Multiphysics simulation of APR1400 Load Follow Operation

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1. Introduction

In this paper, the APR1400's Multiphysics analysis of Load Follow Operation (LFO) is performed in multiphysics package RELAP5/3DKIN [1]. Traditionally, nuclear reactors operate in a baseload regime with constant power output, except for power changes accompanied with planned shutdown for maintenance and refueling. However, with the increasing integration of intermittent renewable energy sources like solar and wind into the electric grid, nuclear reactors must adapt to varying power demands, necessitating LFO capability. This becomes significantly important for countries with a high nuclear share in their energy mix [2].

The overall goal is to analyze whether APR1400 fulfills the EU requirements for LFO. These requirements state that reactors must adjust power output between 50% and 100% of nominal power up to 5 times per week and 200 times per year. These power changes must be performed relatively quickly, using Control Element Assemblies (CEAs), which significantly affect core power distribution and other neutron-physical and thermal-hydraulic parameters. This necessitates a coupled analysis method that considers the mutual interconnection between these properties.

A traditional point kinetics model with reactivity tables and simplified core representation fails to capture the realistic behavior of the core under LFO. Therefore, a Multiphysics approach using RELAP5\SCDAP\3DKIN was selected [1]. This approach accounts for the three-dimensional physical phenomena in the core during power changes, providing a more accurate analysis of the APR1400's LFO performance.

The advantage of using a two-way coupling approach lies in its ability to maintain boundary conditions intact and achieve high fidelity by enabling bi-directional information exchange between codes. This coupling is typically employed to accurately simulate interactions between fluid properties and fuel parameters within the core, affecting core power through phenomena like fission reactions, moderation, neutron slowing, and reactivity feedback from moderator, fuel, and boron [3].

In Korea, LFO control model MODE-K was developed to control the core power altogether with axial power distribution during power variations. In MODE-K, power changes from 100 % to 50 % in 3 hours, than stays on 50 % for the next 6 hours and finally goes back to 100 % in the upcoming 3 hours [4]. MODE-K load follow scheme is shown on Figure 1. At the same time, soluble boron concentration and CEA positions undergo a slight corrections in order to compensate for Xenon accumulation and to maintain a stable 50 % power level.

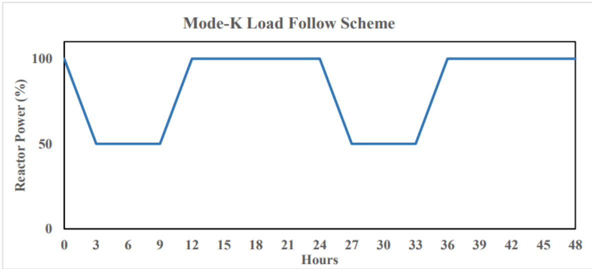

Figure 1: MODE-K LFO Scheme [4]

For Load Follow Operation, there are two main control modes available:

- **Constant coolant average temperature mode** – Where the average temperature of the primary coolant is not changing during the power maneuvering. The main advantage is that moderator temperature coefficient (MTC) does not have a big influence on reactivity. The biggest disadvantage is that the secondary steam pressure and temperature change significantly during, thus affecting the heat transfer between primary and secondary side.

- **Sliding coolant average temperature mode** - Where the primary coolant cold leg temperature is kept fixed, while the hot leg and average temperature change with power. The biggest advantage of this mode is constant steam generator pressure. This control logic was therefore chosen for the analysis.

While most LFO cycles, as well as K-MODE span an entire day, simulating them in real-time is constrained by computation time and hardware storage limitations. During the model development phase, the K-Curve (Figure 1) was simulated over a much shorter time span to expedite the process. This simplification was necessary due to the lengthy simulation time and insufficient hardware storage available for handling a full scope 24 hour real time simulation. Furthermore, code limitations emerged after trials to enlarge the simulation time. The purpose of this work is to develop a LFO RELAP/3DKIN model with implemented control logic for adapting the sliding average temperature control mode to the system for LFO Multiphysics analysis, allowing to perform further investigation once the technical and time constraints are solved.

2. Methodology

For a thorough investigation of LFO, the following approach had to be applied. Firstly, a point kinetics steady state model in RELAP5 was developed, where the channels in the core region were pre-prepared for coupling with neutron transport 3DKIN code in the following step. In the next phase, the model was expanded to couple the thermal hydraulic channels in the core with 3DKIN to include detailed core structures for multiphysics simulation of the steady state. Finally, a transient model was developed, in which the load follow operation was examined. This model underwent multiple changes in order to be adjusted for load follow mode. In addition to the TH input preparation described above, cross-sections for 3DKIN were generated using the CASMO4 neutron code [5][6]. Multiple input files, including core geometry descriptions, also had to be prepared for 3DKIN. The scheme which depicts the upper mentioned steps is shown on Figure 2.

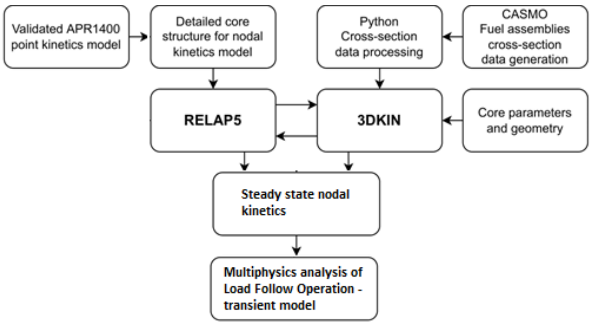

Figure 2: Methodology scheme for LFO Multiphysics analysis

2.1 Thermal hydraulics RELAP model

The thermal-hydraulic (TH) model for LFO was developed using the RELAP5 module to represent the main systems and components of the APR1400. As Load Follow simulation differs from accident analysis, some components were either omitted or simplified. These adjustments were necessary because LFO in a real power plant is managed by I&C systems, that are either simplified or modelled as boundary conditions. Significant changes were made to the model to maintain constant steam generator (SG) pressure and water level during the power maneouvering in order to implement the sliding average coolant temperature control logic.

Figure 3 illustrates the system nodalization for steady state in point kinetics as well as in the coupled analysis.

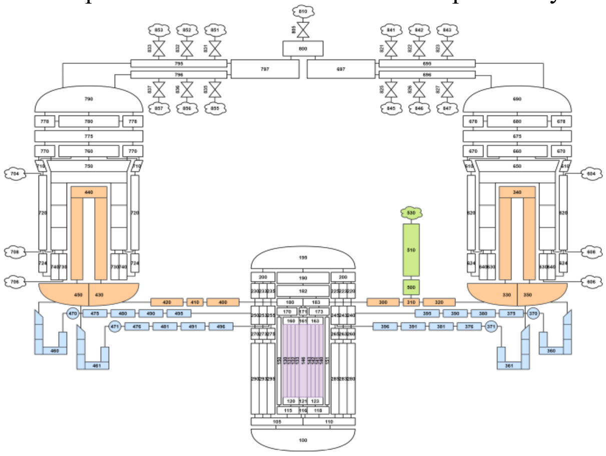

Figure 3: Steady state nodalization

2.1 Nodal Kinetics model

The nodal kinetics model is an improved and enhanced version of the point kinetics model, providing a more detailed core representation. The core is divided into 241 radial sections, each representing a single fuel assembly (FA), and 60 axial nodes, including the axial reflector. This finer discretization allows for real-time prediction of the reactor's response with high fidelity. The fuel loading pattern follows the core design for the first cycle of the APR1400 [7], as illustrated in Figure *4*.

					C0	B0	C0	B0	C0	B0	C0					
			C0	C0	B2	B1	B3	C2	B3	B1	B2	C0	C0			
		C0	C1	B1	A0	C3	A0	B3	A0	C3	A0	B1	C1	C0		
	C0	C1	B3	A0	B3	A0	B1	A0	B1	A0	B3	A0	B3	C1	C0	
	C0	B1	A0	C2	A0	C3	A0	B1	A0	C3	A0	C2	A0	B1	C0	
C0	B2	A0	B3	A0	B3	A0	B3	A0	B3	A0	B3	A0	B3	A0	B2	C0
B0	B1	C3	A0	C3	A0	C2	A0	C3	A0	C2	A0	C3	A0	C3	B1	B0
C0	B3	A0	B1	A0	B3	A0	B3	A0	B3	A0	B3	A0	B1	A0	B3	C0
B0	C2	B3	A0	B1	A0	C3	A0	A0	A0	C3	A0	B1	A0	B3	C2	B0
C0	B3	A0	B1	A0	B3	A0	B3	A0	B3	A0	B3	A0	B1	A0	B3	C0
B0	B1	C3	A0	C3	A0	C2	A0	C3	A0	C2	A0	C3	A0	C3	B1	B0
C0	B2	A0	B3	A0	B3	A0	B3	A0	B3	A0	B3	A0	B3	A0	B2	C0
	C0	B1	A0	C2	A0	C3	A0	B1	A0	C3	A0	C2	A0	B1	C0	
	C0	C1	B3	A0	B3	A0	B1	A0	B1	A0	B3	A0	B3	C1	C0	
		C0	C1	B1	A0	C3	A0	B3	A0	C3	A0	B1	C1	C0		
			C0	C0	B2	B1	B3	C2	B3	B1	B2	C0	C0			
					C0	B0	C0	B0	C0	B0	C0					

Figure 4: Fuel loading pattern

An APR1400 core consists of 241 fuel assemblies in a square lattice, that are divided into 9 groups based on the fuel enrichment, burnable absorber presence and pin geometry according to Table 1 and Figure 5[7].

Table 1: Fuel assembly types and characteristics

Fuel Assembly	Number of FA in the core	Enrichment [%]	Number of fuel rods in FA	Number of Gd_2O_3 fuel rods	Concentration Gd_2O_3 [%w/o]
A0	77	1,71	236	-	-
B0	12	3,14	236	-	-
B1	28	3,14/2,64	172/52	12	8
B2	8	3,14/2,64	124/100	12	8
B3	40	3,14/2,64	168/52	16	8
C0	36	3,64/3,14	184/52	-	-
C1	8	3,64/3,14	172/52	12	8
C2	12	3,64/3,14	168/52	16	8
C3	20	3,64/3,14	120/100	16	8

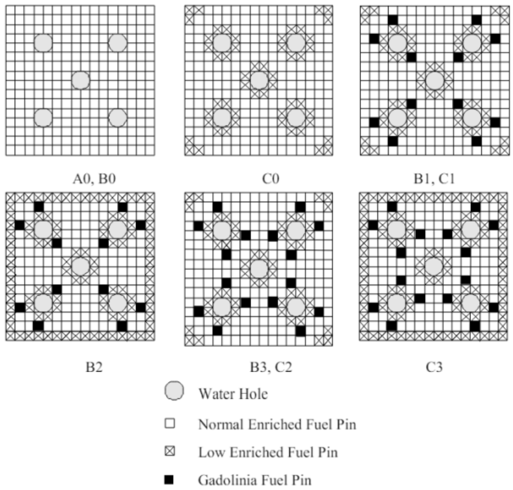

Figure 5: Fuel assembly pin geometry

Control element assemblies (CEA) are divided into 7 groups, from which groups 1-5 are regulating CEAs and group 6 and 7 are shutdown groups. CEA position in the core is depicted on Figure 6.

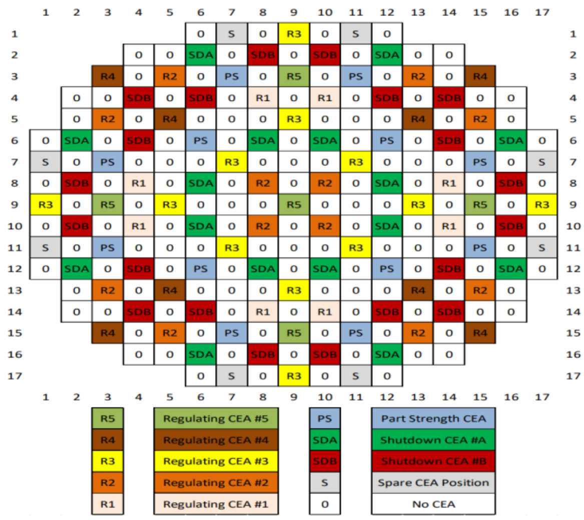

Figure 6: Fuel assembly pin geometry [8]

For Load Follow Simulation, power dependent insertion limits (PDIL) were followed while manipulating with control element assemblies (Figure 7) [7]. PDIL are important in terms of reactivity control, power distribution control and hot spots prevention.

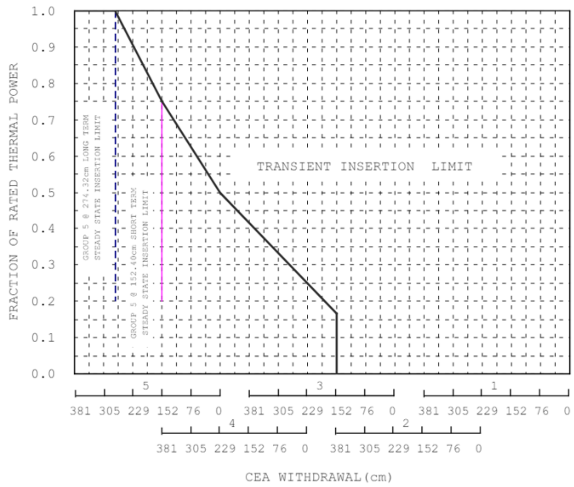

Figure 7: Power dependent insertion limits [7]

3. Model and control logic development, results

For LFO simulation and sliding average temperature mode implementation, maintaining steam generator pressure and water level stable is required. Various changes were applied to the RELAP5 APR1400 model for transient state LFO simulation, as shown in Figure *8*.

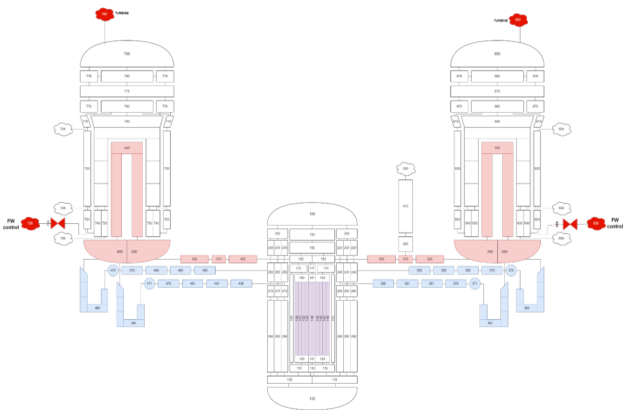

Figure 8: Transient state – LFO nodalization

Model modifications included putting turbine straight to the steam generator steam dome, because pressure losses in the steam line were causing instabilities in SG pressure. In reality, SG pressure and water level is controlled by I&C systems and turbine regulator. In the model however, there is not such control logic present. This necessitates development of a control logic, which would keep SG pressure and water level stable regardless of the reactor power. Such control logic has to be developed based on the feedwater flow. In steady-state, feedwater flow is modeled as a boundary condition using time-dependent volume and junction inputs. However, for transient simulations, this approach is insufficient, since feedwater flow must adjust with reactor power. Reduced core power means less heat transfer from the primary to secondary side, resulting in lower steam production. If the feedwater flow doesn't adjust accordingly, SG water levels and pressure will rise, affecting the primary side. Conversely, insufficient feedwater flow would cause SG water levels to drop. To address this, an automatic mechanism was developed to control feedwater flow based on the heat transferred through the SG U-tubes. A power-dependent feedwater flow function was created using the following formula (1)(2):

$$Q_{SG} = Q_{Economizer} + Q_{Evaporator} \quad (1)$$

$$Q_{SG} = m_{fw} * \left(h_s - h_{fw}\right) + m_{fw} * \left(h_{steam} - h_s\right) \quad (2)$$

Where Q_{SG} [W] is the heat transferred from primary to the secondary side through SG U-tubes. This heat can be splitted into the economizer and evaporator parts. Additionally, m_{fw} [$kg.s^{-1}$] is feedwater flow rate, h_s [$J.kg^{-1}$] is water enthalpy at saturation temperature, h_{fw} [$J.kg^{-1}$] is feedwater enthalpy at feedwater temperature and h_{steam} [$J.kg^{-1}$] is steam enthalpy. Steam enthalpy h_{steam} was obtained from steam tables [9], h_{fw} and h_s were obtained from the following (3) and (4) respectively.

$$h_{fw} = c_p\left[T_{fw}\right] * T_{fw}(°C) \quad (3)$$

$$h_s = c_p[T_{sat}] * T_{sat}(°C) \quad (4)$$

Where c_p [$kJ.kg.K^{-1}$] is specific heat at constant pressure [9], T_{fw} and T_{sat} are feedwater and water saturation temperatures respectively. As saturation temperature during transient remains practically constant, one can assume that the enthalpies will also be constant. Therefore (2) can be simplified to the form of (5).

$$m_{fw} = \frac{Q_{SG}}{\left(h_{steam} - h_{fw}\right)} \quad (5)$$

Feedwater flow rate calculated by (5) varies at nominal power from the steady state flow rate (reference value) by 5,21%. Therefore, a correctrion coefficient of 1,0521 was applied to (5). Based on the upper mentioned logic, feedwater flow table was calculated for various power levels.

3.1 Simulation results and sensitivity analysis

Figure 9 and *Figure 10* compare the steam flow rate and feedwater flow rate using an approximate time function based on CEA movement for feedwater flow with the feedwater flow rates calculated by applying the aforementioned logic.

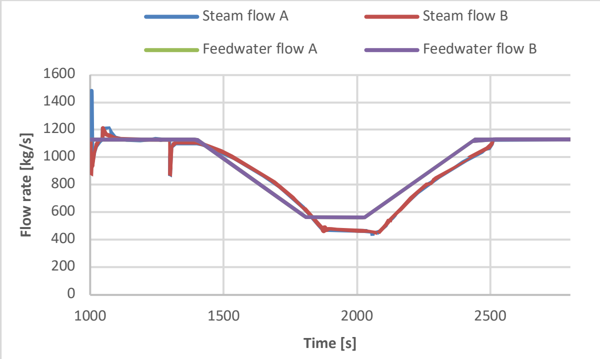

Figure 9: Steam flow rate and feedwater flow rate based on the CEA movement time function

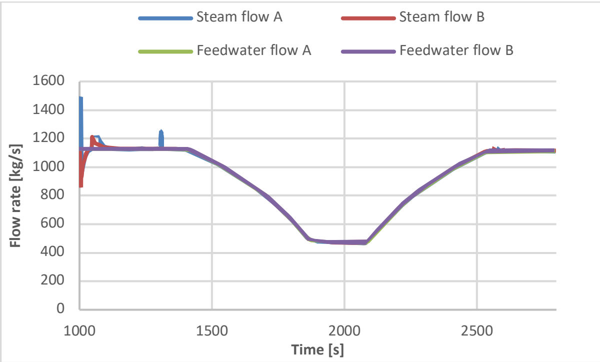

Figure 10: Steam flow rate and feedwater flow rate based on the aforementioned power dependent logic

Unlike the Figure 9, on Figure 10, where the power dependent control logic was applied, the steam flow rate and feedwater flow rate match during the whole time of power maneuvering.

At the time t = 1400 s, the CEA were being inserted into the core, respecting the PDIL as well as maximum CEA speed of 76.4 cm/min [7] (Figure 11). For reaching power level around 43 % (Figure 12), CEA groups 5, 4 and 3 had to be inserted into the core.

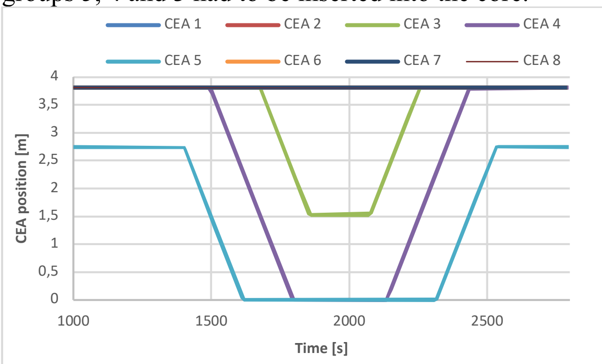

Figure 11: CEA position

With such control rod movement function, the core power decreased to 43 % and went back to 100 % in a short time interval of 1150 s (Figure 10).

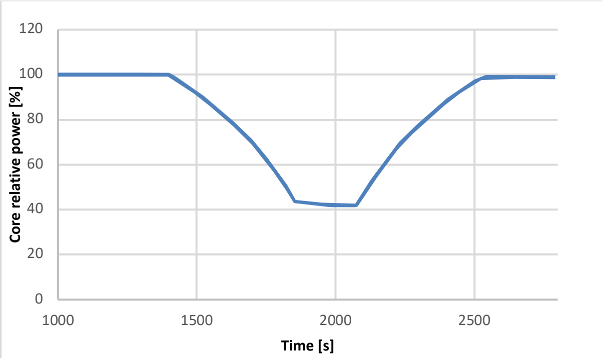

Figure 12: Core relative power

Mismatch between steam flow rate and feedwater flow rate on Figure 9 was causing unacceptable SG water level oscillations (Figure 13). These oscillations were significantly corrected after applying power dependent feedwater flow control logic, which is depicted on Figure 14.

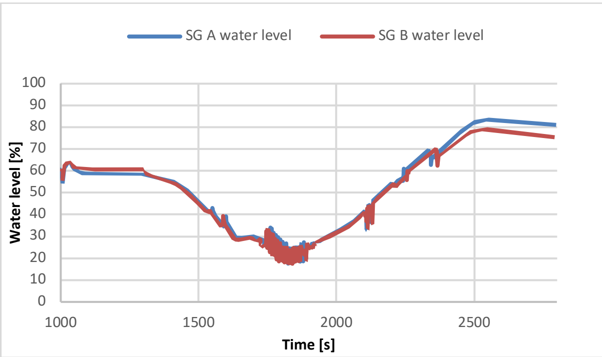

Figure 13: Steam generator water levels with CEA insertion time dependent feedwater flow logic applied

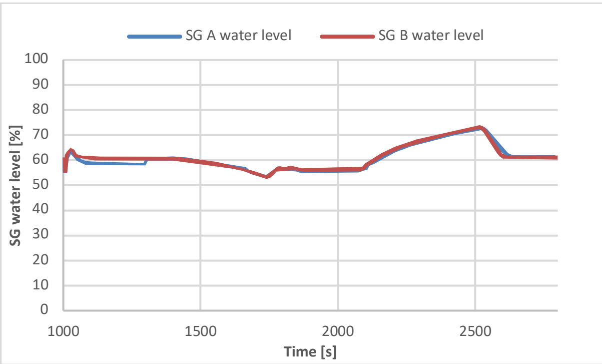

Figure 14: Steam generator water levels with power dependent feedwater flow control logic applied

Because of assumptions and not exact correction factors in control logic developed, steam generator water level still oscillates during the power maneuvering. Therefore, a control valves were implemented to the model that add a small amount of additional feedwater to the steam generator if the water level drops below 59,5 % and discharges water if the water level exceeds 60,5 % (Figure 8). This way, the steam generator water level was stabilized (Figure 15).

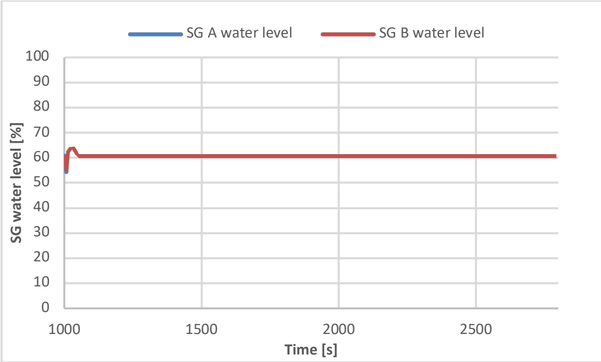

Figure 15: Steam generator water levels with power dependent feedwater flow control logic and control valves applied

Applying power dependent control logic and control valves into the system helped to stabilize other important parameters as well, such as SG pressure (Figure 16) and core inlet temperature (Figure 17).

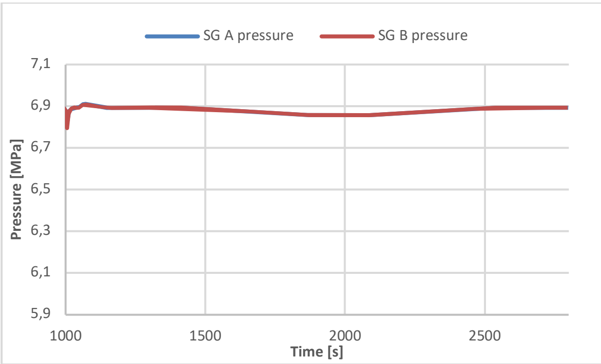

Figure 16: Steam generator pressure

After aforementioned model improvements, the SG pressure varies only by 0.46 %, which corresponds to a 0,03 MPa pressure drop while power maneuvering (Figure 16). That is a reasonably acceptable change. This pressure variation causes change in the heat transfer, causing core inlet water temperature to oscillate during power maneuvering as well (Figure *17*).

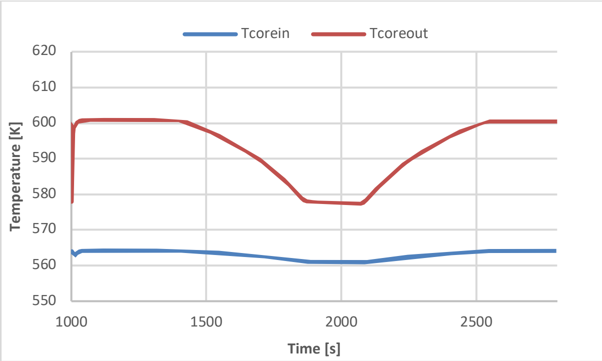

Figure 17: Core inlet and outlet temperatures

Core inlet temperature (Figure 17) varies only by 0,54 %, which corresponds to the 3 °C temperature change. Figure 17, Figure 16 and Figure 15 proof that after applying power dependent control logic altogether with control valves, the sliding average temperature control mode was successfully adapted to the RELAP5 APR1400 model. Small deviations in core inlet temperature are caused by the heat transfer change influenced by SG pressure.

4. Conclusion

In this work, a sliding average temperature control mode for Load Follow Operation of APR1400 was successfully implemented. The proposed power dependent control logic altogether with other modifications has proven to work reasonably well. After implementing this logic, steam generator pressure varies by only 0,46 %, which equals 0,03 MPa during power maneuvering. Steam generator water level is kept stable at its 60 % nominal value. The core inlet temperature was influenced by slight variations in secondary pressure and the resulting changes in heat transfer. The power change was set to happen during 1050 s, when it drops to approximately 43 % power level and then grows back to 100 %. The simulation time and power curve had to be significantly reduced compared to MODE-K due to the time and hardware storage constraints. Furthermore, code limitations emerged in the later phase of the analysis that prevented the LFO to be analyzed on a full 24 hours cycle. Nevertheless, this work is set to be the first step to the full scope Multiphysics analysis of APR1400 Load Follow Operation.

5. Acknowledgement

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