Seismic failure probability evaluation of redundant FBR piping system by probabilistic structural response analysis

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ABSTRACT: The seismic failure probability and the correlation coefficient of the multiple failure mode of the heat transport system of a three-loop fast breeder reactor have been evaluated based on a probabilistic structural response analysis. The author has discussed the most probable failure mode and its influence on the core cooling capability.

1 INTRODUCTION

Structural and equipment fragilities, i.e., seismic failure probabilities are evaluated in a Seismic Probabilistic Safety Analysis (SPSA) study of a Fast Breeder Reactor (FBR) (Nakai, Yamaguchi and Morishita, 1993). In the SPSA, one makes full utilization of the power plant systems logic models developed in the internal events analyses. By making full use of the internal event models, an external event analysis becomes consistent in level of detail with the internal events analysis. Redundant components composing a safety system are often treated as dependent and the redundancy is neglected in SPSAs. This simplified assumption is reasonable and verified as long as the neglect of the redundancy does not influence the core damage frequency. Otherwise the correlation of the multiple components failure should be quantified and the redundancy be taken into consideration. It seems the simplification used in the SPSA in treating the multiple component failure is not consistent with the internal event analysis.

As pointed out by Bohn and Lambright (1990), the common-cause failure possibility represents a potentially significant risk to the nuclear power plant during an earthquake. In the Seismic Safety Margins Research Program (SSMRP) (Smith, et al. 1981), extensive multiple time history analyses have been performed and a distinct pattern was observed. On the basis of the findings, a set of rules was formulated which predicted the correlation coefficients between components. These correlation coefficients are looking at the nature and location of the responses and is applicable to both PWR and BWR. The rule describes components on the same floor slab, and sensitive to the same spectral frequency range will be assigned response correlation = 1.0 (Bohn and Lambright, 1990).

The quantification of the correlation coefficient is not straightforward in general and the common cause failure is not easily evaluated under the seismic conditions. If one follows the rule mentioned above, the correlation coefficient of a heat transport system (HTS) of a three-loop FBR becomes 1.0. In this study, the correlation coefficient of the multiple failure mode and the seismic failure probability of the HTS has been evaluated based on probabilistic structural response analyses. The FBR has preferable passive safety characteristics that emergency reactor shutdown and decay heat removal do not rely on alternating current power supply at all. Hence the coolant boundary structure of the FBR plays important role for the safe shutdown during the seismic event, being compared with electrical equipment.
2 SYSTEM DESCRIPTION

The FBR plant analyzed in this study has three HTS loops. The schematic drawing of the HTS is shown in Fig. 1. Major components of the HTS are a reactor vessel (RV), intermediate heat exchangers (IHXs) and coolant pumps. They are connected with the hot, crossover, and cold leg pipes. The hot leg piping in which coolant temperature is around 550°C connects the RV and the IHX. The piping running from the pump to the RV is the cold leg. The pipe between the IHX and the pump is called crossover leg. The coolant temperature in the cold and crossover legs is approximately 400°C. The three HTS loops are placed in every 120 degree direction each as shown in Fig. 1. The structure of the HTS is thin-walled because the internal pressure is almost atmospheric and the maximum design temperature is beyond those of light water reactors. Therefore, the seismic load is one of the critical design consideration.

It is noted that decay heat in the core of the FBR can be removed by only one of the three HTS loops, i.e., the HTS is triply redundant with regard to the decay heat removal. It is achieved by natural circulation and is not dependent on the electricity at all. Therefore, the diesel generator and off-site power are not essential for the seismic accident sequence in the FBR. Then the FBR plant is free from the alternating current power supply to achieve the emergency cold shutdown. It was found in the internal event PSA, that the reliability of decay heat removal is extremely high. To take advantage of the preferable characteristics of the FBR, it is important to maintain the structural integrity of the system and to bear the coolant inside the structure. The seismic failure probability of the triply redundant HTS is a point of concern in the SPSA of the FBR.

3 PROBABILISTIC RESPONSE ANALYSIS OF HEAT TRANSPORT SYSTEM

In a preliminary SPSA, failure of the multiple HTS loops may be assumed dependent each other for simplicity because the design and qualification method is common to the three loops. However, the correlation should be quantified in the detailed analysis because the three loops are placed in every 120 degree direction each and the response is expected to be varied. Computer program, SMACS (Seismic Methodology Analysis Chain for Statistics) has been applied to the coupled analysis of reactor building structures and primary equipment such as RV, IHX, pump, and piping system (Morishita, 1993). Thirty ensembles of artificial time histories of input earthquakes are generated so their statistical response spectrum is in accordance with a prescribed site-specific target spectrum. Variabilities also included in the analysis are soil and structural properties.

The failure mode of the piping is assumed to be inelastic buckling because the maximum load is observed in most cases at elbow sections. An applied external load $S_i$, i.e., the primary membrane plus bending stress is compared with the capacity of the piping material to evaluate the factor of safety. Each response analysis is performed with a set of random earthquake time history and soil and structure properties. From the individual response analysis, maximum load in $j$-th loop ($j=1, 2, 3$) is obtained for $i$-th simulation ($i=1, 2, ..., 30$). Here one denotes the maximum applied load in $j$-th loop as $S_{ij}$ for $i$-th simulation. One obtains statistics of the maximum load for each loop and each leg. Table 1 shows the median value and lognormal standard deviation $\beta$ of the maximum load for each loop and leg. Also included in Table 1 are those for the union of the three legs, that give the largest load in a loop. It is seen that the difference of the median and $\beta$ among the three loops is small. The last column is the statistics for all the three loop data. By fitting the 90 values of $S_{ij}$ (30 simulations times three loops) to a lognormal
distribution, a cumulative probability function is obtained for the maximum seismic load in a single HTS loop. Therefore, comparing the cumulative probability function of $S$ with the strength of the material and multiplying other factor of conservatism or unconservatism, one obtains seismic fragility of the HTS piping.

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Median and lognormal standard deviation of membrane plus bending stress.</th>
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<tbody>
<tr>
<td></td>
<td>Loop #1</td>
</tr>
<tr>
<td></td>
<td>Median</td>
</tr>
<tr>
<td>Hot Leg</td>
<td>3.443</td>
</tr>
<tr>
<td>Crossover Leg</td>
<td>3.921</td>
</tr>
<tr>
<td>Cold Leg</td>
<td>2.158</td>
</tr>
<tr>
<td>Union</td>
<td>4.018</td>
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</table>

In each structural response analysis, the seismic loads in three loops vary each other. One obtains the maximum load for each HTS loop. The smallest one of the loads in the three loops for each simulation is defined as $S_{min} = \min\{S_1, S_2, S_3\}$. If the material strength is less than $S_{min}$, it is expected that three loops fail. Therefore, the smallest one corresponds to the multiple failure of three loops. On the other hand, the largest one $S_{max}$ of $\{S_1, S_2, S_3\}$ is equivalent to the applied stress that causes a single loop failure with survival of the remaining two loops. Likewise, the midvalue of $\{S_1, S_2, S_3\}$ designated as $S_{mid}$ corresponds to the response level at which two loops fail. Table 2 shows the median and $\beta$ values of $S_{min}$, $S_{max}$ and $S_{mid}$. The fitting of $S$ to the lognormal distribution is excellent and the correlation is 0.96 or more. It should be noted that the present coupled dynamic analysis takes the partial correlation of the three loops into account automatically. If the three loops are totally dependent, the values derived from all the data in Table 1 are to be used.

<table>
<thead>
<tr>
<th>Table 2</th>
<th>Median and lognormal standard deviation of membrane plus bending stress for multiple failure mode.</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>$S_{min}$</td>
</tr>
<tr>
<td></td>
<td>Median</td>
</tr>
<tr>
<td>Hot Leg</td>
<td>3.181</td>
</tr>
<tr>
<td>Crossover Leg</td>
<td>3.763</td>
</tr>
<tr>
<td>Cold Leg</td>
<td>2.030</td>
</tr>
<tr>
<td>Union</td>
<td>3.828</td>
</tr>
</tbody>
</table>

4 SYSTEM LEVEL FRAGILITY OF SEISMIC FAILURE

The seismic fragility of equipment is defined as a failure probability on condition that an earthquake takes place. The fragility is usually defined as a function of the intensity of the earthquake, i.e., peak ground acceleration $a$. Lognormal distribution is assumed to describe the seismic fragility. Three parameters are used, i.e., the median factor of safety $F_S$, uncertainty $\beta_U$, and the randomness $\beta_R$. $\beta_U$ is a variability that can be reduced by additional efforts while $\beta_R$ is an intrinsic variability that cannot be reduced. In this study, the composite variability $\beta_C$ is used in the following.

The composite variability is defined by:

$$\beta_C = \sqrt{\beta_U^2 + \beta_S^2}$$

Thus the seismic fragility is expressed as:

$$P_f(a) = \Phi\left[\frac{1}{\beta_C} \ln \left(\frac{a}{F_S}\right)\right]$$

where $a$ is the ratio of the intensity of an earthquake to the $S_2$ earthquake level, $\Phi$ is cumulative normal probability distribution function, and $P_f(a)$ is the conditional failure probability as a function of $a$. 779
The seismic fragility is a product of factors of safety with regard to the equipment capacity $F_C$, inelastic energy absorption capability $F_\mu$ and system redundancy $F_{SYS}$ as follows:

$$F_S = F_C F_\mu F_{SYS}$$ (3)

The system redundancy factor reflects that a complex piping systems usually have potential for force and moment redistribution at failure threshold. Then $F_{SYS}$ is the ratio of the system collapse load to a single pipe element collapse load.

When allowable load for failure $\sigma_c$ and applied load $S$ of a component are known to follow lognormal distribution, we define a factor of safety with respect to the seismic capacity as the ratio of strength to load:

$$F_C = \frac{\sigma_c - \sigma_n}{S}$$ (4)

where $\sigma_n$ is normal load such as dead weight. It is conservatively assumed that $\sigma_n=0$ because the internal pressure is atmospheric in FBRs and the normal load is small in comparison with the seismic load.

The allowable load is evaluated as follows. The operating temperature in the hot leg is around 550 °C. From the median yield strength test data of type 304 stainless steel at 550°C is 13.25 kg/mm² with lognormal standard deviation of 0.095. Those for the crossover leg and cold leg where the sodium temperature is 400 °C are 14.36 kg/mm² and 0.083, respectively. The design allowable load is expressed as:

$$\sigma_c = 1.5 K_S S_m$$ (5)

where $K_S$ and $S_m$ are shape factor and 90 percent of material yield stress, respectively.

### Table 3 Median safety factors and the lognormal standard deviation.

<table>
<thead>
<tr>
<th></th>
<th>Total (Fragility)</th>
<th>Minimum (3 Loop Failure)</th>
<th>Maximum (1 Loop Failure)</th>
<th>Maximum (2 Loop Failure)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hot Leg</td>
<td>9.21</td>
<td>0.398</td>
<td>9.96</td>
<td>0.404</td>
</tr>
<tr>
<td>Crossover Leg</td>
<td>8.431</td>
<td>0.387</td>
<td>9.125</td>
<td>0.385</td>
</tr>
<tr>
<td>Cold Leg</td>
<td>15.93</td>
<td>0.386</td>
<td>16.92</td>
<td>0.397</td>
</tr>
<tr>
<td>Union</td>
<td>7.679</td>
<td>0.386</td>
<td>8.277</td>
<td>0.385</td>
</tr>
</tbody>
</table>

According to Kennedy and Campbell (1985), the following values are recommended for the ductility factor and system redundancy factor: $F_\mu$=1.96, $b_\mu=0.226$, $F_{SYS}$=1.22, and $b_{SYS}=0.10$. Using these values and Table 2, the factor of safety relative to the design earthquake can be calculated as shown in Table 3.

Based on the probabilistic response analysis using SMACS, the seismic fragilities for the HTS components (not as the system) were obtained. The summary is shown in Fig. 2. It is seen that the IHX and the coolant pump are rugged and the failure probability is quite low. Within the three legs of the piping system, seismic failure of the cold leg is not probable. This fact is important because the cold leg pipe is just downstream of the primary pump. This result suggests that sudden decrease of coolant flow caused by the pumping coolant out is less probable than the slow flowing out of the hot or crossover legs.

The fragilities of the crossover leg and hot leg pipes are comparable to that of RV as seen from Fig. 2. The three components are the dominant contributors to the HTS failure. It is noted that the piping seems to be slightly more fragile than the RV.
RV is common to all the loops and its failure results in loss of core cooling capability. On the other hand, the piping is triply redundant because one loop natural circulation is sufficient for decay heat removal. The loss of decay heat removal results from the union of the RV failure and triple failure of the three loops. Therefore it is necessary to estimate the triple failure of the pipe legs.

Figure 3 shows the fragilities for the three loop failure of the crossover leg piping which probability becomes largest as shown in Fig. 2. The piping system fragilities evaluated with dependent or independent assumptions and RV fragility are also included in Fig. 3. If one assumes some dependency among the three loops, Fig. 3 suggests that the primary HTS failure is dominated by the piping failure. However, if the three loops are independent each other, the RV would be the most critical component in the HTS.

The fragilities of the union of three legs are shown in Fig. 4. It can be said that the loss of decay heat removal capability is caused by piping failure rather than RV failure. In other words even if the decay heat cannot be removed by the HTS piping, the RV is expected to be filled with coolant. Therefore, another decay heat removal system that is different in design, location and direction from the primary HTS is effective for maintaining decay heat removal capability after the HTS piping failure takes place. Such an example is direct reactor auxiliary cooling system (DRACS) that flow path directly comes out of the RV and does not rely on the primary HTS.

The correlation coefficients of the response among the three loops are obtained from the above-mentioned coupled analysis (it is named Case 1). For example the scattergram of the seismic load between loops 1 and 2 are shown in Fig. 5. It was found that the structural response of the piping system is different by each loop because the three loops are placed in different directions relative to the seismic input motion. According to Bohn and Lambright (1990), the correlation coefficient of 1.0 is recommended in the HTS. However, this analysis suggests the correlation coefficient of 0.9 is the best estimate as shown in Table 4 and Fig. 5. Additional analysis is performed to see the change of the correlation coefficient by neglecting the variability of soil and structural properties (designated as Case 2). Comparing Cases 1 and 2, $\beta$ can be separated into the variability deriving from seismic input and that from soil and structural properties. In Case 2, the correlation coefficients lie around 0.75 (see Fig. 6 and Table 4). If the variability $\beta$ is divided into the independent part $\beta_{Ind}$ and common cause part $\beta_{Com}$ as:

$$\beta = \sqrt{\beta_{Ind}^2 + \beta_{Com}^2}$$

(6)

one can easily perform the systems analysis of the HTS considering the partial correlation (Yamaguchi, 1991). Because $\rho$ and $\beta$ are evaluated by the response analyses, one can separate the variability into seismic input and soil and structural portions (Reed, et al., 1985) by:
\[ \beta_{\text{Com}} = \rho \beta \]

The independent and common portions are evaluated as shown in Table 5. It is seen that the correlation comes mostly from common structural properties rather than common seismic input.

5 CONCLUSIONS

(1) The fragilities for the HTS in the FBR have been evaluated by the probabilistic structural response analysis for all the failure modes of the system. It has been found that the dominant failure mode of the HTS is the crossover leg piping failure. This failure mode has the least impact on the core cooling capability.

(2) The correlation coefficient of the HTS loops is approximately 0.9. Furthermore, it is reduced to 0.75 if the correlation dependence of the soil and structure properties are neglected. The variability comes from the common structural properties rather than the common seismic input.

(3) The present approach is useful for quantifying the correlation coefficient and the seismic fragility of the redundant component failure that is used in the systems analysis.

REFERENCES


