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A Critical Review of the Current PWR Containment Response Analysis Methodologies for Postulated Severe Accident

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중대사고 분석에 적용하기 위한 가압경수로형 격납용기 반응분석의 최근방법론들의 연구

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Abstract

The EVNTREISS code, used as a basis of the present work, is highly complex and versatile in comparison with the previous CET used in the WASH-1400 study. Since the construction of the EVNTREISS code is very complex and has not gone through a thorough validation and review process by an independent referee it is not surprising to find a few areas of improvement and several inherent problems of the code. The present study is thus initiated to identify all the problems and areas of improvement for the EVNTREISS code and modify the code according to the insights gained from the experience of reproducing the Zion containment response analysis performed at the Brookhaven National Laboratory. As a result of this study, several areas of improvement for the EVNTREISS code have been identified and a few problems of the code have been resolved in addition to the reproduction of the Zion results. Finally, the modified code can now be run by a personal computer and can be used in the analysis of a Large Dry PWR containment response for severe accidents.

요 약

본 연구의 기초로 사용된 CET와 CET 정량화코드(EVNTREISS)는 WASH-1400 이후로 기존 발전소 안전성평가에 적용되어온 어떠한 CET 보다도 상세하며 다양성을 지니고 있다. EVNTREISS 코드의 구성이 대단히 복잡하고, 코드 Validation이 철저히 수행되지 않았으며 또한 독립적 검토가 이루어지지 않음으로 인하여 코드와 CET의 한계점과 개선할 몇가지 문제점이 충분히 내포될 수 있었다. 본 연구는 BNL에서 수행된 Zion 격납용기 사건수목을 재구성하는 과정에서, 상기된 문제점과 개선분야를 파악하고 이전에 수행된 여러 PRA에서 사용된 CET와의 비교를 통하여 EVNTREISS 코드를 개선시키고자 하였다. 결과로서, Zion에서 수행된 CET가 만족스럽게 재구성되었고, 코드에 대한 여러 개선분야가 파악되었으며 그중의 몇가지 문제점이 해결되었다. 이 개선된 코드는 PC에서 간단히 작업할 수 있으며 중대사고시 대형건식 가압경수로형 격납용기반응의 분석에 효과적으로 사용될 수 있다.

I. Introduction

The analysis of severe accident may be classified into deterministic and probabilistic approach. Since the deterministic approach offers less information the probabilistic approach[1,2] has been principally used in current studies.

More recently, the modified containment event trees constructed by the probabilistic approach in the form of a computer code (EVNTREISS) to quantify the release category from the containment event tree(CET) were developed at Sandia National Laboratory(SNL) as part of the Severe Accident Risk Reduction Program(SARRP).[3] Also, these have been used to analyze the containment response of a few nuclear power plants such as Surry and Zion for severe accidents.[3,4] However, the code has several problems that is difficult to treat the CET directly. The present study is centered around the containment event tree code(EVNTREISS) as well as the containment event tree itself.

The main objectives of this study are (1) to convert the original EVNTREISS code (a Vax version) into PC version to run on the PC, and to simplify the code, (2) to verify the Zion containment response analysis performed at the Brookhaven National Laboratory(BNL), and (3) to identify all the problem areas of the EVNTREISS code, and to improve them for application in the containment response analysis.

II. An Overview of the Current Methodologies of Containment Response Analysis

The major objective of the containment response analysis is to determine, given a core-melt accident, when and how the containment conditions could affect a release. Therefore, the containment response analyses for postulated severe accidents focus on identifying the various pathways that could lead to the release of fission products beyond the containment boundaries and on estimating their frequency of occurrence.

The containment response analysis for severe accidents deals with the events that occur after the initiating event and until the release of radioactive material from the containment. They cover the physical processes induced in the containment by each accident sequence as well as the transport and deposition of radionuclides released within the containment. The analysis examines the response of the containment to these processes, including possible failure modes, and evaluates the releases of radionuclides to the environment. The results of these risk assessments are analyzed and interpreted to identify the plant features that are the most significant contributors to risk.[5,6]

A. CET Quantification

Assessment of risk from operating nuclear power plant involves determination of the likelihood of various accident sequences and their potential offsite consequences. The risk from a nuclear power plant can be defined as follows :[3]

$$R_k = \sum_i f_i \sum_j C_{i,j}\, r_{j,k}(S_{i,j}) \qquad (1)$$

where

R_k = risk of consequence type k

f_i = frequency of plant damage state i

$C_{i,j}$ = conditional probability of containment release category j given PDS i

$S_{i,j}$ = fission product source term for containment release category j of PDS i

$r_{j,k}$ = consequence of type k, given fission product source term $S_{i,j}$, for j

There are five distinct but closely related phases in the risk analysis of nuclear power plant operation. The five phases are : (1) The 'systems analysis' that considers the accidents from the initiating events to the onset of core damage. Accident initiator frequency(a_l) and conditional probability of PDS i, given initiator 1 ($m_{i,l}$) are obtained in this phase. (2) The 'accident progression analysis' that treats the thermal and physical course of accidents from the onset of core damage to the release of radioactive fission products to the environment. The $C_{i,j}$ is obtained in this analysis. (3) The 'source term analysis' determines the behavior of the fission products from their release from the fuel to their release to the environment. The $S_{i,j}$ is obtained as a result of this analysis. (4) The 'consequence analysis' calculates the dispersal of the radionuclides in the environment and estimates their effect on the exposed population. The $r_{j,k}$ is obtained at this phase. (5) The result of the four constituent analyses are then combined to yield an overall integrated estimate of risk R_k and the uncertainty in risk. For containment analysis, plant damage states as initiating event, containment event tree to treat accident progression in containment, release category sets to analyze containment response and source term are needed.

The current method for quantification of a PWR containment matrix $C_{i,j}$ for postulated severe accidents include following steps ; [3,4]

1) Accident sequence evaluation and characterization of the plant damage states.

2) Identification of the containment release modes.

3) Construction of the plant-specific containment event tree.

4) Quantification of the containment event tree(CET) and CET matrix via code.

B. Plant Damage States

In a typical PRA, the number of system sequences that are identified is very large-much too large for the physical processes of each to be analyzed. One approach to resolve this problem is development of 'plant damage states(or bins)'[3,5]. The categories are identified by the characteristics of the system sequence that affect the release of radionuclides to the environment. All system sequences within a bin are assumed to have the same containment event tree, in that branching probabilities are the same, and the end points are assigned to the same radionuclide release categories.[6]

A plant damage state used in the Zion study[4] is labelled by up to four letters.

The first letter represents the initiating event :

A=large or medium LOCA, core damage at low pressure

S=small LOCA, core damage at high pressure,

T=transient initiator, RCS remains intact until core damage,

V=interfacing system LOCA.

The second letter represents the timing of core melt :

E=early core melt(ECC failure in the injection),

L=late core melt(ECC failure in the recirculation).

The third and fourth letters indicate the containment safeguard systems :

F=success of containment fan coolers,

C=success of containment spray system.

In order to provide a complete framework for containment response analysis, it is necessary to consider for each of the five accident sequence classes(ECC failure in recirculation and injection phases for LOCA, and T sequence), four combinations of fan cooler system and containment spray system operation (each success or failure). The 14 PDSs with high frequency of occurrence were used to calculate conditional probabilities for source term release categories.

C. Containment Event Tree

A modified Zion plant specific CET was developed by identifying the types of containment response, at a level of detail that could reasonably be supported by the information currently available. This lead to the construction of an event tree that is significantly expanded beyond those previously used in PRAs ; The structure of the Zion CET is based on 59 top events,[3] many of which have more than two branch points. These top event questions are posed in ways that require the answers to be expressed in terms of likelihoods.

On the other hand, because many portions of the analysis relies heavily on expert opinion and limited data from actual experience, it was judged that a direct statistical treatment[7,8] of all uncertainties was neither practical nor necessarily meaningful. For methodological consistency with the containment and source term analysis, a series of seven accident sequence issues that are most sensitive to accident results are selected. All issues except for containment capacity is considered as modelling uncertainty.

The Limited Latin Hypercube[9] uncertainty approach used in the Zion and Surry power plants relies on the selection of key uncertainty issues that can have a significant impact on the risk estimate. These phenomenological issues in nature were the best representation of the uncertainty selected by an expert review group.[3] The details of the evaluation of these issues and their significance in terms of risk can be found in Reference 1.

Treatment of these issues in the CET input data(LLHS) is made by considering levels for each issue and weighting factors for each level used as cumulative probability. Here, the 'level' means the possible all sequence model that each issue can have. And the 'weighting factor' means fraction of possibility of any one level of all level in one issue. In general, these issues should be sampled through the LLH technique by considering correlation between issues.

The current CET shows that even though in some cases the issues are not independent, the relations between most issues become independent. That is, the LLHS among most issues was produced randomly, rather than represented through correlations imposed upon the weighting factors applied to the relevant issue levels. In fact, significant complication can be introduced when the correlations between the various issues are specified.

D. Containment Release Categories

The release categories were defined for the various combinations of plant damage bins and CET sequences by correlating the combinations according to their effect on the release characteristics that most affect the offsite consequences.[5,6] These characteristics(i.e., release time, warning time, energy duration, and radionuclide inventory) are consistent with those that were used in choosing CET top events. For convenience, the release categories can be divided into two subcategories : that is, 'source term bin' and 'containment bin'. The containment bin is considered as the subset of source term bin.

The radioactive inventory passing through outer boundary of the containment is conventionally known as the 'source term'. The outcomes of the containment event tree consist of very large number of scenarios. Therefore, to analyze these outcomes, it is necessary to combine the scenarios into a smaller set of groups, called source term bins, which are judged to be similar in terms of parameters considered to be important to the source terms. Here, scenario defined by the combination of a given accident sequence and a given path through the containment event tree provides a description of the initial and boundary conditions required to assess the resulting source term. Six source term bins were used in the Zion study.[4]

Containment bins represented different combinations of core, cavity, and containment states. For Zion study, the containment bins are classified into 19 groups. Bins 1–4 and 16–19, respectively, are equivalent except that bins 16–19 do include effects due to direct heating, and bins 1–4 do not. For point-estimate containment response analysis, the likelihood of the 15 containment bins was calculated for each of the 8 PDSs. For statistical LLH containment analysis, on the other hand, the likelihood of the 19 containment bins was calculated for each of the 14 PDSs. That is, SEFC, AEFC, TEFC, SEC, SE, AEC, AL, TEC, SLFC, ALFC, SLC, SL, ALC, and V.

E. CET Code

The EVNTREISS code[10] provides the necessary framework for quantification of the likelihood of various containment failure modes. The major features of this code are as follows:

1) Flexible manipulation of top events and branching points and treatment of dependency are possible.

2) Any combination of dependencies on prior questions is possible.

3) Information can be fed to the program in the form of 'parameter'(pressure increase) which the program can manipulate at a later node to internally calculate a branch point probability based on user input criterion.

4) The outcomes of the event tree are binned by input specified by the user.

For actual deterministic or statistical (with some input from LLHS) quantification of the containment matrix, this code requires three or four different types of input data : [4]

1) Binning data
2) Branch point probability data
3) Dependency data
4) Uncertainty Issue data

F. Release Category Frequencies

The frequencies of the release categories are calculated by combining the frequencies of the plant damage bins with frequencies estimated for the containment event tree. The first step is the construction and execution of a model that assigns each combination of CET sequences and PDS to a release category. The model reflects the dependency of the CET top events on each PDS. The conditional probatility of the release category for each PDS is found and combined with the PDS probabilities to determine the release category frequencies as follows:[3,6]

$$P_{1,EF}=\frac{\sum_{j}^{EF}\sum_{i}^{PDS}F_{1,i}\,C_{1,i,j}}{\sum_{i}^{N}F_{1,i}} \qquad (2)$$

where,

$P_{1,EF}$=conditional probability of any early containment failure for issue sample 1

$F_{1,i}$=plant damage bin frequencies

$C_{1,i,j}$=containment matrix

1=LLH sample index, 1=1,...,100

N=total number of LLH sample, 100

i=PDS index

j=containment bin index, j=1,...,19

III. Verification of the Previous Results for Zion and Improvements Made

A. CET Construction

(1) Point Estimate

The point estimate calculates probability of CET sequences when the issues are not considered and the branch point probability of direct containment heating event is assumed to be zero (that is, Bin 16–19 are not considered) for Zion power plant.

Tables 1 and 2 show the containment matrix and source term category for the point estimate calculations obtained to verify the previous result for Zion.[4] This containment matrix indicates that the results are exactly the same as the previous results obtained for Zion. This verifies that the previous work is reproducible and the numerical values are dependable. At the same time, the result shows that for most accident sequences except the plant damage state 'SE', there is a high likelihood that containment integrity will be maintained.

(2)LLH Estimate

The statistical analysis was implemented through the 100 LLH samples. They do contain more informations than does a single point. This approach results in a more realistic estimate to risk. A valuable insights concerning the LLH calculations can be gained by simply comparing the LLH results with that of the point estimate.

The quantities of 100 LLH outcomes were sorted into five percentile quantities and one average value for each bin. These bounds were subjectively based on the available specific information and the general uncertainty in the data and modelling. For the purpose of comparisons with the results for Zion plant, the probabilities of 19 containment bins calculated from the modified EVNTREISS code, given all 14 PDS used for the LLH estimate are presented in Tables 3 and 4, respectively. Because late ECC failure nearly does not influence the probability of all the containment bins, some PDSs are not presented in these tables. That is, SEFC=SLFC, SEC=SLC, AEFC=ALFC, and SE=SL. These results are due to insufficient dynamics of the ESFs. The conditional frequencies of release categories, given all core damage states, when each frequency of PDS sequences is treated as weighting factor for overall frequency, are shown in Tables 5 and 6: Table 5 is the previous result for Zion, whereas Table 6 is the present result obtained. The main reason for the difference between the two is due to the slightly different dependency with those of the Zion. However, this result does not induce a critical problem because of the essential similarity with the CETs of Zion.

B. Improvement of the EVNTREISS Code

Several problems and areas for improvement of the EVNTREISS code were identified during the process of verification of the previous Zion work as well as the construction of the containment event tree for all possible plant damage states and the conversion of the code from Vax to PC version. The major problems identified and improvements made are summarized here :

(1) Preparation and checking of input data for the code is too time-consuming and difficult:

The containment event tree has 59 top events; in many cases, the top event is dependent on the previous events. Furthermore, the event tree was made as non-visual logics. Therefore, visualization of the event tree is not possible. Even if the event tree were constructed, identifying inappropriate dependent input values is also difficult to the same degree of constructing the event tree.

Improvement:

As an approach to resolve this problem, the containment event tree was simplified from the original 59 top events to the 48 top events. This simplification has been made by eliminating those top events that are independent on the accident progression. The compact CET makes it more convenient to prepare and check the input data, while the original results remain unchanged. However, a substantial simplification is needed from the detailed analysis of various accident mechanisms.

(2) A mechanism or a procedure to identify dominant accident pathways is not available in the original code:

Improvement:

For identification of pathways of the output bin, a simple program has been developed to show the numbers of the top events and levels of dependent cases involved. This program transforms the complex event tree into a simpler form that is comprised of only dependent pathways. Identification of pathways becomes possible by reconstructing a simpler event tree. But the larger the number of top events, the more difficult is the identification of the exact pathway because of a large number of accident sequences assigned to the given bin.

(3) Treatment of the issues is too complex:

Proposal:

The issues consist of models and parameters having many discrete levels. The discrete parameters could be treated in less complex form by using the distributions and multipliers displaying the degree of possibility relative to the base case. But the discrete models are difficult to be treated by this method. Any correction factor and correlation coefficients can be used to resolve this problem for these models.

(4) A procedure to idei tify sequence independency of LLH issues is not available:

Proposal:

When the input data of the code is being prepared, the inappropriate dependency among the top events could easily be overlooked. That is, any pathway of the input data might be cut during accident propagation because of deficiency of the appropriate dependency. In this case, the current EVNTREISS code has only a mechanism to stop to run the code. However, the identification of the inappropriate dependency of the top event and corresponding sample index(i.e., run number of the LLH issue samples) by the existing mechanism of the code is very time-consuming and difficult. Therefore, when an inappropriate dependency among any top events is present, a procedure to identify the top event, their dependency case and corresponding sample index that result in cutting the accident pathway is needed. This procedure in the form of a sub-program must be added to the current EVNTREISS code.

(5) Questions of whether to treat the state of the containment safety systems(i.e., Spray and Fan Coolers) to be dependent on the CET or simply follow the definition of each PDSs which specifically includes the state of the containment safety systems:

Proposal:

For the more realistic approach to the containment response analysis, the state of the containment safety systems in the EVNTREISS code should be made to depend on the accident progression, because the state of the containment safety systems greatly influence the final results of the accident. This approach, however, may cause some inconsistency between the final outcome and the definition of the PDSs.

IV. Conclusion and Recommendations

One of the major objectives of this work, that is, the original conversion of the CET code was completed. Based on this converted code, a few subprograms were added to the modified CET code to sort the outcomes and identify the dominant accident pathways. Also, simplification of the CET code and CET itself has been made as a result of this work. In addition, all the containment event trees for given dominant plant damage states were constructed from the Zion sample event tree(S_3D), and these results were compared with the original result of the Zion CETs. All sequences, except the two PDSs of TEFC and TEC, agree well with the original Zion results for statistical estimates. The minor difference between the present work and the previous Zion work for the above PDSs might be due to the different dependency of any level of LLH samples in the containment event tree.

Finally, several areas of improvement for the code have been identified through the present study of the EVNTREISS code and containment event trees, and major problems have been resolved. By further improvements, the modified EVNTREISS code and containment event trees can be used as an important tool in the plant specific risk assessments.

Following recommendations are made for further study:

1) Development of more detailed subprograms to completely trace the output bins and to identify user-specified accident pathways.

2) Further simplification of the containment event trees.

3) Identification of the sequence dependency of LLH issue samples.

4) More detailed analysis of model uncertainty and sensitivity.

The complete program should have the capability to unravel the dominant pathway contributions to each containment failure bin.

List of Abbreviations Used

AFWS =Auxiliary feed water system

BMT =Basemat melt-through
CCW =Component cooling water
CET =Containment event tree
ECC =Emergency core cooling
ECOPF =Early containment overpressure failure
ISF =Isolation failure
LCOPF =Late containment overpressure failure
LLH =Limited latin hypercube
LOCA =Loss of coolant accident
LOP =Loss of offsite power
NoF =Containment no-failure
PDS =Plant damage state
PRA =Probabilistic risk assessment
PWR =Pressurized water reactor
RCS =Reactor coolant system
SARRP =Severe accident risk reduction program
SI =Safety injection
SWS =Service water system
V =V sequence

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Table 1. Containment Matrix(Point Estimate)

PDS	SEFC	SLFC	TEFC	AEFC	ALFC	SEC	SE	V
BIN1							1.8-4	
BIN2			1.0-4					
BIN3								
BIN4	1.0-4	1.0-4		1.0-4	1.0-4	1.0-4		
BIN5								
BIN6							2.5-3	
BIN7	2.5-3	2.5-3	2.5-3	2.5-3	2.5-3	2.5-3		
BIN8	3.3-3	3.3-3	3.3-3	3.3-3	3.3-3	3.3-3		
BIN9							4.54-1	
BIN10							3.08-1	
BIN11								
BIN12								1.0
BIN13							2.35-1	
BIN14								
BIN15	9.94-1	9.94-1	9.94-1	9.94-1	9.94-1	9.94-1		

Table 2. Probability of Release Category for Point Estimate

PDS	SEFC	TEFC	AEFC	SEC	SE
Early Failure(ECOPF)	1.0E-4	1.0E-4	1.0E-4	1.0E-4	1.8E-4
Late Failure(LCOPF)	3.3E-3	3.3E-3	3.3E-3	3.3E-3	7.62E-1
Isolation Failure(CIF)	2.5E-3	2.5E-3	2.5E-3	2.5E-3	2.5E-3
Melt Through(BMT)	0.0	0.0	0.0	0.0	2.35E-1
Containment Bypass(V)	0.0	0.0	0.0	0.0	0.0
No Failure(NoF)	0.994	0.994	0.994	0.994	0.0

Table 3. Containment Matrix(Mean Conditional Probability) : This Study

PDS	SEFC	SEC	SLF	SE	AEFC	AEC	ALF	AL	TEFC	TEC
BIN1	0.000	0.000	3.9–3	3.0–2	0.000	0.000	1.7–2	4.9–2	4.6–3	4.6–3
BIN2	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	2.2–3	2.2–3
BIN3	3.9–3	3.9–3	0.000	0.000	1.7–2	1.4–2	0.000	0.000	0.000	0.000
BIN4	1.2–4	1.2–4	0.000	0.000	4.2–3	4.2–3	0.000	0.000	0.000	0.000
BIN5	0.000	0.000	0.000	0.000	2.0–6	2.0–6	2.0–6	0.000	0.000	0.000
BIN6	0.000	0.000	2.1–3	2.1–3	0.000	0.000	2.5–3	2.4–3	0.000	0.000
BIN7	2.3–3	2.3–3	0.000	0.000	2.4–3	2.4–3	0.000	0.000	1.9–3	1.9–3
BIN8	1.5–2	6.9–2	0.000	0.000	1.4–2	1.4–2	0.000	0.000	9.9–3	9.9–3
BIN9	5.1–3	3.2–2	1.7–2	3.0–1	4.7–3	1.4–2	1.9–2	3.8–1	3.3–3	1.1–2
BIN10	0.00	8.5–3	0.000	2.5–1	0.000	9.6–3	0.000	3.6–1	0.000	6.7–3
BIN11	0.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
BIN12	0.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	7.0–2	7.0–2
BIN13	0.00	0.000	0.000	1.6–1	0.000	0.000	0.000	2.2–1	0.000	0.000
BIN14	0.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
BIN15	9.6–1	8.7–1	9.0–1	0.000	9.6–1	9.4–1	9.6–1	0.000	8.0–1	7.9–1
BIN16	0.000	0.000	7.4–2	2.7–1	0.000	0.000	0.000	0.000	2.7–2	2.7–2
BIN17	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	8.1–2	8.1–2
BIN18	4.5–3	4.5–3	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
BIN19	1.4–2	1.4–2	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

Table 4. Containment Matrix(Mean Conditional Probability) : Zion

PDS	SEFC	SEC	SLF	SE	AEFC	AEC	ALF	AL	TEFC	TEC
BIN1	0.000	0.000	3.9–3	3.0–2	0.000	0.000	1.7–2	4.9–2	8.1–3	5.7–2
BIN2	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
BIN3	3.9–3	3.9–3	0.000	0.000	1.7–2	1.7–2	0.000	0.000	0.000	0.000
BIN4	1.2–4	1.2–4	0.000	0.000	4.2–3	4.2–3	0.000	0.000	0.000	0.000
BIN5	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
BIN6	0.000	0.000	2.1–3	2.1–3	0.000	0.000	2.5–3	2.4–3	0.000	0.000
BIN7	2.3–3	2.3–3	0.000	0.000	2.4–3	2.4–3	0.000	0.000	2.0–3	2.0–3
BIN8	1.5–2	6.9–2	0.000	0.000	1.4–2	1.4–2	0.000	0.000	1.0–2	7.1–3
BIN9	5.1–3	3.2–2	1.7–2	3.0–1	4.7–3	1.4–2	1.9–2	3.8–1	3.5–3	2.4–2
BIN10	0.00	8.6–3	0.000	2.4–1	0.000	9.8–3	0.000	3.6–1	0.000	0.000
BIN11	0.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	7.0–2	7.0–2
BIN12	0.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
BIN13	0.00	0.000	0.000	1.6–1	0.000	0.000	0.000	2.2–1	0.000	0.000
BIN14	0.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
BIN15	9.6–1	8.7–1	9.0–1	0.000	9.6–1	9.4–1	9.6–1	0.000	8.2–1	6.8–1
BIN16	0.000	0.000	7.4–2	2.7–1	0.000	0.000	0.000	0.000	9.0–2	1.9–1
BIN17	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
BIN18	4.5–3	4.5–3	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
BIN19	1.4–2	1.4–2	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

Table 5. Conditional Probability of Containment Failure Modes(All Sequences Included) : Zion Original Result

Failure	min	5–th	median	95–th	max	mean
ECOPF	3.4E–4	1.0E–3	1.1E–2	1.7E–1	6.6E–1	4.0E–2
LCOPF	3.5E–5	3.5E–3	1.9E–2	1.6E–1	5.4E–1	5.9E–2
ISF	2.0E–4	1.1E–3	2.5E–3	2.5E–3	2.5E–3	2.3E–3
BMT	0.0E–0	4.3E–5	1.9E–3	8.1E–3	4.4E–2	3.0E–3
V	5.3E–4	6.6E–4	2.7E–3	1.8E–2	1.4E–1	6.8E–3
NoF	3.0E–1	5.2E–1	9.4E–1	9.8E–1	9.9E–1	8.9E–1

Table 6. Conditional Probability of Containment Failure Modes(All Sequences Included) : Present Result

Failure	min	5–th	median	95–th	max	mean
ECOPF	3.61E–4	9.98E–4	9.99E–3	1.19E–1	5.64E–1	3.08E–2
LCOPF	3.68E–3	1.54E–2	3.92E–2	2.77E–1	3.17E–1	6.18E–2
ISF	2.14E–4	1.41E–3	2.45E–3	2.49E–3	2.49E–3	2.31E–3
BMT	1.02E–4	1.05E–3	4.50E–3	5.36E–3	5.40E–3	3.84E–3
V	1.82E–3	1.82E–3	1.82E–3	4.92E–2	4.92E–2	5.14E–3
NoF	4.22E–1	5.89E–1	9.54E–1	9.70E–1	9.73E–1	8.96E–1