ENCLOSURE 23

APP-GW-GLR-093 Non-Proprietary

Executive Summary

In consideration of Generic Safety Issue (GSI) 191, Westinghouse has performed a series of fuel assembly head-loss experiments for the AP1000 (WCAP-17028 Revision 4). The purpose of this work is to use available test data to show that there is a low probability that the AP1000 debris bed resistance will exceed the analyzed safety analysis limit which shows acceptable results. The analyzed safety analysis limit from WCOBRA/TRAC long term core cooling analysis is a core flow of 65 lbm/s with 4.1 psid pressure drop across the core inlet.

Long-term following a loss of coolant accident, it is possible that debris present in the containment may be transported to the core with the recirculating flow. The purpose of the upflow tests in the AP1000 fuel assembly debris test program was to quantify the head-loss across the fuel assemblies during the long term cooling phase following a loss of coolant accident, considering debris loadings applicable to the AP1000. The debris loadings considered in the test series were fibrous, particulate and chemical debris. The upflow tests are applicable to break scenarios where the long term core flow is in the normal flow direction (e.g. from the downcomer into the lower plenum, through the core and upper plenum, into the hot legs and out of ADS-4) and the break location is flooded during long term sump recirculation. Examples are the long term cooling phase following a direct vessel injection or cold leg break.

The AP1000 fuel assembly test data were examined and the subset of tests of interest for the statistical analysis were identified (Tests 18-34). The test subset of interest was identified based on which tests were performed with a similar approach and were more prototypic of the long term core cooling behavior expected in the AP1000. The test subset was characterized by [

]^{a,c}

For the statistical analysis, first a linear regression of the adjusted pressure drop results was performed. From the linear regression results of the adjusted pressure drop and natural log of the adjusted pressure drop data, [ ]^{a,c} and the dataset of interest was further refined to the concurrent addition tests from Tests 18-34. A separate study of earlier AP1000 fuel assembly tests (Test 1-15) indicated [

]^{a,c}

Therefore, a simple additive model was set up to model the adjusted pressure drop of the concurrent addition tests as the function of a constant and a Gaussian noise factor. The constant [ ]^{a,c} Using [ ]^{a,c} upper bound confidence levels on the standard deviation of the test data were determined. With this model the probability of exceeding the pressure drop limit was calculated for different confidence levels on the upper bound standard deviation.

A sensitivity to this statistical analysis was repeated by modeling the natural log of the concurrent addition test adjusted pressure drop results as the figure of merit.

The assumption that the test data follow a normal distribution was examined. It was concluded that the assumption that the data follow a normal Gaussian distribution [ ]^{a,c}

Table 9 and Table 17 summarize the probability of an individual fuel assembly to exceed the acceptance criteria for the direct pressure drop model and the natural log model, respectively; the results are summarized below. As the confidence in the upper bound standard deviation increases the probability to exceed the acceptance criteria increases. Sensitivity calculations with the direct pressure drop and natural log pressure drop models to examine first [

]^{a,c} in selected tests and then the effect of [

]^{a,c} compared to [ ]^{a,c} exponent values.

a,c

The pressure drop model results showed [

]^{a,c} The natural log pressure drop results [

]^{a,c}

There are four primary conservatisms in this analysis: (1) the dataset of Tests 18-34 and in particular the concurrent addition tests are biased for higher adjusted pressure drop results; (2) upper bound standard deviations are examined; (3) in the plant, non-uniform debris bed buildup across the 157 fuel assemblies is expected and the effective core inlet resistance is expected to be considerably less than the safety analysis limit; and (4) the results of Tests 36 and 37 qualitatively indicate that at more prototypic post-LOCA conditions [

]^{a,c} lower adjusted pressure drop results are expected. Therefore considering these conservatisms and the results of the pressure drop and natural log pressure drop model analyses, following a cold leg or DVI break loss of coolant accident in the AP1000 there is low probability that debris bed buildup will be such that core cooling and core boron concentration limits will be exceeded.

Based on the test data and consistent with the statistical analysis results, a conservative distribution of the adjusted pressure drop across the core was developed. Using this conservative distribution, the effective adjusted pressure drop at the core inlet is [

]^{a,c} This demonstrates considerable margin to the safety analysis limit of 4.1 psid with core flow of 65 lb/s.

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1.0 Background

In consideration of Generic Safety Issue (GSI) 191, Westinghouse has performed a series of fuel assembly head-loss experiments for the AP1000 (WCAP-17028-P Revision 4). Following a loss of coolant accident (LOCA), it is possible that debris present in the containment may be transported to the core with the recirculating flow. The purpose of the upflow tests in this test program was to quantify the head-loss across the fuel assemblies during the long term cooling phase following a loss of coolant accident, considering debris loadings applicable to the AP1000. The debris loadings considered in the test series were fibrous, particulate and chemical debris. The upflow tests are applicable to break scenarios where the long term core flow is in the normal flow direction (e.g. from the downcomer into the lower plenum, through the core and upper plenum, into the hot legs and out of ADS-4) and the break location is flooded during long term sump recirculation. Examples are the long term cooling phase following a direct vessel injection (DVI) or cold leg break.

AP1000 long term core cooling analysis is performed using the WCOBRA/TRAC (WC/T) code. In the scenarios described above, a debris bed may form [

]^{a,c} This may be simulated as an increased resistance at the core inlet in the AP1000 long term core cooling WC/T model. As discussed in WCAP-17028-P Revision 4, Section 5, sensitivity studies on the AP1000 long term core cooling response to an increased resistance at the core inlet have been performed using the WC/T code. These sensitivity calculations define the acceptance criteria for the fuel assembly debris tests.

The WC/T long term core cooling (LTCC) sensitivity calculations (Case 10) show that at 8.6 hours after break, sufficient resistance to result in a core flow of 65 lbm/s with 4.1 psid pressure drop across the core inlet can be sustained without impacting safety margins. This reference base case is chosen to determine the current safety analysis limit related to core inlet debris blockages.

WCAP-17028-P Revision 4 Section 5.1.2 discusses a second, very conservative acceptance criterion for concurrent addition tests based on LTCC analysis Case 3. This acceptance criteria is very conservative primarily because the LTCC Case 3 was performed with decay heat at 2.6 hours after break, which conservatively assumes that the debris had been transported to the core inlet at the beginning of recirculation which is earlier than when the debris loading can be transported to the core inlet and cause the associated pressure drop; also the exponents used to determine the adjusted pressure drops in this case are conservatively reduced [

]^{a,c} WCAP-17028-P Revision 4 shows that the maximum measured pressure drop [

]^{a,c} These considerations support the use of the LTCC analysis Case 10 results which specify a limit of 4.1 psid with minimum core flow of 65 lbm/s as the appropriate limit to be applied in the statistical analysis discussed herein.

Note that the LTCC sensitivity calculations provide simply an analysis limit, with a pre-set resistance input to these calculations. The simulation does not reflect a mechanistic response to debris build up in the core inlet.

The purpose of this work is to use available test data to show that there is a low probability that the AP1000 debris bed resistance will exceed the analyzed safety analysis limit which shows acceptable results for cold leg and DVI break scenarios where the debris enters the core from the lower plenum / downcomer. Note that fuel assembly debris tests were performed simulating hot leg breaks where debris can enter the core from the upper plenum. These tests indicate [ ]^{a,c} are not of interest in this work.

2.0 Test data

2.1 Background on Test Matrix

The AP1000 fuel assembly debris bed tests are documented in WCAP-17028-P Revision 4. Revision 0 of this document included Tests 1-4; Revision 1 of this document added Tests 5-16 except Tests 7, 12, and 15 ; Revision 2 of this document added Test 15, corrected errors and discussed invalid Tests 7 and 12; Revision 3 of this document added Tests 17-30; Revision 4 of this document added Tests 31-39.

WCAP-17028 Revision 4 shows that over the fuel assembly debris tests performed for AP1000 a number of parameters were varied.

As the AP1000 fuel assembly debris testing progressed, the test designs changed, reflecting modifications in the design basis debris loads and considerations of expected AP1000-specific long term core cooling behaviors, in particular the expected flow rate and the way debris is transported to the core. All tests were pumped flow tests. Tests 1-16 were constant flow or oscillatory flow tests. Constant flow tests were run at constant specified flow rate. Selected tests were oscillatory flow test in which the flow rate [

]^{a,c}

However, the AP1000 long term recirculation flow is provided by natural circulation and therefore will not be constant as the debris bed builds up and the pressure drop across the debris bed increases. Tests 17-34 and 36, 37 were variable flow tests in which the flow was reduced as a function of the measured pressure drop in order to simulate the natural circulation flow response. Test 34 [
]^{a,c}

With respect to debris transport to the core, Tests 1-21 and Test 23 were sequential debris addition tests. In sequential debris addition tests the particulates were added first [
]^{a,c} then the fibrous debris was added [
]^{a,c} and finally the chemical additions [ ]^{a,c} In contrast, Test 22 and Tests 24-34 were concurrent debris addition tests which were designed to be more prototypic of debris transport conditions in the plant. In concurrent debris addition tests [

]^{a,c}

Tests 36 and 37 were performed at higher temperature [
]^{a,c} in order to simulate more prototypic post-LOCA conditions.

These varied parameters are summarized in Table 1 with a description of and basis for the variation as applicable.

Note that Tests 35, 38, and 39 described in WCAP-17028 Revision 4 were tests that simulated hot leg (HL) LOCAs. These tests indicate [
]^{a,c} are not of interest in this work.

Table 1. Summary of Varied Parameters in AP1000 Fuel Assembly Debris Tests 1-34, 36, 37 (WCAP-17028 Revision 4)

a,c

Table 1. Summary of Varied Parameters in AP1000 Fuel Assembly Debris Tests 1-34, 36, 37 (WCAP-17028 Revision 4)

a,c

2.2 Identification of Tests of Interest for Statistical Analysis

Over the course of performing the AP1000 fuel assembly debris tests there was an evolution in the amount of debris considered as the design basis and in the execution of the test to be more prototypic of the long term core cooling scenario (sequential vs. concurrent debris addition; constant, oscillating or variable flow, [ ]a,c It is necessary to identify the subset of tests of interest for the statistical analysis.

Note that the purpose of the statistical analysis is to assess the process variability for a given scenario, namely that a cold leg break or direct vessel injection line break has occurred, the loss of coolant accident has progressed to the long term core cooling stage, debris is swept into the core through the break and begins to form a blockage at the core inlet. Therefore, the tests of interest for the statistical analysis are those which were performed with a similar approach and which are considered more prototypic of the expected plant behavior.

Tests 18-34 are considered the test subset of interest for the purpose of the statistical analysis of the AP1000 fuel assembly debris tests to calculate the probability of exceeding the pressure drop criteria. These tests are variable flow tests [ ]a,c The differences in the [ ]a,c are related to the type of tests (concurrent or sequential debris addition) [ ]a,c Therefore these tests are considered more representative of the expected plant conditions than Tests 1-16, which were constant flow and [ ]a,c

Tests 36 and 37 were performed [ ]a,c Since Tests 36 and 37 were performed at higher initial temperature [ ]a,c they are considered more prototypic of expected post-LOCA conditions than the previous tests. However, in order to minimize the number of varied parameters between the tests considered in the statistical analysis, Tests 36 and 37 are not considered in the analysis but the results of these tests are qualitatively compared to the subset of Tests 17-34 in order to consider the effect of more prototypic temperatures and chemical conditions relative to the results of the statistical analysis.

Test 17 is eliminated from the statistical analysis as an invalid test. Test 17 is eliminated due to the irregularities in the test execution.

As previously noted, Tests 35, 38, 39 were hot leg break tests and therefore are not considered in this analysis.

In the subset of tests of interest, [ ]a,c were performed as repeat tests with identical initial conditions and addition sequences. [ ]a,c For the purposes of the statistical analysis, [ ]a,c The repeat tests provide input to the variability of the test results and the standard deviation of the adjusted pressure drops.

The varied and constant parameters in Tests 18-34, the subset of tests of interest, are considered; these parameters are summarized in Table 2. The qualitative basis for the variation of these parameters is briefly discussed in Table 1. Factors which were varied across Tests 1-16, 36, 37 but were held constant for the test subset of interest are considered.

The AP1000 passive core cooling systems provide long term core cooling following a LOCA with natural circulation. Therefore the variable flow tests are judged to be more representative of the AP1000 expected behavior than the constant flow tests, or the oscillating flow tests [ ]a,c

[ ]a,c

As shown in Table 1, [ ]a,c

Inspection of the WCAP-17028 Revision 4 [ ]a,c is consistent with the conclusions of Section 4.5.

As previously discussed, Tests 18-34 were performed [ ]a,c Although these conditions are less prototypical than the conditions in Tests 36, 37, they are consistent and therefore acceptable for the purposes of the statistical analysis.

Therefore, it is acceptable to examine the identified subset of tests of interest for the statistical analysis and not consider these constant parameters.

Therefore, Tests 18-34 form the subset of tests of interest for statistical analysis.
It is noted that the primary criterion for selection of this subset is the difference between the constant and variable flow approaches. Another criterion for selection of the subset of interest could be the sequential vs. concurrent debris addition tests; this is discussed further in Section 3.1.

Table 2. Summary of Varied and Constant Parameters in AP1000 Fuel Assembly Debris Tests 18-34, 36, 37 (WCAP-17028 Revision 4)

a,c

2.3 *Characterization of the Test Input Parameters for Statistical Analysis*

As noted previously, Tests 18-34 are the test subset of interest for the statistical analysis. Subsequent reference in this report to the test data for the statistical analysis is limited to this subset of tests, or as otherwise specified.

[

]a,c Next it is necessary to identify the characteristics of these tests which are input parameters to the statistical analysis. [

]a,c

In the sequential addition tests [

]a,c In the concurrent addition tests, [

]a,c

Considering these differences [

]a,c

[ ]a,c

- [ ]a,c
  - [ ]a,c
  - [ ]a,c
- [ ]a,c
  - [

]a,c

[

]a,c

[

]a,c.

The figure of merit in these tests is the maximum adjusted head loss determined with [ ]a,c exponent. The maximum adjusted head loss is determined by scaling the measured head loss to the value which would have been observed at a flow rate of 3.1 gpm in the test assuming the same [ ]a,c resistance. The 3.1 gpm is selected based on flow from the WC/T reference base case which provides the pressure drop limit, as discussed in discussed in WCAP-17028-P Revision 4, Section 5. The method for head loss adjustment is described in WCAP-17028-P Revision 4 Section 5. Since the adjusted head loss values are scaled to the same flow rate, they may be compared as a reflection of the debris bed resistance in each test.

Table 3 summarizes the input parameters of interest for the subset of tests of interest in the statistical analysis.

a,c

Table 3. Summary of Parameters of Interest in Statistical Analysis Test Subset

3.0 Statistical Analysis

The statistical analysis is performed in two parts. First a linear regression is performed to identify whether any of the varied parameters in the test subset of interest have a statistically significant effect (within the range of the parameter variation in the test subset) on the adjusted pressure drop across the debris bed. Then a simple model is developed using Gaussian noise to model the variation not explained by the input variables. An upper confidence bound for the standard deviation is determined from [ ][a,c] From this model a statement of the probability of exceeding the acceptance criteria is determined.

This process may be followed to directly model the adjusted pressure drop, or to model the natural log of the adjusted pressure drop. Both approaches are examined in this work; first the adjusted pressure drop is modeled directly. The natural log model is considered in Section 4.1.

3.1 Linear Regression Analysis

First, standard statistical analysis software (MINITAB) is used to perform a linear regression analysis on the data summarized in Table 3.

In the first approach for the linear regression, the measured output variable is the adjusted pressure drop. The adjusted pressure drop is postulated to be a linear function of the test input parameters in the form:

[ ][a,c] (Equation 1)

a,c

Where:

The coefficients from the linear regression analysis results are summarized in Table 4.

Although the data can be fit in the form of Equation 1, it is necessary to determine if there is statistical significance to the constant and coefficients obtained from the linear regression. This is evaluated through inspection of the P-values.

The P-value for each coefficient ranges from 0 to 1 and corresponds to the smallest level of significance that would lead to rejection of the null hypothesis; the null hypothesis is that the correlation coefficient is zero (for example, the debris bed resistance is not correlated to the particulate mass). As the P-value increases, the probability increases that the null hypothesis is correct. A typical P-value limit is $\alpha = 0.05$. Therefore, if the P-value for the coefficient of a parameter in Equation 1 is greater than 0.05, it is reasonable to conclude that the parameters are not significantly correlated over the range of the data set. For additional reference, see Box, Hunter and Hunter.

Table 4 summarizes the P-values associated with the coefficients from the linear regression analysis of the Table 3 data. Inspection of Table 4 shows that [

]^{a,c}

[

]^{a,c}

In order to further investigate these considerations, a linear regression analysis of only the concurrent addition tests presented in Table 3 is performed (Tests 22 and Tests 24-34). The results of this linear regression are presented in Table 5. Table 5 shows [

]^{a,c}

As the concurrent addition tests are more representative of the prototypic debris transport, the data analysis will be refined to consider only the concurrent addition tests (Tests 22 and Tests 24-34). For these tests, [

]^{a,c}

The sensitivity to [ ]^{a,c} is considered in Section 4.3.

a,c

Table 4. Summary of Coefficients for Linear Regression Analysis

a,c

Table 5. Summary of Coefficients for Linear Regression Analysis of Concurrent Addition Tests

a,c

Figure 1. **Matrix of Scatter Plots for Tests 18-34: [**

]a,c

3.2 Development of Simple Statistical Model

From the linear regression [ ]a,c Therefore, a simple additive model of the debris bed resistance is formulated [ ]a,c

$$dP = C + \sigma * Z \qquad \text{(Equation 2)}$$

a,c

Where:

With this model, the probability that the adjusted pressure drop of an individual assembly exceeds the limit dP_{max} may be determined:

$$P[dP > dP_{max}] = P[C + \sigma * Z > dP_{max}] \qquad \text{(Equation 3)}$$

Rearranging Equation 3:

$$P[dP > dP_{max}] = P\left[Z > \frac{dP_{max} - C}{\sigma}\right] \qquad \text{(Equation 4)}$$

In Equation 4, $\frac{dP_{max} - C}{\sigma}$ is a known value; dP_{max} is set by the WC/T analysis results, C is [the intercept constant, from the linear regression analysis or determined by other means,]a,c and the standard deviation σ may be estimated from the data.

The cumulative distribution function (CDF) is the probability that a random variable is less than or equal to a specific value 'x'.

Since Z is defined as a random variable with standard normal distribution, the probability that Z is greater than some value $x = \frac{dP_{max} - C}{\sigma}$ may be determined through the cumulative distribution function for a normal distribution.

The CDF for a standard normal distribution is defined:

$$\Phi(x) = \frac{1}{2}\left[1 + erf\left(\frac{x}{\sqrt{2}}\right)\right] \qquad \text{(Equation 5)}$$

In this case, the ultimate parameter of interest is the probability that the adjusted pressure drop of an individual assembly is greater than a specified limit. Therefore, the complement of the cumulative distribution is of interest. For a normal distribution:

$$1 - \Phi(x) = 1 - \frac{1}{2}\left[1 + erf\left(\frac{x}{\sqrt{2}}\right)\right] \qquad \text{(Equation 6)}$$

Therefore, combining Equations 4 and 6:

$$P\left[dP > dP_{\max}\right] = P\left[Z > x\right] = 1 - \frac{1}{2}\left[1 + erf\left(\frac{x}{\sqrt{2}}\right)\right] \qquad \text{(Equation 7)}$$

$$\text{where } x = \frac{dP_{\max} - C}{\sigma}$$

In order to evaluate Equation 7 the limiting pressure drop dP_{max}, constant intercept value C and standard deviation σ must be defined.

The limiting pressure drop dP_{max} is defined from the WC/T long term core cooling sensitivity calculations:

$dP_{max} = 4.1$ psid

The constant intercept value C and standard deviation σ are considered in the following sections.

3.2.1 Consideration of Intercept for Simple Statistical Model

In order to evaluate Equation 7 the constant intercept value C must be defined.

[

]a,c

[

]a,c

Table 6. Summary of Constant Intercept Values [

]a,c

a,c

3.2.2 Confidence in Standard Deviation for Input to Statistical Model

3.2.2.1 Estimate of Standard Deviation

The nominal standard deviation of the adjusted pressure drop values in the Table 3 dataset may be estimated in two ways.

The standard deviation may be estimated from the repeat tests: [ ][a,c] Using the adjusted pressure drop data in Table 3:

a,c

[ ]

In the same manner, the standard deviation may be determined from the concurrent addition tests in Table 3:

[ ][a,c]

These are nominal estimates of the true standard deviation σ of the test data. The magnitude of the estimates from the full dataset and the repeat tests only [ ][a,c] Using the repeat tests [

][a,c]

3.2.2.2 Background on the Chi-Square Distribution

This section provides general background on properties of the chi-square distribution.

For *n* independent Gaussian random variables $Z_1, Z_2, \ldots, Z_d$, each with mean $\overline{Z}_d = 0$ and variance $\sigma^2 = 1$ (centered random variables), the sum of their squares is:

$$U = Z_1^2 + Z_2^2 + \ldots + Z_d^2$$

The sum of the squares *U* has a chi-square distribution with *d* degrees of freedom.

The probability distribution function of a chi-square distribution is given by:

$$f_d(u) = \frac{1}{2^{d/2}\Gamma\left(d/2\right)} u^{(d-2)/2} e^{-u} \qquad \text{for } u > 0$$

$$f_d(u) = 0 \qquad \text{for } u \leq 0$$

For the chi-square distribution, for $0 \leq \alpha \leq 1$ a cutoff $c_{1-\alpha}^{(d)}$ may be defined which satisfies:

$$1 - \alpha = P\left(U \geq c_{1-\alpha}^{(d)}\right) = \int_{c_{1-\alpha}^{(d)}}^{\infty} f_d(u)du \qquad \text{(Equation 8)}$$

Equation 8 states that the probability that a parameter with chi-square distribution is greater than the cutoff is equal to the integral of the chi-square probability distribution function between $c_{1-\alpha}^{d}$ and infinity.

Cutoff values may be determined from standard tables or statistical packages such as MINITAB as a function of the desired confidence $1 - \alpha$ and degrees of freedom *d*.

3.2.2.3 Determination of Test Data Standard Deviation Upper Confidence Bound

The [ ]a,c in Table 3 are regarded as independent Gaussian random variables, $X = (X_1, X_2, ...X_n)$ with unknown true mean and true standard deviation.

For the data, the upper confidence bound $\delta_n(X)$ is such that

$$P[\sigma \le \delta_n(X)] = 1 - \alpha \qquad \text{(Equation 9)}$$

In other words, the true standard deviation of the test data is less than the upper confidence bound with some level of probability or confidence equal to $1-\alpha$.

Statistical theorems state that for a series of independent Gaussian random variables $X = (X_1, X_2, ...X_n)$, the quantity $\frac{(n-1)s_n^2}{\sigma^2}$ has a chi-square distribution with (n-1) degrees of freedom (for example, see Kreyszig Section 23.3). In this parameter:

- n Number of sampled values
- s_n Estimated standard deviation from the sample, $s_n = \sqrt{\frac{1}{n-1}\sum_{j=1}^{n}(X_j - \overline{X})}$
- σ True standard deviation (σ^2 is the variance)

Applying Equation 8, since $\frac{(n-1)s_n^2}{\sigma^2}$ has a chi-square distribution, we can find $c_{1-\alpha}^{(n-1)}$ such that

$$1-\alpha = P\left[\frac{(n-1)s_n^2}{\sigma^2} \ge c_{1-\alpha}^{(n-1)}\right] = P\left[\sigma \le \sqrt{\frac{(n-1)s_n^2}{c_{1-\alpha}^{(n-1)}}}\right] \qquad \text{(Equation 10)}$$

Combining Equations 9 and 10, the upper confidence bound for sample size *n* and desired confidence $1-\alpha$ is:

$$\delta_n = \sqrt{\frac{(n-1)s_n^2}{c_{1-\alpha}^{(n-1)}}}. \qquad \text{(Equation 11)}$$

For the [ ]a,c the degrees of freedom are:
[ ]a,c

From MINITAB, the cutoff limits [ ][a,c] The cutoff limits are summarized in Table 7. Using the cutoff levels and [ ][a,c] the upper confidence bounds may be estimated. The upper confidence bounds are summarized in Table 7.

Table 7. Summary of Cutoff Limits and Upper Confidence Bounds [Based on Repeat Test Data][a,c]

a,c

Therefore, from the existing data:

[ ][a,c]

To conservatively address variation in the standard deviation in the calculation of the probability to exceed the acceptance criteria, the standard deviation may be set to the upper confidence bound at a specific confidence level.

3.3 Determination of Probability to Exceed Acceptance Criteria

In order to evaluate Equation 7 to determine the probability of an individual assembly exceeding the limiting pressure drop, the limiting pressure drop dP_{max}, constant intercept value C and standard deviation σ must be defined. Table 8 summarizes the values of these parameters of interest to the probability calculations, from the discussion in previous sections.

In Table 8 the constant intercept values of interest are taken from Table 6. The standard deviation values of interest are [

][a,c] upper bound values from Table 7.

Table 8. Summary of dP_{max}, Constant Intercept C and Standard Deviation σ for Consideration in Calculation of Probability to Exceed Acceptance Criteria

a,c

Therefore, using Equation 7 and the Table 8 values the probability to exceed the acceptance criteria may be calculated. The results of the probability calculations are summarized in Table 9.

Table 9 shows that as the confidence increases that the standard deviation is below some value, the probability to exceed the pressure drop increases.

Table 9. Simple Statistical Model Probability for an Individual Assembly to Exceed Acceptance Criteria for Varied Standard Deviation

a,c

4.0 Alternate Statistical Analysis and Additional Considerations

Additional evaluations are proposed to examine the statistical evaluation of the Table 3 dataset using the natural log of the adjusted pressure drop as the figure of merit; to consider the sensitivity of the statistical evaluation to variation in the adjusted pressure drop due changes in the scaling exponent; to consider the sensitivity of the statistical evaluation to [ ]^{a,c} to consider the assumption of normality in the Section 3.0 statistical evaluation approach; to consider additional information from AP1000 fuel assembly debris Tests 1-15; and to evaluate the distribution of adjusted pressure drop over the core fuel assemblies.

In Section 3.0 the adjusted pressure drop results were considered directly. An alternate empirical model is to consider the natural log of the adjusted pressure drop results as the figure of merit compared to the natural log of the pressure drop limit. An advantage of the natural log model is that it will not result in negative pressure drops regardless of the Gaussian noise factor examined. The test adjusted pressure drop data and corresponding natural log of the resulting adjusted pressure drop are summarized in Table 10.

WCAP-17028 Revision 4 Section 5 and Section 8 discuss the effect of the scaling exponent on the adjusted pressure drop, compared to using [ ]^{a,c} exponent values. A sensitivity calculation is performed to evaluate the impact of [

]^{a,c} on the overall probability to exceed the acceptance criteria. The adjusted pressure drop and natural log of adjusted pressure drop for the exponent sensitivity calculations are summarized in Table 11.

The linear regression results of Test 18-34 as summarized in Table 4 indicate [

]^{a,c}

In addition, the Equation 2 simple additive model and the natural log model approach assume that the distribution of the noise is Gaussian. A normality test of the adjusted pressure drop results is performed to examine the applicability of that assumption.

As discussed in Section 2.2, several parameters which were varied across the total AP1000 fuel assembly debris test matrix were held constant across the test subset of interest. Earlier AP1000 fuel assembly debris tests are considered to examine the impact on the adjusted pressure drop of some of the input parameters varied in those tests which were not varied in Tests 18-34.

The data are used to examine the distribution of adjusted pressure drop across the core.

Table 10. Summary of Test 18-34 Pressure Drop Results and Natural Log of Adjusted Pressure Drop Results

a,c

Table 11. Summary of Exponent Sensitivity Calculation Test 18-34 Adjusted Pressure Drop Results and Natural Log of Adjusted Pressure Drop Results

a,c

4.1 Alternate Simple Statistical Model – Natural Log Model

As discussed above, the Equation 2 simple additive model has the disadvantage that there is a small probability that a non-physical negative adjusted pressure drop would be calculated for a random sampling of the Gaussian noise Z. An alternate simple statistical model may be proposed:

$$\ln(dP) = C' + \sigma' * Z \qquad \text{(Equation 12)}$$

Where: a,c

Equation 12 in effect transforms the simple additive model for the adjusted pressure drop to a simple multiplicative model where the final calculated adjusted pressure drop will be positive. From Equation 12 the pressure drop may be expressed:

$$dP = \tilde{C} e^{\sigma' * Z} \qquad \text{(Equation 13)}$$

Where: a,c

The Equation 12 natural log model may be applied in the same manner as the simple additive model as discussed in Section 3.0 to analyze the Table 10 test data results. Following the method in Section 3.2 it is ultimately desired to determine the probability that the natural log of the adjusted pressure drop for an individual assembly will exceed the natural log of the pressure drop limit, as shown in Equation 14.

$$P[\ln(dP) > \ln(dP_{\max})] = P[Z > x] = 1 - \frac{1}{2}\left[1 + erf\left(\frac{x}{\sqrt{2}}\right)\right] \qquad \text{(Equation 14)}$$

$$\text{where } x = \frac{\ln(dP_{\max}) - C'}{\sigma'}$$

In order to evaluate Equation 14 the limiting pressure drop $\ln(dP_{max})$, constant intercept value C' and standard deviation σ' must be defined.

The limiting pressure drop dP_{max} is defined from the WC/T long term core cooling sensitivity calculations:

$$dP_{max} = 4.1 \text{ psid}$$

Therefore, the natural log of the pressure drop limit is:

$$\ln(dP_{max}) = \ln(4.1) = 1.41$$

The constant intercept value C' and standard deviation σ' are considered in the following sections, following the Section 3.0 method.

As for the direct pressure drop model discussed in Section 3.0, first, a linear regression analysis is performed for the natural log data in order to show that the simple natural log model in Equation 12 is appropriate based on the available data.

4.1.1 Linear Regression Analysis of Natural Log Data

A linear regression of the Table 10 natural log data is performed to examine the correlation between the natural log of the adjusted pressure drop results and the test input parameters summarized in Table 3.

In this approach, the measured output variable is the natural log of the adjusted pressure drop. The natural log of the adjusted pressure drop is postulated to be a linear function of the test input parameters in the form:

[ ][a,c] (Equation 15)

a,c

Where:

The coefficients from the natural log model linear regression analysis results and their corresponding P-values are summarized in Table 12; Table 13 summarizes the linear regression results for only the concurrent addition tests. The P-values for the natural log model are [ ][a,c] the statistical analysis proceeds per the Section 3.2 method, using the Equation 12 simple model.

a,c

Table 12. Summary of Coefficients for Natural Log Model Linear Regression Analysis

Table 13. Summary of Coefficients for Natural Log Model Linear Regression Analysis of Concurrent Addition Tests

a,c

4.1.2 Intercept Values for Natural Log Simple Model

In order to evaluate Equation 14 the constant intercept value C' must be defined.

Table 14 summarizes [

][a,c]

Table 14. Summary of Natural Log Model Constant Intercept Values [------------ --][a,c]

a,c

4.1.3 Confidence in Standard Deviation for Input to Natural Log Statistical Model

In order to evaluate Equation 14, the standard deviation must be determined. Following the Section 3.2.2 method, the nominal standard deviation is determined from the data set and upper confidence bounds are determined.

4.1.3.1 Estimate of Standard Deviation from Natural Log Dataset

The nominal standard deviation of the natural log adjusted pressure drop values in the Table 10 dataset may be estimated in two ways.

The standard deviation may be estimated from the repeat tests: [ ][a,c] Using the adjusted pressure drop data in Table 10:

[ ][a,c]

In the same manner, the standard deviation may be determined from the concurrent addition tests in Table 3:

[ ][a,c]

These are nominal estimates of the true standard deviation σ of the natural log of the test data. The magnitude of the estimates from the full dataset and the repeat tests only [are similar.][a,c] Consistent with the approach for the direct pressure drop model, the upper confidence bound on the standard deviation [ ][a,c]

4.1.3.2 Upper Bound Confidence Levels

Per the method in Section 3.2.2, using the standard deviation from the repeat test data, the upper bound confidence limits may be determined for the natural log data standard deviation. The results are summarized in Table 15.

Table 15. Summary of Cutoff Limits and Upper Confidence Bounds [ ]a,c

a,c

Therefore, from the existing data:

[ ]a,c

4.1.4 Determination of Probability to Exceed Acceptance Criteria

In order to evaluate Equation 14 to determine the probability of an individual fuel assembly exceeding the limiting pressure drop, the limiting pressure drop dP_{max}, constant intercept C' and standard deviation σ' for the Equation 12 natural log model must be defined. Table 16 summarizes the values of these parameters of interest to the probability calculations from the development in previous sections.

Table 16. Summary of dP_{max}, Constant Intercept C' and Standard Deviation σ' for Consideration in Calculation of Probability for an Individual Assembly to Exceed Acceptance Criteria for Natural Log Model

a,c

Therefore, using Equation 14 and the Table 16 values the probability for an individual assembly to exceed the acceptance criteria may be calculated. The results of the probability calculations are summarized in Table 17.

Table 17 shows, consistent with the direct pressure drop model calculations, as the confidence increases that the standard deviation is below some value, the probability to exceed the pressure drop increases.

Table 17. Simple Statistical Model Probability for an Individual Assembly to Exceed Acceptance Criteria for Varied Standard Deviation a,c

4.2 Exponent Sensitivity Calculations for Probability to Exceed Acceptance Criteria

The methodology presented in Section 3.0 and Section 4.1 is followed to perform a sensitivity calculation of the probability for an individual assembly to exceed the acceptance criteria using the data presented in Table 11. Both the pressure drop model and natural log pressure drop model are considered.

4.2.1 Linear Regression

Linear regression analyses of the Table 11 adjusted pressure drop data and natural log adjusted pressure drop data, using the test input parameter summarized in Table 3, shows that the P-values [

]a,c

4.2.2 Consideration of Intercept

For these sensitivity calculations, [ ]a,c is of interest. The nominal intercept values of interest to the sensitivity calculations for the pressure drop and natural log pressure drop models are summarized in Table 18.

Table 18. Summary of Constant Intercept Value of Interest in Exponent Sensitivity Calculations

a,c

4.2.3 Upper Bound Standard Deviation Values

Table 19 summarizes the standard deviation [ ]a,c sensitivity data presented in Table 11. Table 20 and Table 21 summarize the upper bound confidence limits for the pressure drop and natural log pressure drop sensitivity calculations, respectively.

Table 19. Summary of Nominal Standard Deviation - Exponent Sensitivity Calculations

a.c

Table 20. Summary of Cutoff Limits and Upper Confidence Bounds [ ]^a,c – Adjusted Pressure Drop Exponent Sensitivity

a,c

Table 21. Summary of Cutoff Limits and Upper Confidence Bounds [ ]^a,c – Natural Log Adjusted Pressure Drop Exponent Sensitivity

a,c

4.2.4 Probability to Exceed the Acceptance Criteria

Using the intercept and standard deviation values summarized in Table 18, Table 20, and Table 21 the probability for an individual assembly to exceed the acceptance criteria for the sensitivity calculations is determined. The probability to exceed the acceptance criteria are summarized in Table 22 and Table 23 for the adjusted pressure drop and natural log adjusted pressure drop sensitivity calculations, respectively.

Comparison of the Table 22 and Table 23 sensitivity results to the nominal intercept results shown in Table 9 and Table 17 for the pressure drop and natural log pressure drop models, respectively, shows [

]^a,c

Table 22. Probability for an Individual Assembly to Exceed Acceptance Criteria – Adjusted Pressure Drop Exponent Sensitivity

a,c

Table 23. Probability for an Individual Assembly to Exceed Acceptance Criteria – Natural Log Adjusted Pressure Drop Exponent Sensitivity

a,c

4.3 Sensitivity Calculations for [ ]^a,c

[

]^a,c a sensitivity analysis of Tests 18-34 data summarized in Table 3 and Table 10, considering [ ]^a,c is performed.

4.3.1 Linear Regression

As the linear regression analysis of Tests 18-34 showed [

]^a,c The results of this regression approach are summarized in Table 24 and Table 25 for the pressure drop and natural log pressure drop data, respectively. Table 24 and Table 25 show that [

]^a,c

Inspection of Table 4 and Table 5 [

]^a,c

Table 24. Summary of Coefficients for Sensitivity Test 18-34 Linear Regression Analysis – [ ]^a,c

a,c

Table 25. Summary of Coefficients for Sensitivity Test 18-34 Natural Log Model Linear Regression Analysis – [ ]^a,c

a,c

4.3.2 Consideration of Intercept

For these sensitivity calculations [

]a,c Therefore, for the adjusted pressure drop and natural log adjusted pressure drop models, [ ]a,c respectively:

[ ]a,c (Equation 16a)

[ ]a,c (Equation 16b)

[

]a,c

Therefore, the intercept values of interest to the sensitivity calculations for the pressure drop and natural log pressure drop models are summarized in Table 26.

Table 26. Summary of Constant Intercept Value of Interest [ ]a,c Test 18-34 Sensitivity Calculations

a,c

4.3.3 Upper Bound Standard Deviation Values

Using [ ]a,c the upper bound standard deviation values summarized in Table 7 and Table 15 are applicable for this sensitivity calculation.

4.3.4 Probability to Exceed the Acceptance Criteria

Using the intercept and standard deviation values summarized in Table 26, Table 7 and Table 15 the probability for an individual assembly to exceed the acceptance criteria for the sensitivity calculations is determined. The probability to exceed the acceptance criteria are summarized in Table 27 and Table 28 for the adjusted pressure drop and natural log adjusted pressure drop sensitivity calculations, respectively.

Comparison of the Table 27 and Table 28 sensitivity results to the nominal intercept results shown in Table 9 and Table 17 for the pressure drop and natural log pressure drop models, respectively, [

]a,c

Table 27. Probability for an Individual Assembly to Exceed Acceptance Criteria – Adjusted Pressure Drop [ ]^{a,c}

a,c

Table 28. Probability for an Individual Assembly to Exceed Acceptance Criteria – Natural Log Adjusted Pressure Drop [ ]^{a,c}

a,c

4.4 Normality of the Test Data Results

MINITAB was used to perform normality tests of the Table 10 concurrent addition test adjusted pressure drop results and natural log of the adjusted pressure drop results. The plotted results are shown in Figure 2 and Figure 3, respectively. In this test the null hypothesis is that the data follows a normal distribution and therefore the hypothesis being tested is that the data do not follow a normal distribution.

The normality test on [ ]^{a,c} concurrent addition test adjusted pressure drop and natural log of adjusted pressure drop results indicate [ ]^{a,c}

The normality test of the concurrent addition test adjusted pressure drop and natural log adjusted pressure drop sensitivity data shown in Table 11 [ ]^{a,c}

[ ]^{a,c} It is concluded that the assumption that the data follow a normal Gaussian distribution [ ]^{a,c}

a,c

Figure 2. Normality Test of Table 10 Concurrent Addition Adjusted Pressure Drop Results

a,c

Figure 3. Normality Test of Table 10 Concurrent Addition Natural Log of Adjusted Pressure Drop Results

4.5 Linear Regression Analysis of AP1000 Fuel Assembly Debris Tests 1-15

As discussed in Section 2.2, several parameters which were varied across the total AP1000 fuel assembly debris test matrix were held constant across Tests 18-34. [

]a,c Therefore, a different subset of AP1000 tests is identified and a linear regression analysis is performed to examine whether the data indicates that these input parameters have a statistically significant effect on predicting the adjusted pressure drop results.

4.5.1 Selection of Test Subset of Interest

In order to examine the effects on the adjusted pressure drop of input parameters held constant across Tests 18-34, [ ]a,c a different subset of tests of interest for this linear regression is identified.

[ ]a,c AP1000 fuel assembly debris Tests 1-16; therefore the characteristics of these tests are considered. All of these tests were sequential addition tests. [ ]a,c

[ ] a,c

Note that Tests 7 and 12 are excluded from the subset as invalid tests. Test 7 is eliminated due to a modification on the test loop that reduced the flow to the test column below allowable levels. Test 12 is eliminated because the chemicals were not mixed outside of the loop; the in-loop mixing of chemicals resulted in significant flow anomalies during the test.

[ ]a,c

1. [ ]a,c
2. [ ]a,c

Therefore, in order to examine the effects on the adjusted pressure drop of input parameters held constant across Tests 18-34, the subset of Tests 1-15, excluding invalid Tests 7 and 12, is of interest.

4.5.2 Characterization of Tests 1-15 Excluding Tests 7, 12

For the linear regression, the varied parameters across Tests 1-15, excluding Tests 7 and 12, are characterized. [

]a,c

[

]a,c

[ ] a,c

Therefore, the data for linear regression of Tests 1-15 is summarized in Table 29.

Table 29. Summary of Parameters of Interest for Linear Regression of Tests 1-15 Excluding Tests 7, 12

[ ] a,c

4.5.3 Linear Regression Results of Tests 1-15 Excluding Tests 7, 12

Similar to the linear regressions discussed in Section 3.1 and Section 4.1.1 a linear regression is performed on the adjusted pressure drop from Tests 1-15 excluding Tests 7, 12, based on the varied input parameters summarized in Table 29. The coefficients and associated P-values from the linear regression are summarized in Table 30.

Inspection of Table 30 shows [

][a,c]

Table 30. Summary of Coefficients for Linear Regression Analysis of Table 29 Data for Tests 1-15 Excluding Tests 7, 12

a,c

4.6 Distribution of Adjusted Pressure Drop Across the Core and Effective Core Inlet Resistance

As discussed in Section 2.3, the adjusted pressure drop data shown in Table 3 and Table 10 are effectively a measure of the debris bed resistance. In Section 3.0 and Section 4.1 the AP1000 fuel assembly test data were used to calculate the probability that an assembly in the core would have a debris bed resistance such that the limiting pressure drop criteria would be exceeded. This approach is extended to calculate the distribution of adjusted pressure drop across all 157 fuel assemblies in the core following a LOCA and the effective core inlet resistance.

4.6.1 Discrete Distribution of Adjusted Pressure Drop Across the Core

The concurrent addition test data may be considered as samples of adjusted pressure drop, or the debris bed resistance, from 12 of the 157 fuel assemblies in the core. The probability for any one assembly to exceed the adjusted pressure drop criterion, with either the pressure drop or natural log pressure drop models, is based on the assumption that the test data follow a normal distribution. The normal distribution assumption [ ]a,c as discussed in Section 4.4. Therefore, [ ]a,c

[ ]a,c The mean and standard deviation [ ]a,c are summarized in Table 31.

The cumulative distribution function (CDF) of [ ]a,c with mean and standard deviation as given in Table 31 may be used to identify the characteristic adjusted pressure drop for a discrete percentage of the fuel assemblies in the core. For the purpose of determining a discrete census to describe the adjusted pressure drop distribution across the core inlet, eight bins are defined.

- Bins 1, 2: [ ]a,c
- Bins 3-6: [ ]a,c
- Bin 7: [ ]a,c
- Bin 8: [ ]a,c

The distribution of adjusted pressure drop across the core inlet based on the above approach is summarized in Table 32. The conversion of [ ]a,c to the discrete census is visually shown in Figure 4. The discrete census is a conservative representation of the continuous [

]a,c

Table 31. Mean and Standard Deviation of [ ]a,c for Calculation of Core Inlet Effective Resistance

a,c

Table 32. Distribution of Adjusted Pressure Drop Across the Core Fuel Assemblies

a,c

a,c

Figure 4. Conversion of [ ]a,c CDF to Discrete Census for Calculation of Effective Core Inlet Resistance

4.6.2 Core Inlet Pressure Drop

The AP1000 concurrent debris addition tests show that the fuel assembly resistance measurements are quite variable (WCAP-17028-P Revision 4). Considering the range of adjusted pressure drop results observed in the tests, there is strong support for the premise that following a LOCA the 157 fuel assemblies will experience significant variability in their flow resistances. Consistent with the results of Section 4.6.1, [

]^{a,c} Based on this distribution, a discrete distribution which groups the fuel assemblies into eight bins was developed; each bin [
]^{a,c} at the minimum core flow of 3.1 gpm per assembly (based on the long term core cooling safety analysis results.)

Using the conservative discrete census summarized in Table 32, the pressure drop at the core inlet at the minimum core flow of 65 lbm/s (3.1 gpm per assembly) is calculated. The following assumptions are made in this calculation:

1. The pressure drop across [ ]^{a,c} is the same for each fuel assembly in the core. [
]^{a,c}
2. The total core flow is the sum of the flow through each fuel assembly. Similarly the total flow for a bin of fuel assemblies is the sum of the flow through the number of fuel assemblies in the bin.
3. The pressure drop, dP, across each fuel assembly is a function of the flow resistance, R, of that fuel assembly times the flow rate through the fuel assembly, Q, raised to an exponent, e.
4. The exponent , e, [
]^{a,c}

The pressure drop across each fuel assembly is:

$$dP_i = R_i Q_i^e \qquad \text{(Equation 17a)}$$

Rearranging:

$$Q_i = \left(\frac{dP_i}{R_i}\right)^{1/e} \qquad \text{(Equation 17b)}$$

or

$$R_i = \frac{dP_i}{Q_i^e} \qquad \text{(Equation 17c)}$$

The total flow through N parallel assemblies in a bin is the sum of the flow through each assembly:

$$Q_B = Q_1 + Q_2 + \ldots + Q_N \qquad \text{(Equation 18)}$$

The pressure drop across each assembly is equal:

$$dP = dP_1 = dP_2 = \ldots = dP_N \qquad \text{(Equation 19)}$$

Substituting Equation 17b, Equation 19 into Equation 18 and raising to the exponent:

$$Q_B = \left(\frac{dP_1}{R_1}\right)^{1/e} + \left(\frac{dP_2}{R_2}\right)^{1/e} + \ldots + \left(\frac{dP_N}{R_N}\right)^{1/e} \qquad \text{(Equation 20)}$$

$$Q_B = dP^{1/e}\left[\frac{1}{R_1^{1/e}} + \frac{1}{R_2^{1/e}} + \ldots + \frac{1}{R_N^{1/e}}\right] \qquad \text{(Equation 21)}$$

$$Q_B^e = dP\left[\frac{1}{R_1^{1/e}} + \frac{1}{R_2^{1/e}} + \ldots + \frac{1}{R_N^{1/e}}\right]^e \qquad \text{(Equation 22)}$$

From Equation 17b, therefore, the equivalent resistance for the bin is:

$$R_{B,i} = \frac{1}{\left[\frac{1}{R_1^{1/e}} + \frac{1}{R_2^{1/e}} + \ldots + \frac{1}{R_N^{1/e}}\right]^e} \qquad \text{(Equation 23)}$$

If the resistance of each assembly in the bin is equal, consistent with the discrete distribution of assemblies summarized in Table 32:

$$R_{B,i} = \frac{R_i}{N^e} \qquad \text{(Equation 24)}$$

where R_i is the resistance of each assembly in the bin: $R_i = R_1 = R_2 = \ldots = R_N$

The resistance of each assembly in the bin may be determined from Equation 17c where dP_i is the characteristic adjusted pressure drop for each assembly in the bin and Q_i is the corresponding 3.1 gpm flow per assembly. Therefore, substituting Equation 17c into Equation 24:

$$R_B = \frac{dP_i}{Q_i^e N^e} \qquad \text{(Equation 25)}$$

The resistance of each bin of assemblies is summarized in Table 33.

The approach in Equations 17-23 is general and therefore Equation 23 is used to calculate the effective core inlet resistance now that the resistance of each bin is known.

$$R_{core} = \frac{1}{\left[\frac{1}{R_1^{1/e}} + \frac{1}{R_2^{1/e}} + \ldots + \frac{1}{R_8^{1/e}}\right]^e} \qquad \text{(Equation 26)}$$

Using the bin resistances summarized in Table 33:

[ ]a,c

Using the core inlet resistance, the pressure drop across the core inlet at the minimum core flow of 65 lb/s may be calculated using Equation 17a where Q_{core} = 3.1 gpm * 157 fuel assemblies:

[ ][a,c]

[ ][a,c]

Using the discrete census shown in Table 32, Table 33, the effective adjusted pressure drop at the core inlet [ ][a,c] Considering the conservative development of the distribution [ ][a,c] this demonstrates considerable margin to the safety analysis limit of 4.1 psid.

[a,c

Table 33. Effective Bin Resistance

]

5.0 Summary of Conservatisms in Statistical Analysis Approach

There are four main conservatisms in the statistical analysis approach:

1. Bias of the test matrix
   The Table 3 test matrix and in particular the concurrent addition tests are biased towards high adjusted pressure drop results. As the AP1000 fuel assembly debris tests progressed, different parameters were bounded in subsequent tests. In the subset of tests analyzed, most notably [ ]^{a,c} derived from the design basis amount. In addition, the analyzed test matrix includes [ ]^{a,c} repeat tests which were performed at the conditions of Test 27, which had the highest adjusted pressure drop from Tests 1-28. The repeat testing of the case with highest adjusted pressure drop conservatively biases the average maximum adjusted pressure drop from the test matrix.

2. Application of upper bound estimates of the standard deviation
   In order to estimate the probability of exceeding the pressure drop limit, the upper bound standard deviation values at various confidence levels is considered.

3. Expected non-uniform debris bed buildup in plant
   The fuel assembly debris tests were performed for a single fuel assembly. Considering [ ]^{a,c} it is reasonable to conclude that debris bed buildup at the bottom nozzles of the 157 fuel assemblies will not result in a uniform resistance at the core inlet. In the open lattice of the core, cross flow is expected at the bottom of the core from assemblies with lower inlet resistance to assemblies with higher inlet resistance.

4. Consideration of temperature and coolant chemistry
   Tests 36 and 37 were performed [ ]^{a,c} to reflect conditions which are more prototypic of post-LOCA conditions at the plant.

   Test 36 and 37 had low adjusted pressure drops, [ ]^{a,c}

6.0 Summary of Results

The AP1000 fuel assembly test data were examined and the subset of tests of interest for the statistical analysis were identified (Test 18-34). From the linear regression results of the adjusted pressure drop and natural log of the adjusted pressure drop data, [ ]^{a,c} and the dataset of interest was further refined to the concurrent addition tests from Tests 18-34. A separate study of earlier AP1000 fuel assembly tests (Test 1-15) indicated [ ]^{a,c} Therefore, simple additive and multiplicative models were set up to model the adjusted pressure drop as a function of a constant and a Gaussian noise factor. The constant [ ]^{a,c} upper bound confidence levels on the standard deviation of the test data were determined. For the direct pressure drop model (additive model) and the natural log pressure drop model (multiplicative model) the probability to exceed the acceptance criteria were determined for different confidences levels on the upper bound standard deviation.

Table 9 and Table 17 summarize the probability for an individual assembly to exceed the acceptance criteria for the direct pressure drop model and the natural log model, respectively; the results are summarized below. As the confidence in the upper bound standard deviation increases the probability to exceed the acceptance criteria increases. Sensitivity calculations with the direct pressure drop and natural log pressure drop models to examine first the effect of [ ]^{a,c} and then the effect of [ ]^{a,c} compared to [ ]^{a,c} exponent values.

a,c

The pressure drop model results showed [ ]^{a,c} The natural log pressure drop results [ ]^{a,c}

There are four primary conservatisms in this analysis: (1) the dataset of Tests 18-34 and in particular the concurrent addition tests are biased for higher adjusted pressure drop results; (2) upper bound standard deviations are examined; (3) in the plant, non-uniform debris bed buildup across the 157 fuel assemblies is expected and the effective core inlet resistance is expected to be considerably less than the safety analysis limit; and (4) the results of Tests 36 and 37 qualitatively indicate that at more prototypic post-LOCA conditions [

]^{a,c} lower adjusted pressure drop results are expected. Therefore considering these conservatisms and the results of the pressure drop and natural log pressure drop model analyses, following a cold leg or DVI break loss of coolant accident in the AP1000 there is low probability that debris bed buildup will be such that core cooling and core boron concentration limits will be exceeded.

Based on the test data and consistent with the statistical analysis results, a conservative distribution of the adjusted pressure drop across the core was developed. Using this conservative distribution, the effective adjusted pressure drop at the core inlet is [

]^{a,c} This demonstrates considerable margin to the safety analysis limit of 4.1 psid with core flow of 65 lb/s.

7.0 References

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