, depletion and transient analyses.

Python preprocessor created in McSAFE utilized in generation of calculation mesh and interpolations.

Goose

Small modular reactors for heat production are recognized as an emerging topic in the VTT challenge frame.

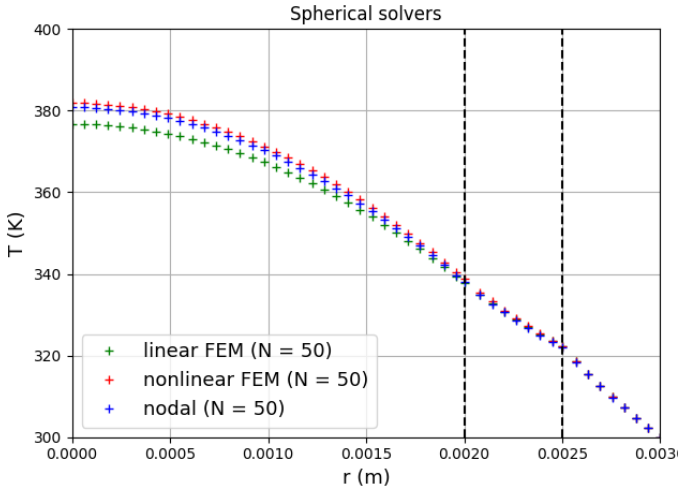
- Low temperature district heating and desalination reactor (LDR) concept developed at VTT since 2020.
- Industrial processes need a high temperature heat source for decarbonisation.
- HTGRs are a specific research focus at VTT.

Neutronics can be solved using Serpent or (with some reservations) using Ants. Helium flow can be easily modelled with OpenFOAM.

- Need for a specific fuel behaviour solver identified recently as the limiting factor.

Work for developing one started in 2021 with the writing of a temperature solver kernel.

Development work is ongoing.



Testing the different spherical heat equation solvers of Goose.

System codes

Apros

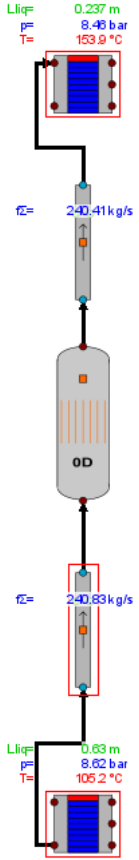
A system code / process simulator developed at VTT and Fortum for a long time.

https://www.apros.fi/

Used in the safety analyses of Finnish NPPs.

Also used in the development of VTT's LDR-50 district heating reactor concept.

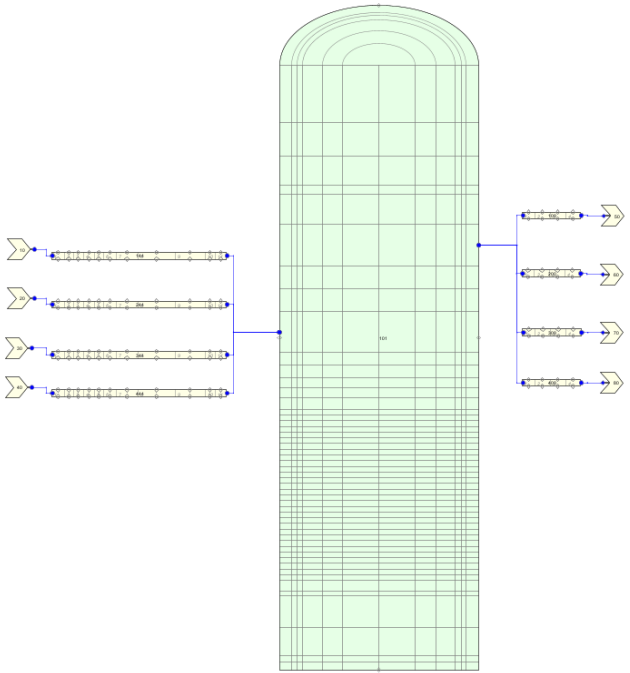
Coupling work with Kraken ongoing.



E. Silvennoinen et al., "The APROS software for process simulation and model development", Technical Research Centre of Finland, Research reports 618 (1989).

TRACE

- TRAC/RELAP Advanced Computational Engine (TRACE)
- A system code developed by US NRC for LWR transient analyses.
- Being adopted in Finland for independent deterministic safety analyses.
- Finland participates in US NRC's Code Applications and Maintenance Program (CAMP).
- Coupled to Kraken using a separate wrapper TRACEWrap*, which communicates with TRACE using the Exterior Communications Interface (ECI).
- Used as an independent verification tool for Apros analyses.



*Tuominen, R., Komu, R., Valtavirta, V.,
Coupling TRACE with Nodal Neutronics Code Ants Using the Exterior Communications Interface and VTT's Multiphysics Driver Cerberus
PHYSOR 2022, May 15-20, 2022, Pittsburgh, PA

Current status and future plans

Current status of Kraken

- Capabilities ready for stationary, operating cycle and transient analyses.
- Modular structure with several options for different solver modules.
- Validation work for safety analyses ongoing (a large future topic).
- Widely used in the core design of VTT‘s district heating reactor concept LDR-50.
- Applied in EU-McSAFER to REA and MSLB analyses of the NuScale concept.

J. Leppänen *et al.* “Load Follow Simulations for the LDR-50 District Heating Reactor Using the Kraken Computational Famework.”, Proceedings of PHYSOR2022

J. Leppänen *et al.* “A Finnish district heating reactor: Background and general overview”. Proceedings of ICONE-28, August 4-6, 2021, Virtual Conference, USA.

J. Leppänen *et al.* “A Finnish district heating reactor: Neutronics design and fuel cycle simulations”. Proceedings of ICONE-28, August 4-6, 2021, Virtual Conference, USA.

- REA:
  - Ants – SUBCHANFLOW.
  - Serpent – SUBCHANFLOW.
  - Serpent – SUBCHANFLOW – TRANSURANUS.
- MSLB:
  - Ants – TRACE.
  - Ants – TRACE – OpenFOAM.

Future plans for Kraken

- Distribution for non-commercial use via OECD/NEA Data Bank and RSICC.
- Development of Ants nodal neutronics program continues:
    - Adjoint flux solver and related capabilities.
    - Improved group constant models.
    - From diffusion to transport?
- Validation for safety analyses:
    - International benchmarks.
    - Finnish NPP models.
- Improved capabilities for reactor design (LDR-50 development).
- Secondary analyses: Final disposal, radiation shielding, dosimetry, safeguards etc.

Licensing and distribution

Licensing and distribution (1/3)

- Ongoing work for drafting a non-commercial license, establishing export control practices and starting distribution via OECD/NEA Data Bank and RSICC.
- Practices similar to Serpent 2.2.0.
- Initially covers:
  - The **Ants** nodal neutronics code.
  - The **FINIX** fuel performance code.
  - The **SuperFINIX** core level fuel behaviour solver.
  - The **Kharon** thermal hydraulics code.
  - The **libFluid** fluid properties library.
  - The **Cerberus** multi-physics driver package.
  - The **KrakenTools** package of accessory modules.
- Further modules most likely added on yearly basis (requires modifications to licenses and export control documents).
- At this point, changes are still likely to happen between updates.

Licensing and distribution (2/3)

Neutronics solvers

- Serpent:
  - Distribution for non-commercial use via OECD/NEA DB and RSICC (pending for Serpent 2.2.0).
- Ants:
  - Included in Kraken 1.1.22.05 for non-commercial use.

Thermal hydraulics solvers

- Kharon
  - Included in Kraken 1.1.22.05 for non-commercial use.
- OpenFOAM
  - Freely available at https://openfoam.org/
  - Kraken coupling layer will be distributed as open source when completed.
- SUBCHANFLOW
  - Licensed and distributed by KIT: https://www.inr.kit.edu/english/1008.php
  - Kraken coupling layer *SCFWrap* will be included in a future Kraken distribution.

Licensing and distribution (3/3)

Fuel behavior solvers

- FINIX
  - Included in Kraken 1.1.22.05 for non-commercial use.
- SuperFINIX
  - Included in Kraken 1.1.22.05 for non-commercial use.
- TRANSURANUS
  - Licensed and distributed by JRC: https://data.jrc.ec.europa.eu/collection/transuranus
  - Kraken coupling layer *TUWrap* will be included in a future Kraken distribution.
- Goose
  - Included in a future Kraken distribution.

System codes:

- Apros
  - Licensed and distributed separately by VTT.
- TRACE
  - Licensed and distributed by US NRC.
  - Kraken coupling layer *TRACEWrap* will be included in a future Kraken distribution.

VTT

beyond
the obvious

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Some references 2018 - 2019

Sahlberg, V., Rintala, A.
“Development and first results of a new rectangular nodal diffusion solver of Ants”
In Proc. PHYSOR 2018, Cancun, Mexico, April 22-26, 2018

Rintala, A., Sahlberg, V.
"Extension of Nodal Diffusion Solver of Ants to Hexagonal Geometry"
In Proc. 28th Symposium of AER on VVER Reactor Physics and Reactor Safety, October 8 – 12, 2018, Olomouc, Czech Republic.

Valtavirta, V., Peltonen, J., Lauranto, U., Leppänen, J. “SuperFINIX – A Flexible-Fidelity Core Level Fuel Behavior Solver for Multi-Physics Applications” NENE 2019, September 9-12, 2019, Portoroz, Slovenia

Rintala, A., Sahlberg, V. “Pin Power Reconstruction Method for Rectangular Geometry in Nodal Neutronics Program Ants” 28th International Conference Nuclear Energy for New Europe, September 9-12, 2019, Portoroz, Slovenia

Rintala, A., Sahlberg, V. "Extension of Nodal Diffusion Solver of Ants to Hexagonal Geometry"
Kerntechnik 84 (2019)

Valtavirta, V., Hovi, V., Loukusa, H., Rintala, A., Sahlberg, V., Tuominen, R., Leppänen, J.,
“Kraken – an upcoming Finnish reactor analysis framework” M&C 2019, August 25-29, 2019, Portland, OR, USA.

Lauranto, U., Valtavirta, V., Rintala, A., Leppänen, J.
Evaluating the fulfilment of control rod related nuclear design bases for an SMR core using the Kraken computational framework, symposium article at Nuclear Science and Technology Symposium – SYP2019, Helsinki, Finland, 30-31 October 2019

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Unna Lauranto
Developing a generic Python based group constant library generator module for Serpent
Special Assignment Report, PHYS-E0441, Aalto University, School of Science, Department of Applied Physics, 2020.

Valtavirta, V., Lauranto, U., Hovi, V., Peltonen, J., Rintala, A., Tuominen, R., Leppänen, J.
“High fidelity and reduced order solutions to an SMR-level progression problem with the Kraken computational framework”
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Validating the Serpent-Ants calculation chain using BEAVRS fresh core HZP data
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Some references 2022

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Evaluating the X2 initial core zero power physics tests with Serpent–Ants
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Coupling TRACE with Nodal Neutronics Code Ants Using the Exterior Communications Interface and VTT's Multiphysics Driver Cerberus
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Leppänen, J., Valtavirta, V., Rintala, A., Hovi, V., Tuominen, R., Peltonen, J., Hirvensalo, M., Dorval, E., Lauranto, U., Komu, R.
Current Status and On-Going Development of VTT's Kraken Core Physics Computational Framework, Energies 15 (2022)

Unna Lauranto
Verification of Ants time-dependent nodal neutronics model
M.Sc. Thesis, Department of Applied Physics, School of Science, Aalto University, 2022.

Valtavirta, V., Rintala, A., Lauranto, U. "Pin power reconstruction for hexagonal geometry in nodal neutronics program Ants"
Submitted to Annals of Nuclear Energy, 2022

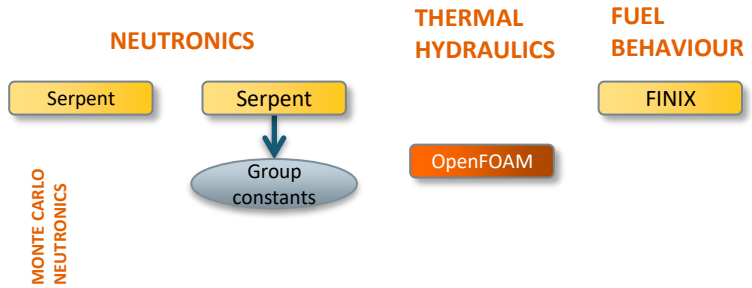
Development history and future plans

Development history and future plans

Pre 2017:

- Serpent developed at VTT since 2004.
- Serpent 2.1.0 in 2012.
- Serpent 2 development focused on:
  - Group constant generation for reduced order solvers.
  - Coupled multi-physics calculations.
- FINIX fuel behaviour solver developed at VTT since 2012.
- VTT participates in OpenFOAM development.

Previous computational framework in use at VTT for deterministic safety analyses.

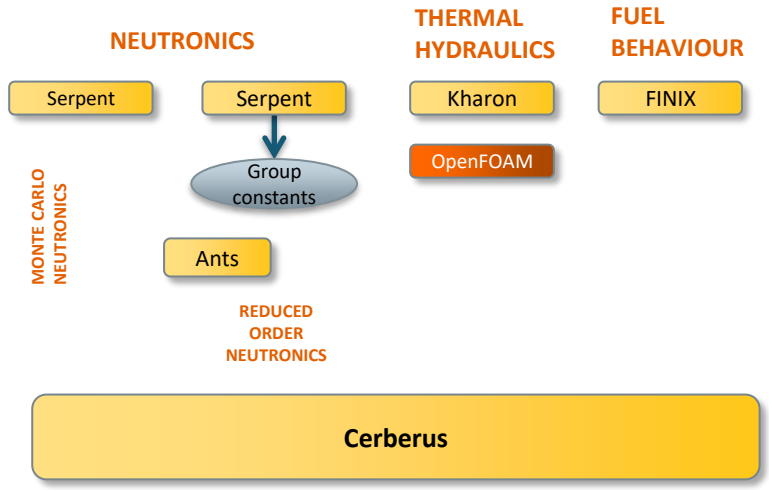


Development history and future plans

2017:

The idea of the renewal of VTT‘s reactor analysis framework and expertise proposed and accepted.

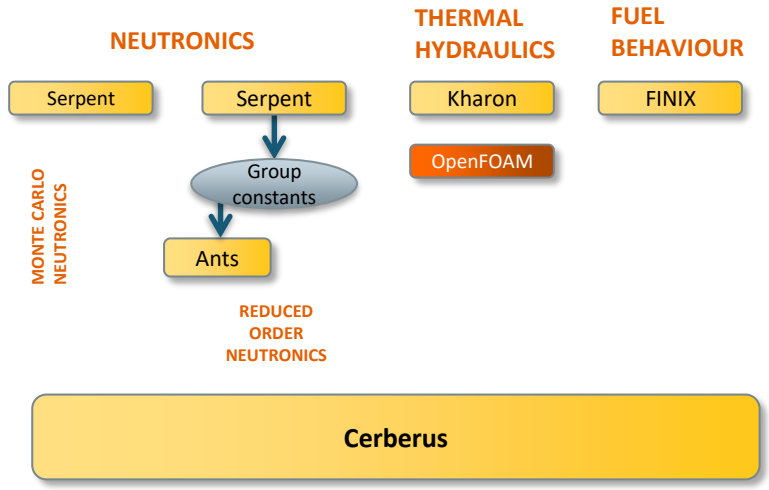
- Development of Ants nodal neutronics program starts.
- Development of the simple two phase closed channel porous medium TH solver Kharon starts.
- First commit in the Cerberus multi-physics driver repository.



Development history and future plans

2018:

- Development work related to Ants.
- Kharon development.
- Drafting plans and project proposals related to large scale Kraken development.



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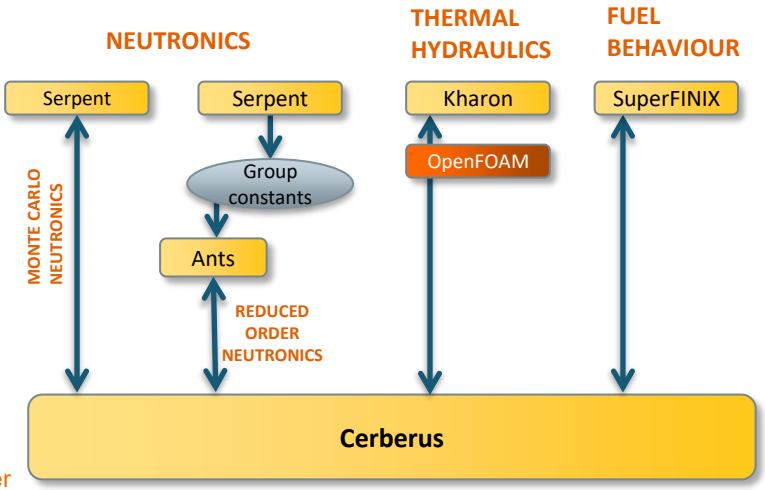
October 8 – 12, 2018, Olomouc, Czech Republic.

Development history and future plans

2019:

LONKERO 2019-2022 project starts.

- SuperFINIX core level fuel behaviour solver created.
- Socket communication syntax established for Cerberus.
- Couplings to several solver modules.
- Coupled steady state calculations (reactivity coefficients etc.)



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Rintala, A., Sahlberg, V. "Extension of Nodal Diffusion Solver of Ants to Hexagonal Geometry" Kerntechnik 84 (2019)

Valtavirta, V., Hovi, V., Loukusa, H., Rintala, A., Sahlberg, V., Tuominen, R., Leppänen, J., “Kraken – an upcoming Finnish reactor analysis framework” M&C 2019, August 25-29, 2019, Portland, OR, USA.

Lauranto, U., Valtavirta, V., Rintala, A., Leppänen, J. Evaluating the fulfilment of control rod related nuclear design bases for an SMR core using the Kraken computational framework, symposium article at Nuclear Science and Technology Symposium – SYP2019, Helsinki, Finland, 30-31 October 2019

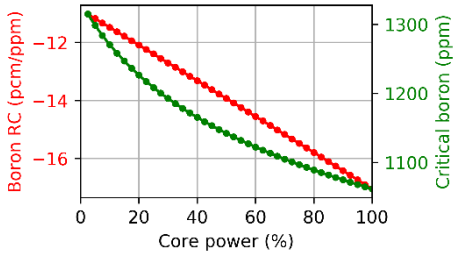
Some work conducted in 2019

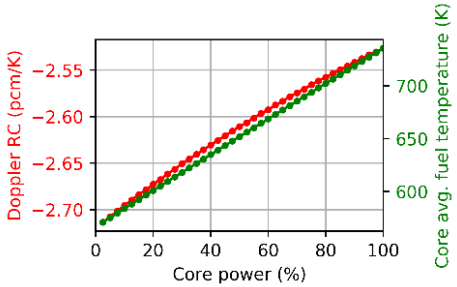
- Demonstrating the **capability** and **modularity** at steady state:

Valtavirta, V., Lauranto, U., Hovi, V., Peltonen, J., Rintala, A., Tuominen, R., Leppänen, J.
"High fidelity and reduced order solutions to an SMR-level progression problem with the Kraken computational framework"
PHYSOR 2020, March 29-April 2, 2020, Cambridge, UK.

	CZP			HZP			HFP		
	Ants	**Serpent**	**A–S**	**Ants**	**Serpent**	**A–S**	**Ants**	**Serpent**	**A–S**
RB1	861	874	–13	1974	2012	–38	2084	2221	–137
RB2	2094	2092	+2	2218	2161	–57	2290	2285	+5
SB3	2592	2597	–5	3547	3559	–12	3612	3697	–85
SB4	2592	2596	–4	3547	3560	–13	3612	3703	–91

Using high-fidelity solver to verify reduced order solver performance also in coupled calculations: Control rod group worths in an SMR core evaluated by Ants and Serpent based coupled calculation sequences in cold-zero-power (CZP), hot-zero-power (HZP) and hot-full-power (HFP) conditions.





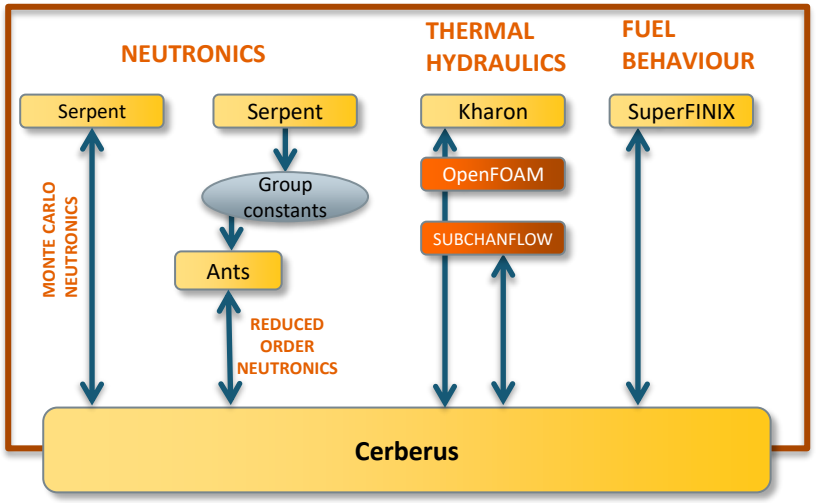
Evaluating licensing relevant data:
Two reactivity coefficients calculated with Ants-Kharon-SuperFINIX for the SMR core at various power levels:
Top: Boron reactivity coefficient (red) and critical boron (green).
Bottom: Doppler reactivity coefficient (red) and core average fuel temperature (green).

Development history and future plans

2020:

Moving from steady state to operating cycle analyses.

- Burnup capabilities implemented.
- A separate reactor simulator Python module automates fuel cycle analyses.
- Coupling SUBCHANFLOW through SCFWrap.



Unna Lauranto
Developing a generic Python based group constant library generator module for Serpent
Special Assignment Report, PHYS-E0441, Aalto University, School of Science, Department of Applied Physics, 2020.

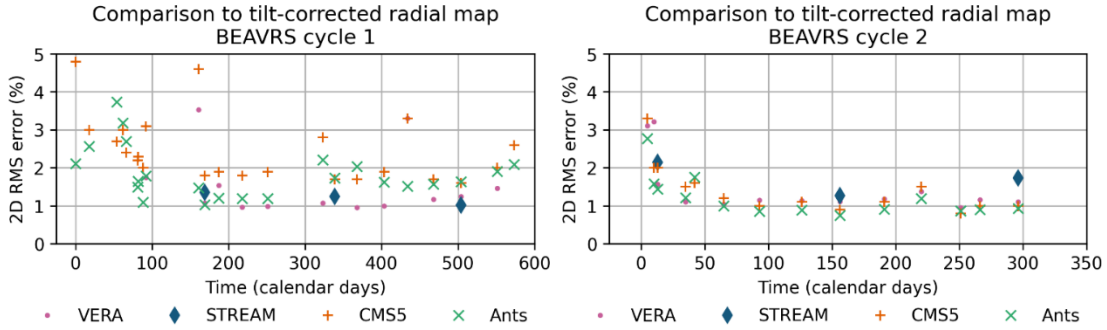
Valtavirta, V., Lauranto, U., Hovi, V., Peltonen, J., Rintala, A., Tuominen, R., Leppänen, J.
"High fidelity and reduced order solutions to an SMR-level progression problem with the Kraken computational framework"
PHYSOR 2020, March 29-April 2, 2020, Cambridge, UK.

Valtavirta, V., Rintala, A., Lauranto, U.
Validating the Serpent-Ants calculation chain using BEAVRS fresh core HZP data
29th International Conference Nuclear Energy for New Europe, September 7-10, 2020, Portoroz, Slovenia

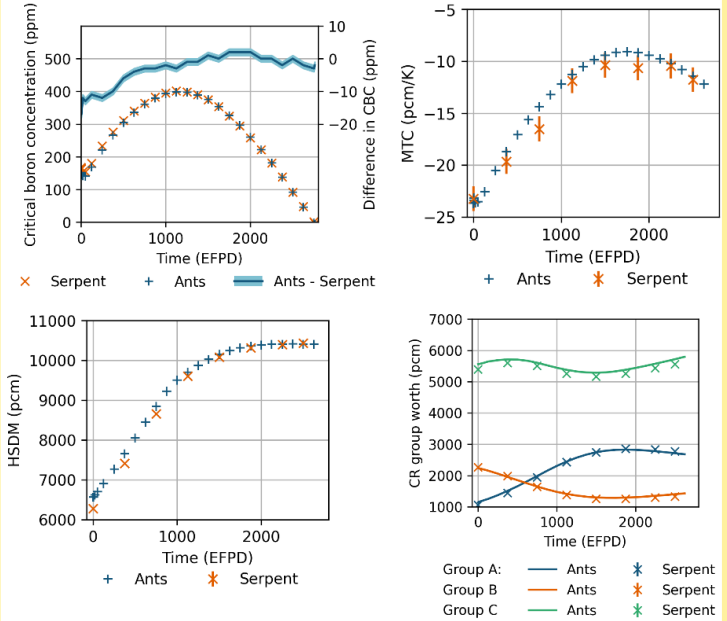
Some work conducted in 2020

- Demonstrating the **capability**, **usability** and **modularity** of the core simulator in operating cycle analyses.
- Beginning the validation of the framework for operating cycle analyses.

Valtavirta, V., Tuominen, R.
A simple reactor core simulator based on VTT's Cerberus Python package
M&C 2021, April 11-15, 2021, Raleigh, NC



Validation: 2D RMS errors when comparing calculated results to measured detector maps during the two operating cycles of the BEAVRS benchmark. Various industry and scientific leaders and Kraken (Ants).



Automatic evaluation of licensing relevant data during the simulation of an SMR operating cycle. Verification by switching one physics from reduced order solver (Ants) to a high-fidelity one (Serpent), while Kharon and SuperFINIX models are kept constant

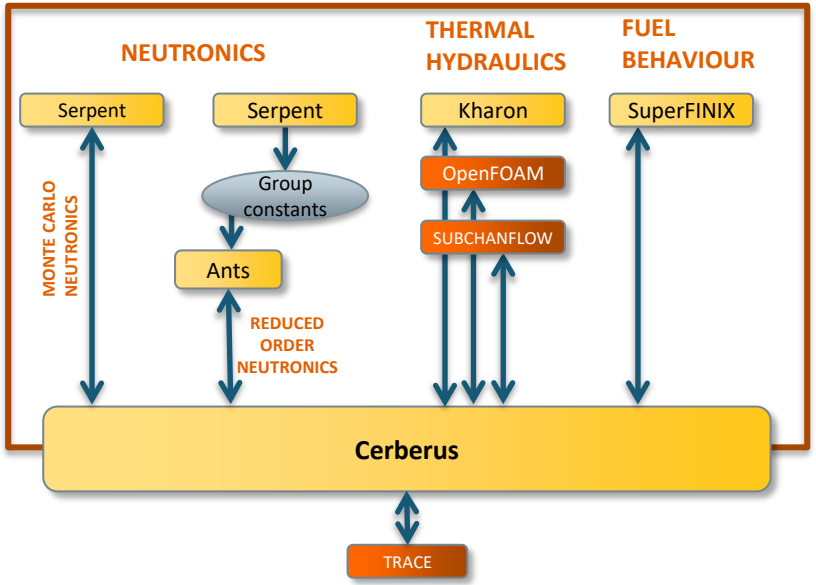
Top left: Boron letdown curve.
Top right: Moderator temperature reactivity coefficient.
Bottom left: Instantaneous hot shutdown margin.
Bottom right: Control rod group worths.

Development history and future plans

2021:

From operating cycle analyses to transient calculations.

- Coupling to TRACE via TRACEWrap and ECI.
  - Paper in this conference by Riku Tuominen (Coupling TRACE with Nodal Neutronics Code Ants Using the Exterior Communications Interface and VTT's Multi-Physics Driver Cerberus)
- Initial coupling to OpenFOAM.
- Begin drafting a non-commercial license.



Valtavirta, V., Tuominen, R.
A simple reactor core simulator based on VTT's Cerberus Python package
M&C 2021, April 11-15, 2021, Raleigh, NC

Hirvensalo, M., Rintala, A., Sahlberg, V.
Triangular geometry model for Ants nodal neutronics solver
M&C 2021, April 11-15, 2021, Raleigh, NC

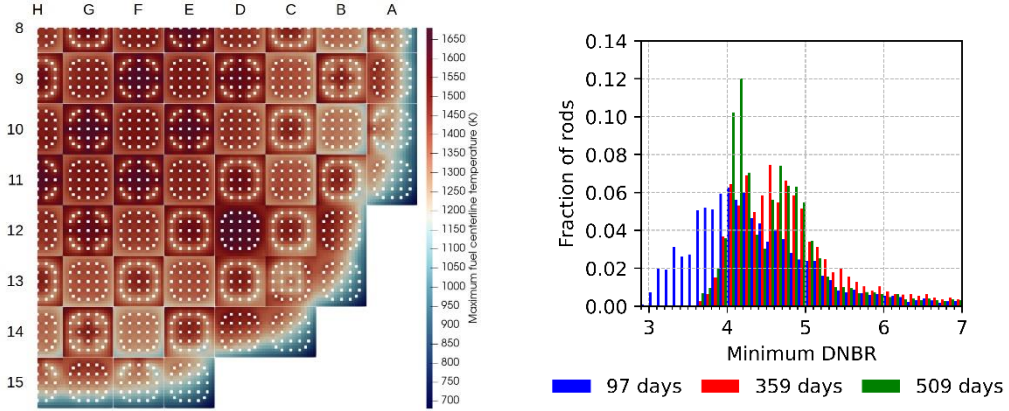
Markus Hirvensalo
Runtime optimization of SuperFINIX multi-rod fuel performance program
M.Sc. Thesis, Department of Applied Physics, School of Science, Aalto University.

Rintala, A., Valtavirta, V., Leppänen, J.
Microscopic cross section calculation methodology in the Serpent 2 Monte Carlo code
Annals of Nuclear Energy 164 (2021)

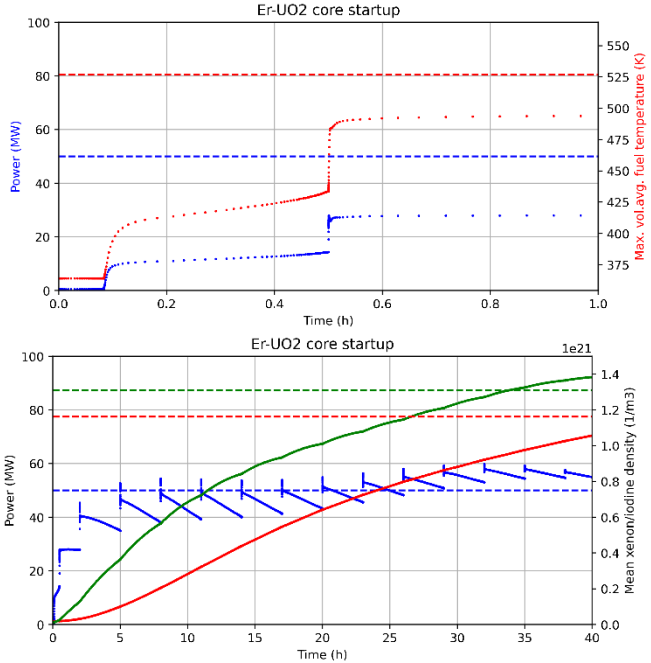
Valtavirta, V., Rintala, A., Lauranto, U. "Validating the Serpent-Ants Calculation Chain Using BEAVRS Fresh Core HZP Data"
Journal of Nuclear Engineering and Radiation Science (2021),

Some work conducted in 2021

- Extending the solvers and coupled solution to **time dependent simulations**.
- Verification of Ants neutron kinetics and dynamics.
- Verification of the Serpent-Ants chain in hexagonal lattice neutronics.
- Advanced methods for in-line thermal margin evaluation.



Rod resolved operating cycle analyses: PWR operating cycle modelled with Ants (pin power reconstruction) - SUBCHANFLOW (subchannel resolved) - SuperFINIX (rod resolved): **Left:** Maximum fuel centreline temperatures at 97 days. **Right:** Rod minimum DNBR distributions at 97, 359 and 509 days.



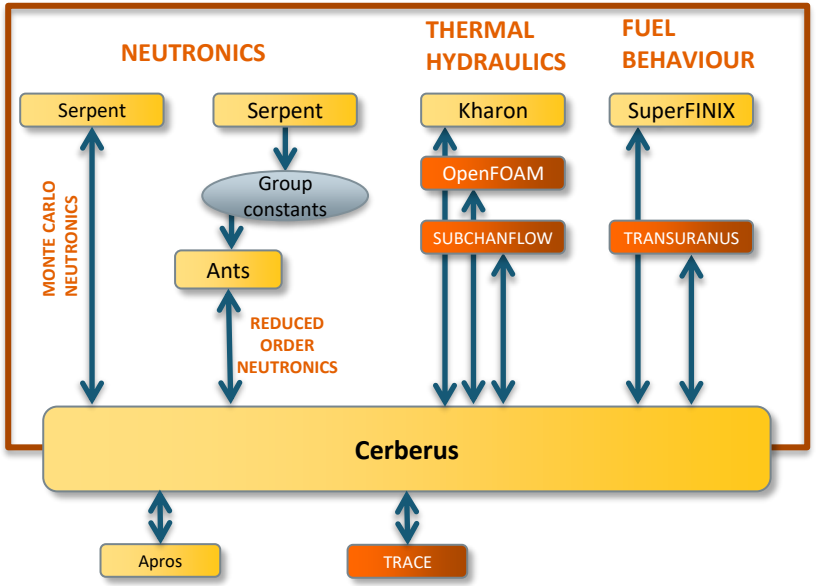
Starting an SMR from hot zero power to full power over several days. Modelled with Ants-SUBCHANFLOW.
Top row: Reactor power and maximum volume averaged fuel temperature during the first hour of the startup
Bottom: Reactor power and concentrations of ^{135}I and ^{135}Xe during the first 40 hours of the startup process.
Dashed lines indicate hot full power steady state values.

Development history and future plans

2022 (ongoing):

Various applications in McSAFER. Validation in LONKERO.

- Coupling to TRANSURANUS via TUWrap, coupling to Apros.
- Ants axial rehomogenization.
- First one-day Kraken training (McSAFER training course).
- First international Kraken workshop at an ANS conference (PHYSOR2022)



Valtavirta, V., Lauranto, U., Rintala, A.
Evaluating the X2 initial core zero power physics tests with Serpent–Ants
PHYSOR 2022, May 15-20, 2022, Pittsburgh, PA

Tuominen, R., Komu, R., Valtavirta, V.
Coupling TRACE with Nodal Neutronics Code Ants Using the Exterior Communications Interface and VTT's Multi-Physics Driver Cerberus
PHYSOR 2022, May 15-20, 2022, Pittsburgh, PA

Leppänen, J., Valtavirta, V., Rintala, A., Hovi, V., Tuominen, R., Peltonen, J., Hirvensalo, M., Dorval, E., Lauranto, U., Komu, R.
Current Status and On-Going Development of VTT's Kraken Core Physics Computational Framework, Energies 15 (2022)

Unna Lauranto
Verification of Ants time-dependent nodal neutronics model
M.Sc. Thesis, Department of Applied Physics, School of Science, Aalto University.

Valtavirta, V., Rintala, A., Lauranto, U. "Pin power reconstruction for hexagonal geometry in nodal neutronics program Ants"
Submitted to Annals of Nuclear Energy