

A Review of the Resilience Studies to External Hazards in Nuclear Power Plants

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1. Introduction

With respect to external hazards, the design of nuclear power plants has conventionally relied on event tree analysis and fault tree analysis. That is, risk assessment has primarily been conducted in terms of accident sequences, occurrence probabilities, and frequencies. This focus on hazards, risks, and failures does not provide useful insights into high impact low probability events [1,2]. Accordingly, there is a need to extend the focus of traditional design practices toward resilience-based design, which aims to mitigate the impacts of external hazards, establish countermeasures, and enable systems to anticipate, withstand, and recover from unexpected events. This involves not only reducing the probability of accident occurrence but also considering how quickly and to what extent system can recover its functionality after an accident [2,3]. In nuclear power plants, resilience-based approaches are particularly needed because disasters can result in severe social and economic costs due to physical damage and recovery delays. Particularly in the aftermath of the Fukushima accident, the importance of resilience has been increasingly emphasized, encompassing all aspects of nuclear safety from design and operation to accident response and recovery [1].

2. Resilience

Resilience is defined as the capability of a system to withstand, respond to, and recover from disruptions. Bruneau et al. (2003) [4] conceptualized the seismic resilience of systems as the ability of both physical and social systems to withstand earthquake-generated forces and demands, and to cope with earthquake impacts through situation assessment, rapid response, and effective recovery strategies.

The quantification of resilience is typically achieved by modeling the loss and subsequent recovery of functionality over time through mathematical formulations or probabilistic simulations. To quantify resilience, it is necessary to employ a resilience curve [5].

$$R = \int_{T_{0E}}^{T_{0E}+T_{LC}} \frac{Q(t)}{T_{LC}} dt \quad (1)$$

Eq. (1) defines the resilience, where T_{0E} denotes the time of hazard occurrence and T_{LC} the time at which recovery is completed. This resilience can be defined as the normalized area under the functionality curve of the system or its components and is expressed as $Q(t)$. Formally, a resilience curve, which represents the loss and recovery function of functionality over time, illustrates the temporal evolution of performance measures of a system or its components [6].

$$Q(t) = [1 - L(I, T_{RE})][H(t - t_{0E}) - H(t - (t + T_{RE}))] \times f_{REC}(t, t_{0E}, T_{RE}) \quad (2)$$

where, $L(I, T_{RE})$ denotes the loss function, $f_{REC}(t, t_{0E}, T_{RE})$ denotes the recovery function, and $H(\cdot)$ is the Heaviside step function.

The conceptualization of resilience varies depending on the type of infrastructure system, as the direct and indirect losses considered (e.g., repair, replacement, and reconstruction costs, as well as economic losses) and the recovery processes involved (e.g., gradual or immediate recovery) differ substantially.

2.1 Studies of General Structure Resilience

For example, in the case of schools and industrial facilities, the functionality for resilience incorporates loss functions as follows. Direct losses are represented by the repair and replacement costs of structural components. Indirect losses encompass the economic impacts of business interruption and income reduction during the recovery period, together with the losses of non-structural elements [7,8].

For power grids, the resilience index quantifies grid capacity resilience by accounting for the system's adaptation and recovery capabilities [9].

2.2 Studies of Nuclear Power Plant Resilience

The resilience of critical infrastructure has received considerable attention in recent years; however, it continues to be a novel notion in the field of nuclear engineering [10].

As nuclear power plants consist of multiple interconnected components and subsystems, they

inherently involve complex interactions including correlations among components and cascading effects. Therefore, realistically representing the time-dependent processes of system or component loss and recovery through mathematical functions alone remains highly challenging. In some resilience studies on nuclear power plants, the loss or recovery functions in Eq. (2) were simply expressed in linear, triangular, or exponential forms [3]. Yan et al. (2023) [2] quantified the resilience of nuclear power plants using a probabilistic simulation approach based on Petri Nets and Monte Carlo analysis. Suzuki et al. (2017) [11] evaluated the resilience of nuclear power plants by assessing, for each accident management scenarios, the execution failure probability, the required time, and the functional margin. Here, the Resilience index is defined as the expected value of the probabilities of accident management scenarios that successfully recover safety functions.

3. Conclusions

The definition of a resilience model based on the interdependencies among components requires a comprehensive understanding of the diverse functionalities of the system [3]. To this end, resilience modeling for nuclear power plants needs to incorporate various factors such as structural, thermal-hydraulic, operational, and safety analysis variables, as well as interdependencies and resource constraints [10]. That is, both qualitative and quantitative research in this field generally require interdisciplinary collaboration.

The objective of this study is to develop a nuclear power plant resilience index that takes into account variables from structural and thermal-hydraulic analyses. In particular, functionality curves for plant components under external hazard scenarios are to be estimated, and resilience is to be quantified. On this basis, if the resilience index can be quantified, it would enable more effective support for accident management and operational decision-making.

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