Recommendation of Optimal Mitigation Actions Using Causal Inference in LOCA Events at Nuclear Power Plants

Ji Hun Park[a], Hye Seon Jo[b], Ho Jun Lee[c] and Man Gyun Na[d]
Department of Nuclear Engineering, Chosun University, 10 Chosundae 1-gil, Dong-gu, Gwangju, Republic of Korea

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Abstract: In nuclear power plants, ensuring safety during abnormal situations is of paramount importance. This study focuses on the loss of coolant accident, a design basis accident, and applies the use of causal inference to recommend optimal mitigation actions. The study utilizes data collected from the compact nuclear simulator to analyze the effectiveness of various actions, including the activation of charging pumps and adjustments to control valves. The results indicate that the simultaneous activation of charging pumps #2 and #3 yields the highest cumulative absolute effect on maintaining the pressurizer water level. Additionally, keeping the charging control valve and letdown back pressure valve fully open (100%) also contributes significantly to managing the pressurizer water level during loss of coolant accident scenarios. These findings provide valuable insights into improving nuclear power plant safety by guiding operators in choosing the most effective mitigation strategies during LOCA situation.

1 INTRODUCTION

Nuclear power plants (NPPs) are electricity-generating facilities that use nuclear fuel to produce electricity. The use of nuclear fuel can involve the release of radioactive materials, making safety a top priority for NPPs.

However, accidents can occur in NPPs for various reasons. In NPPs, accidents are categorized as abnormal, emergency, or severe. This study focuses on abnormal situations in NPPs. Abnormal situations are defined as the period from when one or more preset alarms are triggered due to the occurrence of an abnormal event under normal conditions until the reactor is shut down. When abnormal situations occur in NPPs, operators diagnose the issue and take mitigation actions based on procedures known as abnormal operating procedures. These procedures suggest appropriate mitigation actions but do not specify them in detail.

For example, in a loss of coolant accident (LOCA) situation, one of the design basis accidents for NPPs, the general response is to activate a charging pump. LOCA situations involve a rupture in the primary piping of NPPs with a closed-loop configuration, leading to the leakage of primary coolant into the containment and a reduction in the primary coolant inventory. The primary coolant is crucial for cooling the heat generated by nuclear fuel, necessitating the maintenance of an adequate coolant inventory. Operating a charging pump, which draws water from a separate source and injects it into the primary system, can be an appropriate mitigation action. However, the procedures typically do not specify how many of the three available charging pumps should be operational. This ambiguity provides flexibility for operators but also places the burden of decision-making on them, making it challenging to ensure the optimal mitigation action for each situation.

In this study, we introduce a method that uses causal inference to suggest mitigation actions for operators in LOCA situations in NPPs. The causal inference method estimates and quantifies the causal effect of specific mitigation actions, providing a

[a] https://orcid.org/0000-0001-6225-5621
[b] https://orcid.org/0000-0002-4413-5244
[c] https://orcid.org/0009-0001-5155-9483
[d] https://orcid.org/0000-0003-0097-3403

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quantitative evaluation of these actions. The quantified effectiveness of these actions can inform operators about the most likely means of mitigation. This study is a foundational research effort on mitigation action suggestion systems for NPPs and focuses exclusively on LOCA situations, a design basis accident for NPPs. In addition, a critical safety function in LOCA situaitons is the primary coolant inventory. The crticial safety function is a key feature that must be maintained to mitigate an accident. Based on the pressurizer (PRZ) water level, which is an indicator of the primary coolant inventory, the appropriate action is determined (i.e., maintaining a normal PRZ water level is a primary goal).

Data were collected using a simulator, the Compact Nuclear Simulator (CNS). The mitigation measures investigated included 1) the activation of charging pumps, 2) adjustments to the charging control valve, and 3) adjustments to the letdown Back Pressure Valve (BPV). Based on these measures, the following five scenarios were organized to obtain data: 1) activation of charging pump #2, 2) activation of charging pump #3, 3) simultaneous activation of charging pumps #2 and #3, 4) adjusting the opening state of the charging control valve (ranging from 10% to 100% in 10% intervals), and 5) adjusting the opening state of the letdown BPV (ranging from 10% to 100% in 10% intervals).

By using the causal inference method and providing the evaluated results to operators, this approach is expected to significantly enhance accident management in NPPs.

2 METHOD

Causal inference is a statistical method that aims to identify and quantify cause-and-effect relationships between variables. In this study, we utilize the causal impact method (Brodersen et al., 2015), a specific approach within the broader field of causal inference. This method is based on Bayesian structural time-series models and estimates the causal effect of an intervention (e.g., mitigation actions) by comparing data from before and after the intervention. The causal impact method has three main components: 1) time series modeling, 2) posterior analysis, and 3) synthetic control and flexibility.

The causal impact method employs structural time-series models, which include state-space representations to account for trends, and other temporal patterns in the data. The model comprises an observation equation, which links observed data to latent state variables, and a state equation, which describes how these state variables evolve over time.

Using a Bayesian framework, the causal impact method estimates the causal effect of an intervention by comparing the observed data post-intervention to a predicted counterfactual scenario based on pre-intervention data. This comparison allows for the quantification of the intervention's impact, including absolute and relative effects, with uncertainty intervals that provide insights into the confidence of these estimates.

Additionally, the method constructs a synthetic control group using a combination of control series that closely match the treated unit's pre-treatment behavior. This approach avoids rigid assumptions about the control group and allows for the flexible incorporation of multiple sources of variation in the data, such as local trends and seasonality. This flexibility is crucial for accurately capturing the impact of interventions in complex real-world scenarios.

3 DATA

The data were collected using the compact nuclear simulator (CNS), developed by the Korea Atomic Energy Research Institute. The CNS is a simulator modeled after the Westinghouse 930 MWe 3-loop pressurized water reactor (Park et al., 1997). This simulator can replicate a variety of abnormal, emergency, and normal situations, and is capable of introducing various malfunctions.

Figure 1 illustrates the configuration of the chemical and volume control system (CVCS), which is responsible for maintaining the primary inventory.

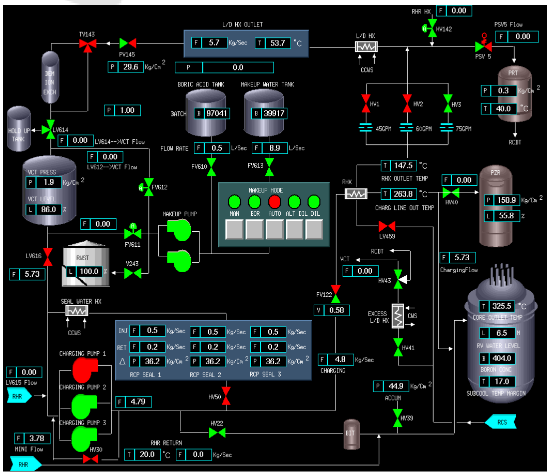

Figure 1: Configuration of CVCS.

In this study, data were collected for five scenarios based on the CVCS components. The components selected for this study are those that operators can directly control: the charging pumps, the charging control valve (FV122 in Figure 1), and the letdown BPV (PV145 in Figure 1). Specifically, charging pump #1 is always operational, so the controllable options included charging pumps #2 and #3. Additionally, the control valves were tested in 10% increments, ranging from 10% to 100% open. The fully closed state (0%) was not considered, as it is not implemented in the simulator.

The accident scenario used in this study involved a LOCA, with the assumption that a malfunction is introduced 30 seconds after a normal situation, and each mitigation action is initiated at 90 seconds. The primary variable of interest is the PRZ water level, while the input variables include charging flow, letdown flow, reactor vessel water level, volume control tank outlet flow, and the open state of the charging control valve and letdown BPV.

4 RESULT

The causal inference method was utilized to quantify the impact of PRZ water level on the operator's mitigation actions. First, the causal effect of charging pump #2 is shown in Table 1 and Figure 2. It can be seen in Table 1 that the PRZ water level averages 37.83% with the mitigation action, compared to 20.87% without it. The absolute effect is the water level difference between these two scenarios, while the relative effect represents the relative difference compared to no mitigation. As a result, the use of charging pump #2 shows an 81.31% increase in the PRZ level compared to no mitigation action. Additionally, the reactor shutdown time without mitigation action is 267 seconds compared to 487 seconds after mitigation action.

In Figure 2, "y" is the data with mitigation action, and "predicted" is the result of predicting the data without mitigation action. In other words, the causal impact method performs a counterfactual analysis by predicting data without mitigation action based on data with mitigation action. Additionally, the second row of Figure 2 shows the absolute effect over time, and the third row shows the cumulative effect over time.

Second, the results for the mitigation actions using charging pump #3 are presented in Table 2 and Figure 3. The findings indicate that charging pumps #2 and #3 have similar causal effects, with features consistent within the margin of error. However, it can be seen that each charging pump #2 and #3, which should have the same treatment effect (i.e., same reactor shutdown time), have different predictions (i.e., different no mitigation action). This is caused by uncertainty in the predictions.

Table 1: Causal effect on charging pump #2.

	PRZ water level (%)	
	Average	Cumulative
Mitigation action	37.83	15018.9
No mitigation action	20.87	8283.57
Absolute effect	16.97	6735.33
Relative effect	81.31%	81.31%
Reactor shutdown time	487 seconds	

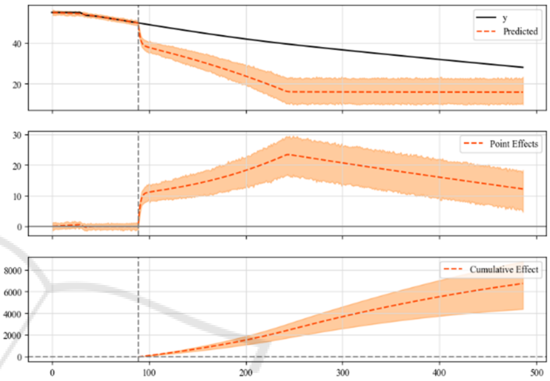

Figure 2: Results of estimating causal effects over time on charging pump #2.

Table 2: Causal effect on charging pump #3.

	PRZ water level (%)	
	Average	Cumulative
Mitigation action	37.83	15018.9
No mitigation action	20.74	8232.47
Absolute effect	17.09	6786.45
Relative effect	82.44%	82.44%
Reactor shutdown time	487 seconds	

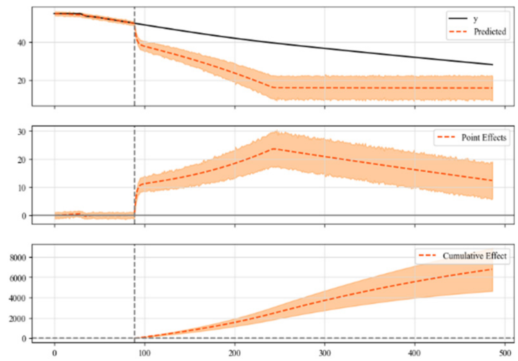

Figure 3: Results of estimating causal effects over time on charging pump #3.

Third, the effects of using both charging pumps #2 and #3 simultaneously are illustrated in Table 3

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and Figure 4. The results show that the relative effect of starting both pumps together is greater than starting them separately. However, when charge pumps 2 and 3 are started together, the average PRZ level is lower compared to when the charge pumps are started individually. This is because the simultaneous start-up of the charging pumps causes the abnormal situation to persist longer, resulting in lower PRZ water levels, illustrating the average fallacy.

Table 3: Causal effect on charging pumps #2 and #3.

	PRZ water level (%)	
	Average	Cumulative
Mitigation action	31.9	23477.15
No mitigation action	10.7	7871.57
Absolute effect	21.2	15605.58
Relative effect	198.25%	198.25%
Reactor shutdown time	826 seconds	

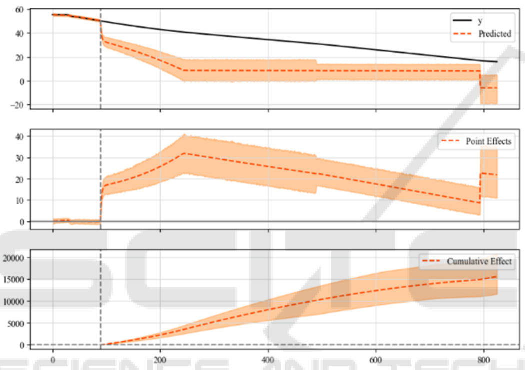

Figure 4: Results of estimating causal effects over time on charging pumps #2 and #3.

Fourth, the results related to the charging control valve's opening state are shown in Figure 5. It is observed that the effectiveness of the mitigation actions is significantly reduced when the valve is open below 70%. This indicates the necessity of maintaining an opening state of 80% or more to sustain the PRZ water level effectively.

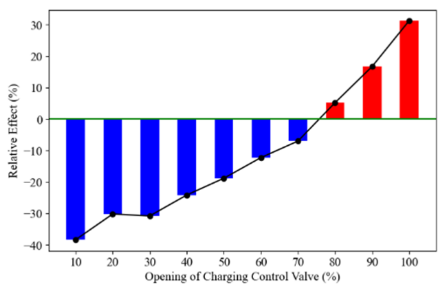

Figure 5: Relative effect of charging control valve opening state.

The detailed causal effect when the charging control valve is 100% open is provided in Table 4 and Figure 6.

Table 4: Causal effect on charging control valve 100%.

	PRZ water level (%)	
	Average	Cumulative
Mitigation action	42.35	9061.96
No mitigation action	32.27	6905.24
Absolute effect	10.08	2156.72
Relative effect	31.23%	31.23%
Reactor shutdown time	304 seconds	

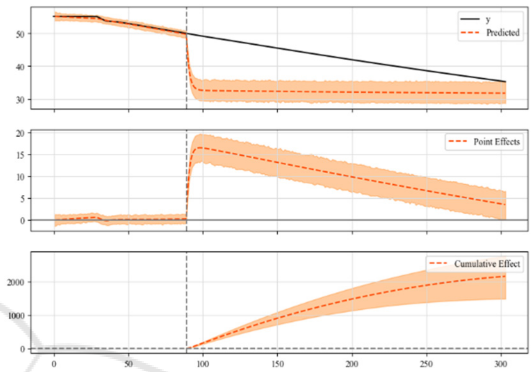

Figure 6: Causal effect of a 100% open charging control valve.

Finally, the impact of the letdown BPV's opening state is depicted in Figure 7. Unlike the charging control valve, there isn't a proportional relationship between the opening state and effectiveness, but a significant mitigation effect is observed at 100% open. This is due to the fact that the charging control valve exhibits a proportional increase in charging flow in accordance with the opening state of the valve, whereas the letdown BPV demonstrates a variation in letdown flow as a consequence of the pressure difference. A 100% opening of the letdown BPV indicates that the pressure at the front and back are equal, resulting in a letdown flow of 0. Consequently, only when the letdown BPV is fully open is the letdown flow 0, which yields a superior treatment effect compared to other conditions.

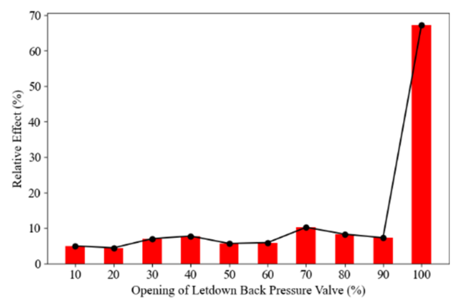

Figure 7: Relative effect of letdown BPV opening state.

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Specifically, the causal effect of a fully open letdown BPV is shown in Table 5 and Figure 8.

Table 5: Causal effect on letdown BPV 100%.

	PRZ water level (%)	
	Average	Cumulative
Mitigation action	34.28	20262.02
No mitigation action	20.5	12114.5
Absolute effect	13.79	8147.52
Relative effect	67.25%	67.25%
Reactor shutdown time	681 seconds	

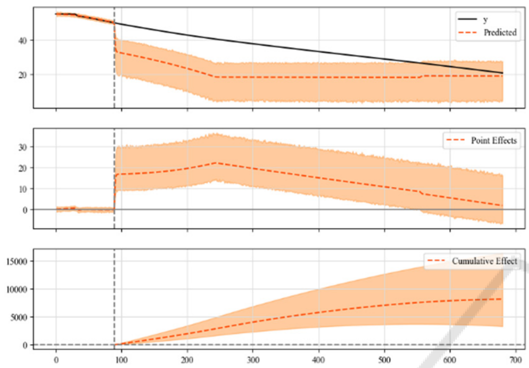

Figure 8: Causal effect of a 100% open letdown BPV.

In conclusion, the most effective mitigation action for maintaining the PRZ water level involves the simultaneous activation of charging pumps #2 and #3, as evidenced by the cumulative absolute effect. Additionally, the recommended actions based on the results are: 1) simultaneous start-up of charging pumps #2 and #3, 2) keeping the charging control valve fully open at 100%, and 3) keeping the letdown BPV fully open at 100%.

5 CONCLUSIONS

In accident situations at NPPs, operators perform mitigation actions based on established procedures. However, these procedures often lack specificity and leave critical decisions to the operators. This study aims to recommend optimal mitigation actions for LOCA situations in NPPs.

We explored the application of causal inference to evaluate and recommend optimal mitigation actions during LOCA situations. By analyzing the effects of various mitigation actions on the PRZ water level, we identified the most effective strategies for managing abnormal conditions.

The study utilized data collected from simulations involving different combinations of charging pumps and control valve settings. The results consistently showed that the simultaneous activation of charging pumps #2 and #3 led to the most significant improvement in maintaining the PRZ water level, evidenced by the highest cumulative absolute effect. Additionally, keeping the charging control valve and the letdown BPV fully open (100%) was found to be particularly effective.

The findings suggest that adopting these specific mitigation strategies can substantially enhance reactor safety during LOCA events. By providing operators with clear and quantifiable recommendations, this approach helps ensure that the most effective actions are taken promptly, reducing the risk of reactor damage and improving overall safety protocols in NPPs. This study lays the groundwork for developing more detailed and specific guidelines for emergency response, potentially leading to better-prepared operators and safer nuclear plant operations.

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REFERENCES

Brodersen, K. H., Gallusser, F., Koehler, J., Remy, N., & Scott, S. L. (2015). Inferring causal impact using Bayesian structural time-series models.

Park, J. C., Kwon, K. C., Sim, B. S., Kim, J. T., Lee, D. Y., Kim, C. H., ... & Yang, K. N. (1997). *Performance and equipments upgrade of compact nuclear simulator* (No. KAERI/RR--1794/97). Korea Atomic Energy Research Institute.