*Transactions of the Korean Nuclear Society Spring Meeting*
*Gyeongju, Korea, May 29-30, 2008*

# The Effect of Probability Distributions in a Failure Criterion for the Reliability of a Passive Safety System

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## 1. Introduction

A safety issue of a Very High Temperature Reactor (VHTR) is to estimate the Reliability of a Passive safety System (RoPS). The Stress-Strength Interference (SSI) approach is widely adopted to estimate the RoPS [1,2]. Major efforts for the RoPS addressed a quantification of the operational uncertainty of a passive safety system given a postulated accident scenario. However, another important problem is to determine the failure criteria of a passive safety system, because there is an ambiguity in the failure criteria for a VHTR due to the inherent safety characteristics [3,4].

In order to define the failure criteria of a passive safety system, those facts as follows should be considered;

- Understanding of required performance of that system.
- Identification of failure modes and effect.
- Relationship to risk impact.

This means a characterization of the functional requirements of a passive system for the quantification of the RoPS.

A VHTR has a large difference of inherent characteristics of reactor safety compared with light water reactors (LWR). Especially, TRISO fuel particle for a VHTR has unique features as follow [3];

- There is no severe core damage (no large release of radiation material in any accident conditions).
- A major mechanism for radiation release is the diffusion not a mechanical failure of TRISO.

This paper focuses on an investigation of the reliability characteristics due to a change of the probability distribution in a failure criterion for the quantification of the RoPS.

## 2. Reliability of Passive Safety System

### *2.1. Description of Reliability Estimation*

There are several kinds of approach for the RoPS [1,2]. These approaches are to estimate a possibility of the functional failure of that system not a hardware failure. A quantification of the RoPS consists of 5 essential processes:

- Identification of the system.
- Characterization of the system functional requirements.
- Evaluation of the system operational performance.
- Estimation of the reliability of the system.
- Modeling of the system.

The determination of failure criteria, i.e., reliability criteria is related to the characterization of the system functional requirements. Several kinds of the definition of values for failure criteria can be considered as follows:

1. Single value,
2. Single probability distribution,
3. Multiple values, and
4. Multiple probability distributions.

We investigate 1 & 2 cases in order to obtain basic insights from the above mentioned definitions.

### *2.2. Quantification of Reliability*

A reliability estimation based on the SSI approach is to evaluate the possibility that the load will exceed the capacity in a reliability physics framework [2]. A limit state function or performance function $g(z)$ can be defined as follow.

$$g(z) = r(z) - s(z)\begin{cases} > 0 \text{ for mission success} \\ = 0 \text{ at limit state} \\ < 0 \text{ for mission failure} \end{cases} \quad (1)$$

A failure probability $\Pr_f$ can be defined as follow.

$$\Pr_f = \Pr(g(z) < 0) \quad (2)$$

For continues distributions, $\Pr_f$ can be obtained by

$$\Pr_R = \Pr(Y < X) = \int F(x)dG(x) = \int [1 - G(y)dF(y) \quad (3)$$

$F$ and $G$ are cumulative distribution functions and $f$ is a probability density function. If one knows a probability distribution of a limit state function $g(z)$, one can estimate the failure probability of a given system.

## 3. Example

An application example was considered for a Reactor Cavity Cooling System (RCCS) of a VHTR. The RCCS that consists of (1) an air cooling system and (2) a direct vessel cooling are designed to remove decay and residual heat of a VHTR without any active power. Fig. 1 shows a brief conceptual layout of the RCCS [4].

For an example, the load factor, i.e., probability distribution of the peak fuel temperature for an operational performance of the RCCS for a low pressure conduction cooldown (LPCC) accident scenario, is assumed as a normal distribution that $Pr(z) = N(\mu, \sigma) = N(1550\ ℃, 25\ ℃)$.

### 4. Influence of probability distributions

*4.1. Case 1: Single-point value*

If the failure criterion of the RCCS has a single value, the failure probability of the system can be estimated by a simple relationship. According to a safety design criterion of a VHTR, TRISO fuel should not exceed $T_m$ = 1600 ˚C in any conditions if the RCCS operable.

For this case, the failure probability can be calculated by $Pr_f = Pr(s > T_m)$. For this load factor, $Pr(s > T_m)$ = 2.5E-02, because $T_m$ is near the 2σ point in $N(1550\ ˚C, 25\ ˚C)$ since a 95% confidence interval is 1.96σ.

In this case, it seems that the result of the RoPS is much conservative because the designer expected that RoPS to be more reliable than that of an active system for the same safety function. This feature exclusively reveals that a case that applies a single value for failure criterion can be too conservative to estimate the RoPS.

*4.2 Case 2: Single probability distribution*

We can consider the failure criterion of the RCCS has a single probability distribution. The simplest case applies the normal distribution for the capacity function.

For a normal-normal distributions case, reliability probability in SSI approach is estimated by follow equation;

$$\Pr_R = \Pr(Y < X) = \Phi\left(\frac{\mu_x - \mu_y}{\sqrt{\sigma_x^2 + \sigma_y^2}}\right) \qquad (4)$$

A probability distribution of the failure criterion for the TRISO fuel was not proposed. Several distributions based the safety design criterion of TRISO can be considered. The $T_m$ can be considered as a specific value $Z_d$ in a normal distribution, i.e., $d$ confidence level, we obtain a relation between $\mu_y$ and $\sigma_y$;

$$\mu_y = \frac{T_m}{Z_d \sigma_y} \qquad (5)$$

where $Z_{d=0.95}$ = 1.95996, $Z_{d=0.99}$ = 2.57583 and $Z_{d=0.999}$ = 3.29053.

For each confidence level $d$, the variation of the failure probability according to $\mu_y$ can be estimated (Fig. 2).

It is noted that the overall failure probability of case 2 is less than that of case 1. The other aspect on the estimated failure probability is related with the interference density. Fig. 3 shows that the interference density distributions for $d$ = 0.99 (blue line in Fig. 2).

For $\mu_y$ > 1675˚C, a large portion of the failure probability appeared at less 1600˚C, the safety design criterion as shown in Fig. 3. This fact means that the applied normal distribution has poor characteristics for the representation of a TRISO fuel performance.

### 5. Concluding Remark

This paper preliminarily investigated the reliability characteristics due to a change of the probability distribution in a failure criterion for the quantification of the RoPS. This work provides a basis for the determination of the failure criteria of TRISO for the RoPS, which is still a R&D item so it will be provided in the future.

### ACKNOWLEDGEMENT

This study was performed as a part of the '*long term research and development plan for the nuclear energy*' to be supported by the "Ministry of Science and Technology, Republic of Korea".

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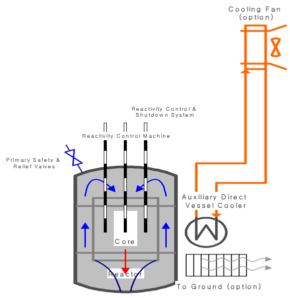


Fig. 1. A brief conceptual layout of the RCCS

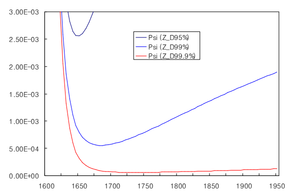

Fig. 2. Variation of failure probability

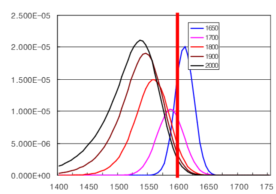

Fig. 3. Interference density distributions of a failure probability for $Z_{0.99}$