About Multiple Failure States Criteria in Quantification of Reliability of Passive Systems for VHTR's PSA

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1. Introduction

An essential safety issue of Generation IV reactors including a Very High Temperature Gas-Cooled Reactor (VHTR) is to estimate the Reliability of a Passive safety System (RoPS). Because of the unique features of VHTR [1], such as no severe core damage and release characteristics of TRISO fuel elements [2], the status of a passive system in VHTRs does not become a robust form such as success or failure. In Probabilistic Safety Assessment (PSA), the status of individual systems including passive systems should be assessed to identify the integrated behavior of a nuclear system. This unfavorable feature should be resolved in order to evaluate the RoPS for VHTR's PSA.

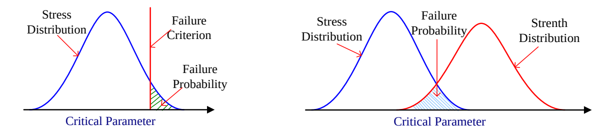
For this purpose, a concept of Multiple Failure States Criteria (MFSC) was proposed to evaluate the status of a passive system under this unfavorable feature [3]. The current work was to provide the basic features of MFSC for determining the status of a passive system needed in VHTR's PSA.

2. Reliability of Passive Safety System

Typical approaches to estimate RoPS were based on the concept that the failure of the considered system occurs when a given stress exceeds a certain allowable limit, i.e., strength of the given system [4].

The available quantification methods by using this concept are classified into two kinds of approaches according to assignment methods of the failure criterion; (1) the exceedance probability (EP) model that applies a certain limit value as the failure criterion and (2) the stress-strength interference (SSI) model that utilizes a probability distribution function as the failure criterion [5].

The conceptual difference of the two approaches is shown in Fig.1. In an EP approach, the failure probability is estimated by the exceedance probability as shown in Fig. 1-(a), whereas the failure probability in an SSI model approach is assumed as an interference probability between a stress distribution and a strength distribution as shown in Fig. 1-(b).



(a) A typical EP approach *(b) A typical SSI approach*
Fig.1. Two Kinds of Quantification Approaches for RoPS

3. Multiple Failure States

If the system status could not be expressed as a clear form such as success or failure, system status should be considered as several states. The basic concept of MFSC is to divide the status of a system as several states including normal state, (i.e., multiple states) according to the state parameters which can be used in classifying the system status (Fig. 2). For VHTR, the release levels of radioactive materials can be considered as the system state parameters of the considered passive system.

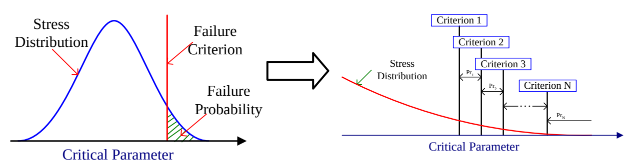


Fig.2. A Conceptual Diagram of MFSC

The formula for the MFSC to estimate the system status can be easily extended from the basic RoPS approach.

3.1. EP Model

In an EP model, the system failure probability is directly estimated by using the stress distribution of the estimation parameter comparing with a system criterion as shown in Fig. 1-(a). Conceptually, this model estimates the system failure probability by using the exceedance probability $\Pr(Z > z)$, i.e., for any threshold z it defines the probability that the random variable Z will exceed some z.

In order to apply MFSC of the considering system, the expression of a system criterion in this EP model should be extended to MFSC. For a MFSC, let *i*'s state probability $\Pr_i$ indicate a probability between *i*'s criterion C_i and (*i*+1)'s criterion C_{i+1} for S, i.e.,

$$\begin{aligned}\Pr_i &= \Pr(C_i < S < C_{i+1}) \\ &= \int_{C_i}^{C_{i+1}} f(s)ds = F(C_{i+1}) - F(C_i)\end{aligned} \quad (1)$$

These relationships are defined as following:

$$\begin{aligned}&\Pr_0 = \Pr(S < C_1) \\ &\Pr_1 = \Pr(C_1 < S < C_2) \\ &\Pr_2 = \Pr(C_2 < S < C_3) \\ &\vdots \\ &\Pr_N = \Pr(C_N < S)\end{aligned} \quad (2)$$

where C_i is the *i*'s criterion for the system strength for $1 \le i \le N$. S is a random variable of system stress, and f and F are the probability density function (pdf) and the cumulative distribution function (cdf) of S, respectively.

If cases where the system stress exceeds the smallest criterion C_1 are considered as a kind of degradation of the system, the system reliability $\Pr_R$, i.e., where there is no degradation, could be regarded as $\Pr_0$ in Eq. (2).

$$\Pr_R = \Pr_0 = 1 - \sum_{i=1}^{N} \Pr_i \quad (3)$$

3.2.SSI Model

In an SSI approach, the system failure probability $\Pr_F$ is defined as

$$\Pr_F = \Pr(S > R), \quad (4)$$

where S and R are random variables of system stress and system strength, respectively.

In order to apply an SSI approach in a system having MFSC, it is necessary to manipulate MFSC of the system by using multiple probability distributions. If a relationship between the failure states of a system is known, it could consider this relationship to obtain a formulation for modeling multiple failure states of the system.

As an example, this study considers only that failure states occur sequentially by a unique characteristic parameter [6]. A relationship between each failure state could be defined by applying an independent distribution approach. Let the system strength for *i*'s failure state be a random variable R_i. If index i of failure state could arrange according to the occurring order with a characteristic parameter, i.e., *j*'s failure state occurs after occurring *i*'s failure state for all *j* > *i*, a failure probability $\Pr_i(s)$ for *i*'s failure state can be defined by combining the probabilities $G_i(s)$ of each failure state exclusively at given load s as the following formula,

$$\Pr_i(s) = G_i(s) \prod_{j>i}^{N} [1 - G_j(s)], \quad (5)$$

where g_i and $G_i(s) = \int_{-\infty}^{s} g_i(\tau) d\tau$ are pdfs and cdfs of random variables R_i for all system failure states ***i***.

The total failure probability $\Pr(s)$ at given load s can be calculated by

$$\Pr(s) = \sum_{i=1}^{N} \Pr_i(s) = 1 - \prod_{i=1}^{N} [1 - G_i(s)] \quad (6)$$

By using this definition, the *i*'th state probabilities $\Pr_i$ for all i under given stress distribution f defined as the following:

$$\begin{aligned}\Pr_i &= \Pr(S > R_i) = \int_{-\infty}^{\infty} f(s) \Pr_i(s) ds \\ &= \int_{-\infty}^{\infty} f(s) G_i(s) \prod_{j>i}^{N} [1 - G_j(s)] ds\end{aligned} \quad (7)$$

4. Concluding Remark

A concept of Multiple Failure States Criteria (MFSC) was proposed to evaluate the status of a passive system under unfavorable feature of VHTR. The basic features of MFSC for determining the status of a passive system needed in VHTR's PSA were investigated by the EP and SSI approach to estimate RoPS.

ACKNOWLEDGEMENT

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