Use of Serpent-Kraken in VTT's LDR-50 district heating reactor project

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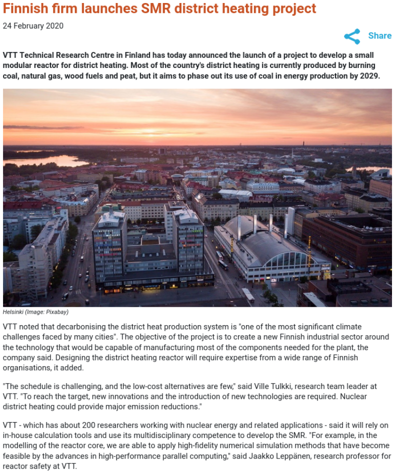
Background: motivation



Finnish firm launches SMR district heating project

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VTT Technical Research Centre in Finland has today announced the launch of a project to develop a small modular reactor for district heating. Most of the country's district heating is currently produced by burning coal, natural gas, wood fuels and peat, but it aims to phase out its use of coal in energy production by 2029.

Helsinki (Image: Pixabay)

VTT noted that decarbonising the district heat production system is "one of the most significant climate challenges faced by many cities". The objective of the project is to create a new Finnish industrial sector around the technology that would be capable of manufacturing most of the components needed for the plant, the company said. Designing the district heating reactor will require expertise from a wide range of Finnish organisations, it added.

"The schedule is challenging, and the low-cost alternatives are few," said Ville Tulkki, research team leader at VTT. "To reach the target, new innovations and the introduction of new technologies are required. Nuclear district heating could provide major emission reductions."

VTT - which has about 200 researchers working with nuclear energy and related applications - said it will rely on in-house calculation tools and use its multidisciplinary competence to develop the SMR. "For example, in the modelling of the reactor core, we are able to apply high-fidelity numerical simulation methods that have become feasible by the advances in high-performance parallel computing," said Jaakko Leppänen, research professor for reactor safety at VTT.

The development of a low temperature SMR for district heating purposes was started at VTT in February 2020:

- Finnish climate goals: carbon neutrality by 2035
- More than 85% of domestic electricity is already from low-carbon generation
- Fossil fuels still widely used in heating, industrial and transportation sectors, coal to be phased out by the end of this decade
- District heating is the most common heating form in Finland, and a major contributor to CO_2 emissions
- Nuclear energy is considered an economically viable option, with strong political and societal support

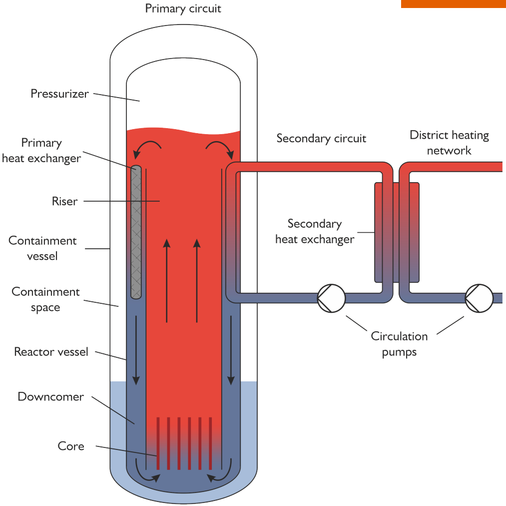
Practical challenge: the heat market is divided into more than 100 separate distribution networks – most existing SMR designs are too large to fit the purpose.

Background: overview

The Low-temperature District Heating and Desalination Reactor (LDR-50):

- 50 MW_{th} reactor module designed to supply heat at 65–120°C temperature without turbine cycle
- Low operating temperature (100–155°C) and pressure (0.3–0.7 MPa)
- Combination of conventional LWR technology and innovative passive safety design
- Heating plant may consist of one or several independent reactor modules

Pre-conceptual design phase completed by the end of 2020, results presented at the ICONE-28 conference.[1]



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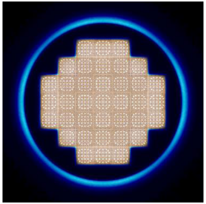
[1] Leppänen, J. et al. *"A Finnish District Heating Reactor: General overview."* In proc. ICONE-28, Virtual Conference, Aug. 4–6, 2021 (2021).

Background: overview

3D visualizations

Background: core design



Neutronic design relies on conventional LWR technology:

- 17×17 PWR fuel assemblies, truncated to 100 cm active length
- Enrichment 1.5/2.4%
- 37 assemblies in core, three-batch loading scheme
- Low power density, equilibrium cycle length 580 EFPD

Unconventional features related to boron-free operation:

- Reactivity control by control rods and burnable absorber (Gd)
- More emphasis in control rod design
- Control rods in every assembly positions
- 20 regulating rods, 17 safety rods

Boron injection can be used as secondary diverse shut-down mechanism.

Background: computational model

System-scale model:[2]

- Primary- and secondary circuits and associated components modeled using VTT's Apros process simulator
- Simulation of natural convection in primary circuit in various operating conditions (e.g. performance of primary heat exchangers)
- Evaluation of passive safety features in transient and accident conditions (e.g. SBO, ATWS, LOCA)

Core physics model:[3]

- Coupled core physics model constructed using VTT's Kraken computational framework
- Core design calculations (e.g. assembly design, cycle length)
- Evaluation of safety margins (e.g. feedback coefficients, shut-down margins)

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[2] Komu, R. et al. *"A Finnish District Heating Reactor: Thermal-Hydraulic Design and Transient Analyses."* In proc. ICONE-28, Virtual Conference, Aug. 4–6, 2021 (2021).

[3] Leppänen, J. et al. *"A Finnish District Heating Reactor: Neutronics Design and Fuel Cycle Simulations."* In proc. ICONE-28, Virtual Conference, Aug. 4–6, 2021 (2021).

This study

In this study, the simulations for the LDR-50 reactor module were extended from steady-state operation to load-follow mode. Major goals:

1) Evaluate reactor behavior in operating conditions where the output and supply temperature follow the demand from the DH network
2) Evaluate the overall feasibility of the calculation chain applied to this task
3) Identify any development needs in the applied methodologies and practices

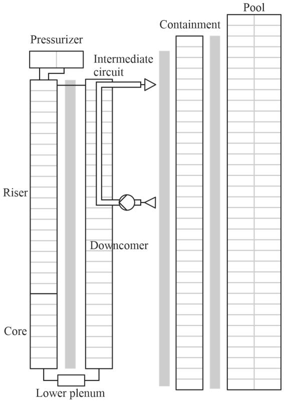
The focus in this presentation is in the core physics calculations using the Kraken framework. The Apros simulations are presented at the NUTHOS-13 conference.

Computational tools: Apros

Apros is a dynamic system-scale process simulation software developed by VTT and Fortum:

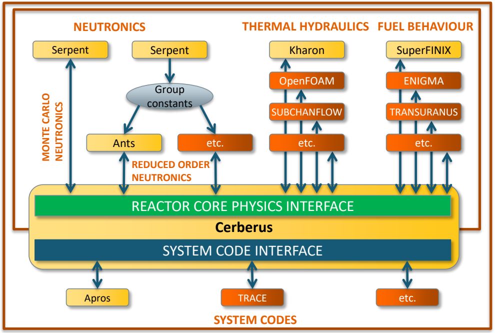
- Widely used for the modeling of industrial processes and conventional and nuclear power plants
- Several solvers for two-phase flows, models for pipes, pumps, valves, electric components and plant automation
- The LDR-50 model covers primary and secondary circuits, containment vessel, reactor pool, district heating network as boundary conditions, heat exchangers and shut-down cooling system
- Reactor modeled as a heat element or using the point-kinetics approximation (ATWS), with an ANS standard based model for decay heat

In this study, the Apros model was used to simulate reactor operation in load follow mode, and provide TH boundary conditions for Kraken



Computational tools: Kraken

Kraken is an emerging state-of-the-art computational framework for core-level design and safety analyses of conventional LWRs, SMRs and next-generation reactor designs:



- Developed at VTT since 2017
- Modular multi-physics platform (neutronics, thermal hydraulics, fuel behavior)
- Reduced-order and high-fidelity computational sequences
- Designed to accommodate computational modules developed at VTT and third-party solvers
- Coupling to system-scale simulations via external boundary conditions

Computational tools: Kraken

Computational modules used in this study:

Serpent	Continuous-energy Monte Carlo code, developed at VTT since 2004, used for producing homogenized group constants for the Ants nodal neutronics code
Ants	State-of-the art AFEN/FENM-based nodal neutronics code developed at VTT since 2017, used for the neutronics solution in the core physics coupling
Finix	Fuel behavior module developed at VTT since 2012, used for solving the thermo-mechanical behavior of fuel rods in the core physics coupling
Kharon	Closed channel two-phase steady-state thermal hydraulics solver developed for Kraken, used for the TH solution in the core physics coupling
Cerberus	Python package handling the communication between the modules

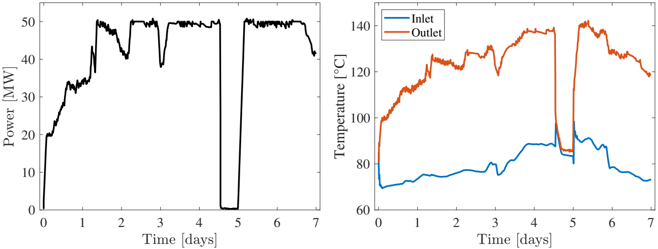
All user interaction occurs via a Cerberus-based reactor simulator, which also features control rod algorithms and other functionality required to simulate the reactor operation.

Computational tools: Kraken

Procedure for group constant generation (see also Ville's presentation on Tuesday):

- 3 assembly types
- 1/4 fuel assembly model, 8 energy groups (later condensed to 2)
- Nominal and perturbed history calculation up to 20 or 40 MWd/kgU burnup
- 56 branch variations: coolant temperature and density, fuel temperature, control rods, soluble boron (used as a secondary shut-down system)
- 20 million active neutron histories
- A total of 3954 transport simulations run in parallel in VTT's computer cluster using the casematrix features in Serpent
- Completed in 14.5 hours

Calculation case



Load-follow simulation based on real district heating network data was run for a period of 7 days using the Apros code:[4]

0 days : The reactor is started when heat demand is relatively low. Power is raised from zero to 20 MW over a period of two hours.

0–1.5 days : Outside temperature begins to drop, increasing the heat demand. Reactor power is gradually increased to 50 MW.

1.5–4.5 days : Reactor is operated near full power for several days, until a leak in the district heating network main pipe enforces reactor to shut down.

4.5–5 days : Reactor is maintained in a hot shut-down state for 12 hours.

5–7 days : Heat supply is resumed and the reactor is restarted to full power.

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[4] The interruption in operation at 4.5 days was added for complexity.

Calculation case

The Apros simulation provided reactor power and thermal hydraulics boundary conditions for the Kharon module in Kraken:

- One-way coupling (no feedback from Kraken back to Apros)
- Kraken simulations repeated for an equilibrium core at beginning-of-cycle (0 EFPD), middle-of-cycle (290 EFPD) and end-of-cycle (580 EFPD) conditions

Core performance evaluated using the following criteria:

1) Reactor stability – All feedback coefficients must remain negative throughout the operating cycle.
2) Shutdown margin – Sufficient negative reactivity must be available for maintaining a cold shut-down state, assuming that the most effective control rod assembly (CRA) is stuck in place.
3) Elimination of fast reactivity transients – Maximum CRA withdrawal worth must remain below 1$.
4) Thermal margins – Maximum coolant temperature must be maintained well below the saturation temperature to prevent coolant boiling.
5) Flat power profile – Axial, radial and nodal peaking factors must remain below $\sim$2.

The last two criteria follow from limitations in the TH solution (closed channel model).

Results

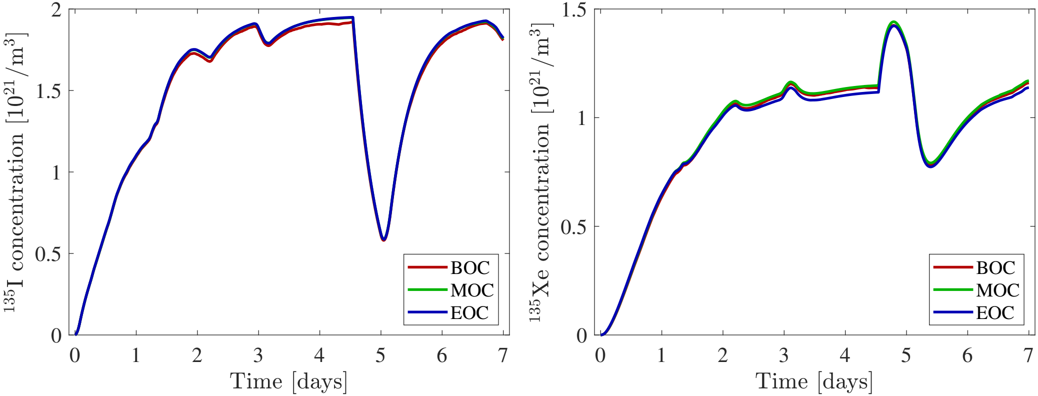

Figure 1: Concentrations of ^{135}I and ^{135}Xe as function of time.

Results

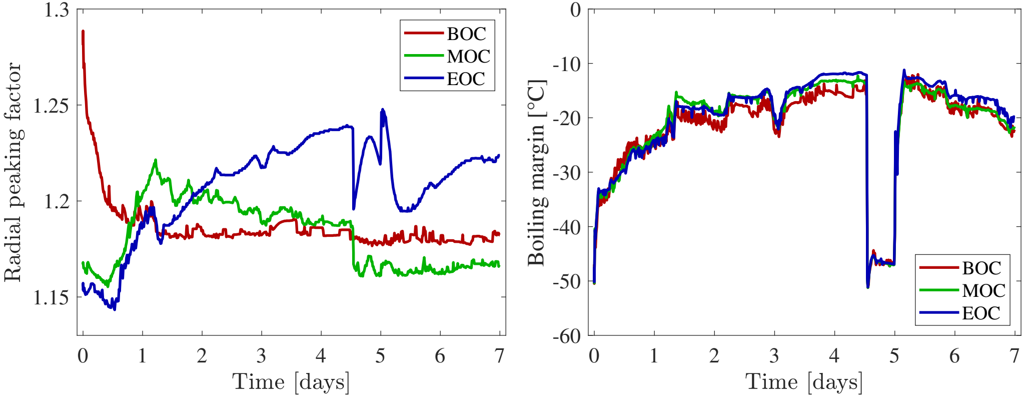

Figure 2: Radial peaking factor and margin to boiling as function of time.

Results

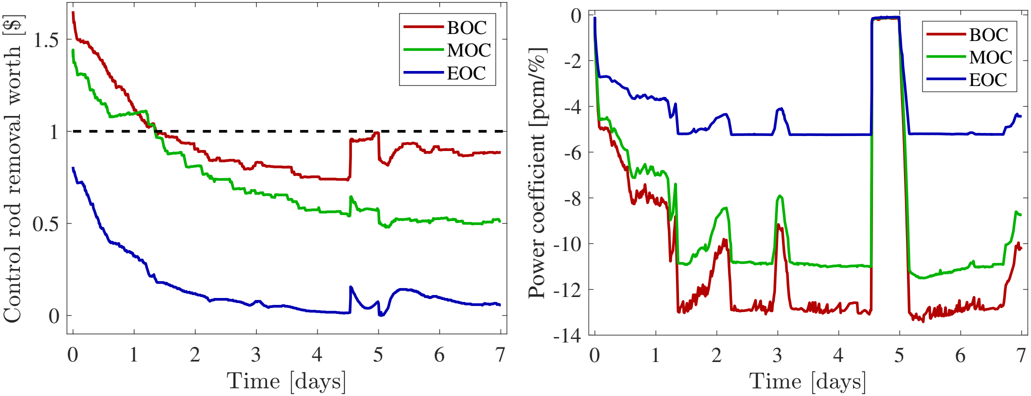

Figure 3: Maximum control rod worth and power coefficient of reactivity as function of time.

Results

Major findings:

- No major problems encountered in the simulation of load-follow operation
- Shut-down margins and stability criteria fulfilled
- Sufficient margin to boiling
- Similar behavior at BOC, MOC and EOC

However:

- 12-hour interruption in operation was too long to evaluate the effect of xenon poisoning
- Control rod algorithm designed for steady-state operation at full power not ideal for start-up and low-power operation
- Methodology used for evaluating power coefficients not reliable at low power

Conclusions and future work

Future work in Kraken:

- Fix shortcomings encountered during this study (control rod algorithm, calculation of power coefficients)
- Replace Kharon with an OpenFOAM based solver for thermal hydraulics
- Implement two-way coupling between Kraken and Apros
- Further development of Ants nodal neutronics code

The work on LDR-50 reactor concept continues:

- Apros-Kraken simulations for 3D transient safety analyses
- PRA model (FinPSA software)
- Severe accident analyses (new capability in Apros)
- Cost analyses in collaboration with Fortum (tools developed at MIT)
- Techno-economical market analyses for district heating networks in Finland and Europe

Thank you for your attention!

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