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Final Project

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1. On the simulator, go to the Alternate (Reactor-Leading) Mode.
2. Request a Power Increase to 115%FP at a rate of 0.15%/s. Freeze the simulator right away.
3. Record all the following values at time 0 (use the Excel spreadsheet attached):
    a. Neutron Power (%)
    b. Thermal Power (%)
    c. Turbine Power (%)
    d. Generator Power (MW)
    e. Steam Pressure (kP)
    f. Liquid-Zone-Controller Reactivity (mk)
    g. Xenon Reactivity (mk)
    h. Power-Change Reactivity (mk)
    i. The ASDV opening (%) – you can see it on the Turbine Generator page
4. Run the Simulator for a 30-s time interval (use a timer), then freeze the Simulator and record all the above values at 30 s.
5. Run the Simulator in 30-s intervals (use a timer) to a total time of at least 8 min, freezing the Simulator after each 30 s and recording all the above values.
6. As you go, note each time (from the Alarms) if there has been a Setback, Stepback or Reactor Trip, and note at which time that has happened, and why, and which devices were active in bringing down the overpower.
7. Write your report, giving:
    a. What you expect to occur in the main PHT circuit
    b. The Excel file of all results (please embed in the WORD file)
    c. If and when the ASDV opened, and why (at which steam pressure), and what point in the transient this occurred, relative to the peak power attained
    d. Plots versus time as follows (please embed the plots in the Word file);
        i. one plot showing a, b, c together
        ii. one plot showing d
        iii. one plot showing e
        iv. one plot showing f and g together
        v. one plot showing i
    e. A brief explanation in your words why each plot is the way it is.
    f. A short conclusion as to what has happened in this power transient.
8. Note: You may have to rerun the transient several times to ensure you pick up all the correct info at the correct times, and that you understand the results.

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Time (s)	Neutron Power (%)	Thermal Power (%)	Turbine Power (%)	Steam Pressure (kP)	Zone-Control Reactivity (mk)	Xenon Reactivity (mk)	Power-Change Reactivity (mk)	Total Reactivity (mk)	ASDV Opening (%)	Comments
0	99.93	100.11	99.91	4701.5	-0.53	0.53	0	0	0	
30	103.92	102	100.01	4702.4	-0.43	0.54	-0.06	0.06	0	
60	108.78	105.25	100.59	4704.4	-0.37	0.55	-0.14	0.08	0	
90	113.37	108.79	102.26	4709.4	-0.37	0.58	-0.23	0.09	0	
120	111.74	109.06	102.71	4726.1	-0.54	0.62	-0.23	0	0	At 95 seconds, Setback Req'd and PRZR Lvl Hi alarm show up
150	108.62	107.46	103.1	4742.4	-0.7	0.64	-0.18	-0.03	0	
180	105.52	105.68	103.39	4755.8	-0.82	0.66	-0.13	-0.05	0	
210	102.43	103.79	103.68	4771.3	-0.89	0.67	-0.07	-0.06	0	
240	99.46	101.97	103.73	4772.1	-0.93	0.67	-0.02	-0.07	0.19	At 215 seconds (at steam pressure 4771.5 kPa), ASDV started opening and went up to approximately 7% before closing again at around 240 seconds. This all happens as neutron power goes to 99.46% from 102.43%
270	98.68	100.95	103.72	4770	-0.89	0.66	0.01	-0.03	0	ASDV reopens to 6% by 247 seconds. From 247 seconds to 260 seconds, ASDV opening (%) falls from 6% back to 0%. Setback and PRZR Lvl Hi alarm go away. Steam Pressure falls to 4770 kPa from 4772 kPa
300	98.71	100.63	103.47	4756.3	-0.84	0.66	0.01	-0.02	0	
330	98.73	100.36	103.13	4738.1	-0.81	0.65	0.01	-0.01	0	
360	98.74	100.1	102.78	4719.6	-0.78	0.64	0.01	-0.01	0	
390	98.75	99.9	102.4	4703.4	-0.76	0.64	0.02	0	0	
420	98.75	99.64	101.47	4698.3	-0.73	0.64	0.02	0	0	
450	98.75	99.31	100.84	4699	-0.71	0.63	0.02	0	0	
480	98.76	99.13	100.37	4699.4	-0.7	0.63	0.02	0	0	

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Report: CANDU 9 Simulator Exercise – Power Increase Maneuver in Alternate (Reactor-Leading) Mode

Introduction

This report provides an analysis of the expected behavior of the main Primary Heat Transfer (PHT) circuit during a power increase maneuver in a CANDU 9 nuclear reactor simulator. The exercise was conducted in Alternate (Reactor-Leading) Mode with a request for a power increase to 115% Full Power (FP) at a rate of 0.15%/s.

Initial Conditions

At the start of the simulation, the reactor is operating at 100% FP, with all parameters stable within normal operating ranges.

Reactor Mode

In Alternate (Reactor-Leading) Mode, the reactor's neutron power output is the leading parameter for system adjustments, with the thermal-hydraulic conditions following the neutron power. This mode is typically used for precise power adjustments and closely monitors the neutron flux to drive the system response.

Power Increase Request

Upon requesting a power increase to 115% FP, the reactor’s control systems begin to increase the rate of fission reactions, thereby increasing the neutron flux and, consequently, the thermal power produced in the core.

Expected PHT Circuit Responses

1. **Increase in Coolant Temperature**: As the rate of fission increases, the coolant (heavy water) in the PHT circuit will absorb more heat, leading to an increase in temperature. This is a direct result of the higher thermal power being generated in the reactor core.

2. **Thermal Expansion of Coolant**: The increase in temperature will cause the coolant to thermally expand. Due to the fixed volume of the PHT system, this expansion will result in an increase in pressure, which must be managed to prevent stress on the system.

3. **Increased Steam Generation**: The heated coolant transfers its thermal energy to the steam generators, resulting in an increased production of steam. This steam is then directed to the turbine, where it is converted into mechanical energy.

4. **Reactivity Feedback**: As the coolant heats up and expands, the density of the moderator decreases (void coefficient of reactivity), which can lead to a decrease in reactivity. However, in the Alternate (Reactor-Leading) Mode, the system anticipates this and makes necessary reactivity adjustments.

5. **Reactor Control Adjustments**: To maintain the requested power level, the reactor's control systems—such as the Adjuster Rods and Liquid Zone Controllers—will modulate the reactivity accordingly. As neutron power increases, these systems work to stabilize the reactor, counteracting any negative reactivity impacts from temperature changes and xenon buildup.

6. **Safety Systems Monitoring**: Throughout the maneuver, safety systems will continuously monitor the pressure within the PHT circuit. Any excessive pressure might prompt actions like opening relief valves, or in some cases, the ASDV, to release steam and reduce pressure.

Setback and Pressurizer Level High Alarm Activation

Functionality of Setback and PRZR Lvl Alarm

A "Setback" is an automatic reactor power reduction process activated when certain predefined conditions are met. The Pressurizer Level High (PRZR Lvl) alarm is a specific alarm that notifies the operator when the water level in the pressurizer exceeds its upper limit, which can indicate potential issues with the primary heat transport system balance.

Activation During Power Increase Maneuver

During the power increase maneuver, both the Setback mechanism and the PRZR Lvl High alarm played critical roles in maintaining reactor safety and stability.

Timing and Triggers

- **Setback Occurrence**: At 95 seconds into the maneuver, a Setback was required, as indicated by the operational data. This coincides with the peak in neutron power at 113%, thermal power at 109%, and subsequently, the increase in steam production.
- **PRZR Lvl Alarm**: The PRZR Lvl High alarm was triggered simultaneously with the Setback. This is typically set to alert before reaching the mechanical design limit, allowing time for corrective action.

Reasons for Activation

- **Thermal Expansion**: As reactor power increases, the coolant in the PHT system absorbs more heat, expanding thermally and leading to a potential increase in the pressurizer water level.
- **Steam Pressure Impact**: Alongside the coolant expansion, the increased steam pressure due to greater thermal power can affect the pressurizer level, as the steam space within the pressurizer is compressed.

Response and Impact on Operation

- **Reactor Power Reduction**: The Setback mechanism acts by reducing the reactor power, thus lowering the heat generation rate, allowing the coolant to contract, and mitigating the pressurizer level increase.
- **Pressurizer Level Management**: The operator is alerted by the PRZR Lvl High alarm to take manual actions if needed, such as adjusting the pressurizer heaters or operating relief valves to maintain the level within safe operating limits.

Devices Active in Managing Overpower

- **Liquid Zone Controllers**: These devices likely adjusted their position to insert negative reactivity, countering the increased reactivity due to the power increase.

- **Adjuster Rods**: As part of the reactor's control mechanisms, adjuster rods might have been engaged to further manage the reactivity and stabilize the power output.
- **Atmospheric Steam Discharge Valves (ASDV)**: The ASDV opened around 215 seconds into the simulation, releasing excess steam to alleviate the high steam pressure, a direct consequence of the overpower.

The activation of the Setback and the PRZR Lvl High alarm during the power increase maneuver was a critical part of the reactor's protective response. These systems worked in tandem to address the issues of thermal expansion in the PHT circuit and pressurizer level control. Occurring at the early phase of power increase, they reflect the reactor's automated safety systems' capacity to pre-emptively mitigate transient challenges before they escalate into more serious conditions.

Atmospheric Steam Discharge Valve (ASDV) Operation

Overview of ASDV Function

The Atmospheric Steam Discharge Valve (ASDV) serves as a safety mechanism to prevent over-pressurization of the steam system by discharging steam into the atmosphere or a secondary condenser. This system is critical in scenarios where steam production exceeds the capacity of the steam system or when non-routine operational transients occur.

ASDV Activation During Power Increase

During the power increase maneuver in the CANDU 9 simulator, the ASDV's role was to accommodate the additional steam pressure resulting from the increased reactor power output.

Timing and Reasons for ASDV Opening

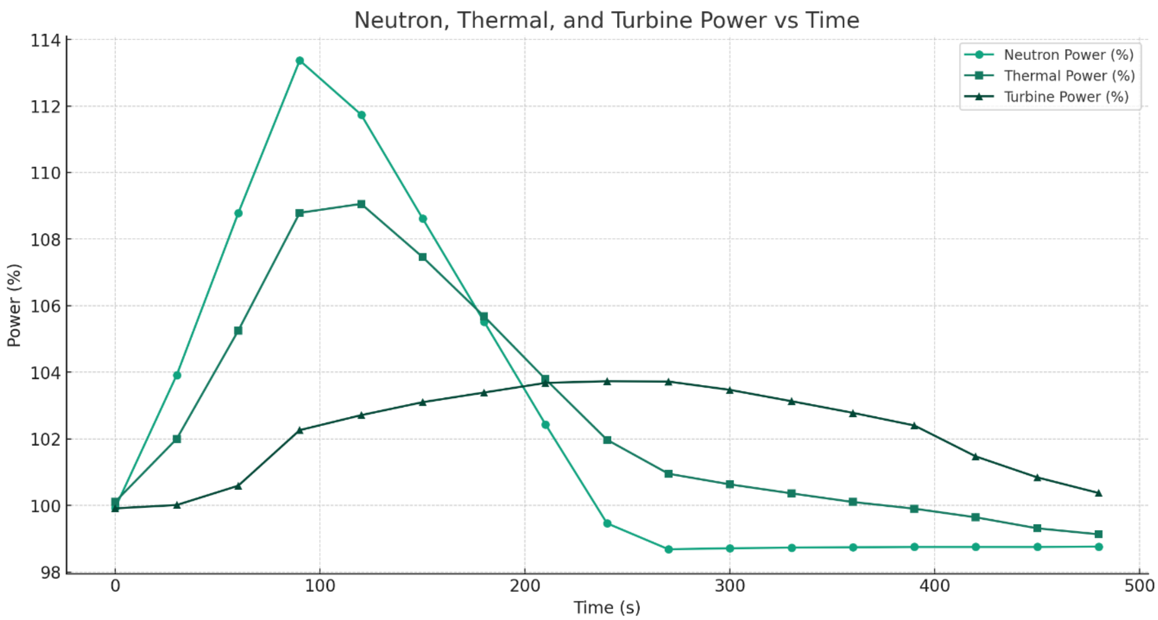
- **Initial Phase**: Initially, the ASDV remained closed, suggesting the steam pressure generated by the increased heat output was within the design capacity of the steam generators and the turbine system could utilize the additional steam for power production.
- **Peak Power and ASDV Opening**: The ASDV actuation occurred following the peak turbine power (103.75%) attained at around 215 seconds into the maneuver, at a steam pressure of approximately 4771.5 kPa (also peak steam pressure). This is a clear indication that steam pressure had reached a threshold where the risk of over-pressurization needed to be mitigated to protect the integrity of the PHT circuit and associated components.
- **Transient Response**: The opening of the ASDV was observed to rise to approximately 7% before closing again at around 240 seconds. This occurs as the neutron power slightly decreases from 102.43% to 99.46% and begins to stabilize. The ASDV reopens to 6% by 247 seconds and then closes again by 260 seconds. This corresponds with the steam pressure dropping slightly, indicating the ASDV has effectively managed the excess steam and brought the pressure back within safe operational limits. By this time, the Setback Req'd and Hi PRZR Lvl alarm go away too and steam pressure continues to consistently drop.

Impact on Reactor Operation

The ASDV's opening is a direct response to the pressure transient caused by the rapid power increase to 115% FP. This pressure increase is anticipated due to the greater amount of steam being produced, which momentarily exceeds the turbine's capacity to convert steam to mechanical energy.

The activation of the ASDV at 215 seconds into the simulation, with a subsequent closing at around 240 seconds, correlates with the peak neutron power achieved and the ensuing reduction. The ASDV operated within its expected parameters, safeguarding the system from over-pressurization and illustrating the reactor's integrated safety responses during a power ramp-up. This event marks a significant point in the transient where the system's capacity to handle the additional load is surpassed temporarily, triggering the ASDV to fulfill its safety function.

Plot 1: Neutron, Thermal, and Turbine Power vs Time:



The relationships between Neutron Power, Thermal Power, and Turbine Power over time during a power increase provide a detailed view of the reactor's operational dynamics. Initially, Neutron Power, which directly reflects the rate of nuclear fission within the reactor core, responds promptly to the power increase request. This rapid rise in Neutron Power is the result of the control systems enhancing the fission rate to reach the desired power level. Following this, as the reactor begins to generate more heat from these reactions, Thermal Power starts to rise, albeit with a slight delay. This lag is attributable to the time taken for the reactor's fuel to absorb heat and subsequently increase the coolant's temperature.

As Neutron and Thermal Powers peak and then begin to decrease due to the reactor's inherent safety mechanisms and control responses, like negative feedback from temperature changes and xenon build-up, Turbine Power demonstrates a more delayed response. This is because Turbine Power depends on the conversion of thermal energy into mechanical energy via steam, and this process inherently possesses thermal inertia. Consequently, Turbine Power continues its ascent even after Neutron and Thermal Powers have started their descent, peaking only after a delay, before it too begins to decrease as the reactor stabilizes at a lower power level.

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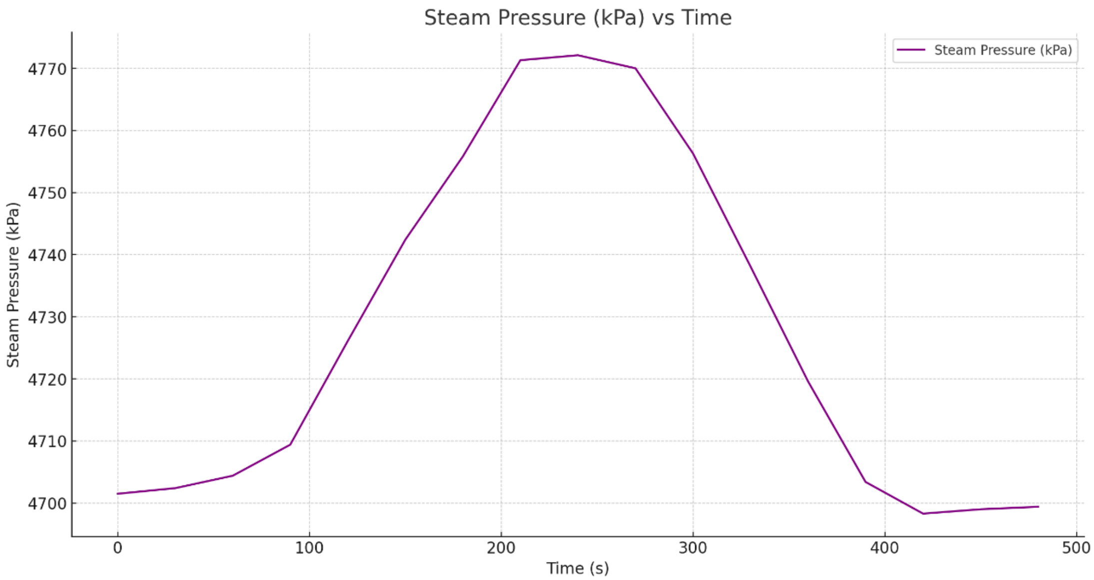
Plot 2: Steam Pressure vs Time



This plot showcasing the variation in steam pressure over time during a power transient, provides a clear representation of the reactor's thermal-hydraulic responses. At the onset of the power increase, the gradual rise in steam pressure is observed, aligning with the incremental heat generation in the reactor core. This heat is effectively transferred to the coolant, which subsequently heats the water in the steam generators, increasing steam production. The rising steam pressure is a cumulative result of this enhanced heat transfer.

As the reactor power peaks, a corresponding peak in steam pressure is noted, albeit with a slight delay. This lag reflects the time required for the increased heat in the reactor core to be conveyed to the steam generators and generate additional steam. Following this peak, a notable decrease in steam pressure occurs. This decrease is attributed to several factors: a reduction in reactor power due to the Setback operation, the activation of the Atmospheric Steam Discharge Valves (ASDV) to release excess steam, and the gradual stabilization of the reactor at a new operational state.

Eventually, the system stabilizes at this new state, marked by a balance between steam production and the system's capacity to handle this steam effectively. This plot encapsulates the intricacies of the reactor's thermal-hydraulic dynamics in response to a power increase and subsequent stabilization

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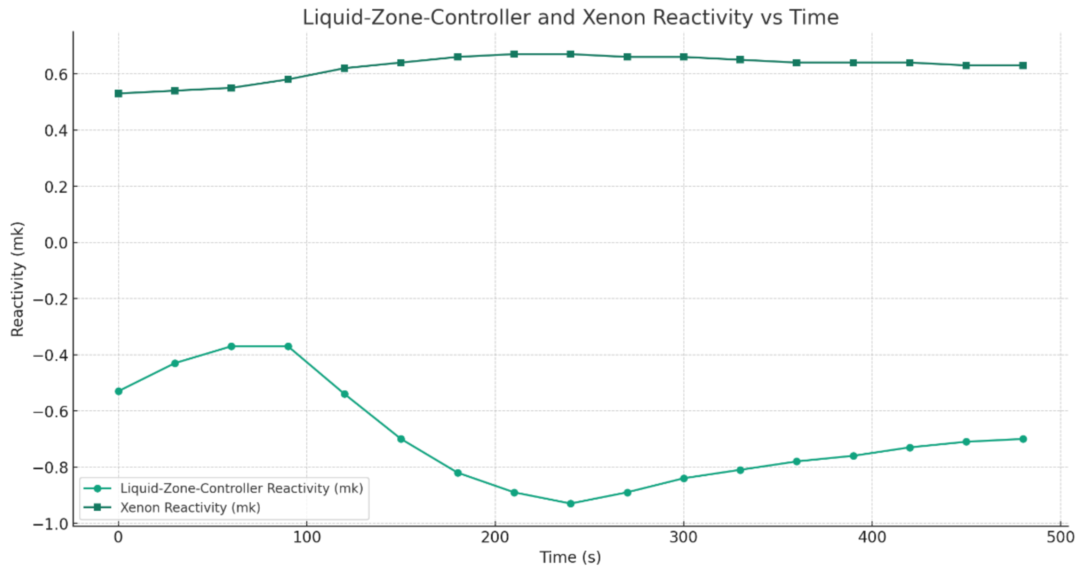
Plot 3: Liquid-Zone-Controller and Xenon Reactivity vs Time:



Throughout the transient, Liquid-Zone-Controller Reactivity (LZCR) primarily shows negative values, highlighting the control systems' active role in inserting negative reactivity, particularly as reactor power increases. This action is crucial for slowing down the fission reaction and maintaining stability. The sharp dips and peaks in LZCR, especially noticeable around the 120-second mark, correlate with the Setback operation, reflecting an aggressive control response to the power peak.

Xenon Reactivity, on the other hand, presents an interesting pattern of initial increase during the power ramp-up, indicative of the burnout of existing xenon-135, which temporarily contributes positive reactivity. However, as the reactor power stabilizes and starts to decrease, xenon reactivity exhibits a gradual shift towards slightly negative values due to the delayed nature of xenon accumulation, which introduces negative reactivity.

The interplay between LZCR and Xenon Reactivity is a delicate balancing act. LZCR adjustments are a direct result of the reactor control system's active management, constantly fine-tuning to the reactor's immediate conditions. Conversely, Xenon Reactivity represents a more passive, inherent feedback mechanism influenced by the reactor's operational history. Together, these reactivity changes underscore the complex nature of reactor management, where active control adjustments and passive reactivity feedbacks intertwine to ensure the reactor's safe and efficient function during power transients.

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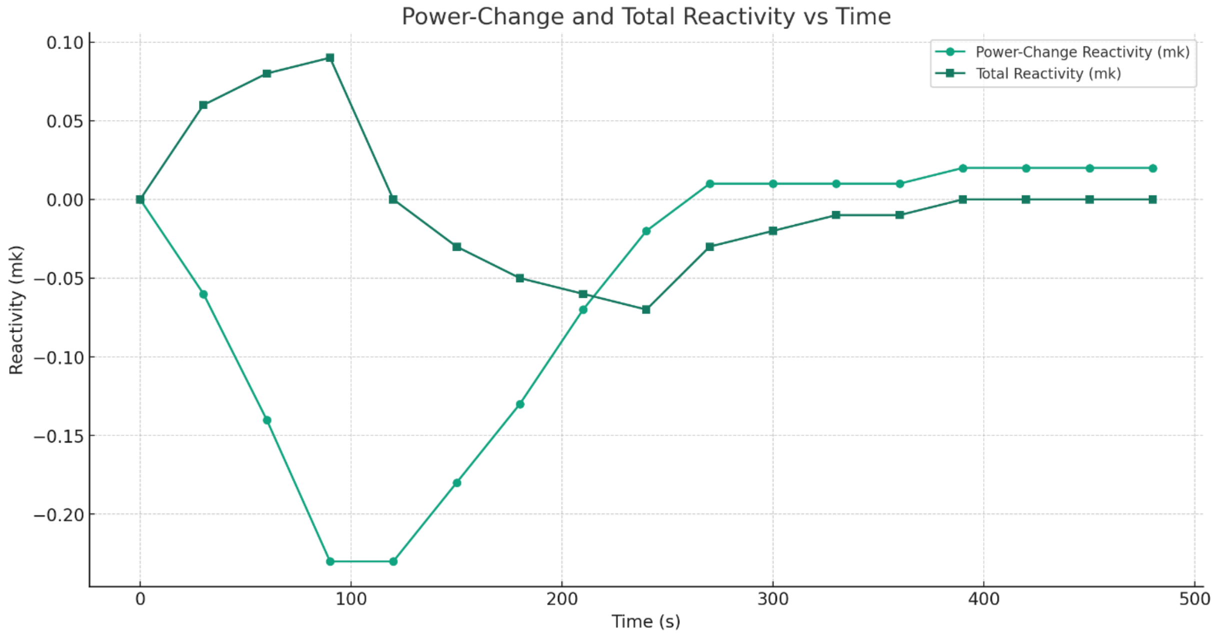
Plot 4: Power-Change and Total Reactivity vs Time:



This plot which juxtaposes Power-Change Reactivity with Total Reactivity, offers a detailed look into the reactor's reactivity dynamics throughout a power transient. The Power-Change Reactivity primarily exhibits a negative trend as reactor power is ramped up, a clear indicator of the reactor's inherent negative feedback mechanism. This is typical in nuclear reactors, where factors like the Doppler effect contribute to increased neutron absorption, effectively reducing reactivity as power levels rise. After reaching the peak power and entering a phase of reduction, Power-Change Reactivity stabilizes, gradually returning toward zero, signifying that the reactor is reaching a new equilibrium.

Concurrently, Total Reactivity, which aggregates various reactivity influences, initially shows stability around zero, reflecting a state of balance in the reactor. During the power increase, it experiences minor fluctuations, echoing the combined effects of all reactivity components, including Power-Change Reactivity and adjustments due to xenon and liquid zone controller dynamics. Post peak power, particularly after the Setback operation, Total Reactivity dips into negative territory, highlighting the reactor control systems' concerted efforts to decrease power and maintain stability.

The interplay between Power-Change Reactivity and Total Reactivity is a critical aspect of this plot. While Power-Change Reactivity mirrors the reactor's immediate response to power level changes, Total Reactivity provides a comprehensive picture of the overall reactivity status, harmonizing various reactivity contributions. As the exercise progresses, both reactivity measures gradually converge towards zero, marking the reactor's return to a steady operational state. This convergence underlines the effective management of reactivity by the reactor's control systems, adeptly handling the complex conditions of the power transient and ensuring a safe, stable reactor operation.

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Conclusion

In this power transient exercise on the CANDU 9 simulator, the reactor was subjected to a power increase maneuver from 100% to 115% Full Power (FP), and then observed over a period of time to understand how various parameters respond.

Initially, upon the power increase request, Neutron Power, Thermal Power, and Turbine Power all increased, reflecting the direct response of the reactor to the increased fission rate. The thermal power generated more steam, leading to a rise in Steam Pressure. The control systems then reacted to these changes: the Liquid-Zone-Controller Reactivity became more negative to counteract the increase in reactivity due to the power rise, and the Xenon Reactivity displayed fluctuations indicative of the dynamic nature of xenon production and burnout in the reactor core.

As the reactor power approached and surpassed the requested 115% FP, safety mechanisms such as the Setback and the ASDV were activated. The Setback reduced reactor power to manage a high pressurizer level, indicating a challenge in the primary heat transport system balance due to rapid power increase. Concurrently, the ASDV opened to relieve excess steam pressure, preventing over-pressurization of the steam system.

Towards the end of the transient, reactor parameters began to stabilize. The Power-Change Reactivity, after initially acting to dampen the power increase, returned towards zero, indicating the reactor reaching a new equilibrium. Similarly, Total Reactivity stabilized, demonstrating the effective management of various reactivity influences by the reactor's control systems.

Overall, this exercise showcased the complex interactions within a nuclear reactor during a power increase maneuver, highlighting the integral role of various control and safety systems in maintaining reactor stability and safety. The ability of these systems to respond effectively to rapid changes in power levels ensured the reactor's safe operation throughout the transient.

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Appendix:

Plot 1 Code:

```
import matplotlib.pyplot as plt

import pandas as pd


# Data from the experiment

data = {

    "Time (s)": [0, 30, 60, 90, 120, 150, 180, 210, 240, 270, 300, 330, 360, 390, 420, 450, 480],

    "Neutron Power (%)": [99.93, 103.92, 108.78, 113.37, 111.74, 108.62, 105.52, 102.43, 99.46, 98.68, 98.71, 98.73, 98.74, 98.75, 98.75, 98.75, 98.76],

    "Thermal Power (%)": [100.11, 102, 105.25, 108.79, 109.06, 107.46, 105.68, 103.79, 101.97, 100.95, 100.63, 100.36, 100.1, 99.9, 99.64, 99.31, 99.13],

    "Turbine Power (%)": [99.91, 100.01, 100.59, 102.26, 102.71, 103.1, 103.39, 103.68, 103.73, 103.72, 103.47, 103.13, 102.78, 102.4, 101.47, 100.84, 100.37]

}


# Creating a DataFrame

df = pd.DataFrame(data)


# Plotting

plt.figure(figsize=(14, 7))

plt.plot(df["Time (s)"], df["Neutron Power (%)"], label='Neutron Power (%)', marker='o')

plt.plot(df["Time (s)"], df["Thermal Power (%)"], label='Thermal Power (%)', marker='s')

plt.plot(df["Time (s)"], df["Turbine Power (%)"], label='Turbine Power (%)', marker='^')


# Adding titles and labels

plt.title('Neutron, Thermal, and Turbine Power vs Time')

plt.xlabel('Time (s)')

plt.ylabel('Power (%)')

plt.legend()

plt.grid(True)


# Show plot

plt.show()
```

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Plot 2 Code:

```
df['Steam Pressure (kPa)'] = [4701.5, 4702.4, 4704.4, 4709.4, 4726.1, 4742.4, 4755.8, 4771.3, 4772.1, 4770, 4756.3, 4738.1, 4719.6, 4703.4, 4698.3, 4699, 4699.4]


# Now plot Steam Pressure vs Time

plt.figure(figsize=(14, 7))

plt.plot(df["Time (s)"], df["Steam Pressure (kPa)"], label='Steam Pressure (kPa)', marker='x', color='purple')


# Adding titles and labels

plt.title('Steam Pressure (kPa) vs Time')

plt.xlabel('Time (s)')

plt.ylabel('Steam Pressure (kPa)')

plt.legend()

plt.grid(True)


# Show plot

plt.show()
```

Plot 3 Code:

```
df['Liquid-Zone-Controller Reactivity (mk)'] = [-0.53, -0.43, -0.37, -0.37, -0.54, -0.7, -0.82, -0.89, -0.93, -0.89, -0.84, -0.81, -0.78, -0.76, -0.73, -0.71, -0.7]

df['Xenon Reactivity (mk)'] = [0.53, 0.54, 0.55, 0.58, 0.62, 0.64, 0.66, 0.67, 0.67, 0.66, 0.66, 0.65, 0.64, 0.64, 0.64, 0.63, 0.63]


# Plot Liquid-Zone-Controller Reactivity and Xenon Reactivity vs Time

plt.figure(figsize=(14, 7))

plt.plot(df["Time (s)"], df["Liquid-Zone-Controller Reactivity (mk)"], label='Liquid-Zone-Controller Reactivity (mk)', marker='o')

plt.plot(df["Time (s)"], df["Xenon Reactivity (mk)"], label='Xenon Reactivity (mk)', marker='s')


# Adding titles and labels

plt.title('Liquid-Zone-Controller and Xenon Reactivity vs Time')

plt.xlabel('Time (s)')

plt.ylabel('Reactivity (mk)')

plt.legend()

plt.grid(True)


# Show plot

plt.show()
```

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Plot 4 Code:

```
df['Power-Change Reactivity (mk)'] = [0, -0.06, -0.14, -0.23, -0.23, -0.18, -0.13, -0.07, -0.02, 0.01, 0.01, 0.01, 0.01, 0.02, 0.02, 0.02, 0.02]

df['Total Reactivity (mk)'] = [0, 0.06, 0.08, 0.09, 0, -0.03, -0.05, -0.06, -0.07, -0.03, -0.02, -0.01, -0.01, 0, 0, 0, 0]


# Now let's plot Power-Change Reactivity and Total Reactivity vs Time.

plt.figure(figsize=(14, 7))

plt.plot(df["Time (s)"], df["Power-Change Reactivity (mk)"], label='Power-Change Reactivity (mk)', marker='o')

plt.plot(df["Time (s)"], df["Total Reactivity (mk)"], label='Total Reactivity (mk)', marker='s')


# Adding titles and labels

plt.title('Power-Change and Total Reactivity vs Time')

plt.xlabel('Time (s)')

plt.ylabel('Reactivity (mk)')

plt.legend()

plt.grid(True)


# Show the plot

plt.show()
```