Kraken workshop

Introduction to the physics solvers

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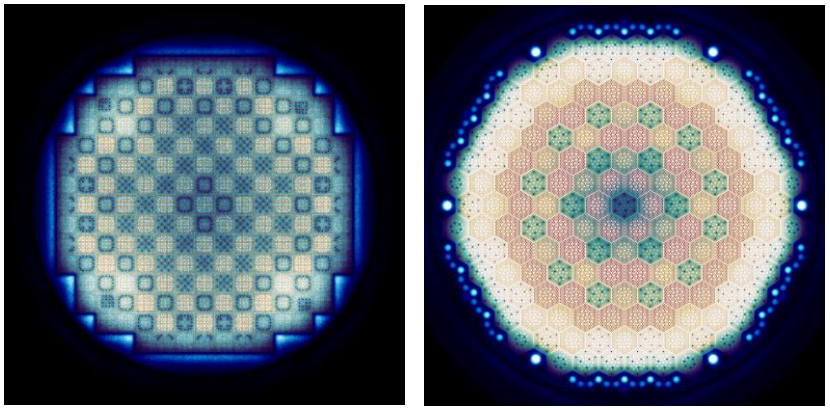
Outline

- 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

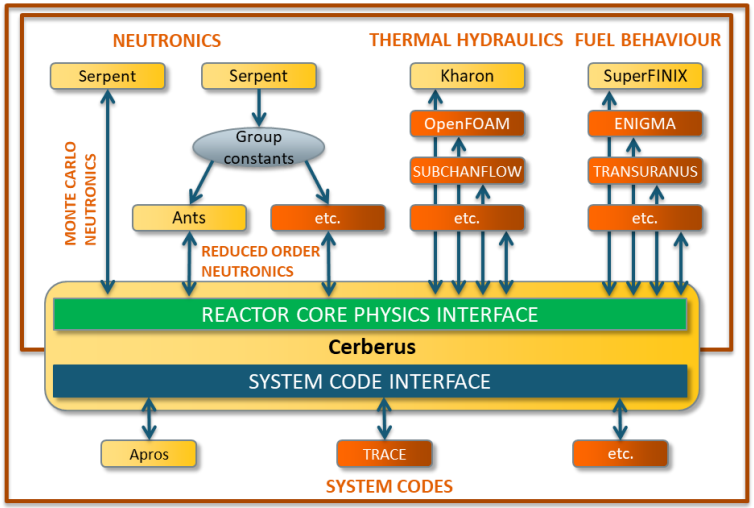
- Continuous-energy Monte Carlo transport calculation code developed at VTT since 2004.
- Neutron, photon and coupled neutron / photon transport modes.
- Originally developed for reactor physics, but scope of applications not limited to reactor modelling
- Advanced features and capabilities:
  - Automated 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 Khemlnitsky 2 (right) initial core. Warm colors indicate fission power and cold colors indicate thermal flux.

Serpent Monte Carlo code

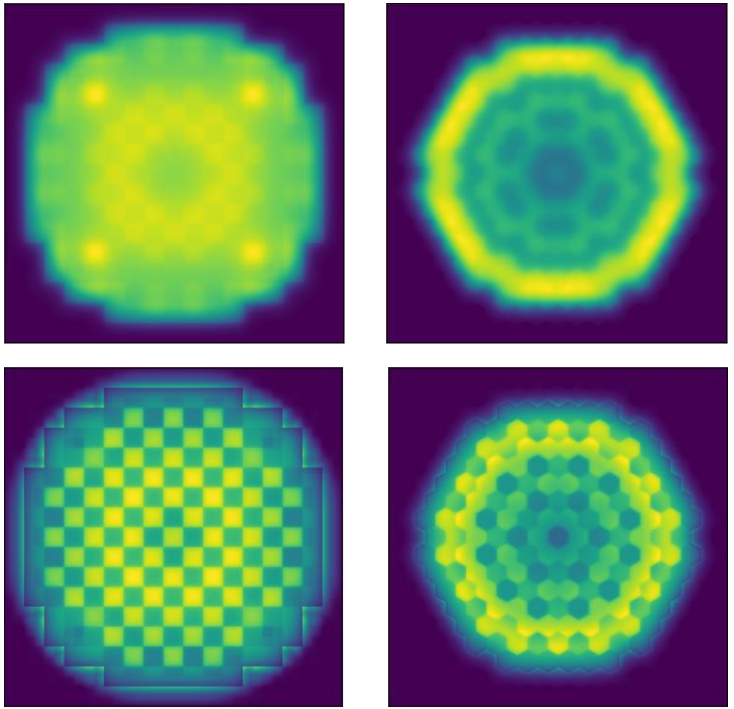
- Dual role in the Kraken framework:
  1) Group constant generation for the Ants nodal neutronics code (reduced-order sequence)
  2) Direct coupling to other physics solvers (high-fidelity sequence)
- The Serpent-based high-fidelity sequence can be used for best-estimate analyses or verification of reduced-order 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

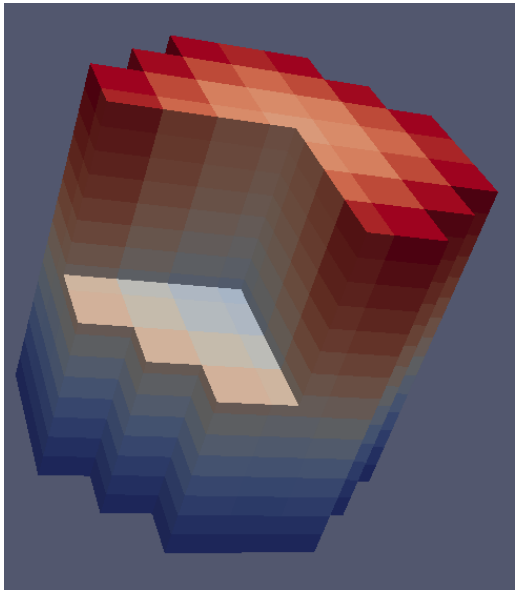
A simple core level thermal hydraulics solver developed at VTT:

- 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

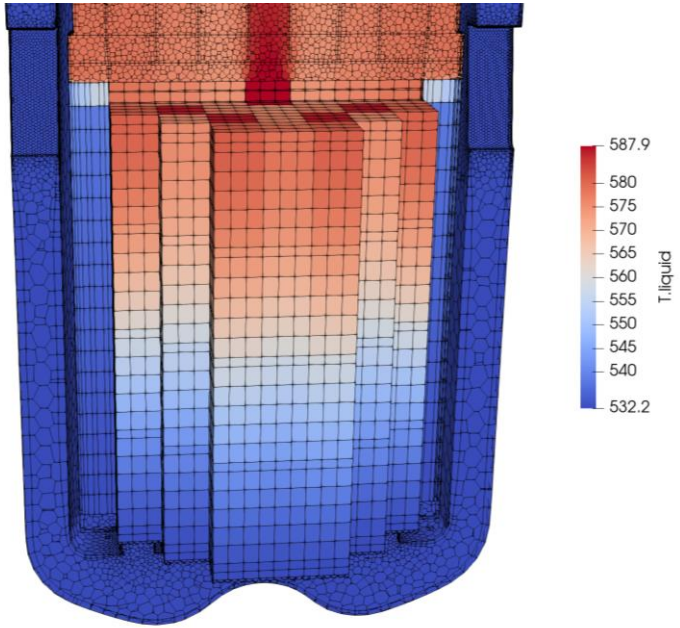
Open source software for CFD modelling and other purposes: https://openfoam.org/

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.

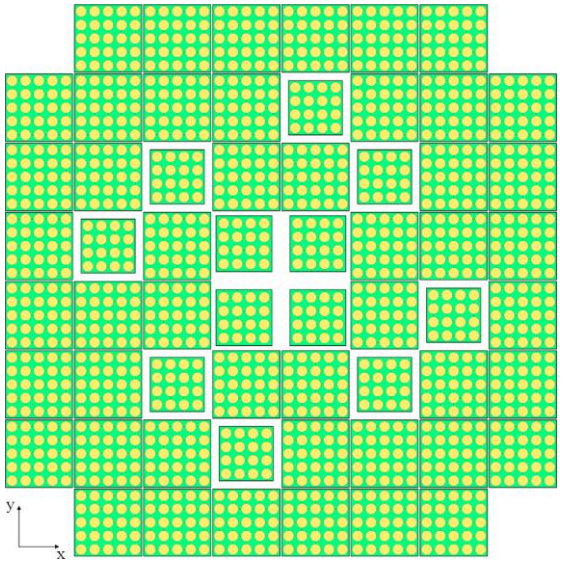
Most recently in the McSAFE project:

- 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.

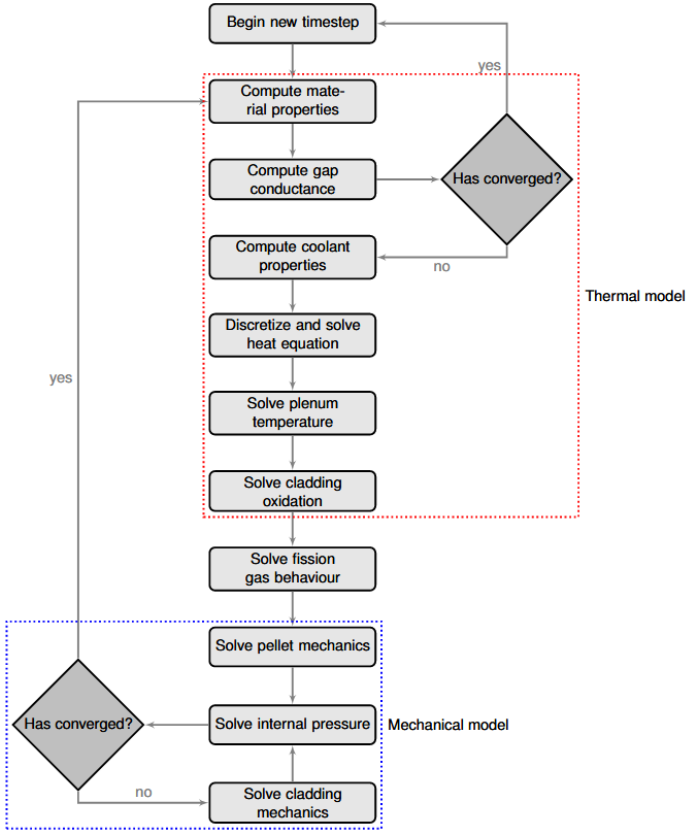
FINIX is a traditional 1.5 dimensional single rod fuel performance code.

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.

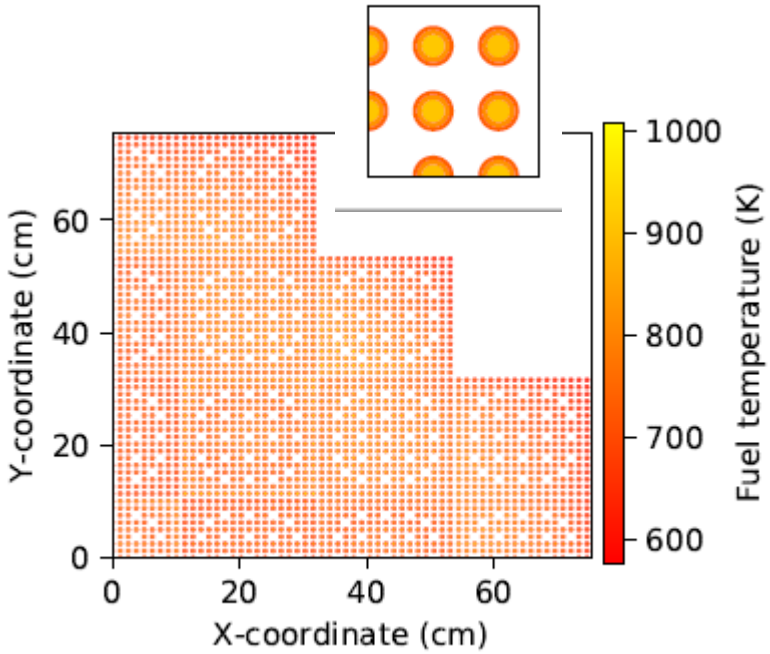
SuperFINIX core level fuel behaviour solver

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.

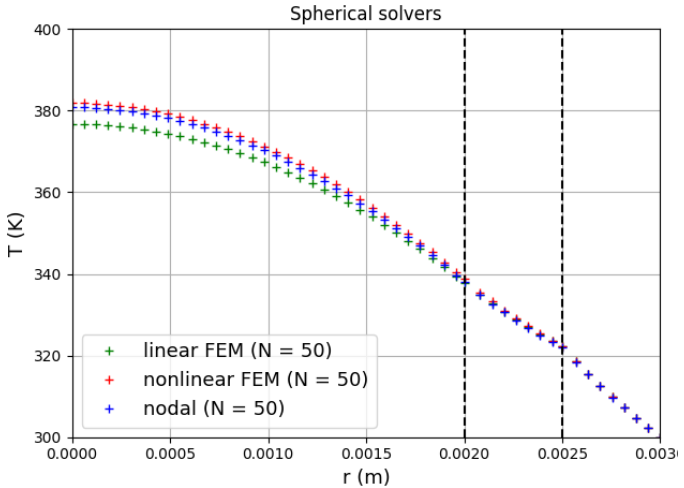
- Low temperature district heating and desalination reactor (LDR) concept developed at VTT since 2020.
- Industrial processes need a high temperature heat source for decarbonisation.
- HTGRs are a specific research focus at VTT.

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

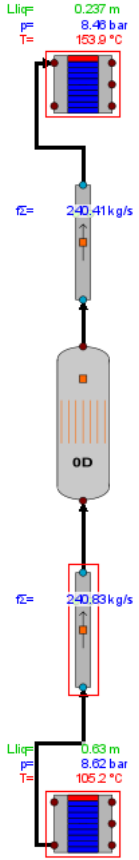
A system code / process simulator developed at VTT and Fortum for a long time.

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.

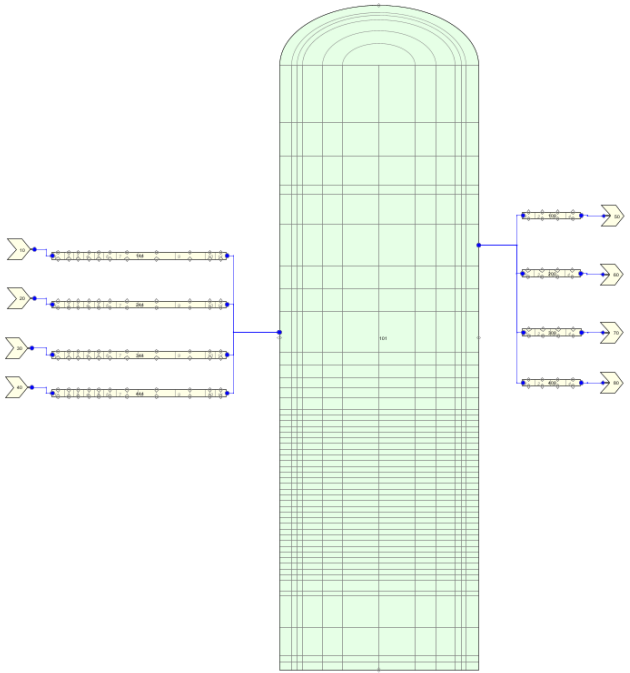
Coupling work with Kraken ongoing.



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

On licensing and distribution

Licensing and distribution (1/2)

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 (2/2)

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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