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SIMULATION OF A LOSS OF FLOW ACCIDENT IN THE SMART NUCLEAR REACTOR USING A RELAP5 MODEL

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ABSTRACT

In recent decades, intensive research has been conducted on the development of small modular reactors (SMRs). Aspects such as their greater flexibility in positioning and distribution, along with their lower construction and operational costs, have garnered significant attention from the community towards these reactors. One particularly noteworthy SMR is the System-integrated Modular Advanced Reactor (SMART), developed by the Korea Atomic Energy Research Institute (KAERI). SMART is a small-scale reactor designed to operate with a thermal power of 330MW, produced in its core consisting of 57 fuel assemblies of a 17x17 array. Its cooling system is based on four reactor coolant pumps that circulate the coolant (water) and ensure heat exchange. One of the worst-case scenarios that can occur in the reactor is a failure in the cooling system, causing a core overheating. Bearing this in mind, the main aim of this work is to investigate the consequences of a loss of flow accident (LOFA) occurring during the normal operation of the SMART reactor, as well as the safety measures in place to mitigate such occurrences. By examining these aspects, it was aimed to confirm the structural integrity and safety features of this reactor design. The core was modeled using the RELAP5 code, to simulate the behavior of the reactor in steady state and transient conditions. The LOFA was investigated mainly to verify the heating of the core in loss of coolant flow conditions. The results indicated that the thermal-hydraulic modeling aligns with expected behavior during the transient phase, characterized by an increase in global fuel temperature and a corresponding rise in coolant temperature, reaching a critical level with approximately 40% flow loss, leading to steam formation.

1. INTRODUCTION

When discussing electricity generation, environmental preservation has increasingly become a primary concern, leading to greater attention being given to less polluting energy sources, such as nuclear power. Nuclear energy is generated within nuclear reactors, where the process of nuclear fission takes place. The nuclear reactors to be analyzed in this article are SMR-type reactors.
As the name suggests, these reactors are small and modular, meaning they are physically a fraction of the size of conventional nuclear reactors [1]. This compact size allows for installation in a wider variety of locations, and their modularity enables components to be easily manufactured and transported. Additional advantages over other reactor types include lower construction and maintenance costs, as SMRs can operate for 3 to 7 years without requiring refueling.
Fig. 1 illustrates a comparison between the power and size of SMRs, conventional power reactors that provide energy to entire cities, and microreactors designed for specific applications, such as industrial sites.
One of the leading reactors in this category currently undergoing validation is the SMART. SMART is a small- to medium-sized pressurized water reactor (PWR) with a nominal thermal power of 330

MWth and 100MWe [2]. Developed by the KAERI since 1997, the SMART reactor is designed not only for electricity generation but also for seawater desalination and district heating applications. The SMART reactor is currently undergoing validation and enhancement, which is crucial for ensuring its operational safety and preventing potential accidents. In this regard, this paper aims to model the thermal-hydraulic behavior of the SMART reactor's primary system using RELAP5 and to analyze the reactor's performance during a hypothetical loss of flow accident.

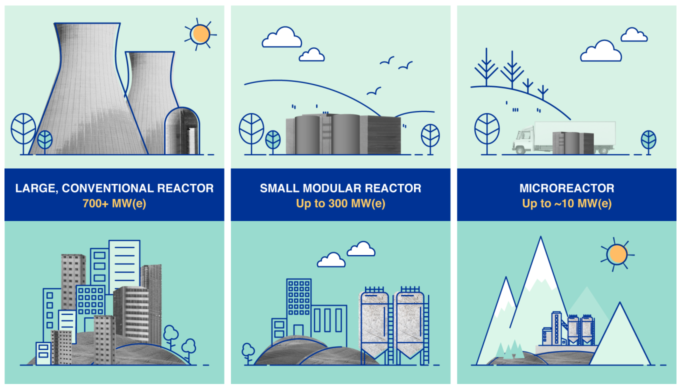

Fig. 1. Comparison between conventional reactors, SMRs, and microreactors [3].

2. TECHNICAL INFORMATION OF THE SMART REACTOR

The SMART reactor core consists of 57 fuel assemblies, designed and performing based on the 17x17 KOFA (Korean Standard Fuel Assembly) technology. Each fuel assembly contains 264 fuel rods, each with a diameter of 8.05 mm and an active height of 2.0 m, 21 guide tubes for control rods, and 4 instrumentation thimbles, totaling 289 components in a 17x17 configuration. The reactor operates at a pressure of 15 MPa, with a flow area of 1.4 m^2 and a mass flow rate of 2090 kg/s [4]. The fuel used is UO_2 enriched to 4.95%, allowing for operation for up to 3 years without refueling. Due to the use of various types of burnable absorbers, the reactor's fuel elements are categorized into 4 groups, with their core arrangement and composition illustrated in Fig. 2 and Tab. 1, respectively.

Tab. 1. SMART Core fuel assemblies description [4].

Assembly Type	No. of Assemblies	Fuel Enrichment (w/o U-235)	No. of Fuel Rods	No. of Al_2O_3-B_4C Rods	No. of Gd_2O_3-UO_2 Rods
A	20	4.95	240	24	-
B	16	4.95	244	20	-
C	1	4.95	236	24	4
D	20	4.95	228	24	12

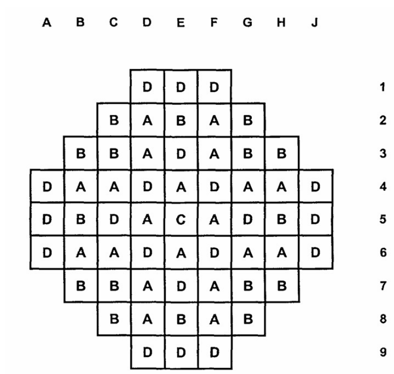

Fig. 2. SMART Core Loading Pattern [4].

3. METHODOLOGY

The SMART reactor core was modeled using RELAP5/MOD3.3 [5], a software program for thermal-hydraulic analysis and simulation of nuclear systems. The nodalization of the core is depicted in Fig. 3. A thermal power of 330 MWth was considered, distributed across 57 thermal-hydraulic channels (one for each fuel assembly), with each channel coupled to a heat structure responsible for transferring thermal energy from the fuel to the coolant (pressurized water). Each channel was divided into 10 axial levels.

To control the core's boundary conditions (inlet temperature, coolant flow rate, and pressure), two *Time Dependent Volume* elements (TMDPV 101 and TMDPV 900) were employed. The incoming coolant is connected to a *Branch* component (BR 200) through a *Time Dependent Junction* (TMDPJUN 150). This branch is further connected to 8 additional branches (BR 251-258), which are linked to the 57 thermal-hydraulic channels (PIPE 301-357). Each channel is a *PIPE* component associated with a heat structure. The *PIPEs* are grouped into 7 sets of 7 fuel assemblies and 1 set of 8, with each group connecting to one of the branches (BR 251-258) via its first axial volume and to one of the branches (BR 401-408) via its tenth axial volume. Subsequently, the branches (BR 401-408) are connected to 4 other branches (BR 500-503), in pairs. Each of these 4 branches (BR 500-503) is connected to a *Single Volume* component (SV 510-513) through *Single Junctions* (SJ 505-508). Each *Single Volume* is linked to a *PUMP* component (PUMP 600-603), which is responsible for pumping the coolant to the *Single Volume* (SV 700). Finally, a *Single Junction* (SJ 800) connects the *Single Volume* to the final *Time Dependent Volume* (TMDPV 900), completing the circuit.

Each heat structure was radially divided into 7 *mesh points*, which can be seen in Fig. 4.

Mesh 1 represents the center of the fuel. The interval between meshes 5 and 6 corresponds to the gap, which is filled with helium gas, while the interval between meshes 6 and 7 corresponds to the cladding, made of Zircaloy-4, a zirconium-based alloy. The fuel radius (the distance between *Mesh Points* 1 and 5) is 4.025 mm. The gap spacing (distance between *Mesh Points* 5 and 6) is 0.085 mm. The cladding thickness (distance between *Mesh Points* 6 and 7) is 0.64 mm. It is important to highlight that the thermal heat transfer characteristics of these materials (fuel, gap and cladding) were inserted as input data in the RELAP5 model to properly reproduce the heat transfer of these materials to the coolant. The data are entered in tables form to ensure the variation of heat

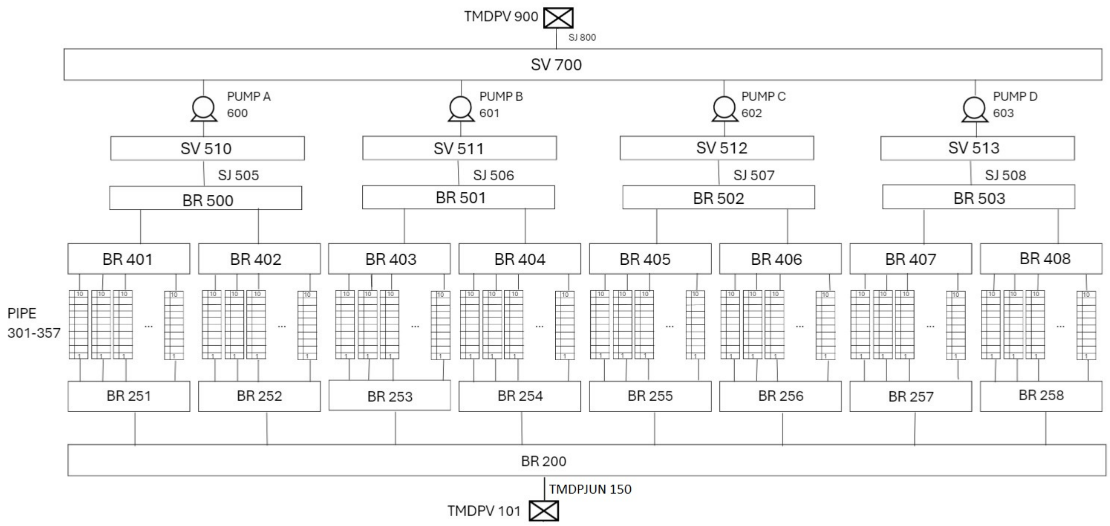

Fig. 3. Core nodalization of the SMART reactor in the RELAP5/MOD3.3 code.

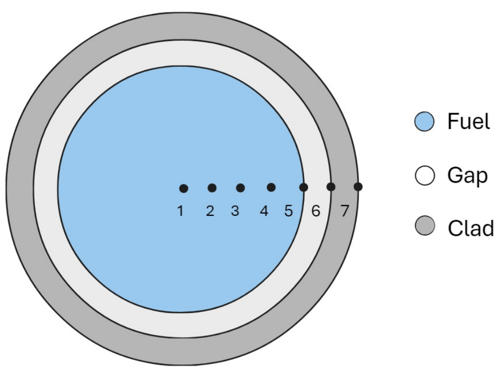

Fig. 4. Radial meshes of the heat structures (out of scale).

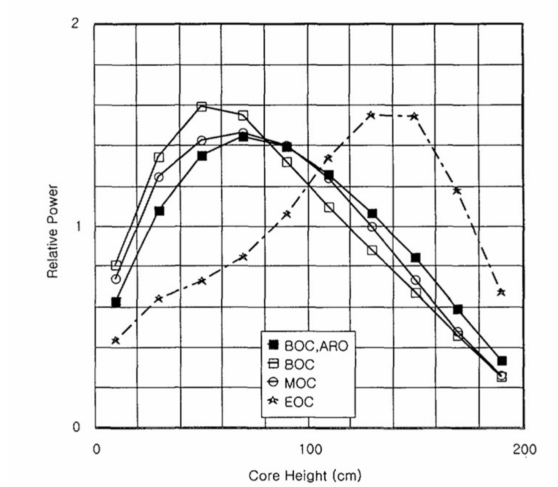

Fig. 5. Core average axial power distributions at hot full power (BOC) [4].

transfer coefficients and heat capacities with the reactor's operating temperature range in steady and transient states.

The axial power generated by each heat structure was calculated based on a relation between the reactor's total power, ensuring the maintenance of the characteristic axial power curve at the Beginning of Cycle (BOC), as represented in Fig. 5.

The SMART reactor model was tested under a loss of flow accident (LOFA) scenario, generated by the gradual reduction of mass flow in the time-dependent junction.

4. RESULTS

The following sections present the results obtained from the simulation of the SMART reactor in steady-state and during a transient LOFA scenario.

4.1. Steady State Results

The SMART reactor model was simulated in steady-state to validate its key safety parameters, namely the coolant temperature rise and the pressure drop.
The variation in coolant temperature is an important parameter to be analyzed, as it indicates whether heat transfer is occurring properly. It was taken based on the temperatures from branch 200 (core inliet) and single volume 700 (core outlet). As observed in Fig. 6, the calculation quickly reaches steady-state, likely due to the model's simplification, which simulates only the reactor core. As expected, the coolant temperature increases by approximately 40°C along the core, as can be seen in Tab. 2, in line with the predictions in the SMART reference document [4]. It can also be observed a gradual increase in coolant axial temperature along one of the simulated channels (channel 316 of the nodalization), as illustrated in Fig. 7, aligning with the expected behavior.

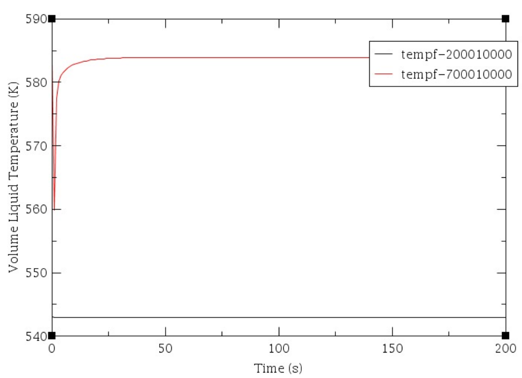

Fig. 6. Coolant temperature at the core inlet and outlet.

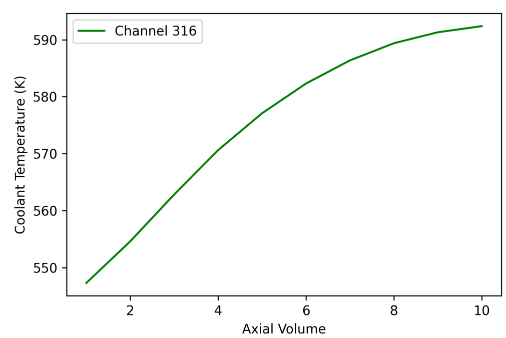

Fig. 7. Axial temperature distribution of the coolant in channel 316.

The analysis of the pressure drop is essential to assess the operational safety of the reactor and serves as a useful tool for detecting potential issues. The system pressure variation was measured based on the pressures in the branch 200 and single volume 700. The value obtained in the simulation was 0.34 MPa, as shown in Fig. 8. This value also falls within the expected pressure variation, further supporting the verification of the model.
Another important parameter to be analyzed is the mass flow rate, which represents the amount of coolant mass circulating in the core per second. The value obtained in steady-state can be seen in Fig. 9 and it is 2090.3 kg/s. This value is within the expected range for the SMART reactor [4].
The Tab. 2 compares the values obtained from the RELAP5 calculation in steady state with the expected values, in order to verify the model for transient state analysis.

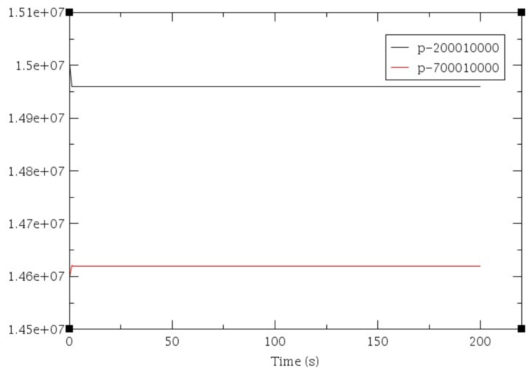

Fig. 8. Pressure at the core inlet and outlet.

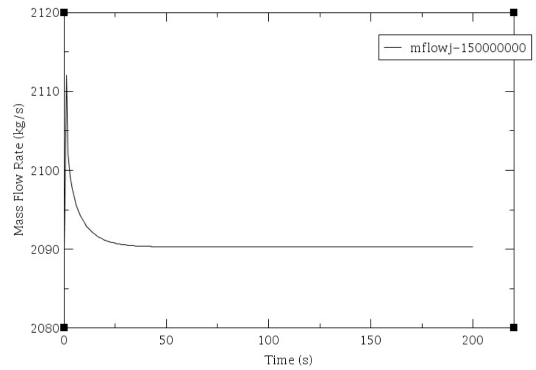

Fig. 9. Core inlet mass flow rate.

Tab. 2. Comparison between calculated values, reference values, and errors

Parameters	Calculated value	Reference value[4]	Suggested**/Error* (%)
Inlet temperature (K)	542.98	543.15	0.50 / 0.03
Outlet temperature (K)	583.93	583.15	0.50 / 0.13
Coolant Δ T (K)	40.95	40.0	10.0 / 2.4
Inlet pressure (MPa)	14.96	15.00	0.50 / 0.27
Outlet pressure (MPa)	14.61	14.60	0.50 / 0.07
System Δ P (MPa)	0.35	0.40	10.0 / 15.0
Mass Flow Rate (kg/s)	2090.3	2090.0	2.00 / 0.01

* Error = (Reference – Calculated)/Reference.
** List of requirements for the steady-state qualification of a nodalization [6].

The values obtained are within the allowable limits according to the safety protocols for PWR-type reactors [6]. Therefore, the SMART reactor model can be used for the analysis of transient states during LOFA accidents.

4.2. Loss Of Flow Accident (LOFA)

With the steady-state model verified, simulations were performed with loss of coolant. The calculations were initially performed under steady-state conditions, and after 100 seconds, the transient phase began. The LOFA process is triggered by a trip in the time-dependent junction (number 150 in Fig. 3), which is implemented in the RELAP5 code by providing a table of mass flow values that decrease over time, shown in Tab. 3. In this simulation, the mass flow was reduced by 20% of its initial value every 100 seconds until the system overheated and the program stopped running (Fig. 10).
The coolant temperature increases (Fig. 11) while the pressure decreases (Fig. 12) when the LOFA begins. This leads to the coolant reaching the saturation temperature for phase change after 200 seconds, resulting in the coolant phase change. (Fig. 13).

Tab. 3. Table used in the time-dependent junction trip.

Simulation Time (s)	Core Mass Flow Rate (kg/s)
0 - 100	2090.0
200	1672.0
300	1254.0
400	836.0
500	412.0
600	0.0

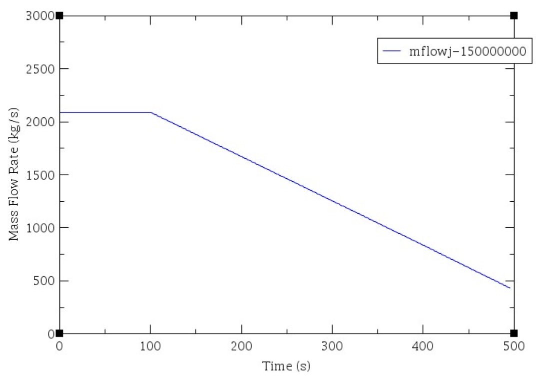

Fig. 10. Core inlet mass flow rate with LOFA.

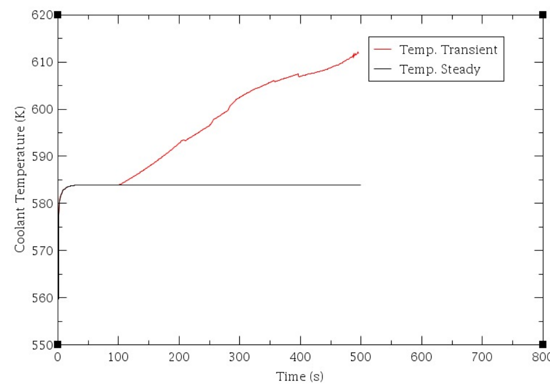

Fig. 11. Comparison of core outlet temperatures for steady and transient states.

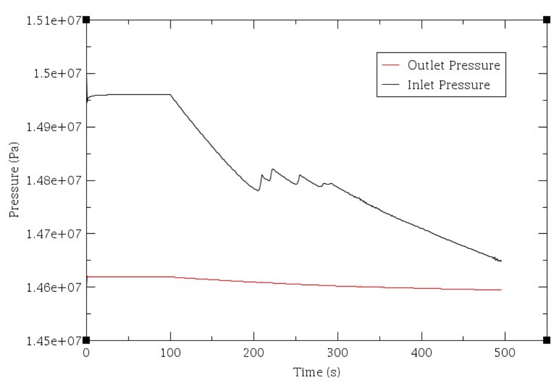

Fig. 12. Core pressure at the inlet and at the outlet.

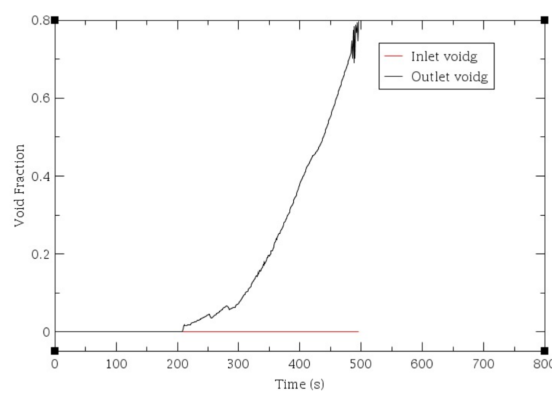

Fig. 13. Void fraction at the inlet and outlet of the core.

Tab. 4. Comparison between values obtained in the simulation of steady-state and transient conditions.

Quantities	Transient (LOFA)
Coolant ΔT (K)	69.0
Coolant ΔT Increase* (%)	68.5
System ΔP (MPa)	0.05
System ΔP Decrease* (%)	85.7

* Compared to the steady-state values.

5. CONCLUSION

The modeling of the SMART reactor core using the RELAP5/MOD3.3 code was evaluated. The steady-state results, presented in Tab. 2, were compared with the expected values for the SMART reactor [4], verifying the model. Subsequently, a transient model simulating a LOFA was tested. As observed in Tab. 4 , at the end of the simulation the coolant temperature increased 69 K (68.5 % higher than the steady-state) while the system pressure decreased only 0.05 MPa (85.7 % less than the steady-state). This outcome was expected, as the loss of coolant reduces heat transfer with the fuel, leading to core overheating.

The pressure drop and temperature increase in the system were significant enough to turn the coolant into steam. This poses a major risk to the reactor, as it could quickly lead to an irreversible state, where a large-scale accident, such as core meltdown, becomes inevitable.

Therefore, it can be concluded that the SMART reactor is not safe with respect to loss of flow accidents. However, this was a simplified simulation. The model needs to be expanded to simulate the entire thermal hydraulic circulation of the reactor to then have a more realistic idea of the system's behaviour. This is a study that can be conducted at a later stage.

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