NF-1583.04
NONPROPRIETARY VERSION

VERIFICATION OF CP&L REFERENCE BWR THERMAL-HYDRAULIC METHODS USING THE FIBWR CODE

TOPICAL REPORT

MAY 1983

CP&L

Carolina Power & Light Company

NF-1583.04 SERIAL: NF-83-139

Verification of CP&L Reference BWR Thermal-Hydraulic Methods Using the FIBWR Code

M. A. Pope

May 1983

Approved By R. K. Kunita 5/18/83
R. K. Kunita (Date)

Principal Engineer - Surveillance & Accountability

Carolina Power & Light Company
411 Fayetteville Street
Raleigh, North Carolina 27602

DISCLAIMER OF RESPONSIBILITY

This document was prepared by Carolina Power & Light Company and is believed to be completely true and accurate to the best of our knowledge and information. It is authorized for use specifically by Carolina Power & Light Company for the appropriate subdivisions within the U.S. Nuclear Regulatory Commission only.

With regard to any unauthorized use whatsoever, Carolina Power & Light Company and their officers, directors, agents, and employees assume no liability nor make any warranty or representation with regard to the contents of this document or its accuracy or completeness.

ACKNOWLEDGEMENTS

The author wishes to acknowledge the code development and qualification work performed by Yankee Atomic Electric Company.

Special appreciation is extended to K. E. Karcher and B. J. Gitnick for the many valuable comments and suggestions on the use and understanding of the code.

ABSTRACT

The verification of a steady-state core flow distribution code (FIBWR) is described for applications specific to Carolina Power & Light Company's Brunswick nuclear station. The ability to predict core pressure drop, bypass flow, and inter-assembly flow distribution is demonstrated by comparisons to plant measured data and process computer calculations. The ability to establish critical power ratios (CPR) as a function of fuel assembly power is also demonstrated by comparisons to vendor data.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

1.0 Introduction

The purpose of this report is to demonstrate the capability of Carolina Power & Light (CP&L) to perform independent, steady-state BWR analysis, using the FIBWR code. The qualification and verification report (Reference 1) on FIBWR was submitted in December of 1980, by Vermont Yankee Nuclear Power Corporation, and subsequently reviewed by the NRC Core Performance Branch (Reference 2). The Yankee submittal which contains the qualification of the hydraulic models in FIBWR, as well as a comparison to a fully verified thermal hydraulics code, has been published as an EPRI report (NP-1923, Reference 3). For this reason, this topical report will not repeat the FIBWR qualification, but will concentrate on the use of FIBWR by CP&L and its application to our Brunswick nuclear plant.

1.1 Description of FIBWR

FIBWR (Flow In Boiling Water Reactors) is a steady-state thermal-hydraulic computer code developed to model the pressure drop, enthalpy rise, void fraction, critical power ratio (CPR), and flow distribution in a BWR. The code solves the equations of mass, momentum, and energy while iterating between core pressure drop and required core flow, calculating variations in leakage and water-tube flow during each iteration. FIBWR was written by Vermont Yankee and made available to CP&L through the Electric Power Research Institute.

1.2 FIBWR Applications

CP&L intends to use FIBWR in the following applications to the Brunswick Plant:

- Calculation of the bypass flow splits for the system transient analysis code (RETRAN)

- Hot bundle analysis of slow transients

- Hot bundle initial conditions for system transient evaluations

- Calculation of steady-state thermal-hydraulic core conditions for use in the nodal simulator (PRESTO-B), training simulator, and plant process computer

- Investigation of core anomalies (e.g., local power peaks, flow maldistribution)

- Calculation of pressure drops across internal components, such as channel walls, core support plate, and core shroud

- Bypass boiling analysis

- Evaluation of CPR-power relationships

This topical will demonstrate the ability of the CP&L FIBWR model to accurately perform calculations required by the above applications. Section 2.0 is an overview of the methods used for steady-state hydraulic simulations and a discussion of FIBWR input. Section 3.0 provides a verification of the FIBWR capability to match vendor-calculated and plant-measured pressure drops, flow rates, and critical power ratios.

2.0 CP&L FIBWR Method

FIBWR has great flexibility in the way it can model vertical parallel channels, allowing for an accurate representation of unique flow conditions. The BWR core can be divided into as many as 100 channel types, with a common bypass region. Single channels can be defined as a separate region for specific study, or can be analyzed individually with controls on the leakage flow to depict active bundle power and flow. Additional flexibility enables the user to either specify total core flow and have FIBWR solve for the pressure drop, or specify pressure drop and allow the code to solve for core flow.

2.1 Geometric Models

Geometric modeling of each fuel assembly is quite detailed, including inlet orifice, fuel support piece, lower tie plate, heated and unheated rodded regions, spacers, water tubes, upper tie plate, and exit region. The CP&L FIBWR model includes the actual physical dimensions of the fuel and core components at the Brunswick Plant. Much of this data was taken from fuel outline drawings, while the lower internals and core design data were obtained primarily from Brunswick specific documents and published General Electric reports. A summary of Brunswick Plant data and rated conditions is given on Table 1.

2.2 Determination of Form-Loss Coefficients

Single-phase form-loss coefficients are required as input for all locations along the vertical channel where there are changes in the channel cross-sectional area. All loss coefficients are referenced to the flow area of the fuel assembly. The Brunswick form-loss coefficients for both the interior and peripheral orifice zones, along with their respective flow areas, were provided by General Electric in Reference 4.

The form-loss coefficients for the lower tie plate, spacer grids, and upper tie plate are those provided in Table 5-1 of the FIBWR Qualification Report (EPRI-NP-1923). These values are fuel-specific, and were developed for application in the FIBWR code. The entrance loss coefficients for the water tubes were determined by running FIBWR to match the water tube flow to that stated by GE (Reference 5) for given bundle power and conditions. Table 2 is a list of form-loss coefficients used in the CP&L FIBWR model.

2.3 Determination of Bypass Flow Coefficients

The complex system of BWR leakage flow paths is illustrated in Figure 1. The leakage flow in each path is represented in FIBWR by the equation:

$$W = C1\ \Delta P^{1/2} + C2\ \Delta P^{C4} + C3\ \Delta P^{2}, \qquad \text{Eq. 1}$$

where

W = flow through the leakage path (lbm/hr)

ΔP = driving pressure differential for the leakage path (psi)

C1,C2,C3,C4 = analytically or empirically determined leakage coefficients

The method described in Section 5.1.4 of EPRI-NP-1923 was used to calculate leakage coefficients for the CP&L FIBWR model. However, the flow through each leakage path was expressed in terms of the flow through the lower tie plate holes (path 9) rather than flow through the finger springs (path 8; see Figure 1). A form of Equation 1 for the flow through path 9 is given in Reference 6. From this equation, the leakage coefficient, C1, for path 9 was defined, and leakage coefficients for each of the other paths were then determined by the ratio of their respective bypass fractions. Table 3 shows how the flow fractions generated from a FIBWR run compare favorably with the intended GE values (Reference 5).

Leakage flow through the finger spring path is known to increase as a function of exposure due to fuel channel deflection. An effort was made to represent this effect in the CP&L FIBWR model by establishing separate path 8 leakage coefficients for new and used fuel. The flow fraction for the finger spring path provided by GE for Brunswick 2, Cycle 5, as well as the coefficient C1 calculated for this path, represents a mixed core of new and used fuel; whereas, the coefficients defined in EPRI-NP-1923, Section 5.1.4.1, for path 8 were developed from a flow test involving clean fuel. By weighting the flow through the finger spring path by the number of new and used fuel assemblies in-core during Cycle 5, a leakage coefficient representative of used fuel was determined as shown:

$$(A)\ W_{mixed} - (B)\ W_{new} = (A-B)\ W_{used} \qquad \text{Eq. 2}$$

$$(A)\ Cl_{mixed}\ \Delta P^{1/2} - (B)\ 702\ \Delta P^{.7106} = (A-B)\ Cl_{used}\ \Delta P^{1/2} \qquad \text{Eq. 3}$$

Solve for Cl_{used}

where A = total number of assemblies

B = number of new assemblies

ΔP = differential pressure across channel wall

A summary of leakage coefficients used in FIBWR is shown in Table 4.

2.4 Hydraulic Models

FIBWR includes a selection of friction multipliers and quality relationships available as input options. The following models were selected for use in CP&L's steady-state methods:

a. Blausius single-phase friction factor expressed in the form:

$$f = AR_e^{-B} \qquad \text{Eq. 4}$$

where R_e = single-phase Reynolds number

A,B = input coefficients provided in Reference 7

b. Homogenious two-phase, form-loss multiplier (Reference 8), given as

$$\emptyset^2_{2\text{-phase local}} = 1 + X\ (\rho_l / \rho_g - 1) \qquad \text{Eq. 5}$$

with x = flow quality

ρ_l, ρ_g = saturation densities

c. Baroczy two-phase friction multiplier. FIBWR interpolates to a value of the friction multiplier, which is graphically expressed in Figures 5-16 and 5-17 of Reference 8.

d. EPRI void model (Reference 9) for void quality and initiation of sub-cooled boiling.

These hydraulic models are those recommended for use by the FIBWR Qualification Report and were included in the NRC review of the Vermont Yankee submittal.

TABLE 1

BRUNSWICK PLANT SPECIFIC DATA
AND RATED CONDITIONS

Core Thermal Power	2436 MWt
Core Flow	77 Mlb./hr.
Total Number of Assemblies	560
Number of Control Rods	137
Number of Incore Instruments	31
Number of Central Assemblies	484
Number of Peripheral Assemblies	76
Unit 1 Central Orifice Diameter	[ ]*
Unit 1 Peripheral Orifice Diameter	
Unit 2 Central Orifice Diameter	
Unit 2 Peripheral Orifice Diameter	
Number of Spacers per Assembly	7

*Bracketed information is General Electric Company Proprietary.

TABLE 2

FORM LOSS COEFFICIENTS USED IN FIBWR

	7 x 7	7 x 7 Orificed	8 x 8	8 x 8R
Orifice, Unit 1 Central	[			]*
Orifice, Unit 1 Peripheral				
Orifice, Unit 2 Central				
Orifice, Unit 2 Peripheral				]
Lower Tie Plate	7.58	[ ]	7.56	7.86
Spacers	1.21	1.21	1.38	1.24
Upper Tie Plate	1.35	1.35	1.41	1.46
Water Rod Entrance	[			]

Note 1: K's for the orifice, lower tie plate, upper tie plate, and spacers are based upon the flow area of the fuel type they are listed under.

Note 2: K's for the entrance of the water rods are based upon the flow area of the water rod of the fuel type they are listed under.

Note 3: 120 initial core assemblies contained a 1.3-inch diameter orifice in the lower tie plate.

*Bracketed information is General Electric Company Proprietary.

FIGURE 1

BWR BYPASS FLOW PATHS

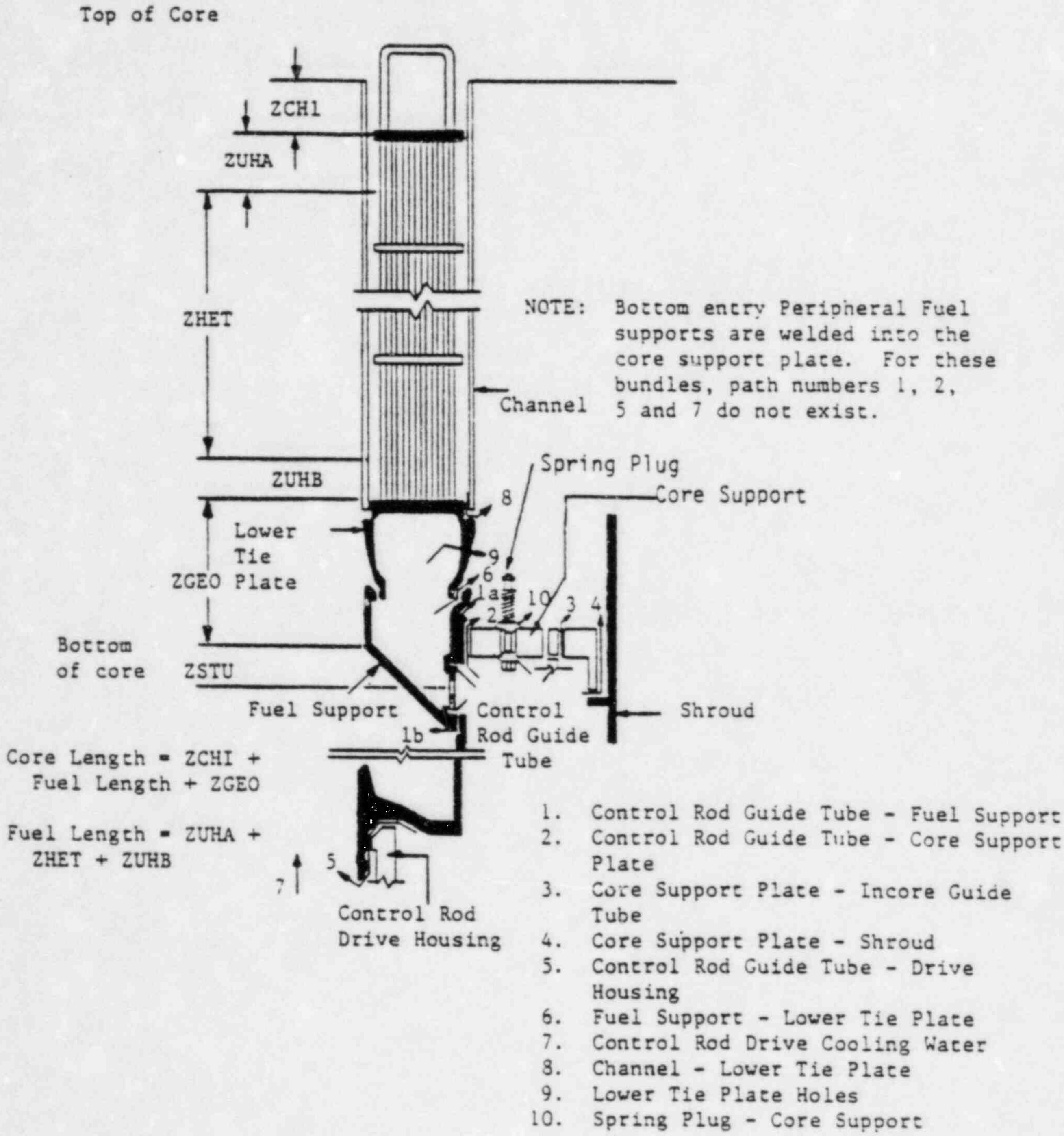


Figure 1-2. Fuel Bundle Geometry and Various Leakage Flow Paths

(From Reference 3)

TABLE 3

SUMMARY OF FLOW FRACTION THROUGH BYPASS FLOW PATHS

ath Number	Path Description	Fraction of Bypass Flow (FIBWR)	Fraction of Bypass Flow (GE, B2C5)
1	Fuel Support Casting/Control Rod Guide Tube		[ ]*
2	Core Support Plate/Control Rod Guide Tube	0.350	
5	Control Rod Guide Tube/Control Rod Drive Housing		
3	Core Support Plate/Instrument Guide Tube	0.002	
4	Core Support Plate/Core Shroud	0.001	
6	Fuel Support Casting/Lower Tie Plate	0.015	
7	Control Rod Drive Cooling Flow	0.004	
8	Channel/Lower Tie Plate	0.278	
9	Lower Tie Plate Holes	0.345	
10	Plugged Holes in Core Support Plate	0.005	

racketed information is General Electric Company Proprietary.

TABLE 4

SUMMARY OF LEAKAGE COEFFICIENTS FOR
BYPASS FLOW PATHS*

Flow Path Description		C1	C2	C3	C4
Channel - LTP (Path 8)	New Fuel	0.0	702.0	0.0	0.7106
	Old Fuel	1624.2	0.0	0.0	0.0
LTP Holes (Path 9)		1782.0	0.0	0.0	0.0
Fuel Support - LTP (Path 6)		77.25	0.0	0.0	0.0
Control Rod Paths (1, 2, 5)		4380.0	0.0	0.0	0.0
Instrument Tube (Path 3)		120.1	0.0	0.0	0.0
Core Shroud (Path 4)		1861.7	0.0	0.0	0.0
Plugged Support Plate Holes (Path 10)		120.9	0.0	0.0	0.0

*The Coefficients C1, C2, C3, and C4 are constants in the equation:

$$W = C1\,\Delta P^{1/2} + C2\,\Delta P^{C4} + C3\,\Delta P^{2}$$

where

W = Flow through the leakage path (lbm/hr)

ΔP = Driving pressure differential for the leakage path (psi)

3.0 CP&L FIBWR Benchmark

Comparisons were made to vendor-calculated and plant-measured data in order to verify the CP&L FIBWR model. The Brunswick Plant process computer served as a source for plant operating conditions, such as power, flow, pressure, inlet sub-cooling, and power shapes; as well as benchmarking data in the form of pressure drops and bundle flow rates. Vendor data was available in the form of process computer input and supplemental reload licensing submittals for the Brunswick Plant.

3.1 Verification of FIBWR Pressure Drop Predictions

FIBWR comparisons were made to the core pressure drop obtained from the P1 edit of the plant process computer. Both models use an iterative calculational technique to determine core pressure drop and assembly flow rates. Unlike FIBWR, however, the process computer model does not have a complete thermal-hydraulic representation of the core and fuel. The leakage flow, for example, is numerically omitted; and the core pressure drop is corrected for this by adjustments to the orifice loss coefficients. In addition, the two-phase friction model actually utilized by the process computer is a curve fit to data points based on a more detailed pressure drop model.

Table 5 shows the FIBWR-calculated and process computer-calculated core pressure drops at various flow and power conditions for each cycle of Brunswick operation. The average ratio of process computer to FIBWR values is 0.99, with a standard deviation of 0.05, illustrated graphically in Figure 2. The difference between the two models for Brunswick 2, Cycle 3, is due to the calculated coefficients for the hydraulic model utilized by the process computer. The process computer databook indicates that these coefficients were different for Cycle 3 than those used in previous cycles and for the following cycle.

FIBWR also calculates the pressure drop across the core support plate. This can be compared directly with plant-measured data. Several cases from Brunswick 1, Cycle 3 (Table 6 and Figure 3), exemplify the difference between FIBWR-predicted and measured core support plate pressure drops. It can be seen from Figure 3 that FIBWR shows better agreement with measured data at higher flows than at low-flow conditions. Jet-pump flow measurements at Peach Bottom (Reference 10) indicate that the process computer uses a jet-pump flow calibration method that accurately represents flow at rated conditions, but conservatively underestimates flow at lower flow rates, resulting in FIBWR pressure drop predictions below the measured values. The average measured-to-FIBWR ratios for the data in Table 6 is 1.06, with a standard deviation of 0.06.

3.2 <u>Verification of FIBWR Leakage Flows</u>

An additional comparison was made to demonstrate the ability of the CP&L FIBWR model to predict the core bypass flow. The Brunswick Plant process computer databook provides cycle-specific bypass flow as a function of total flow along the 100-percent rod line of the power flow map. From this data, bypass/total flow curves are generated for each cycle. Although these curves can be used to estimate leakage flow from a given core flow, they do not correctly model bypass flow away from the 100-percent rod line.

Bypass flow rates were calculated by FIBWR for various power and flow conditions for each of the Brunswick operating cycles. The total flow rate for each case was then used to estimate the bypass flow from the bypass/total flow relationship. A comparison of the two methods is shown on Table 7 and Figure 4. The distribution of the data points produced an average ratio equal to 1.00; however, approximations by the bypass/total flow curves resluted in a standard deviation of 11 percent.

High-flow, low-power conditions have void fractions below those typically expected when operating along with 100-percent rod line. A decrease in voids with a constant core pressure drop results in an increase in the active flow, and therefore reduces bypass flow. For those cases near the 100-percent power-flow line, FIBWR-calculated bypass flow rates are in agreement with bypass flow rates predicted from the process computer databook. As expected for those cases with power levels below the load line core power for a given flow, bypass flow rates calculated by FIBWR are lower than if estimated from the bypass/total flow curves. Several such cases from Brunswick 1, Cycle 1, are clearly shown on Figure 4.

3.3 Verification of FIBWR Flow Distribution

In a steady-state system of parallel vertical flow channels, the pressure drop from inlet plenum to exit plenum is constant, regardless of the flow path. For this reason, in a BWR core with many channels of similar geometry, the flow distribution is a function of the density distribution and therefore ultimately dependent upon the power distribution.

The process computer provides core-wide, bundle-specific radial peaking factors and bundle flow rates. Eighth-core symmetric, 75-channel FIBWR models were established matching the core power and flow conditions, and specifying the independent bundle power factors from the process computer edits. Both high-flow and low-flow cases were selected from each Brunswick Unit. Figures 5A through 5D compare the resulting channel flow rates to the process computer values. RMS differences between FIBWR and the process computer flow distributions were calculated from the data on these figures. The largest RMS difference was found to be 1.58 Klb/hr, which represents only about 1.3 percent of the channel flow rate.

3.4 Verification of FIBWR CPR Methods

The GEXL (Reference 11) critical power correlation has been included in FIBWR for use in CP&L's steady-state methods to calculate CPRs. A FIBWR model of Brunswick 2, Cycle 5, at rated conditions was established with a single interior channel designated as a hot channel. By increasing the relative power of the hot channel, the bundle power/CPR relationship, shown in Figure 6, was developed. In this way, the FIBWR code can be used to establish limiting bundle conditions for a specific critical power ratio. Several data points from Brunswick 2, Reload 4, licensing submittals are also shown on this figure. The best-estimate FIBWR values agree with the vendor data points within about one percent. This slight variation is largely due to the difference between the FIBWR and Vendor's pressure drop models which determine channel flow rates, and therefore the critical power ratio of the hot channel.

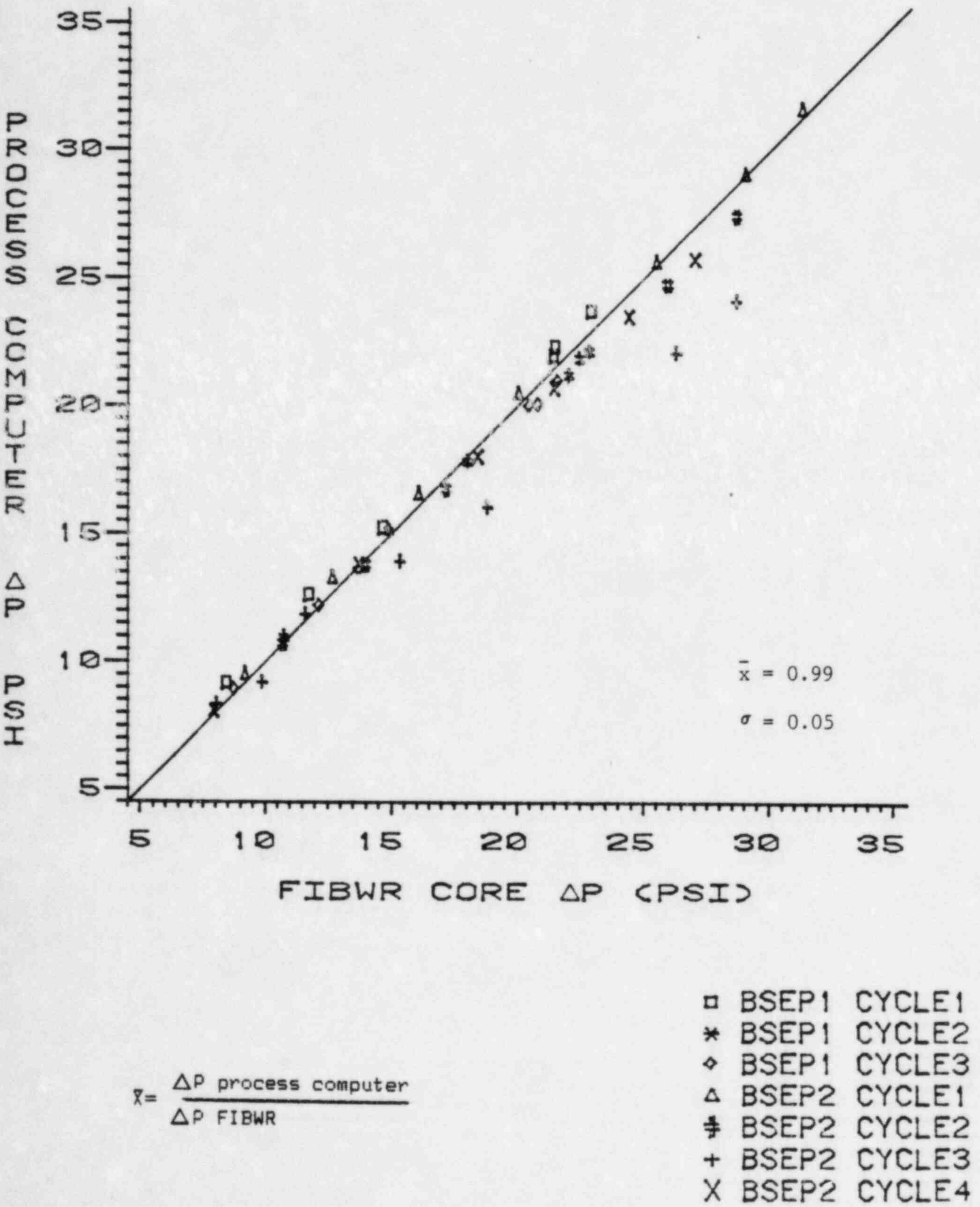
In order to assure that the GEXL correlation had been correctly installed in the FIBWR code, CPRs were calculated by FIBWR for a number of channel conditions defined in reload licensing submittals. Data was obtained from both Brunswick Units and all channel types, and each of the channel conditions were explicitly input into a single-channel FIBWR model to test the correlation specifically. The results, plotted on Figure 7, show an average ratio of 1.00, and a standard deviation of 0.5 percent, within round-off of the vendor-supplied data.

TABLE 5
FIBWR Comparison to Process Computer Core ΔP (psi)

Unit	Cycle	% Power	% Flow	FIBWR Core ΔP	P1 Core ΔP	FIBWR - P1
1	1	72.45	100.61	21.45	21.98	-0.53
1	1	99.63	99.12	22.93	23.73	-0.80
1	1	61.82	94.92	19.35	19.74	-0.39
1	1	98.15	94.16	21.51	22.34	-0.83
1	1	50.70	79.61	14.67	15.25	-0.58
1	1	69.95	64.94	11.76	12.63	-0.87
1	1	55.25	50.52	8.44	9.17	-0.73
1	2	80.71	100.47	22.05	21.22	0.83
1	2	94.83	99.70	22.85	22.15	0.70
1	2	99.30	97.18	22.46	21.87	0.59
1	2	85.26	87.23	18.02	17.82	0.20
1	2	88.51	73.23	14.88	15.11	-0.23
1	2	76.35	57.57	10.76	10.94	-0.18
1	3	99.67	99.66	21.60	21.02	0.58
1	3	99.14	93.83	20.80	20.11	0.69
1	3	99.56	92.33	20.45	20.03	0.42
1	3	82.04	73.43	13.71	13.65	0.06
1	3	80.17	65.74	12.14	12.20	-0.06
1	3	63.01	50.74	8.74	8.94	-0.20
2	1	89.78	100.08	31.28	31.68	-.40
2	1	98.11	94.45	29.03	29.12	-.09
2	1	94.54	87.38	25.50	25.67	-.17
2	1	59.65	77.81	20.05	20.53	-.48
2	1	78.37	65.42	16.06	16.59	-.53
2	1	70.24	55.84	12.68	13.29	-.61
2	1	41.75	45.58	9.17	9.51	-.34
2	2	99.63	100.08	28.67	27.45	1.22
2	2	94.09	94.23	25.95	24.78	1.17
2	2	64.66	74.29	17.18	16.73	0.45
2	2	67.41	64.29	13.99	13.80	0.19
2	2	56.61	53.48	10.74	10.72	0.02
2	2	18.75	42.60	8.04	8.31	-0.27
2	3	90.89	100.05	28.64	24.15	4.49
2	3	87.36	97.23	26.26	22.11	4.15
2	3	84.61	76.68	18.81	16.04	2.77
2	3	84.69	65.84	15.31	13.93	1.38
2	3	43.39	59.09	11.63	11.85	-0.22
2	3	64.29	49.35	9.86	9.17	0.69
2	4	81.44	99.43	27.01	25.76	1.25
2	4	87.89	92.26	24.41	23.52	0.89
2	4	77.59	85.98	21.48	20.70	0.78
2	4	74.34	77.95	18.42	18.03	0.39
2	4	74.63	63.17	13.74	13.83	-0.09
2	4	53.53	40.99	7.93	8.07	-0.14

FIGURE 2

FIBWR COMPARISON TO PROCESS COMPUTER CORE ΔP



$$\bar{X} = \frac{\Delta P \text{ process computer}}{\Delta P \text{ FIBWR}}$$

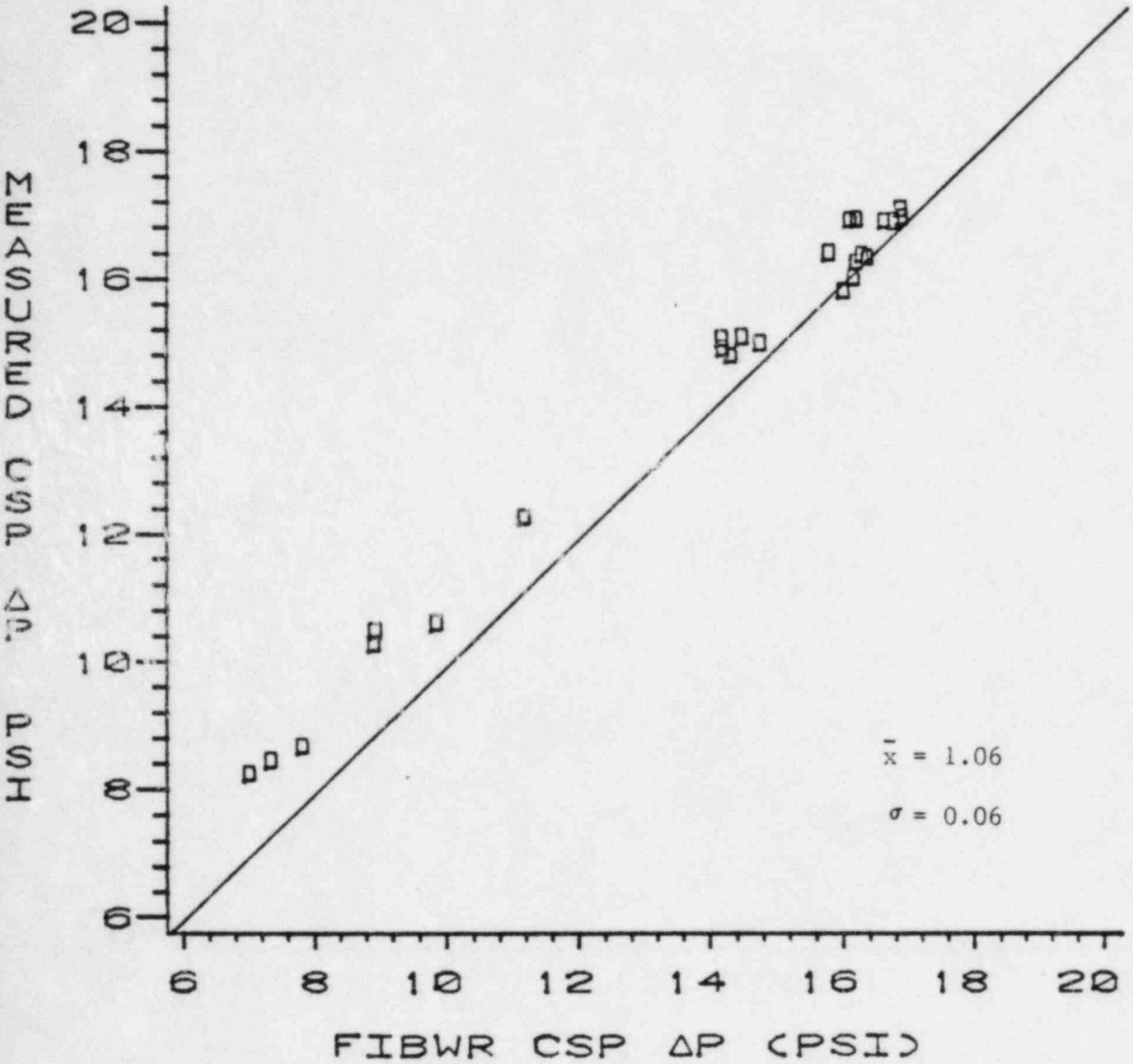
TABLE 6
FIBWR Comparison to Measured ΔP (psi)

% Power	% Flow	FIBWR CSP ΔP	Measured CSP ΔP	FIBWR - Measured ΔP
74.28	100.00	16.14	16.02	0.12
99.68	99.66	16.87	17.12	-0.25
98.73	99.52	16.88	16.99	-0.11
99.14	99.41	16.76	16.92	-0.16
80.44	99.08	16.36	16.35	0.01
77.77	99.08	16.18	16.27	-0.09
91.23	98.90	16.61	16.93	-0.32
99.54	97.62	16.27	16.40	-0.13
95.59	96.56	16.00	15.82	0.18
92.28	95.43	16.19	16.95	-0.76
99.14	93.83	16.09	16.94	-0.85
94.53	92.62	14.75	15.00	-0.25
99.56	92.33	15.78	16.42	-0.64
97.09	90.73	14.31	14.81	-0.50
94.28	89.85	14.48	15.10	-0.62
94.51	88.68	14.19	14.92	-0.73
94.81	88.54	14.17	15.07	-0.90
92.35	78.27	11.17	12.27	-1.10
75.55	76.41	9.84	10.62	-0.78
82.04	73.43	8.91	10.29	-1.38
79.60	71.67	8.93	10.49	-1.56
73.14	68.07	7.82	8.68	-0.86
80.17	65.74	7.34	8.46	-1.12
76.23	64.24	7.01	8.25	-1.24
59.83	54.58	4.72	5.91	-1.19
63.01	50.74	4.03	5.46	-1.43
51.14	47.40	3.24	3.90	-0.66
50.20	44.16	2.56	4.18	-1.62

* CSP - Core Support Plate

FIGURE 3

FIBWR COMPARISON TO MEASURED ΔP



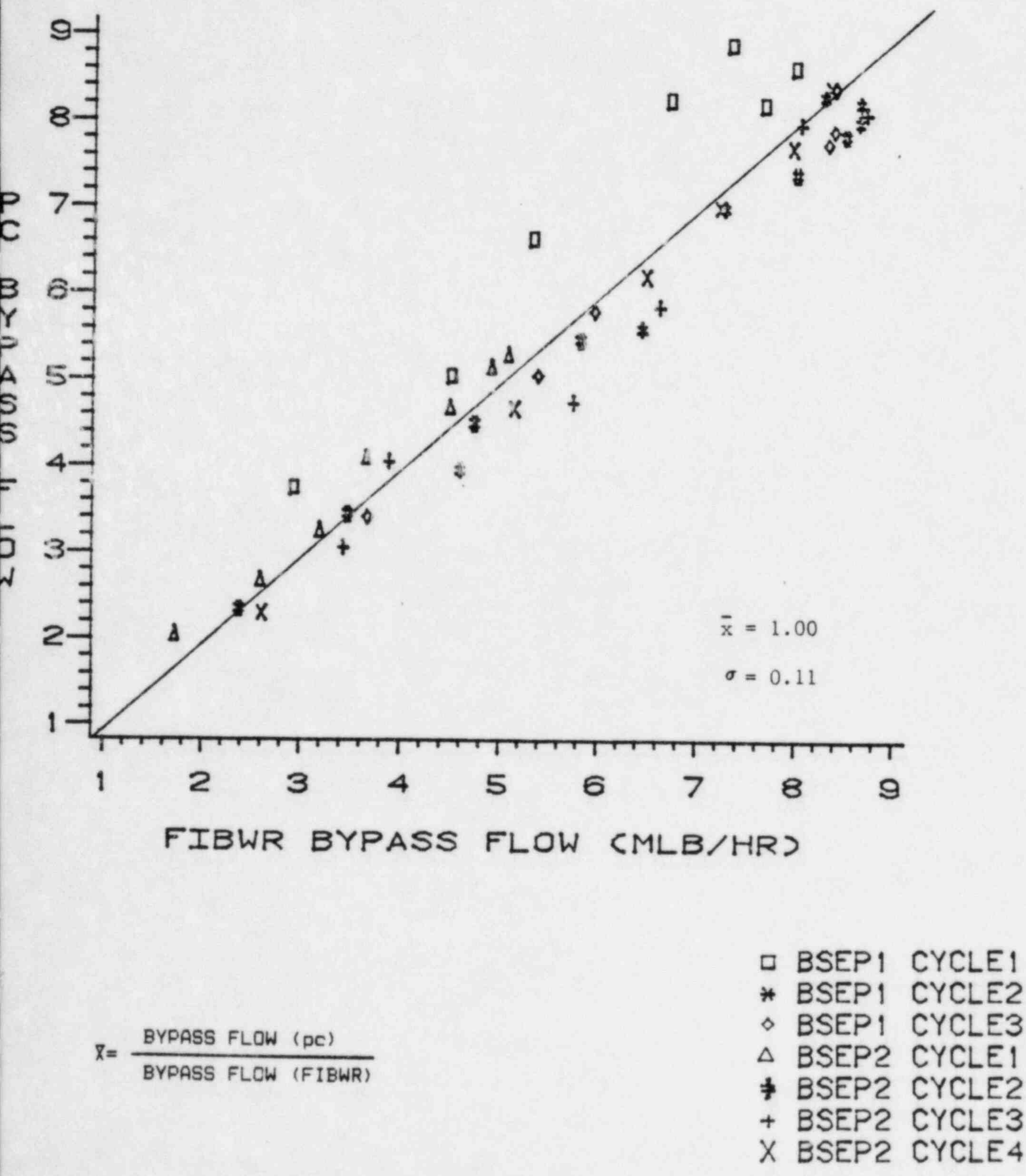
$\bar{X} = \frac{\Delta P \text{ measured}}{\Delta P \text{ FIBWR}}$

TABLE 7
FIBWR Comparison to Process Computer (PC) Bypass Flow (Mlb/hr)

Unit	Cycle	% Power	% Flow	FIBWR Bypass	PC Leakage	FIBWR - PC
1	1	72.45	100.61	7.33	8.90	-1.57
1	1	99.63	99.12	7.98	8.63	-0.65
1	1	61.82	94.92	6.72	8.25	-1.53
1	1	98.15	94.16	7.67	8.20	-0.53
1	1	50.70	79.61	5.34	6.63	-1.29
1	1	69.95	64.94	4.51	5.05	-0.54
1	1	55.25	50.52	2.93	3.75	-0.82
1	2	80.71	100.47	8.28	8.30	-0.02
1	2	94.83	99.70	8.65	8.22	0.43
1	2	99.30	97.18	8.64	8.00	0.64
1	2	85.26	87.23	7.27	7.00	0.27
1	2	88.51	73.23	6.44	5.60	0.84
1	2	76.35	57.57	4.59	3.95	0.64
1	3	99.67	99.66	8.39	8.40	-0.01
1	3	99.14	93.83	8.38	7.90	0.48
1	3	99.56	92.33	8.32	7.75	0.57
1	3	82.04	73.43	5.96	5.80	0.16
1	3	80.17	65.74	5.39	5.05	0.34
1	3	63.01	50.74	3.67	3.40	0.27
2	1	89.78	100.08	5.08	5.30	-0.28
2	1	98.11	94.45	4.91	5.15	-0.24
2	1	94.54	87.38	4.49	4.68	-0.19
2	1	59.65	77.81	3.65	4.10	-0.45
2	1	78.37	65.42	3.19	3.25	-0.06
2	1	70.24	55.84	2.59	2.68	-0.09
2	1	41.75	45.58	1.72	2.05	-0.33
2	2	99.63	100.08	8.51	7.85	0.66
2	2	94.09	94.23	8.00	7.40	0.60
2	2	64.66	74.29	5.82	5.47	0.35
2	2	67.41	64.29	4.74	4.50	0.24
2	2	56.61	53.48	3.47	3.44	0.03
2	2	18.75	42.60	2.38	2.35	0.03
2	3	90.89	100.05	8.71	8.10	0.61
2	3	87.36	97.23	8.04	7.97	0.07
2	3	84.61	76.68	6.62	5.85	0.77
2	3	84.69	65.84	5.75	4.74	1.01
2	3	43.39	59.09	3.88	4.05	-0.17
2	3	64.29	49.35	3.43	3.05	0.38
2	4	81.44	99.43	8.34	8.40	-0.06
2	4	87.89	92.26	7.96	7.70	0.26
2	4	77.59	85.98	7.22	7.00	0.22
2	4	74.34	77.95	6.48	6.20	0.28
2	4	74.63	63.17	5.15	4.67	0.48
2	4	53.53	40.99	2.61	2.30	0.31

FIGURE 4

FIBWR COMPARISON TO PROCESS COMPUTER BYPASS FLOW (MLB/HR)



$$\bar{X} = \frac{\text{BYPASS FLOW (pc)}}{\text{BYPASS FLOW (FIBWR)}}$$

FIGURE 5A

BUNDLE FLOW RATES (1000 LBM/HR)
BRUNSWICK 2 CYCLE 4 3/11/82
83.13% POWER
98.99 FLOW

	27	29	31	33	35	37	39	41	43	45
26	129.4 129.2 0.2									
24	134.5 136.2 -1.7	127.8 128.6 -0.8								
22	127.7 127.4 0.3	133.2 135.0 -1.8	124.6 125.3 -0.7							
20	126.9 126.4 0.5	125.7 125.9 -0.2	131.4 133.6 -2.2	122.6 123.2 -0.6						
18	126.1 126.1 0.0	125.5 125.7 -0.2	122.8 124.4 -1.6	128.8 131.9 -3.1	122.0 122.1 -0.1					
16	138.6 138.8 -0.2	125.6 125.8 -0.2	129.9 132.7 -2.8	* 121.1 123.0 -1.9 *	129.6 131.8 -2.2	121.9 122.3 -0.4				
14	134.3 133.4 0.9	126.1 125.6 0.5	125.5 125.0 0.5	124.9 124.4 0.5	123.1 123.3 -0.2	124.2 124.6 -0.4	125.0 125.0 0.0			
12	132.9 134.4 -1.5	125.1 124.9 0.2	132.1 133.7 -1.6	125.1 124.9 0.2	131.0 133.1 -2.1	127.1 128.7 -1.6	129.7 129.7 0.0	128.3 128.3 0.0		
10	122.0 122.2 -0.2	122.6 122.9 -0.3	123.1 122.9 0.2	123.3 123.3 0.0	125.4 125.5 -0.1	129.3 129.6 -0.3	130.6 131.9 -1.3	130.6 130.3 0.3	135.1 135.2 -0.1	
08	122.8 123.1 -0.3	121.8 122.1 -0.3	123.5 123.2 0.3	124.2 124.2 0.0	127.0 126.6 0.4	128.7 129.0 -0.3	132.0 132.2 -0.2	133.5 133.7 -0.2	137.6 137.4 0.2	75.3 75.1 0.2
06	123.4 122.7 0.7	124.8 123.7 1.1	126.2 125.3 0.9	127.8 126.5 1.3	132.4 131.8 0.6	139.8 139.8 0.0	75.1 74.9 0.2	75.4 75.1 0.3	75.7 75.6 0.1	
04	127.8 126.1 1.7	127.5 126.3 1.2	130.4 128.8 1.6	131.6 130.1 1.5	136.5 135.8 0.7	75.1 74.9 0.2				
02	74.5 74.3 0.2	74.2 72.8 1.4	74.9 74.7 0.2	75.2 75.0 0.2	75.6 75.6 0.0					

FIBWR
PC
Δ

RMS DIFF.=1.00

* HOT CHANNEL

FIGURE 5B

BUNDLE FLOW RATES (1000 LBM/HR)
BRUNSWICK 2 CYCLE 4 12/21/80
49.73% POWER
38.83% FLOW

	27	29	31	33	35	37	39	41	43	45
26	50.4 51.8 -1.4									
24	55.0 56.6 -1.6	51.0 52.2 -1.2								
22	52.9 53.8 -0.9	53.2 55.7 -2.5	47.4 48.7 -1.3							
20	49.6 51.0 -1.4	50.3 51.3 -1.0	* 50.7 * * 53.7 * * -3.0 *	47.9 49.0 -1.1						
18	49.3 50.1 -0.8	47.8 49.4 -1.6	48.5 49.4 -0.9	51.8 54.6 -2.8	48.1 48.9 -0.8					
16	55.0 56.8 -1.8	50.1 51.1 -1.0	52.5 55.3 -2.8	53.2 54.3 -1.1	54.7 56.6 -1.9	49.3 50.2 -0.9				
14	53.3 54.2 -0.9	49.2 50.5 -1.3	50.5 51.2 -0.7	52.8 54.0 -1.2	53.1 53.9 -0.8	49.1 50.4 -1.3	48.6 49.3 -0.7			
12	53.0 55.7 -2.7	50.4 51.3 -0.9	53.7 56.3 -2.6	51.5 52.4 -0.9	53.2 55.8 -2.6	50.6 51.4 -0.8	48.3 49.5 -1.2	49.7 50.4 -0.7		
10	49.9 50.6 -0.7	49.1 50.4 -1.3	49.4 50.0 -0.6	49.1 50.4 -1.3	50.5 51.3 -0.8	49.6 50.8 -1.2	50.0 50.7 -0.7	50.2 51.4 -1.2	52.5 53.2 -0.7	
08	52.8 54.0 -1.2	50.9 51.8 -0.9	49.4 50.7 -1.3	51.6 52.6 -1.0	50.6 51.9 -1.3	51.7 52.6 -0.9	51.6 52.4 -0.8	54.1 55.4 -1.3	54.6 55.7 -1.1	35.6 32.9 2.7
06	54.4 55.7 -1.3	51.1 52.2 -1.1	51.2 51.9 -0.7	51.6 52.9 -1.3	54.0 55.3 -1.3	55.4 57.3 -1.9	35.2 33.0 2.2	34.1 32.5 1.6	32.8 32.6 0.2	
04	52.5 53.9 -1.4	53.2 54.1 -0.9	52.6 53.5 -0.9	53.5 54.8 -1.3	54.6 55.7 -1.1	35.1 32.6 2.5				
02	35.2 33.0 2.2	35.6 32.3 3.3	34.9 33.0 1.9	34.5 32.7 1.8	33.6 33.0 0.6					

FIBWR
PC
Δ

RMS DIFF.=1.51

* HOT CHANNEL

FIGURE 5C

BUNDLE FLOW RATES (1000 LBM/HR)
BRUNSWICK 1 CYCLE 3 2/01/82
98.98% POWER
96.82% FLOW

	27	29	31	33	35	37	39	41	43	45
26	134.1 135.2 -1.1									
24	132.5 133.9 -1.4	129.1 130.4 -1.3								
22	123.1 125.1 -2.0	125.0 127.0 -2.0	118.7 121.1 -2.4							
20	123.7 125.7 -2.0	121.8 123.3 -1.5	121.4 124.2 -2.8	119.0 120.7 -1.7						
18	119.7 121.4 -1.7	121.9 124.8 -2.9	116.9 120.6 -3.7	119.4 122.7 -3.3	123.0 126.1 -3.1					
16	121.7 124.4 -2.7	120.6 122.5 -1.7	119.9 123.1 -3.2	116.9 118.6 -1.7	126.8 128.5 -1.7	126.4 128.5 -2.1				
14	120.2 122.4 -2.2	122.8 124.4 -1.6	125.9 127.5 -1.6	128.1 129.4 -1.3	120.8 122.3 -1.5	123.8 124.9 -1.1	* 116.6 * * 118.1 * * -1.5 *			
12	125.8 127.9 -2.1	132.8 133.7 -0.9	137.9 137.7 0.2	128.0 128.6 -0.6	125.8 127.4 -1.6	124.8 127.1 -2.3	123.8 126.2 -2.4	118.8 120.1 -1.3		
10	127.7 129.3 -1.6	138.0 138.2 -0.2	131.4 133.2 -1.8	125.0 125.9 -0.9	121.8 123.3 -1.5	126.5 128.2 -1.7	122.1 124.6 -2.5	124.3 125.4 -1.1	129.3 130.2 -0.9	
08	131.1 131.7 -0.6	129.2 129.8 -0.6	127.2 128.6 -1.4	123.3 124.6 -1.3	127.8 129.2 -1.4	125.4 126.9 -1.5	125.0 126.2 -1.2	126.1 127.6 -1.5	135.1 135.2 -0.1	66.6 66.3 0.3
06	125.9 126.7 -0.8	127.5 127.8 -0.3	125.2 126.1 -0.9	126.9 127.2 -0.3	128.1 129.2 -1.1	131.0 131.4 -0.4	66.5 66.2 0.3	67.1 66.7 0.4	68.0 67.6 0.4	
04	131.3 1131.1 0.2	131.0 130.8 0.2	131.8 131.6 0.2	131.0 131.3 -0.3	135.7 135.7 0.0	66.2 66.0 0.2				
02	67.2 66.7 0.5	67.2 66.7 0.5	67.4 66.9 0.5	67.5 67.0 0.5	68.2 67.9 0.3					

FIBWR
PC
△

RMS DIFF.=1.58

* HOT CHANNEL

FIGURE 5D

BUNDLE FLOW RATES (1000 LBM/HR)
BRUNSWICK 1 CYCLE 3 9/27/81
50.38% POWER
44.68% FLOW

	27	29	31	33	35	37	39	41	43	45
26	60.9 61.7 -0.8									
24	62.4 64.0 -1.6	60.2 61.1 -0.9								
22	63.0 64.2 -1.2	59.6 60.7 -1.1	58.7 60.1 -1.4							
20	59.2 60.4 -1.2	58.5 59.5 -1.0	58.0 59.4 -1.4	58.3 59.4 -1.1						
18	58.0 59.2 -1.2	57.8 59.2 -1.4	57.4 59.2 -1.8	57.9 59.3 -1.4	59.2 60.5 -1.3					
16	61.5 62.4 -0.9	57.8 59.0 -1.2	57.8 59.2 -1.4	61.4 62.0 -0.6	61.9 62.9 -1.0	59.0 60.2 -1.2				
14	61.8 63.0 -1.2	57.5 58.7 -1.2	58.2 59.7 -1.5	61.4 62.4 -1.0	62.2 63.3 -1.1	58.6 59.6 -1.0	56.3 58.0 -1.7			
12	57.6 59.2 -1.6	56.7 58.1 -1.4	57.8 59.3 -1.5	57.9 59.1 -1.2	58.6 59.8 -1.2	58.1 59.5 -1.4	56.5 58.1 -1.6	56.7 58.3 -1.6		
10	58.1 59.8 -1.7	57.8 59.3 -1.5	* 55.6 57.6 -2.0	56.8 58.6 -1.8	56.8 58.6 -1.8	57.2 58.5 -1.3	56.2 57.9 -1.7	57.4 58.5 -1.1	60.7 61.8 -1.1	
08	61.5 62.6 -1.1	58.3 59.5 -1.2	57.2 58.9 -1.7	59.7 61.5 -1.8	60.1 61.3 -1.2	58.6 60.1 -1.5	57.3 58.5 -1.2	58.6 59.9 -1.3	62.2 62.8 -0.6	36.1 33.5 2.6
06	62.8 64.0 -1.2	60.0 61.1 -1.1	59.2 60.8 -1.6	61.3 62.4 -1.1	62.5 63.4 -1.1	61.5 62.3 -0.8	36.1 33.4 2.7	35.9 33.4 2.5	35.3 33.6 1.7	
04	61.8 62.5 -0.7	61.4 62.1 -0.7	61.2 61.9 -0.7	61.8 62.8 -1.0	63.0 63.7 -0.7	36.1 33.2 2.9				
02	36.0 33.2 2.8	36.0 33.2 2.8	35.5 33.2 2.3	35.3 33.1 2.2	34.3 33.2 1.1					

FIBWR
PC
△

RMS DIFF.=1.50

* HOT CHANNEL

FIGURE 6

Brunswick 2, Cycle 5
Critical Power Ratio (GEXL) vs. Bundle Power
FIBWR Hot Channel Analysis

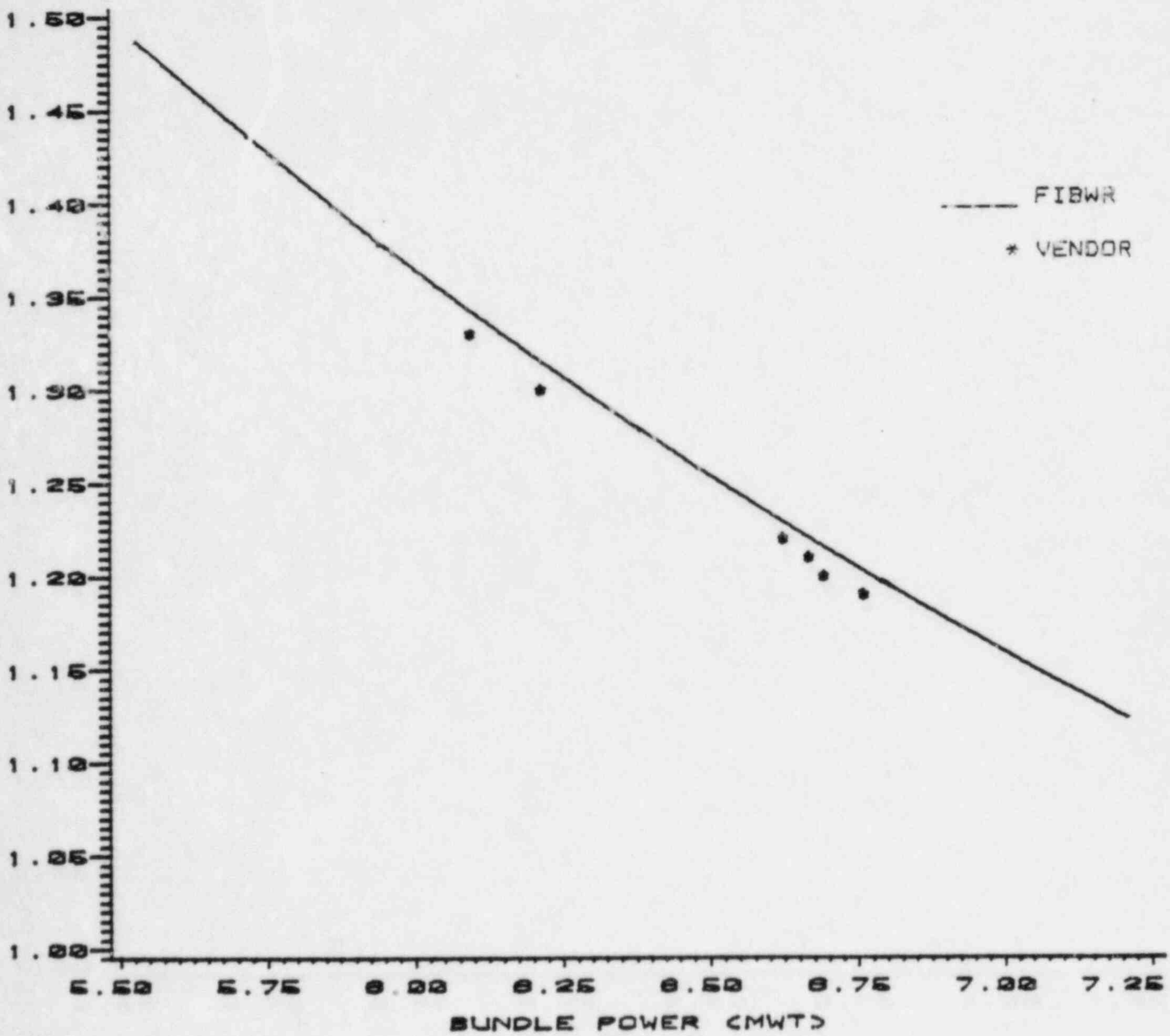
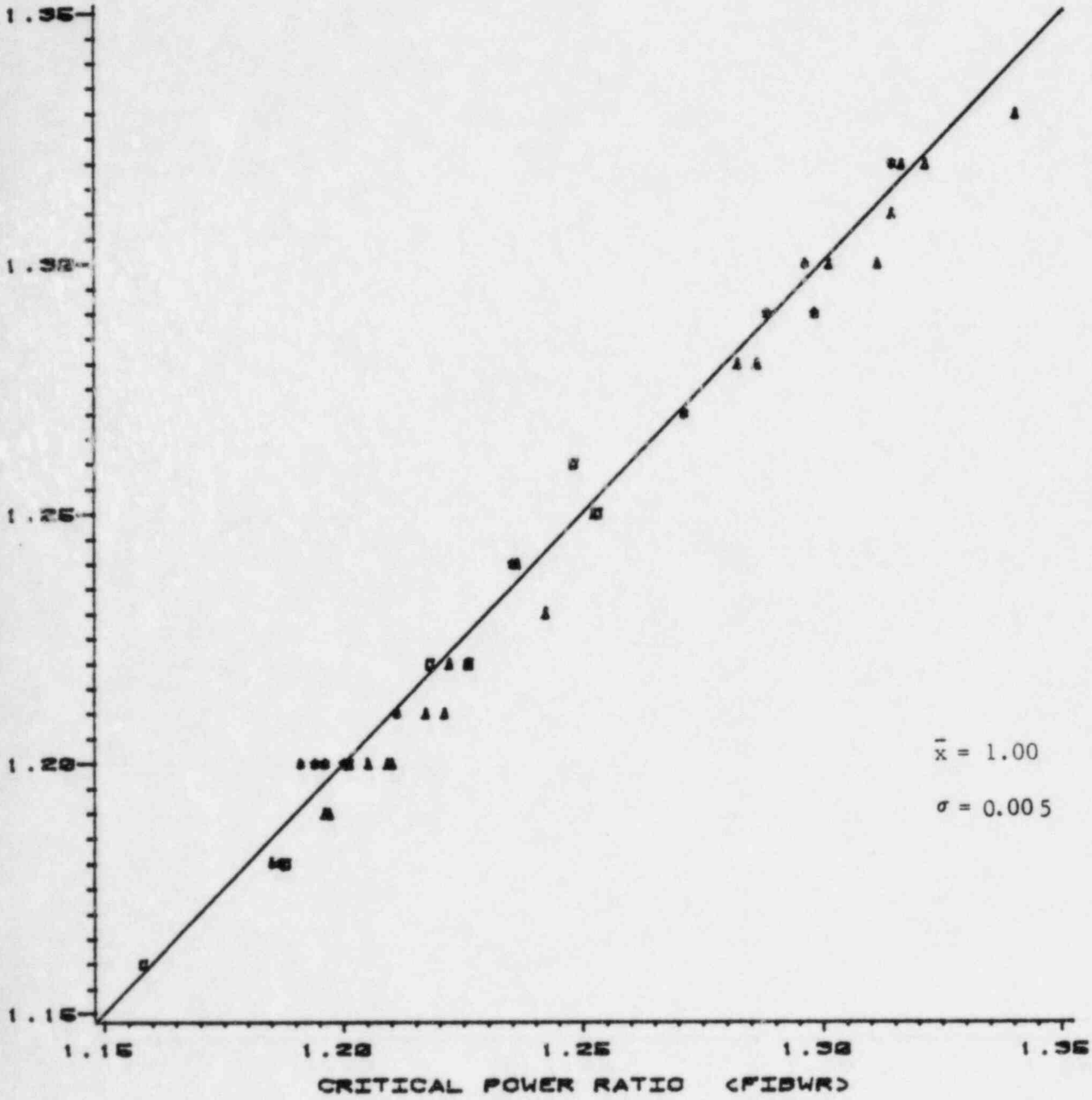


FIGURE 7

FIBWR Comparison to Vendor Critical Power Ratio



$\bar{X} = \frac{\text{CPR vendor}}{\text{CPR FIBWR}}$

□ 7x7
* 8x8
Δ 8x8R

4.0 Summary and Conclusions

A CP&L model of the FIBWR code was developed to perform steady-state thermal hydraulic simulations of the Brunswick plant. A series of verifications to vendor models and measured data was done to evaluate the capability of the code to be used for its intended applications.

The ability of the CP&L FIBWR model to calculate pressure drops was demonstrated by comparisons to the Brunswick Units 1 and 2 process computer P1 edits. This comparison verified the accuracy of FIBWR results to both the process computer calculated plenum to plenum pressure drop, and to the measured core support plate pressure drop.

The FIBWR code has been shown to accurately predict BWR flow distributions between active channels and between the active and bypass regions. In a comparison to process computer bundle flow rates as a function of bundle power, FIBWR predicted the channel flow distributions to within 1.5 percent of the process computer values. Bypass flow rates calculated by FIBWR agreed well with the bypass/total flow relationship developed from the process computer databook for the same core power and flow conditions. FIBWR differed, as expected, from the process computer bypass relationship for conditions where this relationship did not apply.

A comparison of vendor critical power ratio data with FIBWR results has demonstrated that the GEXL CPR correlation has been properly installed in the FIBWR code. A hot bundle CPR analysis was performed using this correlation in FIBWR to verify good agreement with vendor-calculated, limiting-bundle powers for given critical power ratios.

The CP&L FIBWR model has been shown to accurately calculate pressure drops, flow distributions, and critical power ratios for steady-state thermal-hydraulic applications to the Brunswick nuclear plant.

103

5.0 REFERENCES

(1) Vermont Yankee Nuclear Power Corporation; "Methods for the Analysis of Boiling Water Reactors, Steady-State Core Flow Distribution Code (FIBWR);" YAEC-1234; December 31, 1980.

(2) Letter from Domenick B. Vassallo, Chief of Operating Reactors Branch No. 2, to J. B. Sinclair; Vermont Yankee Nuclear Power Corporation; September 15, 1982.

(3) EPRI; "FIBWR: A Steady-State Core Flow Distribution Code for Boiling Water Reactors;" NP-1923; July 1981.

(4) General Electric Company; "Brunswick Steam Electric Plant Units 1 and 2, Reload Fuel Supply and Related Services, Technical Description;" Volume 11, Part 1; July 25, 1979; Pages 3-17. (GE Proprietary)

(5) Letter from J. H. Craven, General Electric Company, to L. H. Martin, Carolina Power & Light Company; Subject: CP&L Reload Fuel Proposal Technical Information; February 25, 1982. (GE Proprietary)

(6) General Electric Company; "Brunswick Steam Electric Plant Unit 1 Safety Analysis Report for Plant Modifications to Eliminate Significant In-Core Vibrations;" NEDC-21215; March 1976; Section 4.2.3. (GE Proprietary)

(7) General Electric Company; "General Electric Standard Application for Reactor Fuel (United States Supplement);" NEDE-24011-P-A-4-US; January 1982; US.B-103. (GE Proprietary)

(8) R. T. Lahey and F. J. Moody; "Thermal Hydraulics of a Boiling Water Nuclear Reactor;" American Nuclear Society; 1973; Page 242.

(9) G. S. Lellouche and B. A. Zolotar; "Mechanistic Model for Predicting Two-Phase Void Fraction for Water in Vertical Tubes, Channels, and Rod Bundles;" EPRI NP-2246-SR; February 1982.

(10) EPRI; "Low-Flow Stability Tests at Peach Bottom Atomic Power Station Unit 2 During Cycle 3;" NP-972; April 1981; Pages 3-1 and 3-3.

(11) General Electric Company; "GEXL Correlation Application to BWR/2-6 Reactors;" NEDE-25422. (GE Proprietary)