ANP-10335Q2NP
Revision 1

ACE/ATRIUM 11 Critical Power Correlation RAIs

Topical Report

March 2017

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Nature of Changes

Item	Section(s) or Page(s)	Description and Justification
1	1-1	Introduction rewritten in entirety
2	2-1, 2-2	Correct errors in the text
3	2-3 to 2-6	Correct errors in Table 1
4	2-7	Correct errors in Table 2
5	3-1	New - add response to Draft RAI A
6	4-1	New - add response to Draft RAI B

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1.0 INTRODUCTION

AREVA is introducing a new fuel assembly design, the ATRIUM 11. To support its introduction, a critical power correlation, ACE/ATRIUM 11 was developed. This new correlation was provided to the U.S. NRC for review in February 2015 (Reference 1). A post-submittal meeting was held on May 12, 2015 that reviewed the test program and correlation development and provided an introduction to the topical report. An audit for understanding was conducted by the U.S. NRC staff on October 27 – 28, 2015 (Reference 2). Following this audit, 30 RAIs were received (Reference 3). AREVA provided the response to each of these 30 RAI's in August 2016 (Reference 4).

The critical power correlation is an essential component of the transient methodologies for determining ΔCPR and setting reactor licensee MCPR operating limits. The transient benchmarking of the ACE/ATRIUM 11 critical power correlation with the licensed transient code XCOBRA-T (Reference 5) was provided in Reference 1 (Section 7.3).

A new transient methodology, AURORA-B (Reference 6), based on S-RELAP5 is also under review by the NRC staff. It is AREVA's intention to apply the ACE/ATRIUM 11 critical power correlation with the AURORA-B transient methodology. The U.S. NRC requested that AREVA provide evidence justifying that the AURORA-B methodology could be applied to the ATRIUM 11 transient evaluation based on the ACE/ATRIUM 11 critical power correlation. To justify this application, AREVA provided the NRC a report benchmarking the S-RELAP5 code to the experimental transient data of ATRIUM 11 (Reference 8). This report was prepared as supplementary information to be considered with the response to RAI #29 (Reference 4) and was sent to the NRC in December 2016. In response to the S-RELAP5 transient benchmarking results, the NRC staff asked two additional questions. The questions were discussed with the NRC staff on January 30, 2017 to make sure that the questions were understood and to confirm that the proposed responses would address the NRC staff concerns.

This report is a revision to the Reference 8 document. The revision corrects errors in the presented data. The report has also been expanded to include the responses to the two additional NRC questions.

2.0 EVALUATION OF TRANSIENT CRITICAL POWER DATA

An industry accepted standard in BWR transient methodology is that steady-state dryout correlations are conservative for use in transient methodology. Transient dryout tests [ ] were performed to reconfirm this for ATRIUM 11 when using the ACE/ATRIUM 11 critical power correlation.

The limiting transient tests of interest are simulated load rejection without bypass (LRNB) events that consist of power and pressure ramps and flow decay; and simulated loss of flow events that consist of flow decay and power decay. The power, pressure, and flow were all controlled by a function generator. The forcing functions were programmed to produce the transient rod surface heat flux typical of the various events. Reference 1, Figure 7.18, page 7.43 shows the forcing function characteristics for a typical LRNB test and Reference 1, Figure 7.19, page 7-43 shows the comparable forcing function characteristics for a typical loss of flow event.

A total of [ ] ATRIUM 11 LRNB and loss of flow transients were run which were either measured or predicted to have dryout. An additional [ ] of these transients were run which were neither measured nor predicted to go into dryout. Of these [ ] transient critical power tests, [ ] The initial conditions for all of the tests are provided in Reference 1, Table 7.20, page 7-36.

The AREVA transient thermal hydraulic code S-RELAP5 (Reference 6), was used to predict the transient test results using the ACE/ATRIUM 11 critical power correlation. The test power forcing function provides the boundary condition of power, which is modeled in S-RELAP5 [ ]

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The results are summarized in Table 1. [

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Table 1 S-RELAP5 ACE/ATRIUM 11 Transient Dryout Results

Table 1 S-RELAP5 ACE/ATRIUM 11 Transient Dryout Results (cont.)

Table 1 S-RELAP5 ACE/ATRIUM 11 Transient Dryout Results (cont.)

Table 1 S-RELAP5 ACE/ATRIUM 11 Transient Dryout Results (cont.)

Table 2 S-RELAP5 K-Factor Iteration Results

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3.0 Draft RAI-A:

In ANP-10335Q2P, AREVA provided additional information to confirm that the ACE/ATRIUM 11 correlation provides conservative predictions of critical power within the S-RELAP5 transient thermal-hydraulic code. The RAI response detailed results from transient critical power testing, for which predictions were also made, to justify that the critical power correlation as applied within S-RELAP5 produces results that are conservative overall.

Of the **[ ]** *tested transients that were measured or predicted to go into boiling transition,* **[ ]** *transients were found to be non-conservatively predicted (i.e., the predicted time of boiling transition was found to be later than that which was measured in the test or no dryout was predicted at all). For each of these* **[ ]** *data points, AREVA determined* **[**

]. *For* **[ ]** *tests,* **[**
needed for a conservative prediction of
]. *However, for* **[**

].

It is the NRC staff's understanding of AREVA's safety limit minimum critical power ratio (SLMCPR) methodology, documented in ANP-10307PA, Rev. 0, "AREVA MCPR Safety Limit Methodology for Boiling Water Reactors," that **[**

]. *Given that* **[**

], *how does AREVA assure that the uncertainty in the ACE/ATRIUM 11 critical power correlation resulting from its application in S-RELAP5 is adequately captured in the safety limit?*

AREVA Response A:

The response to this question is provided in parts. First, the method of stratified random sampling (used in the safety limit methodology) will be described by an example and it will be compared to simple random sampling and shown to be an equivalent method for sampling normal distributions. In the second part, the safety limit methodology will be briefly described in the context of the examples. Finally, expectations on the behavior of data points in the transient benchmarking to S-RELAP5 are described in the context of the critical power correlation uncertainty. Now consider the first part.

Stratified random sampling is applied in the Safety Limit methodology to improve the precision of the estimates of parameters describing the population. It is a method suitable for finite populations (e.g. number of fuel rods in nuclear reactor core) and it minimizes sample selection bias so that certain segments of the population are not over or under represented (e.g. under representing values in the tail of the normal distribution). The advantages of stratified random sampling are demonstrated by an example.

A population is constructed by collecting N=1000 random samples from a normal distribution whose mean is 1.0 and standard deviation is 0.2. The population is examined first by simple random sampling and then by stratified random sampling.

Simple Random Sampling of the Population

20 samples are collected from the population using the Simple Random Sampling (SRS) method (Table 3).

The mean of these n=20 samples is calculated (Reference 7, page 5)

$$\bar{x}=\frac{1}{n}\sum_{i=1}^{n}x_i=\frac{1}{20}\sum_{i=1}^{20}x_i=1.0079 \qquad (1)$$

The sample standard deviation is calculated (Reference 7, page 9)

$$s=\sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(x_i-\bar{x})^2}=\sqrt{\frac{1}{20-1}\sum_{i=1}^{20}(x_i-1.0079)^2}=0.2242 \qquad (2)$$

The standard error (SE) is calculated (Reference 7, page 104)

$$SE=\frac{s}{\sqrt{n}}=\frac{0.2242}{\sqrt{20}}=0.0501 \qquad (3)$$

The behavior of the "mean" statistic as a function of the number of samples is shown in Figure 1 along with the standard error bounds. The standard deviation as a function of the number of samples is provided in Figure 2.

Stratified Random Sampling of the Population

An alternative strategy, stratified random sampling, is applied to the population. The domain of the normal distribution is divided into L=5 non-overlapping strata as shown in Figure 3. The boundaries for the strata are chosen such that any single random sample has equal probability of falling within each of the strata. Thus, the probability (area under the curve) of each strata is equal to 0.2. For a normal distribution with a mean of 1.0 and standard deviation of 0.2, the boundaries of the strata are defined in Table 4.

The population of each strata is

$$N_h = \frac{N}{L} = \frac{1000}{5} = 200 \tag{4}$$

Within each strata, n_h random samples are collected. Four random samples are collected from each of the five strata and placed in Table 5.

The mean value within each strata is calculated

$$\overline{x}_h = \frac{1}{n_h} \sum_{i=1}^{n_h} x_{ih} \tag{5}$$

and shown in Table 6. The combined mean of the stratified samples is calculated (Reference 7, page 476)

$$\overline{x} = \sum_{h=1}^{L} \left(\frac{N_h}{N} \right) \overline{x}_h = \frac{200}{1000} (0.7720 + 0.9071 + 0.9881 + 1.1021 + 1.2977) = 1.0134 \tag{6}$$

The standard deviation within each of the strata is calculated

$$s_h = \sqrt{\frac{1}{n_h - 1} \sum_{i=1}^{n_h} (x_{ih} - \overline{x}_h)^2} \tag{7}$$

and is provided for each strata in Table 7. The standard error is calculated (Reference 7 page 476)

$$
\begin{aligned}
SE &= \sqrt{\sum_{h=1}^{L}\left(\frac{N_h}{N}\right)^2\left(\frac{s_h^2}{n_h}\right)\left(\frac{N_h-n_h}{N_h}\right)} \\
&= \sqrt{\left(\frac{N_h}{N}\right)^2\left(\frac{1}{n_h}\right)\left(\frac{N_h-n_h}{N_h}\right)\sum_{h=1}^{L}s_h^2} \qquad (8)\\
&= \sqrt{\left(\frac{200}{1000}\right)^2\left(\frac{1}{4}\right)\left(\frac{200-4}{200}\right)\left(0.0851^2+0.0361^2+0.0473^2+0.0200^2+0.0884^2\right)} \\
&= 0.0136
\end{aligned}
$$

The “mean” statistic as a function of number of samples from stratified random sampling is provided in Figure 4 along with the standard error bounds. In comparing Figure 1 to Figure 4, it is observed that for a prescribed number of samples, stratified random sampling produces a more accurate estimate of the mean than simple random sampling.

The standard deviation as a function of the number of samples taken is provided in Figure 5. Comparing to Figure 2, it is observed that an accurate estimate of the standard deviation is obtained faster with stratified random sampling than it is with simple random sampling.

Each of the strata represents a sub-population. That sub-population has a characteristic “mean” value. The mean value occurs at the centroid of each of the strata. For the population whose mean is 1.0 and standard deviation is 0.2 (Figure 3), the centroid values are provided in Table 8. [

] The stratification method is theoretically sound since the standard deviation of the normal distribution is not disrupted and it ensures accurate code results with a limited number of trials.

The example above demonstrates that stratified random sampling of a normal distribution provides the same result as would be obtained if simple random sampling is applied except that a good accuracy can be obtained from stratified random sampling with significantly fewer samples than are required with simple random sampling.

Safety Limit Methodology Sampling Methodology

The methodology for sampling uncertainty of significant variables in the Safety Limit Methodology makes use of the stratified random sampling method. The description taken from Reference 10, Section 3.4.1 is:

> *The normal distribution is modeled by a statistical stratification method.* [
>
>]

Figure 3-2 from Reference 10 has been reproduced in this document as Figure 6 . The safety limit methodology applies a Monte Carlo method for perturbing important parameters by their uncertainty. The additive constant uncertainty (and the other sampled parameters) are modeled with a normal distribution. The sampling performed in the safety limit methodology is based on the stratified random sampling methodology described in the example above.

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] This conclusion is consistent with the example shown above.

Transient Benchmarks With S-RELAP5

Now consider the additive constant uncertainty and what it represents. This uncertainty is a 1σ value and only 68.3% of the values fall within ±1σ and only 95.5% of the values are expected to fall within ±2σ. If there were no conservatism in the application of the steady-state critical power correlation to transients, it would be expected that [ ] of the [ ] transients conducted would have values that fall outside of ±2σ. However, in the worst case of the S-RELAP5 transient benchmark calculations, the change in additive constant required to achieve a conservative result is only [ ] times the additive constant uncertainty [ ]. At this level, the number of expected values out of [ ] that are expected to fall outside the interval [ ] in a standard normal distribution is [ ] values. The observed number (on the non-conservative side) is [ ]. Thus, these results confirm that the application of the ACE/ATRIUM 11 critical power correlation, to XCOBRA-T and to S-RELAP5, is conservative.

The additive constant uncertainty is determined from steady-state measurements. It includes experiment uncertainty and model uncertainty. It would be expected that in a transient application there would be [ ]. But the S-RELAP5 (Section 2.0) and XCOBRA-T (Reference 1, Section 7.3, page 7-33) benchmark calculations show the inherent conservatism that results from applying a steady-state critical power correlation in transients (Reference 4, RAI #20, page 59), [ ]. Therefore, the uncertainty in the ACE/ATRIUM 11 critical power correlation applied within the SLMCPR calculation adequately covers [ ].

Table 3 Simple Random Sample of Size 20

i	x_i
1	1.2460
2	0.4820
3	1.0622
4	1.2958
5	1.2953
6	0.9767
7	1.1311
8	0.9831
9	0.9509
10	0.5793
11	1.2597
12	0.7346
13	0.9285
14	0.9865
15	0.8877
16	1.0345
17	0.8922
18	1.2597
19	1.0656
20	1.1059

Table 4 Strata Boundaries

	Strata 1	Strata 2	Strata 3	Strata 4	Strata 5
Minimum	-∞	0.8317	0.9493	1.0507	1.1683
Maximum	0.8317	0.9493	1.0507	1.1683	+∞

Table 5 20 Random Samples – 4 per Strata Times 5 Strata

i	Strata 1	Strata 2	Strata 3	Strata 4	Strata 5
1	0.8095	0.8654	0.9991	1.1126	1.2880
2	0.8250	0.9349	0.9517	1.0842	1.3394
3	0.8087	0.8885	0.9509	1.1251	1.3843
4	0.6448	0.9397	1.0505	1.0865	1.1789

Table 6 Sample Mean For Each Strata

	Strata 1	Strata 2	Strata 3	Strata 4	Strata 5
$\bar{x}_h$	0.7720	0.9071	0.9881	1.1021	1.2977

Table 7 Sample Standard Deviation for Each Strata

	Strata 1	Strata 2	Strata 3	Strata 4	Strata 5
s_h	0.0851	0.0361	0.0473	0.0200	0.0884

Table 8 Centroids of Strata

	Strata 1	Strata 2	Strata 3	Strata 4	Strata 5
Centroid	0.7437	0.8951	1.0000	1.1049	1.2563

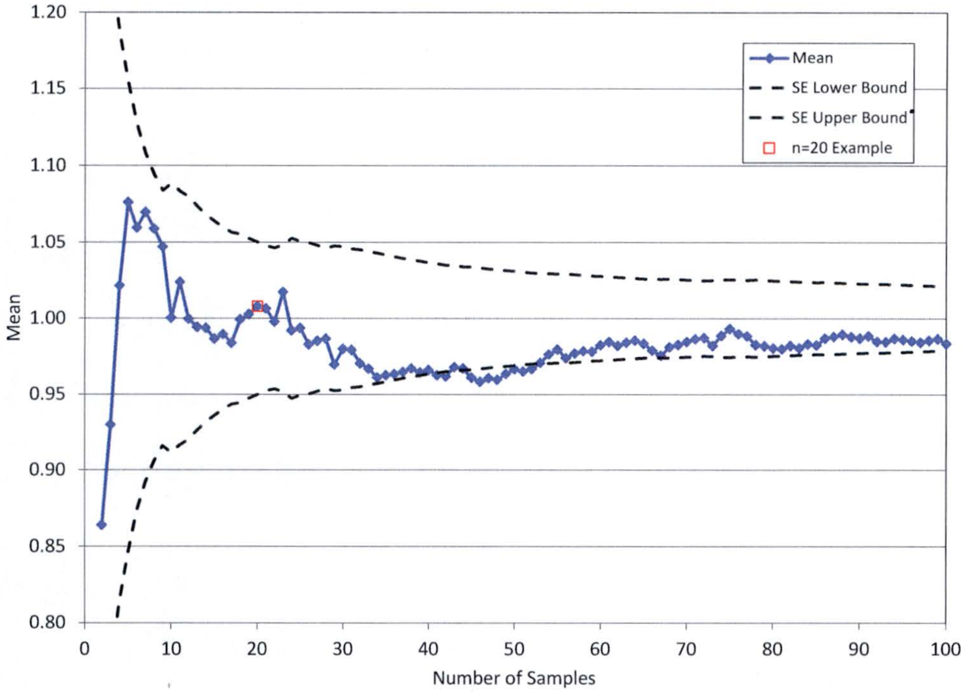

Figure 1 Simple Random Sampling Mean and Standard Error Bound

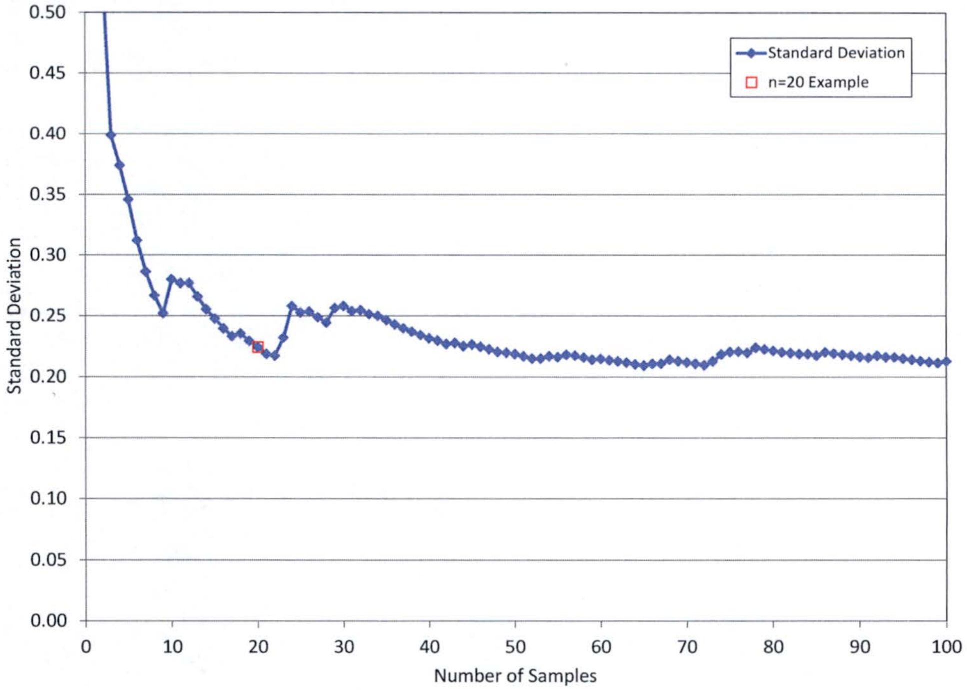

Figure 2 Simple Random Sampling Standard Deviation

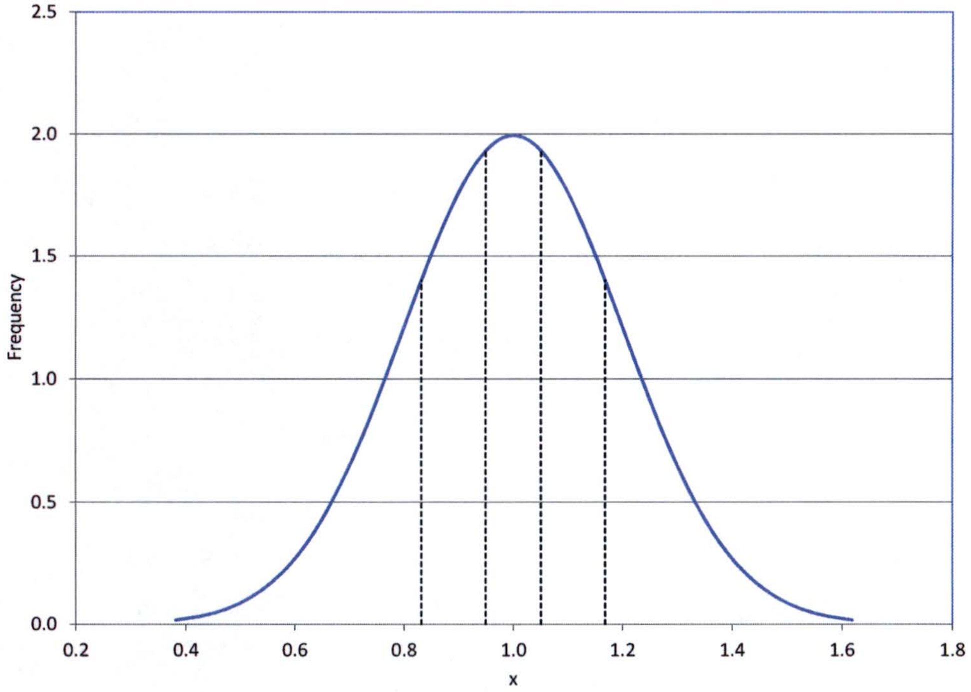

Figure 3 Population Strata

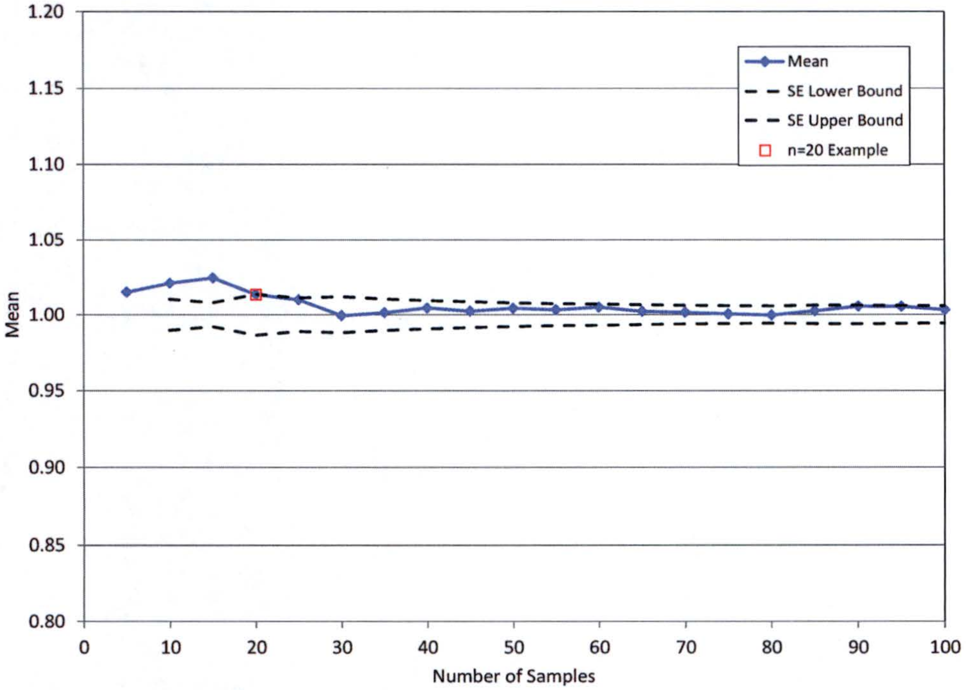

Figure 4 Stratified Random Sampling Mean and Standard Error Bound

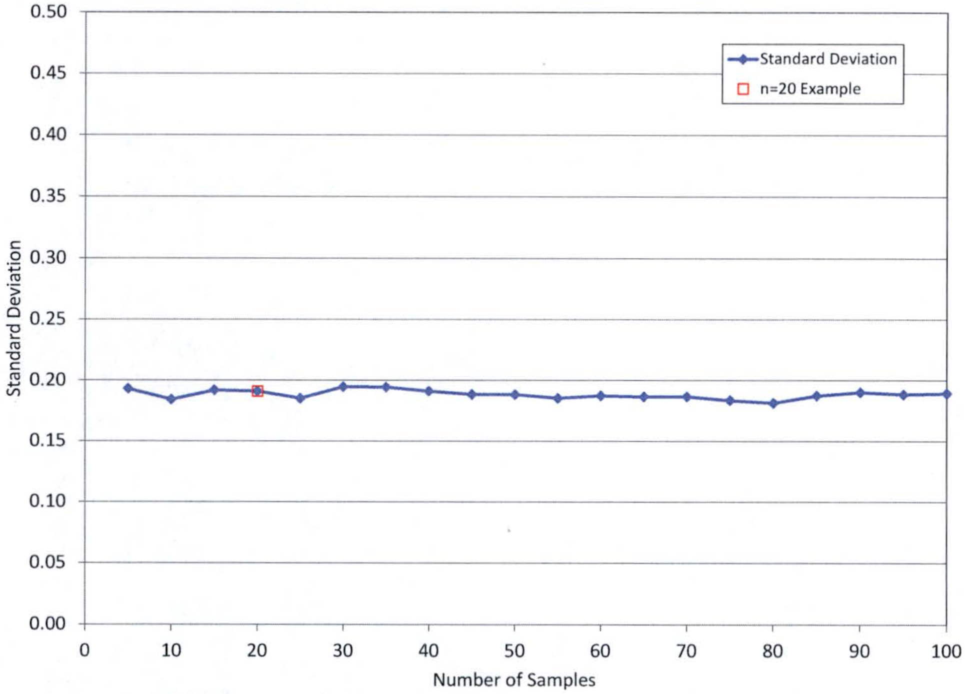

Figure 5 Stratified Random Sampling Standard Deviation

[ ]

Figure 6 Stratified Normal Distribution Curve

4.0 Draft RAI-B:

Though the predictions of time to boiling transition for the transient testing presented in ANP-10335Q2P for S-RELAP5 are similar to those presented in ANP-10335P for XCOBRA-T, there are clear differences in the results between the two codes. In deriving the MCPR safety limit, there appears to be an **[**

within **]** *to be addressed in the ΔCPR calculation. Considering that different codes are used, how does AREVA ensure that* **[**

] *?*

<u>AREVA Response B:</u>

It is expected that there would be some differences in the benchmark results between S-RELAP5 (Reference 8) and XCOBRA-T (Reference 4, Section 7.3, page 7-33). S-RELAP5 features a six equation model and XCOBRA-T features a three equation model. Each has different constitutive relations. This difference is recognized in the correlation development and qualification process by requiring that the critical power correlation be benchmarked prior to use in a new transient code.

It is assumed that **[**

] . In the response to Draft RAI A it is demonstrated that statistically the transient measurements are conservatively modeled relative to the **[**

] . The inherent conservatism in applying a steady-state correlation to transients is **[**

] . This conclusion is derived from code specific benchmarking to transient measurements.

Core monitoring is performed with MICROBURN-B2 (Reference 9). Transients start from a steady-state condition determined by MICROBURN-B2. This ensures that the change (ΔCPR) is derived from a reference condition that is being monitored. The SLMCPR calculation includes MICROBURN-B2 as a key element in the calculations. This assures that the SLMCPR derived from the SAFLIM3D is based on a reference condition that is being monitored. This methodology provides assurance that the appropriate limit is determined and that the monitoring is performed to that limit.

5.0 REFERENCES

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3. "Request for Additional Information RE: AREVA Inc. Topical Report ANP-10335P/NP, 'ACE/ATRIUM 11 Critical Power Correlation,' (TAC No. MF5841)," Letter to Gary Peters, Director, Licensing and Regulatory Affairs, AREVA Inc., dated April 11, 2016.
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5. XN-NF-84-105(P)(A) Volume 1 and Volume 1 Supplements 1 and 2, "XCOBRA-T: A Computer Code for BWR Transient Thermal-Hydraulic Core Analysis," Exxon Nuclear Company, October 1986.
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9. EMF-2158(P)(A) Revision 0, "Siemens Power Corporation Methodology for Boiling Water Reactors: Evaluation and Validation of CASMO-4 / MICROBURN-B2," October 1999.
10. ANP-10307PA, Revision 0, "AREVA MCPR Safety Limit Methodology for Boiling Water Reactors," June 2011.