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Dominion

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United States Nuclear Regulatory Commission
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Serial No. 04-196
NL&OS/GDM: R0
Docket Nos. 50-280/281
50-338/339
50-336/423
License Nos. DPR-32/37
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DPR-65/NPF-49

**VIRGINIA ELECTRIC AND POWER COMPANY (DOMINION)
DOMINION NUCLEAR CONNECTICUT, INC. (DNC)
NORTH ANNA POWER STATION UNITS 1 AND 2
MILLSTONE POWER STATION UNITS 2 AND 3
SURRY POWER STATION UNITS 1 AND 2
REQUEST FOR APPROVAL OF TOPICAL REPORT DOM-NAF-2
REACTOR CORE THERMAL-HYDRAULICS USING THE VIPRE-D COMPUTER CODE INCLUDING APPENDIX A, QUALIFICATION OF THE F-ANP BWU CHF CORRELATIONS IN THE DOMINION VIPRE-D COMPUTER CODE**

As part of a continuing effort to improve core thermal-hydraulics methods, Dominion and DNC are updating their capability for performing nuclear reactor analyses in support of their nuclear power stations. VIPRE is a core thermal-hydraulics computer code currently in wide use throughout the nuclear industry. VIPRE-D is the Dominion/DNC version of VIPRE, which has been enhanced by the addition of several vendor specific CHF correlations. We have validated VIPRE-D with extensive code benchmark calculations, and the accuracy of VIPRE-D has been demonstrated through comparisons with other NRC-approved methodologies. VIPRE-D has been shown to meet or exceed the same standards for accuracy as methodologies currently approved for use by Dominion and DNC.

Therefore, Dominion and DNC are submitting Topical Report DOM-NAF-2, "Reactor Core Thermal-Hydraulics Using the VIPRE-D Computer Code," for NRC review and approval. The topical report is provided in Attachment 1. In addition, we are submitting Appendix A to Topical Report DOM-NAF-2, "Qualification of the F-ANP BWU CHF Correlations in the Dominion VIPRE-D Computer Code," for NRC review and approval. Appendix A is provided in Attachment 2 and documents the qualification of the Framatome ANP BWU CHF correlations (BWU-Z, BWU-ZM and BWU-N) with the VIPRE-D code and the code/correlation DNBR design limits. Please note that in future references to the topical report, Topical Report DOM-NAF-2 is considered to consist of the main report as well as any approved appendices.

Dominion plans to reference this topical report, including Appendix A, in a license amendment request for North Anna Units 1 and 2 that is currently scheduled for submittal to the NRC in the third quarter of 2004.

If you have questions or require additional information, please contact Mr. Gary D. Miller at (804) 273-2771.

Very truly yours,

Leslie N. Hartz
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Attachments

Commitments made in this letter: None

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# Attachment 1

# 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)**

# Reactor Core Thermal-Hydraulics Using the VIPRE-D Computer Code

NUCLEAR ANALYSIS AND FUEL DEPARTMENT
DOMINION
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## CLASSIFICATION/DISCLAIMER



## ABSTRACT

As part of a continuing effort to improve core thermal-hydraulics methods, Dominion (Virginia Electric and Power Company) is updating its capability for performing nuclear reactor analyses in support of its nuclear power stations. VIPRE is a core thermal-hydraulics computer code currently in wide use throughout the nuclear industry. VIPRE-D is the Dominion version of VIPRE, which has been enhanced by the addition of several vendor specific CHF correlations. Dominion has validated VIPRE-D with extensive code benchmark calculations, and the accuracy of VIPRE-D has been demonstrated through comparisons with other NRC-approved methodologies. VIPRE-D has been shown to meet or exceed the same standards for accuracy as methodologies currently being used by Dominion.

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# ACRONYMS AND ABBREVIATIONS

| | |
|---|---|
| AMBW | Advanced Mark-BW |
| AO | Axial Offset |
| BWR | Boiling Water Reactor |
| CHF | Critical Heat Flux |
| CTL | Core Thermal Limit |
| DNB | Departure from Nucleate Boiling |
| DNBR | Departure from Nucleate Boiling Ratio |
| EPRI | Electric Power Research Institute |
| F-ANP | Framatome Advanced Nuclear Power |
| FLC | Form Loss Coefficients |
| FTM | Turbulent Momentum Factor |
| LOCROT | Locked Rotor Accident |
| LOFA | Loss Of Flow Accident |
| MDNBR | Minimum Departure from Nucleate Boiling Ratio |
| MSLB | Main Steam Line Break |
| MSMG | Mid-Span Mixing Grid |
| MVG | Mixing Vane Grid |
| NMVG | Non-Mixing Vane Grid |
| NAPS | North Anna Power Station |
| PWR | Pressurized Water Reactor |
| RWAP | Rod Withdrawal At Power |
| RWSC | Rod Withdrawal from Subcritical |
| SER | Safety Evaluation Report |
| UFSAR | Updated Final Safety Analysis Report |
| USNRC | US Nuclear Regulatory Commission |
| VIPRE | Versatile Internals and Components Programs for Reactors - EPRI |

# 1.0 INTRODUCTION

The basic objective of core thermal-hydraulic analysis is the accurate calculation of reactor coolant conditions to verify that the fuel assemblies constituting the reactor core can safely meet the limitations imposed by departure from nucleate boiling (DNB) considerations. DNB, which could occur on the heating surface of the fuel rod, is characterized by a sudden decrease in the heat transfer coefficient with a corresponding increase in the surface temperature. DNB is a concern in reactor design because of the possibility of fuel rod failure resulting from the increased rod surface temperature.

In order to preclude potential DNB related fuel damage, a design basis is established and is expressed in terms of a minimum departure from nucleate boiling ratio (MDNBR). The departure from nucleate boiling ratio (DNBR) is the ratio of the predicted heat flux at which DNB occurs (i.e. the critical heat flux, CHF) and the local heat flux of the fuel rod. By imposing a DNBR design limit, adequate heat transfer between the fuel cladding and the reactor coolant is assured. DNBRs greater than the design limit indicate the existence of thermal margin within the reactor core. Thus, the purpose of core thermal-hydraulic DNB analysis is the accurate calculation of DNBR in order to assess and quantify core thermal margin.

Dominion (Virginia Power) has used the COBRA IIIc/MIT computer code (Reference 8) to perform the thermal-hydraulic analyses discussed above. COBRA is licensed to evaluate the thermal margin for North Anna Power Station (NAPS) and Surry Power Station cores containing Westinghouse fuel. However, Dominion's nuclear assets and fuel products require new core thermal-hydraulic capabilities. As a consequence, Dominion has decided to implement a new thermal-hydraulic analysis computer program to analyze multiple fuel types.

VIPRE-D is the Dominion version of the computer code VIPRE (Versatile Internals and Components Program for Reactors - EPRI), developed for EPRI (Electric Power Research Institute) by Battelle Pacific Northwest Laboratories in order to perform detailed thermal-hydraulic analyses of reactor cores (References 1 through 5). VIPRE-01 has been approved by the U.S. Nuclear Regulatory Commission (USNRC) (References 6 and 7). VIPRE-D, which is based upon VIPRE-01, MOD-02.1, was modified by Dominion to fit the specific needs of Dominion's nuclear plants and fuel products.

This report describes Dominion's use of the VIPRE-D code, including modeling and qualification for Pressurized Water Reactors (PWR) thermal-hydraulic design. This report demonstrates that the VIPRE-D methodology is appropriate for PWR licensing applications.

This report is organized into six sections. Section 2 provides a description of VIPRE-D methodology and intended applications, including a discussion on VIPRE-D compliance with the VIPRE-01 Safety Evaluation Report (SER). Section 3 describes the VIPRE-D code and its capabilities. Section 4 describes the VIPRE-D modeling of PWR cores and fuel rods. Section 5 provides VIPRE-D benchmark calculations against other subchannel codes for PWR DNB analyses, such as Framatome ANP (F-ANP) LYNXT (Reference 14). Conclusions and references are presented in succeeding sections. The topical allows for a series of appendixes, each one containing the verification and qualification of additional CHF correlations with the VIPRE-D code.

## 2.0 TOPICAL METHODOLOGY

## 2.1 VIPRE-D APPLICATION

The intended VIPRE-D applications are consistent with the Dominion COBRA applications for PWRs using USNRC approved methodologies (Reference 8). The VIPRE-D applications include DNB analyses to define PWR core safety limits that provide the basis for reactor protection setpoints, and to perform DNBR calculations in reactor transients. While VIPRE-D is able to model Boiling Water Reactors (BWR), its BWR features and capabilities are not discussed for qualification in this report. Furthermore, the rod conduction model present in VIPRE-D will not be used. All VIPRE-D models will employ the dummy rod model.

Dominion plans to use the VIPRE-D code for:

1) Analysis of 14x14, 15x15 and 17x17 fuel in PWR reactors.

2) Analysis of deterministic and statistical DNB transients in the Updated Final Safety Analysis Report (UFSAR).

3) Steady state and transient DNB evaluations.

4) Development of reactor core safety limits (also known as core thermal limit lines, CTL).

5) Providing the basis for reactor protection setpoints.

6) Establishing the deterministic code/correlation DNBR design limits of the various DNB correlations in the code. Each one of these DNBR limits would be documented in an appendix to this document.

## 2.2 COMPLIANCE WITH VIPRE-01 SER

In order to meet the USNRC's requirements listed in the VIPRE-01 SER (References 6 and 7), Dominion will apply the VIPRE-D code for PWR licensing applications under the following conditions:

1) The application of VIPRE-D is limited to PWR licensing calculations with heat transfer regime up to CHF. VIPRE-D will not be used for BWR calculations.

2) VIPRE-D analyses will only use DNB correlations that have been reviewed and approved by the USNRC. The VIPRE-D DNBR calculations will be within the USNRC approved parameter ranges of the DNB correlations, including fuel assembly geometry and grid spacers. The correlation DNBR design limits will be derived or verified using fluid conditions predicted by the VIPRE-D code. Each DNB correlation will be verified and qualified in appendixes to this report.

3) This report provides the necessary documentation to describe the intended uses of VIPRE-D for PWR licensing applications. The report provides justification for Dominion's specific modeling assumptions, including the choice of two-phase flow models and correlations, heat transfer correlations and turbulent mixing models.

4) For transient analysis, appropriate time steps are selected to ensure numerical stability and accuracy. The Courant number, which is based on flow velocity, time step and axial node size, is set to be greater than one in VIPRE-D transient calculations whenever a subcooled void model is used.

5) VIPRE-D is maintained within Dominion's 10CFR50, Appendix B Quality Assurance program.

# 3.0 CODE DESCRIPTION

VIPRE-D is the Dominion version of the computer code VIPRE, developed for EPRI by Battelle Pacific Northwest Laboratories in order to perform detailed thermal-hydraulic analyses of reactor cores (References 1 through 5). VIPRE-01 was previously approved by the USNRC (References 6 and 7). VIPRE-D, which is based upon VIPRE-01, MOD-02.1, was modified by Dominion to fit the specific needs of Dominion's nuclear plants and fuel products. However, the computational philosophy of VIPRE-D remains unchanged from VIPRE-01. VIPRE-D uses the subchannel analysis concept where a reactor core is divided into a number of flow channels that communicate laterally by crossflow and turbulent mixing. Conservation equations of mass, axial and lateral momentum, and energy are solved for the fluid enthalpy, axial flow rate, crossflow, and momentum pressure drop. A detailed description of the VIPRE-D subchannel equations can be found in Reference 1. The VIPRE-D flow field is assumed to be incompressible and homogeneous. It is assumed that any lateral flow is directed by the gap through which it flows, and it loses its sense of direction after leaving the region. Since crossflow is assumed to exist only between two adjacent channels, no external lateral boundary conditions are required.

The VIPRE-D heat transfer model is capable of solving the conduction equation for the temperature distribution within the fuel rods and provides the heat source term for the fluid energy equation. The full boiling curve can be incorporated into the heat transfer model, from single-phase convection through nucleate boiling to the DNB point, and from transition boiling to the film boiling regime. A detailed description of the VIPRE-01 heat transfer model can be found in Reference 1. Dominion has not verified and validated the use of the VIPRE-01 heat transfer model. Dominion does not plan to use the conduction model in its methodology.

VIPRE-D offers two numerical solution options: the upflow solution, which is similar to the one in COBRA-IIIC; and the recirculation solution scheme adapted from COBRA-WC. Both solution schemes iteratively solve the same finite difference equations and use the same model and correlations for heat transfer, wall friction, fluid state and two-phase flow. The difference between them is in the numerical method used to obtain the flow and pressure fields. Both solution schemes yield essentially the same results (Reference 4, Section 7.3). However, the recirculation solution scheme is applicable to core conditions having flow reversal and recirculation. Either solution scheme can be used for PWR analysis.

In addition to minor formatting changes and corrections to reported code errors, Dominion has enhanced the capabilities of VIPRE-D. The main enhancement is the addition of several vendor specific CHF correlations. Additional enhancements were made in VIPRE-D's input and output to integrate it seamlessly into Dominion's thermal hydraulic methodologies. Additional CHF correlations may be added to the code in the future. Each one of these DNB correlations will be qualified and validated in its own appendix to this report prior to licensing use.

The VIPRE-D coding changes do not alter the fundamental computational method and solution scheme of the VIPRE-01 code. It has been demonstrated that the additions and modifications made to create VIPRE-D have been correctly implemented into the code and have not affected in any way the original internal models and algorithms in the code. VIPRE-D has been developed and is maintained in accordance with Dominion's 10CFR50 Appendix B Quality Assurance program.

## 4.0 VIPRE-D MODELING

The methodology and guidelines used to create the VIPRE-D model for a typical Dominion reference plant core are described in this section. This modeling, which is not plant-specific, was developed in a manner consistent with the USNRC approved model for PWR cores described in Reference 8. Sections 4.1 (radial nodalization), 4.2 (axial nodalization), 4.4 (power distribution) and 4.9 (CHF correlations) below describe the modeling areas that are fuel and accident dependent and would have to be determined based on the particular core and the type of analysis to be performed. The remaining sections describe modeling choices that do not change with the fuel type.

Section 5.0 of this report describes a specific example applying these guidelines to a North Anna Power Station core containing F-ANP Advanced Mark-BW (AMBW) fuel assemblies. Extensive code benchmark calculations have confirmed that the VIPRE-D models created according to the methodology and guidelines described in this report produce essentially the same results as equivalent F-ANP LYNXT models (Reference 13).

VIPRE-D modeling of a PWR core is based on the one-pass modeling approach (Reference 1), in which hot channels (subchannels with the highest enthalpy rise) and their adjacent region are modeled in detail, while the remainder of the core is modeled simultaneously on a relatively coarse mesh. A reactor core can be modeled in a small number of channels while still maintaining sufficient detail and accuracy around the hot channels. A one-pass model contains lumped channels that comprise total flow area and heated and wetted perimeters of the individual subchannels. The lumped channel gives uniform conditions over the entire flow area of the channel. Some input parameters of the lateral momentum equation in the VIPRE-D code are adjusted in order to obtain the correct crossflow for the lumped channel. The VIPRE one-pass modeling has been approved by the USNRC (References 6 and 7).

## 4.1 RADIAL NODALIZATION

While the techniques used in formulating the hydraulic representation of a typical core are applicable in general to all PWRs, the specifics of the model change with the type of fuel present in the particular core and the type of analysis being performed. In general it is assumed that the core presents 1/8$^{th}$ symmetry, and thus it is only necessary to model 1/8$^{th}$ of the core. It is also assumed that the hot assembly is located at the center of the core, and therefore, the 1/8$^{th}$ core model will contain 1/8$^{th}$ of the hot assembly. The adequate number of channels to model a given core must allow simulating the entire core, while having a detailed subchannel model surrounding the hot channels. A set of subchannels surrounding the hot channels (i.e., hot thimble cell and hot typical cell) is sufficient to provide adequate solution detail of the flow field in the vicinity of the hot subchannels (Reference 2). This modeling approach is applicable to 14x14, 15x15 and 17x17 PWR fuel.

If the model is going to be used for the analysis of main steam line break (MSLB) events, it is also necessary to account for the core inlet enthalpy maldistribution when defining the number of channels. The adequacy of using a one-eighth core model has been verified through benchmark calculations with the F-ANP LYNXT code (References 13 and14), and will be discussed in Section 5.0.

## 4.2 AXIAL NODALIZATION

The finite differences methods used in VIPRE-D require that sufficient axial nodes be provided to resolve the details of the flow field and the axial power profiles. Dominion models use an axial nodalization scheme that places all the mixing and non-mixing vane grids at the upper edges of the axial nodes for better numerical convergence, while preserving the actual grid spacing. This is important because VIPRE-D applies the pressure loss associated with a node at the top edge of the node. Therefore, it is important to create a nodal distribution that ensures that the axial locations where the pressure losses are applied match the actual axial locations for each spacer grid.

VIPRE-D allows a PWR core to be modeled with variable axial nodal length. VIPRE-D offers a great deal of control and flexibility by allowing the user to define both the geometry and the axial power shapes with as much detail as needed in the critical areas of the model and with not so much detail in less critical areas. Dominion models use typical node lengths of 2 inches. A maximum node length of 6 inches will be used in the models. Selection of a very small node length is not reasonable since an excessive number of nodes will add significantly to the run time of the problem and the memory required to store the results without actually improving the precision.

The length of the axial nodes should also be taken into account when running transient problems in order to satisfy the Courant number limit (The Courant number is defined as the axial velocity $u$ times the numerical approximation of the time derivative - $u\Delta t/\Delta x$). In explicit calculations the Courant number is limited to 1.0 or less for numerical stability. Even though VIPRE-D is an implicit code and this limitation does not apply, the relation of time step size to spatial nodalization and average velocity is still a useful concept. Furthermore, sensitivity studies (Reference 4, Section 7.4) have shown that both subcooled void models present in VIPRE-01 (Levy & EPRI) are unstable in transients with time steps smaller than the Courant limit. Therefore, the axial length of the nodes, as well as the time step, are chosen to meet the above criteria.

## 4.3 FUEL ROD MODELING

A typical VIPRE-D model defines the number of rods appropriate for the number of channels selected in the radial nodalization (Section 4.1), normally in accordance with the type of fuel present in the core, and uses the "dummy" rod model to represent them. In the dummy rod model there is no calculation of the heat transfer and the temperature distribution within the fuel rod, and the surface heat flux for each rod is specified as an input parameter. Unheated rods, such as instrument tubes and guide tubes, do not need to be modeled as rods. They are taken into account when calculating the flow area, the wetted and heated perimeters, and the crossflow gaps in the appropriate channels, but they are not modeled as separate entities. Dominion does not plan to use the conduction model present in the code.

The VIPRE-D model accounts for a fraction of the core power being generated directly in the coolant due to gamma heating and neutron absorption. For the safety analysis, it is assumed that 97.4% of the reactor power is generated within the fuel rods, and the remaining 2.6% is generated directly in the coolant. The treatment of the gamma heating is consistent with the current Dominion COBRA production models (Reference 8).

## 4.4 POWER DISTRIBUTION

In the VIPRE-D model, an axial power profile is entered to specify the power generated by each axial node relative to the average. A radial power factor that determines the rod power relative to the average core power is assigned to each rod.

DNBR calculations are typically performed with reference axial power shapes. For example, the typical reference axial power shape used in establishing core thermal limits is a chopped cosine shape with a peak-to-average value of 1.55. This reference power shape is supplemented by other axial shapes skewed to the bottom or to the top of the core to determine the reduction of trip setpoints on excessive axial power imbalance. Dominion's VIPRE-D model interpolates in the axial power table using the spline fit option, as opposed to the default linear interpolation option. The spline fit option was added to VIPRE-01, MOD02.1 and provides a slightly smoother axial power profile integration. A sensitivity analysis of the impact of this option was performed by Dominion, and virtually identical MDNBR results were obtained with both options.

The radial power distribution is specified by assigning to each dummy rod a radial power factor that specifies the rod power relative to the average core power. The power distributions provide a gradual power gradient with the highest peaking around the hot channels (i.e., hot thimble cell and hot typical cell) to reduce the benefit of crossflow into the hot channel. The VIPRE-D models apply the peak $F\Delta H$ to a rod in the hot thimble cell and the hot typical cell. This radial modeling results in a conservative evaluation of DNBR in the hot channel and hot pin, since the mixing effects in the center of the core are significantly reduced. A typical radial power distribution for a $1/8^{th}$ core model of 157 17x17 fuel assemblies, adjusted for a 1.587 maximum peaking factor, is described in Table 4.4-1.

Table 4.4-1. Typical Radial Peaking Factors for a 1/8th core model of 157 17x17 fuel assemblies modeled with 12 channels and 14 rods

| Rod Number | Relative Power $f_i$ | Number of rods $N_i$ | Statistical Maximum FΔH |
|---|---|---|---|
| | | | 1.587 |
| 1 | 1.0 | 0.5 | 1.587 |
| 2 | 0.99748 | 0.5 | 1.583 |
| 3 | 0.993699 | 0.5 | 1.577 |
| 4 | 0.994959 | 1 | 1.579 |
| 5 | 0.986767 | 0.5 | 1.566 |
| 6 | 0.988658 | 1 | 1.569 |
| 7 | 0.996219 | 1 | 1.581 |
| 8 | 0.988028 | 0.25 | 1.568 |
| 9 | 0.986767 | 0.5 | 1.566 |
| 10 | 0.991178 | 0.5 | 1.573 |
| 11 | 0.983617 | 0.5 | 1.561 |
| 12 | 0.980466 | 0.125 | 1.556 |
| 13 | 0.982987 | 26.125 | 1.560 |
| 14 | $\dfrac{\sum_{i=1}^{i=14} N_i - \sum_{i=1}^{i=13} F_{\max \Delta H} \cdot f_i \cdot N_i}{N_{14}}$ | 5148 | 0.99639 |

## 4.5 TURBULENT MIXING

The VIPRE-D turbulent mixing model accounts for the exchange of energy and momentum between adjacent subchannels due to turbulence. This is not a turbulence model, but an attempt to empirically account for the effect of turbulent mixing. The following inputs are needed to setup this model:

- Turbulent Momentum Factor (FTM), which can range from 0.0 to 1.0, measures how efficiently the turbulent crossflow mixes momentum. Reference 2 recommends a value of 0.8 for FTM and explains that VIPRE is not very sensitive to the value of FTM. In Dominion models FTM has been conservatively set to 0.0, which indicates that the turbulent crossflow mixes enthalpy only and not momentum. This modeling approach is consistent with Dominion COBRA models (Reference 8).

- The model for turbulent mixing chosen for single phase mixing describes the mixing as w'=A x S x G, where A is an empirical mixing coefficient (the variable ABETA in VIPRE-D) entered by the user, S is the rod-to-rod gap width (ft), and G is the average mass velocity in the channels linked by a given gap ($lbm/ft^2$-s). This coefficient ABETA, which can range from 0.0 to 0.1, is conservatively set to 0.038. The two phase turbulent mixing is computed in the same way as the single phase. This is the default model in the code.

Since turbulent mixing is a subchannel phenomenon, the value of the turbulent mixing coefficient needs to be corrected for lumped channels to reflect the effect of lumping together many rod-to-rod gaps. The value of ABETA for lumped channels is defined as:

$$ABETA_{lumped} = ABETA_{subchannel} \times \frac{\text{SubchannelCentroidDistance}}{\text{LumpedChannelCentroidDistance}} \quad [4.5.1]$$

The impact of correcting the value of the turbulent mixing coefficient for lumped channels has been quantified with a sensitivity analysis which demonstrated that the modeling of identical values of the turbulent mixing coefficient for subchannels and lumped channels alike yields essentially the same results.

In larger lumped regions, on the order of a bundle or larger, turbulent mixing tends to be smeared out by the effect of averaging on both flow and enthalpy. As a consequence, the turbulent mixing coefficient for a full assembly is set to zero (Reference 4, Section 7.2).

## 4.6 AXIAL HYDRAULIC LOSSES AND CROSSFLOW RESISTANCE

Axial friction losses are calculated with the McAdams correlation, which has been shown to provide an excellent approximation to the Colebrook smooth pipe formulation for single phase axial friction factor for the range $3 \cdot 10^4 < Re < 2 \cdot 10^6$ (Reference 11). This is the same correlation used in Dominion COBRA (Reference 8).

$$F = MAX\,(0.184 * Re^{-0.2} + 0.0\ [\text{turbulent}],\ 64.0 * Re^{-1.0} + 0.0\ [\text{laminar}]) \quad [4.6.1]$$

Lateral resistance for a subchannel is calculated in both the turbulent and laminar regions with a Blasius-type function of the gap Reynolds number, where the coefficient A is calculated using the Idel'Chik empirical correlation for a bundle of circular tubes in vertical columns (Reference 12, p.332).

$$K_G = A \cdot \text{Re}_{lateral}^{-0.2} \quad [4.6.2]$$

where A is defined as: $$A = 1.52 \cdot \left[\frac{SubchannelPitch}{FuelRodOD} - 1\right]^{-0.5} \quad [4.6.3]$$

In order to correctly calculate the effective crossflow resistance for the lumped channels, the subchannel crossflow resistance is multiplied by the ratio of the lumped channel centroid distance and the subchannel centroid distance. This treatment is consistent with the USNRC SER for VIPRE-01 (Reference 6).

## 4.7 FORM LOSS COEFFICIENTS

The local form loss coefficients (FLC) associated with a given fuel assembly type are obtained by the vendor from full-scale hydraulic tests of the fuel assemblies. These form losses are specified for each fuel component (non-mixing grids, mixing grids, mid-span mixing grids, etc.) and for each type of subchannel (unit cell, corner cell, etc). Thus, VIPRE-D allows the definition of different FLCs for different channels and at different axial locations.

In the VIPRE-D models, the FLCs are axially placed at the upper edges of the axial nodes immediately below the corresponding component (mixing vane grids, mid-span mixing vane grids, etc). VIPRE-D places the pressure loss associated with a node at the top edge of the node, thus applying the pressure losses at the actual axial locations for each spacing grid. The impact of slightly varying (upward and downward) the axial location where the FLCs are applied was studied with a sensitivity analysis, which showed an insignificant change in DNBR.

## 4.8 TWO-PHASE FLOW AND HEAT TRANSFER CORRELATIONS

VIPRE-D has a number of empirical correlations available to simulate two-phase flow effects (Reference 1). These correlations can be grouped in three major categories: 1) two-phase friction multipliers; 2) subcooled void correlations; and 3) bulk boiling void correlations. In Reference 4, a sensitivity study was performed to assess the differences in the performance of the various correlations and, although significant differences were not found, the EPRI models were defined as the default models for VIPRE-01. The USNRC, in Reference 6, concluded that the EPRI void models and EPRI correlation for two-phase friction are acceptable for licensing calculations. Dominion performed yet another sensitivity study to verify that this set of two-phase flow correlations was the most suitable for Dominion applications (Section 5.4).

The selections are:

- Subcooled Void Model: EPRI
- Bulk Boiling Void Model: EPRI
- Two-Phase Friction Multiplier: EPRI
- Hot Wall Friction Correlation : NONE

VIPRE-D also requires the user to select the heat transfer correlations that describe the boiling curve. These selections (except the Single Phase Forced Convection Correlation), however, are only applied to the heat transfer solution if the conduction model is used. Since Dominion VIPRE-D models described herein use the "dummy" rod model (Section 4.3), the conduction model is ignored.

The Single Phase Forced Convection is modeled with the standard Dittus-Boelter correlation, which is commonly used for this type of configuration (Reference 2).

$$h_{DB} = 0.023 \cdot \mathrm{Re}_l^{0.8} \cdot \mathrm{Pr}^{0.4} \cdot \frac{k}{D_e} \qquad [4.8.1]$$

where $Re_l$ is the Reynolds number for the liquid, Pr is the Prandtl number, k is the thermal conductivity of the fluid (Btu/s-ft-°F) and $D_e$ is the hydraulic diameter in ft.

## 4.9 CRITICAL HEAT FLUX CORRELATIONS

VIPRE-D currently includes several CHF correlations applicable to various F-ANP and Westinghouse fuel types. Dominion intends to add appendixes to the present report qualifying various CHF correlations for fuel products to be used within the Dominion nuclear units. This modular approach will allow simple submittals of additional CHF correlations for new fuel types in the future. The critical heat flux correlation to be used for a particular fuel type will be qualified in one of the appendixes and will have been approved by the USNRC for use with such fuel product.

The VIPRE-D CHF correlations will be used within the USNRC approved parameter ranges of the CHF correlations, including fuel assembly geometry and grid spacers. The DNBR design limits applied to each CHF correlation will be derived or verified using fluid conditions predicted by the VIPRE-D code.

## 4.10 ENGINEERING FACTORS

Variations in the fuel fabrication and core flow adverse to DNB margin are also considered in the VIPRE-D models. Typical VIPRE-D models account for engineering hot channel factors for both enthalpy-rise and heat flux, as well as for inlet flow maldistribution.

Local Heat Flux Enginering Hot Channel Factor, $F_Q^E$:

$F_Q^E$ accounts for pellet-to-pellet variations in enrichment, density and burnable absorber plus the effects of pellet-to-clad eccentricity and variations in the clad outer diameter. Used in the evaluation of the maximum linear heat generation rate, $F_Q^E$ has been determined to have negligible effect on DNB, and it is not used for most fuel types. $F_Q^E$ will be applied according to fuel vendor approved methodologies.

Engineering Enthalpy-Rise Hot Channel Factor, $F_{\Delta H}^{E}$:

$F_{\Delta H}^{E}$ accounts for variations in the fuel enrichment, density, rod dimensions and pin pitch that affect the heat generation rate along the flow channel. Uncertainties in these variables are determined from sampling of manufacturing data. For deterministic analyses, $F_{\Delta H}^{E}$ is incorporated in the model as a multiplier to the energy input to the hot channel without affecting the surface heat flux. In statistical DNBR methods, $F_{\Delta H}^{E}$ is statistically convoluted into the DNBR design limit.

Stack Height Reduction:

Active fuel stack height varies during reactor operation due to the combined effects of fuel densification, swelling and thermal expansion. However, the treatment of this phenomenon is vendor specific and fuel specific. VIPRE-D models comply with the treatment specified by the fuel vendor.

Inlet Flow Reduction:

Core inlet flow maldistribution accounts for non-uniform flow distribution into each fuel assembly at the core inlet. Consistent with the USNRC approved Dominion COBRA methodology for PWR applications (Reference 8), a 5% flow reduction (maldistribution) to the hot assembly is applied in VIPRE-D models.

## 4.11 BOUNDARY CONDITIONS

The VIPRE-D models require the following parameters as the input or the boundaries for calculations:

- Core inlet temperature or enthalpy
- Core average power
- System pressure
- Core inlet flow rate
- Core power distributions

The core inlet temperature and inlet flow may be uniform or non-uniform, depending on the core conditions being analyzed. The core power defines the thermal energy entering the fluid through the fuel rods. The system pressure is assumed to be uniform throughout the VIPRE-D model. The core inlet flow conservatively excludes flow through bypass leakage, such as through the guide tubes.

The core boundary conditions for VIPRE-D transient calculations can be obtained from system computer codes and neutronic codes. For example, the system code provides time-dependent reactor coolant system pressure, core average power, core flow rate and core inlet temperature for transient DNBR calculations. The neutronic codes provide core power distributions and nuclear peaking factors such as $F\Delta H$.

## 4.12 RUN CONTROL PARAMETERS

The run control parameters determine the maximum and minimum number of iterations to be performed to find a solution, as well as the convergence limits and the damping factors used. After a careful review, these values have been set to the defaults provided by the code (Reference 2). In a few occasions, when convergence problems have been reported by the code, the damping factors and/or the convergence limits have been adjusted in the models to allow the code to converge. These convergence problems do not necessarily mean bad results or false convergence, just some numerical instability. Indeed, in most occasions, the results obtained by the code with the adjusted convergence limits or damping factors are nearly identical to the non-converging results (Reference 6, Section 2.1).

The VIPRE-D solution methods are generally fully implicit and have no time step size limitations for numerical stability. However, solution instability could occur in transient calculations using a subcooled void model that was developed based on steady state data, such as the EPRI subcooled void model. In these cases, and to avoid numerical instabilities, appropriate time step sizes and axial node sizes are selected in transient heat flux and DNBR calculations to ensure that the Courant number is greater than one.

# 5.0 QUALIFICATION OF THE VIPRE-D SUBCHANNEL MODEL

## 5.1 STEADY STATE APPLICATION

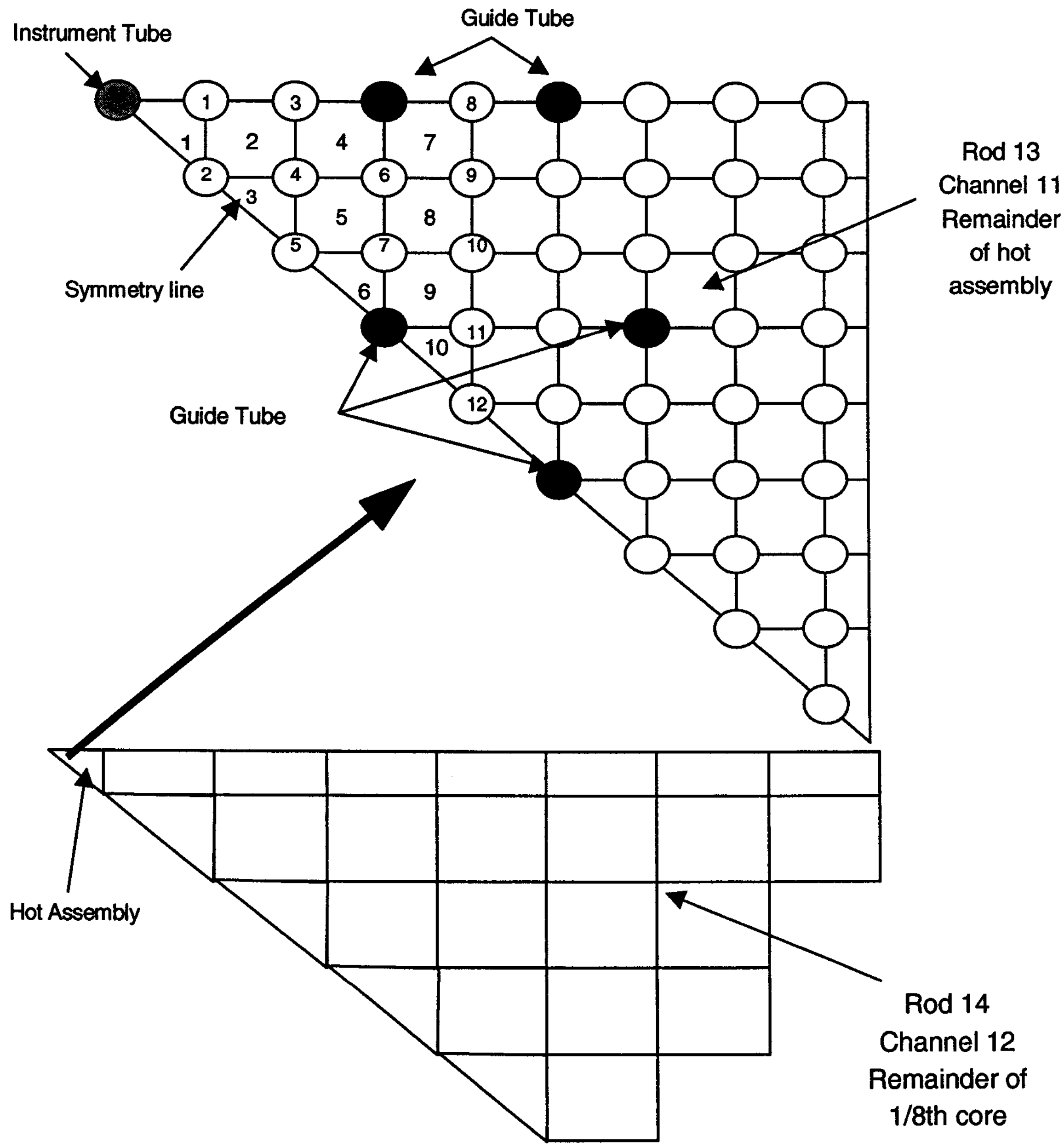
Dominion created a 12-channel model for F-ANP AMBW fuel at North Anna Power Station in accordance with the methodology described in Section 4 of this report. This VIPRE-D model of the 1/8$^{th}$ North Anna core consists of 12 channels (10 subchannels and 2 lumped channels) and 14 rods, as shown in Figure 5.1-1. The axial nodalization used in this model has been customized for F-ANP AMBW fuel assemblies and contains 87 non-uniform axial nodes. The reference axial power profile (1.55 chopped cosine) was defined as an axial power profile table with 37 points. All other axial power shapes are defined as axial power profile tables with 32 points.

The AMBW fuel assembly consists of 264 fuel rods with an outside diameter of 0.374 inches arranged in a 17x17 matrix with a pin pitch of 0.496 inches. The AMBW fuel contains several advanced design features, such as mixing vane grids (MVG) and mid-span mixing grids (MSMG) in the upper two thirds of the heated length (Reference 13). The local FLCs used in this VIPRE-D 12-channel model were developed by F-ANP from full-scale hydraulic tests.

The Framatome BWU CHF correlations, which have been specifically developed for use with the AMBW fuel, were used in the 12-channel model. There are three BWU CHF correlations that constitute the licensing basis for the F-ANP AMBW fuel assembly. These correlations use the same basic equation, but are fit to different databases (References 9 and 10). VIPRE-D applies different BWU correlations at different axial levels, according to the following guidelines:

- BWU-N, which is only applicable in the presence of non-mixing vane grids (NMVG), is used from the beginning of the heated length to the leading edge of the first structural MVG (Reference 9).
- BWU-Z, which is the enhanced mixing vane correlation, is used from the leading edge of the first structural MVG to the leading edge of the second structural MVG (Reference 9).
- BWU-ZM, which is just BWU-Z with a multiplicative enhancement factor and is applicable in the presence of MSMGs, is used from the leading edge of the second structural MVG to the leading edge of the last structural MVG (Reference 10).
- For the uppermost span, in which the end of heated length occurs less than one grid span beyond the last MVG, the BWU-Z correlation is used with a grid spacing equal to the effective grid spacing (the distance from the last grid to the end of heated length) (Reference 9).

Figure 5.1-1. Typical North Anna VIPRE-D 12-Channel Model for F-ANP AMBW Fuel Assemblies



VIPRE-D benchmark calculations were performed with the F-ANP LYNXT code and the 12-channel model created by F-ANP to model North Anna Power Station cores containing AMBW fuel assemblies. This benchmark uses 173 state points 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 to compare the performance of VIPRE-D and LYNXT. These various limits and events 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). The 173 statepoints cover the full range of conditions and axial offsets in UFSAR Chapter 15 evaluations (except for MSLB that is discussed in Section 5.2), and were specifically selected to challenge the three BWU CHF correlations (Table 5.1-1). This benchmark study showed an average deviation between VIPRE-D and LYNXT of less than 0.14% in DNBR, with a maximum deviation of 2.2%. These results are well within the uncertainty typically associated with thermal-hydraulic codes, which has been quantified to be 5% (Reference 15).

Table 5.1-1: Range of VIPRE-D / LYNXT 173 Benchmark Statepoints

| VARIABLE | RANGE |
|---|---|
| Pressure [psia] | 1860 to 2400 |
| Power [%] | 66 to 135 |
| Inlet Temperature [°F] | 506.6 to 626.2 |
| Flow [%] | 64 to 100 |
| FΔH | 1.49 to 1.945 |
| Axial Offset [%] | -48.7 to 57.9 |

## 5.2 MAIN STEAM LINE BREAK APPLICATION

The 12-channel model discussed in section 5.1 does not allow the modeling of the peaking and inlet boundary conditions in the fuel assemblies adjacent to the hot assembly, which is necessary for the analysis of some accidents, such as MSLB. Consequently, a 14-channel model was created to more accurately simulate the behavior of the core during a MSLB event.

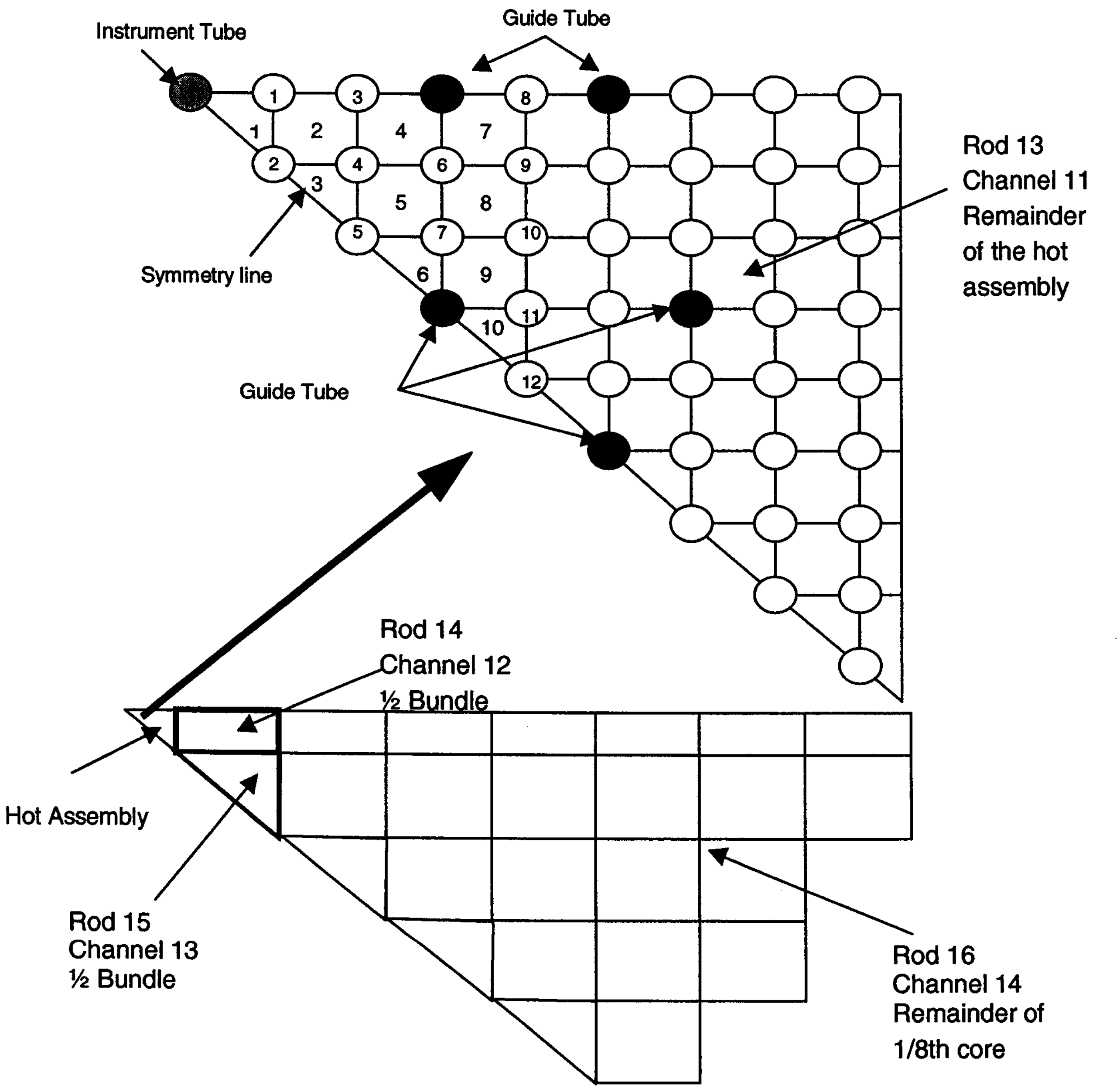
The VIPRE-D 14-channel model for a North Anna core containing F-ANP AMBW fuel assemblies consists of 14 channels (10 subchannels and 4 lumped channels) and 16 rods as shown in Figure 5.2-1. The two additional channels provide adequate solution detail of the flow field in the vicinity of the hot assembly and allow the modeling of the peaking and inlet boundary conditions in the fuel assemblies adjacent to the hot assembly.

The 14-channel model defines the inlet temperature for each one of the 14 channels. In addition, the inlet flow fraction is also specified for each of 14 channels. This modeling choice is of key importance for MSLB events, since the inlet temperature may change for each channel and it is then necessary to adjust the flow fraction to obtain the appropriate values of core inlet flow rate and channel flow rate.

In order to verify the accuracy of the VIPRE-D 14-channel model for MSLB analysis, its performance was compared with the performance of a F-ANP LYNXT model for high flow (with offsite power) and low flow (without offsite power) MSLB evaluations. The results obtained show a maximum deviation of 2.12% in DNBR. These results demonstrate that VIPRE-D can analyze a MSLB event, provided the model has sufficient detail surrounding the hot assembly, such as the 14-channel model described here.

In addition, the accuracy of the 14-channel model was demonstrated through comparison with the DNBR results of the 173 statepoints obtained by the VIPRE-D 12-channel model. This comparison shows that there is essentially no difference between the 12-channel and the 14-channel models (the average deviation in DNBR is 0.03%), which indicates that the VIPRE-D models created following the methodology discussed in Section 4 of this report are adequate.

Figure 5.2-1. Typical VIPRE-D 14-Channel Model for North Anna Cores with F-ANP AMBW Fuel



## 5.3 TRANSIENT APPLICATION

VIPRE-D has the capability to perform transient calculations by using time-dependent forcing functions for pressure, core average power, core flow rate and core inlet temperature provided by a system code. VIPRE-D transient capability was tested by performing two sample transient calculations. These two transient calculations were simply samples designed to exercise the capabilities of the VIPRE-D code and the typical 12-channel model created according to the guidelines discussed in Section 4.

As discussed in Section 4.12, a numerical instability could occur in transient calculations using a subcooled void model that was developed based on steady state data, such as the EPRI model. For that reason, in order to avoid numerical instabilities, the time steps used for these transient simulations were selected to ensure that the Courant number is greater than one.

The damping factors and the convergence limits were set to the defaults provided by the code (Section 4.12). In a few occasions, when convergence problems were reported by the code, the damping factors and/or the convergence limits were adjusted in the models to allow the code to converge. These convergence problems do not necessarily mean bad results or false convergence, just some numerical instability. Indeed, in most occasions, the results obtained by the code with the adjusted convergence limits or damping factors were nearly identical to the non-converging results.

The first sample transient selected to verify the capabilities of the VIPRE-D code and the 12-channel model was the RWAP accident. Forcing functions for the RWAP transient were obtained from a NAPS UFSAR case (Dominion COBRA analysis of record for Westinghouse fuel). The length of the transient was 4.0 seconds, with a 0.05-second timestep. VIPRE-D results show similar behavior to the COBRA analysis of record in the UFSAR, but the MDNBR results are different because the analyses use different fuel types and CHF correlations (see Figure 5.3.1).

The second sample transient selected to perform this verification was the LOFA. Forcing functions for the LOFA transient were obtained from the NAPS UFSAR. In particular, COBRA forcing functions were obtained for a F-ANP uprated core tripping on reactor coolant pump undervoltage. The length of the transient was 20.4 seconds, with a 0.1-second timestep. COBRA analysis of record and VIPRE-D calculations exhibited similar behavior, but the MDNBR results are different because the analyses use different fuel types and CHF correlations (see Figure 5.3.2).

It is then concluded that VIPRE-D is capable of performing transient calculations and the results obtained are adequate.

Figure 5.3-1: VIPRE-D RWAP Transient Sample Calculation Results

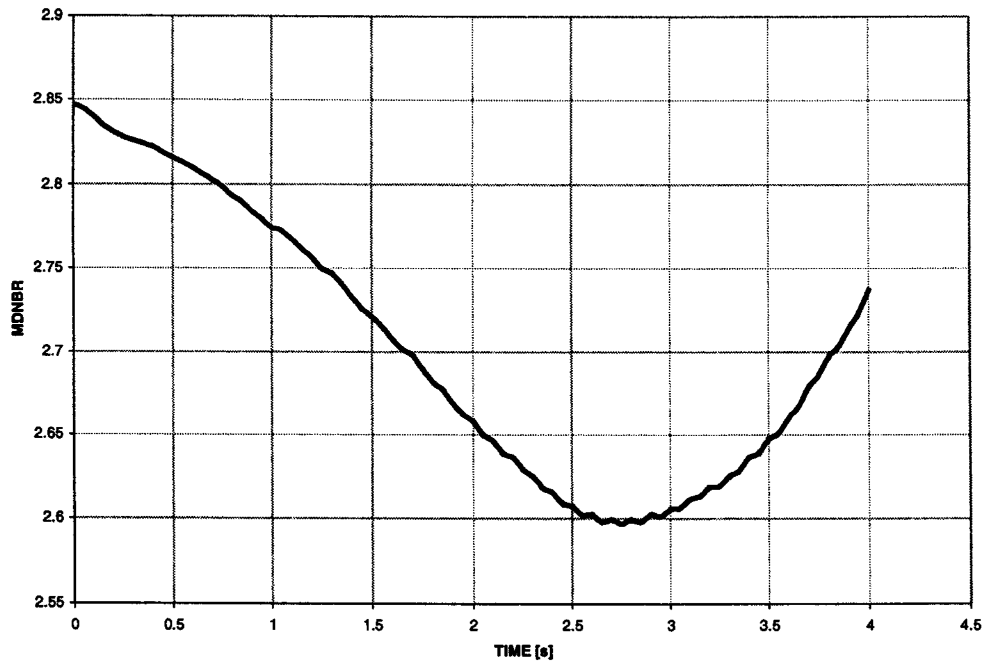
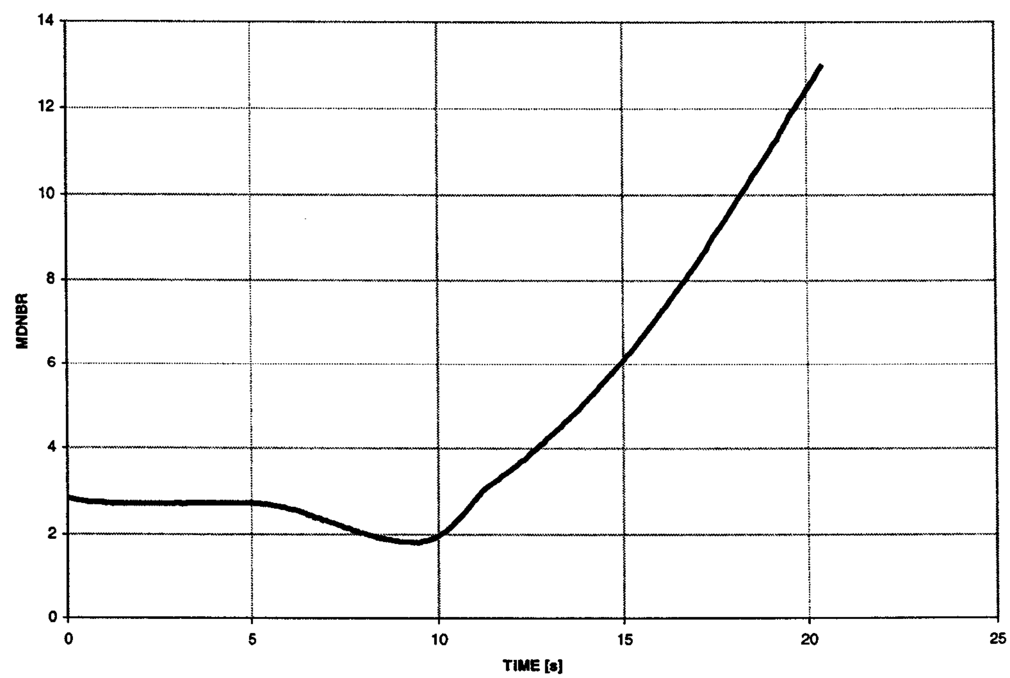



Figure 5.3-2: VIPRE-D LOFA Transient Sample Calculation Results



## 5.4 SENSITIVITY STUDIES

VIPRE-D has a number of empirical correlations available to simulate two-phase flow effects (Reference 1). These correlations can be grouped in three major categories: 1) two-phase friction multipliers; 2) subcooled void correlations; and 3) bulk boiling void correlations. In Reference 4 (Section 3.0), a sensitivity study was performed to assess the differences in the performance of the various correlations and, although significant differences were not found, the EPRI models were chosen as the default models for VIPRE-01. The USNRC staff reviewed these sensitivity studies and concluded in the SER for VIPRE-01 MOD-01 (Reference 6) that the EPRI void models and the EPRI correlations for two-phase friction are acceptable for licensing calculations.

Dominion performed another sensitivity study to determine the set of two-phase flow correlations most suitable for Dominion models. This sensitivity analysis provides justification for Dominion's modeling assumptions as discussed in Section 4.8, thus fulfilling condition (3) of the SER for VIPRE-01 MOD-01 (Reference 6). A detailed analysis of the available correlations was performed, including the modeling assumptions used in deriving the various correlations and four sets of correlations were chosen. 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

The 173 statepoints and the typical 12-channel model described in section 5.1 were executed by VIPRE-D using the four sets of two-phase models and correlations. The results were compared to the results of the USNRC approved code F-ANP LYNXT. Table 5.4-1 lists the average and maximum percent deviations in DNBR between the codes. The set of EPRI correlations (option EEE), which is the default in the code, was then selected for VIPRE-D models.

Table 5.4-1: Statistical Analysis of the MDNBR Results for the Four Sets of Two-Phase Models

| | % DEVIATION IN DNBR<br>LYNXT – VIPRE / LYNXT | | | |
|---|---|---|---|---|
| | EEE | LSE | LHH | LSH |
| AVERAGE | 0.14 | 1.87 | 3.21 | 1.00 |
| STANDARD DEVIATION | 0.89 | 1.26 | 1.48 | 1.28 |

## 6.0 CONCLUSIONS

The VIPRE-01 code has been approved by the USNRC and is widely used throughout the nuclear industry for PWR safety analyses. VIPRE-D is the Dominion version of VIPRE-01. Dominion has shown VIPRE-D compliance with the requirements of the USNRC SERs regarding VIPRE-01 code applications. Dominion has validated VIPRE-D with extensive code benchmark calculations using the modeling methods outlined in this report, and the accuracy of the VIPRE-D models has been demonstrated through comparisons with other NRC-approved methodologies. VIPRE-D has been shown to meet or exceed the same standards for accuracy as other methodologies currently being used by Dominion.

VIPRE-D includes several CHF correlations applicable to various F-ANP and Westinghouse fuel types, and the qualification of each one of them will be documented in the appendixes to this report. The critical heat flux correlation to be used for a particular fuel type will be documented and qualified in one of the appendixes and will have been approved by the USNRC for use with such fuel product prior to use by Dominion. The VIPRE-D CHF correlations will be used within the USNRC approved parameter ranges of the CHF correlations, including fuel assembly geometry and grid spacers. The DNBR design limits applied to each CHF correlation will be derived or verified using fluid conditions predicted by the VIPRE-D code.

With the modeling methods outlined in this report, and in conjunction with the appropriate CHF correlation and DNBR design limits qualified in the appendixes to this report, Dominion plans to use the VIPRE-D code for:

1) Analysis of 14x14, 15x15 and 17x17 fuel in PWR reactors.
2) Analysis of deterministic and statistical UFSAR DNB transients
3) Steady state and transient DNB evaluations.
4) Development of reactor core safety limits
5) Providing the basis for reactor protection setpoints.
6) Establishing the deterministic code/correlation DNBR design limits of the various DNB correlations in the code. Each one of these DNBR limits would be documented in an appendix to this document.

## 7.0 REFERENCES


1. Technical Report, EPRI NP-2511-CCM-A Volume 1, Revision 4, "VIPRE-01: A Thermal-Hydraulic Code for Reactor Cores. Volume 1: Mathematical Modeling," February 2001.

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4. Technical Report, EPRI NP-2511-CCM-A Volume 4, "VIPRE-01: A Thermal-Hydraulic Code for Reactor Cores. Volume 4: Applications," April 1987.

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15. Technical Report, VEP-NE-2-A, "Statistical DNBR Evaluation Methodology," R. C. Anderson, June 1987.

# Attachment 2

# APPENDIX A TO TOPICAL REPORT DOM-NAF-2

# QUALIFICATION OF THE F-ANP BWU CHF CORRELATIONS IN THE DOMINION VIPRE-D COMPUTER CODE

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

DOM-NAF-2, Rev. 0.0
APPENDIX A

# Qualification of the F-ANP BWU CHF Correlations in the Dominion VIPRE-D Computer Code

NUCLEAR ANALYSIS AND FUEL DEPARTMENT
DOMINION
RICHMOND, VIRGINIA
March, 2004

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## CLASSIFICATION/DISCLAIMER



## ABSTRACT

This appendix documents Dominion's qualification of the Framatome-ANP (F-ANP) BWU-N, BWU-Z and BWU-ZM correlations with the VIPRE-D code. This qualification was performed against the same CHF experimental database used by F-ANP to develop and license the correlations. This appendix summarizes the data evaluations that were performed to qualify the VIPRE-D/BWU code/correlation pair, and to develop the corresponding DNBR design limits for each correlation.

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## ACRONYMS AND ABBREVIATIONS

| | |
|---|---|
| ARC | Alliance Research Center |
| CHF | Critical Heat Flux |
| DNB | Departure from Nucleate Boiling |
| DNBR | Departure from Nucleate Boiling Ratio |
| F-ANP | Framatome Advanced Nuclear Power |
| HTRF | Heat Transfer Research Facility at Columbia University |
| M/P | Ratio of Measured-to-Predicted CHF |
| MSMG | Mid-Span Mixing Grid |
| MVG | Mixing Vane Grid |
| NMVG | Non-Mixing Vane Grid |
| P/M | Ratio of Predicted-to-Measured CHF (equivalent to DNBR) |
| PWR | Pressurized Water Reactor |
| USNRC | US Nuclear Regulatory Commission |

## A.1 PURPOSE

Dominion has purchased fuel assemblies from Framatome ANP (F-ANP) for use at North Anna Power Station, Units 1 and 2. These new fuel assemblies are designated as Advanced Mark-BW fuel and are a one-for-one replacement for the resident fuel product, which is the North Anna Improved Fuel with ZIRLO components and PERFORMANCE+ debris resistant features (a Westinghouse fuel product). The thermal-hydraulic analysis of the F-ANP fuel product requires the use of the F-ANP BWU CHF correlations (References A1 and A2).

To be licensed for use, a critical heat flux (CHF) correlation must be tested against experimental data that span the anticipated range of conditions over which the correlation will be applied. Furthermore, the population statistics of the database must be used to establish a departure from nucleate boiling ratio (DNBR) design limit such that the probability of avoiding departure from nucleate boiling (DNB) will be at least 95% at a 95% confidence level.

This appendix documents Dominion's qualification of the BWU-N, BWU-Z and BWU-ZM correlations with the VIPRE-D code. This qualification was performed against the same CHF experimental database used by F-ANP to develop and license the correlations. This appendix summarizes the data evaluations that were performed to qualify the VIPRE-D/BWU code/correlation pair, and to develop the corresponding DNBR design limits for each correlation.

## A.2 DESCRIPTION OF THE F-ANP CHF CORRELATIONS

In pressurized water reactor (PWR) cores, the energy generated inside the fuel pellets leaves the fuel rods at their surface in the form of heat flux, which is removed by the reactor coolant system flow. The normal heat transfer regime in this configuration is nucleate boiling, which is very efficient. However, as the capacity of the coolant to accept heat from the fuel rod surface degrades, a continuous layer of steam (a film) starts to blanket the tube. This heat transfer regime, termed film boiling, is less efficient than nucleate boiling and can result in significant increases of the fuel rod temperature for the same heat flux. Since the increase in temperature may lead to the failure of the fuel rod cladding, PWRs are designed to operate in the nucleate boiling regime and protection against operation in film boiling must be provided.

The heat flux at which the steam film starts to form is called CHF or the point of DNB. For design purposes, the DNBR is used as an indicator of the margin to DNB. The DNBR is the ratio of the predicted CHF to the actual local heat flux under a given set of conditions.

Thus, DNBR is a measure of the thermal margin to film boiling and its associated high temperatures. The greater the DNBR value (above 1.0), the greater the thermal margin.

The CHF cannot be predicted from first principles, so it is empirically correlated as a function of the local thermal-hydraulic conditions, the geometry, and the power distribution measured in the experiments. Since a CHF correlation is an analytical fit to experimental data, it has an associated uncertainty, which is quantified in a DNBR design limit. A calculated DNBR value greater than this design limit provides assurance that there is at least a 95% probability at the 95% confidence level that a departure from nucleate boiling will not occur.

F-ANP has developed and uses the B&W-2, the BWC and the BWCMV CHF correlations. The first two of these correlations apply to fuel assemblies with non-mixing vane spacer grids of inconel or zircaloy. The BWCMV correlation applies to fuel assemblies with mixing vane grids. These correlations are limited to applications in a high flow regime, but modern applications require the use of a correlation in the middle and low flow regimes. Using the response surface model and sequential optimization techniques, F-ANP developed a universal local conditions CHF correlation form. This correlation form, designated BWU, was modified and applied to three different fuel design types over the wider required ranges in Reference A1. This reference describes the CHF tests that provided the bases for the new correlations, analyzes the performance of the correlation for each fuel type, and provides limits and guidelines for its application.

The F-ANP BWU CHF correlations are defined in Reference A1 as:

$$Q_{CHF} = \frac{F_{MSM} \cdot FLS \cdot Q_{unif}}{F_{Tong}} \qquad [A.2.1]$$

where $Q_{CHF}$ is the critical heat flux in Btu/hr-ft$^2$, $F_{MSM}$ is a dimensionless performance factor dependent on the grid arrangement of the assembly and defined in References A1 and A2, FLS is a dimensionless length spacing factor, $F_{Tong}$ is the dimensionless non-uniform flux shape factor (Tong factor) and $Q_{unif}$ is the uniform heat flux in Btu/hr-ft$^2$. The specific formulations for each one of these components, as well as the corresponding constants are F-ANP proprietary and can be found in References A1 and A2.

References A1 and A2 discuss the application of the BWU correlation form to three different grid types:

- BWU-N, which is only applicable in the presence of non-mixing vane grids (NMVG).

- BWU-Z, which is the enhanced mixing vane correlation, is applicable to the DNB analysis of the fuel assembly in the mixing region.
- BWU-ZM, which is BWU-Z with a multiplicative enhancement factor, is applicable in the presence of mid-span mixing grids (MSMGs).

# A.3 DESCRIPTION OF CHF EXPERIMENTAL TESTS

## A.3.1 BWU-Z CORRELATION

F-ANP developed the BWU-Z correlation to be used for fuel designs with mixing spacer grids based on the experimental data obtained at the Heat Transfer Research Facility of Columbia University (HTRF) and with the Mark BW17 spacer grid designs. The HTRF is a ten-megawatt electric facility capable of testing full length (up to 14 ft heated length) rod arrays in up to a 6-by-6 matrix. HTRF testing conditions cover the full range of PWR operating conditions with pressures up to 2,500 psia, mass velocities up to 3.5 Mlbm/hr-ft$^2$ and inlet temperatures approaching saturation. Seven series of tests were used to develop the BWU-Z CHF correlation (References A1 and A4). These same tests were also used by Dominion to qualify the VIPRE-D/BWU-Z code correlation pair. Seven full assembly models were created for VIPRE-D to model these experimental test sections. Table A.3.1-1 summarizes the seven series of tests in the BWU-Z CHF experimental database.

Table A.3.1-1: BWU-Z CHF Experimental Database

| TEST | TYPE | MATRIX | AXIAL HEAT FLUX SHAPE | PIN OD / GUIDE TUBE OD [inches] | HEATED LENGTH [inches] | GRID SPACING [inches] | NUMBER OF TESTS |
|---|---|---|---|---|---|---|---|
| BW 12.0 | Unit Cell | 5 x 5 | 1.55 Symmetric | 0.374 / - | 143.4 | 20.5 | 99 |
| BW 13.1 | Unit Cell | 5 x 5 | 1.55 Symmetric | 0.374 / - | 143.4 | 20.5 | 94 |
| BW 14.1 | Guide Tube | 5 x 5 | 1.55 Symmetric | 0.374 / 0.482 | 143.4 | 20.5 | 76 |
| BW 15.1 | Cold Unit | 5 x 5 | 1.55 Symmetric | 0.374 / - | 143.4 | 20.5 | 92 |
| BW 16.0 | Cold Row | 5 x 5 | 1.55 Symmetric | 0.374 / - | 143.4 | 20.5 | 48 |
| BW 19.0 | Guide Tube | 5 x 5 | 1.55 Symmetric | 0.374 / 0.482 | 143.4 | 20.5 | 94 |
| BW 20.0 | Unit Cell | 5 x 5 | 1.55 Symmetric | 0.374 / - | 143.4 | 20.5 | 48 |

## A.3.2 BWU-ZM CORRELATION

F-ANP developed the BWU-ZM correlation to be used for fuel designs with MSMGs based on the experimental data obtained at the HTRF and with the Mark BW17 spacer grid designs. Three series of tests were used to validate the BWU-ZM CHF correlation (References A2 and A4). These same tests were also used by Dominion to qualify the VIPRE-D/BWU-ZM code correlation pair. Three full assembly models were created for VIPRE-D to model these experimental test sections. Table A.3.2-1 summarizes the three series of tests in the BWU-ZM CHF experimental database.

Table A.3.2-1: BWU-ZM CHF Experimental Database

| TEST | TYPE | MATRIX | AXIAL HEAT FLUX SHAPE | PIN OD / GUIDE TUBE OD [inches] | HEATED LENGTH [inches] | GRID SPACING [inches] | NUMBER OF TESTS |
|---|---|---|---|---|---|---|---|
| BW 18.0 | Unit Cell | 5 x 5 | 1.55 Symmetric | 0.374 / - | 143.4 | 20.5 [mid-span grid] | 18 |
| BW 18.1 | Unit Cell | 5 x 5 | 1.55 Symmetric | 0.374 / - | 143.4 | 20.5 [mid-span grid] | 58 |
| BW 43.0 | Guide Tube | 5 x 5 | 1.55 Symmetric | 0.374 / 0.482 | 143.4 | 20.5 [mid-span grid] | 72 |

## A.3.3 BWU-N CORRELATION

F-ANP developed the BWU-N correlation for fuel designs with NMVGs based on the experimental data obtained at the heat transfer facility at the Alliance Research Center (ARC) with the Mark C and Mark BZ non-mixing spacer grid designs. This experimental facility was similar in capacity to HTRF, but has since been decommissioned. Seven Mark C tests and 3 Mark BZ tests were used to develop the correlation (References A1 and A3). These same tests were also used by Dominion to qualify the VIPRE-D/BWU-N code correlation pair. Ten full assembly models were created for VIPRE-D to model these experimental test sections. Table A.3.3-1 summarizes the ten series of tests in the BWU-N CHF experimental database.

Table A.3.3-1: BWU-N CHF Experimental Database

| TEST | TYPE | MATRIX | AXIAL HEAT FLUX SHAPE | PIN OD / GUIDE TUBE OD [inches] | HEATED LENGTH [inches] | GRID SPACING [inches] | NUMBER OF TESTS |
|---|---|---|---|---|---|---|---|
| C-3 | Unit Cell | 3 x 3[a] | 1.0 Uniform | 0.379 / - | 72.0 | 21.0 | 107 |
| C-6 | Unit Cell | 5 x 5 | 1.0 Uniform | 0.3797 / - | 144.0 | 21.0 | 130 |
| C-7 | Guide Tube | 5 x 5 | 1.0 Uniform | 0.379 / 0.465 | 144.0 | 21.0 | 122 |
| C-8 | Unit Cell | 5 x 5 | 1.662 Cosine Symmetric | 0.379 / - | 144.0 | b | 155 |
| C-9 | Guide Tube | 5 x 5 | 1.662 Cosine Symmetric | 0.379 / 0.465 | 144.0 | b | 85 |
| C-11 | Unit Cell | 5 x 5 | 1.595 Sine Symmetric | 0.379 / - | 144.0 | b | 34 |
| C-12 | Guide Tube | 5 x 5 | 1.595 Sine Symmetric | 0.379 / 0.465 | 144.0 | b | 133 |
| B-15 | Guide Tube | 5 x 5 | 1.68 Cosine Symmetric | 0.430 / 0.554 | 144.0 | 21.1 | 47 |
| B-16 | Unit Cell | 5 x 5 | 1.68 Cosine Symmetric | 0.430 / - | 144.0 | 21.1 | 131 |
| B-17 | Intersection Cell | 5 x 5 | 1.68 Cosine Symmetric | 0.430 / - | 144.0 | 21.1 | 157 |

[a] Bundle C-3 has a heated strip in each of the four walls (1.381" x 72.0").
[b] Grid centerline distances from the end of the heated length are 15.66", 37.66", 59.41", 80.91", 102.16", 123.16", 143.53".

## A.4 VIPRE-D RESULTS AND COMPARISON TO LYNXT/LYNX2

References A3 and A4 describe the mathematical model for each separate test section by providing the bundle and cell geometry, the rod radial peaking values, the rod axial flux shapes, the types, axial locations and form losses associated to the spacer grids, as well as the thermocouple locations. References A1 and A2 provide the data for each CHF observation within a test, including power, flow, inlet temperature, pressure and CHF location (rod and axial location).

Each test section was modeled for analysis with the VIPRE-D thermal-hydraulic computer code as a full assembly model following the modeling methodology discussed in Section 4 in the main body of this report. For each set of bundle data, VIPRE-D produces the local thermal-hydraulic conditions (mass velocity, thermodynamic quality, heat flux, etc) at every axial node along the heated length of the test section. The ratio of measured-to-predicted CHF (M/P) is the variable that is normally used to evaluate the thermal-hydraulic performance of a code/correlation pair. The measured CHF is the local heat flux at a given location, while the predicted CHF is calculated by the code using the CHF correlation of interest (BWU-Z, BWU-ZM or BWU-N). The ratio of these two values provides the M/P ratio, which is the inverse of the DNB ratio. M/P ratios are frequently used to validate CHF correlations instead of DNB ratios, because their distribution is usually a normal distribution, which simplifies their manipulation and statistical analysis.

The axial location, the hot rod and the hot channel that are used to perform the M/P comparison are important. For each test, the M/P ratio must be evaluated at the axial location where burnout was observed experimentally, as listed in References A3 and A4. The axial nodalization for the various VIPRE-D models was developed taking into account the actual test location of the thermocouples, as well as the locations of the various spacer grids. The criteria used to select the hot channel and hot rod are supported by engineering judgment and use the information regarding burnout location provided by References A3 and A4. In general, when burnout was observed experimentally in a hot rod, a hot rod and a central (hot) channel were selected to perform the comparison. When the burnout was observed experimentally on a cold rod, a hot rod was still selected because it was considered unphysical to observe burnout in a cold rod earlier than in a hot rod (experimentally, even though a cold rod was reported to experience burnout first, the reality was that several rods saw burnout almost simultaneously and the limitations of the instrumentation and a desire to minimize damage to the test cell, caused the discrepancy). In this case, however, an external channel (cold) was selected to be the hot channel.

In addition to comparing to the experimental results, the results obtained by VIPRE-D when modeling the Mark BW, Mark C and Mark BZ experiments were benchmarked against the results obtained by F-ANP with the LYNXT/LYNX2 codes (References A1 and A2). This comparison was just a sanity check to verify that there are no suspect datapoints and that the statepoint conditions were correctly input to the code.

Some of the tests analyzed were discarded prior to their incorporation into the VIPRE-D/BWU database. Two criteria were used to justify data deletions.

1) If the M/P ratio obtained for a given data point was greater than 3.5 standard deviations from the average, the data point was eliminated. This criterion is consistent with the methodology used by F-ANP in Reference A1.
2) If any of the local conditions (pressure, mass velocity or thermodynamic quality) was outside the range of applicability of the correlation as given in References A1 and A2, the data point was eliminated. This criterion is also consistent with the methodology used by F-ANP in Reference A1.

Overall, 23 data points were excluded from the BWU-Z database (F-ANP discarded 21 data points in Reference A1), and 11 were excluded from the BWU-N database (F-ANP eliminated 8 data points in Reference A1). No data points were eliminated from the BWU-ZM database. The reason the VIPRE-D/BWU database is slightly smaller than the LYNXT/BWU database is that the local conditions predicted by VIPRE-D for a few test data were just barely outside the range of validity of the BWU correlations as given in Reference A1.

This section summarizes the VIPRE-D results and the associated significant statistics. In addition, this section shows a comparison to the results obtained by F-ANP with the LYNXT/LYNX2 codes as reported in References A1 and A2. This section also shows the variation of the M/P ratio with each independent variable to assess if there are any biases in the data. Finally, it provides the VIPRE-D overall statistics for the seven BWU-Z tests, the three BWU-ZM tests and the ten BWU-N tests, and generates the DNBR design limits for the various BWU CHF correlations with VIPRE-D.

### A.4.1 VIPRE-D/BWU-Z RESULTS

The BWU-Z correlation was developed by F-ANP correlating the CHF experimental results obtained in tests BW 12.0, BW 13.1, BW 14.1, BW 15.1, BW 16.0, BW 19.0 and BW 20.0. Dominion used those same experimental data to develop the VIPRE-D/BWU-Z DNBR limit. Table A.4.1-1 summarizes the relevant statistics for each test, and calculates the aggregate statistics for the entire set of data.

One-sided tolerance theory (Reference A5) is used for the calculation of the VIPRE-D/BWU-Z DNBR design limit. This theory allows us to calculate a DNBR limit so that, for a DNBR equal to the design limit, DNB will be avoided with 95% probability at a 95% confidence level.

Table A.4.1-1: VIPRE-D/BWU-Z M/P Ratio Results

| TEST | NUMBER OF TESTS | M/P RATIO AVERAGE | M/P RATIO STDEV | M/P RATIO MAX | M/P RATIO MIN |
|---|---|---|---|---|---|
| BW 12.0 | 99 | 1.0230 | 0.0848 | 1.1683 | 0.7812 |
| BW 13.1 | 94 | 0.9907 | 0.0900 | 1.1609 | 0.7669 |
| BW 14.1 | 76 | 0.9869 | 0.0951 | 1.1538 | 0.7261 |
| BW 15.1 | 92 | 1.0086 | 0.0917 | 1.2974 | 0.7717 |
| BW 16.0 | 48 | 0.9475 | 0.0716 | 1.0840 | 0.6980 |
| BW 19.0 | 94 | 0.9833 | 0.0893 | 1.1693 | 0.7833 |
| BW 20.0 | 25 | 1.0108 | 0.0971 | 1.1642 | 0.8342 |
| **BWU-Z** | **528** | **0.9950** | **0.0907** | **1.2974** | **0.6980** |

Because all the statistical techniques used below assume that the original data distribution is normal, it is necessary to verify that the overall distribution for the M/P ratios is a normal distribution. To evaluate if the distribution is normal, the D' normality test was applied (Reference A6). A value of D' equal to 3,430.23 was obtained for the VIPRE-D/BWU-Z database. This D' value is within the range of acceptability for 528 data points with a 95% confidence level (3,387.6 to 3,449.4)[c]. Thus, it is concluded that the M/P distribution for the VIPRE-D/BWU-Z database is indeed normal.

Based on the results listed in Table A.4.1-1, the deterministic DNBR design limit can be calculated as:

$$DNBR_L = \frac{1.0}{M/P - K_{N,C,P} \cdot \sigma_{M/P}} \qquad [A.4.1.1]$$

where

M/P = average measured-to-predicted CHF ratio

$\sigma_{M/P}$ = standard deviation of the measured-to-predicted CHF ratios of the database

$K_{N,C,P}$ = one-sided tolerance factor based on N degrees of freedom, C confidence level, and P portion of the population protected. This number is taken from Table 1.4.4 of Reference A5.

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[c] From Table 5 in Reference A6

D' Lower Limit (528) [P = 0.025] = 3,310 + (8 / 20) x (3,504 – 3,310) = 3,387.6

D' Upper Limit (528) [P = 0.975] = 3,371 + (8 / 20) x (3,567 – 3,371) = 3,449.4

Then, the DNBR design limit for the VIPRE-D and the BWU-Z correlation can be calculated as described in Table A.4.1-2:

Table A.4.1-2: VIPRE-D/BWU-Z DNBR Design Limit

| | | | **VIPRE-D/BWU-Z** |
|---|---|---|---|
| Number of data | n | | 528 |
| Degrees of freedom | N | = n - 1 - 14 | 513 |
| Average M/P | M/P | | 0.9950 |
| Standard Deviation | $\sigma_{M/P}$ | | 0.0907 |
| Corrected Standard Deviation | $\sigma_N$ | $= \sigma_{M/P} \cdot [ (n-1) / N ]^{½}$ | 0.0919 |
| Owen Factor | K(513,0.95,0.95) | | 1.7607 |
| BWU-Z Design limit | $DNBR_L$ | $= 1 / (0.9950 - 1.7607 \cdot 0.0919)$ | **1.2002** |

Figures A.4.1-1 through A.4.1-4 display the performance of the M/P ratio, and its distributions as a function of the pressure, mass velocity and quality. The objective of these plots is to show that there are no biases in the M/P ratio distribution, and that the performance of the BWU-Z 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. These plots also show that all the tests in the BWU-Z database are within 3.5 standard deviations from the average. Figures A.4.1-5 through A.4.1-7 display the performance of the P/M ratio (i.e. the DNBR) against the major independent variables for the BWU-Z database. These plots also include a DNBR design limit line at 1.20. It can be seen that only 19 data points (3.6% of the database) are above the DNBR design limit, and that these data in excess of the limit are distributed over the variable ranges tested.

In Reference A1, the USNRC argued that the performance of the BWU-Z correlation might be deficient at the extremely low end of the pressure range. For that reason, F-ANP developed individual DNBR design limits for each low pressure group in the database. This approach allows users to use the BWU-Z correlation at low pressures but imposes a higher DNBR limit to ensure that the correlation is used conservatively. Table A.4.1-3 summarizes the VIPRE-D/BWU-Z DNBR limits calculated for the different pressure groups and compares them with the BWU-Z DNBR design limits obtained by F-ANP in Reference A1.

Table A.4.1-3: VIPRE-D/BWU-Z DNBR Limits for Pressure Groups

| | 400 psia | 700 psia | 1000 psia | 1500 – 2400 psia |
|---|---|---|---|---|
| **AVERAGE M/P** | 0.8504 | 1.0452 | 1.0623 | 0.9883 |
| **STDEV** | 0.0121 | 0.0879 | 0.0787 | 0.0883 |
| **# DATA** | 4 | 20 | 40 | 464 |
| **K(N,0.95,0.95)** | 6.882 | 2.396 | 2.125 | 1.768 |
| **VIPRE-D DNBR LIMIT** | **1.304** | **1.198** | **1.117** | **1.202** |
| ***LYNXT DNBR LIMIT*** | *1.590* | *1.199* | *1.125* | *1.193* |

Dominion will take the VIPRE-D/BWU-Z DNBR limit to be 1.20 for pressures greater than or equal to 700 psia, and 1.59 at pressures lower than 700 psia. Since the VIPRE-D/BWU-Z database at 400 psia only has four datapoints, Dominion has used the F-ANP more conservative DNBR limit of 1.59.

Figure A.4.1-1: Measured vs. Predicted CHF for BWU-Z

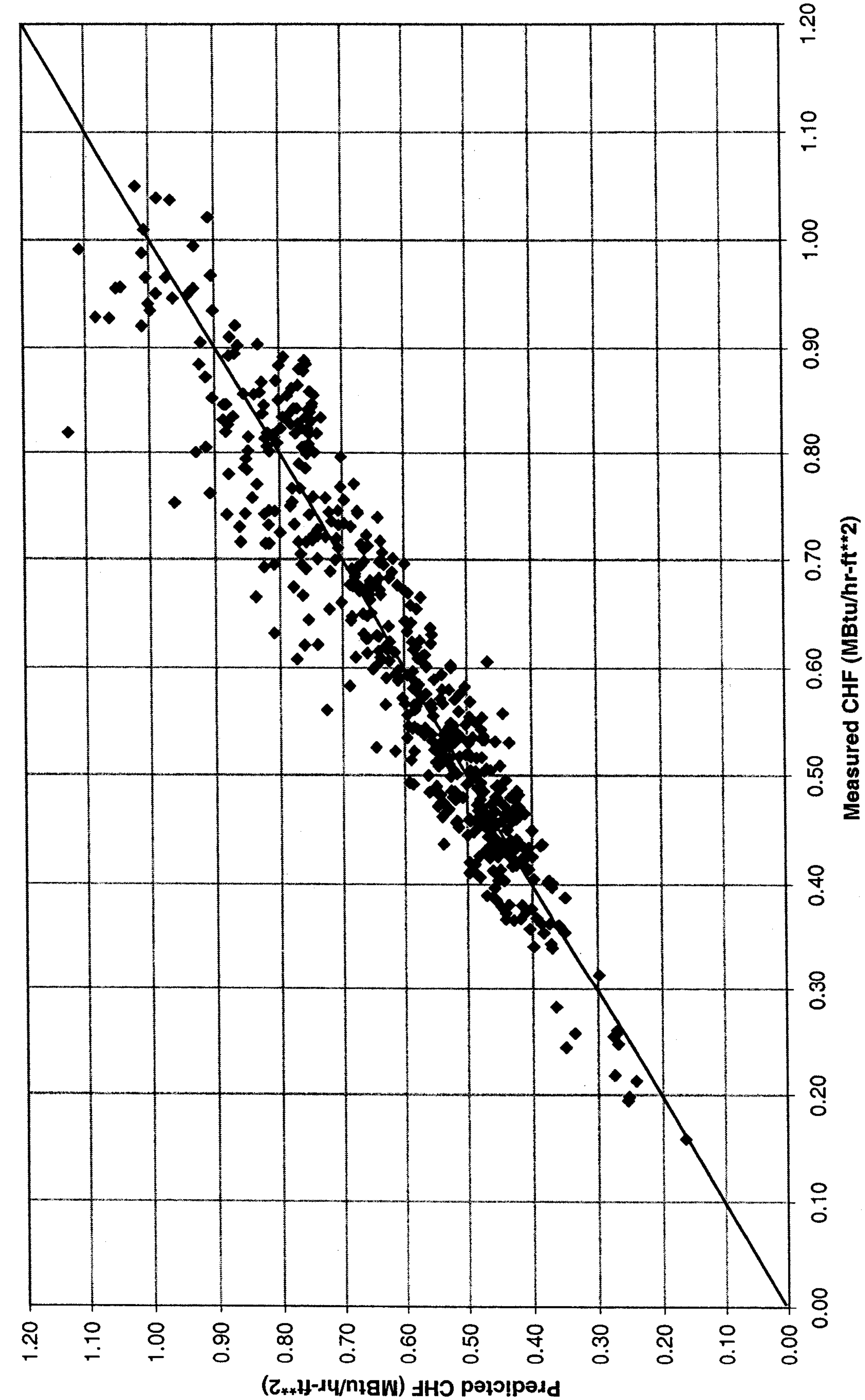


**Figure A.4.1-2: M/P vs. Pressure for BWU-Z**

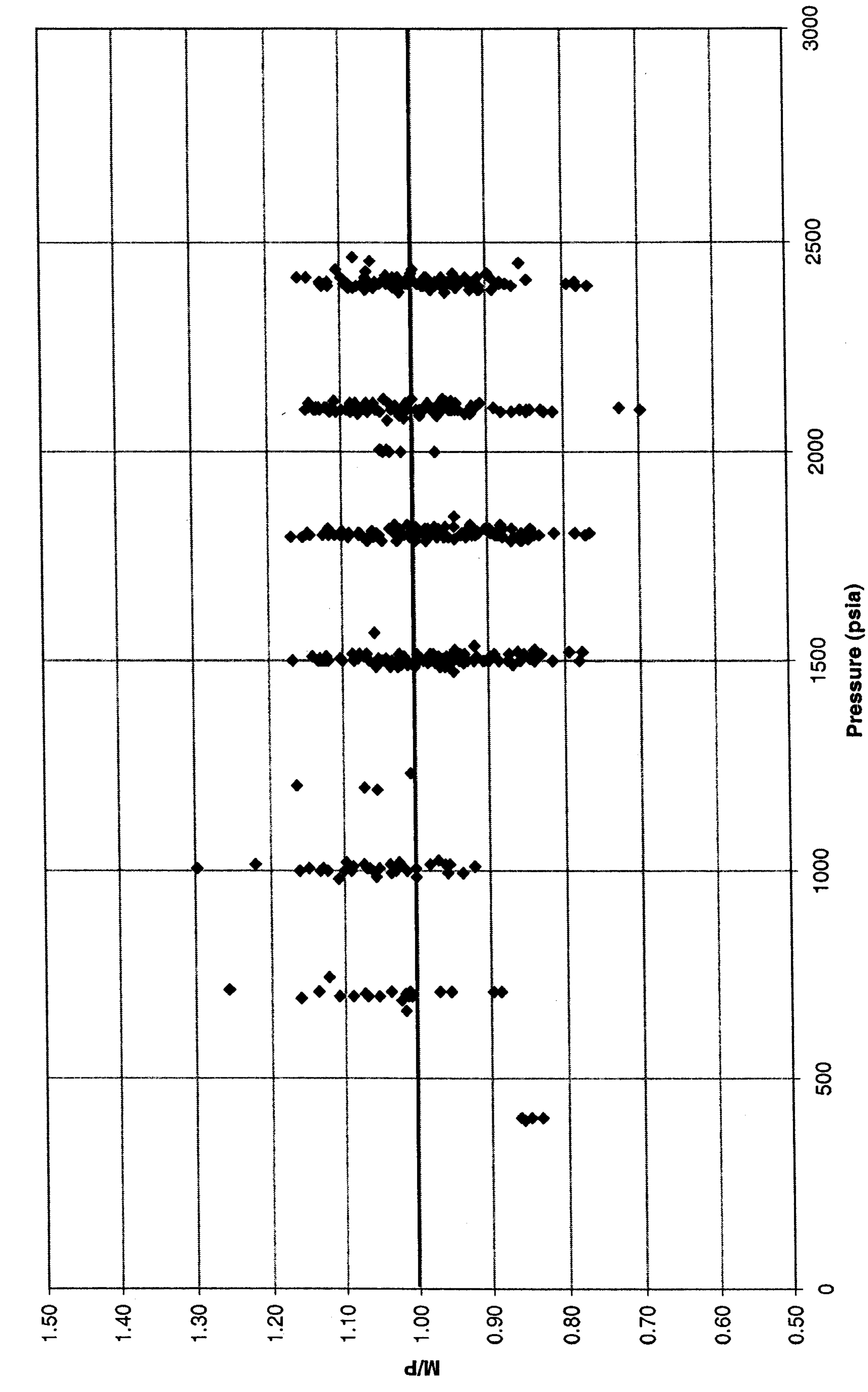


**Figure A.4.1-3: M/P vs. Quality for BWU-Z**

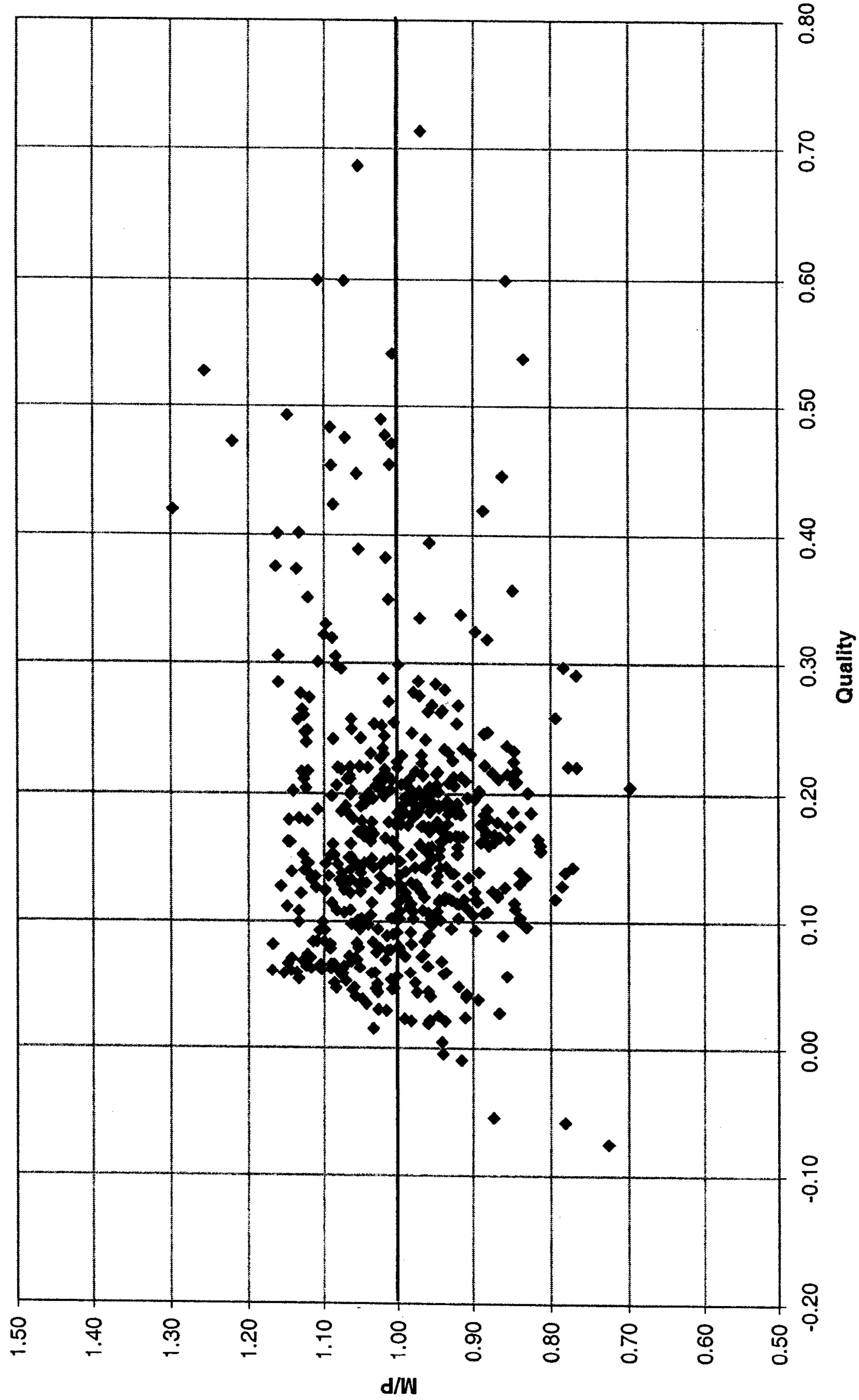


**Figure A.4.1-4: M/P vs. Mass Velocity for BWU-Z**

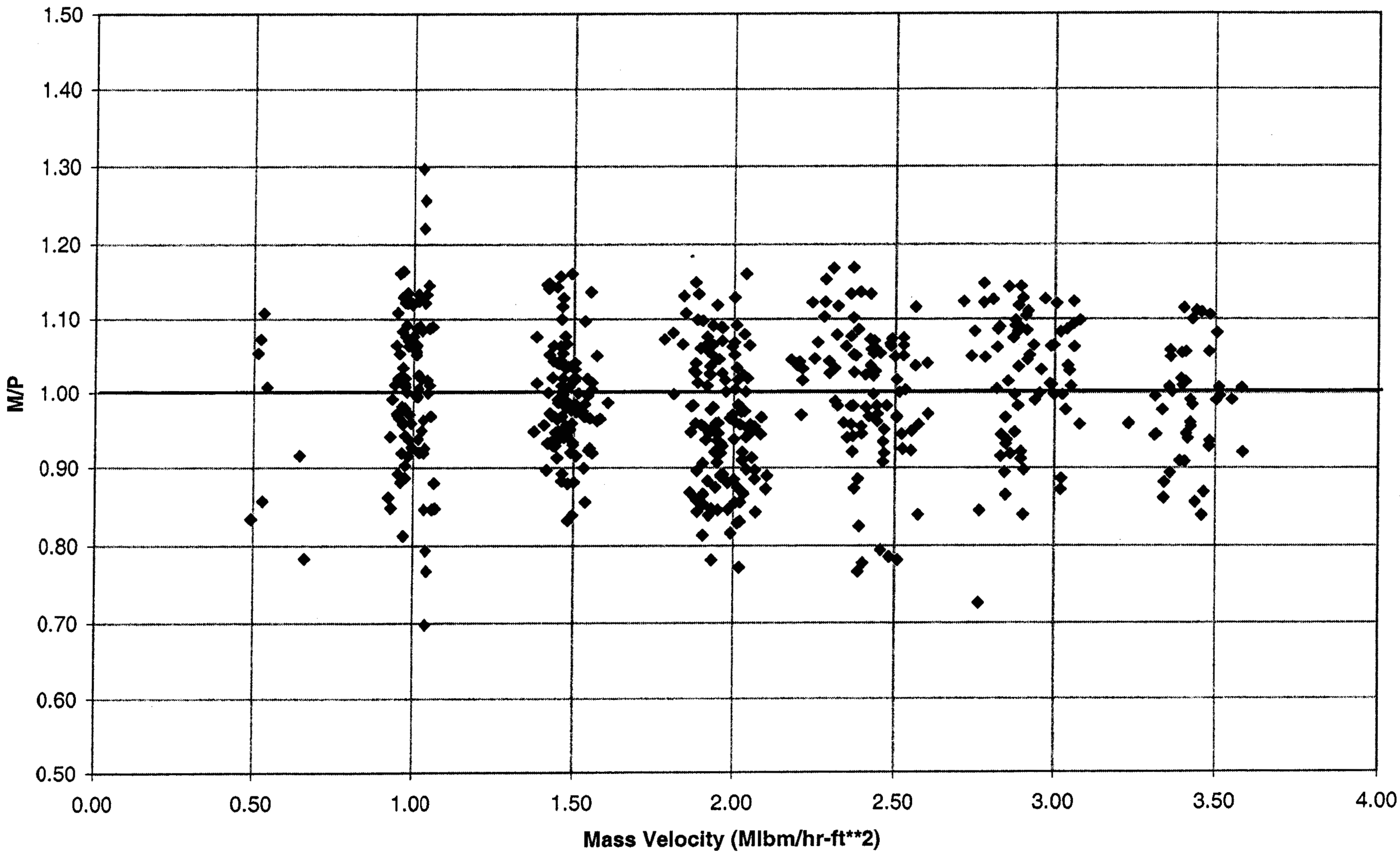


**Figure A.4.1-5: DNBR vs. Pressure for BWU-Z**

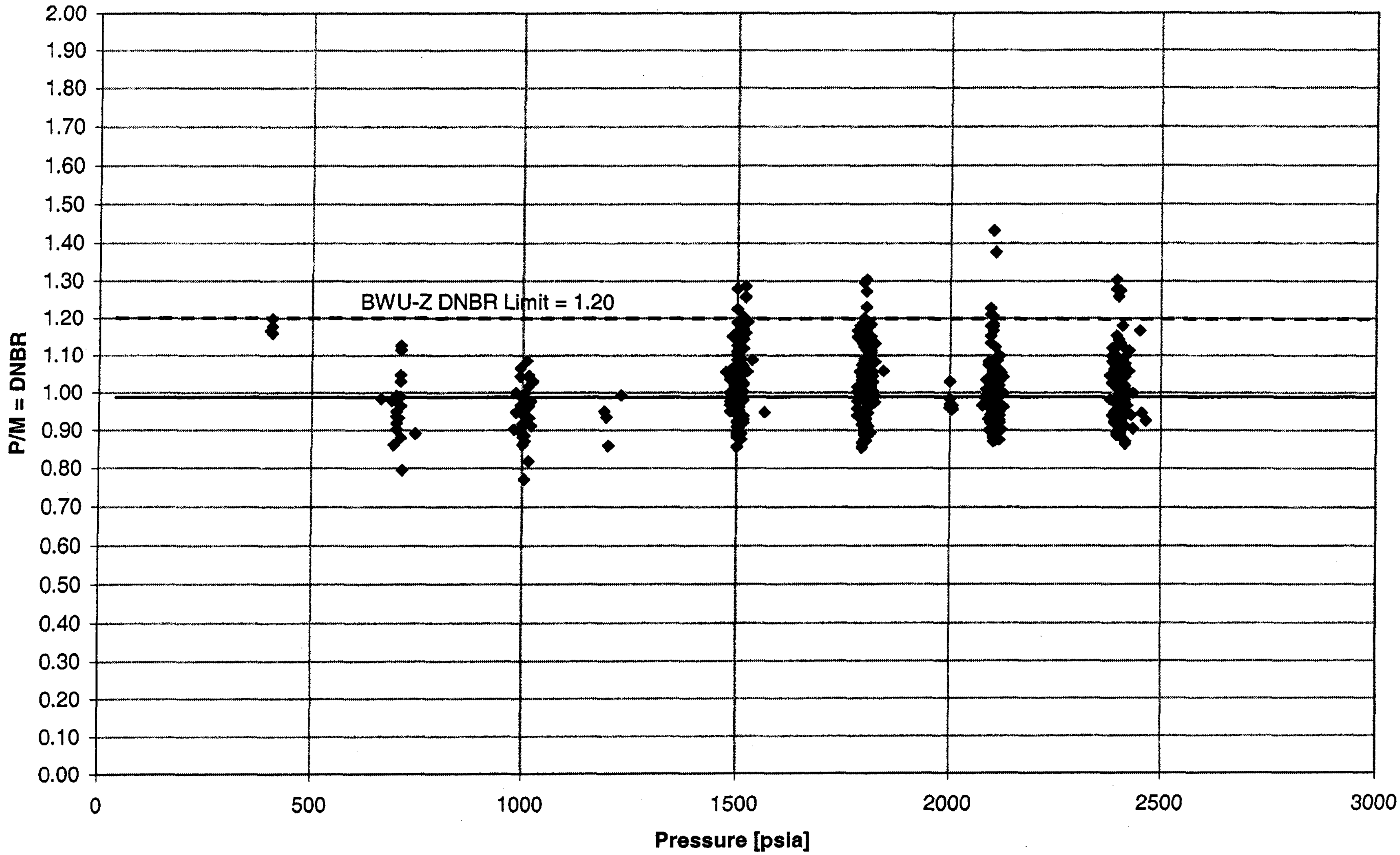


Figure A.4.1-6: DNBR vs. Quality for BWU-Z

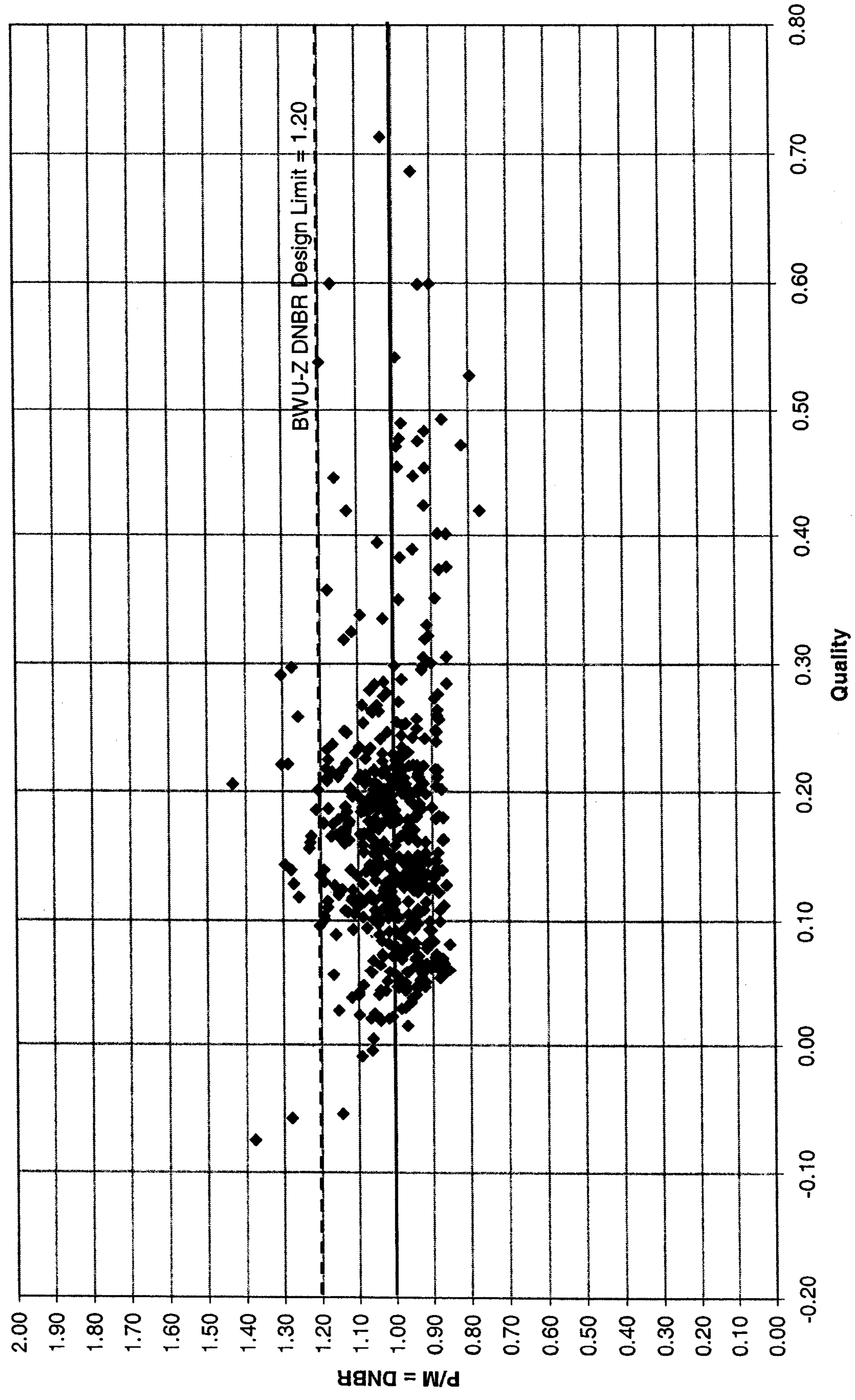
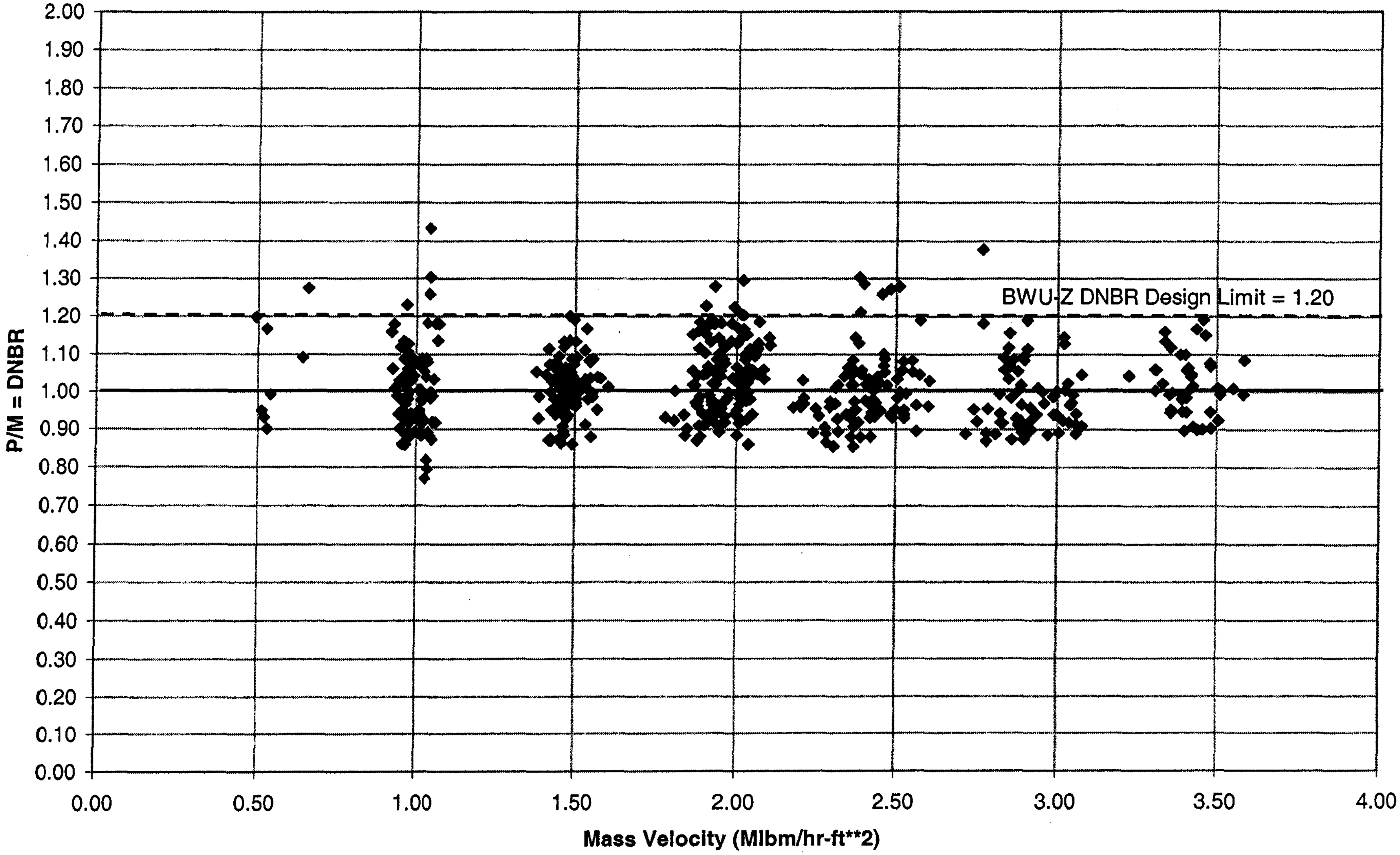


**Figure A.4.1-7: DNBR vs. Mass Velocity for BWU-Z**



## A.4.2 VIPRE-D/BWU-ZM RESULTS

The BWU-ZM correlation was developed by F-ANP correlating the CHF experimental results obtained in tests BW 12.0, BW 13.1, BW 14.1, BW 15.1, BW 16.0, BW 19.0 and BW 20.0. F-ANP used the experimental data obtained in tests BW 18.0, BW 18.1 and BW 43.0 to determine $F_{MSM}$ and to calculate the DNBR limit for the BWU-ZM correlation (Reference A2).

Dominion has used those same experimental data to determine the VIPRE-D/BWU-ZM DNBR limit. Table A.4.2-1 summarizes the relevant statistics for each test, and calculates the aggregate statistics for the entire set of data.

One-sided tolerance theory (Reference A5) is used for the calculation of the VIPRE-D/BWU-ZM DNBR design limit. This theory allows us to calculate a DNBR limit so that, for a DNBR equal to the design limit, DNB will be avoided with 95% probability at a 95% confidence level.

Table A.4.2-1: VIPRE-D/BWU-ZM M/P Ratio Results

| TEST | NUMBER OF TESTS | M/P RATIO AVERAGE | M/P RATIO STDEV | M/P RATIO MAX | M/P RATIO MIN |
|---|---|---|---|---|---|
| BW 18.0 | 18 | 0.9931 | 0.1136 | 1.1467 | 0.8334 |
| BW 18.1 | 58 | 1.0322 | 0.0945 | 1.2299 | 0.8142 |
| BW 43.0 | 72 | 1.0041 | 0.0715 | 1.1747 | 0.7793 |
| **BWU-ZM** | **148** | **1.0138** | **0.0875** | **1.2299** | **0.7793** |

Because all the statistical techniques used below assume that the original data distribution is normal, it is necessary to verify that the overall distribution for the M/P ratios is a normal distribution. To evaluate if the distribution is normal, the D' normality test was applied (Reference A6). A value of D' equal to 510.55, was obtained for the VIPRE-D/BWU-ZM database. This D' value is within the range of acceptability for 148 data points with a 95% confidence level (497.82 to 515.04)[d]. Thus, it is concluded that the M/P distribution for BWU-ZM is indeed normal.

Based on the results listed in table A.4.2-1, the deterministic DNBR design limit can be calculated as:

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[d] From Table 5 in Reference A6

D' Lower Limit (148) [P = 0.025] = 456.9 + (8 / 20) x (559.2 – 456.9) = 497.82

D' Upper Limit (148) [P = 0.975] = 473.2 + (8 / 20) x (577.8 – 473.2) = 515.04

$$DNBR_L = \frac{1.0}{M/P - K_{N,C,P} \cdot \sigma_{M/P}}$$ [A.4.2.1]

where

M/P = average measured to predicted CHF ratio

$\sigma_{M/P}$ = standard deviation of the measured to predicted CHF ratios of the database

$K_{N,C,P}$ = one-sided tolerance factor based on N degrees of freedom, C confidence level, and P portion of the population protected. This number is taken from Table 1.4.3 of Reference A5.

Then, the DNBR design limit for the VIPRE-D and the BWU-ZM correlation can be calculated as described in Table A.4.2-2:

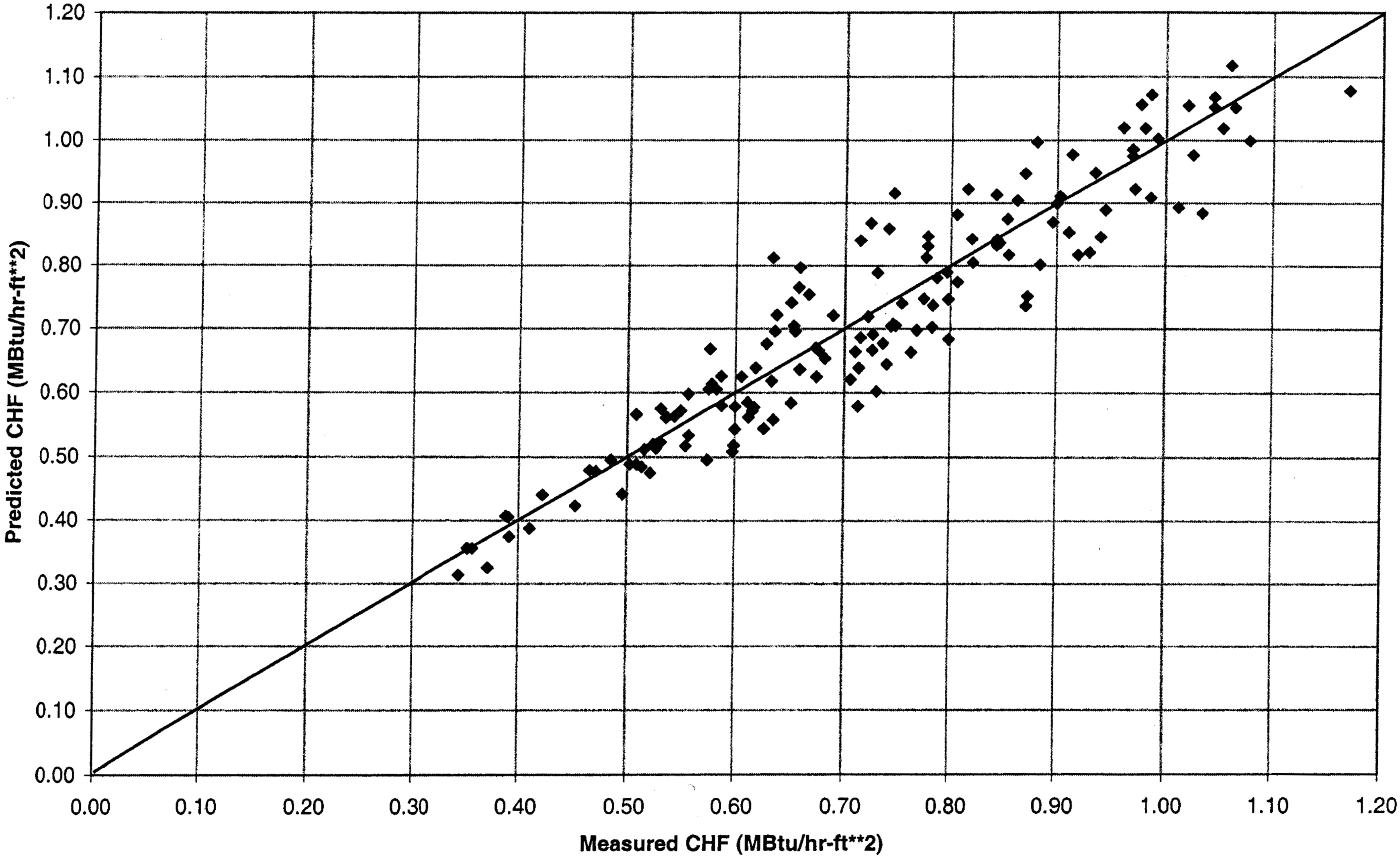
Table A.4.2-2: VIPRE-D/BWU-ZM DNBR Design Limit

| | | | **VIPRE-D/BWU-ZM** |
|---|---|---|---|
| Number of data | n | | 148 |
| Degrees of freedom | N | = n - 1 | 147 |
| Average M/P | M/P | | 1.0138 |
| Standard Deviation | $\sigma_{M/P}$ | | 0.0875 |
| Owen Factor | K(147,0.95,0.95) | | 1.872 |
| BWU-ZM Design limit | $DNBR_L$ | = 1 / (1.0138 – 1.872 · 0.0875) | **1.1765** |

Figures A.4.2-1 through A.4.2-4 display the performance of the M/P ratio, and its distributions as a function of the pressure, mass velocity and quality. The objective of these plots is to show that there are no biases in the M/P ratio distribution, and that the performance of the BWU-ZM 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. Figures A.4.2-5 through A.4.2-7 display the performance of the P/M ratio (i.e. the DNBR) against the major independent variables for the BWU-ZM database. These plots also include a DNBR design limit line at 1.18. It can be seen that only 4 data points (2.7% of the database) are above the DNBR design limit, and that these data in excess of the limit are distributed over the variable ranges tested.

For the BWU-ZM database, no individual DNBR design limits were calculated for the low pressure data. However, in order to extend the validity of the BWU-ZM CHF correlation over the same range as the BWU-Z CHF correlation, the VIPRE-D/BWU-ZM DNBR design limit at pressures less than 594 psia was set to 1.59 (The same as for BWU-Z at low pressures). The DNBR design limit for VIPRE-D/BWU-ZM for pressures equal to or greater than 594 psia is 1.18.

**Figure A.4.2-1: Measured vs. Predicted CHF for BWU-ZM**



## Figure A.4.2-2: M/P vs. Pressure for BWU-ZM

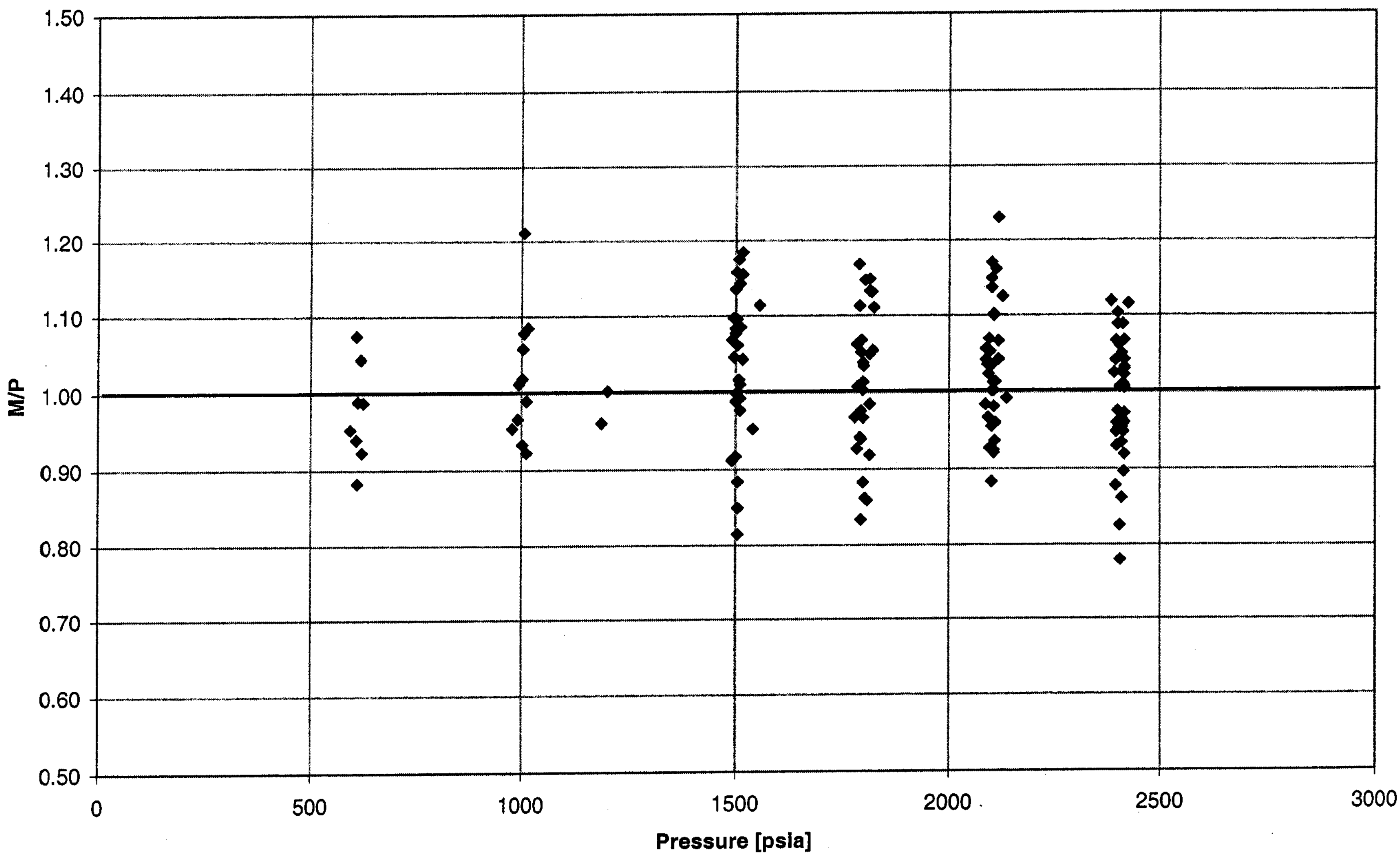
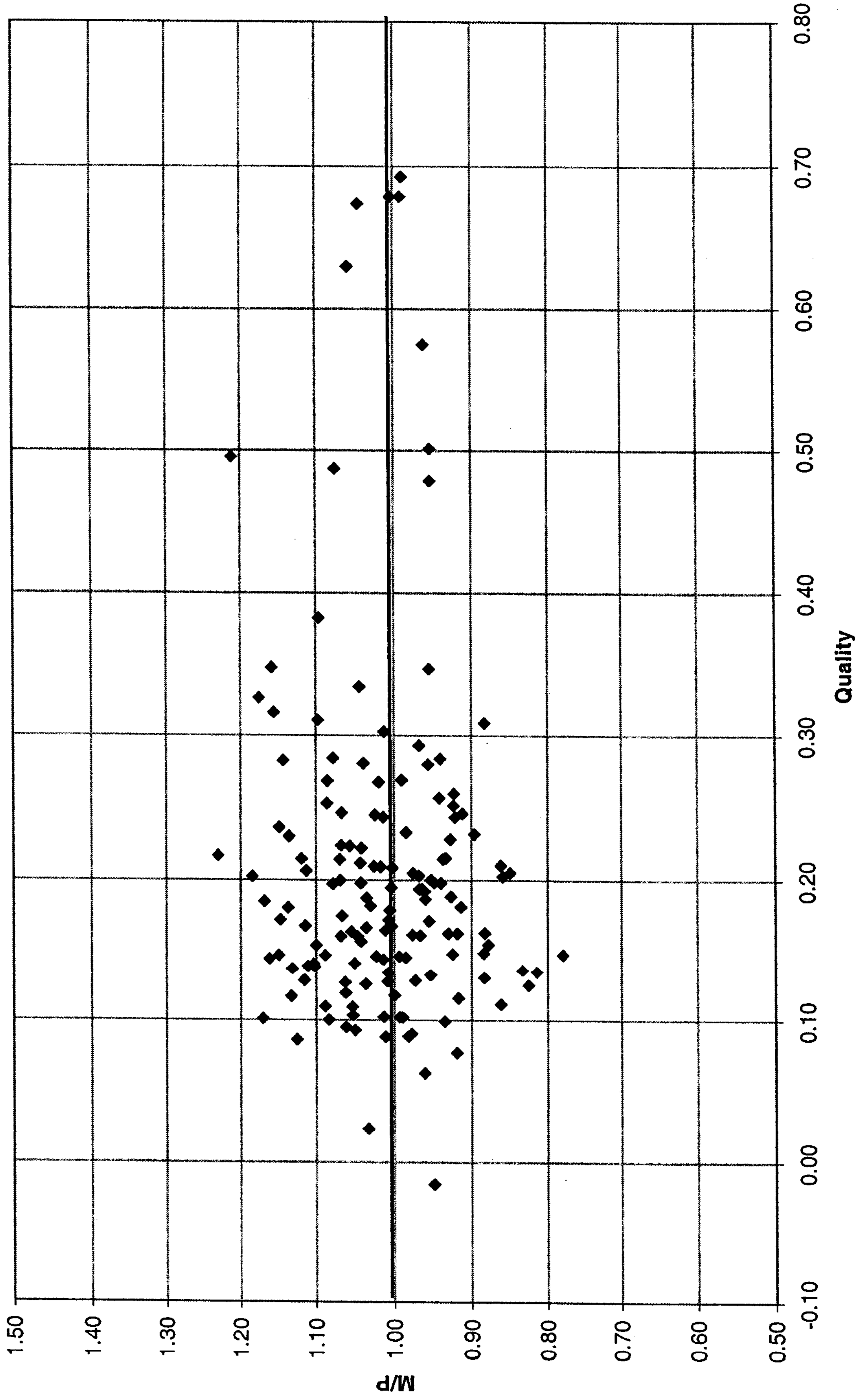


Figure A.4.2-3: M/P vs. Quality for BWU-ZM



## Figure A.4.2-4: M/P vs. Mass Velocity for BWU-ZM

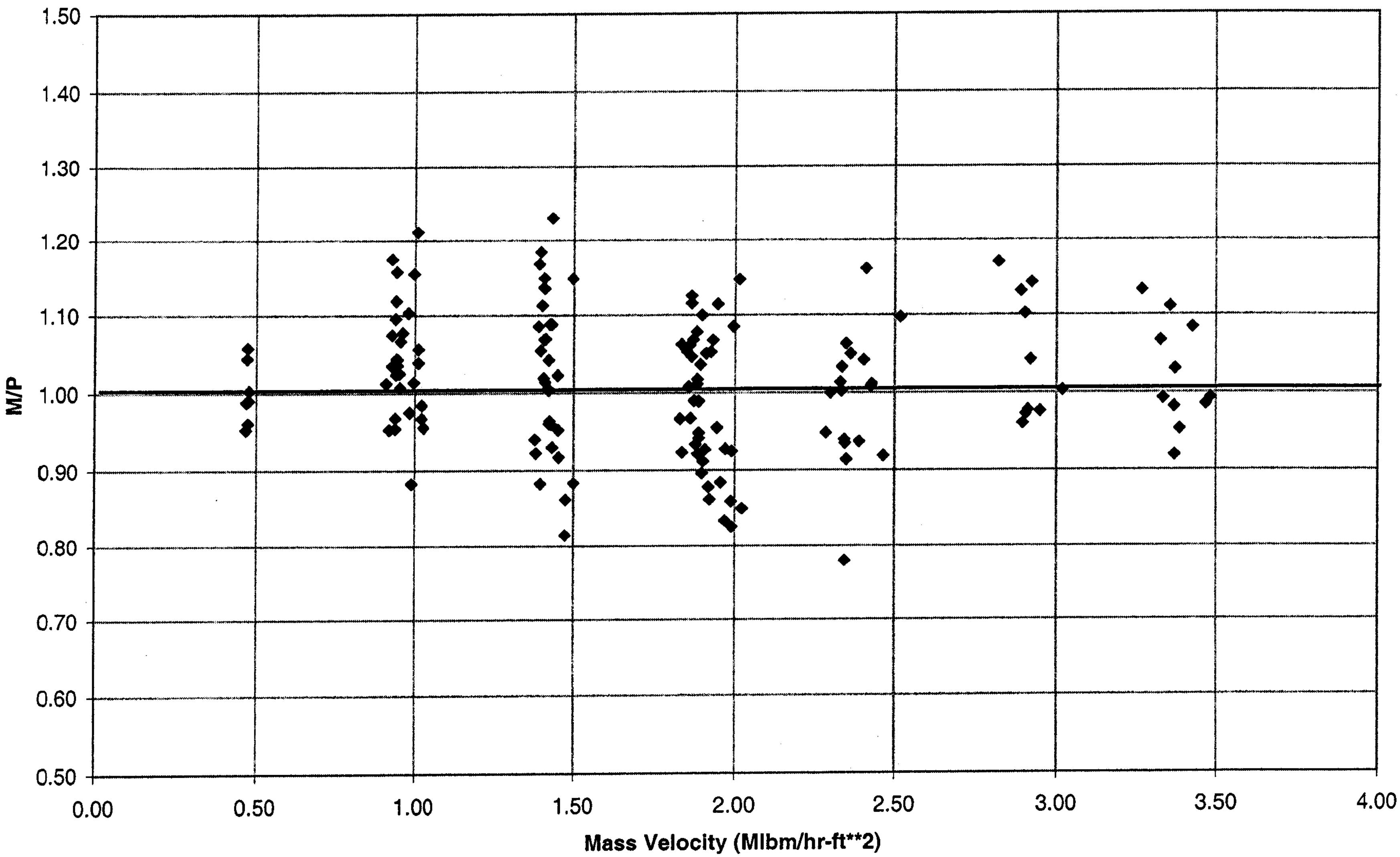


Figure A.4.2-5: DNBR vs. Pressure for BWU-ZM

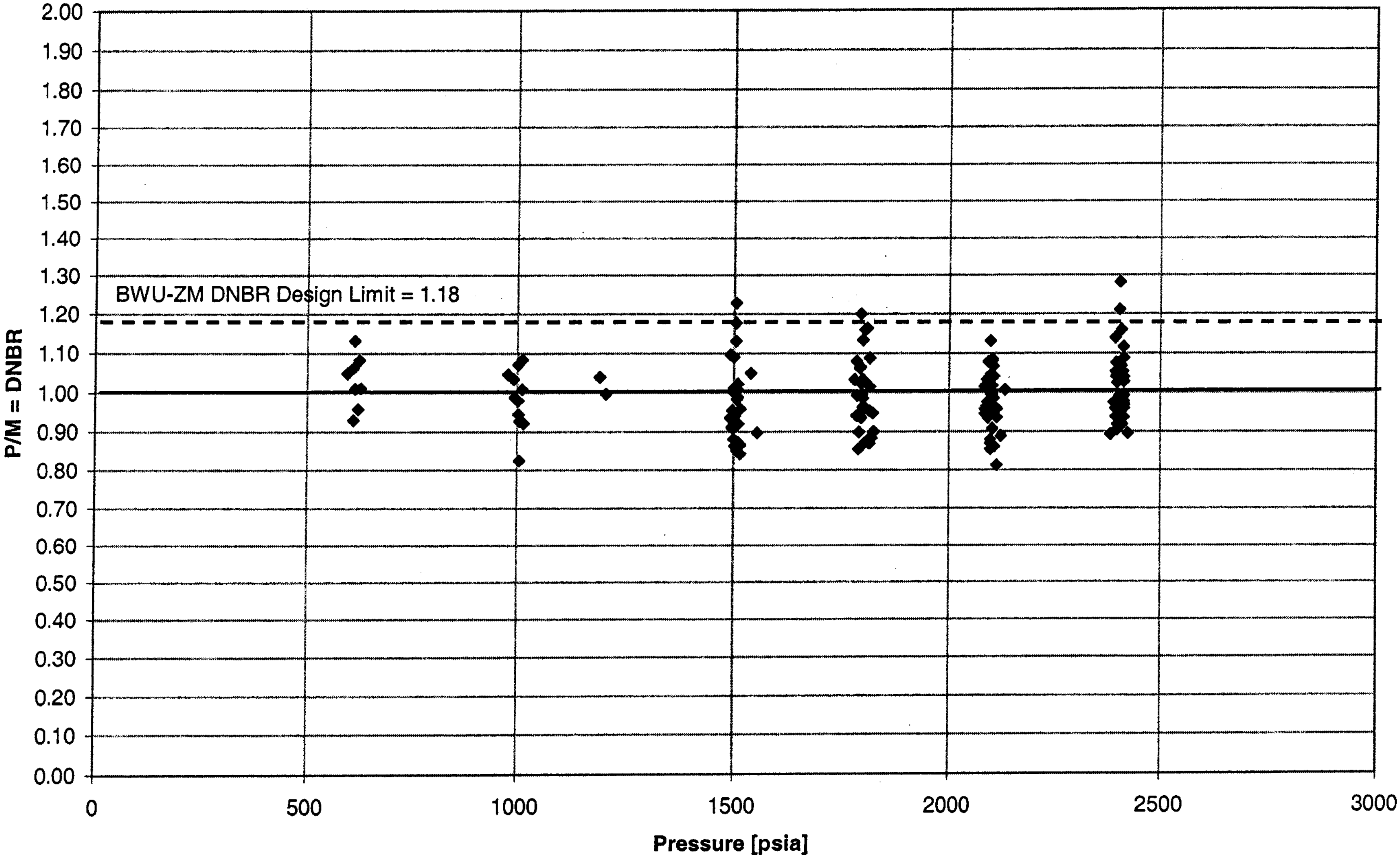


Figure A.4.2-6: M/P vs. Quality for BWU-ZM

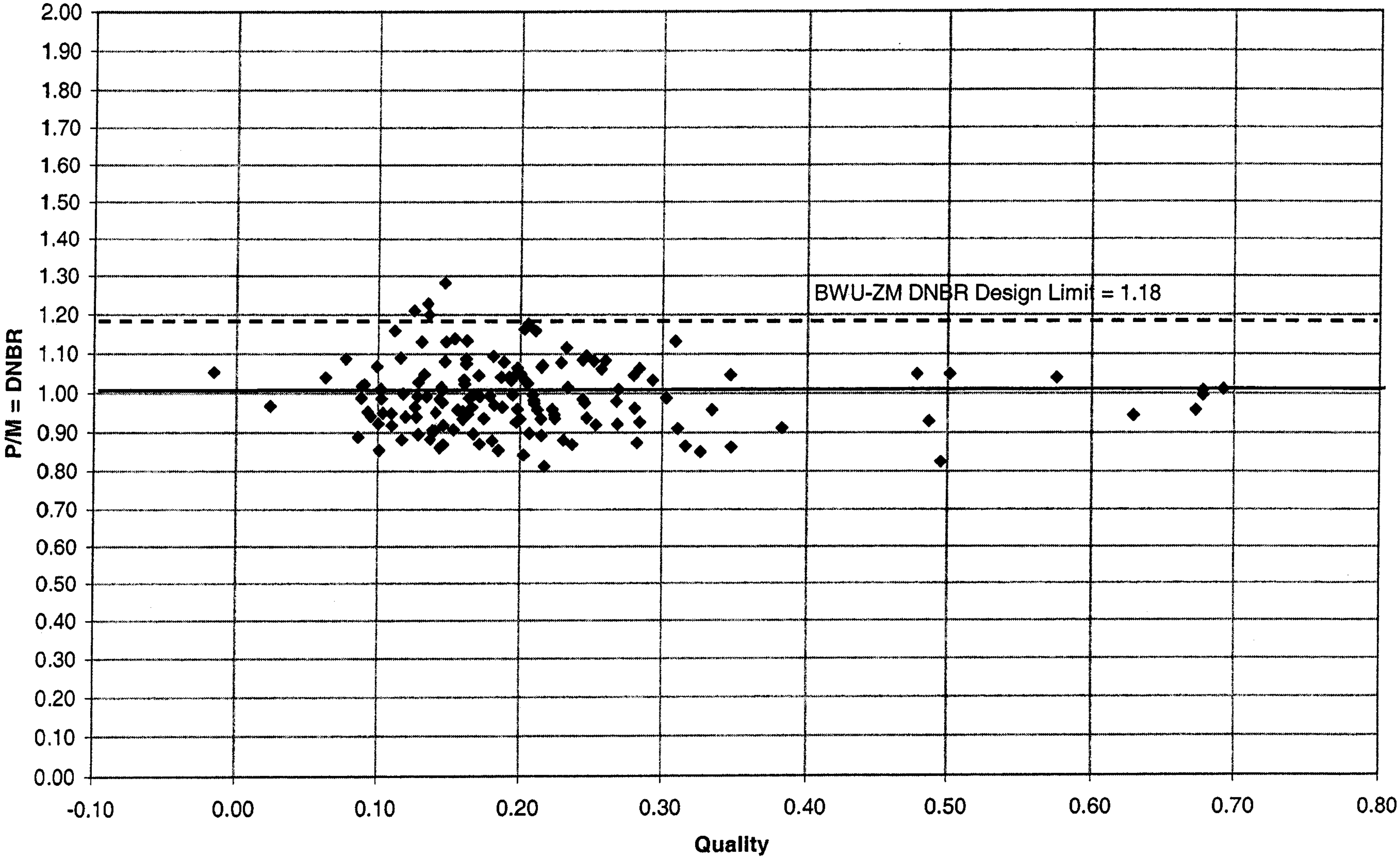
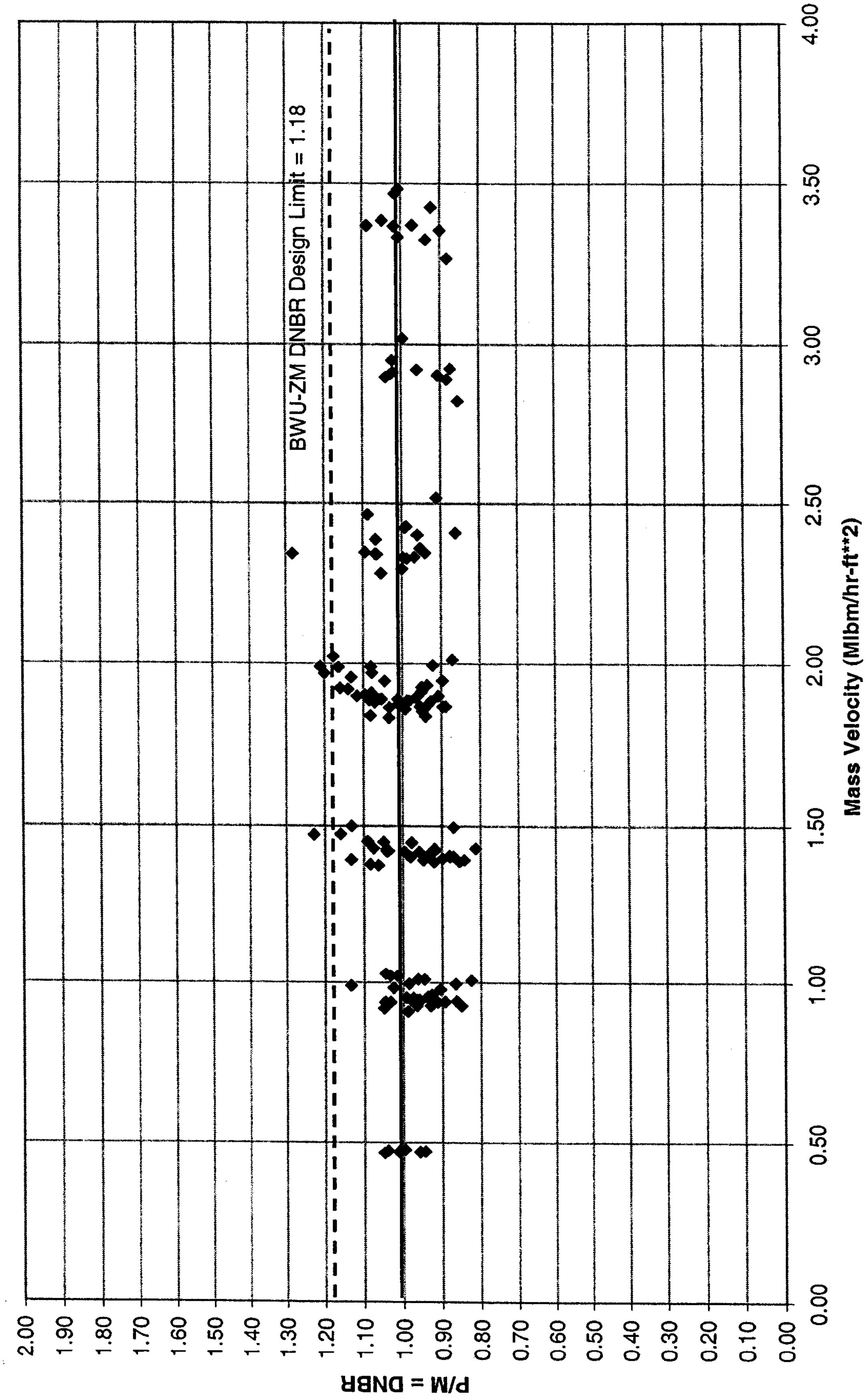


**Figure A.4.2-7: DNBR vs. Mass Velocity for BWU-ZM**



### A.4.3 VIPRE-D/BWU-N RESULTS

The BWU-N correlation was developed by F-ANP correlating the CHF experimental results obtained in the ARC tests C-3, C-6, C-7, C-8, C-9, C-11, C-12, B-15, B-16 and B-17. Dominion has used those same experimental data to determine the VIPRE-D/BWU-N DNBR limit. Table A.4.3-1 summarizes the relevant statistics for each test, and calculates the aggregate statistics for the entire set of data.

Table A.4.3-1: VIPRE-D/BWU-N M/P Ratio Results

| TEST | NUMBER OF TESTS | M/P RATIO AVERAGE | M/P RATIO STDEV | M/P RATIO MAX | M/P RATIO MIN |
|---|---|---|---|---|---|
| **C-3** | 107 | 1.0655 | 0.1128 | 1.3251 | 0.7501 |
| **C-6** | 128 | 0.9445 | 0.1188 | 1.2966 | 0.6635 |
| **C-7** | 120 | 0.9757 | 0.0942 | 1.1553 | 0.6707 |
| **C-8** | 155 | 1.0076 | 0.0816 | 1.2127 | 0.7396 |
| **C-9** | 85 | 1.0373 | 0.0605 | 1.1681 | 0.8934 |
| **C-11** | 34 | 0.9986 | 0.0862 | 1.1389 | 0.8041 |
| **C-12** | 133 | 1.0083 | 0.0881 | 1.2003 | 0.7346 |
| **B-15** | 47 | 0.9806 | 0.0971 | 1.1263 | 0.7438 |
| **B-16** | 129 | 1.0052 | 0.1219 | 1.2627 | 0.6985 |
| **B-17** | 152 | 0.9988 | 0.1004 | 1.3507 | 0.8002 |
| **BWU-N** | **1090** | **1.0018** | **0.1038** | **1.3507** | **0.6635** |

One-sided tolerance theory (Reference A5) is used for the calculation of the VIPRE-D/BWU-N DNBR design limit. This theory allows us to calculate a DNBR limit so that, for a DNBR equal to the design limit, DNB will be avoided with 95% probability at a 95% confidence level.

Because all the statistical techniques used below assume that the original data distribution is normal, it is necessary to verify that the overall distribution for the M/P ratios is a normal distribution. To evaluate if the distribution is normal, the D' normality test was applied (Reference A6). A value of D' equal to 9,963.21 was obtained for the VIPRE-D/BWU-N database. This D' value is not within the range of acceptability for 1090 data points with a 95% confidence level (10,082.0 to 10,210.60)[e]. Since the value of D' is less than the lower critical value, the BWU-N distribution has greater kurtosis

[e] From Table 5 in Reference A6

D' Lower Limit (1090) [P = 0.025] = 9,530 + (40 / 50) x (10,220 – 9,530) = 10,082.0

D' Upper Limit (1090) [P = 0.975] = 9,653 + (40 / 50) x (10,350 – 9,653) = 10,210.6

than a normal distribution. Therefore, the one-sided theory is conservative for VIPRE-D/BWU-N. This behavior was also observed by F-ANP in Reference A1.

Based on the results listed in Table A.4.3-1, the DNBR limit can be calculated as:

$$DNBR_L = \frac{1.0}{M/P - K_{N,C,P} \cdot \sigma_{M/P}} \quad [A.4.3.1]$$

where

$M/P$ = average measured to predicted ratio

$\sigma_{M/P}$ = standard deviation of the measured to predicted ratios of the database

$K_{N,C,P}$ = one-sided tolerance factor based on N degrees of freedom, C confidence level, and P portion of the population protected. This number is taken from Table 1.4.4 of Reference A5.

Then, the DNBR design limit for the VIPRE-D/BWU-N code/correlation pair can be calculated as described in Table A.4.3-2:

Table A.4.3-2: VIPRE-D/BWU-N DNBR Design Limit

| | | | **VIPRE-D/BWU-N** |
|---|---|---|---|
| Number of data | n | | 1090 |
| Degrees of freedom | N | = n - 1 - 14 | 1075 |
| Average M/P | M/P | | 1.0018 |
| Standard Deviation | $\sigma_{M/P}$ | | 0.1038 |
| Corrected Standard Deviation | $\sigma_N$ | $= \sigma_{M/P} \cdot [\,(n-1) / N\,]^{1/2}$ | 0.1045 |
| Owen Factor | K(1075,0.95,0.95) | | 1.7239 |
| BWU-N Design limit | $DNBR_L$ | = 1 / (1.0018 – 1.7239 · 0.1045) | **1.2170** |

Figures A.4.3-1 through A.4.3-4 display the performance of the M/P ratio, and its distributions as a function of the pressure, mass velocity and quality. The objective of these plots is to show that there are no biases in the M/P ratio distribution, and that the performance of the BWU-N 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. Figures A.4.3-5 through A.4.3-7 display the performance of the P/M ratio (i.e. the DNBR) against the major independent variables for the BWU-N database. These plots also include a DNBR design limit line at 1.22. It can be seen that only 65 data points are above the DNBR design limit, and that these data in excess of the limit are distributed over the variable ranges tested.

In Reference A1, the USNRC argued that the performance of the BWU-N correlation might be deficient at the extremely low end of the pressure range. For that reason, F-ANP developed individual DNBR design limits for each low pressure group in the database. This approach allows users to use the BWU-N correlation at low pressures but imposes a higher DNBR limit to ensure that the correlation is used conservatively. Table A.4.3-3 summarizes the VIPRE-D/BWU-N DNBR limits calculated for the different pressure groups and compares them with the DNBR design limits obtained by F-ANP in Reference A1.

Table A.4.3-3: VIPRE-D/BWU-N DNBR Limits for Pressure Groups

| | **800 psia** | **1200 psia** | **1500 – 2616 psia** |
|---|---|---|---|
| **AVERAGE M/P** | 1.0019 | 1.0598 | 1.0007 |
| **STDEV** | 0.1186 | 0.0865 | 0.1036 |
| **N, # DATA** | 20 | 20 | 1050 |
| **K(N,0.95,0.95)** | 2.396 | 2.396 | 1.7249 |
| **VIPRE-D DNBR LIMIT** | **1.393** | **1.173** | **1.217** |
| ***LYNX2 DNBR LIMIT*** | ***1.387*** | ***1.290*** | ***1.207*** |

Dominion will take the VIPRE-D/BWU-N DNBR limit to be 1.22 for pressures equal to or greater than 1200 psia, and 1.39 at pressures less than 1200 psia.

## Figure A.4.3-1: Measured vs. Predicted CHF for BWU-N

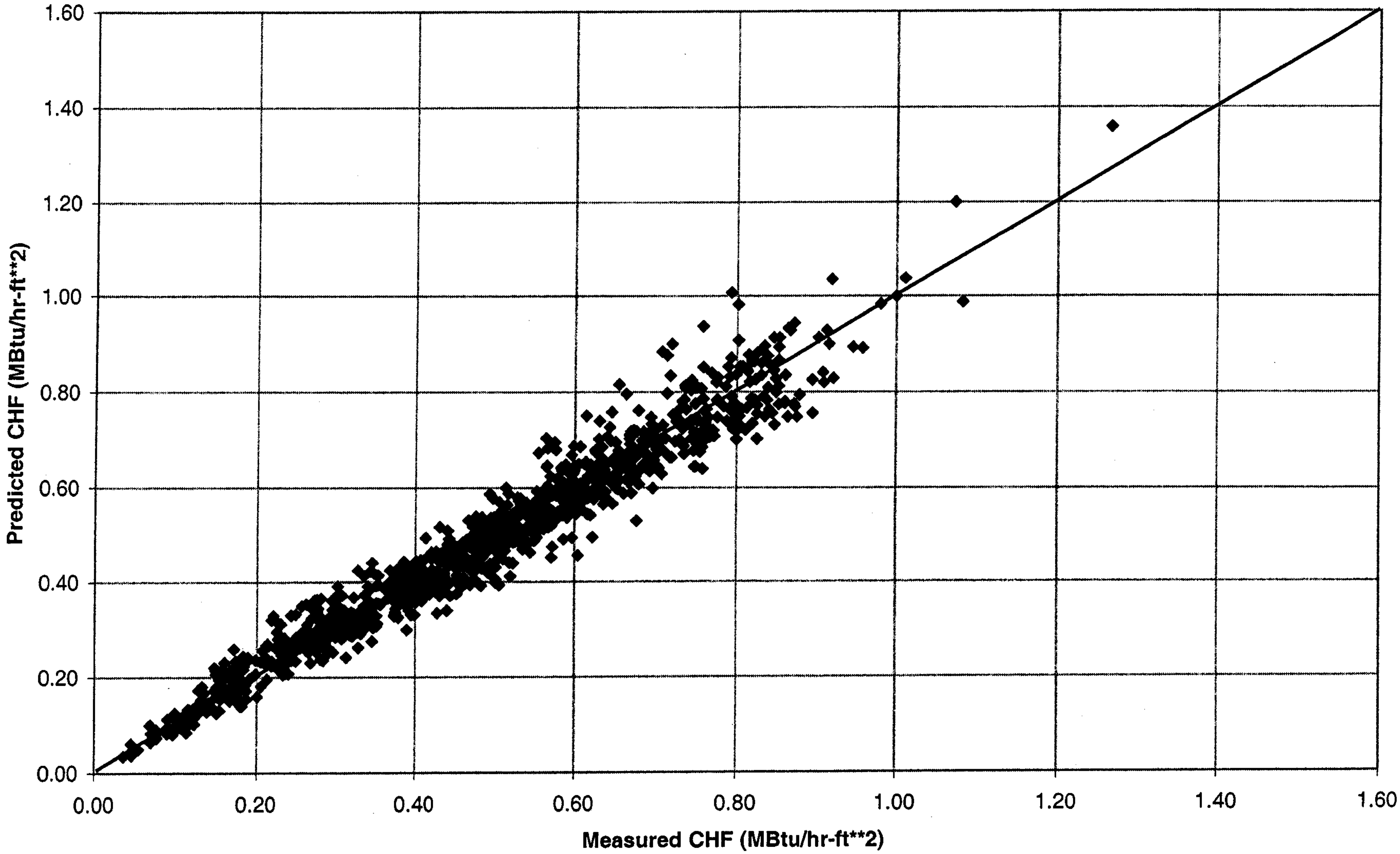


**Figure A.4.3-2: M/P vs. Pressure for BWU-N**

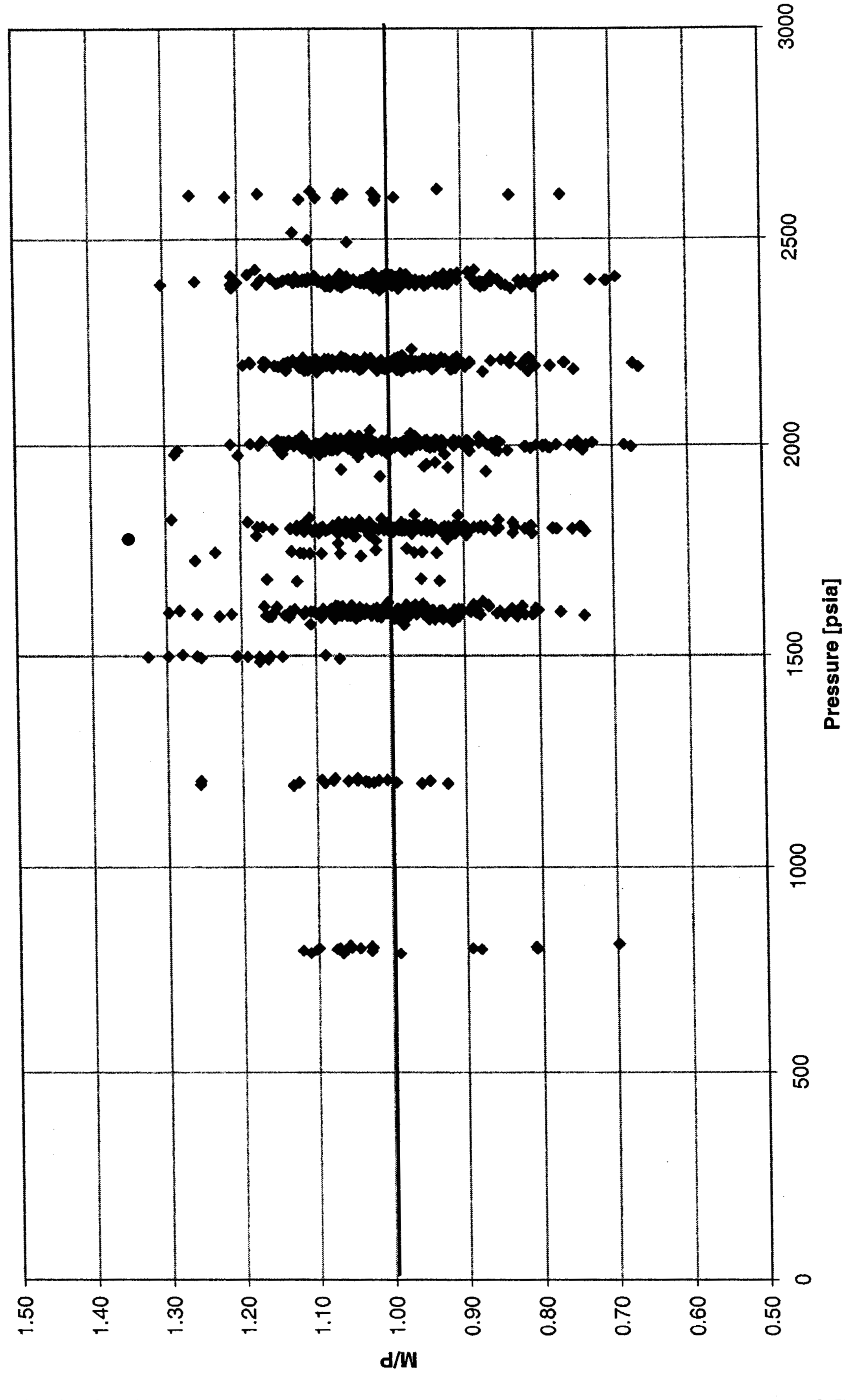
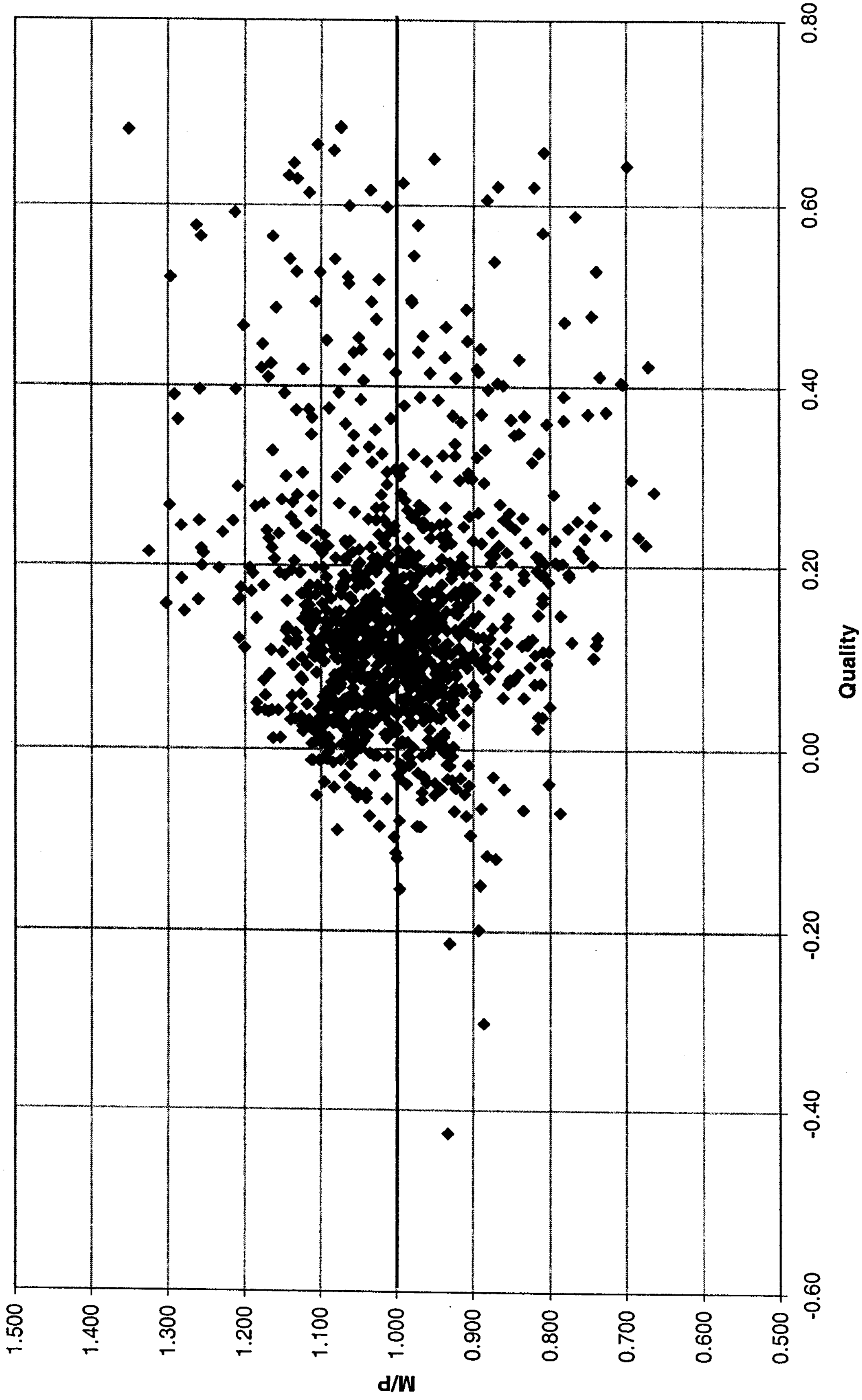


**Figure A.4.3-3: M/P vs. Quality for BWU-N**



## Figure A.4.3-4: M/P vs. Mass Velocity for BWU-N

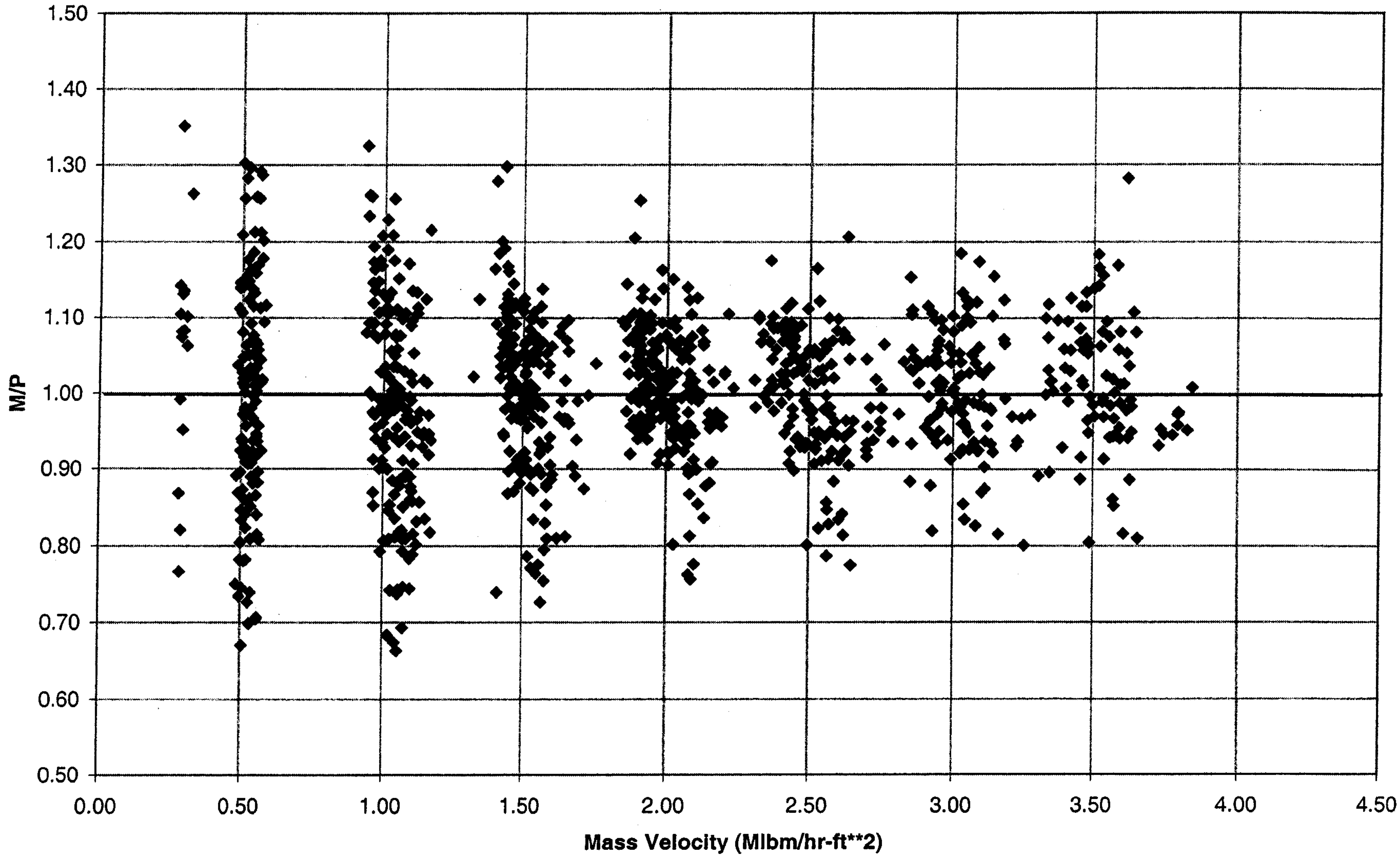


Figure A.4.3-5: DNBR vs. Pressure for BWU-N

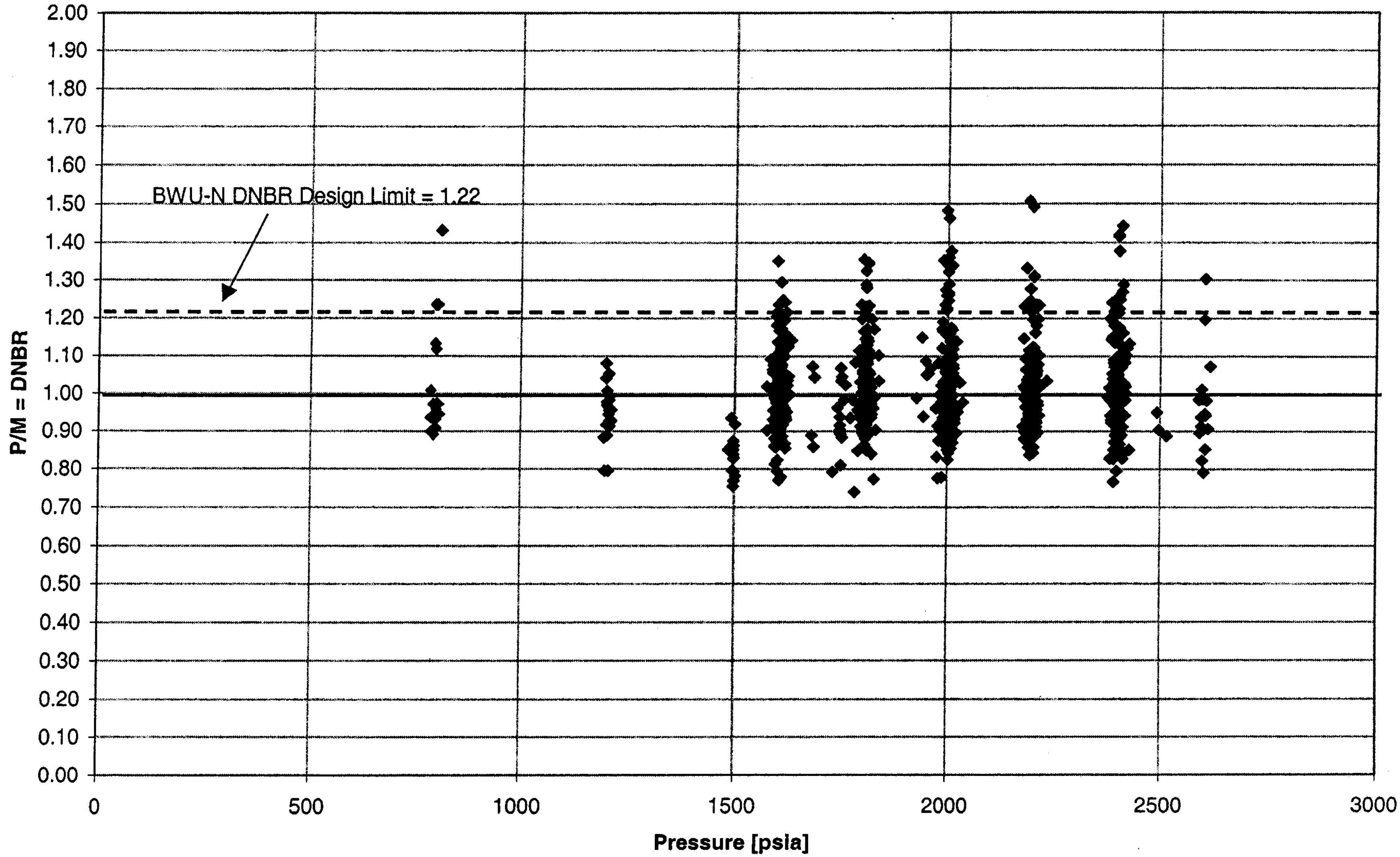
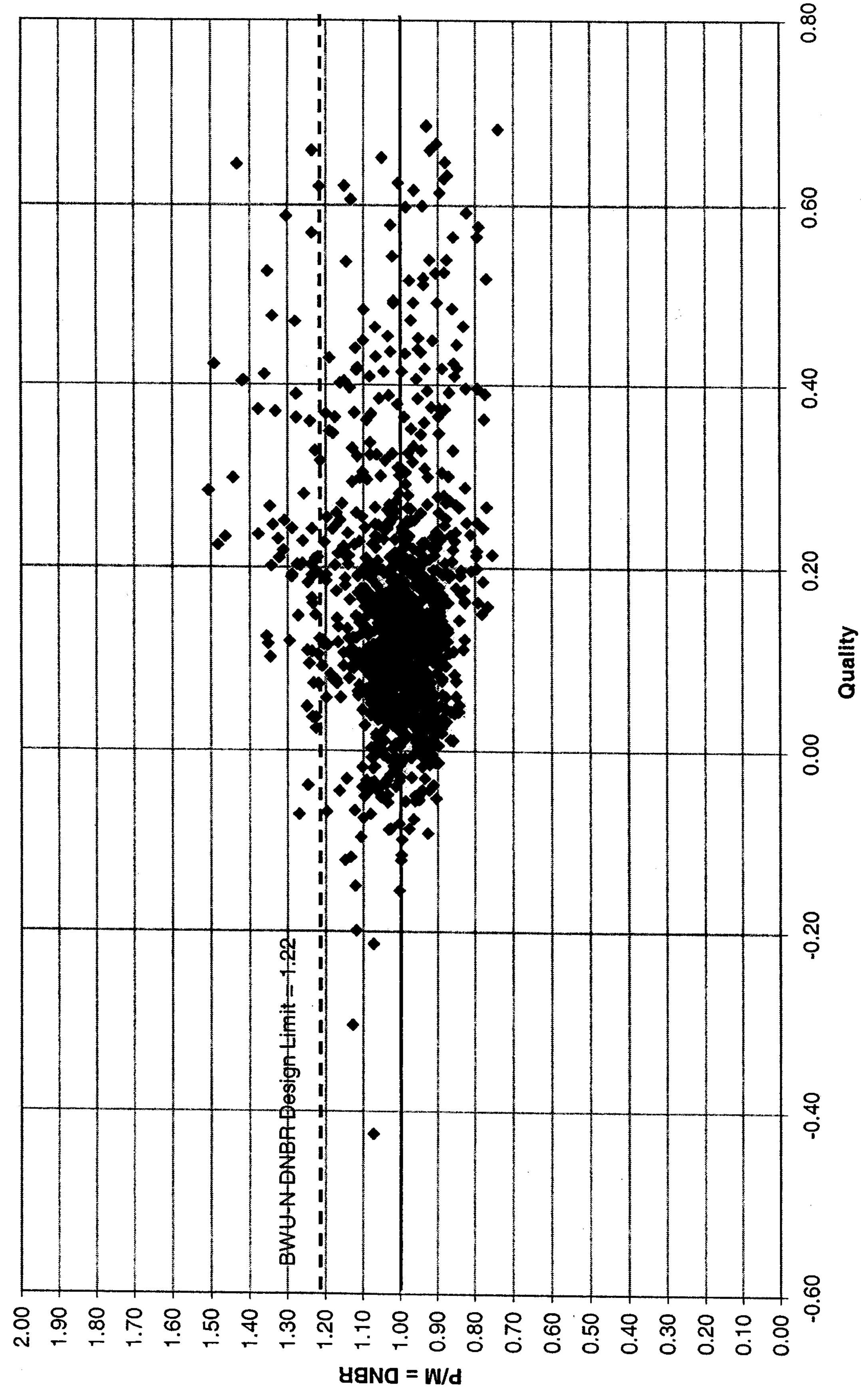
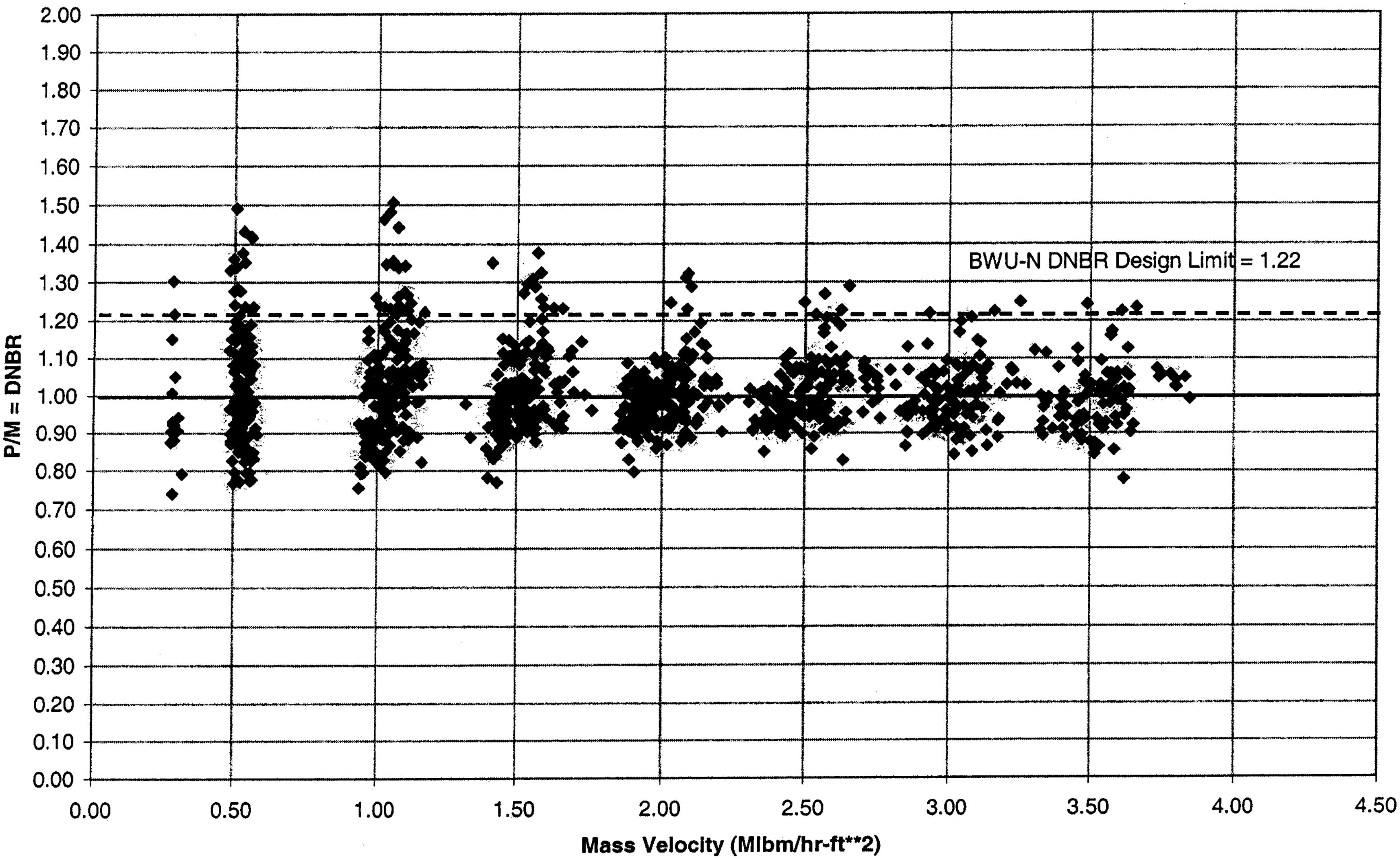


Figure A.4.3-6: DNBR vs. Quality for BWU-N



## Figure A.4.3-7: DNBR vs. Mass Velocity for BWU-N



## A.5 CONCLUSIONS

The BWU-Z, BWU-ZM and BWU-N correlations have been qualified with Dominion's VIPRE-D computer code. Table A.5-1 summarizes the DNBR design limits for VIPRE-D/BWU-Z, VIPRE-D/BWU-ZM and VIPRE-D/BWU-N that yield a 95% non-DNB probability at a 95% confidence level.

Table A.5-2 summarizes the applicability and the ranges of validity for all three CHF correlations, which are the same as those reported by F-ANP in References A1 and A2.

Table A.5-1: VIPRE-D DNBR Limits for BWU-Z, BWU-ZM and BWU-N

| **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 above 594 psia | 1.18 |
| **VIPRE-D/BWU-N** | |
| DNBR limit below 1200 psia | 1.39 |
| DNBR limit above 1200 psia | 1.22 |

Table A.5-2: Range of validity for BWU-Z, BWU-ZM and BWU-N

| | **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 |

## A.6 REFERENCES


A1. Technical Report, BAW-10199P-A, "The BWU Critical Heat Flux Correlations," Framatome Cogema Fuels, August 1996, including Addendum 1, December 2000.

A2. Technical Report, BAW-10199P-A, Addendum 2, "Application of the BWU-Z CHF Correlation to the Mark-BW17 Fuel Design with Mid-Span Mixing Grids," Framatome Cogema Fuels, June 2002.

A3. Technical Report, BAW-10143P-A, "BWC Correlation of Critical Heat Flux," Babcock & Wilcox, April 1985.

A4. Technical Report, BAW-10189P-A, "CHF Testing and Analysis of the Mark-BW Fuel Assembly Design," Framatome Technologies, January 1996.

A5. Technical Report, "Tables for Normal Tolerance Limits, Sampling Plans, and Screening," R. E. Odeh and D. B. Owen, 1980.

A6. Technical Report, "Assessment of the Assumption of Normality (employing individual observed values)," American National Standards Institute, ANSI N15.15.1974.