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A study on reliability assessment of a decay heat removal system for a sodium-cooled fast reactor

Jintae Kim, Moosung Jae *

Department of Nuclear Engineering, Hanyang University, 222 Wangsimni-ro, Seongdong-gu, Seoul, Republic of Korea

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ABSTRACT

Probabilistic risk assessment is expected to play a major role in the design and regulation framework for future reactors. Since the safety of a sodium-cooled fast reactor largely depends on the reliability of a decay heat removal system, which adopts a passive safety feature, it is necessary to assess the reliability of this system in order to conduct probabilistic risk assessment. Currently existing reliability assessment methodology is based on the probability of component failures and human errors. However, this design does not work as a passive safety system consisting of active components that do not need any external input to operate. In this study, a methodology for evaluating the reliability of a passive safety system that includes functional failure is proposed. The Prototype Gen-IV Sodium-cooled Fast Reactor that is currently under development in Korea was selected as the reference reactor, and the functional reliability of the decay heat removal system in the reactor was calculated by uncertainty propagation of the system parameters that can affect system failure. Sensitivity analysis was also performed to determine which parameters have crucial effects on system failure.

1. Introduction

In comparison with light water reactors, the sodium-cooled fast reactor (SFR) has many advantages such as improved safety, more efficient use of uranium resources, and non-proliferation. In particular, the employment of passive safety systems has greatly improved its safety. A passive safety system is a system composed entirely of passive components or using active components in a very limited way to initiate subsequent passive operation (IAEA, 1991). Passive safety systems are considered to have greater reliability than active safety systems because passive ones use natural phenomena that are always present without resorting to external driving forces or operator actions (Zio and Pedroni, 2009). In particular, passive safety systems do not require separate power supplies or operation of active devices such as pumps or blowers. Heat can be removed even if the power is lost, which can considerably enhance the safety of the reactor.

The U.S. Nuclear Regulatory Commission utilizes probabilistic risk assessment (PRA) in almost all areas of regulatory activity and requires PRA when performing design safety assessments of new nuclear reactors. In Korea, there is also a need for risk-informed design and regulation, which assesses whether safety goals are met through PRA implementation from the beginning of design and applies the results to design improvements and regulations. In general, the reliability of a safety system is estimated through fault tree analysis (FTA) in Level 1 PRA that determines the core damage frequency and sequence by using the probability of component failures and human errors. However, when evaluating the reliability of passive safety systems through this traditional FTA, the unreliability is calculated to be zero because there is no probability of component failure or human error. Therefore, a different approach is needed to evaluate the reliability of passive safety systems.

A decay heat removal system (DHRS) employing passive safety features has been designed in an SFR. As the DHRS is one of the most important safety systems reacting to an accident, the reliability of the system must be assessed in order to perform PRA on an SFR. The purpose of this study is to contribute to the improvement of SFR design through risk-informed design by evaluating the func-

Abbreviations: AHX, natural-draft Sodium-to-Air Heat Exchanger; CRDL, Control Rod Drive Line; DHRS, Decay Heat Removal System; DHX, Decay Heat Exchanger; FHX, Forced-draft Sodium-to-Air Heat Exchanger; FTA, Fault Tree Analysis; KAERI, Korea Atomic Energy Research Institute; LHS, Latin Hypercube Sampling; PGSFR, Prototype Gen IV Sodium-cooled Fast Reactor; PRCC, Partial Rank Correlation Coefficient; ULOHS, unprotected loss of heat sink.

* Corresponding author.
E-mail address: jae@hanyang.ac.kr (M. Jae).

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tional reliability of the SFR DHRS. In Section 2, the methodology used for this study is proposed. The methodology is then applied to a reference system, and the results are presented in Section 3. Section 4 provides the conclusions of this study.

2. Methodology

To assess the reliability of a passive safety system consisting of passive components, the functional failure concept (Burgazzi, 2003) was introduced. Although passive safety systems are perceived to be more reliable than active ones, the uncertainties involved in the operation and modeling of passive systems are greater than those of active systems due to the lack of data and operating experience (Burgazzi, 2004). Uncertainties can be divided into aleatory uncertainties and epistemic uncertainties. The former are uncertainties occurring randomly, and the latter are uncertainties arising from a lack of knowledge (Apostolakis, 1990). Both of these uncertainties can affect the reliability of passive safety systems. A passive safety system can fail to perform its intended function because of these uncertainties even if there is no component failure, and there is a safety margin. This failure is called a functional failure, and it occurs when the load given to the system exceeds the capacity of the system according to the load-capacity interference model (Pagani et al., 2005) as shown in Fig. 1.

Due to the complexity and applicability, capacity distribution can be simplified to a point value rather than a random variable (Han and Yang, 2010). The point value becomes the failure criterion of the system. In this case, the failure probability is defined as the part where the load exceeds the system failure criterion, as shown in Fig. 2.

If the load distribution is defined as the distribution of any system variable that can be measured through thermal hydraulic codes, and the capacity is defined as the limit that the variable should not exceed, the probability of a given load exceeding the capacity is the functional failure probability of the system.

Several methodologies for reliability assessment of passive safety systems considering the functional failure concept have been proposed (Burgazzi, 2003; Jafari et al., 2003; Burgazzi, 2004; Marquès et al., 2005; Pagani et al., 2005; Mackay et al., 2008; Zio and Pedroni, 2009). With reference to these papers, a functional reliability estimation methodology in this study is proposed, as illustrated in Fig. 3.

The first step is generation of the capacity distribution. This step includes the definition of the system, selection of the accident scenario, and identification of the system failure criterion. The next step is modeling of the system and the accident. The system should be modeled by a thermal-hydraulic code, and the accident should be simulated by performing best-estimate calculations. Then, generation of the load distribution through uncertainty analysis is needed for reliability assessment. This process is composed of the selection of the uncertain parameters, determination of their probability distributions, and uncertainty propagation based on Monte-Carlo simulation. Only epistemic uncertainties including model and parameter uncertainties that mainly occur in the process of describing the phenomenon and lack of knowledge about the observed phenomenon are considered in this study. The results of the uncertainty analysis are used to estimate the system load distribution. The functional reliability of the system can be acquired by calculating the probability that the load distribution will not exceed the capacity. Lastly, sensitivity analysis is performed to determine how the critical uncertainty parameters affect the performance of the system. Detailed procedures are specified in the next section.

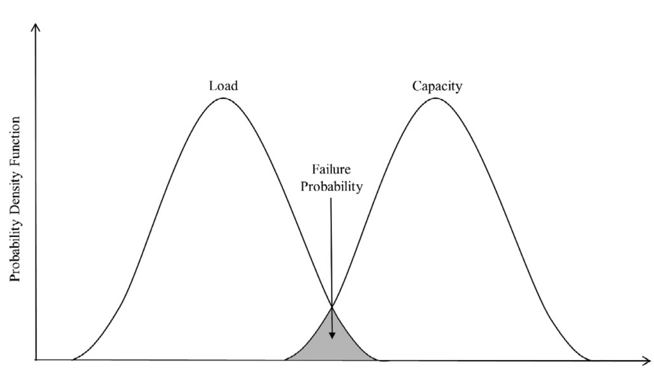

Fig. 1. Functional failure probability in the load-capacity interference model.

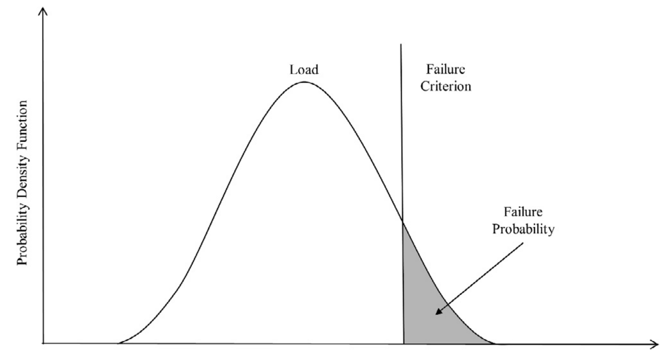

Fig. 2. Functional failure probability when the capacity distribution is a point value.

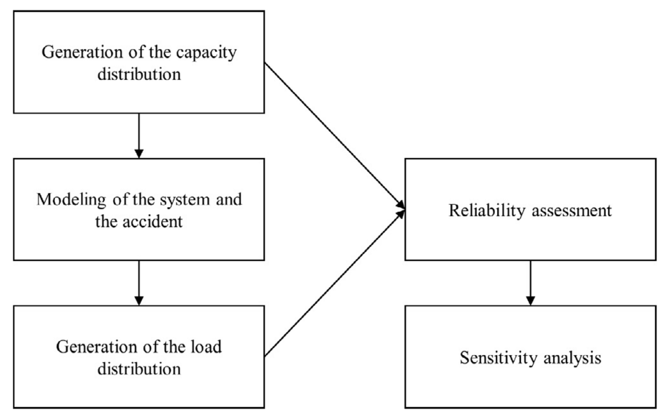

Fig. 3. Framework for functional reliability assessment.

3. Case study

3.1. Generation of the capacity distribution

The Prototype Gen IV Sodium-cooled Fast Reactor (PGSFR) was selected as the reference plant to apply the functional reliability assessment methodology. The PGSFR is a prototype SFR under development at the Korea Atomic Energy Research Institute (KAERI). The characteristics of PGSFR are summarized in Table 1.

The heat transport system of the PGSFR consists of a primary heat transport system (PHTS), an immediate heat transport system (IHTS), and a power conversion system (PCS), as shown in Fig. 4.

The decay heat removal system, which is the object of the reliability assessment of this study, is designed to remove residual heat from the core and the sensible heat of the PHTS through the