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)

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APPENDIX A

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

NUCLEAR ANALYSIS AND FUEL DEPARTMENT
DOMINION
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Prepared by:

Rosa M. Bilbao y León

Reviewed by:

Kurt F. Flaig

Recommended for Approval:

D. M. Knee
Supervisor, Nuclear Safety Analysis

Approved:

K. L. Basehore
Director, Nuclear Analysis and Fuel

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.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

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.

[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	σ_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 · 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.

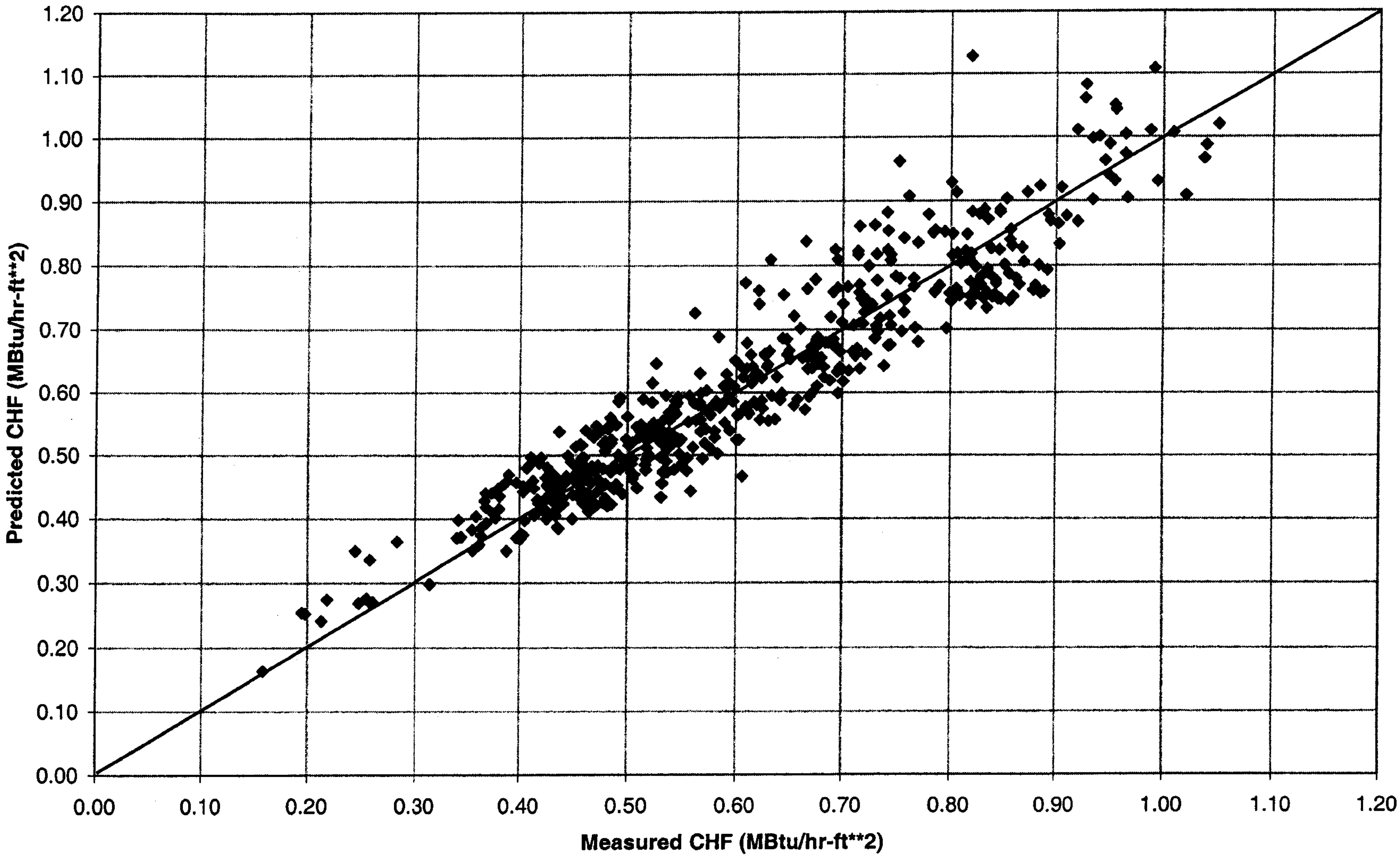
In Reference A1, the USNRC argued that the performance of the BWU-Z correlation might be deficient at the extremely low end of the pressure range. For that reason, F-ANP developed individual DNBR design limits for each low pressure group in the database. This approach allows users to use the BWU-Z correlation 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



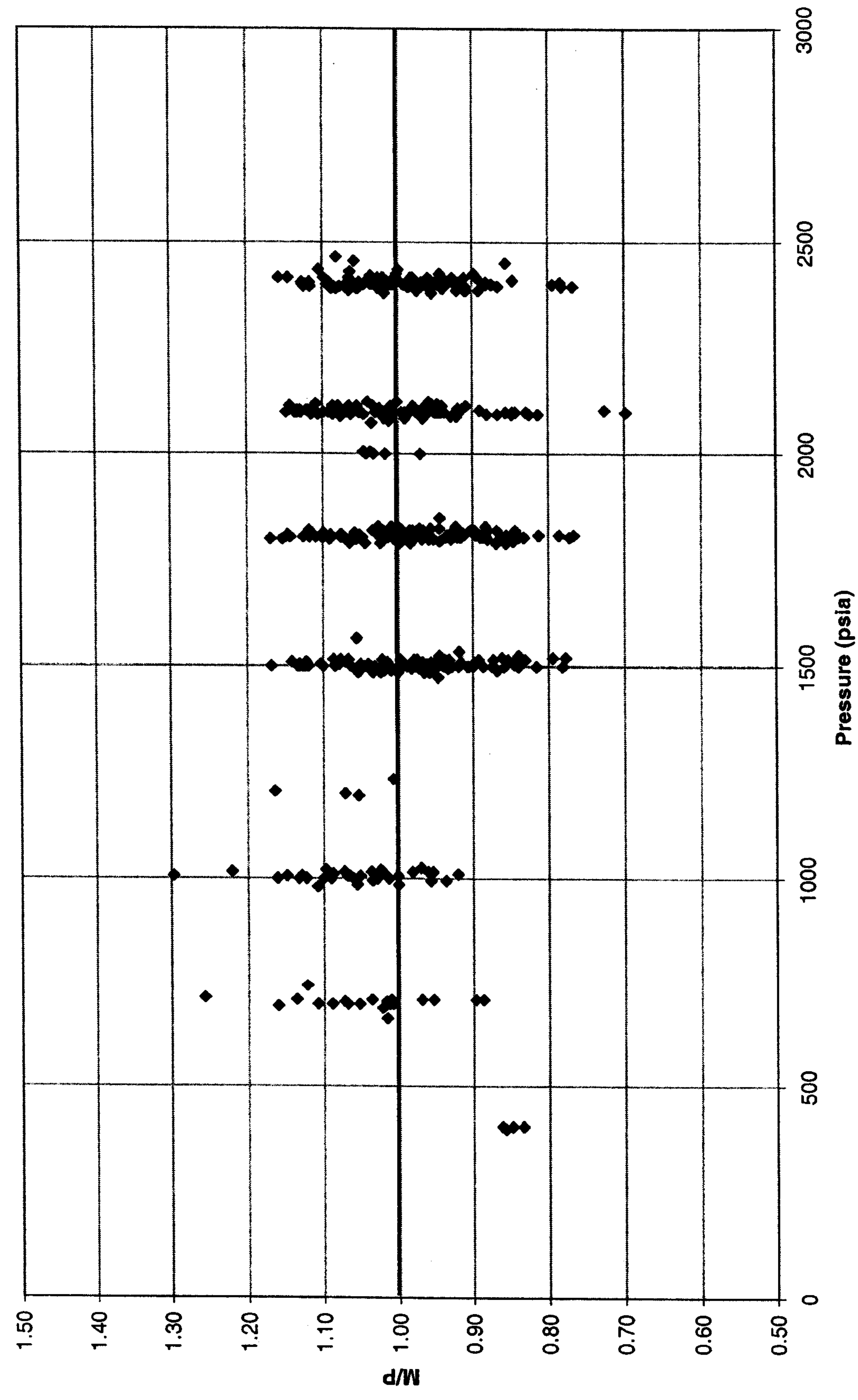


Figure A.4.1-2: M/P vs. Pressure for BWU-Z

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

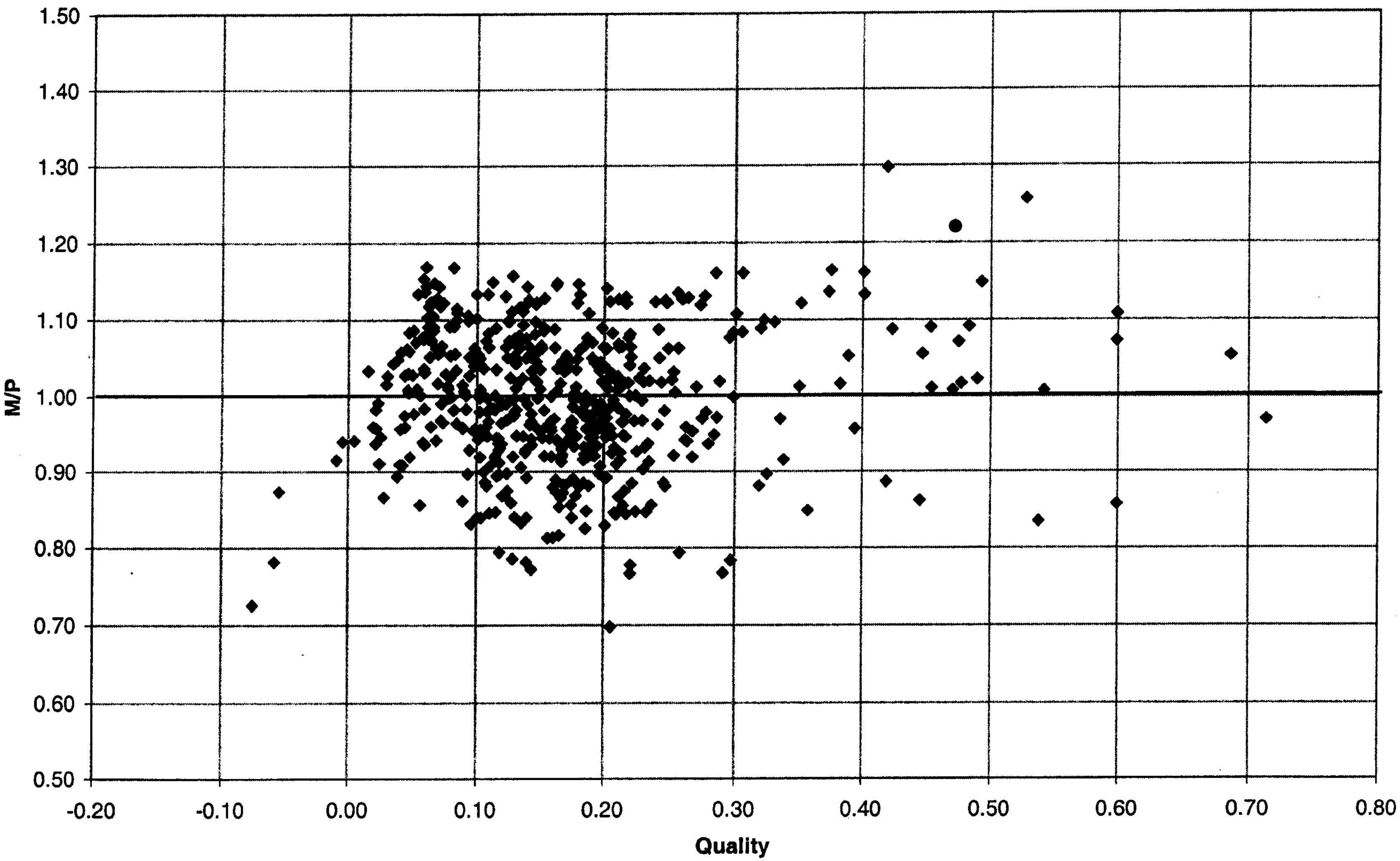


Figure A.4.1-4: M/P vs. Mass Velocity for BWU-Z

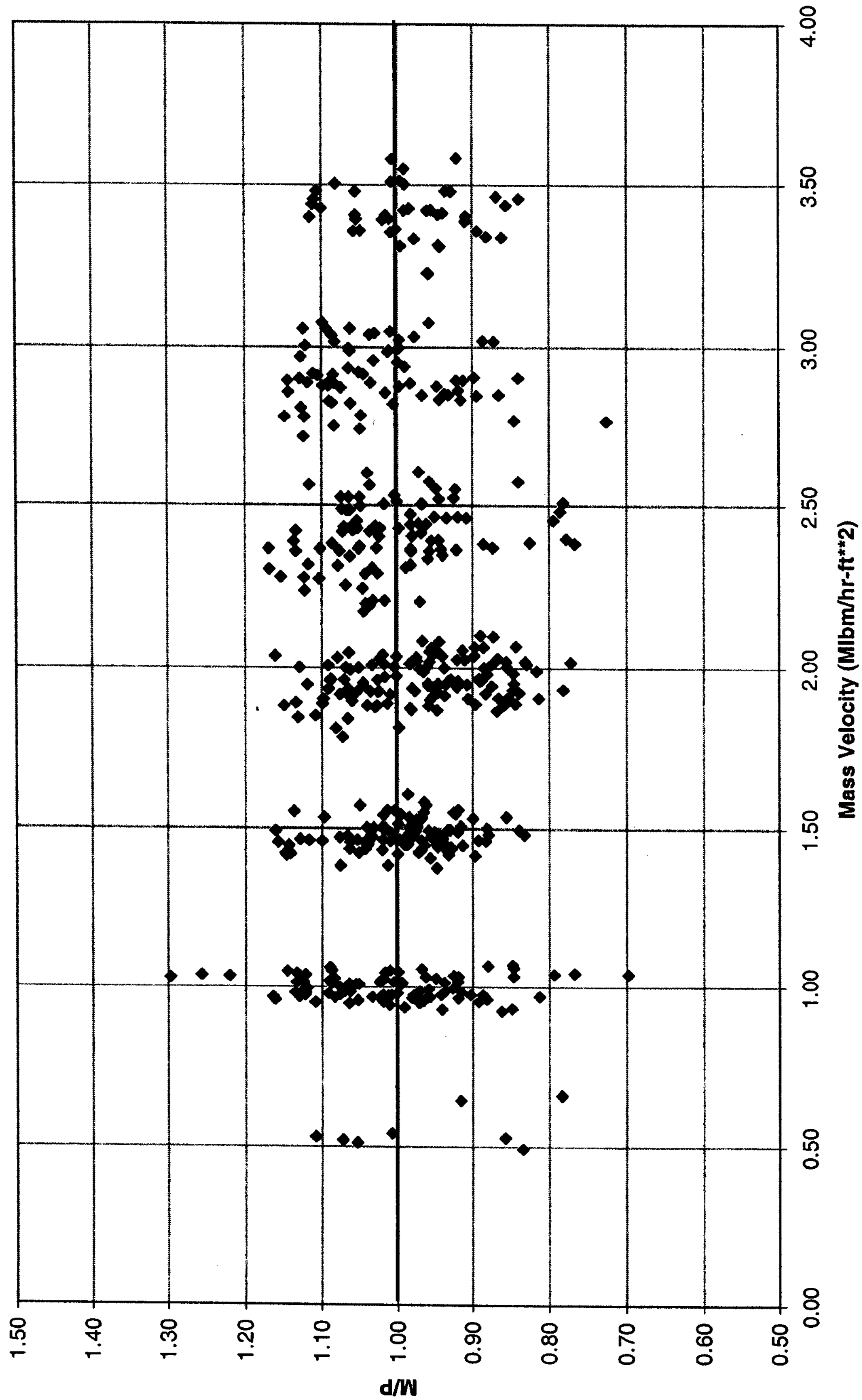


Figure A.4.1-5: DNBR vs. Pressure for BWU-Z

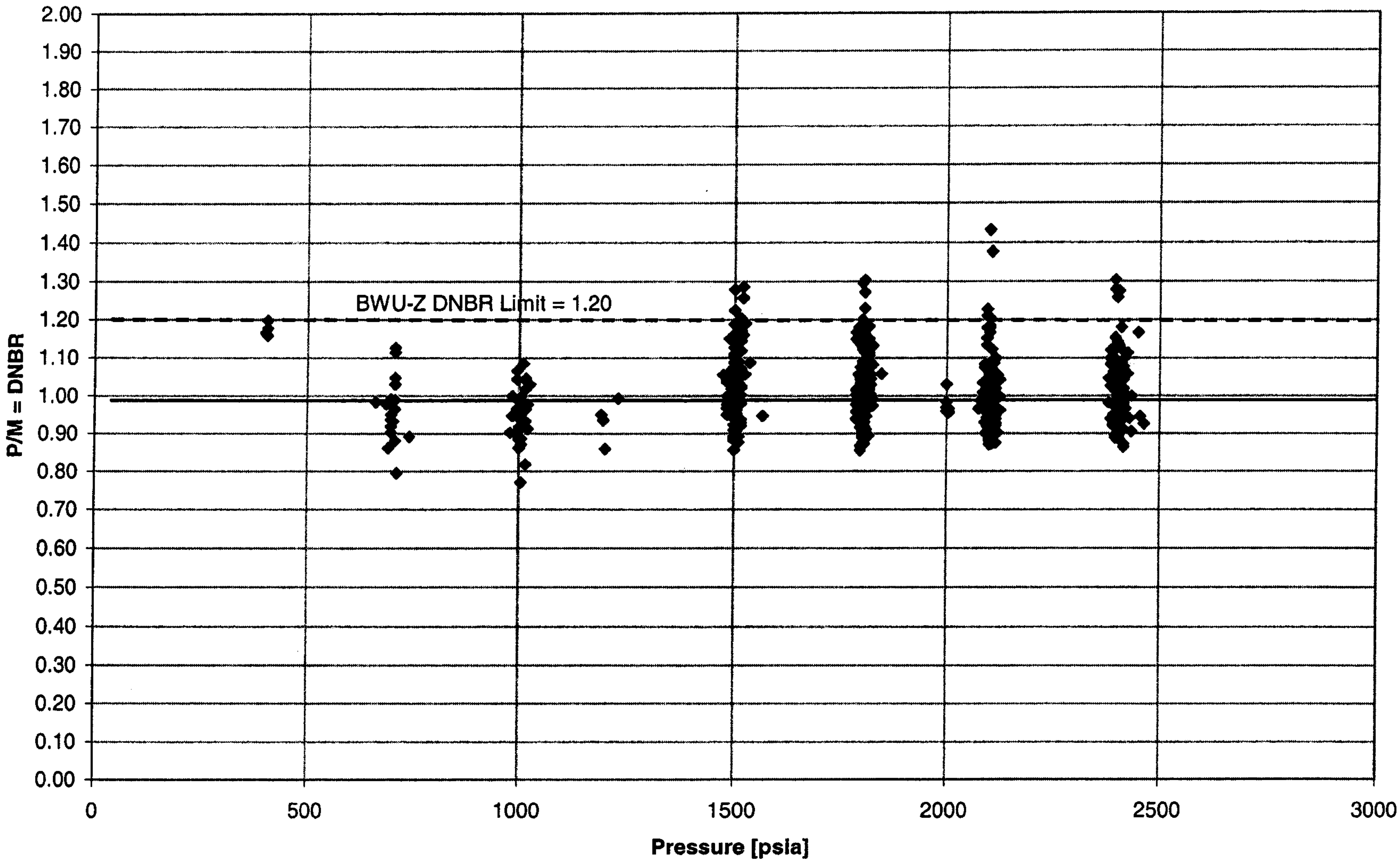


Figure A.4.1-6: DNBR vs. Quality for BWU-Z

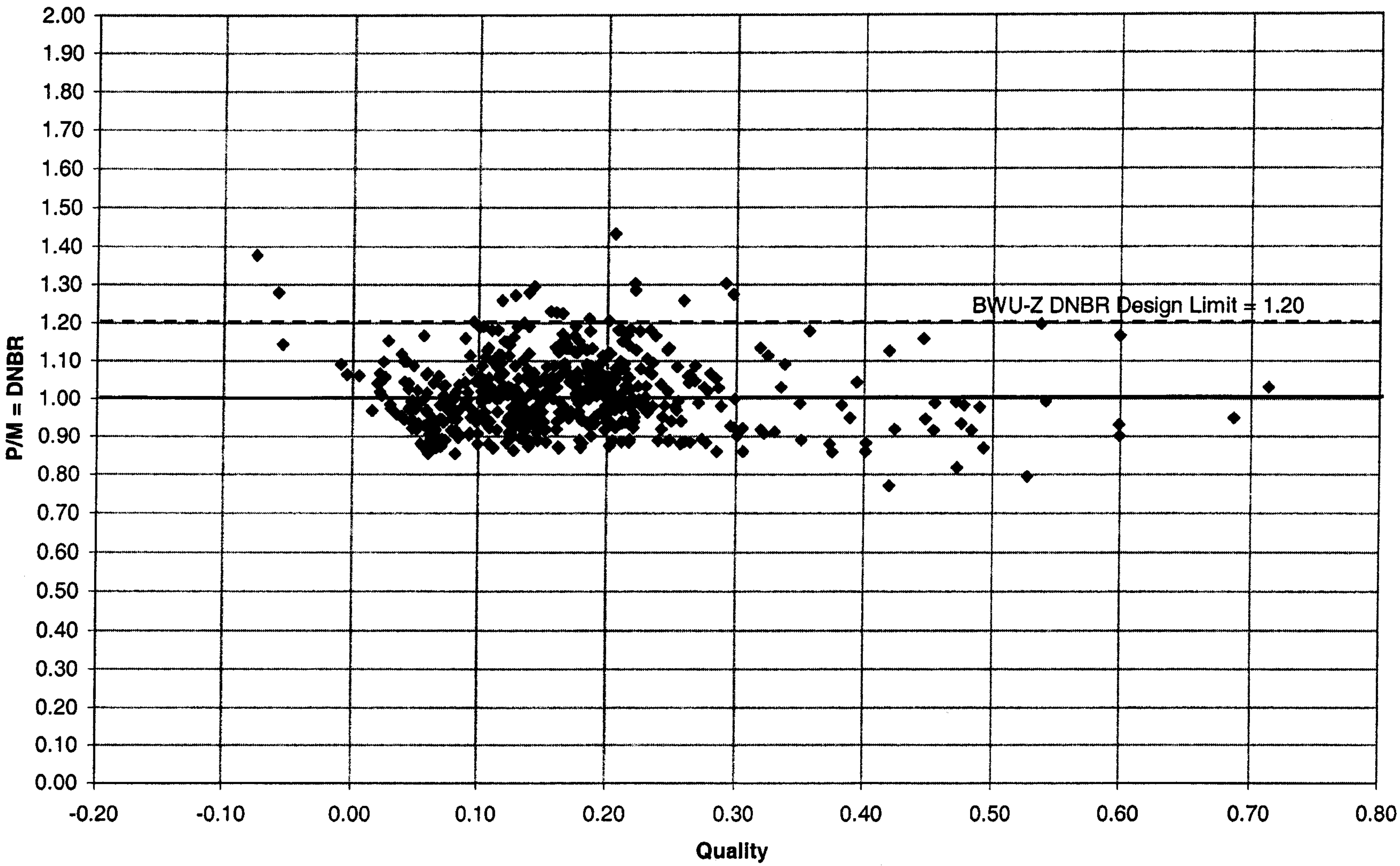
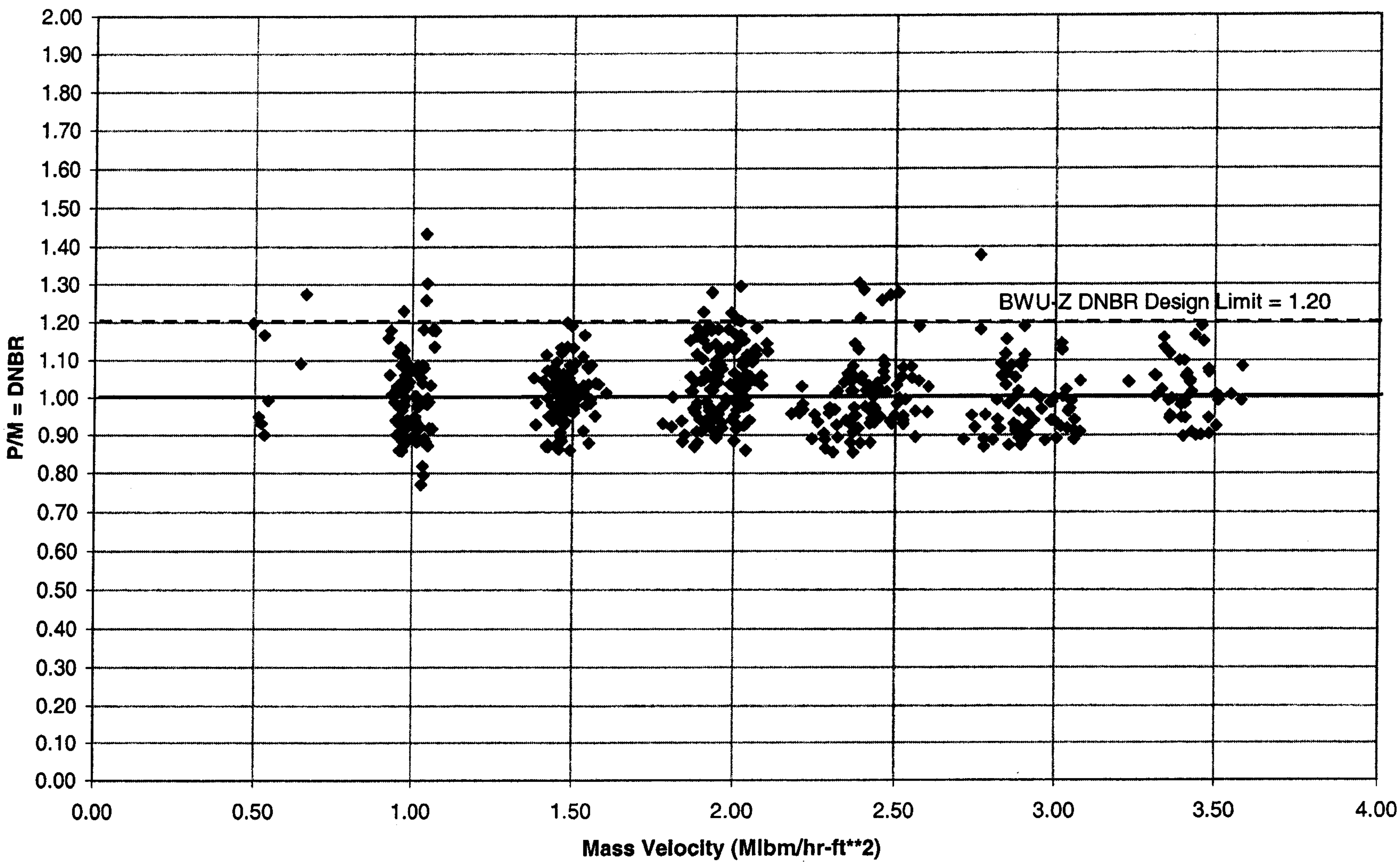


Figure A.4.1-7: DNBR vs. Mass Velocity for BWU-Z



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

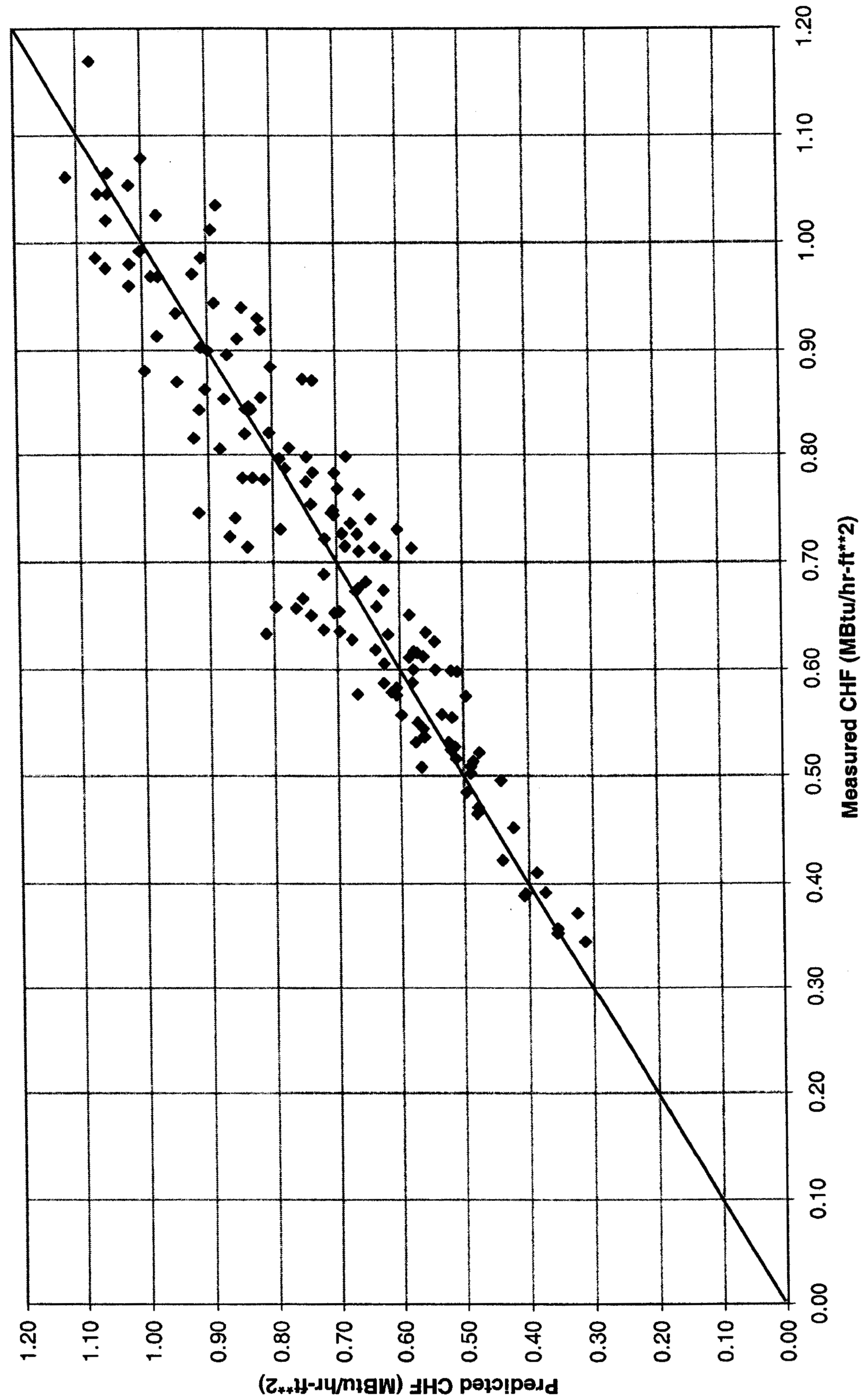


Figure A.4.2-2: M/P vs. Pressure for BWU-ZM

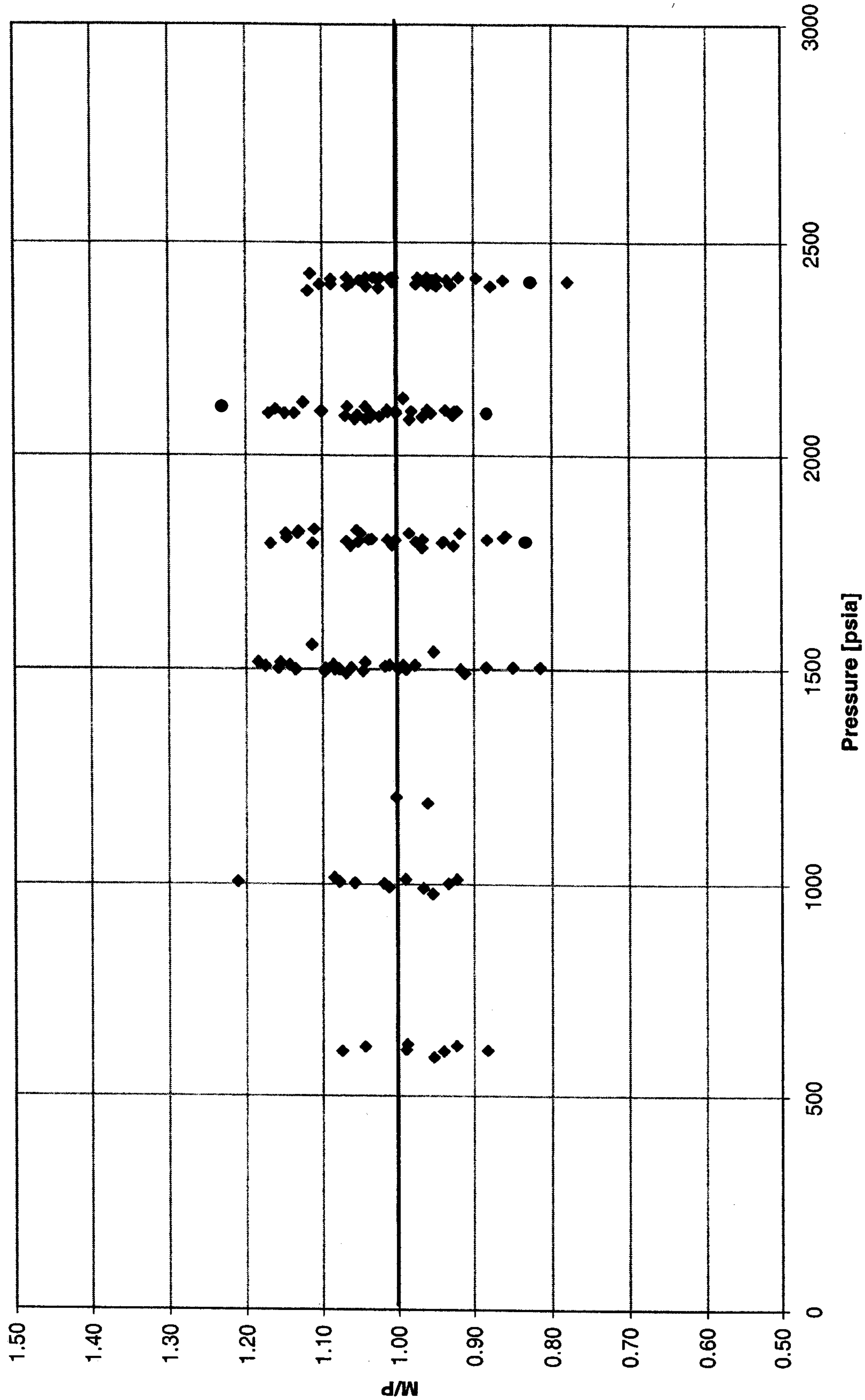


Figure A.4.2-3: M/P vs. Quality for BWU-ZM

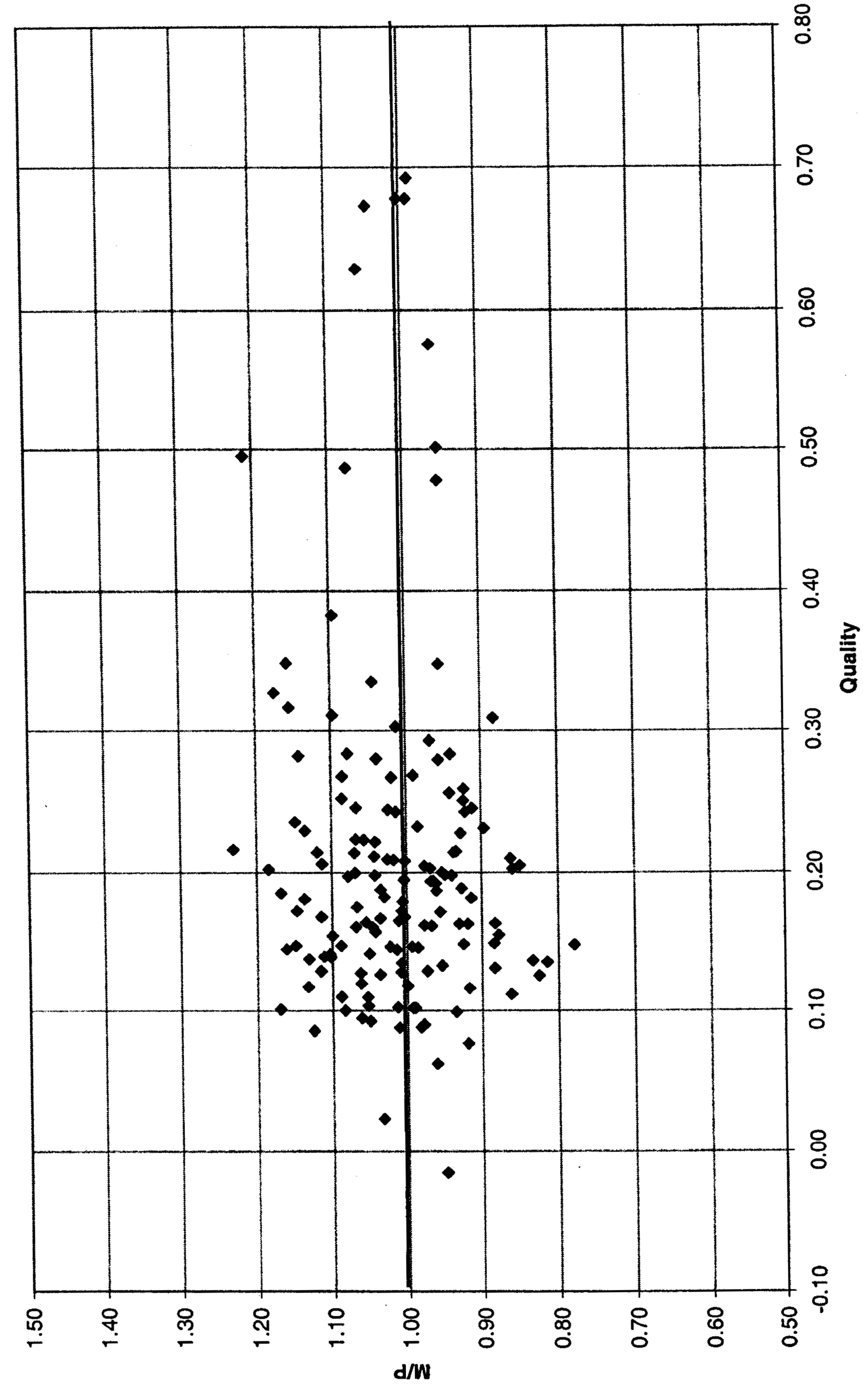


Figure A.4.2-4: M/P vs. Mass Velocity for BWU-ZM

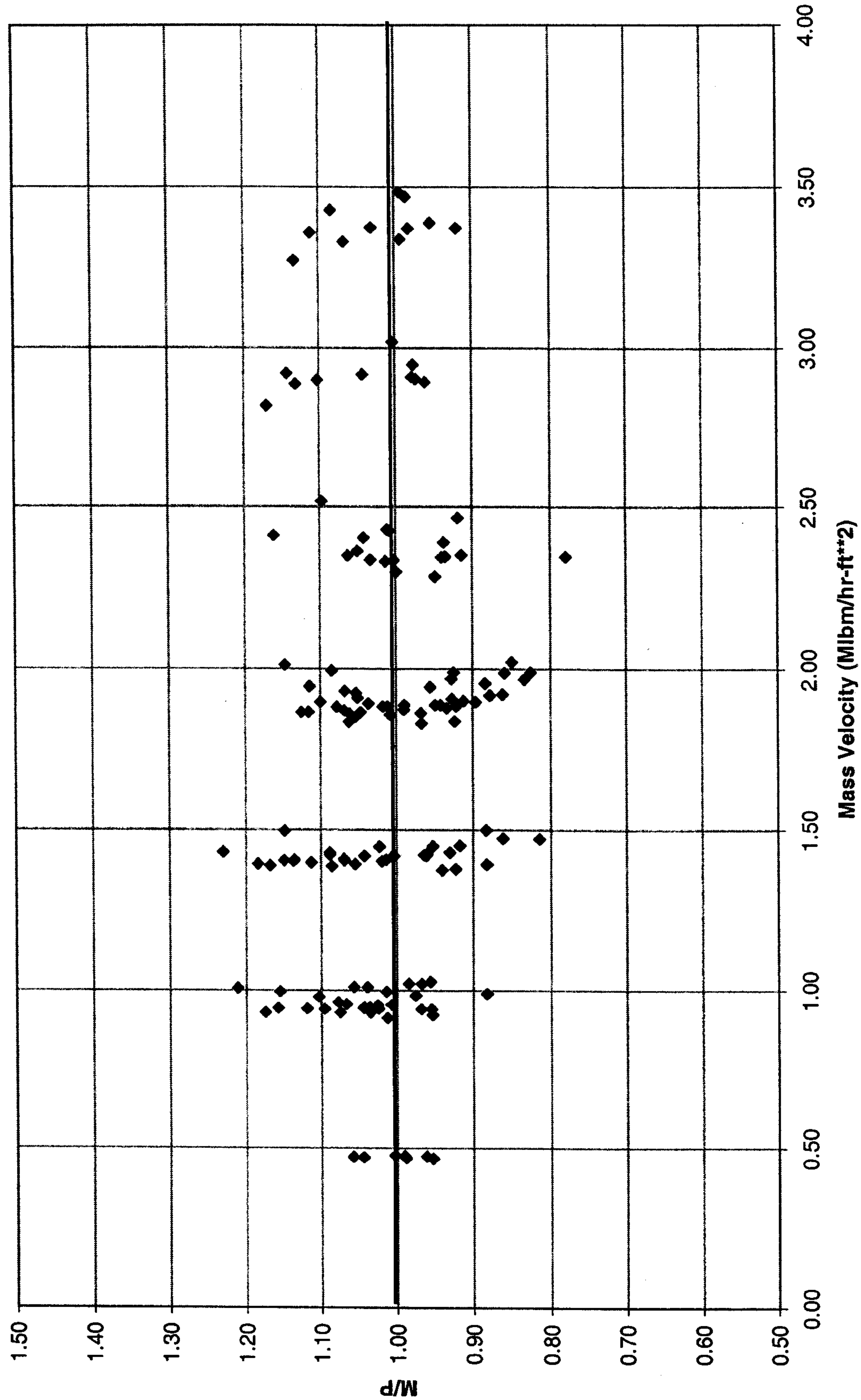


Figure A.4.2-5: DNBR vs. Pressure for BWU-ZM

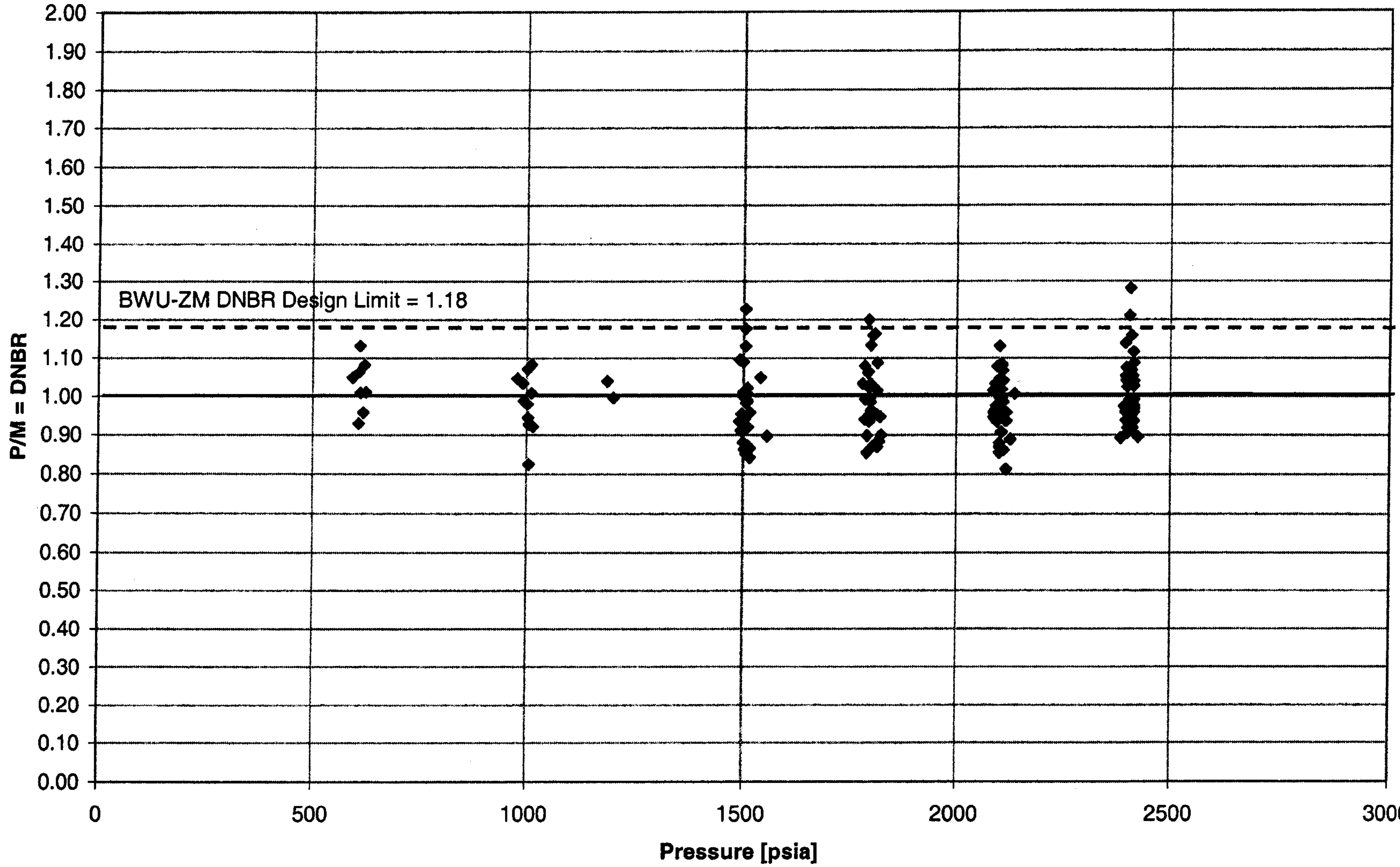


Figure A.4.2-6: DNBR vs. Quality for BWU-ZM

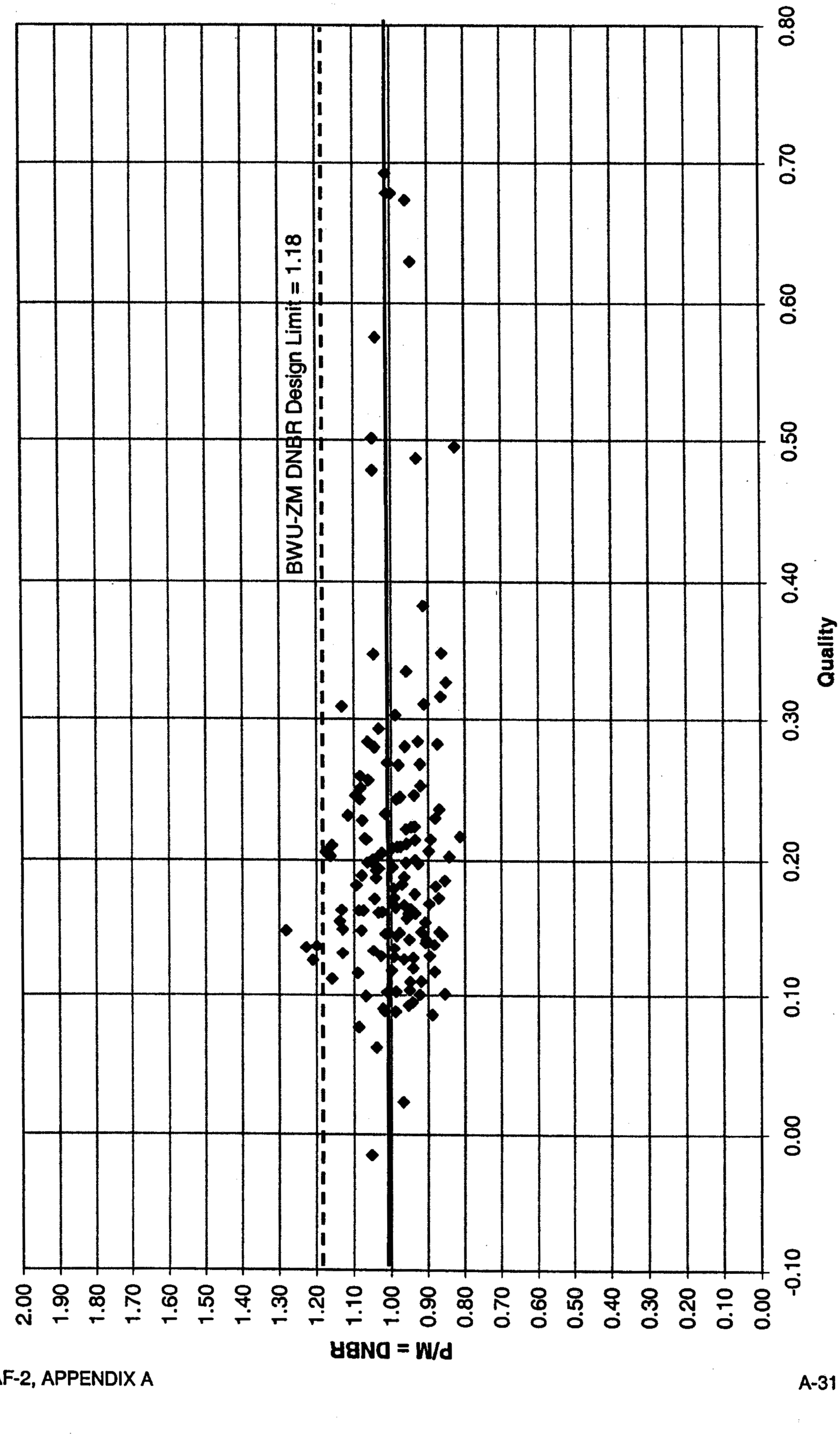
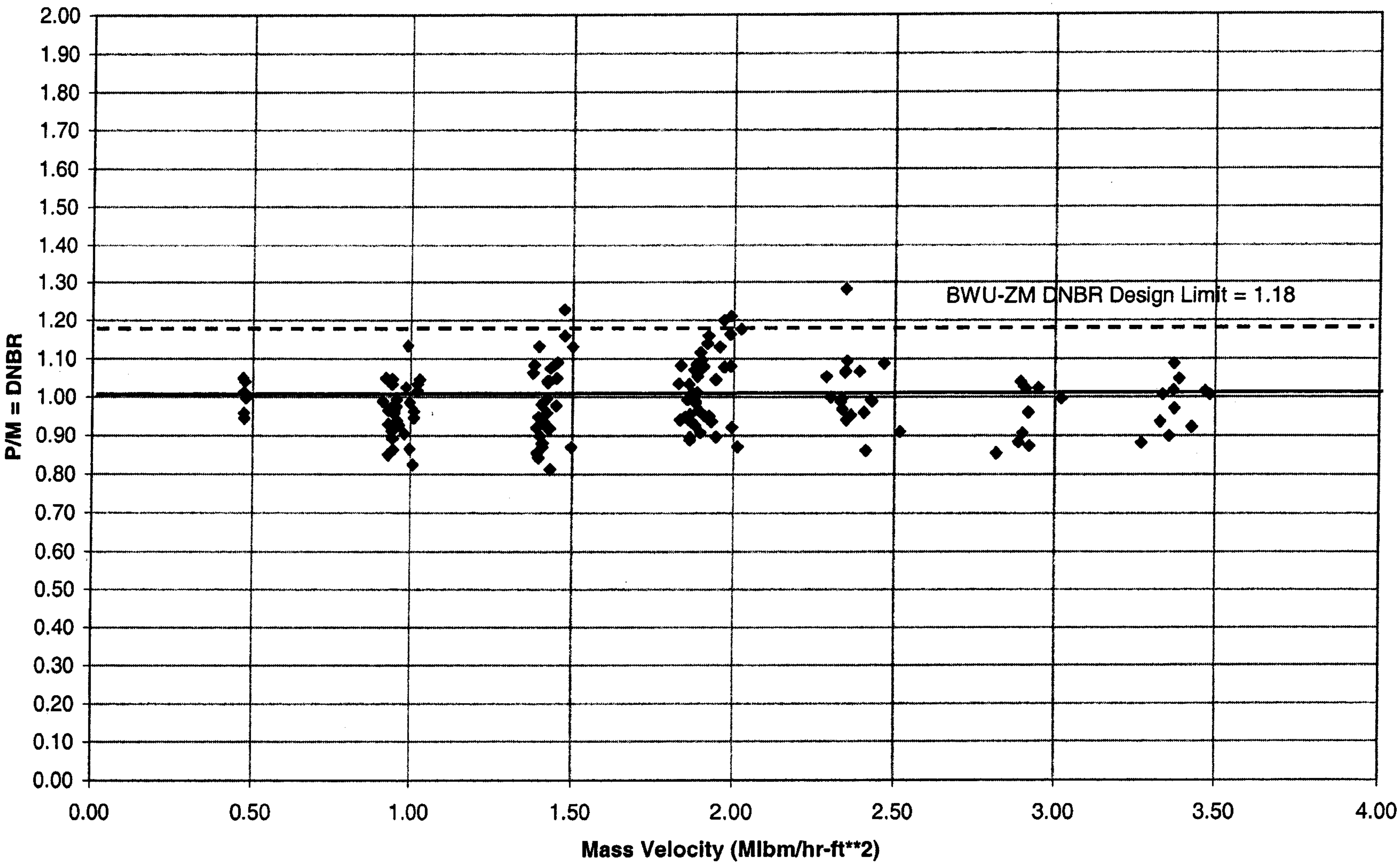


Figure A.4.2-7: DNBR vs. Mass Velocity for BWU-ZM



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:

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

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	σ_N	$= \sigma_{M/P} \cdot [(n-1) / N]^{½}$	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

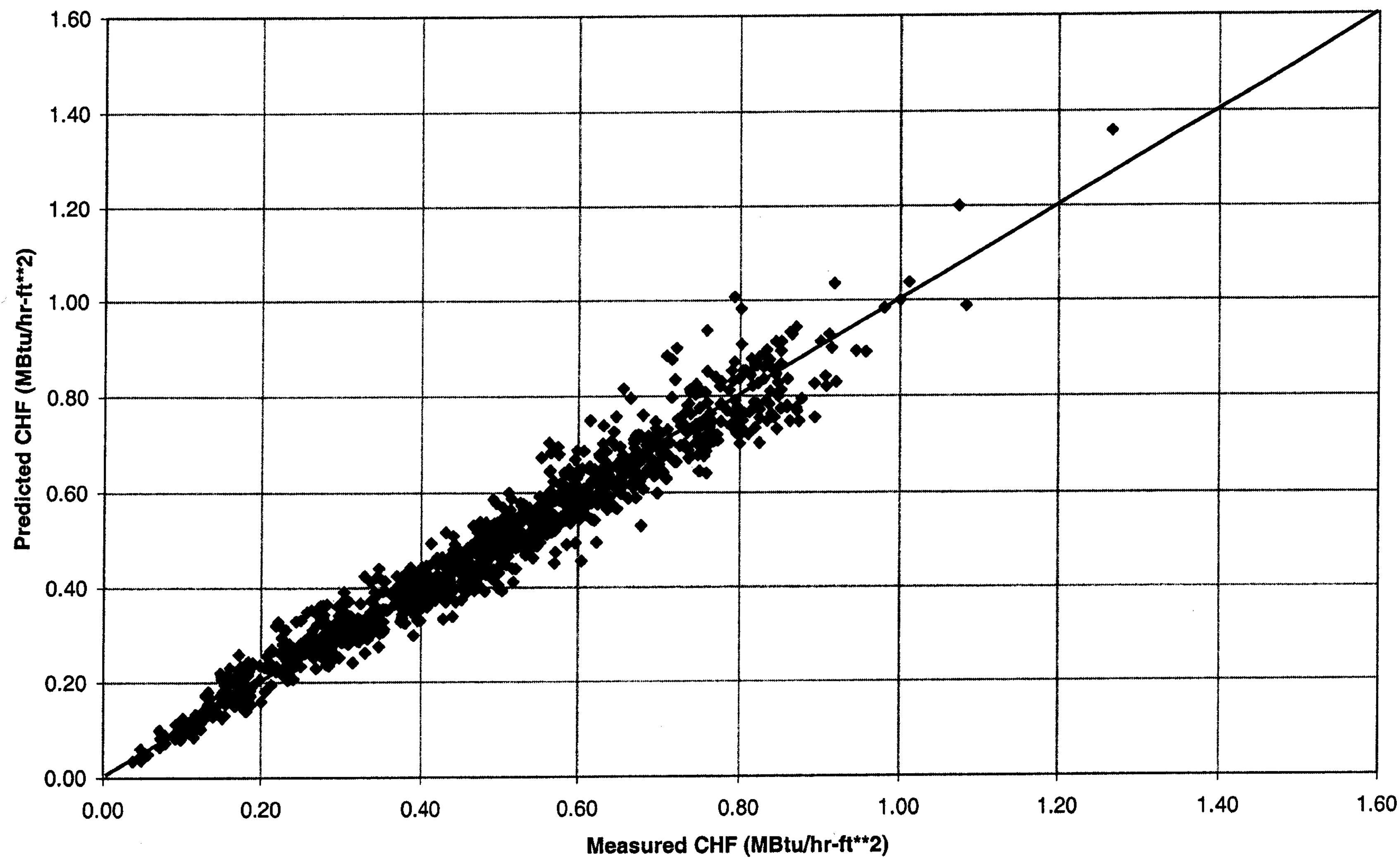


Figure A.4.3-2: M/P vs. Pressure for BWU-N

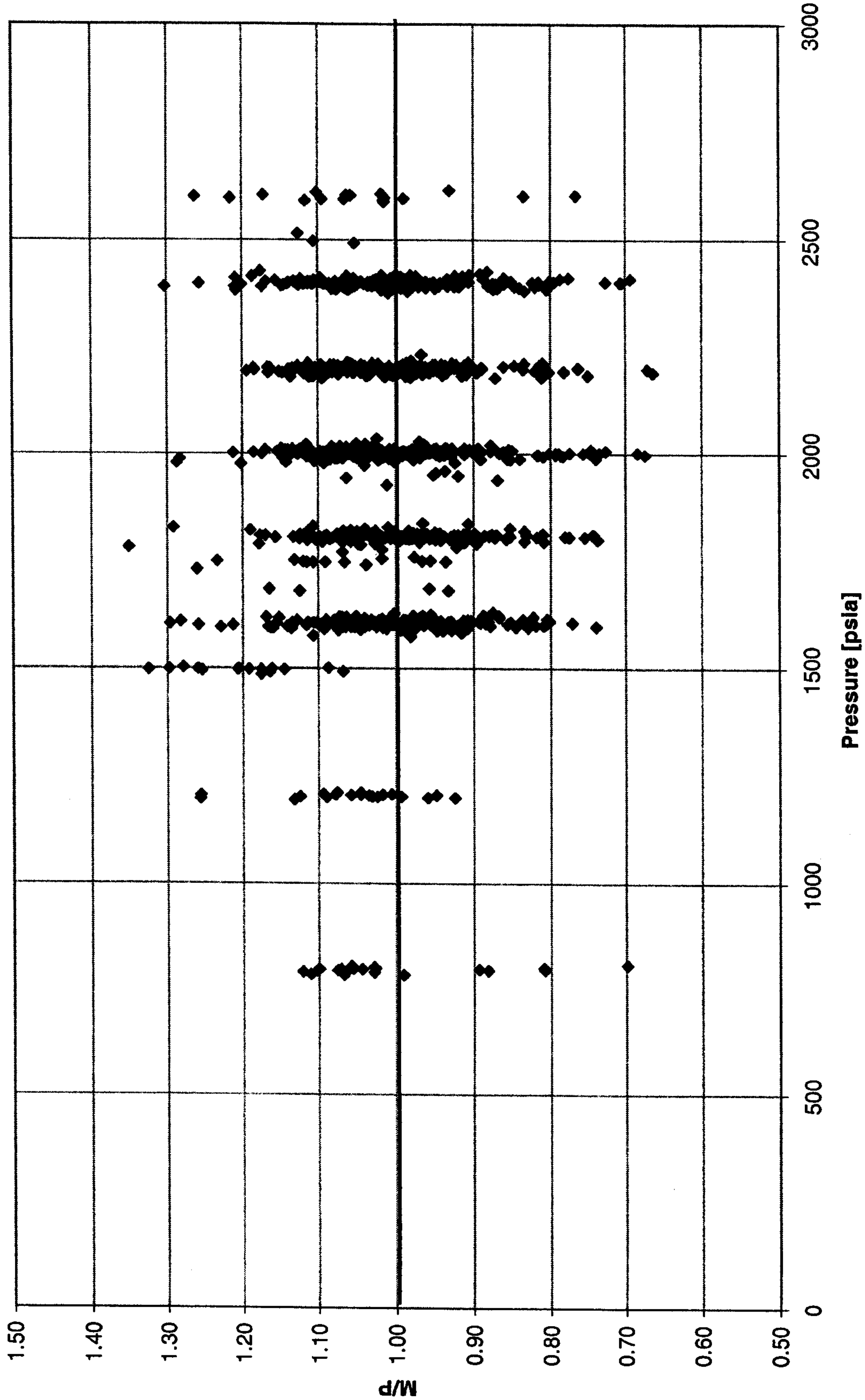


Figure A.4.3-3: M/P vs. Quality for BWU-N

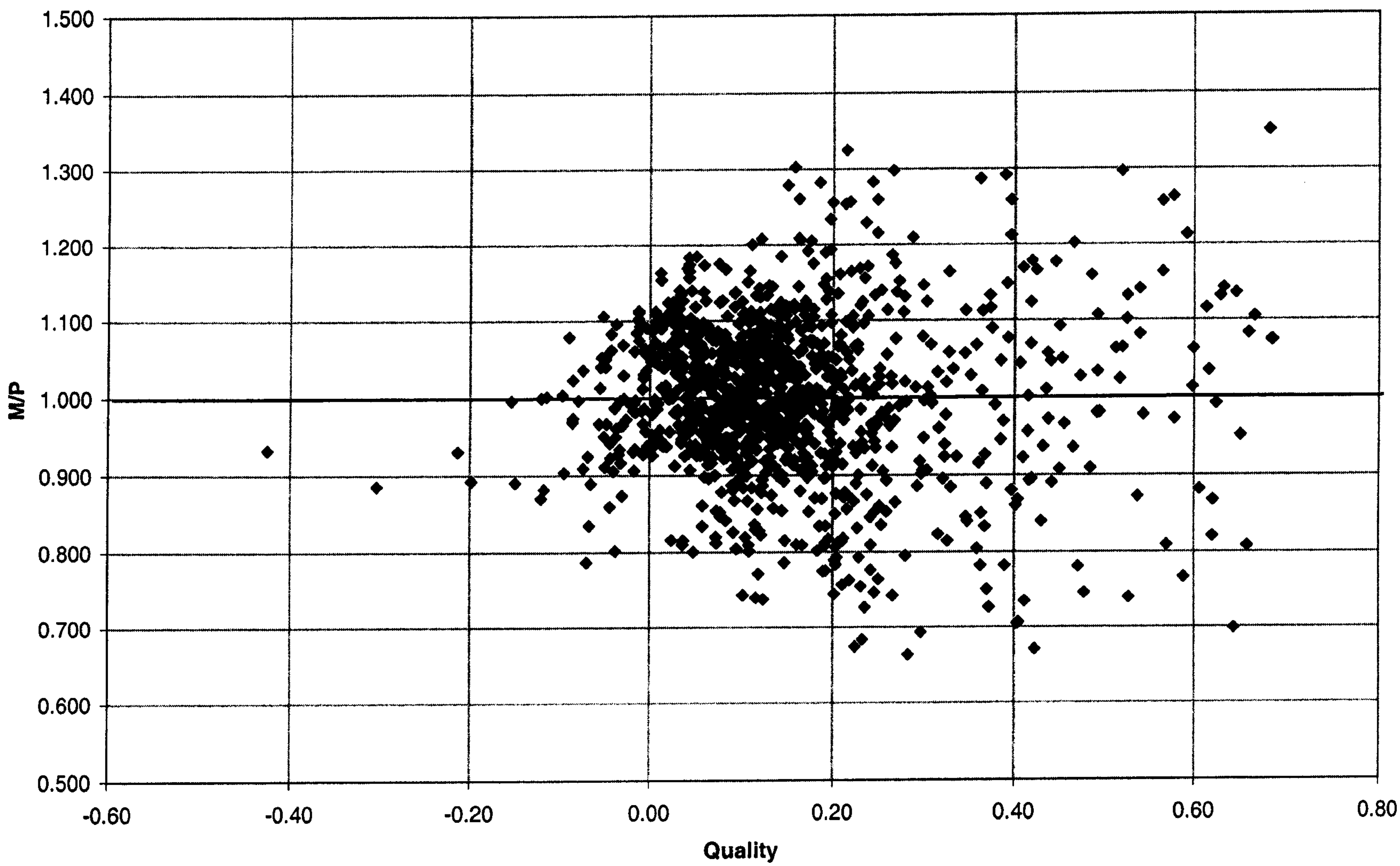


Figure A.4.3-4: M/P vs. Mass Velocity for BWU-N

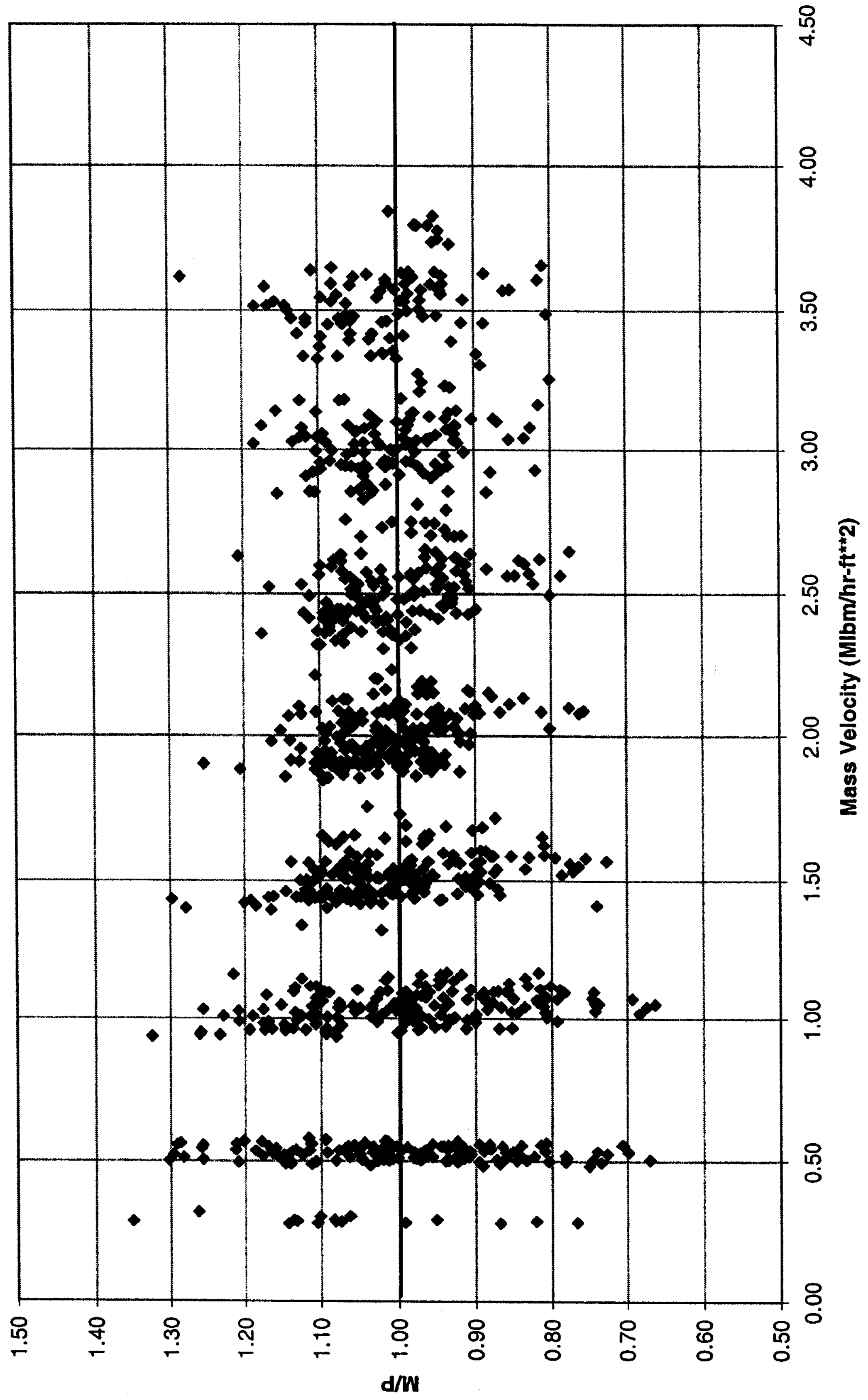


Figure A.4.3-5: DNBR vs. Pressure for BWU-N

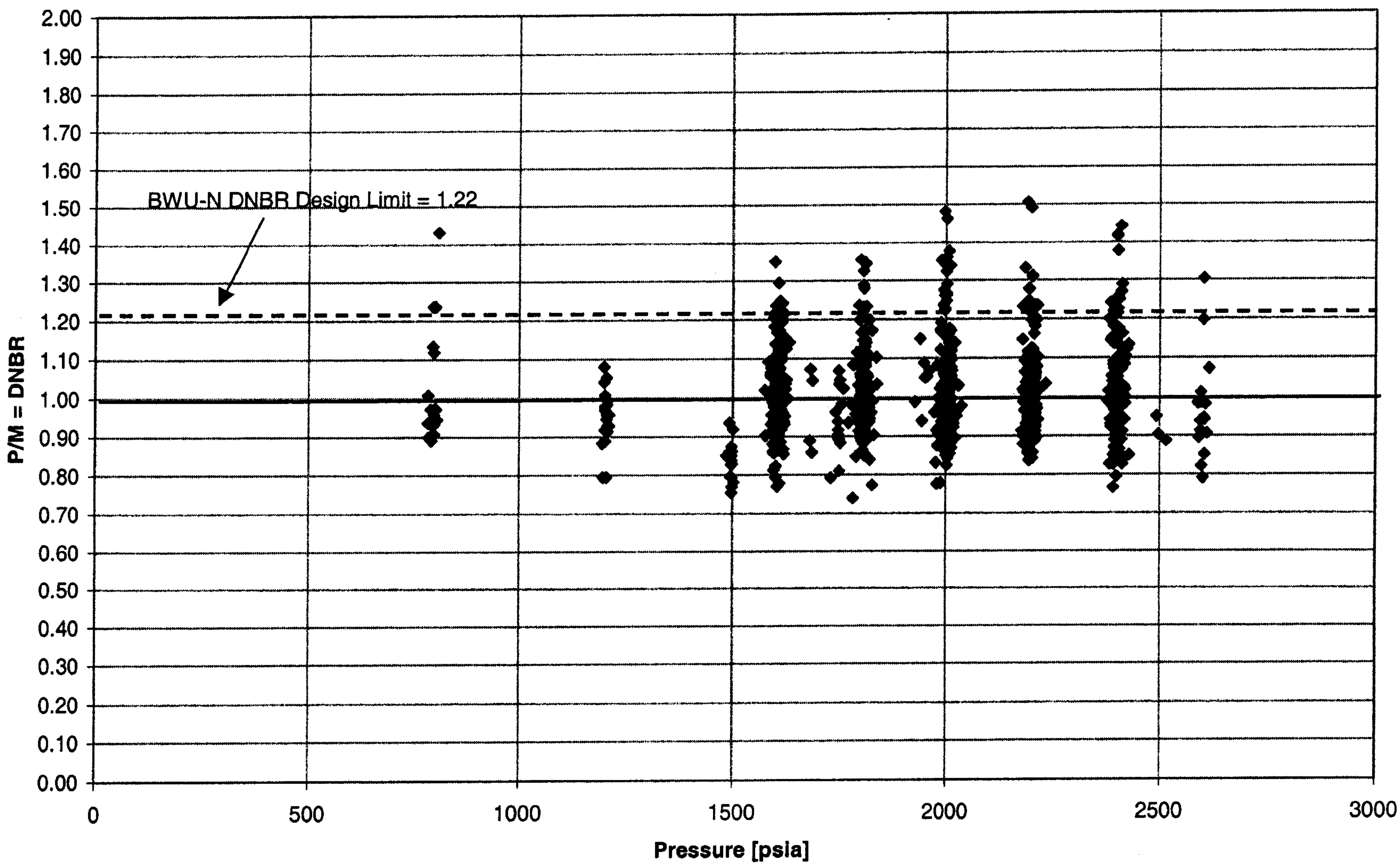


Figure A.4.3-6: DNBR vs. Quality for BWU-N

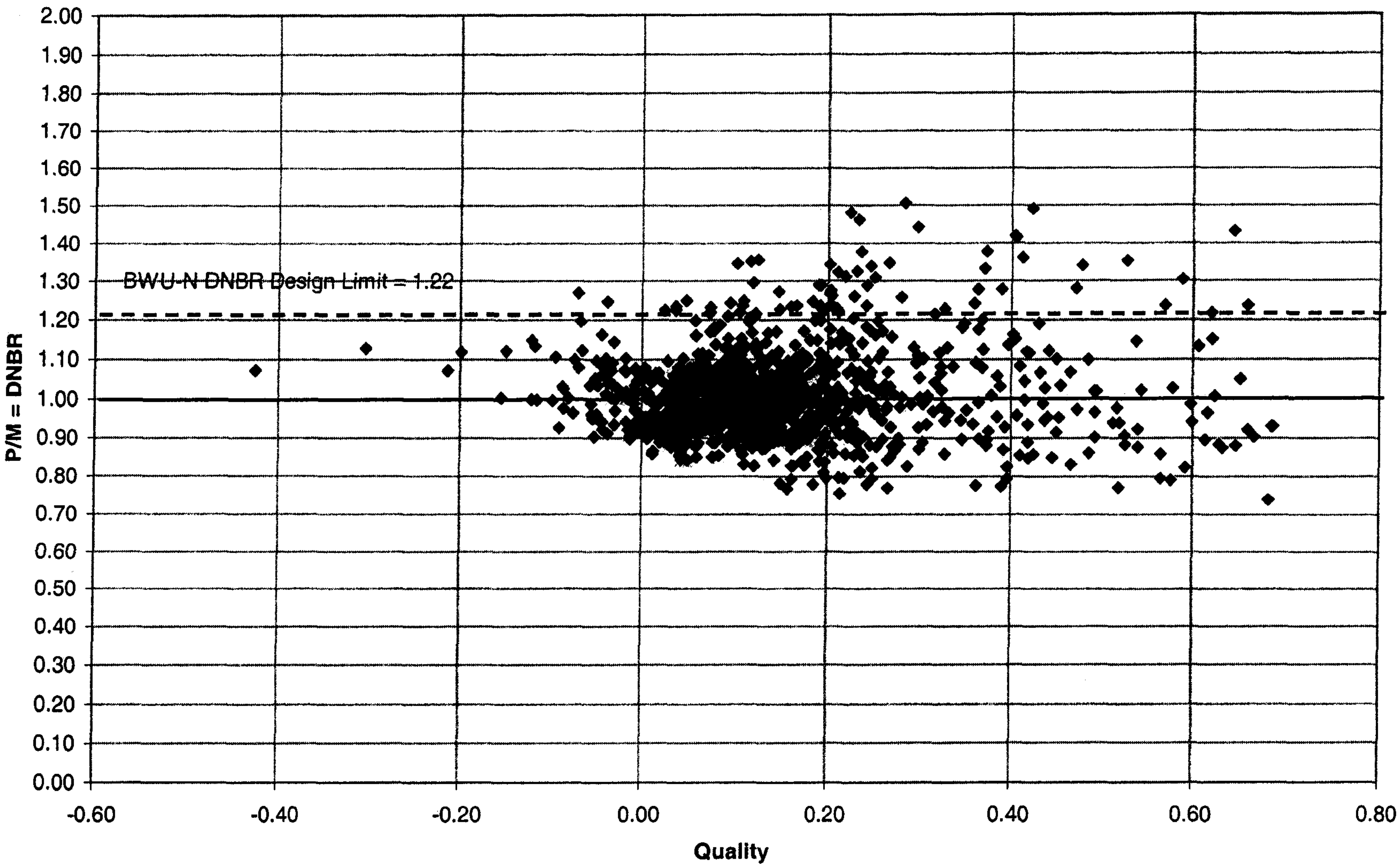
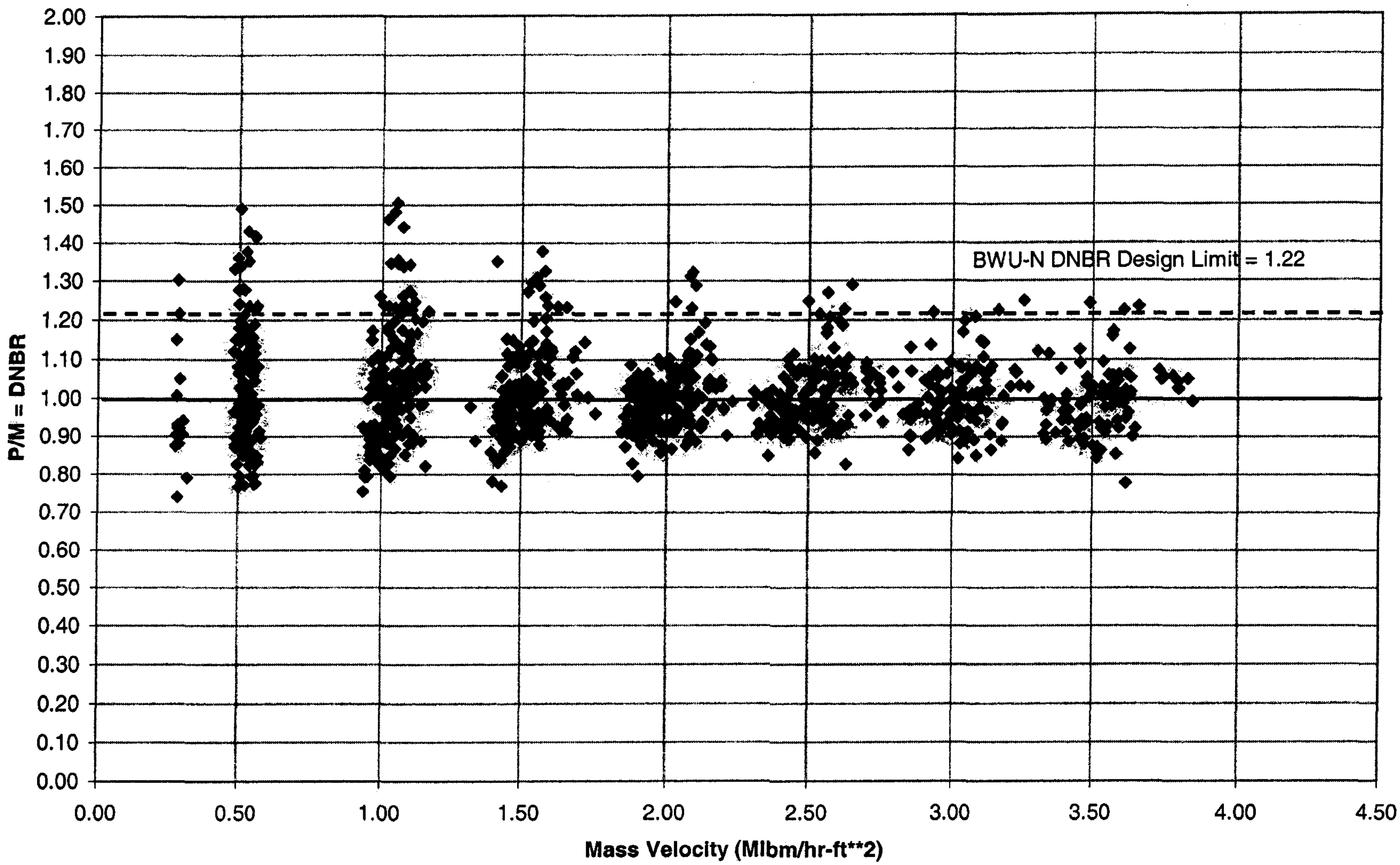


Figure A.4.3-7: DNBR vs. Mass Velocity for BWU-N



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.