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June 30, 2005

United States Nuclear Regulatory Commission
Attention: Document Control Desk
Washington, D.C. 20555

Serial No. 05-328
NL&OS/ETS: R0
Docket Nos. 50-280/281
50-338/339
50-336/423
License Nos. DPR-32/37
NPF-4/7
DPR-65/NPF-49

VIRGINIA ELECTRIC AND POWER COMPANY (DOMINION)
DOMINION NUCLEAR CONNECTICUT, INC. (DNC)
NORTH ANNA AND SURRY POWER STATIONS UNITS 1 AND 2
MILLSTONE POWER STATION UNITS 2 AND 3
REQUEST FOR ADDITIONAL INFORMATION ON
TOPICAL REPORT DOM-NAF-2:
REACTOR CORE THERMAL-HYDRAULICS USING THE VIPRE-D COMPUTER CODE
INCLUDING APPENDICES A AND B

In letters dated September 30, 2004 and January 13, 2005 (Serial Nos. 04-606 and 05-020, respectively), Dominion and DNC submitted the Topical Report DOM-NAF-2, "Reactor Core Thermal-Hydraulics Using the VIPRE-D Computer Code" and associated Appendices A and B, for NRC review and approval. VIPRE-01 is a core thermal-hydraulics computer code developed by EPRI, approved by the NRC, and currently in use throughout the nuclear industry. VIPRE-D is the Dominion version of VIPRE-01, which has been enhanced by the addition of several vendor specific CHF correlations. In a May 19, 2005 letter, the NRC requested additional information to complete their review of VIPRE-D and the associated appendices.

On May 25, 2005 Dominion and NRC held a public meeting on VIPRE-D licensing issues at which Dominion discussed the proposed scope for the RAIs. The NRC staff agreed that the proposed scope for the responses was acceptable. The attachment to this letter provides the detailed responses discussed in the scope at the public meeting, including appropriate references and supporting information. If you have further questions or require additional information, please contact Mr. Thomas Shaub at (804) 273-2763.

Very truly yours,

Eugene S. Grecheck
Vice President – Nuclear Support Services
Virginia Electric and Power Company
Dominion Nuclear Connecticut, Inc.

Attachment

Commitments made in this letter: None

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Serial No. 05-328
Docket Nos. 50-280/281/338/339/336/423

COMMONWEALTH OF VIRGINIA)
)
COUNTY OF HENRICO)

The foregoing document was acknowledged before me, in and for the County and Commonwealth aforesaid, today by Eugene S. Grecheck who is Vice President – Nuclear Support Services, of Virginia Electric and Power Company and Dominion Nuclear Connecticut, Inc. He has affirmed before me that he is duly authorized to execute and file the foregoing document in behalf of these companies, and that the statements in the document are true to the best of his knowledge and belief.

Acknowledged before me this 30th day of June, 2005.

My Commission Expires: August 31, 2008.

Margaret B. Bennett
Notary Public

(SEAL)

Attachment

(Serial No. 05-328)

Request for Additional Information

Topical Report DOM-NAF-2
Reactor Core Thermal-Hydraulics Using the
VIPRE-D Computer Code

Virginia Electric and Power Company (Dominion)
Dominion Nuclear Connecticut (DNC)

REQUEST FOR ADDITIONAL INFORMATION

PROPOSED TOPICAL REPORT DOM-NAF-2

VIRGINIA ELECTRIC AND POWER COMPANY (DOMINION)

DOMINION NUCLEAR CONNECTICUT (DNC)

NRC Question 1

Departure from Nucleate Boiling Ratio (DNBR) is sensitive to the turbulent mixing coefficient, Please justify the value of the turbulent mixing coefficient. Stating it is conservative is insufficient. Please show the sensitivity of the DNBR to the turbulent mixing coefficient.

Dominion/DNC Response:

The turbulent mixing coefficient (ABETA) is obtained empirically by the fuel vendor. Both AREVA and Westinghouse have conducted several subchannel mixing tests in pressurized water loops at Reynolds numbers similar to that of a PWR core under single phase and two-phase flow conditions (References 13, 14, 15) to determine ABETA. It has been determined experimentally that the value of ABETA is a function of grid spacing, and as such, it is dependent on the fuel product design. A turbulent mixing coefficient value of 0.038 has been validated by the NRC for analyzing Westinghouse 17 x 17 and 15 x 15 fuel assemblies with mixing vane grids having a spacer span of 26 inches or less (Reference 15). The Dominion submittal for the AREVA Fuel Transition (Section 4.2.5 in Reference 5) documented a turbulent mixing coefficient of 0.038 for the AREVA Advanced Mark-BW fuel. Therefore, a turbulent mixing coefficient value of 0.038 is applicable to current AREVA and Westinghouse fuel designs, and will be used by Dominion in VIPRE-D models for current fuel products. The turbulent mixing coefficient used by VIPRE-D models for future fuel designs will be provided by the fuel vendor.

As agreed during the May 25, 2005 Dominion-NRC public meeting, the sensitivity of the DNBR to the turbulent mixing coefficient has not been provided herein.

NRC Question 2

Please describe the basis for the use of the drift flux correlations employed as part of the Electric Power Research Institute (EPRI) void model. Please describe the flow regime/regimes that the EPRI drift velocity correlation is applicable to and show that this applies to the flow regimes experienced during DNB in the plant analyses. Comparisons of the drift velocity correlation/correlations to void data in rod bundles and small pipes would be desirable. This could be done using all other particular inputs and correlation choices (and code corrections) included to show the effect/ability to continue to predict the test data presented in Volume 4 of the VIPRE Manual entitled "Applications" dated 1987. Since

the EPRI void model appears to employ only the drift velocity correlation applicable to churn turbulent bubbly flow (for void fractions less than 0.3), please explain and justify why this correlation is applied to slug and annular flow where Critical Heat Flux (CHF) can occur. Define the limitations of the drift flux correlations (i.e. pressure range, flow conditions, etc.). What distribution parameter is assumed? Since more voiding may occur near the walls of the hot rods, how does the distribution parameter account for this condition in the drift flux modeling? Please explain.

Dominion/DNC Response:

VIPRE-01 has been approved by the NRC (References 10 and 11). VIPRE-D, which is based upon VIPRE-01, MOD-02.1, was developed by Dominion to fit the specific needs of Dominion's nuclear plants and fuel products by adding vendor specific CHF correlations and customizing its input and output. Dominion, however, has not made any modifications to the NRC-approved constitutive models and algorithms in VIPRE-01. Therefore, none of the models for bulk void, subcooled void and two-phase friction factor present in VIPRE-01 has been modified in any way in VIPRE-D, including the EPRI models.

The EPRI models for bulk void, subcooled void and two-phase friction factor are described in detail in the VIPRE-01 documentation (Section 2.6 of Reference 16 and Section 2.7 of Reference 7), including their underlying assumptions and ranges of validity. Sections 2.5 and 3.0 of Reference 9 document the VIPRE-01 comparisons performed by the code developer. VIPRE-01 two-phase friction factor models were evaluated against experimental data from the FRIGG rod bundle test loop. VIPRE-01 void models were evaluated against experimental data from the FRIGG rod bundle test loop, ANL void test and Martin void measurements at high pressure. The comparisons show that although all the models available in VIPRE-01 match the experimental data reasonably well, the EPRI set of correlations compare more favorably with the measured data. In consequence, the EPRI models for bulk void, subcooled void and two-phase friction factor are the default selections in VIPRE-01 for PWR analysis.

Based on the evaluation of the benchmark calculations discussed above, NRC staff concluded that the EPRI models for bulk void, subcooled void and two-phase friction are acceptable for use in licensing calculations (Reference 10).

The benchmark studies mentioned above, as well as the NRC approval of the EPRI models provided Dominion a good starting point for the selection of void and two-phase friction multiplier models. In addition, Dominion performed another sensitivity study to determine the most suitable set of models for Dominion applications. This sensitivity analysis, which is summarized in Section 5.4 of DOM-NAF-2, provides justification for Dominion's modeling selections, thus fulfilling condition (3) of the SER for VIPRE-01 MOD-01 (Reference 10).

Dominion performed a detailed analysis of the correlations available in the code, and four sets of correlations were chosen based on the compatibility of the modeling assumptions used in deriving the various correlations. The selected sets use together only those correlations that have consistent or complementary bases and take advantage of previous industry experience and vendor recommendations. The four cases studied were:

- Case 1 (EEE)
  Subcooled Void Model: EPRI
  Bulk Boiling Void Model: EPRI
  Two-Phase Friction Multiplier: EPRI

- Case 2 (LSE)
  Subcooled Void Model: LEVY
  Bulk Boiling Void Model: SMITH
  Two-Phase Friction Multiplier: EPRI

- Case 3 (LHH)
  Subcooled Void Model: LEVY
  Bulk Boiling Void Model: HOMOGENEOUS
  Two-Phase Friction Multiplier: HOMOGENEOUS

- Case 4 (LSH)
  Subcooled Void Model: LEVY
  Bulk Boiling Void Model: SMITH
  Two-Phase Friction Multiplier: HOMOGENEOUS

Although other relevant parameters such as void fraction or quality were verified throughout the benchmark evaluation, Dominion's acceptance criterion was based on the DNBR performance of the analyzed cases. The EPRI models for bulk void, subcooled void and two-phase friction factor provided the best DNBR comparison for all the following:

- VIPRE-D/BWU against the CHF experimental database for the AREVA BWU CHF correlations (DOM-NAF-2 Appendix A).
- VIPRE-D/BWU against the LYNXT/BWU code results for a set of representative operating conditions (DOM-NAF-2 Section 5.0)
- VIPRE-D/WRB-1 against the CHF experimental database for the Westinghouse WRB-1 CHF correlation (DOM-NAF-2 Appendix B).
- VIPRE-D/WRB-1 against the COBRA/WRB-1 code results for a set of representative operating conditions (DOM-NAF-2 Appendix B Section B.7).

Consistent with the results of these external and in-house benchmark studies, Dominion has demonstrated that the selection of the EPRI set of void and two-phase friction models is acceptable for application in DOM-NAF-2.

During the May 25, 2005 NRC-Dominion public meeting, Dominion agreed to provide some graphic comparisons to show VIPRE-D's performance for void fraction and quality. Figures 1 and 2 provide a comparison between the VIPRE-D/WRB-1 and the COBRA/WRB-1 codes. In particular, these figures show the void fraction and quality axial distributions in the hot channel at the time of minimum DNBR (3.0 seconds) for a Locked Rotor Transient event at Surry Power Station. Additional description and results associated with this transient were included in Section B.7.3 of Appendix B to DOM-NAF-2. In addition to the VIPRE-D/WRB-1 with the EPRI-EPRI-EPRI set of models, Figures 1

and 2 show VIPRE-D/WRB-1 with the LEVI-SMITH-HOMOGENEOUS set of models, which is the set of bulk void, subcooled void and two-phase friction models closest to COBRA/WRB-1 modeling in Reference 12 (LEVY-SMITH-BAROCZY).

Figures 1 and 2 show that the different void and two-phase friction models result in comparable void fraction and quality trends for COBRA and VIPRE-D. However, as noted above, DNBR comparisons are the main criterion used to evaluate the performance of VIPRE-D against other thermal-hydraulics codes and models. These comparisons demonstrated the acceptability of the EPRI models for bulk void, subcooled void and two-phase friction factor for use in the Dominion VIPRE-D models.

Figure 1: Locked Rotor Transient Equilibrium Quality Results at Time 3.0 Seconds

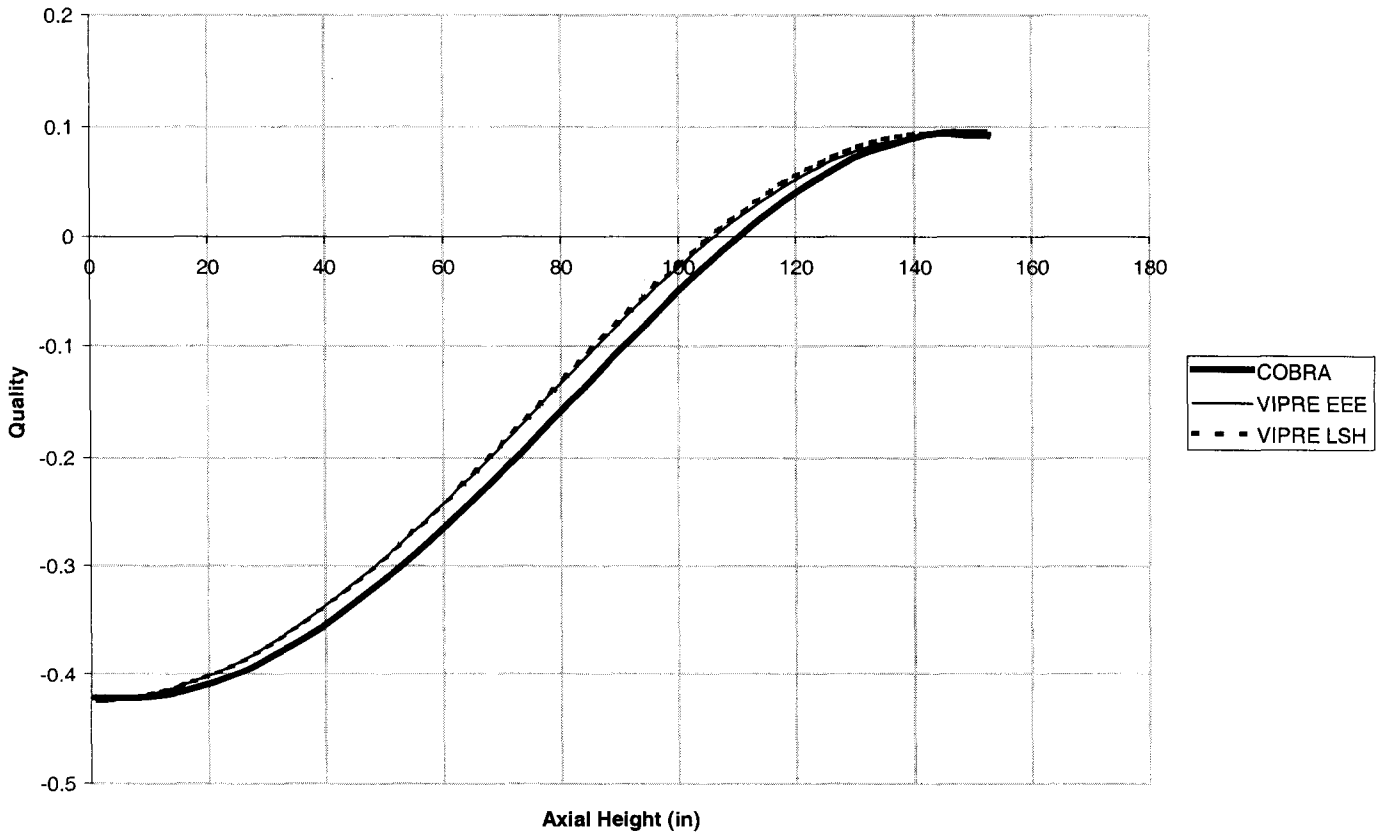
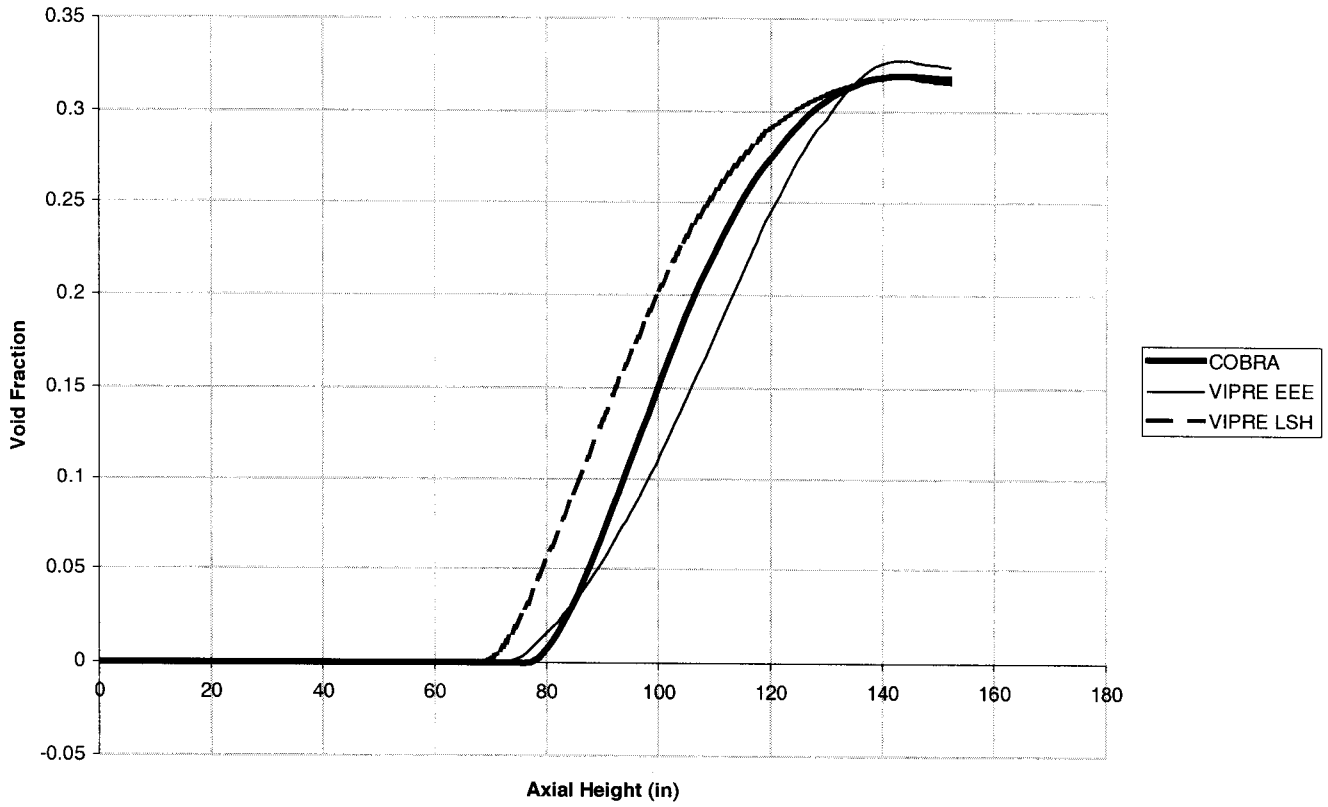


Figure 2: Locked Rotor Transient Void Fraction Results at Time 3.0 Seconds



NRC Question 3

Please explain the basis for choosing the EPRI bulk void model. Please describe the transient test cases employed to determine the values given in Table 5.4-1 and show the void distributions for the VIPRE and LYNXT codes at the initiation of DNB in some example cases. Also provide justification for the choice of the subcooled boiling model as well as the two-phase friction multiplier. Please show comparisons of the VIPRE-D code to data for these models. Please also describe the limitations and identify the ranges of applicability of each of these correlations.

Dominion/DNC Response:

The basis for choosing the EPRI bulk void, subcooled void and two-phase friction multiplier models is provided in the response to Question 2.

The transient test cases employed to determine the values in Table 5.4-1 of DOM-NAF-2 are the same statepoints that were used in Section 5.1 of DOM-NAF-2 to benchmark VIPRE-D/BWU against LYNXT/BWU, and were also used to support the Licensing Amendment Request (LAR) for the Framatome ANP Fuel Transition (Reference 5). These statepoints were obtained from the UFSAR Chapter 15 events including the reactor core safety limits, axial offset envelopes (AO's), rod withdrawal at power (RWAP), rod withdrawal from subcritical (RWSC), control rod misalignment, loss of flow accident (LOFA), and locked rotor accident (LOCROT) events. These various statepoints provide sensitivity of DNB performance to the following: (a) power level (including the impact of the part-power multiplier on the allowable hot rod power FΔH), pressure and temperature (reactor core safety limits); (b) axial power shapes (AOs); (c) elevated hot rod power (misaligned rod); and (d) low flow (LOFA and LOCROT). These statepoints cover the full range of conditions and axial offsets in UFSAR Chapter 15 evaluations (except for MSLB that was evaluated separately), and were specifically selected to challenge the three BWU CHF correlations.

In the May 25, 2004 NRC-Dominion public meeting, Dominion indicated that LYNXT models use different (proprietary) void models, and that as a consequence, void distribution comparisons for VIPRE-D/BWU and LYNXT/BWU would not be expected to match. A comparison of the void and quality distributions for COBRA/WRB-1 and VIPRE-D/WRB-1 is provided in the response to Question 2.

NRC Question 4

In section 4.12, please explain what "nearly identical" means. Identifying the percent difference between the two results would be helpful or show the plot of the two DNBR calculations.

Dominion/DNC Response:

In the few occasions in which VIPRE-D did not converge when using the default values of the convergence criteria and damping factors, and these criteria and/or damping factors

were adjusted to ensure numerical convergence, the difference in the DNBR results reported by the code was 0.5% or less.

NRC Question 5

Section 5.3 describes a comparison with the COBRA code but states the Minimum DNBR (MDNBR) results are different because the analyses use different fuel types and CHF correlations. Please provide the latest comparisons between the codes using the same fuel type and CHF correlations. Please show the channel void distribution and quality at several selected times during the events. Show the steamline break, feedline break, and loss-of-flow events.

Dominion Response:

Section B.7 in Appendix B to Topical Report DOM-NAF-2 includes comparisons of VIPRE-D/WRB-1 with COBRA/WRB-1 for Surry Power Station. These comparisons use the same fuel type (Westinghouse 15x15 SIF) and the same CHF correlation (Westinghouse WRB-1).

The comparisons include:

- A statepoint safety analysis evaluation of 164 statepoints obtained from the Surry UFSAR Chapter 14 events, including the reactor core safety limits, axial offset envelopes (AO's), rod withdrawal at power (RWAP), rod withdrawal from subcritical (RWSC), control rod misalignment, loss of flow accident (LOFA), and locked rotor accident (LOCROT) events.
- A Main Steam Line Break statepoint application.
- A Feedwater Malfunction Transient (FWMAL).
- A Locked Rotor Transient (LOCROT).

Selected examples comparing channel void and quality distributions were provided in the answer to Question 2.

NRC Question 6

The qualification document identifies the DNBR limits for the correlations for several pressure groups. Please explain what DNBR limit is applied or how the situation is handled when the range of validity is exceeded for the other parameters identified in Table A.5.2. Please also define the quality range for the correlation.

Dominion/DNC Response:

The qualification of the BWU CHF correlations with the VIPRE-D code was performed consistent with AREVA's approved Topical Report (Reference 4). The evaluations performed for the various pressure groups as well as the resulting limits were included in Appendix A for completeness. However, Dominion will only apply the DNBR limits listed in Table A.5-1:

VIPRE-D/BWU-Z	
DNBR limit below 700 psia	1.59
DNBR limit 700 – 2,400 psia	1.20
VIPRE-D/BWU-ZM	
DNBR limit below 594 psia	1.59
DNBR limit at or above 594 psia	1.18
VIPRE-D/BWU-N	
DNBR limit below 1200 psia	1.39
DNBR limit at or above 1200 psia	1.22

The ranges of validity for the three BWU CHF correlations, including quality, are listed in Table A.5-2:

	BWU-Z	**BWU-ZM**	**BWU-N**
Pressure [psia]	400 to 2,465	400 to 2,465	788 to 2,616
Mass Velocity [Mlbm/hr-ft^2]	0.36 to 3.55	0.47 to 3.55	0.25 to 3.83
Thermodynamic Quality at CHF	Less than 0.74	Less than 0.68	Less than 0.70
Applicability	Mixing Vane Grids	Mid-Span Mixing Grids	Non-Mixing Vane Grids

The Low Flow Main Steam Line Break (MSLB) statepoint has been identified as the only event that might fall outside of the range of validity of the BWU correlations (for the mass velocity). This issue was already identified in the Framatome Fuel Transition Submittal (Reference 5). The Low Flow MSLB statepoint results in minimum DNBR values of the order of 5.8, which are obviously very far from being limiting. In this case Dominion will use the DNBR limit corresponding to the pressure at which the event takes place.

NRC Question 7

CHF is also sensitive to the axial power distribution. Since the correlations were developed from data with uniform or symmetric power distributions, please justify applicability of the correlations to the asymmetric power distributions that may be limiting in the plant calculations. Explain how the correlations are applied and describe any correction factors that may be applied to accommodate skewed distributions.

Dominion/DNC Response:

This issue is a generic concern with all CHF correlations, since these correlations were developed using a limited number of uniform and non-uniform axial power distributions. Both the AREVA BWU set of correlations (qualified with VIPRE-D in Appendix A) and

the Westinghouse WRB-1 correlation (qualified in Appendix B) include a correction factor, the F-factor proposed by Tong (Reference 8), that is used to correct for non-uniform axial power shapes. The Tong Factor has been extensively verified by both Westinghouse (Reference 6) and AREVA (Reference 4) with numerous CHF test data, that over the years have included uniform and non-uniform power shapes. The use of this F-factor has been previously approved by the NRC staff.

In addition to the verifications performed by both vendors, Dominion performed a statepoint safety analysis evaluation using symmetric and non-symmetric, positively and negatively skewed axial power shapes to benchmark VIPRE-D/BWU with LYNXT/BWU and VIPRE-D/WRB-1 with COBRA/WRB-1. The results of these evaluations do not show differences in the performance of the CHF correlations dependent on the form or uniformity of the axial power distributions.

NRC Question 8

Please justify applicability of the steady-state DNB correlations to steamline breaks since these events have rapid depressurizations where the steady-state correlations may not be applicable. These transients may also transition through slug and annular flow. As such, please justify the use of the EPRI bulk boiling drift flux model since it only applies to bubbly flow.

Dominion/DNC Response:

The issue of the applicability of steady-state CHF correlations to transient analysis is generic to all thermal hydraulics codes and CHF correlations. Section 6.7 of Reference 9 provides a study to determine the applicability of steady-state CHF correlations to transient analysis for VIPRE-01. The NRC staff review concluded that the studies have shown that the transient CHF for power ramp and flow coastdown transients are higher than the steady-state CHF, and that, except for very rapid depressurization events (LOCA), the use of CHF correlations developed with steady-state CHF data can correctly or conservatively predict the transient CHF when the instantaneous local fluid conditions are used (Reference 10).

Dominion's Main Steam Line Break (MSLB) DNBR evaluations are performed at the limiting statepoint. Dominion does not perform full DNBR transient analysis for this event. For MSLB all the DNB limiting statepoints occur after the pressurizer has drained and the upper head has flashed. Therefore, pressure is changing relatively slowly and the quasi steady-state assumption is appropriate.

The use of the EPRI bulk boiling void correlation was justified in the response to Question 2.

NRC Question 9

Please discuss whether the slip option will be used and if so justify the slip ratio employed in the DNBR calculations.

Dominion/DNC Response:

Dominion VIPRE-D models do not use the slip option.

NRC Question 10

Since the conduction model will not be used, please explain how the stored energy in the rod is accounted for. Please explain why use of the dummy rod model is conservative since the conduction model does not include the effects of gap conductance and initial stored energies. Please also describe how the heat flux is calculated for use as input to the VIPRE-D code.

Dominion/DNC Response::

Conduction models are typically used to perform fuel temperature calculations and to simulate delay of energy transport. Dominion does not plan to use VIPRE-D for these applications. The use of the dummy rod model is consistent with previously approved Dominion methodologies (Reference 12).

The use of the dummy rod model requires the user to provide the fuel rod surface heat flux as one of the operating input conditions. For steady-state statepoint analysis this value is easily calculated based on core thermal power. Fuel rod surface heat flux forcing functions for transient calculations are provided by an NRC-approved transient system code (e.g., RETRAN). Transient system codes account for fuel conduction, gap conductance, and delayed energy transport effects. Therefore, the use of the dummy rod model appropriately includes the relevant effects into the analysis.

Appendix A to DOM-NAF-2

NRC Question 1

The appropriate statistical analysis of the data, which form Tables A.3.1-1, A.3.2-1, and A.3.3-1 is an analysis of variance of a mixed-effects model.

a) Give the appropriate analysis of variance tables for these mixed-effects models.
b) Formulate the appropriate statistical hypothesis tests to justify the values for M/P and $\sigma_{M/P}$ used in Eq. A.1.1 based on the data in Tables A.3.1-1, A.3.2-1, and A.3.3-1,
c) For those cases where individual DNBR design limits were developed for each low pressure group, how were the results of the above analysis of variance taken into account?

Dominion/DNC Response:

As clarified in our May 25, 2005 meeting with the NRC staff, this question refers to Tables A.4.1-2, A.4.2-2 and A.4.3-2.

a) The qualification of the BWU CHF correlations with the VIPRE-D code was performed consistent with AREVA's approved Topical Report (Reference 4). An analysis of variance (ANOVA) test was performed for each one of the three BWU correlations. This analysis was not included in the original submission because it was not deemed to provide additional substantial information to the qualification.

   An ANOVA test divides the database in several groupings according to a given variable and then evaluates whether or not the distributions for each one of the groups appear to belong to the overall distribution. If all the groupings belong to the same distribution it can be deduced that the total population does not show a bias with respect to that particular variable Even though it was recognized that ANOVA tests cannot be used as the sole measure of the performance of a CHF correlation, they can be useful to indicate an extremely bad mismatch (very large F statistic). The variables analyzed were mass velocity, pressure, quality, test cell type and axial flux shape type.

   The results of the ANOVA tests for the BWU-Z, BWU-ZM and BWU-N correlations are provided in Tables 1 through 5. The results for the BWU-ZM (Table 3) and BWU-N (Table 4) correlations prove the ANOVA hypothesis: all the groups analyzed belong to the same distribution, i.e. there is no bias of the results regarding the analyzed variables. The results for the BWU-Z correlation (Table 1) show F values slightly above the critical value, but still reasonably small. Following the AREVA approach in Reference 4, an additional ANOVA test was performed excluding the low pressure data from the BWU-Z database. This treatment is consistent with the fact that the low pressure data were taken separately by determining a separate DNBR design limit. Table 2 summarizes the results of this second ANOVA analyses. While the values of the F statistic do decrease somewhat in most cases, they are still slightly above the critical value of F for the appropriate number of degrees of freedom. An additional ANOVA test was also performed for BWU-N without the low pressure data (Table 5), and the trends observed are the same as those shown in Table 4. For all cases, these are the same trends showed by AREVA in Reference 4.

Table 1: M/P CHF Performance by Independent Variable Grouping using the entire BWU-Z database at 95% confidence level

	Number of Data	Average M/P	Standard Deviation	Maximum M/P	Minimum M/P
Analysis by Mass Velocities					
0.5 Mlbm/hr-ft^2	9	0.9559	0.1147	1.1083	0.7833
1.0 Mlbm/hr-ft^2	90	1.0120	0.1088	1.2974	0.6980
1.5 Mlbm/hr-ft^2	97	0.9934	0.0726	1.1609	0.8321
2.0 Mlbm/hr-ft^2	134	0.9721	0.0878	1.1612	0.7717
2.5 Mlbm/hr-ft^2	85	1.0018	0.0908	1.1693	0.7667
3.0 Mlbm/hr-ft^2	71	1.0216	0.0891	1.1481	0.7261
3.5 Mlbm/hr-ft^2	42	0.9853	0.0749	1.1148	0.8387
	$F_{distribution} = 3.4995$		$F_{critical}(6,521) = 2.1159$		
Analysis by Pressures					
Below 1250 psia	64	1.0437	0.0936	1.2974	0.8342
1250 - 1649 psia	111	0.9789	0.0881	1.1683	0.7770
1650 - 1949 psia	108	0.9722	0.0916	1.1693	0.7667
1950 - 2249 psia	116	1.0089	0.0914	1.1481	0.6980
Above 2250 psia	129	0.9914	0.0796	1.1576	0.7669
	$F_{distribution} = 8.3625$		$F_{critical}(4,523) = 2.3889$		
Analysis by Qualities					
Below 5%	34	0.9634	0.0794	1.0840	0.7261
5% to 10%	84	1.0415	0.0740	1.1693	0.8306
10% to 15%	127	0.9886	0.0884	1.1576	0.7717
15% to 20%	122	0.9750	0.0774	1.1479	0.8126
20% to 25%	90	0.9755	0.0913	1.1411	0.6980
25% to 30%	29	0.9969	0.1039	1.1609	0.7669
30% to 40%	18	1.0343	0.1006	1.1642	0.8484
Above 40%	24	1.0553	0.1198	1.2974	0.8342
	$F_{distribution} = 7.9433$		$F_{critical}(7,520) = 2.0271$		
Analysis by Test Cell Type					
Unit Cell	218	1.0077	0.0894	1.1683	0.7669
Guide Tube	170	0.9849	0.0917	1.1693	0.7261
Other	140	0.9877	0.0899	1.2974	0.6980
	$F_{distribution} = 3.6760$		$F_{critical}(2,525) = 3.0128$		
All Data BWU-Z					
All Data	528	0.9950	0.0907	1.2974	0.6980

Table 2: M/P CHF Performance by Independent Variable Grouping
using the BWU-Z database without the low pressure data at 95% confidence level

	Number of Data	Average M/P	Standard Deviation	Maximum M/P	Minimum M/P
Analysis by Mass Velocities					
1.25 Mlbm/hr-ft^2	70	0.9909	0.1025	1.1457	0.6980
1.5 Mlbm/hr-ft^2	86	0.9876	0.0700	1.1576	0.8321
2.0 Mlbm/hr-ft^2	119	0.9626	0.0853	1.1492	0.7717
2.5 Mlbm/hr-ft^2	77	0.9994	0.0945	1.1693	0.7667
3.0 Mlbm/hr-ft^2	70	1.0201	0.0889	1.1481	0.7261
3.5 Mlbm/hr-ft^2	42	0.9853	0.0749	1.1148	0.8387
	$F_{distribution}$ = 4.2356		$F_{critical}(5,458)$ = 2.2337		
Analysis by Pressures					
1250 – 1649 psia	111	0.9789	0.0881	1.1683	0.7770
1650 – 1949 psia	108	0.9722	0.0916	1.1693	0.7667
1950 - 2249 psia	116	1.0089	0.0914	1.1481	0.6980
Above 2250 psia	129	0.9914	0.0796	1.1576	0.7669
	$F_{distribution}$ = 3.8436		$F_{critical}(3,460)$ = 2.6243		
Analysis by Qualities					
< 10%	116	1.0186	0.0839	1.1693	0.7261
10% - 15%	122	0.9859	0.0887	1.1576	0.7717
15% - 20%	115	0.9737	0.0787	1.1479	0.8126
> 20%	111	0.9746	0.0951	1.1411	0.6980
	$F_{distribution}$ = 6.7560		$F_{critical}(3,460)$ = 2.6243		
Analysis by Test Cell Type					
Unit Cell	188	1.0024	0.0880	1.1683	0.7669
Guide Tube	150	0.9810	0.0931	1.1693	0.7261
Other	126	0.9761	0.0805	1.1457	0.6980
	$F_{distribution}$ = 4.1660		$F_{critical}(2,461)$ = 3.0153		
BWU-Z without low pressure data					
All Data	464	0.9883	0.0883	1.1693	0.6980

Table 3: M/P CHF Performance by Independent Variable Grouping using the entire BWU-ZM database at 95% confidence level

	Number of Data	Average M/P	Standard Deviation	Maximum M/P	Minimum M/P
Analysis by Mass Velocities					
<1.25 Mlbm/hr-ft^2	36	1.0338	0.0712	1.2110	0.8828
1.5 Mlbm/hr-ft^2	32	1.0256	0.1039	1.2299	0.8142
2.0 Mlbm/hr-ft^2	41	0.9859	0.0890	1.1467	0.8255
2.5 Mlbm/hr-ft^2	18	0.9918	0.0843	1.1607	0.7793
3.0 Mlbm/hr-ft^2	10	1.0480	0.0809	1.1699	0.9612
3.5 Mlbm/hr-ft^2	11	1.0228	0.0676	1.1324	0.9195
	$F_{distribution}$ = 1.9439		$F_{critical}(5,142)$ = 2.2779		
Analysis by Pressures					
< 1000 psia	11	0.9758	0.0545	1.0749	0.8832
1000 - 1500 psia	15	1.0202	0.0840	1.2110	0.9125
1500 - 2000 psia	53	1.0249	0.0982	1.1844	0.8142
> 2000 psia	69	1.0099	0.0833	1.2299	0.7793
	$F_{distribution}$ = 1.0528		$F_{critical}(3,144)$ = 2.6674		
Analysis by Qualities					
< 10%	11	1.0004	0.0622	1.1249	0.9195
10% - 15%	39	1.0111	0.1023	1.1699	0.7793
15% - 20%	35	1.0082	0.0737	1.1680	0.8783
> 20%	63	1.0209	0.0897	1.2299	0.8496
	$F_{distribution}$ = 0.2794		$F_{critical}(3,144)$ = 2.6674		
Analysis by Test Cell Type					
Unit Cell	76	1.0230	0.1000	1.2299	0.8142
Guide Tube	72	1.0041	0.0715	1.1747	0.7793
	$F_{distribution}$ = 1.7240		$F_{critical}(1,146)$ = 3.9059		
All Data BWU-ZM					
All Data	148	1.0138	0.0875	1.2299	0.7793

Table 4: M/P CHF Performance by Independent Variable Grouping using the entire BWU-N database at 95% confidence level

	Number of Data	Average M/P	Standard Deviation	Maximum M/P	Minimum M/P
Analysis by Mass Velocities					
0.5 Mlbm/hr-ft^2	147	1.0052	0.1469	1.3507	0.6707
1.0 Mlbm/hr-ft^2	172	0.9870	0.1331	1.3251	0.6635
1.5 Mlbm/hr-ft^2	194	1.0018	0.0985	1.2983	0.7262
2.0 Mlbm/hr-ft^2	208	1.0086	0.0758	1.2541	0.7560
2.5 Mlbm/hr-ft^2	149	0.9980	0.0808	1.2061	0.7747
3.0 Mlbm/hr-ft^2	124	1.0050	0.0767	1.1845	0.8154
3.5 Mlbm/hr-ft^2	96	1.0102	0.0882	1.2826	0.8002
	$F_{distribution}$ = 0.9171		$F_{critical}(6,1083)$ = 2.1069		
Analysis by Pressures					
Below 1250 psia	40	1.0309	0.1066	1.2569	0.6985
1250 - 1649 psia	192	1.0092	0.1110	1.3251	0.7396
1650 - 1949 psia	198	0.9900	0.0999	1.3507	0.7372
1950 - 2249 psia	446	1.0021	0.1002	1.2868	0.6635
Above 2250 psia	214	1.0002	0.1069	1.3030	0.6930
	$F_{distribution}$ = 1.6829		$F_{critical}(4,1085)$ = 2.3801		
Analysis by Qualities					
Below 5%	222	1.0129	0.0788	1.1834	0.7867
5% to 10%	192	0.9993	0.0758	1.1845	0.8041
10% to 15%	234	1.0051	0.0885	1.2787	0.7372
15% to 20%	158	1.0110	0.1029	1.3030	0.7747
20% to 25%	106	0.9766	0.1393	1.3251	0.6746
25% to 30%	45	0.9821	0.1371	1.2983	0.6635
30% to 40%	56	0.9915	0.1341	1.2917	0.7264
Above 40%	77	1.0008	0.1533	1.3507	0.6707
	$F_{distribution}$ = 1.8027		$F_{critical}(7,1082)$ = 2.0180		
Analysis by Test Cell Type					
Unit Cell	553	1.0031	0.1140	1.3251	0.6635
Guide Tube	385	1.0012	0.0889	1.2003	0.6707
Intersection	152	0.9988	0.1004	1.3507	0.8002
	$F_{distribution}$ = 0.1133		$F_{critical}(2,1087)$ = 3.0040		
Analysis by Axial Flux Shape Type					
Uniform	355	0.9915	0.1200	1.3251	0.6635
Non Uniform – Symmetric	568	1.0069	0.0968	1.3507	0.6985
Non Uniform - Asymmetric	167	1.0063	0.0875	1.2003	0.7346
	$F_{distribution}$ = 2.6068		$F_{critical}(2,1087)$ = 3.0040		
All Data BWU-N					
All Data	1090	1.0018	0.1038	1.3507	0.6635

Table 5: M/P CHF Performance by Independent Variable Grouping using the BWU-N database without the low pressure data at 95% confidence level

Grouping	Number of Data	Average M/P	Standard Deviation	Maximum M/P	Minimum M/P
Analysis by Mass Velocities					
1.25 Mlbm/hr-ft^2	304	0.9945	0.1387	1.3507	0.6635
1.5 Mlbm/hr-ft^2	188	1.0001	0.0995	1.2983	0.7262
2.0 Mlbm/hr-ft^2	202	1.0074	0.0765	1.2541	0.7560
2.5 Mlbm/hr-ft^2	143	0.9961	0.0814	1.2061	0.7747
3.0 Mlbm/hr-ft^2	117	1.0040	0.0772	1.1845	0.8154
3.5 Mlbm/hr-ft^2	96	1.0102	0.0882	1.2826	0.8002
	$F_{distribution}$ = 0.6302		$F_{critical}(5,1044)$ = 2.2227		
Analysis by Pressures					
1250 – 1649 psia	192	1.0092	0.1110	1.3251	0.7396
1650 – 1949 psia	198	0.9900	0.0999	1.3507	0.7372
1950 - 2249 psia	446	1.0021	0.1002	1.2868	0.6635
Above 2250 psia	214	1.0002	0.1069	1.3030	0.6930
	$F_{distribution}$ = 1.1604		$F_{critical}(3,1046)$ = 2.6134		
Analysis by Qualities					
< 5%	222	1.0129	0.0788	1.1834	0.7867
5% - 10%	186	0.9986	0.0764	1.1845	0.8041
10% - 15%	227	1.0041	0.0891	1.2787	0.7372
15% - 20%	151	1.0076	0.1027	1.3030	0.7747
20% - 25%	102	0.9734	0.1409	1.3251	0.6746
> 25%	162	0.9924	0.1430	1.3507	0.6635
	$F_{distribution}$ = 2.4577		$F_{critical}(5,1044)$ = 2.2227		
Analysis by Test Cell Type					
Unit Cell	537	1.0033	0.1141	1.3251	0.6635
Guide Tube	385	1.0012	0.0889	1.2003	0.6707
Intersection	128	0.9884	0.0979	1.3507	0.8002
	$F_{distribution}$ = 1.0784		$F_{critical}(2,1047)$ = 3.0043		
Analysis by Axial Flux Shape Type					
Uniform	355	0.9915	0.1200	1.3251	0.6635
Non Uniform – Symmetric	528	1.0051	0.0959	1.3507	0.7045
Non Uniform - Asymmetric	167	1.0063	0.0875	1.2003	0.7346
	$F_{distribution}$ = 2.1303		$F_{critical}(2,1047)$ = 3.0043		
BWU-N without low pressure data					
All Data	1050	1.0007	0.1036	1.3507	0.6635

b) As clarified in our May 25, 2005 meeting with the NRC staff, this question refers to Eq. A.4.1.1 and Tables A.4.1-1, A.4.2-1 and A.4.3-1. The validity of this equation is based on two assumptions: 1) the average M/P is 1.0 and 2) the M/P distribution is normal. These two assumptions were demonstrated in Appendix A:

CORRELATION	AVERAGE M/P = 1.0	M/P DISTRIBUTION NORMAL
BWU-Z	Table A.4.1-1	Page A-13
BWU-ZM	Table A.4.2-1	Page A-23
BWU-N	Table A.4.3-1	Page A-33 (Hypernormal distribution, also seen by AREVA in Reference 4)

c) Different DNBR limits were developed for low pressure groups for the BWU-Z and BWU-N correlations following the guidance in Reference 4. The plots (not the ANOVA tests displayed in Tables 1 and 4 respectively) seemed to indicate a poorer performance of the correlation at low pressures, and for that reason a separate DNBR limit was calculated at low pressures. In those cases, a new ANOVA analysis was performed excluding the low-pressure data (Table 2 for BWU-Z and Table 5 for BWU-N). These ANOVA results were similar to the previous results. All Dominion results were similar to AREVA results in Reference 4.

NRC Question 2

As in Appendix B, you state that the plots show that there are no biases in the M/P ratio distributions, and that the performance of the CHF correlations is independent of the three variables of interest. The plots show a mostly uniform scatter of the data and no obvious trends or slopes. The plots again suggest but do not demonstrate that the claims made in those sentences are true. Please give the appropriate statistical analysis, that demonstrates the truth of the claim.

Dominion/DNC Response:

As discussed in the response to Question 1 for Appendix A, an ANOVA analysis was performed for each correlation to formally demonstrate that the performance of the BWU CHF correlations is not biased by the three independent variables present in the correlations (mass velocity, pressure and quality). Please refer to the response to Question 1 for analyses demonstrating no biases in the M/P distributions.

NRC Question 3

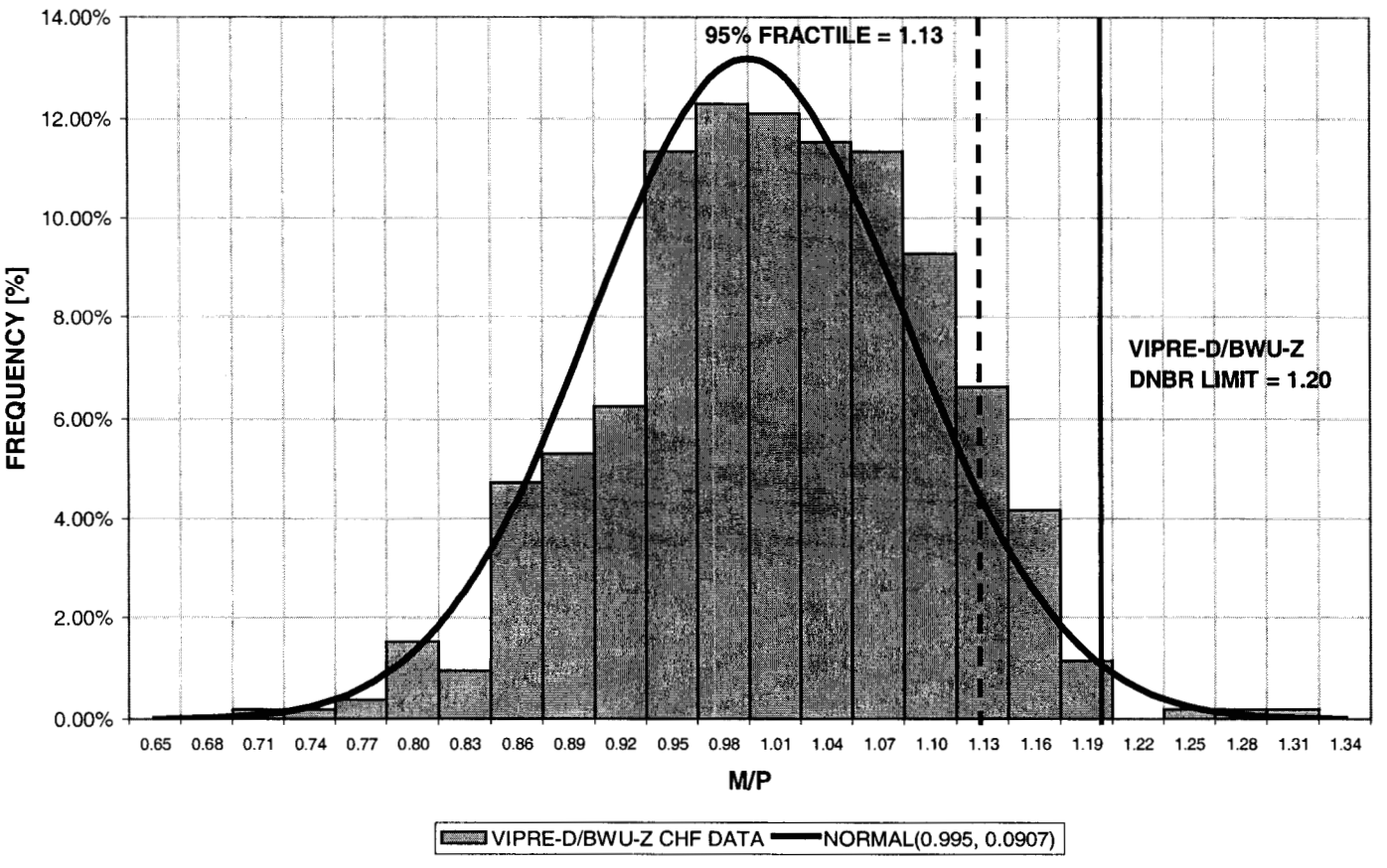
Please show the empirical probability density functions for the M/P values used in the analyses together with the estimate of the 95-percent fractile for each correlation.

Dominion/DNC Response:

The probability density functions for the BWU-Z, BWU-ZM and BWU-N correlations are shown in Figures 3, 4 and 5.

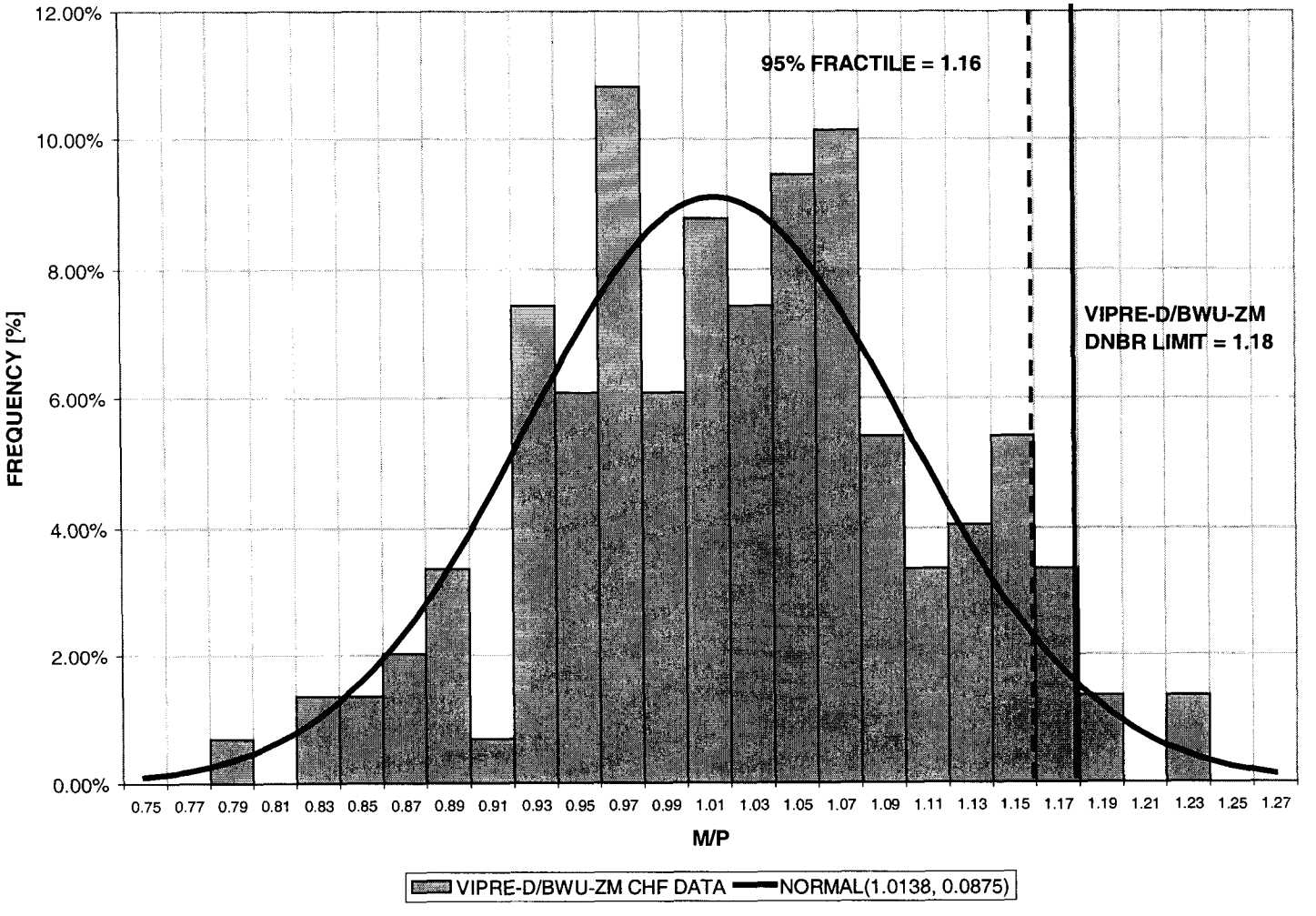
The 528 datapoints of the VIPRE-D/BWU-Z M/P distribution summarized in Section A.4.1 of DOM-NAF-2 Appendix A were used to create the empirical probability density function. These datapoints were distributed among 24 equal bins that covered the entire range of M/P in the VIPRE-D/BWU-Z distribution, and the frequency of data in each bin was determined. The resulting empirical probability density function for the VIPRE-D/BWU-Z M/P distribution was then compared with the probability density function of a normal distribution of mean 0.995 and standard deviation 0.0907, which are the mean and standard deviation calculated for the VIPRE-D/BWU-Z M/P distribution in Section A.4.1 of DOM-NAF-2 Appendix A. Figure 3 also displays the obtained 95% fractile (1.13) for the data and the VIPRE-D/BWU-Z DNBR limit obtained in Section A.4.1 of DOM-NAF-2 Appendix A (1.20).

Figure 3: VIPRE-D/BWU-Z Probability Density Function



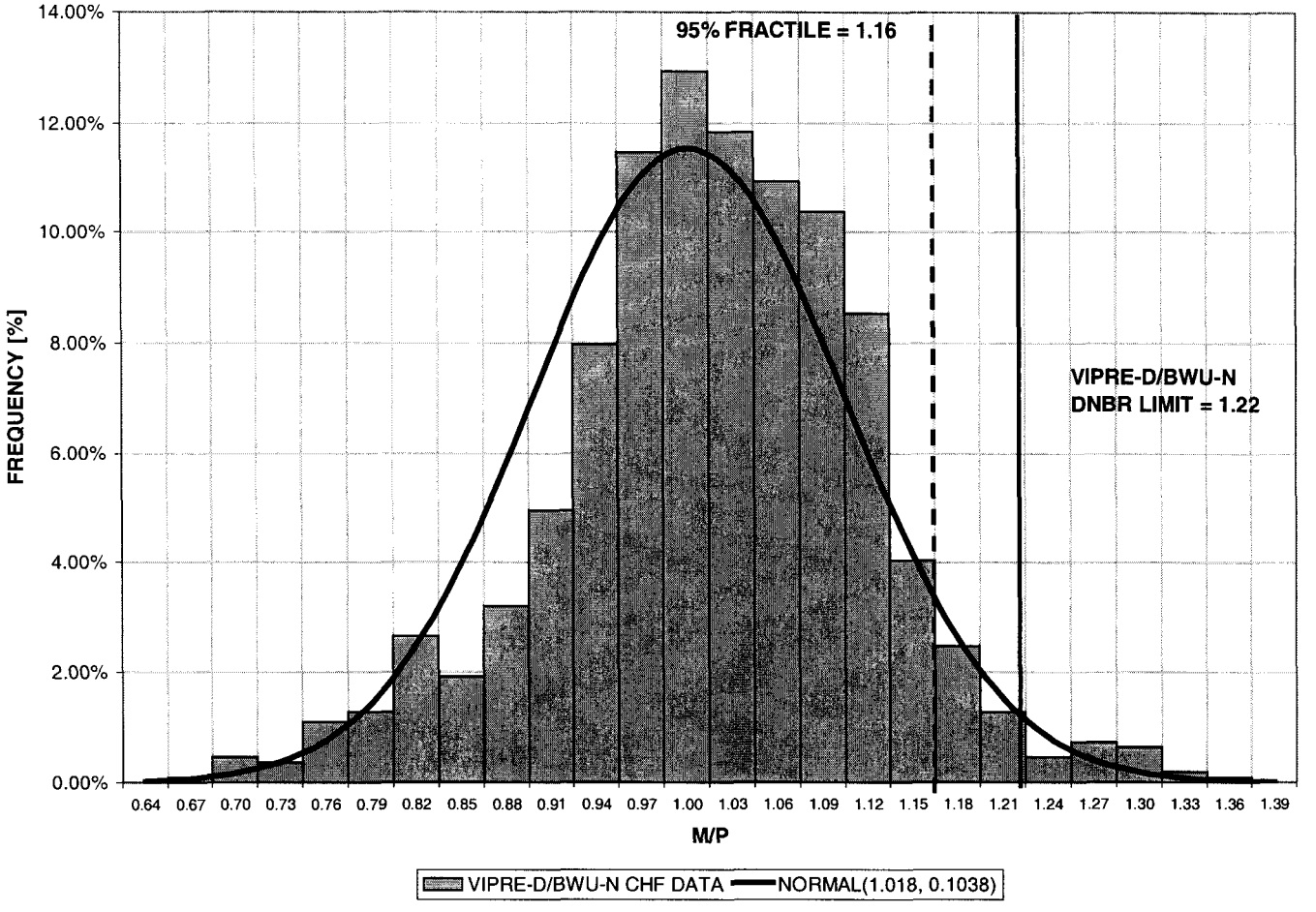
The 148 datapoints of the VIPRE-D/BWU-ZM M/P distribution summarized in Section A.4.2 of DOM-NAF-2 Appendix A were used to create the empirical probability density function. These datapoints were distributed among 27 equal bins that covered the entire range of M/P in the VIPRE-D/BWU-ZM distribution, and the frequency of data in each bin was determined. The resulting empirical probability density function for the VIPRE-D/BWU-ZM M/P distribution was then compared with the probability density function of a normal distribution of mean 1.0138 and standard deviation 0.0875, which are the mean and standard deviation calculated for the VIPRE-D/BWU-ZM M/P distribution in Section A.4.2 of DOM-NAF-2 Appendix A. Figure 4 also displays the obtained 95% fractile (1.16) for the data and the VIPRE-D/BWU-ZM DNBR limit obtained in Section A.4.2 of DOM-NAF-2 Appendix A (1.18).

Figure 4: VIPRE-D/BWU-ZM Probability Density Function



The 1090 datapoints of the VIPRE-D/BWU-N M/P distribution summarized in Section A.4.3 of DOM-NAF-2 Appendix A were used to create the empirical probability density function. These datapoints were distributed among 26 equal bins that covered the entire range of M/P in the VIPRE-D/BWU-N distribution, and the frequency of data in each bin was determined. The resulting empirical probability density function for the VIPRE-D/BWU-N M/P distribution was then compared with the probability density function of a normal distribution of mean 1.0018 and standard deviation 0.1038, which are the mean and standard deviation calculated for the VIPRE-D/BWU-N M/P distribution in Section A.4.3 of DOM-NAF-2 Appendix A. Figure 5 also displays the obtained 95% fractile (1.16) for the data and the VIPRE-D/BWU-N DNBR limit obtained in Section A.4.3 of DOM-NAF-2 Appendix A (1.22).

Figure 5: VIPRE-D/BWU-N Probability Density Function



Appendix B VIPRE-D

NRC Question 1

The appropriate statistical analysis of the data that form Table B.6-1 is an analysis of variance of a mixed-effects model.

a) Give the appropriate analysis of variance table for this mixed-effects model.

b) Formulate the appropriate statistical hypothesis tests to justify the values for M/P and $O_{M/P}$ used in Eq. B.6.1.

Dominion/DNC Response:

a) The qualification of the WRB-1 CHF correlations with the VIPRE-D code was performed consistent with Dominion's approved Topical Report for COBRA/WRB-1 (Reference 12) and Westinghouse's approved Topical Report (Reference 6). An analysis of variance (ANOVA) test was performed but was not included in the original submission because it was not deemed to provide additional substantial information to the qualification. As mentioned in the response to Question 1 on Appendix A, it was recognized that ANOVA tests cannot be used as the sole measure of the performance of a CHF correlation, but they can be useful to indicate an extremely bad mismatch. The variables analyzed were mass velocity, pressure, quality and test cell type.

   The ANOVA results for VIPRE-D/WRB-1 (Table 6) exceed the critical values of F for some comparisons, but other comparisons prove the hypothesis that all the groups belong to the same distribution, i.e. that there is no bias of the results regarding the analyzed variables. These are the same trends discussed in the NRC's Safety Evaluation of WRB-1 (Reference 6).

Table 6: M/P CHF Performance by Independent Variable Grouping using the entire WRB-1 database at 95% confidence level

	Number of Data	Average M/P	Standard Deviation	Maximum M/P	Minimum M/P
Analysis by Mass Velocities					
Below 1.25 Mlbm/hr-ft^2	58	0.9849	0.0753	1.1158	0.8005
1.25 – 1.75 Mlbm/hr-ft^2	131	1.0125	0.0970	1.3069	0.7632
1.75 – 2.25 Mlbm/hr-ft^2	247	0.9930	0.0914	1.2711	0.7600
2.25 – 2.75 Mlbm/hr-ft^2	203	1.0129	0.0688	1.1715	0.8276
2.75 – 3.25 Mlbm/hr-ft^2	159	1.0074	0.0755	1.1858	0.8337
Above 3.25 Mlbm/hr-ft^2	147	1.0137	0.0787	1.2356	0.8017
	$F_{distribution}$ = 2.6870		$F_{critical}(5,939)$ = 2.2236		
Analysis by Pressures					
Below 1575 psia	227	1.0201	0.0851	1.3069	0.8017
1575 - 1850 psia	179	0.9878	0.0861	1.2711	0.7632
1850 - 2250 psia	277	1.0076	0.0774	1.1873	0.7600
Above 2250 psia	262	1.0014	0.0814	1.2356	0.8005
	$F_{distribution}$ = 5.4330		$F_{critical}(3,941)$ = 2.6144		
Analysis by Qualities					
Below 5%	262	1.0000	0.0762	1.3069	0.8017
5% to 10%	199	1.0119	0.0778	1.2034	0.8226
10% to 15%	247	1.0090	0.0810	1.2711	0.8005
15% to 20%	169	0.9927	0.0942	1.2312	0.7600
20% to 25%	68	1.0222	0.0922	1.2234	0.7662
	$F_{distribution}$ = 2.4209		$F_{critical}(4,940)$ = 2.3814		
Analysis by Geometry Type					
4x4	456	0.9941	0.0847	1.3069	0.7600
5x5	489	1.0154	0.0794	1.2711	0.7632
	$F_{distribution}$ = 15.9428		$F_{critical}(1,943)$ = 3.8513		
Analysis by Thimble vs. Typical					
Thimble	207	0.9910	0.0771	1.2229	0.7873
Typical	738	1.0091	0.0838	1.3069	0.7600
	$F_{distribution}$ = 7.8372		$F_{critical}(1,943)$ = 3.8513		
All Data WRB-1					
All Data	945	1.0051	0.0827	1.3069	0.7600

d) The validity of equation B.6.1 is based on two assumptions: 1) the average M/P is 1.0 and 2) the M/P distribution is normal. These two assumptions were demonstrated in Appendix B:

CORRELATION	AVERAGE M/P = 1.0	M/P DISTRIBUTION NORMAL
WRB-1	Table B.6-1	Page B-12

NRC Question 2

On page B-14 you state, "These plots show that there are no biases in the M/P ratio distributions, and that the performance of the WRB-1 CHF correlation is independent of the three variables of interest. The plots show a mostly uniform scatter of the data and no obvious trends or slopes." The plots suggest but do not demonstrate that the claims made in those sentences are true. Please give the appropriate statistical analysis that demonstrates the truth of the claim.

Dominion/DNC Response:

As discussed in the response to Question 1 for Appendix B, an ANOVA analysis was performed to formally demonstrate that the performance of the WRB-1 CHF correlation is not biased by the three independent variables present in the correlation (mass velocity, pressure and quality). Please refer to the response to Question 1 for an analysis demonstrating no biases in the M/P distribution.

NRC Question 3

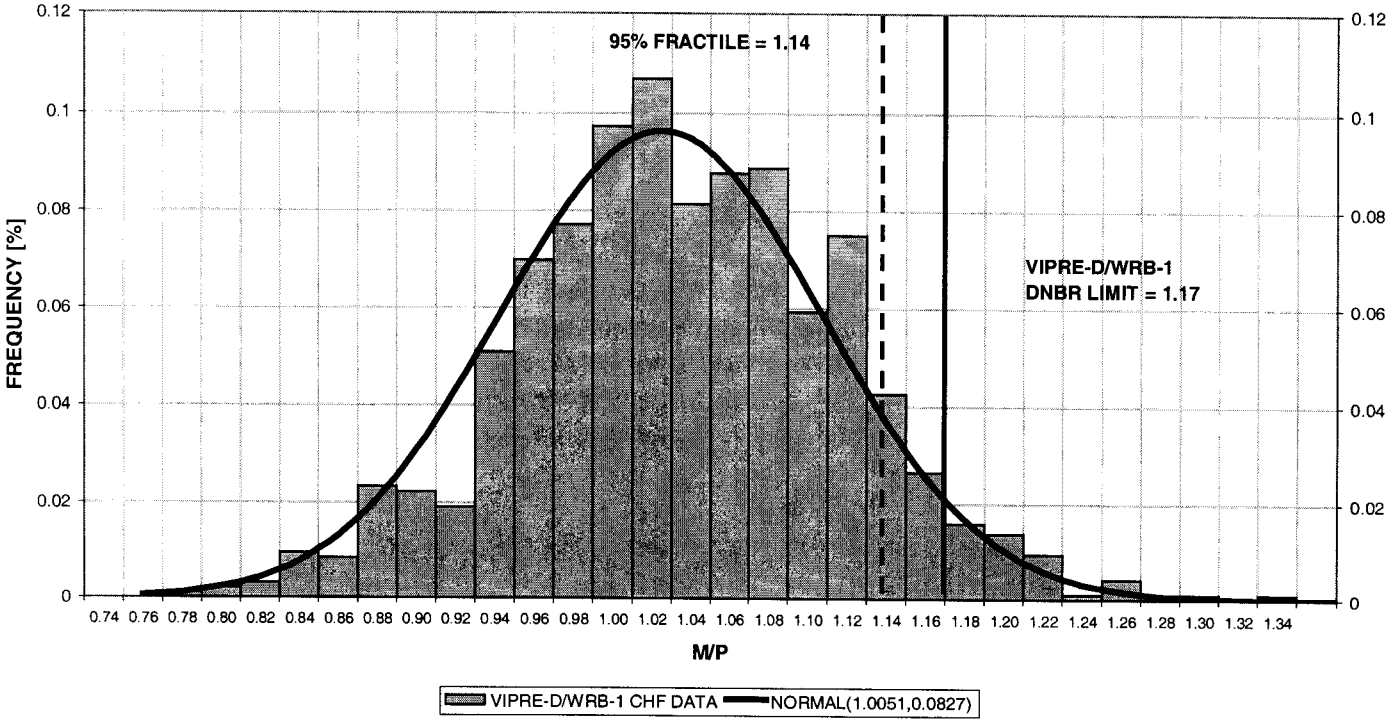
Please show the empirical probability density function for the M/P values used in the analyses together with the estimate of the 95-percent fractile.

Dominion/DNC Response:

The probability density function for the WRB-1 correlation is shown in Figure 6.

The 945 datapoints of the VIPRE-D/WRB-1 M/P distribution summarized in Section B.6 of DOM-NAF-2 Appendix B were used to create the empirical probability density function. These datapoints were distributed among 31 equal bins that covered the entire range of M/P in the VIPRE-D/WRB-1 distribution, and the frequency of data in each bin was determined. The resulting empirical probability density function for the VIPRE-D/WRB-1 M/P distribution was then compared with the probability density function of a normal distribution of mean 1.0051 and standard deviation 0.0827, which are the mean and standard deviation calculated for the VIPRE-D/WRB-1 M/P distribution in Section B.6 of DOM-NAF-2 Appendix B. Figure 6 also displays the obtained 95% fractile (1.14) for the data and the VIPRE-D/WRB-1 DNBR limit obtained in Section B.6 of DOM-NAF-2 Appendix B (1.17).

Figure 6: VIPRE-D/WRB-1 Probability Density Function



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