# RESPONSE TO AUDIT ISSUES

**APR1400 Topical Reports**

**Korea Electric Power Corporation / Korea Hydro & Nuclear Power Co., LTD**

**Docket No. PROJ0782**

| | |
|---|---|
| **Review Section** | **TR Realistic Evaluation Methodology for LBLOCA of the APR1400** |
| **Application Section** | **Topical Report: APR1400-F-A-TR-12004 Realistic Evaluation Methodology for Large-Break LOCA of the APR1400** |
| **Issue Date** | **08/13/2015** |

---

## Audit Issues No. 51

The guidance in RG 1.157, Section 4 establishes acceptable controls for the estimation of uncertainties. The following issues are related to the distribution-free statistics method described in Section 4.3.2 of the topical report:

a. It appears that the method described in Section 4.3.2 is similar to the formulation of Guba, Makai and Pál based on order statistics (Reliability Engineering and System Safety, Vol. 80, Issue 3, pp.217-232, June 2003). Confirm or provide a reference for the method used in the topical report.

b. Section 4.3.2 states that the third highest result of 124 random calculations provides the 95/95 limit. In case the method in the topical report uses order statistics (see part (a) of this issue), it is unclear whether the approach employed in the topical report is the single parameter uncertainty evaluation with the third estimator grade or the multiple parameter uncertainty evaluation with three parameters. Both approaches require 124 random calculations. Clarify the method used in CAREM.

c. In case the distribution-free statistics method is based on the single parameter uncertainty evaluation for the PCT, the approach used to determine the limiting values of local cladding oxidation and hydrogen generation is not clear. It is not possible to determine whether the limiting values of local cladding oxidation and hydrogen generation are those that correspond to the calculations resulting in the limiting PCT or are derived from separate 124 random calculations for each of those two parameters. Explain and justify the approach used.

d. In case the distribution-free statistics method is based on the multiple parameter uncertainty evaluation with three parameters, such a method assumes that the parameters are continuous and independent. During LBLOCA calculations bursting of cladding may be predicted to occur resulting in a discontinuous increase in the cladding temperature. In addition, the local and the core-wide cladding oxidation and hydrogen generation values are dependent on the corresponding cladding temperature. Clarify whether the methodology described in the topical report is limited to pre-burst conditions or justify the applicability of the assumption of the continuity of the parameters in the event of cladding burst. Further, justify the assumption of the independence of the three parameters (e.g., PCT, cladding oxidation and hydrogen generation).

## Response

(a) ~ (d)

[

]TS

- From reference [1];

Let us choose the first row of the sample matrix, and arrange its elements in order of increasing magnitude, $y_1(1), y_1(2), \dots\ y_1(N)$. Select from these $y_1(r_1)$ as $L_1$ and $y_1(s_1) > y_1(r_1)$ as $U_1$: Let $i_1, i_2, \dots, i_{s_1-r_1-1}$ stand for the original column indices of elements $y_1(r_1+1), y_1(r_1+2), \dots\ y_1(s_1-1)$: In the next step, choose the second row, the N observed values of the output variable $y_2$ and arrange the part $y_{2i_1}, y_{2i_2}, \dots\ y_{2_{s_1-r_1-1}}$ of its elements in increasing order to obtain $y_2(1) < y_2(2) < \cdots < y_2(s_1-r_1-1)$. From among these, $y_2(r_2)$ and $y_2(s_2)$ are selected for $L_2$ and $U_2$ and evidently $r_2 \geq r_1, s_2 \leq s_1 - r_1 - 1$: We continue this imbedding procedure to the last row of the sample matrix and define a p-dimensional volume $V_p = \{|L_1, U_1,| \times |L_2, U_2| \times \dots \times |L_p, U_p|\}$, where $L_j = y_j(r_j), U_j = y_j(s_j)$, and $r_j \geq r_{j-1} \geq \cdots \geq r_1$, while $r_j < s_j \leq s_{j-1} - r_{j-1} - 1,\ \forall j = 2 \dots p$.

….

Theorem 4. In the case of $p$ independent output variables with continuous joint density function $g(y_1, \dots y_p)$, it is possible to construct $p$-pairs of random intervals $[L_j, U_j]_{j=1\dots p}$ such that the probability of the inequality

$$\int_{L_1}^{U_1} \dots \int_{L_p}^{U_p} g(y_1, \dots y_p)dy_1 \dots dy_p > \gamma$$

is free of g and is given by

$$Prob\left\{\int_{L_1}^{U_1} \dots \int_{L_p}^{U_p} g(y_1, \dots y_p)dy_1 \dots dy_p > \gamma\right\} =$$

$$\beta = 1 - I(\gamma, s_p - r_p, N - s_p + r_p + 1) \qquad (1)$$

Here,

$$s_p \leq s_{p-1} - r_{p-1} - 1 \leq s_1 - \sum_{j=1}^{p-1}(r_j + 1) \qquad (2)$$

$$r_p \geq r_{p-1} \dots \geq r_1 \qquad (3)$$

Proof of Theorem 4 is given in Appendix D….

Furthermore, if $r_1 = r_2 = \cdots = r_p = 0$ and $s_p = N - p + 1$, then one obtains the following one-sided confidence level.

$$\beta = 1 - I_\gamma(N - p + 1, p) = I_{1-\gamma}(p, N - p + 1) = \sum_{j=p}^{N} \binom{N}{j} (1-\gamma)^j \gamma^{N-j}$$

$$= 1 - \sum_{j=0}^{p-1} \binom{N}{j} (1-\gamma)^j \gamma^{N-j} \quad (4)$$

- [ ]TS

[

]TS

- It is strongly recommended [2] that the estimation of the upper limits should be higher than the first order with the following arguments.

When the upper tolerance limit approaches regulatory acceptance criteria, e.g. 1200°C PCT, the number of code runs may be increased to 150 or 200 calculations instead of the 59 code runs needed, using Wilks' formula at the first order for the estimation of a $\alpha$ = 95% one-sided tolerance limit with a confidence level $\beta$ of 95%. This would be advisable for two reasons:

1) With increasing sample size the uncertainty results will be less dispersed, and consequently more converged (less conservative), and

2) The sensitivity results will be more reliable.

[

]TS

Table 1. Ordering of parameters during estimating confidence level

TS

Reference

[1] Reliability Engineering and System Safety, Vol. 80, Issue 3, pp.217-232, June 2003

[2] H. Glaser, “BEMUSE Phase VI Report, Status report on the area, classification of the methods, conclusions and recommendations”, NEA/CSNI/R(2011)4, 28-Mar-2011; (https://www.oecd-nea.org/nsd/docs/2011/csni-r2011-4.pdf).

## Impact on DCD

There is no impact on the DCD.

## Impact on PRA

There is no impact on the PRA.

## Impact on Technical Specifications

There is no impact on the Technical Specifications.

## Impact on Technical/Topical/Environmental Report

Topical report will be changed based on this response.

There is no impact on Technical or Environmental Report.

data by [ ]TS. The one-sided 95 % limit of blowdown PCT is [ ]TS.

#### 4.3.1.2 Reflood Code Accuracy

In the evaluation of the reflood code accuracy, 27 separate effect tests (i.e., 17 FLECHT-SEASET tests, 7 NEPTUN tests, and 3 ATLAS tests) and 7 integral effect tests (i.e., LOFT L2-2, L2-3, L2-5, LP-02-6, CCTF C2-4, PKL-IIb5, and Semiscale S-06-3) are considered.

The maximum clad temperatures of NEPTUN were measured at various locations of No. 3, 4, and 5 in general depending on experimental conditions. These locations correspond to 0.512 m, 0.744 m, and 0.976 m elevations from the bottom of the 1.68 m effective length. The two highest measurements from each NEPTUN test and their calculational correspondents are considered in this evaluation. Code assessment calculation against NEPTUN is described in Appendix C. In the case of FLECHT-SEASET, three data sets, one at a PCT location and two at neighboring measurement locations, are considered. Calculated temperatures are taken from the results given in Appendix C. Measurements of the FLECHT-SEASET experiments are concentrated at the central part of the core. Three elevations correspond to one or two nodes in the calculation.

In the case of ATLAS, the three highest measurements from each test and their correspondents are considered. ATLAS Tests 9 and 15 showed the three highest temperatures at 1.066 m, 1.271 m, and 1.329 m elevations from the bottom of the 1.905 m active core, while they were measured at 0.953 m, 1.066 m, and 1.329 m elevations in Test 11. Corresponding node numbers are 12, 14, and 15 for test 9 and 15, and 11, 12, and 15 for Test 11. Calculated values are taken from calculations in Appendix E. In the case of CCTF C2-4, the measured peak value at 2.44 m (96 in.) and its correspondent are considered. In the case of PKL-IIb5, the measured peak value at 2.5 m (98 in.) elevation and a comparable peak value at 1.95 m (77 in.), and their correspondents, are considered. In the case of Semiscale S-06-3, the measured peak value at 0.74 m (29 in.) and the neighboring measurement at 0.71 m (28 in.) are selected and compared with their calculational correspondents.

Figure 4-8 shows the reflood code accuracy evaluated using [ ]TS data sets. The code over-predicts the clad temperatures by [ ]TS.

### 4.3.2 Check Data Covering (Step 9.2)

Data covering is checked to confirm the variety, number, and ranges of code uncertainty parameters. If the code uncertainty is quantified using all the code uncertainty parameters in accordance with the bottom-up approach of NUREG-1230 [19], this checking process may not be necessary. In the top-down approach, however, it is necessary to confirm the number of uncertainty parameters with respect to the practicality of the method. Identification and ranking of the phenomena and subsequent selection of uncertainty parameters are dependent on the subjective decision of experts in the field. Accordingly, the objective basis of the determination of the number and the ranges of the parameters needs to be provided.

In principle, this covering check is performed for all the experiments considered in the code accuracy evaluation, especially for the cases where code predictions are lower than the measured peak values. A set of uncertainty parameters confirmed by this covering check can produce the uncertainty encompassing code accuracy.

Distribution-free statistics is utilized in this checking. The probability that $N$ random samples are all within a certain percentile $p$ is $p^N$. The probability that one of $N$ samples exceeds $p$ percentile and the others fall within $p$ percentile is

[ ]TS

The probability that two of them $N$ samples exceeds $p$ percentile is

[ ]TS

Hence the probability that at most two of $N$ samples exceeds $p$ percentile is

[ ]TS

The complement of the above probability,

[ ]TS

means the probability that at least three of $N$ samples exceed $p$ percentile.

The confidence level $q$ is calculated by

[ ]TS

If $p = q = 0.95$, the minimum number of samples ($N$) is calculated as 124 in order to obtain at least three samples exceeding 95 percentile at 95% confidence level. This means that three results (i.e., the highest, the second highest, and the third highest results) drawn from the domain of 124 LBLOCA calculations exceed 95 percentile tolerance limit at 95 % confidence level. Therefore, the third highest result of 124 random calculations is an estimate of the 95 percentile tolerance limit at 95 % confidence level. [ ]TS

4.3.2.1 Check Blowdown Covering

Simple-random sampling (SRS) calculations were performed against the test data obtained from THTF, LOFT, and LOBI in order to check whether the calculations can cover the measured blowdown PCTs.

The eight code uncertainty parameters used for checking the blowdown covering against the THTF tests are: [ ]TS. Because the LOFT and LOBI tests were integral effect tests performed for whole transients of the LBLOCA, other code parameters, which are used during the reflood period, and some system parameters are additionally considered for these tests. The effects of additional code parameters on the blowdown calculation are minimal. Uncertainty parameters used for checking the covering against each test are listed in Appendices C and D for the THTF, and LOBI and LOFT, respectively.

A set of uncertainty parameters is randomly sampled 124 times along their probability distribution functions, and the same numbers of calculations are performed. SRS calculations and measured data from the THTF Test 105 and Test 160 are compared in Figure 4-9 and Figure 4-10, respectively. Out of four sets of THTF SRS calculations in Appendix C, the above two are excerpted for examples, as they have the highest and the lowest rod power. Squared markings represent the upper-bound of the measurement. It is confirmed that the [ ]TS data by [ ]TS. The one-sided 95 % limit of blowdown PCT is [ ]TS.

#### 4.3.1.2 Reflood Code Accuracy

In the evaluation of the reflood code accuracy, 27 separate effect tests (i.e., 17 FLECHT-SEASET tests, 7 NEPTUN tests, and 3 ATLAS tests) and 7 integral effect tests (i.e., LOFT L2-2, L2-3, L2-5, LP-02-6, CCTF C2-4, PKL-IIb5, and Semiscale S-06-3) are considered.

The maximum clad temperatures of NEPTUN were measured at various locations of No. 3, 4, and 5 in general depending on experimental conditions. These locations correspond to 0.512 m, 0.744 m, and 0.976 m elevations from the bottom of the 1.68 m effective length. The two highest measurements from each NEPTUN test and their calculational correspondents are considered in this evaluation. Code assessment calculation against NEPTUN is described in Appendix C. In the case of FLECHT-SEASET, three data sets, one at a PCT location and two at neighboring measurement locations, are considered. Calculated temperatures are taken from the results given in Appendix C. Measurements of the FLECHT-SEASET experiments are concentrated at the central part of the core. Three elevations correspond to one or two nodes in the calculation.

In the case of ATLAS, the three highest measurements from each test and their correspondents are considered. ATLAS Tests 9 and 15 showed the three highest temperatures at 1.066 m, 1.271 m, and 1.329 m elevations from the bottom of the 1.905 m active core, while they were measured at 0.953 m, 1.066 m, and 1.329 m elevations in Test 11. Corresponding node numbers are 12, 14, and 15 for test 9 and 15, and 11, 12, and 15 for Test 11. Calculated values are taken from calculations in Appendix E. In the case of CCTF C2-4, the measured peak value at 2.44 m (96 in.) and its correspondent are considered. In the case of PKL-IIb5, the measured peak value at 2.5 m (98 in.) elevation and a comparable peak value at 1.95 m (77 in.), and their correspondents, are considered. In the case of Semiscale S-06-3, the measured peak value at 0.74 m (29 in.) and the neighboring measurement at 0.71 m (28 in.) are selected and compared with their calculational correspondents.

Figure 4-8 shows the reflood code accuracy evaluated using [ ]TS data sets. The code over-predicts the clad temperatures by [ ]TS.

### 4.3.2 Check Data Covering (Step 9.2)

Data covering is checked to confirm the variety, number, and ranges of code uncertainty parameters. If the code uncertainty is quantified using all the code uncertainty parameters in accordance with the bottom-up approach of NUREG-1230 [19], this checking process may not be necessary. In the top-down approach, however, it is necessary to confirm the number of uncertainty parameters with respect to the practicality of the method. Identification and ranking of the phenomena and subsequent selection of uncertainty parameters are dependent on the subjective decision of experts in the field. Accordingly, the objective basis of the determination of the number and the ranges of the parameters needs to be provided.

In principle, this covering check is performed for all the experiments considered in the code accuracy evaluation, especially for the cases where code predictions are lower than the measured peak values. A set of uncertainty parameters confirmed by this covering check can produce the uncertainty encompassing code accuracy.

Distribution-free statistics is utilized in this checking [23]. Let us choose the first row of the sample matrix, and arrange its elements in order of increasing magnitude, $y_1(1), y_1(2), \dots\ y_1(N)$. Select from these $y_1(r_1)$ as $L_1$ and $y_1(s_1) > y_1(r_1)$ as $U_1$: Let $i_1, i_2, \dots, i_{s_1-r_1-1}$ stand for the original column indices of elements $y_1(r_1+1), y_1(r_1+2), \dots\ y_1(s_1-1)$: In the next step, choose the second row, the

N observed values of the output variable $y_2$ and arrange the part $y_{2i_1}, y_{2i_2}, \dots y_{2_{s_1-r_1-1}}$ of its elements in increasing order to obtain $y_2(1) < y_2(2) < \cdots < y_2(s_1 - r_1 - 1)$. From among these, $y_2(r_2)$ and $y_2(s_2)$ are selected for $L_2$ and $U_2$ and evidently $r_2 \geq r_1, s_2 \leq s_1 - r_1 - 1$: We continue this imbedding procedure to the last row of the sample matrix and define a p-dimensional volume $V_p = \{|L_1, U_1,| \times |L_2, U_2| \times \dots \times |L_p, U_p|\}$, where $L_j = y_j(r_j), U_j = y_j(s_j)$, and $r_j \geq r_{j-1} \geq \cdots \geq r_1$, while $r_j < s_j \leq s_{j-1} - r_{j-1} - 1,\ \forall j = 2 \dots p$.

Theorem.

In the case of $p$ independent output variables with continuous joint density function $g(y_1, \dots y_p)$, it is possible to construct $p$-pairs of random intervals $[L_j, U_j]_{j=1\dots p}$ such that the probability of the inequality

$$\int_{L_1}^{U_1} \dots \int_{L_p}^{U_p} g(y_1, \dots y_p) dy_1 \dots dy_p > \gamma$$

is free of g and is given by

$$Prob\left\{\int_{L_1}^{U_1} \dots \int_{L_p}^{U_p} g(y_1, \dots y_p) dy_1 \dots dy_p > \gamma\right\} =$$

$$\beta = 1 - I(\gamma, s_p - r_p, N - s_p + r_p + 1) \quad (4\text{-}1)$$

Here,

$$s_p \leq s_{p-1} - r_{p-1} - 1 \leq s_1 - \sum_{j=1}^{p-1}(r_j + 1) \quad (4\text{-}2)$$

$$r_p \geq r_{p-1} \dots \geq r_1 \quad (4\text{-}4)$$

Furthermore, if $r_1 = r_2 = \cdots = r_p = 0$ and $s_p = N - p + 1$, then one obtains the following one-sided confidence level.

$$\beta = 1 - I_\gamma(N - p + 1, p) = I_{1-\gamma}(p, N - p + 1) = \sum_{j=p}^{N} \binom{N}{j} (1-\gamma)^j \gamma^{N-j}$$

$$= 1 - \sum_{j=0}^{p-1} \binom{N}{j} (1-\gamma)^j \gamma^{N-j} \quad (4\text{-}4)$$

It is strongly recommended that the estimation of the upper limits should be higher than the first order with the following arguments [24].

When the upper tolerance limit approaches regulatory acceptance criteria, e.g. 1200°C PCT, the number of code runs may be increased to 150 or 200 calculations instead of the 59 code runs needed, using Wilks' formula at the first order for the estimation of a α = 95% one-sided tolerance limit with a confidence level β of 95%. This would be advisable for two reasons:

- With increasing sample size the uncertainty results will be less dispersed, and consequently more converged (less conservative), and
- The sensitivity results will be more reliable.

Firstly, for uncertainty analysis, it is possible to use Wilks' formula for example at the order 3 (124 runs) up to 5 (181 runs) for percentile $\alpha$ and confidence $\beta$ unchanged, which may reduce the effect of conservatism of tolerance limits from a small number of code runs. The dispersion of the estimated tolerance limit in conservative direction tending to substantially overestimate the 95%-quantile one is originally interested in. On the other hand, the underestimation of the 95% percentile with 5% probability decreases when the order of Wilks' formula is increased.

Secondly the results of sensitivity analysis will become more reliable, particularly for less important parameters, because the variances of the estimators of the sensitivity measures will decrease and spurious (artificial) correlations between independent input parameters will appear less frequently when sample sizes increase. The issue of the number of code runs required for a proper sensitivity analysis is independent of that required by Wilks' formula. For example and unlike Wilks' formula, mainly for Regression Coefficients, the number of code runs should be (significantly) higher than the number of input parameters.

TS

4.3.2.1 Check Blowdown Covering

Simple-random sampling (SRS) calculations were performed against the test data obtained from

[18] American National Standard Decay Heat Power in Light Water Reactors, ANSI/ANS-5.1-1979.

[19] D. F. Ross et al., "Compendium of ECCS Research for Realistic LOCA Analysis," USNRC, NUREG-1230, April 1987.

[23] Reliability Engineering and System Safety, Vol. 80, Issue 3, pp.217-232, June 2003.

[24] H. Glaser, "BEMUSE Phase VI Report, Status report on the area, classification of the method, conclusions and recommendations," NEA/CSNI/R(2011)4, March 2011.