WCAP-14788
Revision 3

February 2009

Westinghouse Revised Thermal Design Procedure Instrument Uncertainty Methodology for Point Beach 1 & 2 Power Uprate (1775 MWt – Core Power with Feedwater Venturis, or 1800 MWt – Core Power with LEFM on Feedwater Header)

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1.0 INTRODUCTION

Revision 0 of this report was completed to support an upgrade to the fuel product at uprated conditions of 1650 MWt - core power for both Units 1&2 at the Point Beach Nuclear Plant (PBNP). The fuel product to satisfy the intended requirements was the Westinghouse 14 X 14 PERFORMANCE + 422 fuel assembly. To utilize this new fuel assembly at the uprated conditions, a new accident analysis was required in addition to recalculating and revising the Instrument Uncertainty Methodology. Revision 0 of this report superseded "ITDP Instrument Uncertainty Report" dated June 7, 1984 (84WE*-G-044).

Revision 1 of this report was completed to support a 1.4% uprate from the uprated condition of 1650 MWt -core power. This 1.4% uprate was possible due to the installation of an ultrasonic Leading Edge Flow Meter (LEFM) on the feedwater header. This LEFM is used to perform the required daily calorimetric power measurement and continuous Reactor Thermal Output (RTO) calculation on the Plant Process Computer System (PPCS). The previous fuel analysis was performed at 2% above the rated full power value of 1650 MWt - core power. This 2% accounted for the power measurement uncertainty. Therefore, the improved LEFM feedwater flow measurement allowed an additional power increase equivalent to the difference between the 2% and the reduced power measurement uncertainty obtained using the LEFM. The new power measurement uncertainty was included in this revision.

Revision 2 of this report was completed to reflect additional changes to the calorimetric measurements. The power measurement uncertainty that uses the Caldon LEFM to measure feedwater flow and feedwater temperature was recalculated to include feedwater pressure transmitter P-2245 and its associated computer input to replace channels P-2289 and P-2290. The calorimetric RCS flow measurement uncertainty was recalculated to include the Caldon feedwater temperature measurement to replace the TE-3111 resistance thermometer bridge measurement and to include a feedwater pressure reading from the LEFM display panel, rather than using a digital voltmeter.

Revision 3 of this report is completed to reflect design parameter changes for an Extended Power Uprate to 1800 MWt - core power. Power operation at 1800 MWt - core power is possible only when the Caldon LEFM is operable. If the LEFM is inoperable, the maximum power operation is 1775 MWt - core power based on the use of the feedwater venturis.

Four operating parameter uncertainties are used in the uncertainty analysis of the Revised Thermal Design Procedure (RTDP). These parameters are Pressurizer Pressure, Primary Coolant Temperature (T_{avg}), Reactor Power, and Reactor Coolant System Flow. They are frequently monitored and several are used for control purposes. Reactor power is monitored by the performance of a secondary side heat balance (power calorimetric) at least every 24 hours. RCS flow is monitored by the performance of a calorimetric flow measurement at the beginning of each cycle. Pressurizer pressure is a controlled parameter and the uncertainty reflects the utomatic control system. T_{avg} is a controlled parameter via the temperature input to the automatic rod control system, and the uncertainty reflects this automatic control system. The RTDP(1) is used to predict the plant's DNBR design limit. The RTDP methodology considers the uncertainties in the system operating plant parameters, fuel fabrication and nuclear and thermal parameters and includes the use of various DNB correlations. Use of the RTDP methodology requires that variances in the plant operating parameters are justified. The purpose of the following evaluation is to define the specific PBNP instrument uncertainties for the four primary system operating parameters that are used to predict the plant safety analysis DNBR design limit via the RTDP, and to determine the starting points of certain plant parameters in some of the accident analyses.

Westinghouse has been involved with the development of several techniques to treat instrumentation uncertainties. An early version (for D. C. Cook 2 and Trojan) used the methodology outlined in WCAP-8567 "Improved Thermal Design Procedure," (2,3,4) that is based on the conservative assumption that the uncertainties can be described with uniform probability distributions. Another approach is based on the more realistic assumption that the uncertainties can be described with random, normal, two sided probability distributions.(5) This approach is used to substantiate the acceptability of the protection system setpoints for many Westinghouse plants, e.g., D. C. Cook 2(6), V. C. Summer, Wolf Creek, Millstone Unit 3 and others. The second approach is now utilized for the determination of all instrumentation uncertainties for the RTDP parameters and protection functions.

The determination of pressure, temperature, power and RCS flow uncertainties are applicable for PBNP Units 1 & 2 for power levels up to 1800 MWt - core power when the daily calorimetric power measurement is based on the LEFM on the feedwater header, for 18 month fuel cycles + 25% per the plant Technical Specifications, and for a full power Tavg window of 558.0 to 577.0°F.

2.0 METHODOLOGY

The methodology used to combine the error components for a channel is the Square Root of the Sum of the Squares (SRSS) of those groups of components that are statistically independent. Those errors that are dependent are combined arithmetically into independent groups, which are then combined by SRSS. The uncertainties are considered to be random, two sided distributions. The sum of both sides is equal to the range for that parameter, e.g., Rack Drift is typically [ ]^{a,c}, the range for this parameter is [ ]^{a,c}. This technique has been utilized before as noted above, and has been endorsed by the NRC staff(7,8,9,10) and various industry standards(11,12). This report meets the requirements of ISA-67.04.01-2006(12) and Regulatory Guide 1.105, Revision 3(9).

The relationships between the error components and the channel instrument error allowance are variations of the basic Westinghouse Setpoint Methodology(13) and are defined as follows:

1. For precision parameter indication using Special Test Equipment or a digital voltmeter (DVM) at the input to the racks;

$$\mathrm{CSA} = \{(\mathrm{SMTE} + \mathrm{SCA})^2 + (\mathrm{SPE})^2 + (\mathrm{STE})^2 + (\mathrm{SMTE} + \mathrm{SD})^2 + (\mathrm{SRA})^2 + (\mathrm{RDOUT})^2\}^{1/2} + \mathrm{BIAS} \qquad \text{Eq. 1}$$

2. For parameter indication utilizing the plant computer;

$$\begin{aligned}\mathrm{CSA} = \{&(\mathrm{SMTE} + \mathrm{SCA})^2 + (\mathrm{SPE})^2 + (\mathrm{STE})^2 + (\mathrm{SMTE} + \mathrm{SD})^2 + (\mathrm{SRA})^2 \\ &+ (\mathrm{RMTE} + \mathrm{RCA})^2 + (\mathrm{RTE})^2 + (\mathrm{RMTE} + \mathrm{RD})^2 \\ &+ (\mathrm{RMTE}_{\mathrm{PC}} + \mathrm{RCA}_{\mathrm{PC}})^2 + (\mathrm{RTE}_{\mathrm{PC}})^2 + (\mathrm{RMTE}_{\mathrm{PC}} + \mathrm{RD}_{\mathrm{PC}})^2\}^{1/2} \\ &+ \mathrm{BIAS}\end{aligned} \qquad \text{Eq. 2}$$

3. For parameters with closed-loop automatic control systems, the calculation takes credit for [ ]^{a,c};

$$
\begin{aligned}
CSA = \{[(PMA^2 + (PEA)^2 \\
&+ (SMTE + SCA)^2 + (SPE)^2 + (STE)^2 + (SMTE + SD)^2 + (SRA)^2 \\
&+ (RMTE + RCA)^2 + (RTE)^2 + (RMTE + RD)^2 + (RMTE + RCA)^2_{IND} + (RTE)^2_{IND} \\
&+ (RMTE + RD)^2_{IND} + (RDOUT)^2_{IND}]/N + (REF)^2 + (CMTE + CA)^2\}^{1/2} \\
&+ BIAS \qquad \text{Eq. 3}
\end{aligned}
$$

where:

CSA = Channel Statistical Allowance
PMA = Process Measurement Accuracy
PEA = Primary Element Accuracy
SRA = Sensor Reference Accuracy
SCA = Sensor Calibration Accuracy
SMTE = Sensor Measurement and Test Equipment Accuracy
SPE = Sensor Pressure Effects
STE = Sensor Temperature Effects
SD = Sensor Drift
RCA = Rack Calibration Accuracy
RMTE = Rack Measurement and Test Equipment Accuracy
RTE = Rack Temperature Effects
RD = Rack Drift
RDOUT = Readout Device Accuracy
CA = Controller Allowance
CMTE = Controller Measurement and Test Equipment Accuracy
REF = Reference signal for automatic control system
IND = Indicator.
PC = Plant Computer.
N = Number of credited redundant indicators

PMA and PEA terms are not included in Equations 1 and 2 since the equations are to determine instrumentation uncertainties only. PMA and PEA terms are included in the determination of control system uncertainties.

The parameters above are defined in References 5 and 12 and are based on ANSI/ISA-51.1-1979 (R1993)(14). However, for ease in understanding they are paraphrased below:

PMA - non-instrument related measurement errors, e.g., temperature stratification of a fluid in a pipe.
PEA - errors due to a metering device, e.g., elbow, venturi, orifice.

SRA - reference accuracy for a sensor/transmitter.
SCA - calibration tolerance for a sensor/transmitter.
SMTE - measurement and test equipment used to calibrate a sensor/transmitter.
SPE - change in input-output relationship due to a change in static pressure for a differential pressure (d/p) transmitter.
STE - change in input-output relationship due to a change in ambient temperature for a sensor or transmitter.
SD - change in input-output relationship over a period of time at reference conditions for a sensor or transmitter.
RCA - calibration accuracy for all rack modules in loop or channel.
RMTE - measurement and test equipment used to calibrate rack modules.
RTE - change in input-output relationship due to a change in ambient temperature for the rack modules.
RD - change in input-output relationship over a period of time at reference conditions for the rack modules.
RDOUT - the measurement accuracy of a special test local gauge, digital voltmeter or multimeter on its most accurate applicable range for the parameter measured, or 1/2 the smallest increment on an indicator (readability).
CA - allowance of the controller rack module(s) that performs the comparison and calculates the difference between the controlled parameter and the reference signal.
CMTE - measurement and test equipment used to calibrate the controller rack module(s) that perform(s) the comparison between the controlled parameter and the reference signal.
REF - the reference signal uncertainty for a closed-loop automatic control system.
IND - indicator accuracies are used for these uncertainty calculations. Control board indicators are typically used.
PC - plant computer accuracies are used for these uncertainty calculations.
BIAS - a one directional uncertainty for a sensor/transmitter or a process parameter with a known magnitude.

A more detailed explanation of the Westinghouse methodology noting the interaction of several parameters is provided in Reference 13.

3.0 INSTRUMENTATION UNCERTAINTIES

The instrumentation uncertainties will be discussed first for the two parameters which are controlled by automatic systems, Pressurizer Pressure and T_{avg} (Through automatic rod control).

3.1 Pressurizer Pressure

Pressurizer pressure is controlled by a closed-loop automatic control system that compares the measured vapor space pressure to a reference value. This uncertainty calculation takes credit for the closed-loop control system design where [ ]^{a,c}. The control channel uncertainties for the automatic control system include allowances for the pressure transmitters, the process racks, and the control system reference setpoint. The pressurizer pressure control system reference setpoint is generated by the setting of a variable potentiometer on the Main Control Board manual/automatic station. The reference setpoint (Pref) is adjusted and verified by the plant operators with the control board indicators. This uncertainty calculation also includes the control board indicators for verification of the automatic control system performance.

On Table 3-1, the calculated control system uncertainty for this function using Equation 3 is [ ]^{a,c} with a [ ]^{a,c} bias corresponding to [ ]^{a,c} with a [ ]^{a,c} bias. Included in the control system uncertainty is an allowance for pressure overshoot or undershoot due to the interaction and thermal inertia of the heaters and spray. An allowance of [ ]^{a,c} is made for this effect. The standard deviation for the control system is [ ]^{a,c} for a normal, two sided probability distribution.

Table 3-1
Pressurizer Pressure Control and Indication Uncertainty[***]

Parameter	Allowance[*]
	a,c
Process Measurement Accuracy (PMA)	
Primary Element Accuracy (PEA)	
Sensor Reference Accuracy (SRA)	
Sensor Calibration Accuracy (SCA)	
Sensor Measurement & Test Equipment Accuracy (SMTE)	
Sensor Temperature Effects (STE)	
Sensor Drift (SD)	
Rack Calibration Accuracy (RCA)	
Rack Measurement & Test Equipment (RMTE)	
Rack/Indicator Temperature Effect (RTE)	
Rack Drift (RD)	
Indicator Calibration Accuracy (RCA_{IND})	
Indicator Measurement & Test Equipment ($RMTE_{IND}$)	
Indicator Drift (RD_{IND})	
Indicator Readability ($RDOUT_{IND}$)	
Reference Accuracy (REF)	
Thermal Inertia (TI)	
Bias (Sensor Ambient Pressure (SAP))	
Bias (Seismic (SSE))	

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[*] In percent span (800 psig) Range = 1700 – 2500 psig

[**] 15 psi setting tolerance around 2235 psig

Channels P-429, -430, -431 & -449 (channel indications are not averaged)

[***] Results have been rounded to reflect the appropriate number of significant digits based on the accuracy of the input information.

Table 3-1 (continued)
Pressurizer Pressure Control and Indication Uncertainty

Control Uncertainty =

$$\pm\sqrt{\begin{array}{l}(\text{PMA})^2+(\text{PEA})^2+(\text{SRA})^2+(\text{SCA}+\text{SMTE})^2+\text{STE}^2+(\text{SD}+\text{SMTE})^2+\\(\text{RCA}+\text{RMTE})^2+\text{RTE}^2+(\text{RD}+\text{RMTE})^2+\\(\text{RCA}_{\text{IND}}+\text{RMTE}_{\text{IND}})^2+(\text{RD}_{\text{IND}}+\text{RMTE}_{\text{IND}})^2+\text{RDOUT}_{\text{IND}}{}^2+\text{REF}^2\end{array}} \quad \text{(random)}$$

$$+\text{TI}$$

$$\pm\,\text{SAP} \quad \text{(bias)}$$

a,c

(random)

(bias)

a,c

Control System Uncertainty

(random)

(bias)

3.2 Tavg

T_{avg} is controlled by a system that compares the high T_{avg} from the loops with a reference derived from the First Stage Turbine Impulse Chamber Pressure. T_{avg} is the average of the narrow range T_H and T_C values. The high loop T_{avg} is then used for rod control. Allowances are made (as noted on Table 3-2) for the RTDs, transmitter and the process racks/indicators and controller. The CSA for this function is dependent on the type of RTD, pressure transmitter, and the locations of the RTDs, i.e., in the Hot and Cold Leg bypass manifolds. Based on one T_H and one T_C RTD per channel to calculate T_{avg} and with the RTDs located in the hot and cold leg bypass manifolds, the calculated CSA for the channel using Equation 3 is [$]^{a,c}$. Assuming a normal, two sided probability distribution results in a channel standard deviation (s_1) of [$]^{a,c}$.

However, this does not include the deadband of ±1.5°F for automatic control. The T_{avg} control sytem accuracy is the combination of the instrumentation accuracy and the deadband. The probability distribution for the deadband has been determined to be [

$]^{a,c}$ The variance for the deadband uncertainty is then:

$$(s_2)^2 = [\quad]^{a,c} = [\quad]^{a,c}$$

where [$]^{a,c}$. Combining the variance for instrumentation and deadband results in a control system variance of:

$$(s_T)^2 = (s_1)^2 + (s_2)^2 = [\quad]^{a,c}$$

The control system s_T = [$]^{a,c}$ for a total random uncertainty of [$]^{a,c}$.

An additional bias of [$]^{a,c}$ for T_{cold} streaming (in terms of Tavg) based on a conservative [$]^{a,c}$ T_{cold} streaming uncertainty is included in Table 3-2. An additional bias of [$]^{a,c}$ for R/E (Resistance to voltage) linearization (in terms of Tavg) based on a [$]^{a,c}$ R/E uncertainty is included in Table 3-2. An additional bias of [$]^{a,c}$ for the RTD self-heating effect (in terms of Tavg) based on a [$]^{a,c}$ RTD self-heating uncertainty is included in Table 3-2. The total uncertainty of the control system with the additional biases is [$]^{a,c}$ random and [$]^{a,c}$ bias.

Table 3-2
Tavg Control and Indication Uncertainty*

Parameter	Allowance (% of Tavg 530-630 °F range)
Tavg	^{a,c}
Process Measurement Accuracy (PMA_1) [ ]^{a,c}	
PMA_2 [ ]^{a,c}	
Sensor reference accuracy (SRA)	
Sensor calibration accuracy (SCA)	
Sensor drift (SD)	
$Bias_1$ (cold leg temperature streaming)	
$Bias_2$ (R/E linearization)	
$Bias_3$ (Self-heating effect)	
Dual current source - Dana amplifier calibration accuracy ($RCA_{TT\text{-}401A/TM\text{-}401A}$)	
Dual current source - Dana amplifier measurement & test equipment ($RMTE_{TT\text{-}401A/TM\text{-}401A}$)	
Dual current source – Dana amplifier temperature effect ($RTE_{TT\text{-}401A/TM\text{-}401A}$)	
Dual current source - Dana amplifier drift ($RD_{TT\text{-}401A/TM\text{-}401A}$)	
E/I converter calibration accuracy ($RCA_{TM\text{-}401BB}$)	
E/I converter measurement & test equipment ($RMTE_{TM\text{-}401BB}$)	
E/I converter temperature effect ($RTE_{TM\text{-}401BB}$)	
E/I converter drift ($RD_{TM\text{-}401BB}$)	

* Results have been rounded to reflect the appropriate number of significant digits based on the accuracy of the input information.

Table 3-2 (continued)
Tavg Control and Indication Uncertainty*

Tavg	a,c
Isolator calibration accuracy ($RCA_{TM\text{-}401C}$)	
Isolator measurement and test equipment ($RMTE_{TM\text{-}401C}$)	
Isolator temperature effect (RTE_{TM401C})	
Isolator drift ($RD_{TM\text{-}401C}$)	
Indicator calibration accuracy ($RCA_{TI\text{-}401}$)	
Indicator measurement and test equipment ($RMTE_{TI\text{-}401}$)	
Indicator temperature effect ($RTE_{TI\text{-}401}$)	
Indicator drift ($RD_{TI\text{-}401}$)	
Indicator readability (RDOUT)	

Turbine Pressure	**Allowance (% of pressure 0-650 psig range)** a,c
Sensor reference accuracy (SRA)	
Sensor calibration accuracy (SCA)	
Sensor measurement & test equipment accuracy (SMTE)	
Sensor temperature effect (STE)	
Sensor drift (SD)	
Sensor seismic effect (SSE) – treated as a bias	
Isolator calibration accuracy ($RCA_{PM\text{-}485A}$)	
Isolator measurement & test equipment ($RMTE_{PM\text{-}485A}$)	
Isolator temperature effect ($RTE_{PM\text{-}485A}$)	
Isolator drift ($RD_{PM\text{-}485A}$)	

* Results have been rounded to reflect the appropriate number of significant digits based on the accuracy of the input information.

Table 3-2 (continued)
Tavg Control and Indication Uncertainty*

Parameter	Allowance (% of Tavg 530-630 °F range)
Tavg Control Racks	a,c
Module TM401EE calibration accuracy ($RCA_{TM401EE}$)	
Module TM401D calibration accuracy (RCA_{TM401D})	
Module TM401H calibration accuracy (RCA_{TM401H})	
Module TM401M calibration accuracy (RCA_{TM401M})	
Module TM401P calibration accuracy (RCA_{TM401P})	
Module TM401N calibration accuracy (RCA_{TM401N})	
Module TM401I calibration accuracy (RCA_{TM401I})	
Module TM401EE drift accuracy ($RD_{TM401EE}$)	
Module TM401D drift accuracy (RD_{TM401D})	
Module TM401H drift accuracy (RD_{TM401H})	
Module TM401M drift accuracy (RD_{TM401M})	
Module TM401P drift accuracy (RD_{TM401P})	
Module TM401N drift accuracy (RD_{TM401N})	
Module TM401I drift accuracy (RD_{TM401I})	
Module TM401EE M&TE accuracy ($RMTE_{TM401EE}$)	
Module TM401D M&TE accuracy ($RMTE_{TM401D}$)	
Module TM401H M&TE accuracy ($RMTE_{TM401H}$)	
Module TM401M M&TE accuracy ($RMTE_{TM401M}$)	
Module TM401P M&TE accuracy ($RMTE_{TM401P}$)	

* Results have been rounded to reflect the appropriate number of significant digits based on the accuracy of the input information.

Table 3-2 (continued)
Tavg Control and Indication Uncertainty*

Parameter **Allowance**

Tavg Control Racks

a,c

Module TM401N M&TE accuracy ($RMTE_{TM401N}$)

Module TM401I M&TE accuracy ($RMTE_{TM401I}$)

Number of Hot Leg RTDs per channel Nh=1

Number of Cold Leg RTDs per channel Nc=1

Number of Tavg channels N=4 (3 of 4 channel indications are averaged)

Tavg at no load = 547 °F

Tavg at full power = 577 °F

Tavg range = 530-630 °F

Range of pressure = 0-650 psig

Turbine pressure at full power = 544 psig

Deadband = ± 1.5 °F

$$s_{rtd} = SRA^2 + SCA^2 + SD^2$$

$$re = (RMTE_{TT\text{-}401A/TM\text{-}401A} + RD_{TT\text{-}401A/TM\text{-}401A})^2 + (RMTE_{TT\text{-}401A/TM\text{-}401A} + RCA_{TT\text{-}401A/TM\text{-}401A})^2 + RTE^2{}_{TT-401A/TM-401A}$$

$$rack_{temp} = (RMTE_{TM\text{-}401BB} + RD_{TM\text{-}401BB})^2 + (RMTE_{TM\text{-}401BB} + RCA_{TM\text{-}401BB})^2 + RTE^2{}_{TM\text{-}401BB}$$

$$iso_{temp} = (RMTE_{TM\text{-}401C} + RD_{TM\text{-}401C})^2 + (RMTE_{TM\text{-}401C} + RCA_{TM\text{-}401C})^2 + RTE^2{}_{TM-401C}$$

$$ind = (RMTE_{TI\text{-}401} + RD_{TI\text{-}401})^2 + (RMTE_{TI\text{-}401} + RCA_{TI\text{-}401})^2 + RTE^2{}_{TI-401} + RDOUT^2$$

TPP= (upper range of pressure - lower range of pressure)/ (turbine pressure at full power – lower range of pressure) = (650-0)/ (544-0) =119.49%

Turb_sens= (TPP/Tavg span)*(Tavg at full power - Tavg at no load) =0.36

* Results have been rounded to reflect the appropriate number of significant digits based on the accuracy of the input information.

Table 3-2 (continued)
Tavg Control and Indication Uncertainty

$$\text{sensor}_{\text{turb}} = \left[(\text{SMTE}+\text{SD})^2{}_{\text{turb}} + \text{STE}^2{}_{\text{turb}} + (\text{SMTE}+\text{SCA})^2{}_{\text{turb}} + \text{SRA}^2{}_{\text{turb}}\right] \times \text{Turb\_sens}^2$$

$$\text{rack}_{\text{turb}} = \left[(\text{RMTE}_{\text{PM-485A}} + \text{RD}_{\text{PM-485A}})^2 + \text{RTE}^2{}_{\text{PM-485A}} + (\text{RMTE}_{\text{PM-485A}} + \text{RCA}_{\text{PM-485A}})^2\right] \times \text{Turb\_sens}^2$$

$$\begin{aligned} rack_{control} = {} & (RMTE_{TM401EE} + RCA_{TM401EE})^2 + (RMTE_{TM401D} + RCA_{TM401D})^2 + (RMTE_{TM401H} + RCA_{TM401H})^2 \\ & + (RMTE_{TM401M} + RCA_{TM401M})^2 + (RMTE_{TM401P} + RCA_{TM401P})^2 + (RMTE_{TM401N} + RCA_{TM401N})^2 \\ & + (RMTE_{TM401I} + RCA_{TM401I})^2 + (RMTE_{TM401EE} + RD_{TM401EE})^2 + (RMTE_{TM401D} + RD_{TM401D})^2 \\ & + (RMTE_{TM401H} + RD_{TM401H})^2 + (RMTE_{TM401M} + RD_{TM401M})^2 + (RMTE_{TM401P} + RD_{TM401P})^2 \\ & + (RMTE_{TM401N} + RD_{TM401N})^2 + (RMTE_{TM401I} + RD_{TM401I})^2 \end{aligned}$$

Channel Uncertainty =

$$\sqrt{\frac{PMA_1^{\,2} + \left(\sqrt{\frac{s_{rtd}}{Nh}} + \sqrt{\frac{s_{rtd}}{Nc}}\right)^2 + \left(\sqrt{\frac{re}{Nh}} + \sqrt{\frac{re}{Nc}}\right)^2 + rack_{temp} + iso_{temp} + ind}{N-1} + PMA_2^{\,2} + sensor_{turb} + rack_{turb} + rack_{control}}$$

$= [\qquad\qquad]^{a,c}$

Negative Bias = negative value of Bias_1 + negative value of Bias_2 - SSE = $[\qquad]^{a,c}$

Positive Bias = positive value of Bias_1 + positive value of Bias_2 + Bias_3 + SSE = $[\qquad]^{a,c}$

Summary of results:

	$[\qquad]^{a,c}$	
Channel Sigma		(random)
Control System Sigma		(random)
Control System Uncertainty		(random)
Control System Bias		(bias)

3.3 Calorimetric RCS Flow Measurement (Using LEFM on Feedwater Header)

RTDP and Point Beach's Technical Specifications require an RCS flow measurement with a high degree of accuracy. A total RCS flow measurement every fuel cycle, typically 18 months, is performed to verify RCS flow and to normalize the RCS flow instrument channels. Interim surveillances performed with the plant computer ensure that the RCS flow is maintained within the assumed safety analysis values, i.e., Minimum Measured Flow (MMF). The 18 month RCS flow surveillance is satisfied by a secondary side power-based calorimetric RCS flow measurement. The calorimetric flow measurement is performed at the beginning of a fuel cycle near full power operation.

Eighteen month instrument drift is used in this uncertainty analysis for hot and cold leg RTDs, and for feedwater pressure, steam pressure and pressurizer pressure transmitters.

A LEFM installed on the feedwater header is used to determine total feedwater flow and feedwater temperature. Feedwater temperature indication by the LEFM is compared to individual loop feedwater temperatures that are then adjusted, if necessary.

The flow measurement is performed by determining the Steam Generator thermal output (corrected for the RCP heat input and the loop's share of primary system heat losses) and the enthalpy rise (Delta-h) of the primary coolant. Assuming that the primary and secondary sides are in equilibrium, the RCS total vessel flow is the sum of the individual primary loop flows, i.e.,

$$W_{RCS} = \Sigma_{i=1}^{N}(W_L)_i \qquad \text{Eq. 4}$$

The individual primary loop volumetric flows are determined by correcting the thermal output of the Steam Generator for Steam Generator blowdown (if not secured), subtracting the RCP heat addition, adding the loop's share of the primary side system losses, dividing by the primary side enthalpy rise and multiplying by the Cold Leg specific volume. The equation for this calculation is:

$$W_L = \frac{(A)\{Q_{SG} - Q_P + (Q_L/N)\}(V_C)}{(h_H - h_C)} \qquad \text{Eq. 5}$$

where;

W_L = Loop Flow (gpm)

A = Constant conversion factor 0.1247 gpm/(ft^3/hr)

Q_{SG} = Steam Generator thermal output (BTU/hr)

Q_P = RCP heat addition (BTU/hr)

Q_L = Primary system net heat losses (BTU/hr)

V_C = Specific volume of the Cold Leg at T_C (ft^3/lb)
N = Number of primary side loops
h_H = Hot Leg enthalpy (BTU/lb)
h_C = Cold Leg enthalpy (BTU/lb).

The thermal output of the Steam Generator is determined by a secondary side calorimetric measurement, which is defined as:

$$Q_{SG} = (h_s - h_f)W_f \qquad \text{Eq. 6}$$

where;

h_s = Steam enthalpy (BTU/lb)
h_f = Feedwater enthalpy (BTU/lb)
W_f = Feedwater flow (LEFM feedwater header flow divided by # loops)(lb/hr).

The steam enthalpy is based on the measurement of steam generator outlet steam pressure assuming saturated conditions. The feedwater enthalpy is based on the measurement of feedwater temperature and nominal feedwater pressure. The feedwater flow is determined by LEFM measurements.

RCP heat addition is determined by calculation, based on the best estimate of coolant flow, pump head, and pump hydraulic efficiency.

The primary system net heat losses are determined by calculation, considering the following:

Charging flow
Letdown flow
Seal injection flow
RCP thermal barrier cooler heat removal
Pressurizer spray flow
Pressurizer surge line flow
Component insulation heat losses
Component support heat losses
CRDM heat losses

A single calculated sum for 100% Rated Thermal Power (RTP) operation is used for these losses or heat inputs.

The Hot Leg and Cold Leg enthalpies are based on the measurement of the Hot Leg temperature, Cold Leg temperature and the nominal Pressurizer pressure. The Cold Leg specific volume is based on measurement of the Cold Leg temperature and nominal Pressurizer pressure.

The RCS flow measurement is thus based on the following plant measurements:

Steamline pressure (P_S)
Feedwater temperature from LEFM (T_f)
Feedwater pressure (P_f)
Feedwater flow from LEFM
Hot Leg temperature (T_H)
Cold Leg temperature (T_C)
Pressurizer pressure (P_p)
Steam Generator blowdown flow (if not secured)

and on the following calculated values:

Feedwater density (ρ_f)
Feedwater enthalpy (h_f)
Steam enthalpy (h_S)
Moisture carryover (impacts h_S)
Primary system net heat losses (Q_L)
RCP heat addition (Q_p)
Hot Leg enthalpy (h_H)
Cold Leg enthalpy (h_C).

The derivation of the measurement and flow uncertainties on Table 3-5 are noted below.

Secondary Side

The secondary side uncertainties are in four principal areas, Feedwater flow, Feedwater enthalpy, Steam enthalpy and net pump heat addition. These areas are specifically identified on Table 3-5.

For the measurement of Feedwater flow, the LEFM is located on the feedwater header and provides a total flow. The accuracy to which the total flow is determined is based on calculations performed by the manufacturer of the LEFM.

Using the NBS/NRC Steam Tables it is possible to determine the sensitivities of various parameters to changes in Feedwater temperature and pressure. Table 3-3 notes the instrument uncertainties for the hardware used to perform the measurements. Table 3-4 lists the various sensitivities. As can be seen on Table 3-5, Feedwater temperature uncertainties have an impact on Feedwater density and Feedwater enthalpy. Feedwater pressure uncertainties impact Feedwater density and Feedwater enthalpy.

Using the NBS/NRC Steam Tables, it is possible to determine the sensitivity of Steam enthalpy to changes in Steam pressure and Steam quality. Table 3-3 notes the uncertainty in Steam pressure and Table 3-4 provides the sensitivity. For Steam quality, the Steam Tables were used to determine the sensitivity at a moisture content of [ ]^{a,c}. This value is noted on Table 3-4.

The net pump heat addition uncertainty is derived from the combination of the primary system net heat losses and pump heat addition and for PBNP is:

Net Heat input to RCS	+6.0 MWt

The uncertainty on system heat losses, which is essentially all due to charging and letdown flows, has been estimated to be [ ]^{a,c} of the calculated value. Since direct measurements are not possible, the uncertainty on component conduction and convection losses has been assumed to be [ ]^{a,c} of the calculated value. Reactor coolant pump hydraulics are known to a relatively high confidence level, supported by system hydraulics tests performed at Prairie Island Unit 2 and by input power measurements from several other plants. Therefore, the uncertainty for the pump heat addition is estimated to be [ ]^{a,c} of the best estimate value. Considering these parameters as one quantity, which is designated the net pump heat addition uncertainty, the combined uncertainties are less than [ ]^{a,c} of the total, which is [ ]^{a,c} of core power.

Primary Side

The primary side uncertainties are in three principal areas, hot leg enthalpy, cold leg enthalpy and cold leg specific volume. These are specifically noted on Table 3-5. Three primary side parameters are actually measured, T_H, T_C and Pressurizer pressure. Hot Leg enthalpy is influenced by T_H, Pressurizer pressure and Hot Leg temperature streaming. The uncertainties for the instrumentation are noted on Table 3-3 and the sensitivities are provided on Table 3-4. The hot leg streaming is split into random and systematic components. For PBNP where the RTDs are located in bypass manifolds, the hot leg temperature streaming uncertainty components are [ ]^{a,c} random and [ ]^{a,c} systematic.

The cold leg enthalpy and specific volume uncertainties are impacted by T_C and Pressurizer pressure. Table 3-3 notes the T_C instrument uncertainty and Table 3-4 provides the sensitivities.

Parameter dependent effects are identified on Table 3-5. Westinghouse has determined the dependent sets in the calculation and the direction of interaction, i.e., whether components in a dependent set are additive or subtractive with respect to a conservative calculation of RCS flow. The same work was performed for the instrument bias values. As a result, the calculation explicitly accounts for dependent effects and biases with credit taken for sign (or direction of impact).

Using Table 3-5, the 2 loop uncertainty equation (with biases) is as follows:

$$\left[\qquad \right]^{a,c}$$

(random)

(bias)

$$\left[\qquad \right]^{a,c}$$

(random)

(bias)

Based on the number of loops; number, type and measurement method of RTDs, and the vessel Delta-T, the flow uncertainty is:

# of loops	flow uncertainty (% flow)	
2	$\left[\quad \right]^{a,c}$	(random) (bias)

Table 3-3
Calorimetric RCS Flow Measurement Uncertainties*

(% Span)

a,c

	FW TEMP	FW PRES	FW FLOW	STM PRESS	TH	TC	PRZ
LEFM =							
SRA =							
SCA =							
SMTE =							
SPE =							
STE =							
SD =							
BIAS =							
R/E =							
RMTE =							
RTE =							
RD =							
RDOUT =							
RCA_{pc} =							
$RMTE_{pc}$ =							
RD_{pc} =							
CSA =							
# OF INSTRUMENTS USED	1/Header	1	1/Header	3/Loop	2/Loop	2/Loop	4
	°F	psi	% Flow	psi	°F	°F	psi
INST SPAN =	(1)	1500(2)	100(3)	1400(4)	150(5)	150(5)	800(6)
INST UNC. (RANDOM) =							
(BIAS) =							
NOMINAL =	458.0 °F	701 psia	100% Flow	601 psia	611.1 °F	542.9 °F	2250 psia

a,c

(1) Feedwater temperature measurement is from an LEFM on the feedwater header.
(2) Pressure (P-2245) is read from the LEFM display panel.
(3) Flow (F-3110) is measured with an LEFM on the feedwater header.
(4) Pressure (P-468, -469, -478, -479, -482, -483) is measured with a digital voltmeter at the input of the process instrumentation.
(5) Temperature is measured with a digital voltmeter at the output of the R/E process instrumentation modules.
(6) Pressure (P-429, -430, -431, -449) is measured with a digital voltmeter at the input of the process instrumentation.
(7) Provided by PBNP.

* Results have been rounded to reflect the appropriate number of significant digits based on the accuracy of the input information.

Table 3-4
Calorimetric RCS Flow Measurement Sensitivities**

a,c

FEEDWATER FLOW

LEFM =

DENSITY
TEMPERATURE =
PRESSURE =
FEEDWATER ENTHALPY
TEMPERATURE =
PRESSURE =

h_s =
h_f =
Dh (SG) =

STEAM ENTHALPY

PRESSURE =
MOISTURE =
HOT LEG ENTHALPY
TEMPERATURE =
PRESSURE =

h_H =
h_C =
Dh (VESS) =

COLD LEG ENTHALPY
TEMPERATURE =
PRESSURE =

COLD LEG SPECIFIC VOLUME

TEMPERATURE =
PRESSURE =

* Provided by PBNP.

** Results have been rounded to reflect the appropriate number of significant digits based on the accuracy of the input information.

Table 3-5
Calorimetric RCS Flow Measurement Uncertainty****

a,c

COMPONENT	INSTRUMENT UNCERTAINTY	FLOW UNCERTAINTY (% flow)
FEEDWATER FLOW		
LEFM		
DENSITY		
TEMPERATURE		
PRESSURE		
FEEDWATER ENTHALPY		
TEMPERATURE		
PRESSURE		
STEAM ENTHALPY		
PRESSURE		
MOISTURE		
NET PUMP HEAT ADDITION		
HOT LEG ENTHALPY		
TEMPERATURE		
STREAMING, RANDOM		
STREAMING, SYSTEMATIC		
PRESSURE		
COLD LEG ENTHALPY		
TEMPERATURE		
PRESSURE		
COLD LEG SPECIFIC VOLUME		
TEMPERATURE		
PRESSURE		

*, **, +, ++ Indicates Sets of Dependent Parameters

*** Provided by PBNP

**** Results have been rounded to reflect the appropriate number of significant digits based on the accuracy of the input information.

Table 3-5 (continued)
Calorimetric RCS Flow Measurement Uncertainty****

COMPONENT	FLOW UNCERTAINTY (% flow)	
BIAS VALUES		a,c
COLD LEG ENTHALPY TEMPERATURE		
COLD LEG SPECIFIC VOLUME TEMPERATURE		
FLOW BIAS TOTAL VALUE		
		a,c
SYSTEM UNCERTAINTY		(random) (bias)

**** Results have been rounded to reflect the appropriate number of significant digits based on the accuracy of the input information.

(1) The bias and random portions of the calculated uncertainties have been separated for proper use by Westinghouse thermal hydraulic analysis.

3.4 Reactor Power Measurement

3.4.1 Power Measurement (Using Feedwater Venturis)

The plant is required to perform a primary/secondary side heat balance at least every 24 hours when power is above 15% Rated Thermal Power. This heat balance is used to verify that the plant is operating within the limits of the Operating License of 1800 MWt - core power when using the LEFM (or 1775 MWt – core power when using the feedwater venturis), and to adjust the Power Range Neutron Flux channels when the difference between the Power Range Neutron Flux channels and the heat balance is greater than allowed by the plant Technical Specifications. PBNP also continuously calculates the reactor thermal output (RTO) to ensure that the power limit is not exceeded.

Assuming that the primary and secondary sides are in equilibrium; the core power is determined by summing the thermal output of the steam generators, correcting the total secondary power for Steam Generator blowdown (if not secured), subtracting the RCP heat addition, adding the primary side system losses, and dividing by the core Btu/hr at rated full power. The equation for this calculation is:

$$RP = \frac{\{\sum_{i=1}^{N}\{Q_{SG} - Q_P + (Q_L/N)\}_i\}(100)}{H} \qquad \text{Eq. 7}$$

where;

RP = Core power (% RTP)
N = Number of primary side loops
Q_{SG} = Steam generator thermal output (BTU / hr) as defined in Eq. 6
Q_P = RCP heat addition (BTU / hr) as defined in Eq. 5
Q_L = Primary system net heat losses (BTU / hr) as defined in Eq. 5
H = Rated core power (BTU / hr).

For the purposes of this uncertainty analysis (and based on H noted above) it is assumed that the plant is at 100% RTP when the measurement is taken. Measurements performed at lower power levels will result in different uncertainty values. However, operation at lower power levels results in increased margin to DNB far in excess of any margin losses due to increased measurement uncertainty.

The feedwater flow in Equation 6 is determined by multiple measurements and the following calculation:

$$W_f = (K)(F_a)\{(\rho_f)(d/p)\}^{1/2} \qquad \text{Eq. 8}$$

where:

W_f = Feedwater loop flow (lb/hr)
K = Feedwater venturi flow coefficient

F_a = Feedwater venturi correction for thermal expansion

ρ_f = Feedwater density (lb/ft^3)

d/p = Feedwater venturi pressure drop (inches H_2O).

The feedwater venturi flow coefficient is the product of a number of constants including as-built dimensions of the venturi and calibration tests performed by the vendor. The thermal expansion correction is based on the coefficient of expansion of the venturi material and the difference between feedwater temperature and calibration temperature. Feedwater density is based on the measurement of feedwater temperature and feedwater pressure. The venturi pressure drop is obtained from the output of the differential pressure transmitter connected to the venturi.

The power measurement is thus based on the following plant measurements:

Steamline pressure (P_s)
Feedwater temperature (T_f)
Feedwater pressure (P_f)
Feedwater venturi differential pressure (d/p)
Steam generator blowdown (if not secured);

and on the following calculated values:

Feedwater venturi flow coefficients (K)
Feedwater venturi thermal expansion correction (F_a)
Feedwater density (ρ_f)
Feedwater enthalpy (h_f)
Steam enthalpy (h_s)
Moisture carryover (impacts h_s)
Primary system net heat losses (Q_L)
RCP heat addition (Q_p)

Secondary Side

The secondary side power calorimetric equations and effects are the same as those noted for the calorimetric RCS flow measurement (secondary side portion), Equation 6.

For the measurement of feedwater flow, each feedwater venturi is calibrated by the vendor in a hydraulics laboratory under controlled conditions to an accuracy of [ ]^{a,c}. The calibration data that substantiates this accuracy is provided to the plant by the vendor. An additional uncertainty factor of [ ]^{a,c} is included for installation effects, resulting in a conservative overall flow coefficient (K) uncertainty of [ ]^{a,c}. Since the calculated steam generator thermal output is proportional to feedwater flow, the flow coefficient uncertainty is expressed as [ ]^{a,c}. It should be noted that no allowance is made for feedwater venturi fouling. The effect of fouling results in an indicated power higher than actual, which is conservative.

The uncertainty applied to the feedwater venturi thermal expansion correction (F_a) is based on the uncertainties of the measured feedwater temperature and the coefficient of thermal expansion for the venturi material, 304 stainless steel. For this material, a change of ± 1.0 °F in the nominal feedwater temperature range changes F_a by [ ]^{a,c} and the steam generator thermal output by the same amount.

Based on data introduced into the ASME Code, the uncertainty in F_a for 304 stainless steel is ± 5 %. This results in an additional uncertainty of [ ]^{a,c} in power.

Using the NBS/NRC Steam Tables it is possible to determine the sensitivities of various parameters to changes in feedwater temperature and pressure. Table 3-6 notes the instrument uncertainties for the hardware used to perform the measurements. Table 3-7 lists the various sensitivities. As can be seen on Table 3-7, feedwater temperature uncertainties have an impact on venturi F_a, feedwater density and feedwater enthalpy. Feedwater pressure uncertainties impact feedwater density and feedwater enthalpy.

Feedwater venturi d/p uncertainties are converted to % feedwater flow using the following conversion factor:

$$\% \text{ flow} = (\text{d/p uncertainty})(1/2)(\text{FLOWmax}/\text{FLOWnominal})^2.$$

The feedwater flow transmitter span (FLOWmax) is 123.6% of nominal flow.

Since it is necessary to make this determination daily, the plant computer is used for the calorimetric power measurement. As noted in Table 3-8, Westinghouse has determined the dependent sets in the calculation and the direction of interaction. This is the same as that performed for the calorimetric RCS flow measurement, but applicable only to power. The same was performed for the bias values.

Using the power uncertainty values noted on Table 3-8, the 2 loop uncertainty (with bias values) equation is as follows:

[ ]^{a,c}

(random)

(bias)

a,c

(random)

(bias)

Based on the number of loops and the instrument uncertainties for the four parameters, the uncertainty for the secondary side power calorimetric measurement using the feedwater flow venturis is:

# of loops	power uncertainty (% power)	
	a,c	
2	[ ]	(random) (bias)

Table 3-6
Calorimetric Power Measurement Uncertainties (venturi)*

(% Span)

a,c

	FW TEMP	FW PRES	FW D/P	STM PRESS
SRA =				
SCA =				
SMTE =				
SPE =				
STE =				
SD =				
BIAS =				
RCA =				
RMTE =				
RTE =				
RD =				
A/D =				
RCA_{ISO} =				
$RMTE_{ISO}$ =				
RTE_{ISO} =				
RD_{ISO} =				
CSA =				

a,c

# OF INSTRUMENTS USED	1/Loop	1/Loop	2/Loop	3/Loop
	°F	psi	% d/p	psi
INST SPAN =	500[1]	1600[2]	123.6% Flow[3]	1400[4]
INST UNC. (RANDOM) =				
(BIAS) =				
NOMINAL =	458.0 °F	701 psia	100 % Flow	601 psia

(a) Included in RCA

(1) Feedwater temperature measurement is from channels T-2104 and -2105

(2) Feedwater pressure measurement is from channels P-2289 and -2290

(3) Feedwater flow measurement is from channels F-466, -467, -476 and -477

(4) Steam pressure measurement is from channels P-468, -469, -478, -479, -482 and -483.

* Results have been rounded to reflect the appropriate number of significant digits based on the accuracy of the input information.

Table 3-7
Calorimetric Power Measurement Sensitivities (venturi)*

a,c

FEEDWATER FLOW

F_a

TEMPERATURE =

MATERIAL =

DENSITY

TEMPERATURE =

PRESSURE =

DELTA P =

FEEDWATER ENTHALPY

TEMPERATURE =

PRESSURE =

h_s =

h_f =

Dh (SG) =

STEAM ENTHALPY

PRESSURE =

MOISTURE =

* Results have been rounded to reflect the appropriate number of significant digits based on the accuracy of the input information.

Table 3-8
Calorimetric Power Measurement Uncertainty (venturi)***

a,c

COMPONENT	INSTRUMENT UNCERTAINTY	POWER UNCERTAINTY (% power)
FEEDWATER FLOW		
VENTURI		
THERMAL EXPANSION COEFFICIENT		
TEMPERATURE		
MATERIAL		
DENSITY		
TEMPERATURE		
PRESSURE		
DELTA P		
FEEDWATER ENTHALPY		
TEMPERATURE		
PRESSURE		
STEAM ENTHALPY		
PRESSURE		
MOISTURE		
NET PUMP HEAT ADDITION		
BIAS VALUES		
FEEDWATER DELTA P		
POWER BIAS TOTAL VALUE		
2 LOOP UNCERTAINTY		

*, * *, INDICATES SETS OF DEPENDENT PARAMETERS

*** Results have been rounded to reflect the appropriate number of significant digits based on the accuracy of the input information.

(1) The bias and random portions of the calculated uncertainties have been separated for proper use by Westinghouse thermal hydraulic analysis.

3.4.2 Power Measurement (Using LEFM on Feedwater Header)

The plant performs a primary/secondary side heat balance at least every 24 hours when power is above 15% Rated Thermal Power. This heat balance is used to verify that the plant is operating within the limits of the Operating License of 1800 MWt - core power when using the LEFM on the feedwater header, and to adjust the Power Range Neutron Flux channels when the difference between the Power Range Neutron Flux channels and the heat balance is greater than allowed by the plant Technical Specifications. PBNP also continuously calculates the reactor thermal output (RTO) to ensure that the power limit is not exceeded.

Assuming that the primary and secondary sides are in equilibrium; the core power is determined by summing the thermal output of the steam generators, correcting the total secondary power for Steam Generator blowdown (if not secured), subtracting the RCP heat addition, adding the primary side system losses, and dividing by the core Btu/hr at rated full power. Equation 7 is used for this calculation.

For the purposes of this uncertainty analysis it is assumed that the plant is at 100% RTP when the measurement is taken. Measurements performed at lower power levels will result in different uncertainty values. However, operation at lower power levels results in increased margin to DNB far in excess of any margin losses due to increased measurement uncertainty.

The thermal output of the Steam Generator is determined by a secondary side calorimetric measurement that is defined by Equation 9 as:

$$Q_{SG} = (h_s - h_f)W_f - (h_s - h_{sgbd})W_{sgbd} \qquad \text{Eq. 9}$$

where;

h_s = Steam enthalpy (BTU/lb)

h_f = Feedwater enthalpy (BTU/lb)

h_{sgbd} = Steam generator blowdown enthalpy (BTU/lb)

W_f = Feedwater flow (LEFM feedwater header flow divided by # loops)(lb/hr)

W_{sgbd} = Steam generator blowdown flow (lb/hr).

The steam enthalpy is based on the measurement of steam generator outlet steam pressure, assuming saturated conditions. The feedwater enthalpy is based on the measurement of feedwater temperature and feedwater pressure. The feedwater flow and feedwater temperature are determined by a LEFM measurement on the main feedwater header, and it is assumed that the loop feedwater flows are equal.

The steam generator blowdown flow is the outlet flow from the steam generators used to control water chemistry, and is determined by measurement from the steam generator loop blowdown flow orifice and the following calculation:

$$W_{sgbd} = (K)(F_a)(a)\ \{(2)(g_c)(p_f)(d/p)\}^{1/2} \qquad \text{Eq.10}$$

where;

K = Steam generator loop blowdown flow orifice coefficient

F_a = Steam generator loop blowdown flow orifice correction for thermal expansion

a = Steam generator loop blowdown flow orifice area

g_c = Gravitational constant (32.174 ft/sec^2)

p_f = Steam generator loop blowdown flow density (lb/ft^3)

d/p = Steam generator loop blowdown flow orifice pressure drop (inches H_2O).

The steam generator blowdown orifice flow coefficient is the product of a number of constants including as-built dimensions of the orifice and pipe internal diameter. The thermal expansion correction is based on the coefficient of expansion of the orifice material and the difference between steam generator blowdown temperature and calibration temperature. Steam generator blowdown density and enthalpy are based on the measurement of steam generator steam pressure. The blowdown liquid enthalpy is assumed to be equal to that of a saturated liquid at the measured steam pressure. The orifice pressure drop is obtained from the output of the differential pressure indicator.

RCP heat addition is determined by calculation, based on the best estimate of coolant flow, pump head, and pump hydraulic efficiency.

The primary system net heat losses are determined by calculation, considering the previously defined system heat inputs and heat losses.

A single calculated sum for 100% RTP operation is used for these losses or heat inputs.

The power measurement is thus based on the following plant measurements:

- Steamline pressure (P_s)
- Feedwater temperature (T_f - from LEFM)
- Feedwater pressure (P_f)
- Feedwater header flow (from LEFM)
- Steam generator loop blowdown flow orifice differential pressure (d/p)(if not secured);

and on the following calculated values:

- Steam generator loop blowdown flow orifice coefficient (K)
- Steam generator loop blowdown flow orifice thermal expansion correction (F_a)
- Steam generator loop blowdown flow orifice area (a)
- Feedwater density (p_f)

Feedwater enthalpy (h_f)
Steam enthalpy (h_s)
Steam generator blowdown enthalpy (h_{sgbd})
Steam generator blowdown density (ρ_f)
Moisture carryover (impacts h_s)
Primary system net heat losses (Q_L)
RCP heat addition (Q_p)

The derivation of the measurement uncertainties and the calorimetric power measurement uncertainties on Table 3-11 are noted below.

Secondary Side

The secondary side power calorimetric equations and effects are the same as those noted for the calorimetric RCS flow measurement (secondary side portion), Equation 6.

For the measurement of feedwater flow and feedwater temperature, an LEFM is installed on the feedwater header, and the accuracies have been provided by PBNP.

Using the NBS/NRC Steam Tables it is possible to determine the sensitivities of various parameters to changes in feedwater temperature and pressure. Table 3-9 notes the instrument uncertainties for the hardware used to perform the measurements. Table 3-10 lists the various sensitivities. As can be seen on Table 3-11, feedwater temperature uncertainties have an effect on feedwater density and feedwater enthalpy. Feedwater pressure uncertainties affect feedwater density and feedwater enthalpy.

Using the NBS/NRC Steam Tables again, it is possible to determine the sensitivity of steam enthalpy to changes in steam pressure and steam quality. Table 3-9 notes the uncertainty in steam pressure and Table 3-10 provides the sensitivity. For steam quality, the NBS/NRC Steam Tables were used to determine the sensitivity for a moisture content of [$]^{a,c}$, and the value associated with the limiting power measurement uncertainty is noted on Table 3-10.

The net pump heat addition uncertainty is derived from the combination of the primary system net heat losses and pump heat addition and was previously summarized as noted for the calorimetric RCS flow measurement (secondary side portion):

Since it is necessary to make this determination daily, the plant computer is used for the calorimetric power measurement. As noted in Table 3-11, Westinghouse has determined the dependent sets in the calculation and the direction of interaction. This is the same as that performed for the calorimetric RCS flow measurement, but applicable only to power. The same was performed for the bias values.

Using the power uncertainty values noted on Table 3-11, the 2 loop uncertainty (with bias values) equation is as follows:

[ ]^{a,c} (random)

[ ]^{a,c} (random)

Based on the number of loops and the instrument uncertainties for the four parameters, the uncertainty for the secondary side power calorimetric measurement is:

# of loops	power uncertainty (% power)	
2	[ ]^{a,c}	(random)

Table 3-9
Calorimetric Power Measurement Uncertainties (LEFM)*

(% Span)

	FW TEMP (HEADER)	FW PRES	FW FLOW (HEADER)	STM PRESS	SG BLOWDOWN FLOW	
LEFM =						a,c
SRA =						
SCA =						
SMTE =						
SPE =						
STE =						
SD =						
BIAS =						
RCA =						
RMTE =						
RTE =						
RD =						
A/D_cal=						
A/D_mte=						
A/D_drft=						
RDOUT=						
RCA_{ISO} =						
$RMTE_{ISO}$=						
RTE_{ISO} =						
RD_{ISO} =						
CSA =						
# OF INSTRUMENTS USED	1/Header	1	1/Header	3/Loop	1/Loop	
UNITS	°F	psi	% flow	psi	% flow	
INST SPAN =	$^{(1)}$	1500$^{(2)}$	$^{(3)}$	1400$^{(4)}$	1.36% rated$^{(5)}$ feedwater flow(rfwf)	
INST UNC. (RANDOM) =						a,c
(BIAS) =						
NOMINAL =	458.0 °F	701 psia	100 % Flow	601 psia	15000 lb/hr/loop	

(a) Included in RCA
(1) Feedwater temperature measurement is from the LEFM on the feedwater header.
(2) Feedwater pressure measurement is from transmitter P-2245 and read by the plant computer.
(3) Feedwater flow measurement is from the LEFM on the feedwater header.
(4) Steam pressure measurement is from channels P-468, -469, -478, -479, -482 and -483.
(5) Steam generator loop blowdown flow is from channels F-5940 and-5941
(range: 0-50000 lb/hr)
(6) Provided by PBNP
* Results have been rounded to reflect the appropriate number of significant digits based on the accuracy of the input information.

Table 3-10
Calorimetric Power Measurement Sensitivities (LEFM)**

a,c

FEEDWATER DENSITY
TEMPERATURE =
PRESSURE =

FEEDWATER ENTHALPY
TEMPERATURE =
PRESSURE =

h_s =
h_f =
Dh (SG) =

STEAM ENTHALPY

PRESSURE =
MOISTURE =

S.G. BLOWDOWN FLOW
F_a
TEMPERATURE =
MATERIAL =

DENSITY
PRESSURE =
DELTA P =

S .G. BLOWDOWN ENTHALPY
PRESSURE =

* Provided by PBNP
** Results have been rounded to reflect the appropriate number of significant digits based on the accuracy of the input information.

Table 3-11
Calorimetric Power Measurement Uncertainty (LEFM) (1)

a,c

COMPONENT	INSTRUMENT UNCERTAINTY	POWER UNCERTAINTY
FEEDWATER FLOW (HEADER)		(% POWER)
LEFM		
FEEDWATER DENSITY		
TEMPERATURE		
PRESSURE		
FEEDWATER ENTHALPY		
TEMPERATURE		
PRESSURE		
STEAM ENTHALPY		
PRESSURE		
MOISTURE		
NET PUMP HEAT ADDITION		
STEAM GENERATOR LOOP BLOWDOWN FLOW		
ORIFICE (FLOW COEFF.)		
THERMAL EXPANSION COEFF.		
TEMPERATURE		
MATERIAL		
DENSITY		
PRESSURE		
DELTA P		
STEAM GENERATOR BLOWDOWN ENTHALPY		
PRESSURE		
BIAS VALUES		
POWER BIAS (TOTAL VALUE)		
2 LOOP UNCERTAINTY		

*, **,*** Indicates sets of dependent parameters

**** Provided by PBNP

(1) Results have been rounded to reflect the appropriate number of significant digits based on the accuracy of the input information.

(2) The bias and random portions of the calculated uncertainties have been separated for proper use by Westinghouse thermal hydraulic analysis.

4.0 RESULTS / CONCLUSIONS

The preceding sections provide the methodology to account for pressure, temperature, power and RCS flow uncertainties for the RTDP analysis. The uncertainty calculations have been performed for PBNP with the plant specific instrumentation and calibration procedures. The following table summarizes the results and the limiting uncertainties that are used in the PBNP safety analysis.

Parameter	Calculated Uncertainty	Uncertainty Used in Safety Analysis
Pressurizer Pressure	a,c	±50.0 psi (random) ± 2.0 psi (bias)
Tavg		± 5.0 °F (random) ± 1.4 °F (bias)
Power (feedwater venturis)		±2.0% power (random) -0.1% power (bias) (at 1775 MWt - core power)
Power (LEFM on header)		±0.6% power (random) (at 1800 MWt - core power)
RCS Flow (calorimetric measurement)		±2.4% flow (random) +0.2% flow (bias)

5.0 REFERENCES

1. Westinghouse WCAP-11397-P-A, "Revised Thermal Design Procedure", dated 04/89.
2. Westinghouse letter NS-CE-1583, C. Eicheldinger to J. F. Stolz, NRC, dated 10/25/77.
3. Westinghouse letter NS-PLC-5111, T. M. Anderson to E. Case, NRC, dated 5/30/78.
4. Westinghouse letter NS-TMA-1837, T. M. Anderson to S. Varga, NRC, dated 6/23/78.
5. Westinghouse letter NS-EPR-2577, E. P. Rahe Jr. to C. H. Berlinger, NRC, dated 3/31/82.
6. Westinghouse Letter NS-TMA-1835, T. M. Anderson to E. Case, NRC, dated 6/22/78.
7. NRC letter, S. A. Varga to J. Dolan, Indiana and Michigan Electric Company, dated 2/12/81.
8. NUREG-0717 Supplement No. 4, Safety Evaluation Report related to the operation of Virgil C. Summer Nuclear Station Unit No. 1, Docket 50-395, 08/82.
9. Regulatory Guide 1.105 Rev. 3, "Setpoints for Safety-Related Instrumentation", dated 12/99.
10. NUREG/CR-3659 (PNL-4973), "A Mathematical Model for Assessing the Uncertainties of Instrumentation Measurements for Power and Flow of PWR Reactors", 02/85.
11. ANSI/ANS Standard 58.4-1979, "Criteria for Technical Specifications for Nuclear Power Stations".
12. ANSI/ISA-67.04.01-2006, "Setpoints for Nuclear Safety-Related Instrumentation".
13. Tuley, C. R., Williams T. P., "The Significance of Verifying the SAMA PMC 20.1-1973 Defined Reference Accuracy for the Westinghouse Setpoint Methodology", Instrumentation, Controls, and Automation in the Power Industry, June 1992, Vol.35, pp. 497-508.
14. ANSI/ISA-51.1-1979 (R1993), "Process Instrumentation Terminology".