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Original Article

Advanced Reactor Passive System Reliability Demonstration Analysis for an External Event

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ABSTRACT

Many advanced reactor designs rely on passive systems to fulfill safety functions during accident sequences. These systems depend heavily on boundary conditions to induce a motive force, meaning the system can fail to operate as intended because of deviations in boundary conditions, rather than as the result of physical failures. Furthermore, passive systems may operate in intermediate or degraded modes. These factors make passive system operation difficult to characterize within a traditional probabilistic framework that only recognizes discrete operating modes and does not allow for the explicit consideration of time-dependent boundary conditions. Argonne National Laboratory has been examining various methodologies for assessing passive system reliability within a probabilistic risk assessment for a station blackout event at an advanced small modular reactor. This paper provides an overview of a passive system reliability demonstration analysis for an external event. Considering an earthquake with the possibility of site flooding, the analysis focuses on the behavior of the passive Reactor Cavity Cooling System following potential physical damage and system flooding. The assessment approach seeks to combine mechanistic and simulation-based methods to leverage the benefits of the simulation-based approach without the need to substantially deviate from conventional probabilistic risk assessment techniques. Although this study is presented as only an example analysis, the results appear to demonstrate a high level of reliability of the Reactor Cavity Cooling System (and the reactor system in general) for the postulated transient event.

1. Introduction

Advanced reactor designers continue to strive for increased resilience and reliability through the use of passive safety systems. Removal of active components and dependency on operator intervention tends to increase the reliability of these types of systems as significant failure modes are removed. However, integration of the failure of these systems into a traditional risk assessment framework can be challenging, as conventional assessment techniques, which focus on active failures, cannot be applied directly. Additionally, historical U.S. licensing efforts have not included risk-informed

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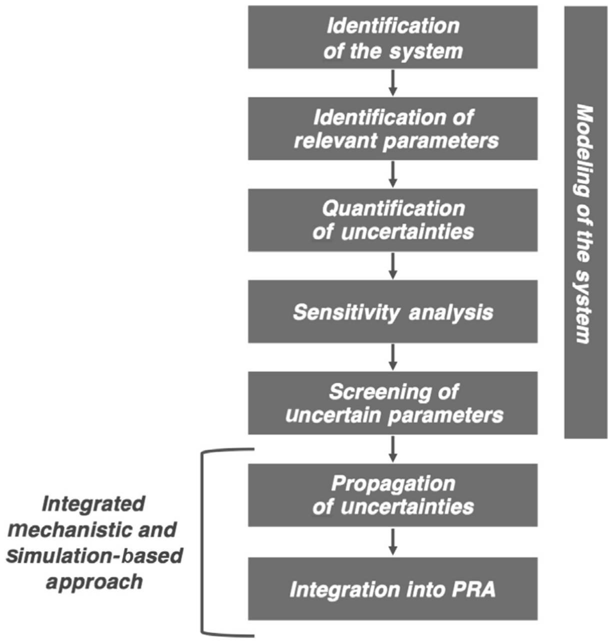

Fig. 1 – Demonstration analysis methodology. PRA, probabilistic risk assessment.

treatment of passive systems, largely because of the omission of passive safety systems from legacy designs. For the future licensing of advanced reactor designs to progress, a path forward must be identified for the inclusion of passive systems in a risk-informed regulatory framework. For these reasons, this effort focuses on the development and demonstration of a reliability analysis methodology for passive systems that addresses the challenges of passive system reliability assessments and its inclusion in a regulatory framework.

The goal of this project is to provide a path forward for advanced reactor vendors who will soon be approaching regulatory bodies and seeking to demonstrate the reliability of the passive safety systems incorporated into their plants. As indicated in the Proposed Risk Management Regulatory Framework [1], published in 2012, the U.S. Nuclear Regulatory Commission (USNRC) foresees a future regulatory environment that combines both traditional deterministic analysis and probabilistic risk assessments (PRAs). A key facet of this plan is the reliance on mechanistic reliability analyses to forgo some of the conservative assumptions of past analyses. This presents advanced reactor designers with an opportunity to realistically demonstrate plant performance, but also requires realistic modeling of all safety-related plant systems, including passive systems.

2. External event demonstration analysis

The approach used for the assessment of passive system reliability in this work is a variation of the Reliability Method for Passive Systems (RMPS) [2]. The RMPS provides a rigorous and structured approach to the assessment of passive system reliability. However, for the analysis conducted here, the RMPS procedure has been modified slightly to include the advanced uncertainty assessment and propagation techniques that were explored in a previous work [3]. These techniques will be discussed in greater detail in Section 2.6. Fig. 1 shows the methodology roadmap used for this external event analysis.

The methodology is similar to the process used for the station blackout analysis described by Brunett et al. [3] with initial steps focused on the identification of the system of interest, and establishment of success/failure criteria. This is followed by the identification of relevant parameters, including quantification and screening of the parameters. In parallel, a best-estimate model of the system of interest is created, which is used in the penultimate step of uncertainty propagation. As will be described in Section 2.6, unlike the analysis performed by Brunett et al. [3], where two uncertainty propagation and PRA integration techniques were assessed (a mechanistic method and a simulation-based method), a single combined methodology is used that seeks to leverage the best features of both of the previously tested methods.

2.1. *Identification of system*

The first step of the analysis process is the identification of the system and scenario. The transient analyzed here is an extreme external event at a small, pool-type, metal-fuel sodium-cooled fast reactor (SFR). Following the accident at the Fukushima Daiichi nuclear power plant, external events are receiving greater attention by both the regulator and industry. In particular, the use of passive systems is seen as one possible strategy for mitigating the effects of such an event. However, combining the difficulties of assessing passive system reliability with the challenges of an extreme external event can make risk analyses problematic. Providing a pathway to address such events was a key motivation for the current work.

The SFR design, shown in Fig. 2 with design characteristics listed in Table 1, was used for the external event assessment. The plant has an intermediate sodium loop that transports

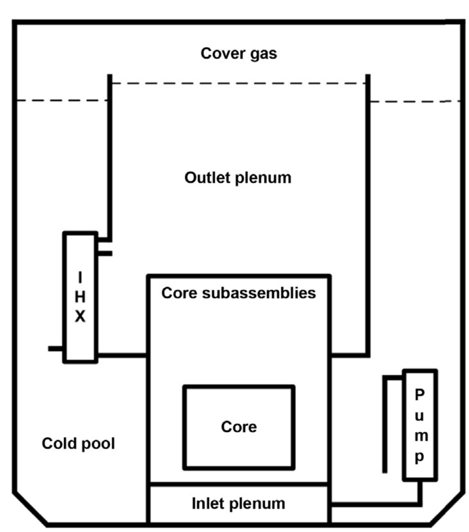

Fig. 2 – Schematic of primary system of demonstration SFR. IHX, intermediate heat exchanger; SFR, sodium-cooled fast reactor.