Multi Hazard Probabilistic Safety Assessment Framework

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Abstract: The 2011 Fukushima Daiichi disaster highlighted the need for comprehensive safety evaluations of nuclear power plants, particularly when facing multi natural disasters either simultaneously or sequentially. With climate change increasing the frequency and severity of extreme events like earthquakes and tsunamis, it's crucial to reassess risk evaluations. This paper identifies and analyzes the natural disasters that can impact nuclear plant and develops a multi-hazard assessment framework. The fragility of nuclear plants to extreme and multi-hazard scenarios is evaluated using statistical data, and accident scenarios are derived through initial event analysis and failure mode and effect analysis (FMEA), considering the correlation between these disasters. Additionally, this paper evaluates mitigation strategies using FLEX (Flexible Mitigation Strategies) and MACST (-barrier Accident Coping Strategy) to enhance plant safety during multi-hazard scenarios. These evaluations aim to improve risk assessments and safety measures for nuclear plant facing multi-hazard risks.

Keywords: Extreme Hazard, Multi Hazard, Nature Hazard, Risk Assessment, MACST/FLEX.

1. INTRODUCTION

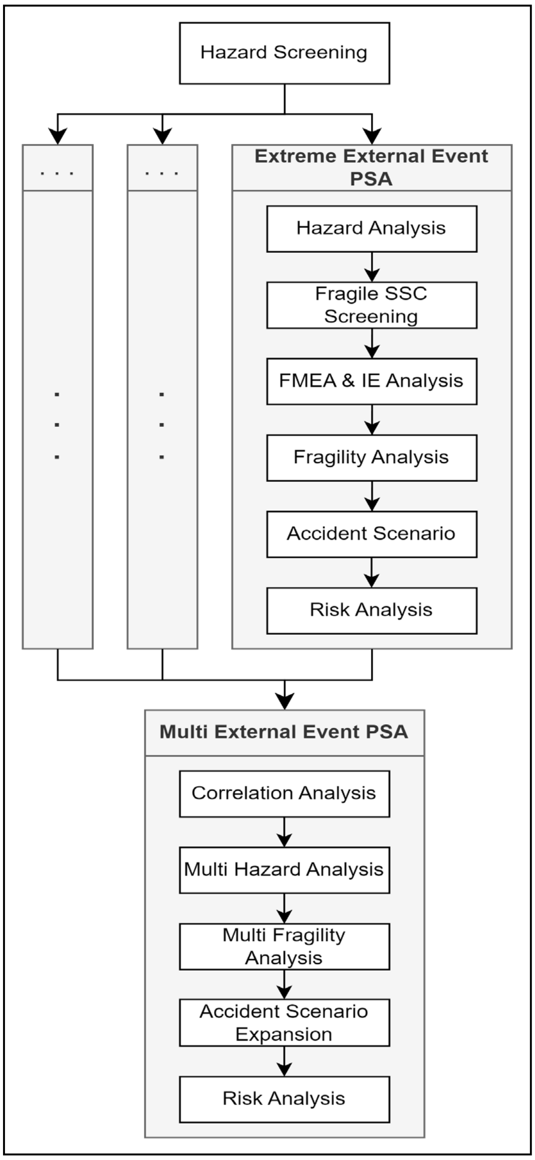
The 2011 Fukushima Daiichi Nuclear Power Plant disaster clearly showed how external hazards can lead to severe nuclear accidents. It also highlighted the importance of assessing the safety of nuclear plants when multi disasters occur at the same time. In the past, safety assessments for nuclear plant often assumed that the chance of two hazards happening together was very low, so they did not include this possibility in the design process. However, the Fukushima incident proved that this assumption can be very dangerous, especially for critical plant like nuclear power plants. It demonstrated the need to consider the potential for multi hazards happening simultaneously or one after another [1],[2],[3].

Climate change makes this issue even more pressing by causing more unpredictable weather patterns and increasing the frequency and severity of natural disasters. In particular, the Korea Climate Change Assessment Report predicts that temperature, precipitation, typhoons, seawater temperature, and sea level will increase. The average temperature is increasing by about 1.8°C from 1912 to 2017, and the average precipitation is increasing by 11.6mm per decade from 1912 to 2017. Sea temperature is rising by 0.024°C per year from 1984 to 2013, and sea level rose by 2.9mm per year from 1989 to 2017 Events like typhoons, floods, and earthquakes are becoming more common and intense. These hazards, whether they occur alone or together, pose significant risks to the safety of nuclear power plants. Therefore, it is crucial to adopt a new approach to safety evaluations that includes the possibility of multi hazards [4].

This paper aims to discuss the need for multi-hazard assessment methods and to propose a way to evaluate the safety of nuclear plants under complex conditions involving hazards. By using statistical data, this study will develop a method to assess the impact of multi hazards on the safety of nuclear plant. Additionally, it will assess mitigation strategies using FLEX (Flexible Mitigation Strategies) and MACST (Multi-barrier Accident Coping Strategy) to evaluate how these approaches can improve plant safety during external event scenarios.

2. Multi Hazard Probabilistic Safety Assessment Framework.

This research proposes a framework for evaluating the safety of nuclear power plants under various natural disaster scenarios, as illustrated in Figure 1. The framework is structured into two primary phases: the assessment of single extreme external events and the evaluation of multi-hazard scenarios.
In the single hazard assessment phase, the process begins with hazard screening, where potential natural disasters that could impact the nuclear plant are identified. This is followed by hazard analysis to understand



the nature and characteristics of each identified hazard. Next, the framework focuses on fragile SSC (Systems, Structures, and Components) screening, where plant components vulnerable to these hazards are identified. The process continues with Failure Mode and Effect Analysis (FMEA) and Initial Event (IE) Analysis to examine potential failure modes and their implications for plant safety. Fragility analysis is then conducted to assess how susceptible these components are to failure under extreme conditions. Following this, accident scenario development involves creating detailed scenarios describing potential accidents that could result from these hazards. The phase concludes with risk analysis, where a probabilistic safety assessment (PSA) evaluates the risks associated with these single-event scenarios.

The multi-hazard assessment phase builds upon the insights from the single hazard assessment. It begins with correlation analysis, examining how different natural disasters might be interrelated or occur in conjunction. The framework then proceeds to multi-hazard analysis, where a profile is developed to consider the combined effects of these correlated hazards. Following this, a multi-fragility analysis assesses the compounded vulnerabilities of plant components under the influence of multiple hazards. Accident scenario expansion then broadens the previously developed scenarios to include the interactions and cumulative impacts of these multiple hazards. Finally, the framework employs a comprehensive risk analysis using advanced tools such as ARES (Advanced Risk assessment program considering Earthquake Scenario) [5] and AIMS-PSA (Advanced Information Management System) [6] to evaluate the risks associated with multi-hazard scenarios.

This framework ensures a thorough and detailed assessment of both individual and combined natural disasters, aiming to enhance the safety and mitigation of nuclear power plants against complex multi-hazard events.

Figure 1. Extreme/Multi External Event PSA framework.

2.1. Hazard Screening.

In this stage, natural disasters that could impact the nuclear power plant are identified using data from the Operational Performance Information System for Nuclear Power Plants (OPIS) [7]. Natural disasters such as earthquakes, high winds, and flooding can be selected as factors that potentially affect the plant.

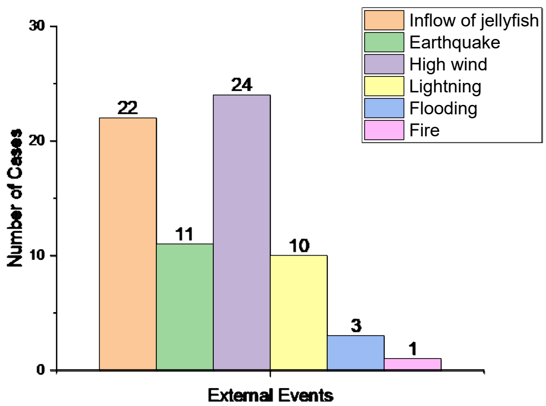


Figure 2. Number of each external event (1978~2023)

2.2. Correlation Analysis

In this stage, the correlations between different natural disasters, such as earthquakes, high winds, and flooding, are analyzed. The criteria for high wind and heavy rain are defined based on Korea Meteorological Administration (KMA) advisory.

Table 1. KMA advisory, warning criteria

	Advisory	**Warning**
High Wind	Wind speed exceeding **14m/s** or wind speed of moment exceeding 20m/s are expected on land.	Wind speed exceeding 21m/s or wind speed of moment exceeding 26m/s are expected on land.
Heavy Rain	The precipitation **for 3 hours** is expected to be more than **60mm** or the precipitation for 12 hours to be over 110mm.	The precipitation for 3 hours is expected to be more than 90mm or the precipitation for 12 hours to be over 180mm.

The analysis is conducted using an Interaction Matrix to understand the interrelationships between these hazards. In the matrix, the cells in the upper right corner are used to analyze how Hazard 1 influences Hazard 2, illustrating the directional relationship and impact between different natural disasters.

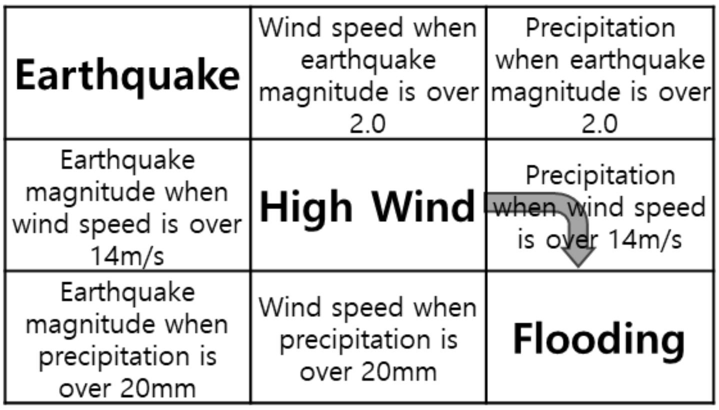


Figure 3. Interaction Matrix about earthquake, high wind, and flooding

To analyze the correlations between different natural disasters, meteorological data were used for each cell in the interaction matrix. The Korea Meteorological Administration (KMA) data was utilized from the Gijang weather station for the period 1987–2023. Correlation analysis was conducted to derive correlation coefficients, which were then used to identify interactions between natural disasters. The analysis revealed that there is a slight correlation between high winds and flooding. This finding is particularly evident in the case of typhoons, where heavy rainfall often accompanies high winds.

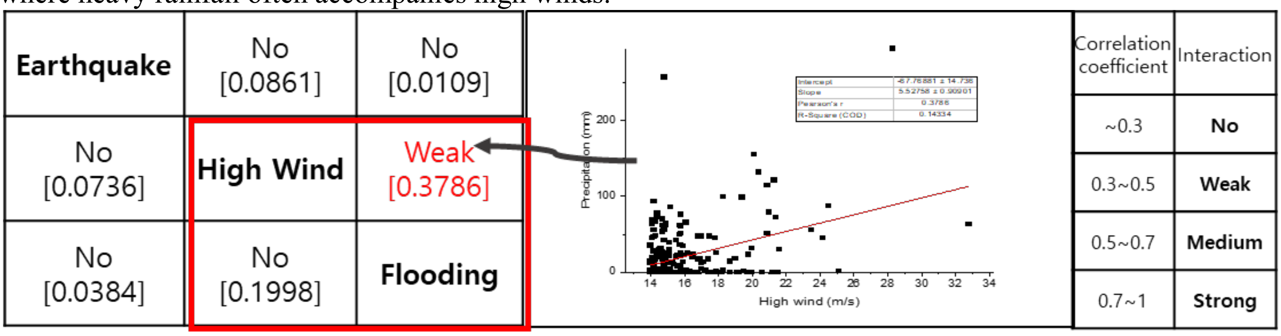


Figure 4. Result of correlation analysis

2.3. Multi Hazard Analysis

Based on the correlations identified through the correlation analysis, multi-hazard scenarios are derived. These multi-hazard are derived using the copula function. A copula function represents the joint distribution of two or more random variables and describes the relationship between these variables.

In this approach, the parameter θ in the copula function is crucial. It is determined using Kendall's tau, a correlation coefficient that measures the strength and direction of association between the variables. By applying Kendall's tau, the appropriate value for θ is calculated, which helps accurately define the dependency structure between the hazards in the multi-hazard model.

Table 2. Copula Function Type

	Range of θ	τ	$C_\theta(u,v)$
Gumbel	$\theta \in [1,\infty)$	$\frac{\theta-1}{\theta}$	$exp(-[(-lnu)^\theta + (-lnv)^\theta]^{\frac{1}{\theta}})$
Clayton	$\theta \in [0,\infty)$	$\frac{\theta}{\theta+2}$	$(u^{-\theta} + v^{-\theta} - 1)^{\frac{1}{\theta}}$
Frank	$\theta \in (-\infty,\infty)$	$1-\frac{4}{\theta}[1-D_1(\theta)]$	$-\frac{1}{\theta}ln(1+\frac{(e^{-\theta u}-1)(e^{-\theta v}-1)}{(e^{-\theta}-1)})$

In this study, a multi-hazard assessment was conducted for the combined effects of high winds and flooding. The parameter θ for the copula function was determined to be 1.153

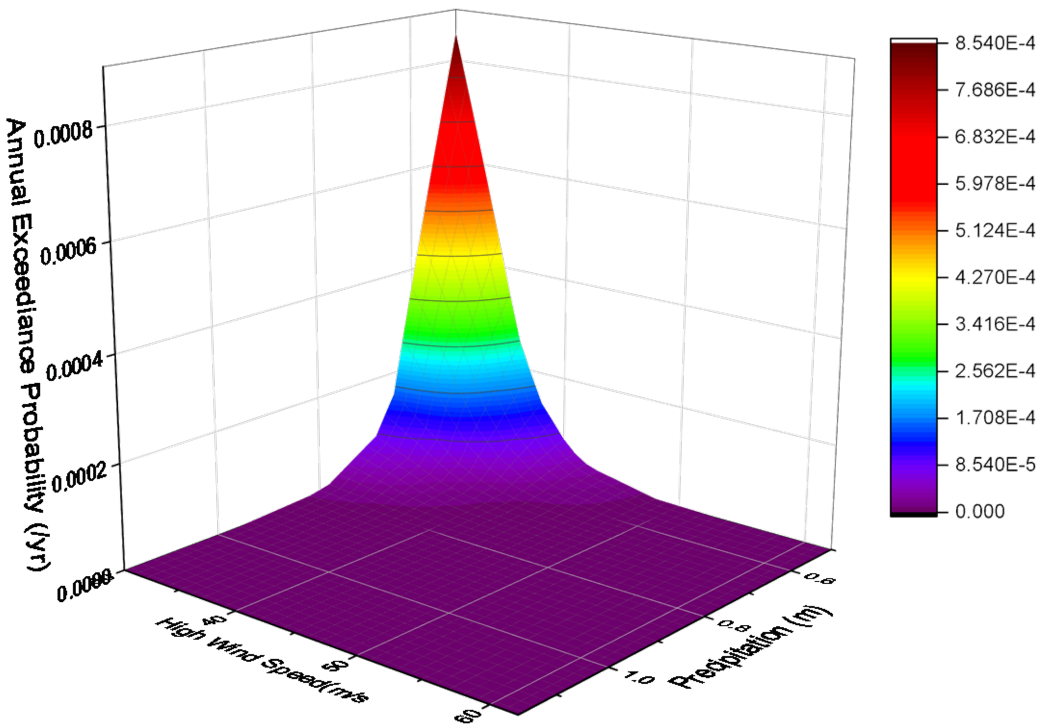


Figure 5. Multi Hazard (High wind and Flooding)

2.4. Multi Fragility Analysis

For the combined effects of high winds and flooding, the analysis focused on SSCs (Systems, Structures, and Components) that are located outdoors. Initiating Event (IE) analysis and Failure Mode and Effect Analysis (FMEA) were conducted for these fragile SSCs. The failure modes identified include destruction by wind-borne missiles and failure due to wind pressure for high wind scenarios. In the case of flooding, the failure mode considered was failure due to flooding. These analyses are crucial for understanding how outdoor SSCs are vulnerable to these combined natural hazards.

Table 3. FMEA & IE analysis

Structure	Component	Failure Mode		Initiating Event
		High Wind	**Flooding**	
Aux Building	CCW Pump	Wind-borne missile	Flooding	LOCCW
	CCW Surge tank			LOCCW
	Diesel Generator			SBO
	Aux. Feedwater Pump			-
	ECW Pump			LOCCW
	Safety Injection Pump	-		-
EDG Building		Wind-borne missile	Flooding	SBOx
AAC DG Building		Wind-borne missile	Flooding	SBO
CCW Hx Building		Wind-borne missile	Flooding	LOCCW
ESW Intake Structure		Wind-borne missile	Flooding	LOCCW
Swithch Yard Structure		Wind-borne missile /wind pressure	Flooding	SBO/LOOP

To evaluate the fragility of SSCs under high wind and flooding conditions, the lognormal distribution is used to derive the fragility functions for each hazard.

$$F_{(v)} = \phi\left[\frac{\ln(v) - \ln(V_m) + \beta_u \phi^{-1}_{(Q)}}{\beta_r}\right]$$

The Median Capacity(V_m) is the value with a 50% failure probability. β_r is uncertainty of hazard, β_u is uncertainty of structure.

For high wind, most of the median capacity values are 60m/s and only the switch yard is 54.9m/s. For flooding, fragility is calculated at each elevation, considering the failure of watertight doors and waterspouts. The failure rate of these components are based on internal flooding scenarios.

Table 4. Fragility Data by External Events

Structure	Component	Position	Flooding			High Wind		
			Median(m)	β_r	β_u	Median(m/s)	β_r	β_u
Aux Building	Safety Injection	1 floor	0.71	0.15	0.15	-	-	-
	CCW Component	1 floor	0.71	0.15	0.15	60	0.1	0.15
	AFW Pump	1 floor	0.71	0.15	0.15			
	Dissel Generator	3 floor	0.91	0.1	0.1			
	ECW Pump	3 floor	0.91	0.1	0.1			
ESW IS Building		Underground	0.71	0.15	0.15	60	0.1	0.15
EDG Building		Ground	0.91	0.1	0.1	60	0.1	0.15
AAC DG Building		Ground	0.91	0.1	0.1	60	0.1	0.15
CCW Hx Building		Ground	0.91	0.1	0.1	60	0.1	0.15
Swithch Yard Structure		Ground	1	0.15	0.15	54.9	0.1	0.15

2.5 Accident Scenario

In accident scenario analysis, fault tree and event tree are combined to model due to external hazards. The primary event tree outlines sequences of failures triggered by hazards like high winds or flooding. The secondary event tree includes the plant's mitigation systems, assessing how well they manage these failures. Fault tree analysis identifies the root causes, while event tree analysis maps out possible event sequences. This integrated approach provides a comprehensive view of the impacts of external hazards and the effectiveness of safety measures.

Using the identified SSCs, multi hazard accident scenarios were developed to assess the impact of hazard. For high wind scenarios, it was assumed that the wind is blowing from the south, thus focusing on components located on the southern wall of the plant. For flooding scenarios, the accident scenarios were created based on the plant's elevation. The derived scenarios include: LOOP1 (Loss of Offsite Power 1), where the Diesel Generator (DG) fails due to wind impact; LOOP2 (Loss of Offsite Power 2), involving DG failure and damage to the Emergency Diesel Generator (EDG) building from high winds; SBO1 (Station Blackout 1), which entails DG failure, EDG building damage, and damage to the Alternate AC (AAC) building due to a combination of wind and flooding; LOCCW1 (Loss of Component Cooling Water 1), where Component Cooling Water (CCW) components and buildings are damaged by flooding while Auxiliary Feedwater (AFW) remains available; and LOCCW2 (Loss of Component Cooling Water 2), which sees CCW components and buildings damaged by flooding with AFW unavailable. These scenarios illustrate the potential complex impacts of combined high winds and flooding on fragile components and structures in a nuclear plant, leading to failure modes and the potential for severe accidents.

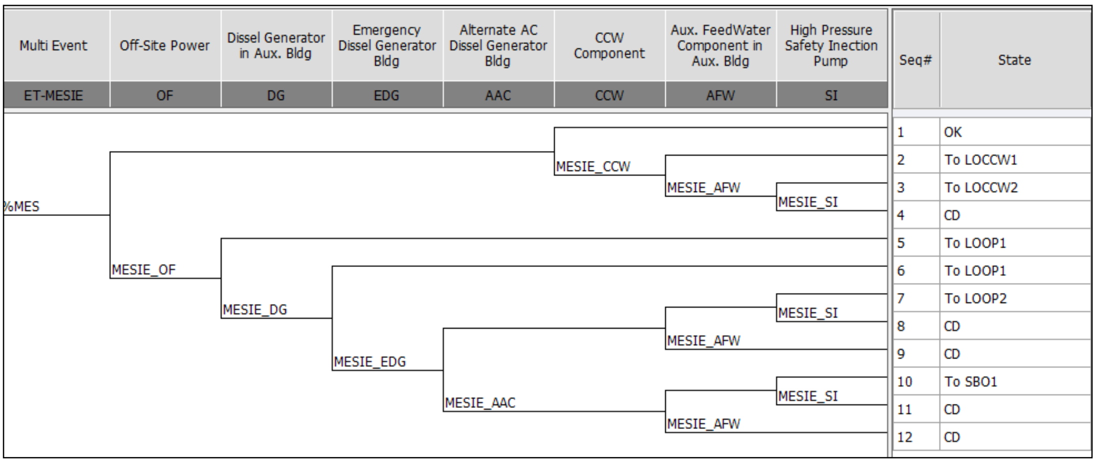


Figure 6. Primary Event Tree (Accident Scenario)

2.6 Risk Analysis

Risk assessments were conducted using the AIMS and ARES tools to evaluate the impact of multi hazards of flooding and high winds. The assessment yielded a risk result of 8.0e-9. The analysis revealed that the multi-hazard risk closely follows the trends associated with high wind events. Additionally, a significant proportion of the risk is attributed to Loss of Offsite Power (LOOP) accidents, highlighting the vulnerability of power systems under these conditions.

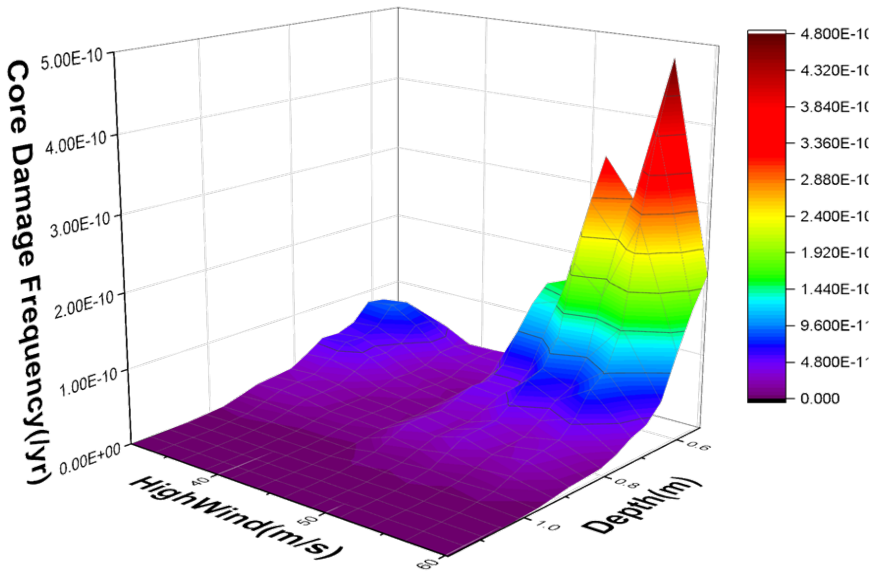


Figure 7. Result of muti external events (high wind and flooding)

Additionally, this study analyzed the critical FLEX and MACST equipment used during natural disasters. Modeling was conducted for mobile generators, portable low-pressure pumps, and portable high-pressure pumps. The results indicated that these measures significantly mitigate the risk of Station Blackout (SBO) scenarios, with a reduction rate of over 90%.

Table 5. CCDP change rate using FLEX/MACST equipment

Event	Rate of change (CCDP)
SBO	-90%
LOOP	-48%
LOCCW	-25%

3. CONCLUSION

In this study, the evaluation of high wind and flooding risks for a Korean nuclear power plant site was conducted using the external event framework depicted in Figure 1. Using the copula function, we derived multi-hazard scenarios that consider the correlation between different natural disasters. Fragile SSCs (Systems, Structures, and Components) vulnerable to strong winds and flooding were identified. These SSCs were then used to model various accident scenarios. Risk assessments for these multi natural disasters were performed using the AIMS and ARES tools.
Additionally, the effectiveness of critical mitigation systems, specifically FLEX (Flexible Mitigation Strategies) and MACST (Multi-barrier Accident Coping Strategy) equipment, was evaluated. These systems were incorporated into the secondary event tree to analyze their impact on risk reduction during natural disasters. The analysis demonstrated how these mitigation strategies significantly reduce the risk associated with multi-hazard events.

All paper should have a conclusion section to highlight the findings.

Acknowledgements

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