



HACETTEPE UNIVERSITY

Department of Nuclear Engineering

NEM 217 FINAL EXAM - PROJECT

**Power Rise from 0% to 100% of an iPWR – System Behavior and
Parameter Evaluation**

Group No. : 6

**Students Name : Cansu Karakoç, Yunus Atasever, Emre Sakarya, Eren
Gürel, Selman Vicdan.**

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1 INTRODUCTION

This report details the simulation, analysis, and interpretation of reactor behavior during a controlled power increase from 0% to 100%, as outlined in Section 2.4 of the Integral Pressurized Water Reactor Simulator Manual: Exercise Handbook (Training Course Series No. 65).

The primary objective of this exercise is to provide hands-on experience and insight into the operational characteristics of an Integral Pressurized Water Reactor (iPWR) during a controlled power ascent. By simulating the reactor power rise from 0% to 100%, we aim to understand the various physical processes and system engineering concepts involved, and how the reactor responds to operator actions and changes in plant conditions during normal operation. This includes observing and analyzing key system parameters such as reactor power reduction, coolant flow dynamics, pressurizer response, steam flow and turbine load, safety system activation, reactivities and control rod behavior, coolant temperature, feedwater system response, steam flow to turbine, reactor thermal power, steam flow rate in lines 1 and 2, and steam flow reduction. The report will discuss the development of these parameters throughout the transient. The exercise also helps us get really good at following the instructions in the handbook step-by-step. This means we'll fully understand how the simulator works and all the important ideas behind iPWRs.

2 METHODS AND CALCULATIONS

For this simulation exercise, we followed the detailed, step-by-step operating instructions provided in Section 2.4, "REACTOR POWER RISE FROM 0% TO 100%," of the Integral Pressurized Water Reactor Simulator Manual: Exercise Handbook. The simulation was initiated from either Initial Condition (IC) #7, '0% BOL, NC, before rod withdrawal,' or IC #10, '0% BOL, FC, before rod withdrawal'. (iPWR Simulation Handbook, 2025)

The core methodology involved a controlled increase in reactor power from a subcritical state to 100% full power. This was achieved through a series of actions, including:

Reactor Reset and Initial Checks (Step 1-3): We started by making sure all the important stuff was stable at its starting point (0% power). This meant checking that thermal power was around 1.59 MW(th) and neutron power was at 0%. We also double-checked that the main plant controls were set correctly, like the plant mode being in 'reactor leading' and rod control in 'manual'. The main steam bypass (MSB) also needed to be controlling steam pressure. We then confirmed the alarm conditions (reactor trip, turbine trip, turning gear, generator breaker open) were as expected for the initial state.

Reset Reactor Trip (Step 4): The reactor trip alarm was then deactivated by resetting the reactor trip.

Check Boron Concentration Stable (Step 5): We verified that the boron concentration remained stable.

Rod Withdrawal for Criticality (Step 6-8): Next, we slowly pulled out the shutdown bank (Bank A) until it was fully withdrawn, monitoring neutron flux. Then, control bank B was withdrawn fully while monitoring neutron flux. Finally, control bank C was withdrawn to the

estimated critical condition (49 steps) while continuously monitoring neutron flux. We kept a close eye on the neutron flux to make sure the "startup rate" (SUR) didn't go above a sustained 0.5 dpm after the point of adding heat.

Boron Dilution for Criticality (Step 9): To get the reactor critical, we diluted the Reactor Coolant System (RCS) by introducing a new boron concentration setpoint (max 20 ppm per badge) and placing the selector in 'dilution'. We carefully watched the boron levels and neutron flux to ensure criticality was observed, where neutron flux slowly rises without control rod movement, and the point of adding heat occurs when intermediate range is around 10^{-8} . The selector was then placed in 'OFF'.

Power Ascension (Manual and Auto) (Step 10-11): We first brought the reactor power up to 8% using manual rod control. Then, we switched to automatic control by setting the reactor power demand to 15% at a rate of 5%/min, pressing GO, and placing control rods in auto. Neutron power rose and stabilized at 15%.

Turbine Startup (Step 12): We then started up the turbine by resetting the turbine trip, ensuring the turbine control valve (MSSV07) was in auto and opened around 3%. We pushed 'run-up' to increase turbine speed to 3600 rpm. Once the 'ready to sync' light appeared, we pushed the 'sync' button to close the generator breaker. We verified the turbine accepted a minimum load and that the turbine control valve was in manual. The note reminded us that upon closing the generator breaker, turbine load should be raised to 3% to prevent motoring of the generator.

Raise Turbine Load Manually to 3% (Step 13): We manually opened the turbine control valve to 3% and checked that the generator load began to rise, with steam through the MSB lowering.

Place Turbine Control in Auto (Step 14): The turbine control valve was then placed in auto, and we checked that the turbine control was now controlling steam pressure. A note cautioned that switching to turbine leading mode with a big temperature error could lead to power oscillations and turbine trip (for reactor power < 4%).

Transition to Turbine Leading Mode (Step 15-17): If the temperature error was greater than 2.50°C , we first placed rod control in manual, repositioned bank C to make the temperature error less than 2.80°C , changed the plant mode to turbine leading mode, and checked the MSB mode to T_{avg} mode. The note explained that the $T_{\text{avg}} - T_{\text{ref}}$ deviation correction (after moving bank C) would only last for a few seconds. If the error was less than 2.5°C , we changed the plant mode directly to turbine leading mode and checked the MSB mode to T_{avg} mode.

Raise Turbine Load to Full Power (Step 18): We then raised the turbine load to full power (45 MW) by introducing a turbine load demand of 20 MW with a turbine load rate of 1 MW/min and pressing GO. We checked that the turbine control valve began to open and the generator load began to rise. Once 20 MW was reached, we checked that the variables from step 1 were stable. We then continued to raise the turbine load to 45 MW at a rate of 1 MW/min.

Continuous Reactivity Management (Step 19-20): All through this power increase, we kept diluting the RCS to compensate for power defect, Xenon concentration, and rod position

reactivity changes. We introduced new boron concentration setpoints, selected 'dilution', checked boron concentration decreased to the setpoint, and repeated as required, finally placing the selector in 'OFF'. If Bank C reached 80 steps (fully withdrawn), we would normally hold the turbine load, dilute the RCS to reposition bank C, and then continue increasing turbine load.

Check Main Steam Flow (Step 21): We observed that the main steam flow began to rise due to the increase in load, and the reference temperature began to rise.

Verify Control Rod Withdrawal (Step 22): We verified that the control rods withdrew to increase the average temperature, and the neutron power increased.

Check Pressurizer Level (Step 23): We checked that the pressurizer level began to rise due to coolant expansion and how the level control system recovered the level, also observing charge/discharge flows.

Verify Thermal Power Rise (Step 24): We verified that the thermal power increased in accordance with the generator load, with both changing at similar rates.

Turbine Load Reaches Setpoint (Step 25): Once the turbine load reached its demand (45 MW), we verified that there was no further change, and the generator load settled at this demand.

Check Axial Imbalance (Step 26): We continuously checked that the Axial Imbalance (AI) was maintained within the target band. A note explained that if AI was to the left, rods were excessively inserted (depressing flux in the upper half), requiring borating the RCS to withdraw rods. If AI was to the right, rods were excessively withdrawn (higher flux in the upper half), requiring diluting the RCS to insert rods.

Check Neutron Power (Step 27): We checked that neutron power settled at the correct value (100%) and verified using the startup rate (SUR) that there was no further change.

Final Conditions Check (Step 28): Finally, we confirmed the following conditions: reactor power at 100%, turbine load at 45 MW, turbine leading mode selected, control rods in auto, MSB in T_{avg} mode, FW system in auto, CW and condensate systems in service, and no active alarms.

No complex calculations were performed manually during the simulation, as the simulator itself provides real-time data and trends for all relevant parameters. The objective was to interpret the simulated responses and ensure they aligned with expected reactor behaviour for a controlled power increase. Data points and trends for key variables, as observed on the GUI sheets (Overview, Rod Position Control, Turbine Control, PZR Level Control, Systems, Core, Trips, etc.), were used for analysis and discussion of the transient.

3 RESULTS

3.1 Pressurizer Pressure and Level Analysis

The primary circuit pressurizer pressure (Primary Pressure) and level (Primary Level) graphs during power boost operation were analyzed. These two parameters are critical for understanding the thermal state of the reactor.

Pressurizer pressure and level graphs are directly or indirectly related to many of the topics mentioned:

Pressurizer response: This is the most direct relationship. The two graphs examined show the pressure and level parameters of the pressurizer itself. This is the pressurizer's response to the operation.

Coolant temperature: This is the main cause of changes in the pressurizer level. Increased coolant temperature during power increase causes thermal expansion of the water in the primary circuit. This excess volume fills the pressurizer, causing the level to rise. (Savree)

Reactor thermal power: It is the main trigger of the level change. An increase in reactor thermal power increases the coolant temperature, resulting in a rise in the pressurizer level.

Coolant flow dynamics: Coolant flow allows heat to be transported through the reactor heart. Changes in flow and temperature cause effects in the pressurizer known as insurge and outsurge.

Reactor power reduction: Although the graphs show a power increase, stable operation of the pressurizer indicates that the system is capable of managing both a power increase and a possible power decrease. Pressure and level control systems are designed to react to a change in the opposite direction.

Safety system activation: Pressurizer pressure and level are important input parameters for reactor protection systems. If the pressure and level remain within the specified limits in these graphs, it indicates that the operation is within normal operating limits without triggering the safety systems.

The most significant feature of the two graphs is that one (pressure) is very stable while the other (level) shows a large variation throughout the operation.

Pressurizer Pressure (PZR Pressure):

The PZR pressure graph was kept stable in a very narrow band, around 15.5 MPa, throughout the entire power upgrade process. Although small and rapid oscillations are observed, there is no general upward or downward trend. This is because the primary circuit pressure is an actively and tightly controlled parameter to prevent boiling of the coolant. Heaters (to increase the pressure) and sprays (to decrease the pressure) inside the pressurizer operate continuously to dampen the pressure effects of large changes in coolant temperature and keep the system at a constant pressure value. This graph shows the success of the pressure control system.

Pressurizer Level (PZR Level):

In contrast, the PZR level graph shows a clear upward trend with operation. The level increased from around 23% at the beginning to over 43% at the end of the power ramp. The reason for this difference is that there is no attempt to keep the pressurizer level at a fixed set point, such as pressure. The level is an indicator of the total water inventory in the primary

circuit and is allowed to vary depending on changes in coolant temperature. As reactor power and hence coolant temperature increases, the coolant water expands thermally. This expanding volume of water fills the pressurizer and causes the level to rise naturally. This graph therefore shows the expected physical response of the system, not the failure of a control system.

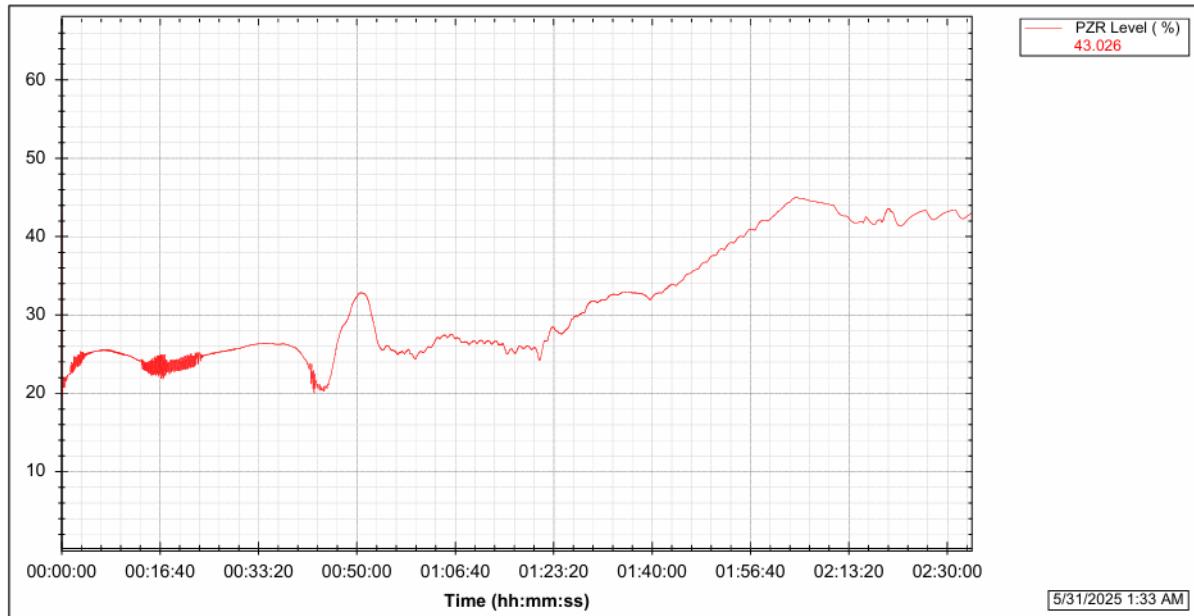


Figure 1. Time Dependent Variation of Pressurizer Parameters-PZR Level (%) in this graph- During the Increase of the Reactor from 0% to 100% Power.

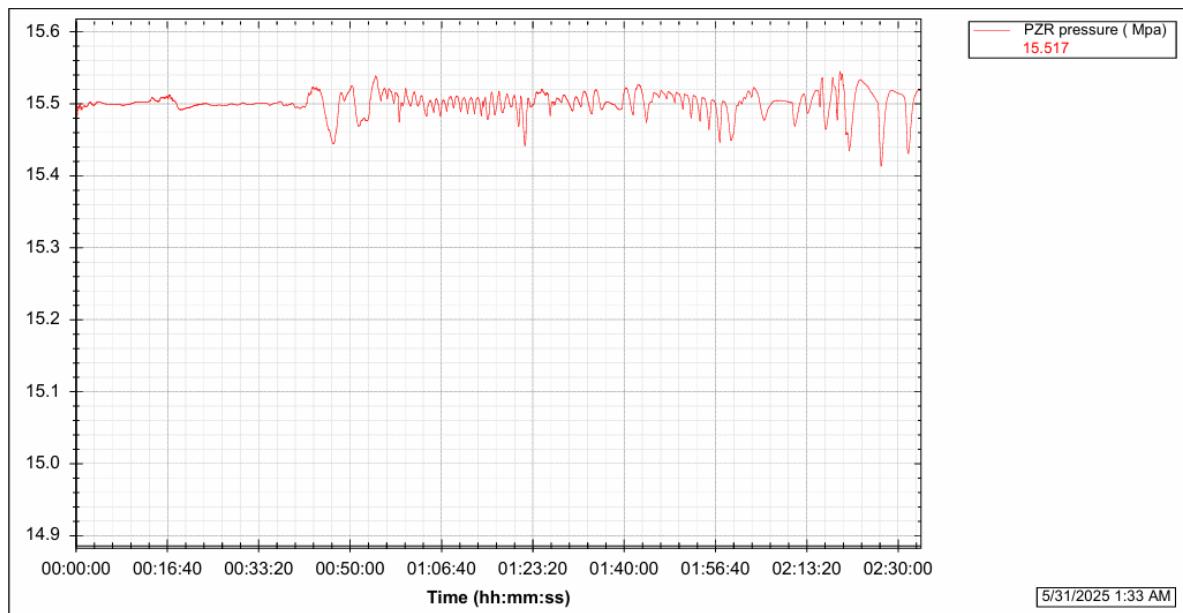


Figure 2. Time Dependent Variation of Pressurizer Parameters-PZR pressure (MPa) in this graph- During the Increase of the Reactor from 0% to 100% Power.

3.2 Thermal Power and Reactor Nuclear-Neutron Power Analysis

We see that the reactor power is 0 until around the 40th seconds, in this period we made the necessary controls before startup and after that we reset reactor trip, and then withdraw the control rods in Shutdown Bank A, and then Control Bank B. At this stage neutron flux increases but thermal power does not, because of the high boron concentration the reactor has not reached criticality. After we withdraw control rods in Bank C to 49 steps, we diluted the boron concentration. When the reactor has reached criticality, the power started rising without any control rod movement. After a slow rise, the reactor power started lowering after it reaches a point called Point of Adding Heat. (Nuclear-power.com, 2025) After this point, the power rise starts affecting the temperature of water and this causes negative feedback on criticality. So, without any control rod movement the reactor power starts decreasing. After that point, we adjusted the control rods to stabilise around %15 reactor power while we are working with the turbines. Introducing a power demand of 45MW on the turbines we see the thermal power rising to 150MW fast but fluctuating. This fluctuation is because the control rods withdraw step by step, and the boron dilution is done while the control rods are withdrawn. This causes instability. And because of the negative void coefficient the increase in temperature causes a drop in the neutron flux.

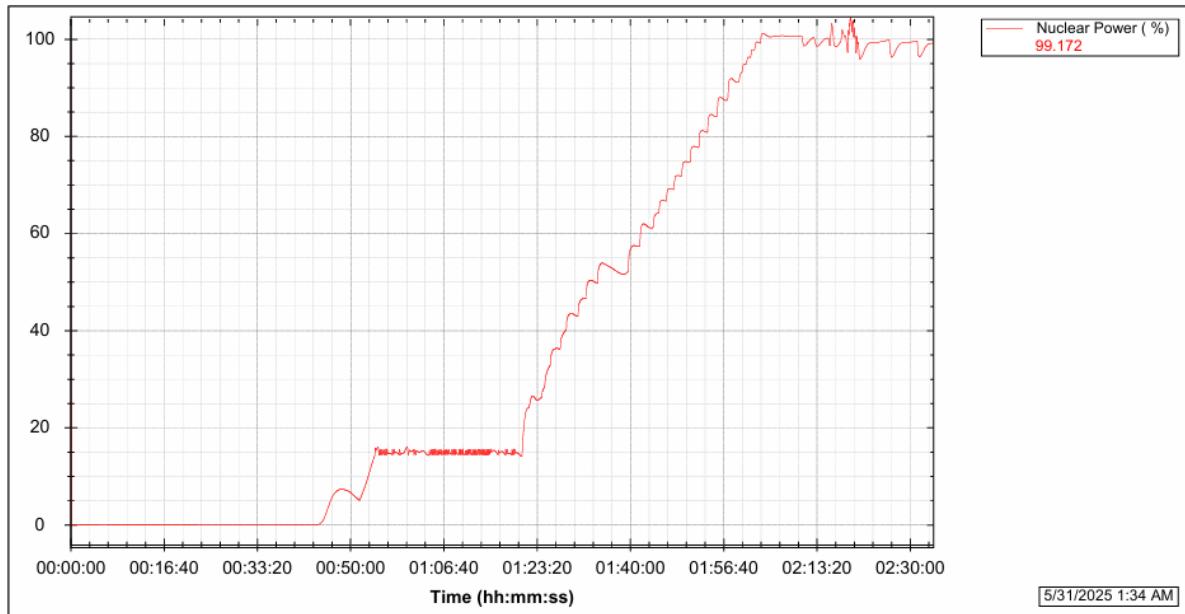


Figure 3. Variation of Percentage Nuclear Power with Time during Reactor Power Upgrade Operation.

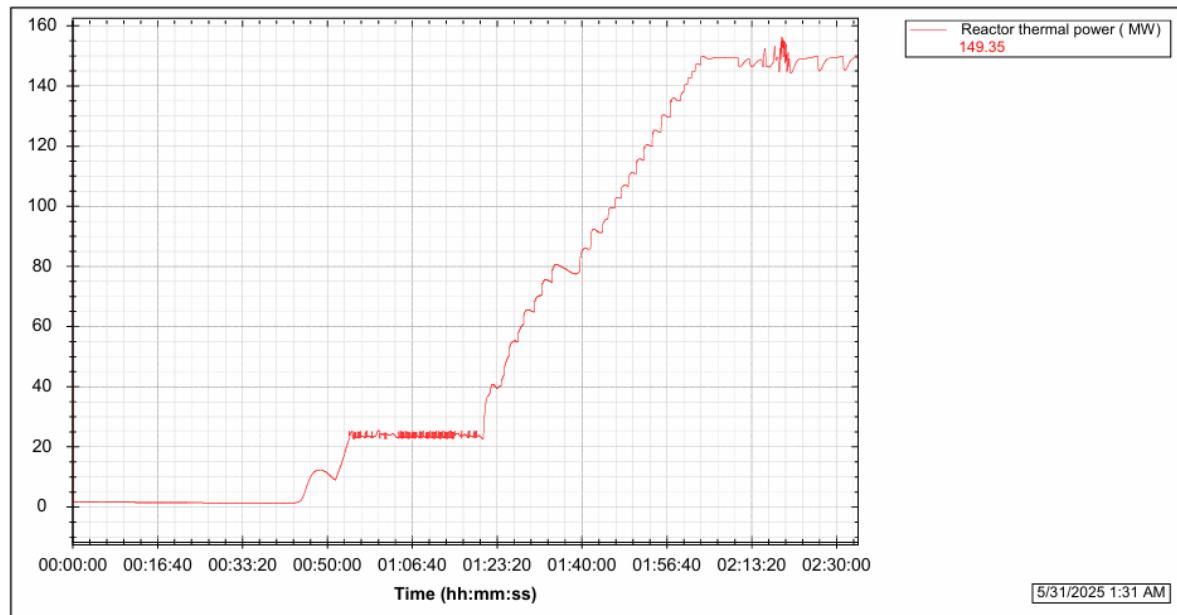


Figure 4. Variation of Reactor Thermal Power (MW) with Time during Reactor Power Upgrade Operation.

3.3 Core Cooling System Analysis

When reactor power is zero, there is no fission reactions so very low heat is produced in the core. However, the core still produces decay heat, so the temperature increases slightly and the cooling systems are still working. (Union of Concerned Scientists, 2014) Since heat transfer continues, the outlet temperature may drop more quickly, because as decay heat production in the core decreases, the temperature difference between the outlet and the coolant decreases.

At this stage, fission resumes, and power is slowly increased. As core heat production increases, the outlet temperature rises rapidly, but the inlet temperature tends to remain more stable (because the cooling system tries to keep the inlet constant). The average temperature also shows an increasing trend accordingly. However, this increase is not linear:

Initially, there is a slow increase because the core is still thermally unstable. Later, with the effective withdrawal of the control rods, reactivity increases, which causes heat to be produced more quickly → the temperature increase slope rises. When 100% Power is Reached the system reaches a new equilibrium. The outlet temperature stabilizes (~318.97 °C) because the core is now operating at a constant power. The inlet temperature is kept constant (~256.78 °C) because the coolant pump and cycle operate at a constant rate. In this case, the average temperature also stabilizes (~287.87 °C). The graph approaches a straight line.

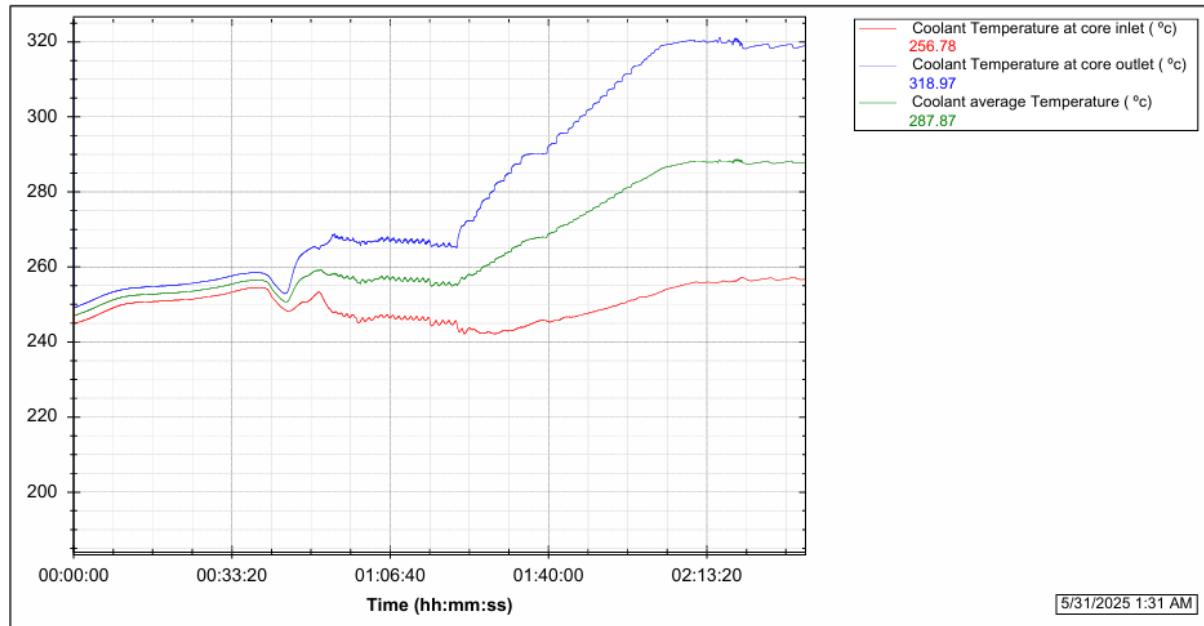


Figure 5. Variation of Coolant Temperatures during Reactor Power Upgrade.

3.4 Start-Up Rate (SUR) Analysis

The change in the Start-Up Rate (SUR) value during the reactor's ramp-up from zero power to full power was also examined. SUR is a parameter that shows the rate at which the reactor power increases over time and is of great importance for the safe operation of the reactor. (Nuclear-power.com, 2025) The degree of controlled progress of the reactor during the power ramp-up can be monitored from the graph below. During the range where the reactor power is increased to 100%, the SUR parameter fluctuates frequently and the observed deviations are generally below $\pm 0.5\text{ %/s}$. This SUR value primarily reflects the careful addition of reactivity by careful manipulation and withdrawal of control rods. However, the SUR value and reactivity are not simply values that change with the control rod. Once the control rods are removed, the reactivity and, indirectly, the SUR value, increases again with the dilution of Boron. The maximum amount valid for each step of Boron dilution is 20 ppm. (iPWR Simulation Handbook, 2025) However, care should be taken not to maintain the SUR value continuously above 0.5. If the SUR value stays above 0.5 for a "long" time, it can cause a big problem. A sudden power increase in the reactor can be considered dangerous and the reactor can switch itself into SCRAM mode and shut down. Momentary increases and overshoots do not cause this and this graph shows it very well. Even if the SUR value exceeds 1, the reactor does not shut itself down and continues because it is "momentary" and not continuous.

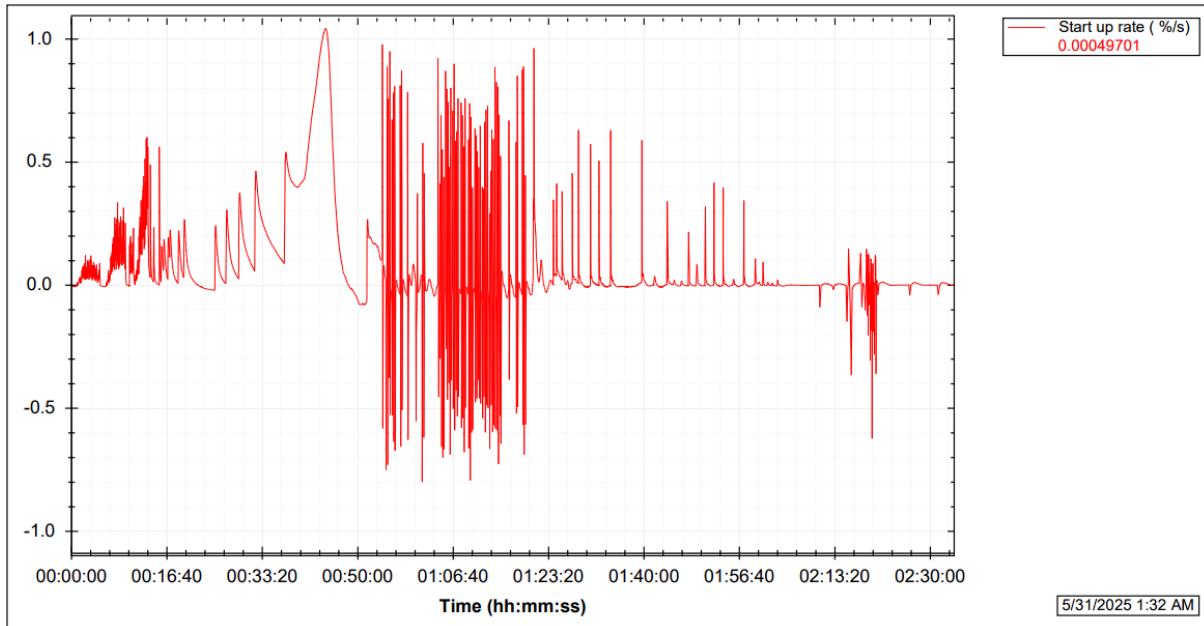


Figure 6. Change in Reactor Start-up Rate (SUR) During Power Ramp-up.

3.5 Feedwater System (FWS) Analysis

The FWS (Feedwater System) Total Flow graph clearly reflects the progression of the reactor from a shutdown state to low-power operation. At the beginning of the scenario, reactor power is zero and no steam is produced, so feedwater flow remains near zero. During this phase, only decay heat is present, and no significant flow is required. As the startup sequence progresses, control rods are gradually withdrawn and boron concentration is reduced. These actions increase reactivity and lead the reactor toward criticality. During this phase, small fluctuations in FWS flow begin to appear, corresponding to the early stages of fission heat generation and system response to temperature rise. Once the reactor becomes critical and passes the Point of Adding Heat, thermal power starts to increase more noticeably. This causes a rise in outlet temperature, which in turn increases feedwater demand. The graph shows a sharp and steady increase in FWS flow, especially after a 45 MW turbine load is introduced. This power demand causes thermal power to rise to ~150 MW, and feedwater flow increases rapidly to ~77.5 kg/s. Some fluctuations occur during this transition due to the combined effect of boron dilution and control rod movement. However, these variations are short-term and remain within safe limits. Eventually, the system reaches a stable state, where the FWS flow levels off, indicating that the reactor has achieved thermal equilibrium at the target low-power level. This overall trend demonstrates a well-controlled startup, where power increase, thermal behavior, and reactivity feedback all interact as expected. (iPWR Simulation Handbook, 2025)

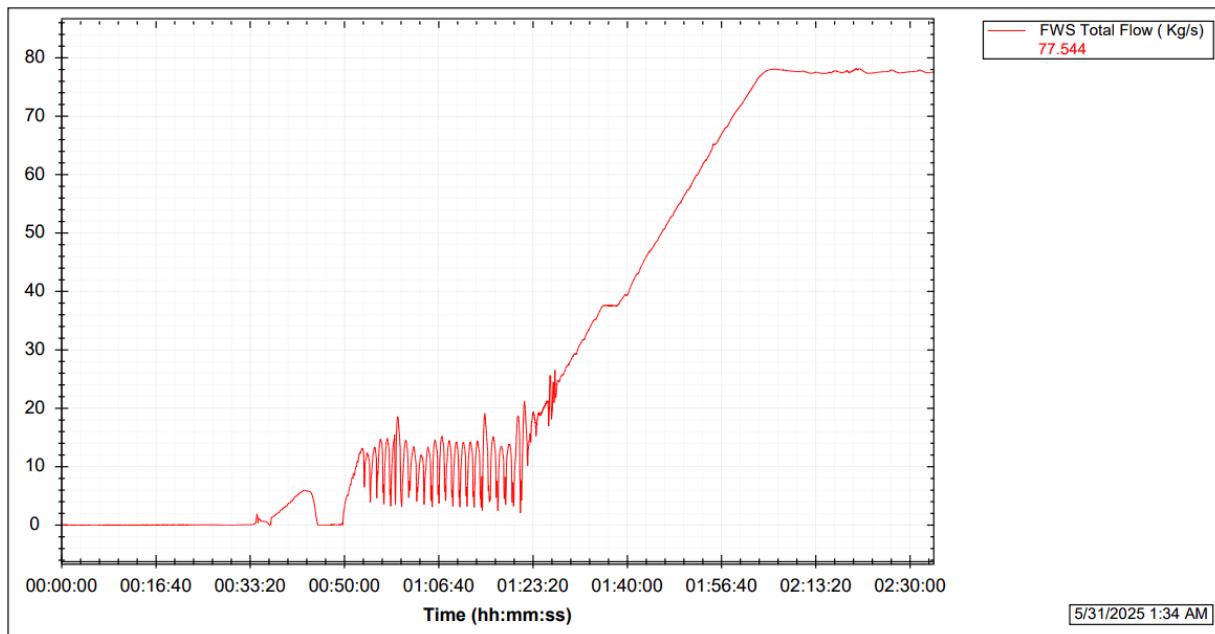


Figure 7. Change in Total Feed Water Flow During Power Boosting

The initial and final values of the basic system parameters examined during the power upgrade operation are summarized in the table below. This table shows the overall effect of the operation on the system in numerical terms.

Table 1. Start and End Values of Key Parameters During the Power Boost Operation

Parameter	Unit	Initial Value	Final Value	Relevant Figure
Nuclear Power	%	0	99.172	Figure 3.
Thermal Power	MW	1.59	149.35	Figure 4.
PZR Pressure	MPa	15.5	15.517	Figure 2.
PZR Level	%	23	43.026	Figure 1.
Coolant Inlet Temperature	°C	248	256.78	Figure 5.
Coolant Outlet Temperature	°C	252	318.97	Figure 5.
SUR	%/s	0	0(stable)	Figure 6.
Feedwater Flow	Kg/s	0	77.544	Figure 7.
Turbine Load	MW	0	45	---

4 CONCLUSION

Increasing reactor power from 0% to 100% is not a simple process of simply pulling the control rods in one direction. It is a dynamic operation that requires continuous reactivity adjustments to ensure the stability and safety of the reactor. Therefore, the power increase maneuver must also include the capacity for controlled power reduction.

Pressure booster (PZR) analysis has demonstrated the effectiveness of two different control strategies. While the primary circuit pressure is actively maintained at a set point of ~15.5 MPa to prevent boiling, the PZR level is allowed to rise in a controlled manner in response to thermal expansion of the coolant as power increases. This demonstrates that the system successfully manages parameters that are both strictly controlled and allowed to reflect physical processes.

It has been determined that the intense oscillations in the Start-Up Rate (SUR) graph are a direct result of controlled rod and boron dilution actions taken to manage reactivity. The system's ability to increase power without continuously maintaining the SUR value above 0.5 dpm (despite momentary peaks) confirmed that the operation was conducted in a controlled manner within safety limits.

The nearly perfect correlation observed between the nuclear power, thermal power, and feedwater flow graphs has demonstrated the tight and efficient coupling between the primary (heat generation) and secondary (heat transfer) circuits. Similarly, the increase in the difference between the inlet and outlet temperatures of the reactor core (ΔT), which is an indicator of the heat extracted from the reactor, in line with the power output, has confirmed that the cooling system is functioning as expected.

As a result, this simulation study successfully verified that the basic parameters of an iPWR's power increase process behave in accordance with theoretical expectations.

5 REFERENCES

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