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APPLICATION OF THE SALOME PLATFORM TO THE LOOSE COUPLING OF THE CATHENA AND ELOCA CODES

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Abstract

Use of coupled codes for the safety analysis of nuclear power plants is highly desirable, as it permits multi-disciplinary studies of complex reactor behaviors and, in particular, accident simulations.

The present work demonstrates the potential of the SALOME platform as an interface for creating integrated, multi-disciplinary simulations of reactor scenarios. For this purpose two codes currently in use within the Canadian nuclear industry, CATHENA and ELOCA, were coupled by means of SALOME. The coupled codes were used to model the Power Burst Facility (PBF)-CANDU Test, which was to test the thermal-mechanical behavior of PHWR (pressurized heavy water reactor) fuel during a simulated Large Loss-Of-Coolant Accident (LLOCA). The results of the SALOME-coupled simulations are compared with a previous analysis in which the two codes were coupled using a package of scripts.

1. Introduction

Nuclear energy is a multidisciplinary domain involving many codes which were developed within different technical disciplines. The codes are used to simulate different physical phenomena occurring in nuclear reactors, which are often coupled and interact with each other. The rapid development of multi-core computing technology over the last two decades has opened opportunities for the creation and use of multi-disciplinary coupled systems of codes intended to model complex physical phenomena. At the same time new tendencies are observed in the nuclear energy industry, namely such as plans to build new nuclear power plants, to extend the life of aging reactors, to develop next generation of nuclear reactors and to enhance the safety of nuclear power facilities as much as possible. Consequently, there is an interest in advanced modelling and simulation which permits coupling of different physical phenomena and hence, to have a more detailed and profound understanding of processes occurring in all systems of nuclear plants. An ability to conduct, promptly and efficiently, a certain study which includes computation, data analysis and visualization are also desirable. As a result, many countries have renewed their research and development programs in the domain of code coupling. Atomic Energy of Canada (AECL) is actively developing a next generation tool suite, intended to operate as a multi-disciplinary integrated code system.

In the frame of this activity, a need was identified to obtain a rapid prototyping tool to test the impact of different configurations in the coupled system. The SALOME platform appears to offer such a tool. SALOME is open source software distributed under the terms of the GNU LGPL and has been under development since 2001 by EDF, CEA and OPEN CASCADES. Its goal is to supply a suite of tools for integrating different codes into the same numerical framework. The SALOME project uses common interfaces and common data models, and

provides high level functionality for pre-processing (CAD/solid modelling/meshing) and post-processing (visualization) [1].

In order to evaluate the feasibility to use the SALOME platform for coupling of the codes used in the Canadian nuclear sector (industry, regulator and research institutions) and to estimate the time required for creating of a coupled system in SALOME, this platform was employed for the creation of a coupled system of the thermal-hydraulic code CATHENA (Canadian Algorithm for THErmal-hydraulic Network Analysis) and the thermo-mechanical code ELOCA (Element Loss Of Coolant Accident), and analysis of a Large LOss-of-Coolant Accident (LLOCA). In particular, the Power Burst Facility (PBF)-CANDU Test was modeled and the results were compared with the results obtained by Baschuk [2], in which the codes were coupled by means of Perl scripts.

2. Brief overview of the experiment

The PBF-CANDU Test was aimed to provide an evaluation of the thermal-mechanical behavior of fuel elements typical of Canadian power reactors during a simulated Loss-of-Coolant Accident (LOCA). The experiment took place at the Power Burst Facility (PBF) reactor (see Figure 1) at the Idaho National Engineering Laboratory (ENEL) in 1984.

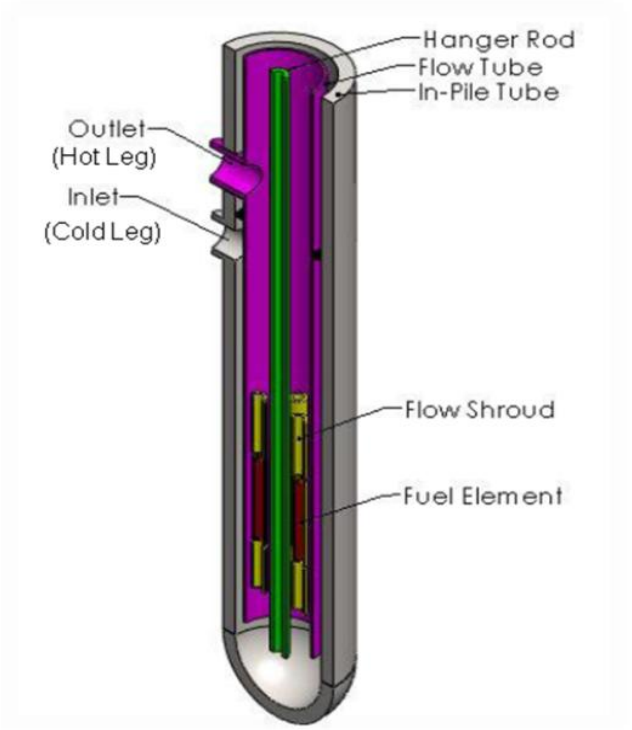

Figure 1: Section view of the setup [2].

The main specifications of the experiment were the following:

- *Coolant and moderator:* light water.
- *Pressures, temperatures, and flow rates of light water:* similar to the normal operating conditions of a Canadian heavy water power reactor
- *Orientation of fuel elements:* vertical.
- *The system pressure before the transient phase of the test:* ~10 MPa.
- *Hydraulic diameters of the fuel element/shroud assembly:* ~5 mm (for a typical bundle in a power reactor they are ~ 7-8 mm).
- *Sheath material:* Zircaloy
- *Fuel:* enriched for the purpose of the test (10 wt% U-235 in U)
- *Fuel elements tested during the experiment:* 4 fuel elements denoted as BA-01, BA-03 and BA-05 (pre-irradiated to approximately120 MWh/kgU at ~53 kW/m), and BA-07 (fresh fuel)

The complete scenario description can be found in the reference [2]. Briefly, the experiment had the fowling stages:

1. 16 hours of in-reactor fuel conditioning in the PBF reactor. The flow over the fuel elements was in the upwards (vertical) direction;
2. The transient phase of the test was triggered by isolating the IPT from the pressurized loop, and then depressurizing the IPT through the cold leg blowdown lines.
3. The blowdown also included an increase in fuel pin power, similar to the power pulse that would be encountered in a LLOCA;
4. The first 50 s of the blowdown was similar to a postulated LLOCA (power pulse, followed by reduction in pin power to decay heat). However, after 50 s, the power to the fuel elements was increased in order to obtain a sheath temperature of ~ 1350 K;
5. Termination of the experiment with a reactor SCRAM and reflood of the test section at 99.7 s after the initiation of the blowdown and power transient.

3. Main modeling aspects

In the simulation of the PBF-CANDU Test, the thermal-hydraulic and thermal responses of the system are modelled by CATHENA. The detailed information about the CATHENA model parameterization can be found in Reference [2]. Since CATHENA does not contain a

model describing the thermal-mechanical behavior of fuel elements, ELOCA is used to model their performance during the transient. The initial conditions for ELOCA are provided by ELESTRES (ELEment Simulation and sTRESses). An iterative method is used for the coupling of the CATHENA and ELOCA codes (see Figure 2). In this case it is so called "loose" coupling: codes exchange the information after the end of their execution and not during an execution.

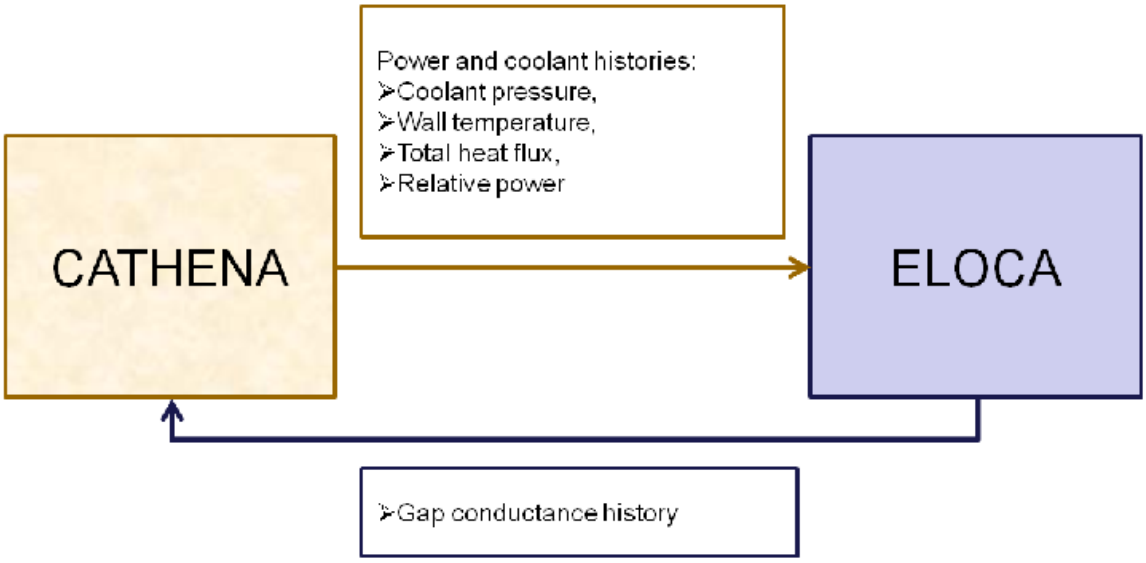

Figure 2: Iterative coupling scheme used to model the transient phase of the PBF-CANDU Test.

Coolant pressure, wall temperature, total heat flux and relative power data from CATHENA are used as the boundary conditions for the fuel elements in ELOCA simulations. ELOCA in turn provides the fuel-to-sheath heat transfer coefficient, which is used as the gap conductance in CATHENA's modelling of the fuel elements.

In ELOCA, one axial segment was used to model each fuel element. In the CATHENA simulation, fuel elements are divided into four axial segments and averaging is applied to the variables which are transferred to ELOCA.

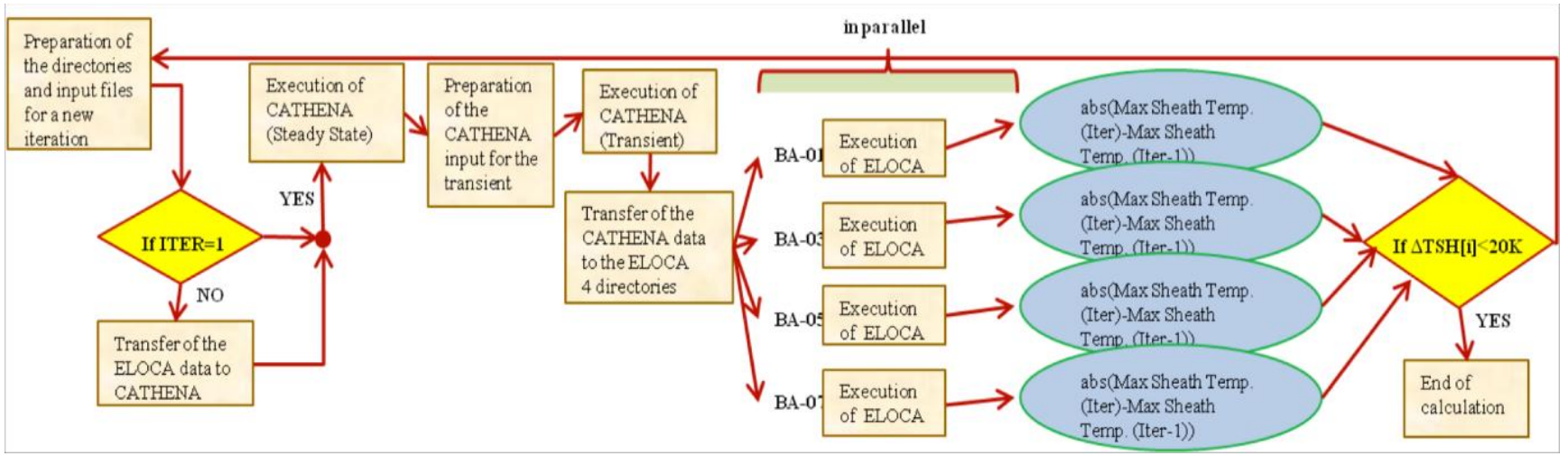

Figure 3: Block diagram of the coupling algorithm.

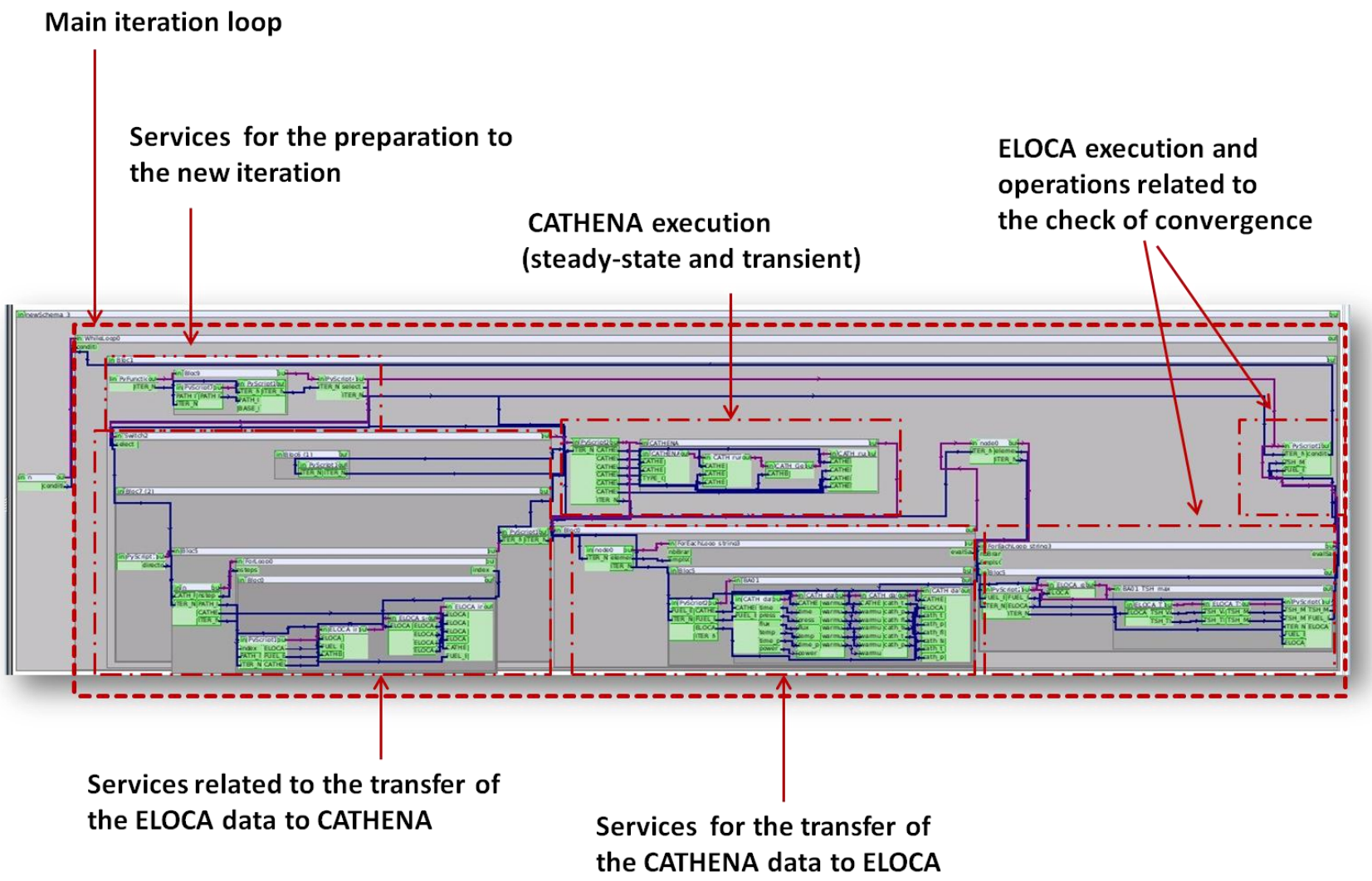

Figure 4: The SALOME calculation scheme of the CATHENA/ELOCA coupled system.

The block diagram of the chain of the calculations of the coupled system is shown in Figure 3:

- At the first iteration, the fuel-to-sheath heat transfer coefficient is constant with respect to time and is taken from the steady-state analysis of fuel elements conducted by means of the code ELESTRES.
- The CATHENA simulation consists of three parts:
  - Execution of CATHENA for the steady-state
  - Preparation of the CATHENA input file for the transient.
  - Calculation of the transient by CATHENA.
- Then, coolant pressure, wall temperature, total heat flux and relative power from CATHENA are transferred to ELOCA.
- At the next step ELOCA is executed.
- Afterwards, the convergence criterion is checked. If the change in maximum sheath temperature provided by ELOCA is less than 20 K between iterations, then it is assumed that the calculation is converged.
- If the system did not converge, the fuel-to-sheath heat transfer coefficient (calculated by ELOCA), as a function of time, is transferred to the fuel element representation in the CATHENA model and the simulation is repeated.

4. Technical details related to the CATHENA/ELOCA coupling using SALOME

The CATHENA and ELOCA modules, based on the use of the code executable files, were created and integrated into the SALOME environment. To couple the codes, it is necessary to use the YACS module of the SALOME platform [3]. In particular, it is necessary to build a calculation scheme which represents the chain of calculations and is executed by the YACS module. This calculation scheme is represented by SALOME using an interface inspired by graphical programming languages.

In the present work, the communications between the code executables are made by means of Python built-in system functions, together with the use of the SALOME environment. The codes were integrated to SALOME using CORBA objects, which allows for the possibility of remote access to the executables, if required.

The calculation scheme of the CATHENA/ELOCA coupled system is shown in Figure 4. The main blocks of the scheme are denoted. They correspond to the main elements of the block diagram in Figure 3. Inside of each block there are nodes representing codes or services for codes execution and data treatment. The scheme can be executed either in the batch regime or by using the SALOME interface, which allows for a step by step execution.

From a developer's point of view, it is an advantage to use SALOME because the platform has built-in structures which facilitate the creation of complex calculation chains. Once codes are

integrated into SALOME as modules, they may be used in different calculation schemes, which can involve a single code, a sequence of codes (loose coupling) or strong coupling (exchange of the information during an execution).

From a user's point of view, the use of SALOME simplifies the execution of a coupled system and it is more transparent, than a package of scripts. The coupled system is represented by a scheme and can be loaded into SALOME. Execution can be done either through a console or graphical user interface, which has different options for execution mode). The platform can be used for post-processing as well, as will be demonstrated in the next section.

5. Results

One of the key output parameters of the simulation is the sheath temperature of the fuel elements which was measured during the PBF-CANDU Test. Figure 5 a) shows a comparison of the ELOCA predictions of the sheath temperature of the BA-07 fuel element made by the coupled system created and run using SALOME with the results published in the paper [2] (called "reference"), as well as the experimental data. First 20 second of simulation corresponds to a "steady-state" period, then the transient is initiated and starting from this time the experimental data are presented. A very good agreement between the "SALOME" coupling and reference results is observed. One of the reasons of the discrepancy between the predicted and measured values is a delay of the onset of CHF in the experiment by thermocouples. Detailed discussions of on this subject can be found in [2]. Comparison of the CATHENA predictions of the sheath temperature for the four segments of the BA-05 fuel element made by the system coupled with the aid of SALOME with the reference data is presented on the graph b) of Figure 5. There is a very good agreement between the computed results as well. For the sheath temperature, the maximum percent difference between the SALOME results and reference data is ~1.6% for both CATHENA and ELOCA.

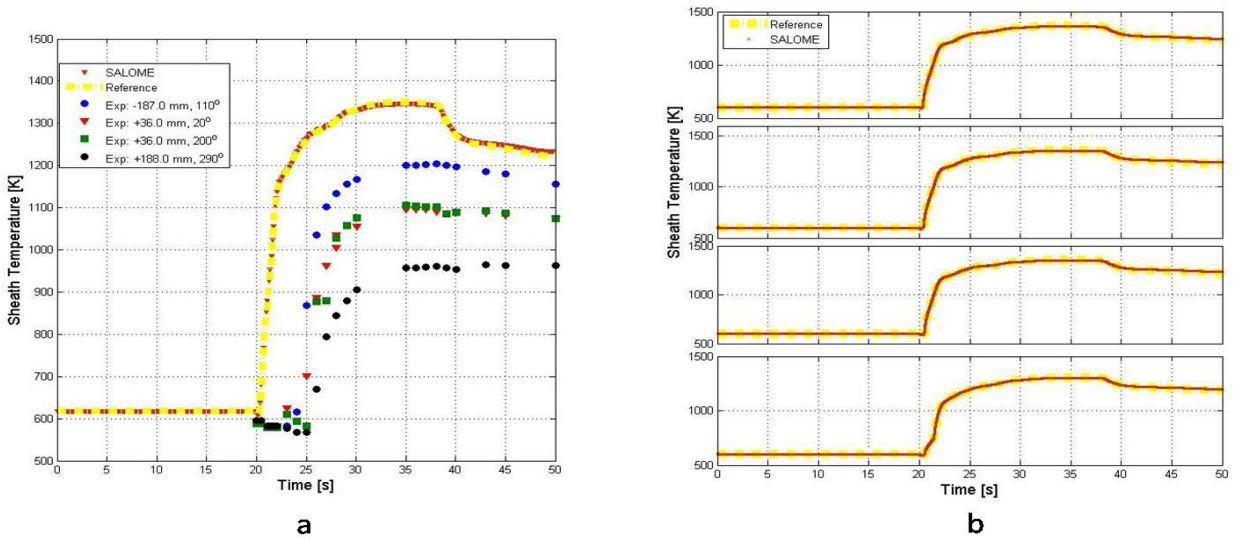

Figure 5: The ELOCA and CATHENA predictions (a) and (b) respectively for the sheath temperature of the BA-07 fuel element made with the aid of SALOME and from the reference work. The experimental data are shown on (a) as well.

The graphs a) and b) of the Figure 6 show the ELOCA and CATHENA predictions respectively, for the centreline fuel temperature of the BA-07 fuel element obtained from the calculations made in SALOME and from the reference work. For the both codes there is a very good agreement agreement between the values computed by the means of the SALOME platform and previous results. For the case of centreline fuel temperature, the maximum percent difference is also ~1.6% for both CATHENA and ELOCA.

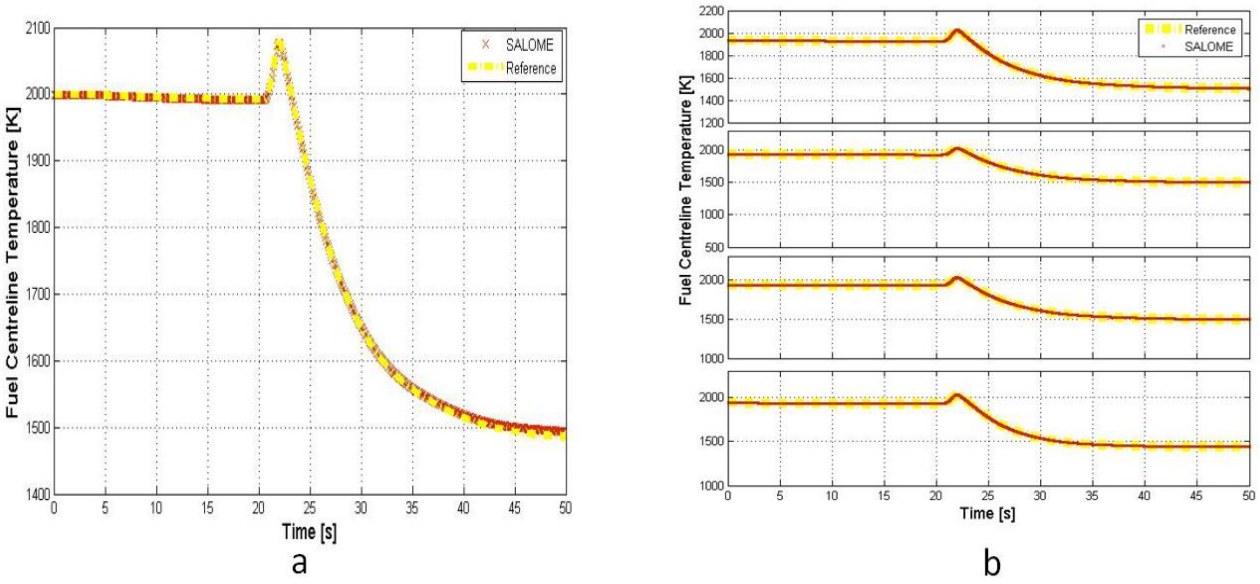

Figure 6: The ELOCA and CATHENA predictions (a) and (b), respectively, for the centreline fuel temperature of the BA-07 fuel element made by means of SALOME and from the reference work.

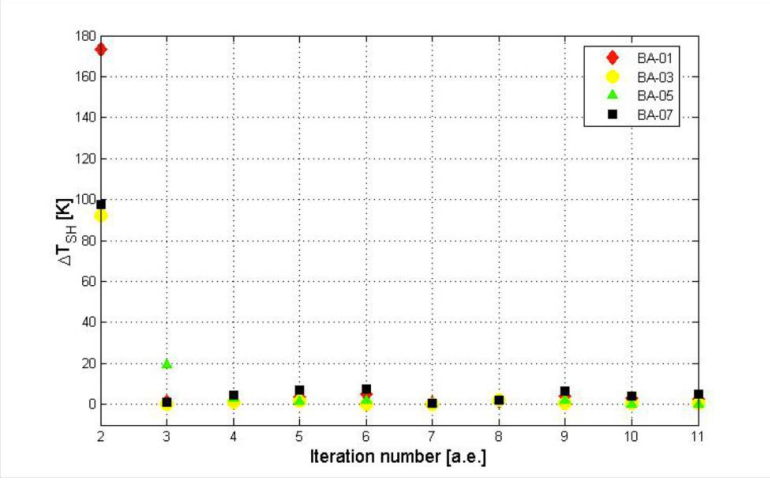

Figure 7: Evolution of ΔT_{SH} (where T_{SH} is a maximum sheath temperature predicted by ELOCA and Δ represents the difference in T_{SH} between the two consequent iterations) during the iterative calculation for the four fuel elements and consequently for the four ELOCA executions.

The comparison of all modelled parameters showed that the maximum percent difference is ~3.2% for both ELOCA and CATHENA. The difference is related to slightly different values being transferred from code to code in the SALOME runs versus the Perl script.

Figure 7 shows the evolution of the convergence criterion during the iterative calculation of the system coupled in SALOME. Small oscillations of the criterion are related to the use of the "loose" coupling of the codes CATHENA and ELOCA.

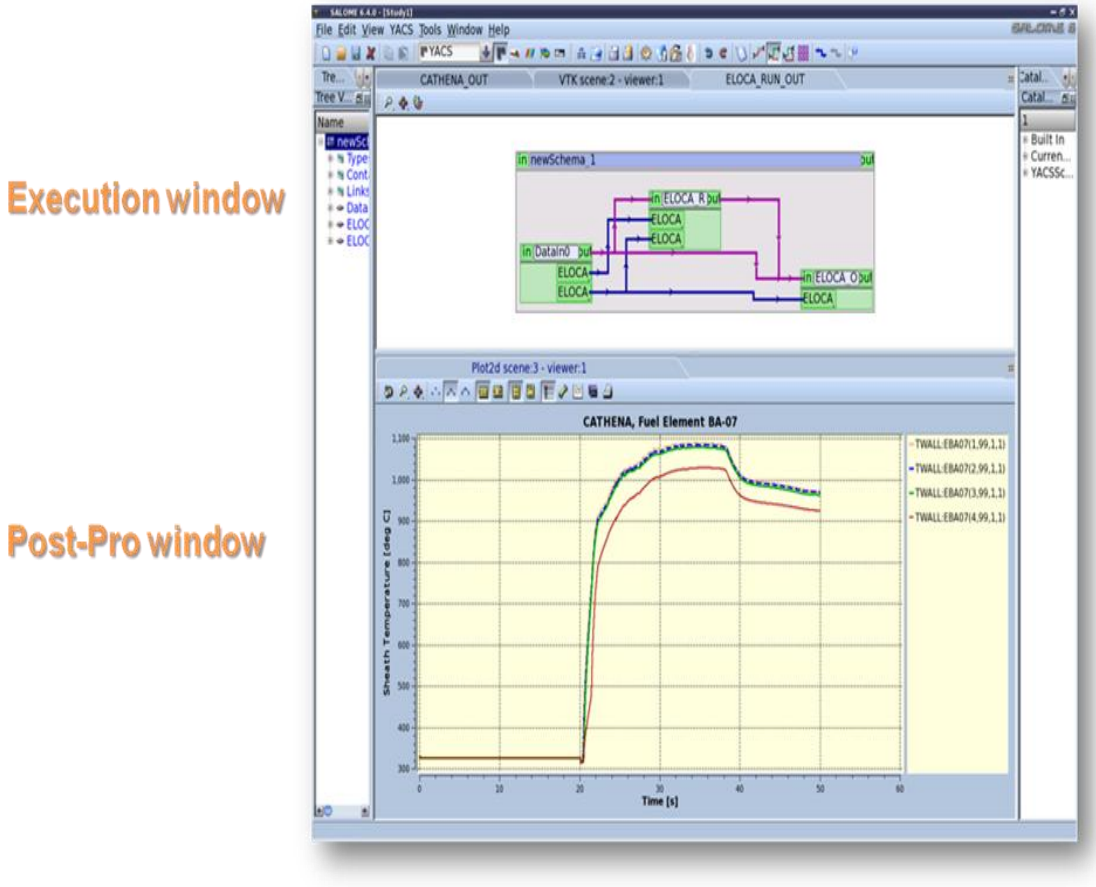

Figure 8: View of the SALOME application with the CATHENA execution and Post-Pro window.

The SALOME platform is a convenient tool for code execution and result post-processing. Figure 8 shows an example of the windows with a simple scheme for the CATHENA execution and post-processing of the results. It is an important feature of SALOME, as most of the current safety codes are console based with a lack of visualisation ability.

6. Conclusion

The conducted study shows that SALOME is stable at all stages of work and it is convenient for creating and debugging of a coupled system, its executing and post-processing of the results. The predictions, made by the coupled system created and run using SALOME are in very good agreement with the reference results.

The present work demonstrates that the SALOME platform has a potential to be used as an interface for creating integrated, multi-disciplinary simulations based on the codes currently in use within the Canadian nuclear sector.

7. Acknowledgements

I would like to acknowledge Nicolas Crouzet from CEA-Saclay for providing very helpful information about the SALOME platform and Jeffrey Baschuk from AECL for valuable discussions and supplying the data related to the existing CATHENA/ELOCA "loosely" coupled system.

8. References

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[2] J.J. Baschuk, "Simulation of the PBF-CANDU test with coupled thermal-hydraulic and fuel thermo-mechanical responses", Proceedings of ICAPP'12, Chicago, USA, 2012 June 24-28, paper 12177

[3] SALOME platform, online documentation, http://www.salome-platform.org/user-section/documentation/current-release