Coupling TRACE with VTT's Fuel Solver SuperFINIX for Transient Analysis

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ABSTRACT

In this paper, the recent work on coupling thermal-hydraulic system code TRACE with VTT's fuel solver SuperFINIX is presented. The coupling utilizes VTT's multi-physics driver Cerberus and the Exterior Communications Interface (ECI), which is supplied with TRACE. Previously TRACE has been used with nodal neutronics solver Ants to calculate VVER-1000 coolant transients. Now SuperFINIX is added to the coupling and the results are compared with the previous calculation.

KEYWORDS: TRACE, SuperFINIX, coupling, transient

1. INTRODUCTION

TRACE is U.S. NRC's thermal-hydraulic system code used widely in nuclear applications [1]. In 2021, TRACE was coupled with VTT's new computational framework Kraken [2,3]. The coupling utilizes TRACE's built-in coupling interface, the External Communication Interface (ECI), and VTT's multi-physics driver Cerberus. A wrapper code TRACEWrap was developed to handle the communication between TRACE and Cerberus. It has since then been used together with nodal neutronics solver Ants [4,5] for coupled VVER-1000 transient calculations [6].

Now VTT's fuel solver SuperFINIX [7] is added to the coupling. Using an external fuel solver has a few advantages: including the thermomechanical behavior of fuel in simulation, allowing source code level development of fuel modelling, enhancing the modularity of Kraken, and restarting the fuel solution based on a preceding fuel cycle simulation to better represent the initial fuel state in the transient. Previously, Idaho National Laboratory has coupled TRACE with the fuel solver BISON through the MOOSE framework for LOCA applications [8].

In this work, the Ants-SuperFINIX-TRACE coupling is applied to a VVER-1000 main steam line break (MSLB) transient. The results are compared to a Ants-TRACE calculation without the external fuel solver.

2. TRACE-SuperFINIX COUPLING

The fields transferred between the codes, presented in Fig. 1, are cladding temperature from SuperFINIX to TRACE, and wall to liquid heat transfer coefficient (HTC) and liquid temperature from TRACE to SuperFINIX. The fields are passed through Cerberus and interpolated so that they fit the mesh of the receiving solver. So far only one-phase conditions have been considered, but the coupling can be later extended to two-phase applications.

The time discreatization is the same in TRACE and SuperFINIX. It is driven by TRACE, because TRACE has an adaptive time-step size and it cannot be forced to use a certain step size. After TRACE has solved the time step, the step size is communicated to SuperFINIX, which then solves the same time interval. The

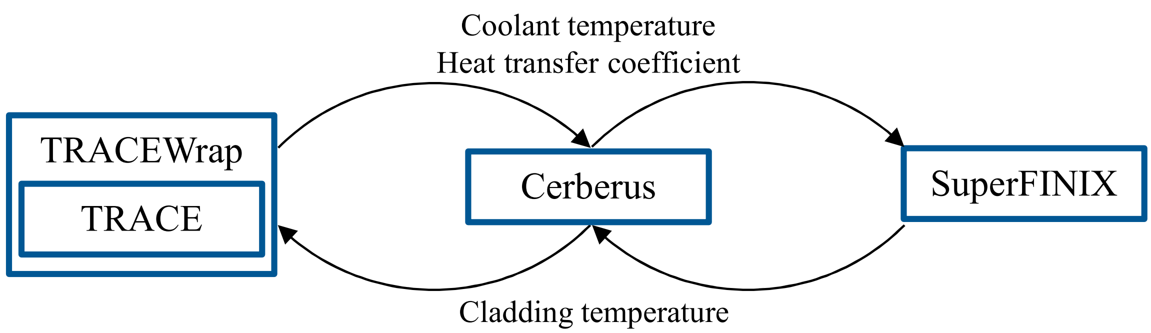

Figure 1: Data transfer between TRACE and SuperFINIX in the coupling.

TRACE-SuperFINIX time loop is as follows:

1. TRACE solves time step *n*
2. Coolant temperature and liquid HTC are interpolated from TRACE VESSEL component to SuperFINIX
3. SuperFINIX solves time step *n* with the coolant boundary conditions
4. Cladding temperature from SuperFINIX is interpolated to TRACE heat structures to be used in time step *n+1*

In addition to the fuel temperatures, SuperFINIX solves also the mechanical behavior of the fuel rod, which means that the radii of the rod changes both axially and temporally, whereas in TRACE the radius is constant. As the heat transfer rate is a function of the heat transfer area, using a different radius in the codes would change the amount of transferred power. For now, this has been addressed by scaling the cladding temperature based on the radii. The TRACE cladding temperature is calculated so that the energy is preserved between the solvers. In the future this could be addressed by changing the cladding radius in TRACE during the calculation.

TRACE version 5 Patch 7 was used in the coupling. The source code was modified so that TRACE does not solve the conduction equation and wall temperature in the fuel heat structures. The coupling was first tested with a simple test case consisting of one fuel assembly to make sure that the fields are transferred correctly between the codes and energy is preserved. Once this was verified, the actual benchmark could be calculated to demonstate the coupling.

3. V1000CT-2 BENCHMARK – MAIN STEAM LINE BREAK

The test case selected for the Ants-SuperFINIX-TRACE coupling is Phase 2 of the VVER-1000 Coolant Transient Benchmark (V1000CT-2) main steam line break problem [9]. The MSLB causes an asymmetric overcooling in the core thus making it an interesting case for coupled neutronics and thermal-hydraulics. Exercise 2 of the benchmark is a coupled 3D core problem with imposed vessel thermal-hydraulics boundary conditions. Two scenarios are included – realistic and pessimistic – from which the pessimistic Scenario 2 is calculated in this paper. In Scenario 2, it is assumed that the pump in the broken loop does not trip causing even stronger overcooling effect and the reactor to returns to power. This benchmark has been calculated previously with Ants-TRACE coupling [6]. Now SuperFINIX is added to the coupling to see the effects of more detailed fuel modelling on the results. The coolant boundary conditions are the same, so that the effect of the fuel modelling can be seen clearly.

The TRACE VVER-1000 reactor pressure vessel model with boundary conditions is presented in Fig. 2. The vessel includes six sectors and three radial rings for the active core and one for radial reflector. There is one heat structure per one vessel radial node. Therefore TRACE solves one representative rod per several fuel assemblies, whereas SuperFINIX solves one representative rod per fuel assembly. The TRACE radial nodalization and the mapping of the fuel assemblies to the nodes is presented in Fig. 3. Same mapping is used as between Ants and TRACE in [6]. Both have 30 uniform axial nodes for the active area. TRACE heat structures have also axial reflectors at the top and bottom. The mapping between the codes is done with a separate file. Ants and SuperFINIX nodalization have one-to-one correspondence for the active core.

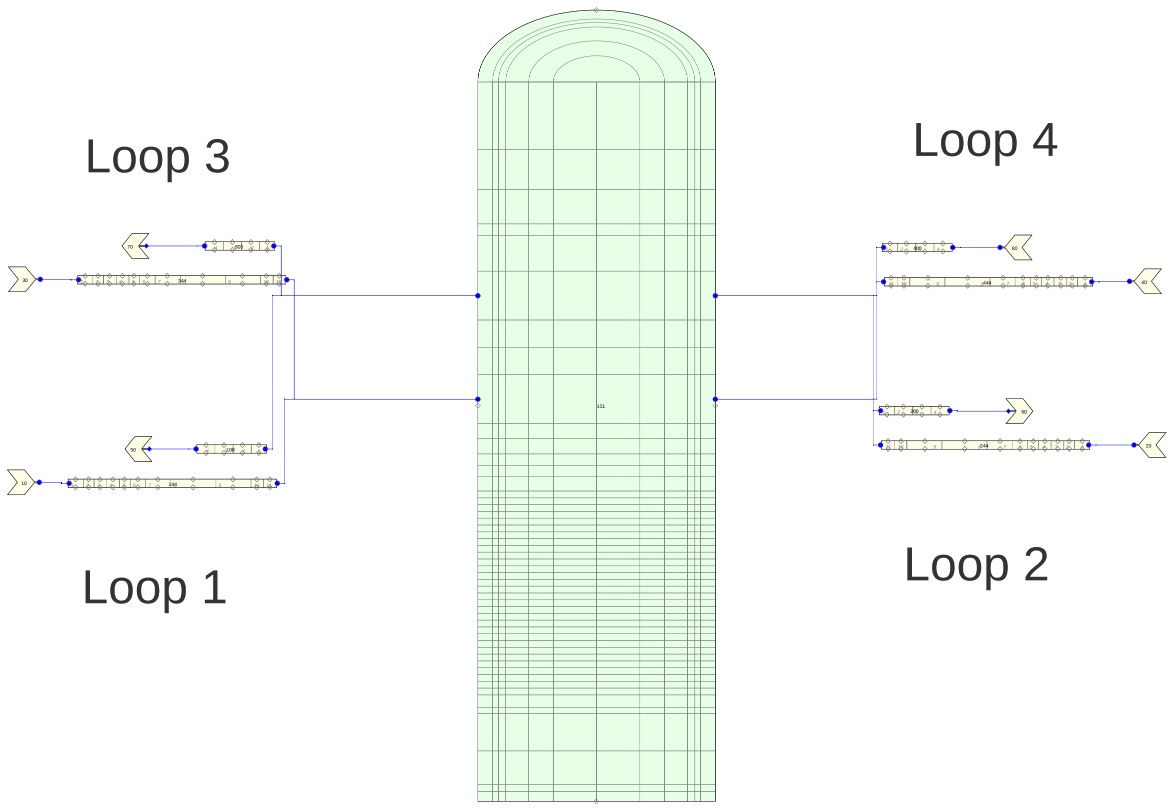

Figure 2: VVER-1000 reactor pressure vessel model with flow boundary conditions.

In the Ants-SuperFINIX-TRACE coupling, Ants receives the fuel temperature from SuperFINIX and coolant temperature and density from TRACE. The calculated power is then transferred to SuperFINIX, and TRACE calculates the heat transfer from the cladding surface. The coupling is illustrated in Fig. 4. Otherwise the Ants-TRACE coupling is executed in the same way as described in [2].

4. RESULTS

Fig. 5 shows results from the Ants-SuperFINIX-TRACE V1000CT-2 benchmark MSLB transient calculation compared to Ants-TRACE. The MSLB event causes overcooling in the core resulting in the reactor returning to power. There are small differences in the calculated power and nodal peaking factor (Fxyz) caused by the different fuel temperatures. SuperFINIX calculates slightly lower ($\sim 5\%$) mean fuel temperature in the initial state and at the highest peak when the reactor returns to power. Causes for this might be found in the in-built material properties or the fact that SuperFINIX calculates also the thermo-mechanical behaviour of the fuel. SuperFINIX calculates higher maximum fuel temperature, which is likely caused by the finer nodalization. As SuperFINIX calculates one rod per fuel assembly, the effects of the power

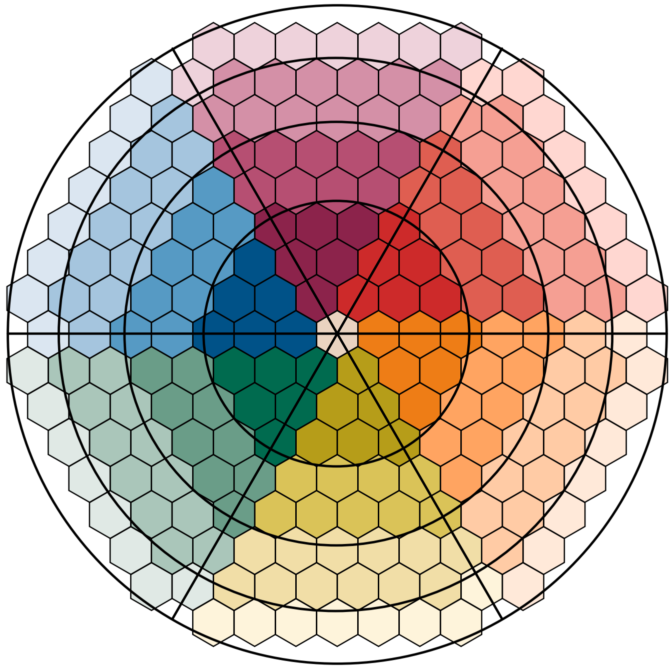

Figure 3: VVER-1000 fuel assemblies mapped to the TRACE nodalization.

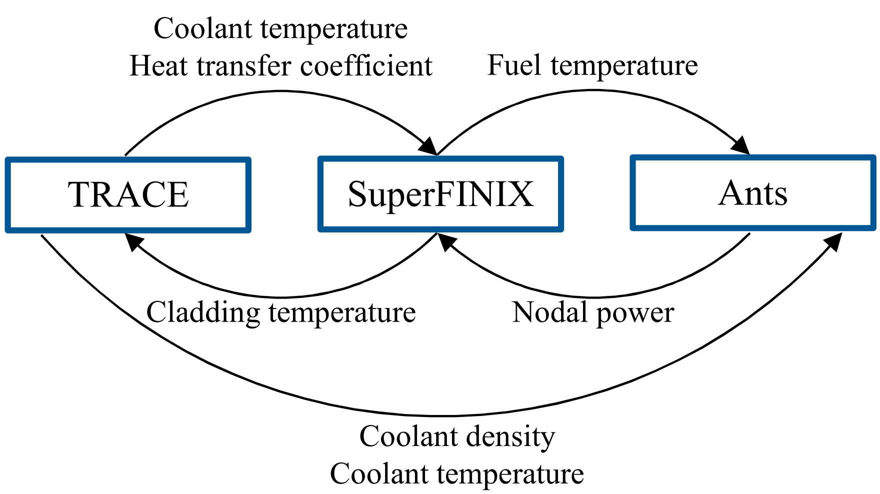

Figure 4: Data transfer between TRACE, SuperFINIX and Ants in the coupled calculation.

peaking are more clearly visible in the fuel temperature. In TRACE, the fuel temperature averages out over several assemblies. The core average coolant temperature and density are about the same in both cases as they should, because the same inlet coolant flow boundary conditions are used.

Fig. 6 presents the radial power distribution during the strongest overcooling at 69 seconds and the relative difference compared to Ants-TRACE. The power peaks at the sector where the coolant temperature is the lowest. The effect of the TRACE nodalization is seen on the results, and the biggest differences are on

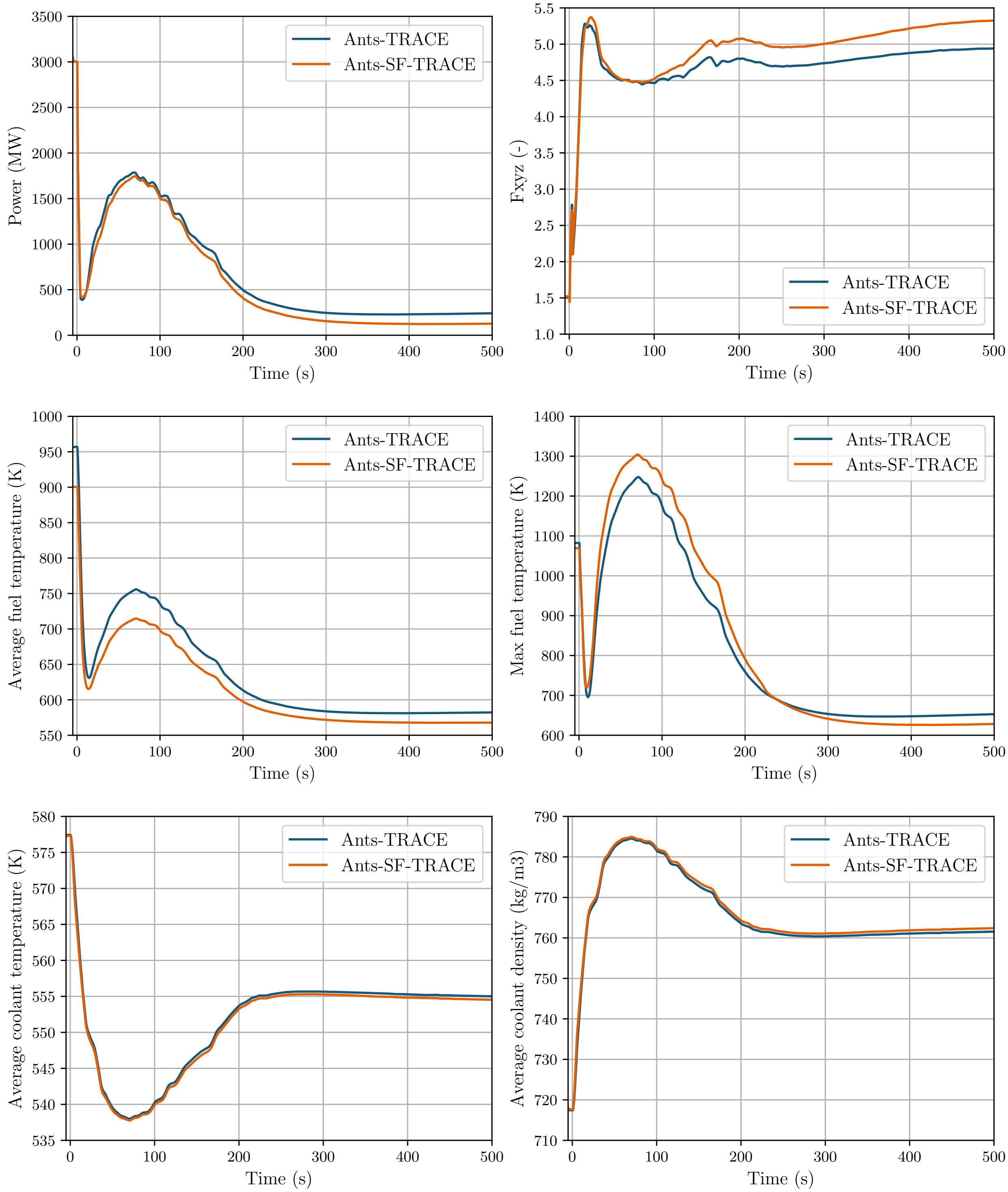

Figure 5: Ants-SuperFINIX-TRACE calculation results on V1000CT-2 Scenario 2 MSLB problem compared to Ants-TRACE [6].

the sector with the highest power. In Ants-TRACE calculation, the fuel temperature averages out over several fuel assemblies. In the sector with the highest power peak, this effect reduces the power in the fuel assemblies with lower power. Therefore, with Ants-SuperFINIX-TRACE, the calculated power is higher in this sector. The difference is small in the assembly with the highest power. Overall, the differences between Ants-TRACE and Ants-SuperFINIX-TRACE are around the same magnitude or smaller compared to the differences between Ants-TRACE and the original benchmark results [6].

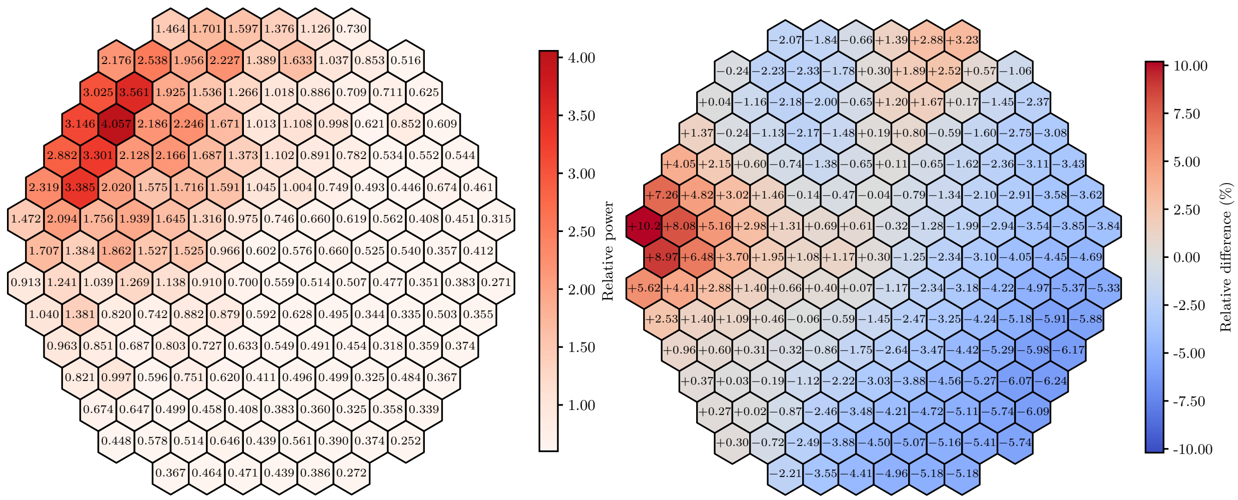

Figure 6: Relative power during the strongest overcooling at 69 seconds calculated with Ants-SuperFINIX-TRACE and relative difference compared to Ants-TRACE.

5. DISCUSSION

VTT's fuel solver SuperFINIX was coupled with U.S. NRC's thermal-hydraulic system code TRACE. In the coupling, SuperFINIX solves the fuel thermo-mechanical behaviour and TRACE the coolant properties. Cladding surface temperature acts as the interface between the codes. Nodal diffusion code Ants solves the reactor power distribution in the coupled transient calculation.

A main steam line break transient for VVER-1000 reactor with vessel boundary conditions was calculated with Ants-SuperFINIX-TRACE calculation chain and compared to Ants-TRACE. The results show good agreement. Some differences can be seen in calculated fuel temperature, which can be explained by the differences in the fuel solvers. The results demostrate that the coupling is capable of modelling the relevant phenomena and can be used in further transient calculations. Future work includes expanding the coupling for two-phase applications.

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REFERENCES

[1] *TRACE V5.0 PATCH 5 THEORY MANUAL - Field Equations, Solution Methods, and Physical Models*. U. S. Nuclear Regulatory Commission, Washington, DC (2017).

[2] R. Tuominen, R. Komu, and V. Valtavirta. "Coupling of TRACE with Nodal Neutronics Code Ants Using the Exterior Communications Interface and VTT's Multiphysics Driver Cerberus." In *Proceedings of the PHYSOR 2022*. Pittsburgh, PA (2022).

[3] J. Leppänen, V. Valtavirta, A. Rintala, V. Hovi, R. Tuominen, J. Peltonen, M. Hirvensalo, E. Dorval, U. Lauranto, and R. Komu. "Current Status and On-Going Development of VTT's Kraken Core Physics Computational Framework." *Energies*, **volume 15**(3) (2022). URL https://www.mdpi.com/1996-1073/15/3/876.

[4] V. Sahlberg and A. Rintala. "Development and first results of a new rectangular nodal diffusion solver of Ants." In *Proceedings of the PHYSOR 2018*. Cancun, Mexico (2018).

[5] A. Rintala and V. Sahlberg. "Extension of nodal diffusion solver of Ants to hexagonal geometry." *Kerntechnik*, **volume 84**(4), pp. 252–261 (2019).

[6] U. Lauranto, R. Komu, A. Rintala, and V. Valtavirta. "Validation of the Ants-TRACE code system with VVER-1000 coolant transient benchmarks." *Annals of Nuclear Energy*, **volume 190**(109879) (2023).

[7] V. Valtavirta, J. Peltonen, U. Lauranto, and J. Leppänen. "SuperFINIX — A Flexible-Fidelity Core Level Fuel Behavior Solver for Multi-Physics Applications." In *Proceedings of NENE 2019*. Portorož, Slovenia (2019).

[8] R. Gardner, C. Permann, M. Bernard, and R. Williamson. "Demonstration of Bison-TRACE Coupling (CRAB) Through Validation Case LOFT L2-5." In *Proceedings of Top Fuel 2019*, pp. 450–455. Seattle, WA (2019).

[9] N. Kolev, N. Petrov, J. Donov, D. Angelova, S. Aniel, E. Royer, B. Ivanov, K. Ivanov, E. Lukanov, Y. Dinkov, D. Popov, and S. Nikonov. "VVER-1000 Coolant Transient Benchmark PHASE 2 (V1000CT-2) Vol. II: MSLB Problem – Final Specifications." Technical Report NEA/NSC/DOC(2006)6, OECD/NEA (2006).