# Development and Application of Computer Codes to Quantify the Effect of Correlation of Responses on the System Reliability

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## 1 INTRODUCTION

In the seismic risk analysis of nuclear power plants, various kinds of common cause failures (CCFs) must be taken into account (Ref.1). Some CCFs can be explicitly represented by fault trees or event trees but others can not. An example of the former types of CCFs is multiple component failures due to a collapse of wall and ceiling, and an example of the latter ones is multiple component failures due to "correlation of responses". Correlation of responses means the tendency for pairs of responses to have simultaneously high or low values for an earthquake occurrence.

Even when correlation of responses is taken into account, the failure probability of each component is not different from that calculated under the assumption of independent responses. However, the unavailability of a system is affected by taking account of correlation of responses. Figure 1 shows a simplified example. When correlation of responses is taken into account, the probability of the system failure which occurs by the simultaneous failure of two components is higher than that calculated under the assumption of independent responses. However, the system failure due to either failure of two components is lower when correlation of responses is taken into account.

The Japan Atomic Energy Research Institute (JAERI) developed a new computer code which can reflect the effect of correlation of responses on system reliability. This paper describes the outlines of the code and its application results to some safety systems in a nuclear power plant.

## 2 ANALYTICAL METHOD

Figure 2 and 3 show the logical flows to calculate a failure probability of each component and a simultaneous failure probability of each set of multiple components. Figure 2 shows the flow based on the "usual" response factor method under the assumption of independent responses and Figure 3 shows the flow based on the newly developed method to take account of correlation of responses.

In the usual method shown in Figure 2, response factors are given as probability density functions expressed by mean values and log-normal standard deviations. JAERI has defined and quantified response factors for generation of seismic wave, propagation of seismic wave, response of buildings and response of components or piping (Ref. 2). For every level of ground motions, the realistic response of each component is calculated by dividing its response which was conservatively

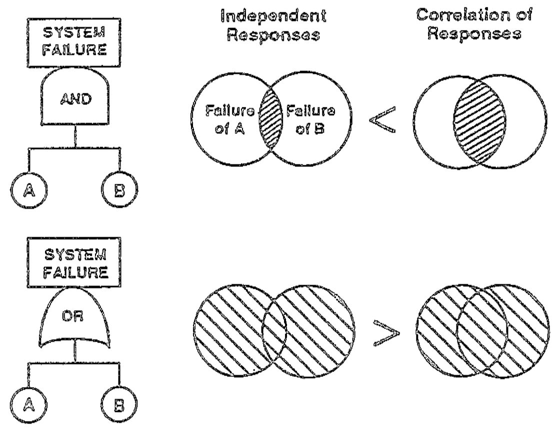


Figure 1 Effect of Correlation of Responses on System Reliability

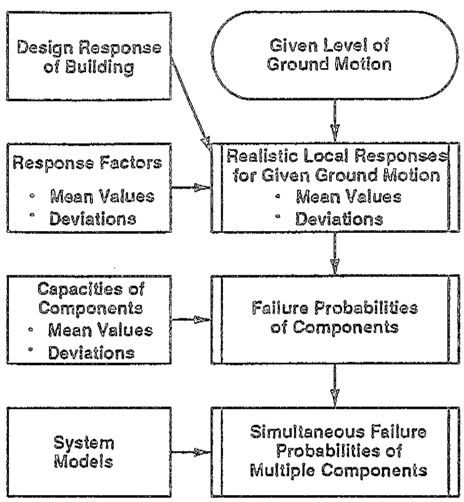


Figure 2 Logical Flow Path to Calculate Failure Probability of Components and Simultaneous Failure Probability of Multiple Components Based on the Usual Response Factor Method

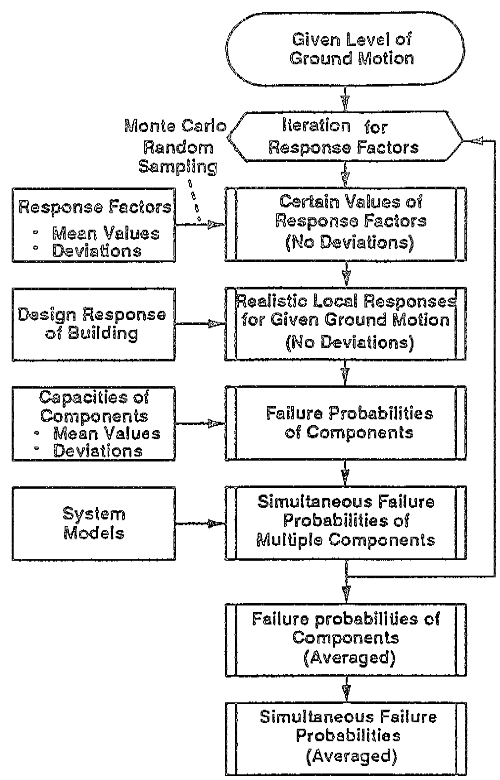


Figure 3 Logical Flow Path to Calculate Failure Probability of Components and Simultaneous Failure Probability of Multiple Components Taking Account of Correlation of Responses

calculated for the design earthquake ground motion by the response factors which remove the conservativeness. The realistic response is, as a matter of cause, represented by a probability density function. Then the response is compared with the capacity of the component, which is also represented by a probability density function. Then the failure probability of the component is calculated as a conditional probability that the response is larger than the capacity. Finally the simultaneous failure probability of multiple components is calculated but it does not include the effect of correlation of responses.

In the newly developed method shown in Figure 3, Monte Carlo simulation technique is adopted. For every level of ground motions, a large number of iterations are done. In each iteration, certain values are given to the four response factors defined above by random sampling from the probability density functions. Then the realistic response of a component is calculated by dividing its response for the design earthquake ground motion by the response factors. Since the response factors in this case have no deviations, the realistic response of the component also has no deviation. The realistic response thus calculated is compared with the capacity of component to calculate its failure probability. The simultaneous failure probability of multiple components is next calculated. Since the same values of response factors (high or low) are used for all the components in every Monte Carlo iterations, the effect of correlation of responses can be taken into account. After a lot of iterations, the failure probability of each component is averaged. If a number of iterations is large enough, the averaged component failure probability is almost same as that calculated by the method shown in Figure 2. The averaged simultaneous failure probability of multiple components is also calculated in the same way. However, the calculated probability is different from that calculated by the Figure 2 method because of correlation of responses. The Boolian Algebra analysis using the Truth Table is used for calculating the simultaneous failure probability of multiple components.

## 3 APPLICATION OF THE NEW METHOD TO SYSTEM RELIABILITY ANALYSIS

The reliabilities of some safety related systems of a BWR were analyzed with the two method described above. The TOP events whose probabilities were evaluated are :

(1) Failure of the high pressure coolant injection system (HPCI),
(2) Failure of the reactor core isolation cooling system (RCIC), and
(3) Simultaneous failure of HPCI and RCIC (Loss of high pressure injection)

The fault trees (FTs) were developed for HPCI and RCIC so as to deal with both internally induced (random) failures and seismically induced failures, referring the FTs developed for the internal event analysis in the PSA of the Browns Ferry Unit 1 (Ref. 3). The component random failures in the original FTs were replaced by the seismically induced failures. Instead, all the random failures in each of the original FTs were lumped with a single 'diamond' named "Internally Induced Failure" and added to the newly developed FTs. Then the two FTs were combined for analyzing the simultaneous failures of the two systems.

The random failure rate of the components are also from the Browns Ferry PSA. The component capacities are those used in the LaSalle PSA (Ref. 4). The seismically induced failure probabilities were calculated for six levels of ground motions.

Figure 4 to 6 show the results for HPCI, RCIC and the high pressure injection function, respectively. In each figure, the broken line is under the assumption of

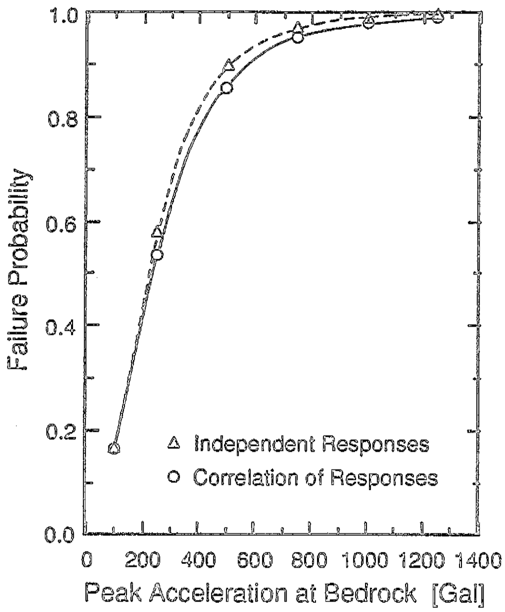


Figure 4 System Failure Probability of HPCI

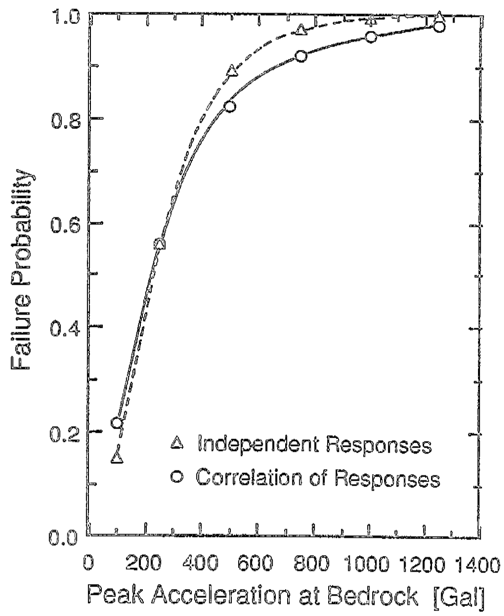


Figure 5 System Failure Probability of RCIC

independent responses (hereinafter referred to 'IR case') and the solid line is when correlation of responses is taken into account (hereinafter referred to 'CR case').

The important findings are as follows :

(1) There is no large difference between the TOP event probabilities calculated for the IR and CR cases.

(2) At lower levels of ground motions, the failure probability calculated for CR case tends to be similar to or larger than that calculated for IR case. After higher levels of ground motions, however, the former tends to be smaller than the latter.

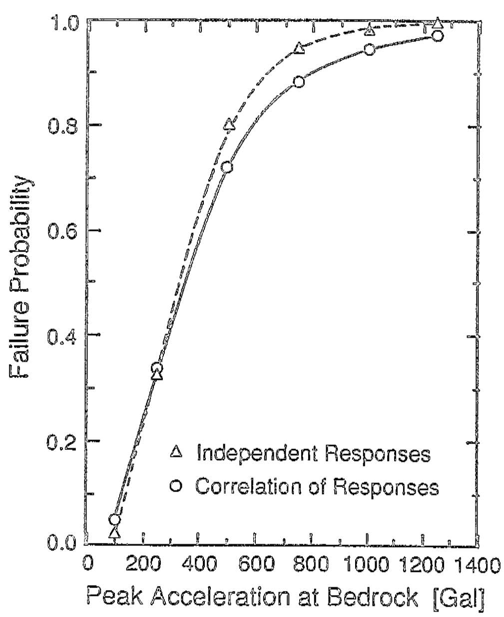


Figure 6 Simultaneous Failure Probability of HPCI and RCIC

The first finding implies that there may not be strong necessity to take account into correlation of responses in the seismic risk analysis, where the effect of another common cause (ground motion intensity) is significantly large. The second finding will be discussed in the next section.

## 4 DISCUSSION OF ANALYSIS RESULTS

Figures 7 and 8 show the probability calculated for each gate which appears in the RCIC FT at 100 Gal and 500 Gal of ground motion levels, respectively. The FT includes both AND gates and OR gates. As introduced in Section 1, consideration of correlation of responses increases the failure probability for AND gates but decreases the failure probability for OR gates.

In the calculation for 100 Gal (Figure 7), the largest difference between CR case and IR case appears at GATE3 and GATE4. Since these gates are AND gates, the failure probabilities of these gates are larger in CR case. Although the difference becomes smaller at the upper levels of gates (OR gates), the TOP event probability is still larger in the CR case.

In the calculation for 500 Gal (Figure 8), many gates have large failure probabilities. Although GATE3 and GATE4 have larger failure probabilities in the CR case, the tendency is opposite at the adjacent upper gate (GATE1) and the effect is larger at the TOP event. At this ground motion level, the effect of OR gates is stronger and the TOP event probability is smaller in the CR case.

The analysis results suggest that the effect of correlation of responses will be different if the structure of a fault tree and a level of ground motion are different. In this study, only a few systems were analyzed and hence the conclusions are not yet generic. Looking at the probabilities in the FTs, however, the authors believe that correlation of responses will not affect so much the results of seismic PSA's.

## 5 CONCLUSIONS

A new computer code was developed to quantify the system reliability taking into account the effect of correlation of responses based on Monte Carlo simulation technique. This code was applied to the reliability analysis for some safety systems of a BWR. The results implied that correlation of responses would have insignificant effect on the failure probabilities of systems or functions.

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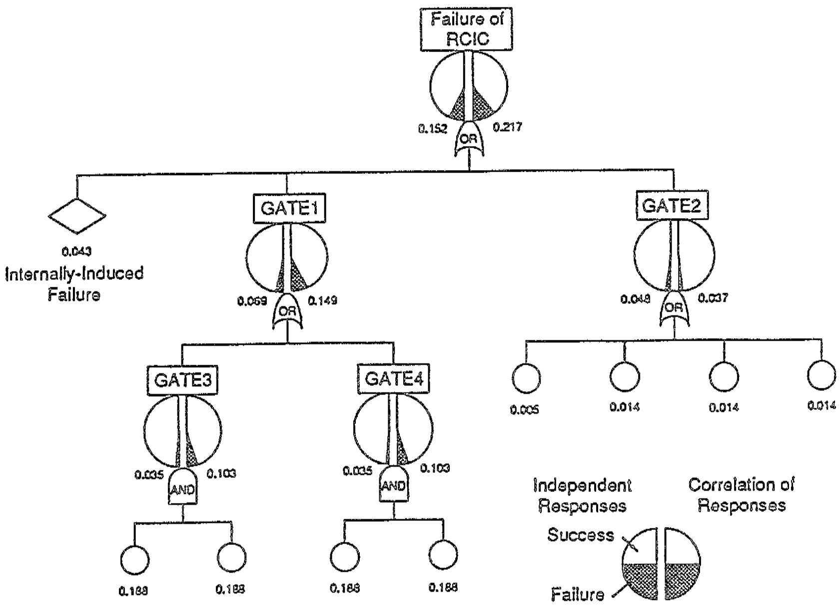


Figure 7 Failure Probabilities Caluculated for the Gates in the RCIC Fault Tree (at 100Gal)

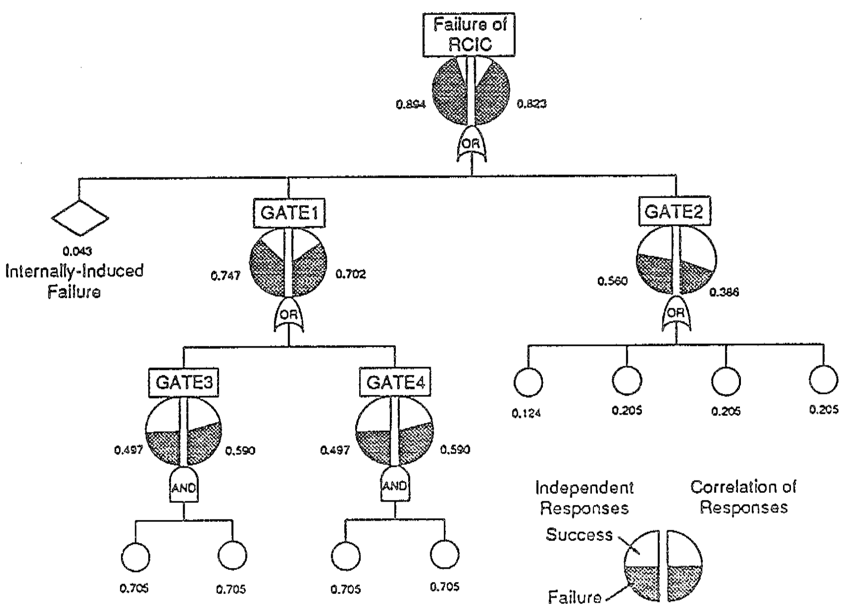


Figure 8 Failure Probabilities Caluculated for the Gates in the RCIC Fault Tree (at 500Gal)