ATTACHMENT D-3

Beaver Valley Power Station, Unit No. 1
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Attached is WCAP 15336 Rev. 2 "Revised Thermal Design Procedure Instrument Uncertainty Methodology for FirstEnergy Nuclear Operating Company Beaver Valley Unit 1." (Non-Proprietary Class 3)

Westinghouse Non-Proprietary Class 3

WCAP - 15336
Revision 2

Westinghouse Revised Thermal Design Procedure Instrument Uncertainty Methodology for FirstEnergy Nuclear Operating Company Beaver Valley Unit 1

Westinghouse Electric Company LLC

WESTINGHOUSE NON-PROPRIETARY CLASS 3

WCAP-15336, Rev. 2

WESTINGHOUSE REVISED THERMAL DESIGN PROCEDURE INSTRUMENT UNCERTAINTY METHODOLOGY FOR FIRSTENERGY NUCLEAR OPERATING COMPANY BEAVER VALLEY UNIT 1

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I. INTRODUCTION

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 once every 24 hours. RCS flow is monitored by the performance of a calorimetric flow measurement at the beginning of each cycle. The RCS Cold Leg loop flow indicators are compared with the calorimetric flow measurement. Pressurizer pressure is a controlled parameter and the uncertainty reflects the control system. T_{avg} is a controlled parameter via the temperature input to the rod control system, and the uncertainty reflects this control system.

Westinghouse has been involved with the development of several techniques to treat instrumentation uncertainties. An early version used the methodology outlined in WCAP-8567 "Improved Thermal Design Procedure",[1,2,3] which 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.[4] This approach is used to substantiate the acceptability of the protection system setpoints for many Westinghouse plants, e.g., D. C. Cook 2[5], 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 purpose of this revision is to document the calculation of the instrumentation uncertainties for the daily power calorimetric measurement at the 1.4 % uprated conditions when using the Caldon Leading Edge Flow Meter (LEFM) in the feedwater header.

II. 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 which are statistically independent. Those uncertainties that are dependent are combined arithmetically into independent groups, which are then systematically combined. The uncertainties used are considered to be random, two-sided distributions. This technique has been utilized before as noted previously, and has been endorsed by the NRC staff [6,7,8,9] and various industry standards [10,11].

The relationships between the error components and the channel instrument error allowance are variations of the basic Westinghouse Setpoint Methodology [12] and are based on Beaver Valley Power Station Unit 1 (BVPS 1) specific procedures and processes 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;

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

2. For parameter indication utilizing the plant process computer;

$$CSA = \{(PMA)^2 + (PEA)^2 + (SMTE+SCA)^2 + (SPE)^2 + (STE)^2 + (SRA)^2 + (SMTE+SD)^2 + (RMTE + RCA)^2 + (RTE)^2 + (RMTE + RD)^2 + (COMPMTE + COMPCAL)^2 + (COMPMTE + COMPDRIFT)^2\}^{1/2} + BIAS \qquad \text{Eq. 2}$$

3. For parameters which have control systems, the control board indicators are used as the verification method for proper control system operation.

$$CSA = \{(PMA)^2 + (PEA)^2 + (SMTE + SCA)^2 + (SPE)^2 + (STE)^2 + (SMTE + SD)^2 + (SRA)^2 + (RMTE + RCA)^2 + (RTE)^2 + (RMTE + RD)^2 + (CA)^2 + (RMTE + RCA)^2_{IND} + (RDOUT)^2_{IND} + (RMTE + RD)^2_{IND}\}^{1/2} + BIAS \qquad \text{Eq. 3}$$

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
COMP	=	Plant Computer
IND	=	Indicator.

The parameters above are defined in References 5 and 12 and are based on ISA S51.1-1979 (R93)[13]. 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 (calibration) 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) cell.
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 assuming the loop or channel is string calibrated, or tuned, to this accuracy.

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.

COMP - allowance for the uncertainty associated with the use of the plant computer.

IND - allowance for the uncertainty associated with the use of an indication meter. Control board indicators are typically used.

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 References 5 and 12.

III. INSTRUMENTATION UNCERTAINTIES

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

Pressurizer Pressure Uncertainties

Pressurizer pressure is controlled by a system that compares the measured vapor space pressure to a reference value. This uncertainty calculation accounts for a 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/indicators and the control system. This uncertainty calculation includes control board indicator uncertainties for performance verification of the automatic control system.

On Table 1, the electronics uncertainty for this function is [$]^{+a,c}$ which corresponds to [$]^{+a,c}$. In addition to the control system uncertainty, an allowance is made 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 and an additional bias of [$]^{+a,c}$ is included for temperature compensation of Barton transmitters. The total control system uncertainty, including the bias, is [$]^{+a,c}$ with a standard deviation of [$]^{+a,c}$ presuming a normal, two-sided probability distribution.

TABLE 1
PRESSURIZER PRESSURE CONTROL SYSTEM UNCERTAINTY

[Fischer and Porter 50EP Transmitter (control); Barton 763A Transmitter (indication)]

All Values in % Span

		(Control)	(Indication)
PMA	=		
PEA	=		
SRA	=		
SCA	=		
SMTE	=		
STE	=		
SD	=		
BIAS	=		
RCA	=		
RMTE	=		
RTE	=		
RD	=		
RCA_{IND}	=		
$RMTE_{IND}$	=		
RTE_{IND}	=		
RD_{IND}	=		
$RDOUT_{IND}$	=		
CA	=		

+a,c

SPAN = 800 psi

CSA (% span)	=	
CSA (PSI)	=	
CONTROLLER UNCERTAINTY	=	

+a,c

Tavg Uncertainties

T_{avg} is controlled by a system that compares the median T_{avg} (via Median Signal Selector) from the loops with a reference derived from the First Stage Turbine Impulse Chamber Pressure. Appropriate operation of the control system is verified through indication. T_{avg} is the average of the narrow range T_H and T_C values for a loop. The median loop T_{avg} is then used for rod control. Allowances are made (as noted on Table 2) for hot leg and cold leg streaming, the RTDs, turbine pressure transmitter, process racks/indicators and controller. Based on the assumption that 2 Thot and 1 Tcold cross-calibrated RTDs are used to calculate T_{avg} (assuming one failed Thot RTD per loop) and that the RTDs are located in the hot and cold legs, i.e., the RTD bypass manifolds are removed, the electronics uncertainty is calculated to be [ ]$^{+a,c}$. Assuming a normal, two-sided probability distribution results in an electronics standard deviation (s_1) of

[ ]$^{+a,c}$.

However, this does not include the deadband of [ ]$^{+a,c}$ associated with automatic control. The T_{avg} controller 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:

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

Combining the variance for instrumentation and deadband results in a controller variance of:

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

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

A bias of [ ]$^{+a,c}$ for T_{cold} streaming (in terms of T_{avg}), based on a conservative [ ]$^{+a,c}$ T_{cold} streaming uncertainty is included in Table 2. Therefore, the total uncertainty of the controller with the bias is [ ]$^{+a,c}$ random and [ ]$^{+a,c}$ bias.

TABLE 2

TAVG ROD CONTROL SYSTEM UNCERTAINTY

		T_{avg} *	Turbine Pressure **
PMA_{random}	=		
$PMA_{systematic}$	=		
SRA	=		
SCA	=		
SMTE	=		
STE	=		
SD	=		
BIAS	=		
RCA	=		
RMTE	=		
RTE	=		
RD	=		
RCA_{IND}	=		
$RMTE_{IND}$	=		
$RDOUT_{IND}$	=		
RTE_{IND}	=		
RD_{IND}	=		
CA	=		
TP_SEN	=		

+a,c

Hot Leg RTDs = 2/Channel   # Cold Leg RTDs = 1/Channel

*% of Inst. span = 100 °F (530-630 °F)

**% of Inst. span = 600 psi

+a,c

ELECTRONICS CSA =

ELECTRONICS SIGMA =

CONTROLLER SIGMA =

CONTROLLER CSA =

CONTROLLER BIAS =

+a,c

@[ ]

RCS Flow Measurement Uncertainties

RTDP and BVPS 1 Technical Specifications require an RCS flow measurement with a high degree of accuracy. A total RCS flow measurement is performed every fuel cycle, 18 months, to verify RCS flow and to normalize the RCS flow instrument channels. Periodic surveillance is performed with the process computer/control board indicators to ensure that the RCS flow is maintained above the assumed safety analysis value, i.e., Minimum Measured Flow (MMF). The 18 month RCS flow surveillance is satisfied by performance of a secondary side power-based calorimetric RCS flow measurement. The calorimetric flow measurement is performed at the beginning of a cycle, near full power operation.

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 (Δh) 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.,

$$W_{RCS} = \Sigma(W_L). \qquad \text{Eq. 4}$$

The individual primary loop volumetric flows are determined by correcting the thermal output of the Steam Generator (presuming Steam Generator blowdown is 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 (lb/hr).

The Steam enthalpy is based on the measurement of Steam Generator outlet pressure assuming saturated conditions. The Feedwater enthalpy is based on the measurement of Feedwater temperature and inferred Feedwater pressure. The Feedwater flow is determined by multiple measurements and the following equation:

$$W_f = (K)\,(F_a)\,\{(\rho_f)(d/p)\}^{1/2} \qquad \text{Eq.7}$$

where;

K	=	Feedwater venturi flow coefficient
F_a	=	Feedwater venturi correction for thermal expansion
ρ_f	=	Feedwater density (lb/ft^3)
d/p	=	Feedwater venturi Δp (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 Δp is obtained from the output of the differential pressure cell connected to the venturi.

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 system heat inputs and heat losses:

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 % 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 (T_f)
Feedwater pressure (P_f) (assumed value)
Feedwater venturi differential pressure (d/p)
Hot Leg temperature (T_H)
Cold Leg temperature (T_C)
Pressurizer pressure (P_p)

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 (affects h_s)
Primary system net heat losses (Q_L)

RCP heat addition (Q_p)
Hot Leg enthalpy (h_H)
Cold Leg enthalpy (h_C).

These measurements and calculations are presented schematically in Figure 1. The derivation of the measurement and flow uncertainties on Table 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 5.

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 which 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 RCS flow is proportional to Steam Generator thermal output which is proportional to Feedwater flow, the flow coefficient uncertainty is expressed as [ ]$^{+a,c}$. It should be noted that no allowance is made for venturi fouling. The venturis should be inspected, and cleaned if necessary, prior to performance of the precision measurement. If fouling is present but not removed, its effects must be treated as a flow bias.

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, typically 304 stainless steel. For this material, a change of ± 1 °F in the nominal Feedwater temperature range changes F_a by [ ]$^{+a,c}$ and the Steam Generator thermal output by the same amount.

An allowance in F_a of ± 5 % for the material variance of the composition of 304 stainless steel is used in this analysis. This results in an additional uncertainty of [ ]$^{+a,c}$ in Feedwater flow. Westinghouse uses a conservative value of [ ]$^{+a,c}$ in the uncertainty calculation.

Using the NBS/NRC 1984 Steam Tables, it is possible to determine the sensitivities of various parameters to changes in Feedwater temperature and pressure. Table 3 notes the instrument

uncertainties for the hardware used to perform the measurements. Table 4 lists the various sensitivities. As can be seen on Table 5, Feedwater temperature uncertainties have an effect on venturi F_a , Feedwater density and Feedwater enthalpy. Feedwater pressure uncertainties affect Feedwater density and Feedwater enthalpy.

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

$$\% \text{ flow} = (\text{d/p uncertainty})(1/2)(\text{transmitter span}/100)^2$$

The feedwater flow transmitter span is [ ]$^{+a,c}$ of nominal flow.

Using the NBS/NRC 1984 Steam Tables, it is possible to determine the sensitivity of Steam enthalpy to changes in Steam pressure and Steam quality. Table 3 notes the uncertainty in Steam pressure and Table 4 provides the sensitivity. For Steam quality, the 1984 Steam Tables were used to determine the sensitivity at a moisture content of [ ]$^{+a,c}$. This value is noted on Table 4.

The net pump heat addition uncertainty is derived from the combination of the primary system net heat losses and pump heat addition and are summarized for Beaver Valley as follows:

System heat losses	- 2.0 MWt
Component conduction and convection losses	- 1.4 MWt
Pump heat adder	+ 11.4 MWt
Net Heat input to RCS	+ 8.0 MWt

The uncertainty on system heat losses, which is essentially 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 less than [ ]$^{+a,c}$ 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 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 and the sensitivities are provided on Table 4. The hot leg streaming is split into random and systematic components. For BVPS 1 where the RTDs are located in thermowells placed in the scoops of the eliminated bypass manifold piping, the hot leg temperature streaming uncertainty components are [ ]$^{+a,c}$ random and [ ]$^{+a,c}$ systematic.

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

Parameter dependent effects are identified on Table 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 evaluation was performed for the instrument bias values. As a result, the calculation explicitly accounts for dependent effects and biases accounting for sign (or direction of effect).

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

Flow = [ ] +a,c

Eq. 8

Flow = [ ] +a,c

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)
3	[ ] +a,c

standard deviation (% flow)

[ ] +a,c

TABLE 3
FLOW CALORIMETRIC INSTRUMENTATION UNCERTAINTIES

+a,c

	FW TEMP °F	FW PRES	FW ΔP % ΔP	STM PRESS % SPAN	TH °F	TC °F	PRZ PRESS % SPAN
SRA =							
SCA =							
SMTE =							
SPE =							
STE =							
SD =							
BIAS =							
R/E =							
RCA =							
CompCAL =							
RMTE =							
CompMTE =							
RTE =							
CompTE =							
RD =							
CompDrift =							
RDOUT =							
CSA =							

TABLE 3 (continued)
FLOW CALORIMETRIC INSTRUMENTATION UNCERTAINTIES

	FW TEMP	FW PRES	FW ΔP	STM PRESS	TH	TC	PRZ PRESS
# OF INSTRUMENTS USED	1/Loop	1/Loop	2/Loop	3/Loop	3/Loop	1/Loop	3
INST SPAN =	600(1)	1500(2)	119(3)	1400(4)	120(5)	120(5)	800(6)
	°F	psi	%ΔP	psi	°F	°F	psi
INST UNC. (RANDOM) =	[						] +a,c
INST UNC. (BIAS) =							
NOMINAL =	437.5 °F	911 psia	100 % Flow	811 psia	610.4 °F	542.0 °F	2250 psia

(1) Plant Computer is used for this measurement.
(2) Feedwater Pressure is not measured.
(3) Flow is measured with a DVM at the transmitter output.
(4) Steam Pressure is measured via the plant computer.
(5) Temperature is measured with a digital voltmeter at the output of the cold leg R/E and hot leg Tavg process instrumentation modules.
(6) RCS Pressure is measured via the plant computer.

TABLE 4
FLOW CALORIMETRIC SENSITIVITIES

+a,c

FEEDWATER FLOW		
Fa		
TEMPERATURE	=	
MATERIAL	=	
DENSITY		
TEMPERATURE	=	
PRESSURE	=	
FEEDWATER ENTHALPY		
TEMPERATURE	=	
PRESSURE	=	
h_s	=	
h_f	=	
Δh (SG)	=	
DELTA P	=	
STEAM ENTHALPY		
PRESSURE	=	
MOISTURE	=	
HOT LEG ENTHALPY		
TEMPERATURE	=	
PRESSURE	=	
h_H	=	
h_C	=	
Δh (VESS)	=	
COLD LEG ENTHALPY		
TEMPERATURE	=	
PRESSURE	=	
COLD LEG SPECIFIC VOLUME		
TEMPERATURE	=	
PRESSURE	=	

TABLE 5
CALORIMETRIC RCS FLOW MEASUREMENT UNCERTAINTY

COMPONENT	INSTRUMENT UNCERTAINTY	FLOW UNCERTAINTY
FEEDWATER FLOW		+a,c
VENTURI (FW_v)		
THERMAL EXPANSION COEF.		
TEMPERATURE (Fa_t)		
MATERIAL (Fa_m)		
DENSITY		
TEMPERATURE (ρ_t)		
PRESSURE (ρ_p)		
ΔP ($F_{\Delta p}$)		
FEEDWATER ENTHALPY		
TEMPERATURE (h_t)		
PRESSURE (h_p)		
STEAM ENTHALPY		
PRESSURE (h_{sp})		
MOISTURE ($h_{s\ moist}$)		
NET PUMP HEAT ADDITION (NPHA)		
HOT LEG ENTHALPY		
TEMPERATURE (h_{Ht})		
STREAMING, RANDOM (h_{Hsr})		
STREAMING, SYSTEMATIC (h_{Htss})		
PRESSURE (h_{Hp})		
COLD LEG ENTHALPY		
TEMPERATURE (h_{ct})		
PRESSURE (h_{cp})		
COLD LEG SPECIFIC VOLUME		
TEMPERATURE (ν_{ct})		
PRESSURE (ν_{cp})		

*, **, +, ++ INDICATES SETS OF DEPENDENT PARAMETERS

TABLE 5 (continued)

CALORIMETRIC RCS FLOW MEASUREMENT UNCERTAINTY

COMPONENT	FLOW UNCERTAINTY
BIAS VALUES	[ ] +a,c
STEAM PRESSURE	
ENTHALPY ($h_{cp\ bias}$)	
PRESSURIZER PRESSURE	
ENTHALPY - COLD LEG ($h_{sp\ bias}$)	
SPECIFIC VOLUME - COLD LEG ($\nu_{cp\ bias}$)	
COLD LEG ENTHALPY	
R/E ($h_{ct\ bias}$)	
FLOW BIAS TOTAL VALUE	

3 LOOP UNCERTAINTY (WITHOUT BIAS VALUES)	[ ] +a,c
3 LOOP UNCERTAINTY (WITH BIAS VALUES)	

Loop RCS Flow Indication Uncertainty (Using Control Board Indicators)

As noted earlier, the calorimetric RCS flow measurement is used as the reference for normalizing the loop RCS flow indicators from the cold leg elbow tap transmitters. Since the cold leg elbow tap transmitters feed the control board indicators, it is a simple matter to perform an RCS flow surveillance to look for relative change on a periodic basis. Table 6 notes the instrument uncertainties for determining flow by using the loop RCS flow indicators, assuming three RCS flow indication channels per reactor coolant loop. The d/p transmitter uncertainties are converted to percent flow using the following conversion factor:

$$\% \text{ flow} = (\text{d/p uncertainty})(1/2)(\text{transmitter span} / 100)^2$$

The loop RCS flow indication uncertainty is then combined with the calorimetric RCS flow measurement uncertainty. This combination of uncertainties results in the following total RCS flow indication uncertainty:

# of channels / loop, 3 RCS loops	flow uncertainty (% flow)
3	[ ] +a,c

The corresponding value used in RTDP is:

# of channels / loop, 3 RCS loops	standard deviation (% flow)
3	[ ] +a,c

TABLE 6
COLD LEG LOOP RCS FLOW INDICATION UNCERTAINTY
CONTROL BOARD INDICATOR

INSTRUMENT UNCERTAINTIES

3 RCS Flow Channels Per Reactor Coolant Loop

	% d/p SPAN	% Flow
PMA =		
PEA =		
SRA =		
SCA =		
SMTE =		
SPE =		
STE =		
SD =		
BIAS =		
RCA =		
RMTE =		
RTE =		
METER =		
METER_MTE =		
METER_DRIFT=		
RDOUT =		
FLOW CALORIMETRIC BIAS =		
FLOW CALORIMETRIC =		
INSTRUMENT SPAN =		

+a,c

SINGLE LOOP ELBOW TAP FLOW UNCERTAINTY =	
3 LOOP RCS FLOW UNCERTAINTY (WITHOUT BIAS VALUES) =	
3 LOOP RCS FLOW UNCERTAINTY (WITH BIAS VALUES) =	

+a,c

[ ]+a,c

Reactor Power Measurement Using a Feedwater Venturi Measurement

The daily power measurement assumes the measurement of the feedwater flow using the ΔP transmitters and the flow venturis placed in the feedwater lines. This method of measurement is sensitive to fouling in the venturi throat which results in an indication of higher-than-actual flow which results in a conservative over-estimate of power.

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, 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:

$$RP = \frac{\{(\sum Q_{SG}) + Q_L - Q_P\}(100)}{H} \qquad \text{Eq. 9}$$

where;

RP	= Core power (% RTP)
Q_{SG}	= Steam generator thermal output (BTU / hr) as defined earlier
Q_P	= RCP heat addition (BTU / hr) as defined earlier
Q_L	= Primary system net heat losses (BTU / hr) as defined earlier
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.

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

$$Q_{SG} = (h_s - h_f)W_f - (h_s - h_{bd})W_{bd} \qquad \text{Eq. 10}$$

where;

h_s	=	Steam enthalpy (BTU/lb).
h_f	=	Feedwater enthalpy (BTU/lb).
W_f	=	Feedwater flow (lb/hr).
h_{bd}	=	Steam Generator blowdown enthalpy (BTU/lb).
W_{bd}	=	Steam Generator blowdown flow (lb/hr).

The Steam enthalpy is based on the measurement of Steam Generator outlet pressure assuming saturated conditions. The Feedwater enthalpy is based on the measurement of Feedwater temperature and inferred Feedwater pressure. Blowdown enthalpy is based on the measurement of steam generator outlet pressure assuming saturated conditions.

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

$$W_f = (K)(F_a)\{(\rho_f)(d/p)\}^{1/2} \qquad \text{Eq. 11}$$

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 inferred feedwater pressure. The venturi pressure drop is obtained from the output of the differential pressure transmitter connected to the venturi.

The steam generator blowdown flows are read from local indicators and manually entered into computer address points.

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

Steamline pressure (P_s)
Feedwater temperature (T_f)
Feedwater pressure (P_f), inferred from steamline pressure
Feedwater venturi differential pressure (d/p)
Steam generator blowdown flow (W_{bd});

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 (affects h_s)
Steam Generator blowdown enthalpy (h_{bd})
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). The measurements and calculations are presented schematically on Figure 2.

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 which 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.

An allowance of [ ]$^{+a,c}$ was used for the steam generator blowdown (orifice) flow coefficient. Based on the small ratio of blowdown flow to feedwater flow, this results in an uncertainty of [ ]$^{+a,c}$ power.

The allowance applied to the steam generator blowdown orifice thermal expansion correction (F_a) is based on the uncertainties of the measured steam generator outlet pressure converted to temperature (Tsat) and the coefficient of thermal expansion for the orifice material, stainless steel. For this material, a change of ± 1.0 °F in the nominal temperature range changes F_a by [$]^{+a,c}$ but the change in steam generator thermal output is negligible.

An allowance of ± 5.0 % in F_a for the material variance of the composition of 304 stainless steel is used in this analysis. This results in an additional uncertainty conservatively bounded by [$]^{+a,c}$ power for the venturi. Based on the small ratio of blowdown flow to feedwater flow, this results in no additional uncertainty in power for the orifice.

Using the NBS/NRC 1984 Steam Tables, it is possible to determine the sensitivities of various parameters to changes in feedwater temperature and pressure. Table 7 notes the instrument uncertainties for the hardware used to perform the measurements. Table 8 lists the various sensitivities. As can be seen on Table 8, Feedwater temperature uncertainties have an effect on venturi F_a, Feedwater density and Feedwater enthalpy. Feedwater pressure uncertainties affect Feedwater density and Feedwater enthalpy.

Feedwater venturi d/p uncertainties are converted to % Feedwater flow and S/G blowdown d/p uncertainties are converted to % S/G blowdown flow using the following conversion factor:

$$\% \text{ flow} = (\text{d/p uncertainty})(1/2)(\text{transmitter span} / 100)^2.$$

(Refer to page 13 for the discussion on moisture carryover and net pump heat addition.)

Since it is necessary to make this determination daily, the plant computer is used for the calorimetric power measurement. As noted in Table 9, 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.

Using the power uncertainty values noted on Table 9, the 3 loop uncertainty equation is as follows:

Power = [ ] +a,c

Eq. 12

Power = [ ] +a,c

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

# of loops	power uncertainty (% RTP)
3	[ ] +a,c

TABLE 7
POWER CALORIMETRIC INSTRUMENTATION UNCERTAINTIES

	FW TEMP	FW PRES	FW D/P	STM PRESS	SG BLOWDOWN FLOW
	°F	% SPAN	% SPAN	% SPAN	% FLOW

+a,c

SRA =					
SCA =					
SMTE =					
SPE =					
STE =					
SD =					
BIAS =					
RCA =					
COMPCAL =					
INDCAL =					
RMTE =					
COMPMTE =					
INDMTE =					
RTE =					
COMPTE =					
INDREAD =					
RD =					
COMPDRIFT =					
INDDRIFT =					
CSA =					

# OF INSTRUMENTS USED	1/Loop	1/Loop	2/Loop	3/Loop	1/Loop
INST SPAN =	568	1500	119 % Flow	1400	2.5 % rated Feedwater flow
	°F	psi	% d/p	psi	% flow

+a,c

INST UNC. (RANDOM) =					
INST UNC. (BIAS) =					
NOMINAL =					

All parameters are read by the process computer, except feedwater pressure which is not measured and S/G blowdown flow which is read from the local indicators and manually entered into the computer point address.

* [ ]+a,c

** Provided by FENOC

TABLE 8
POWER CALORIMETRIC SENSITIVITIES

FEEDWATER FLOW			+a,c
F_a			
TEMPERATURE	=		
MATERIAL	=		
DENSITY			
TEMPERATURE	=		
PRESSURE	=		
DELTA P	=		
FEEDWATER ENTHALPY			
TEMPERATURE	=		
PRESSURE	=		
h_s	=		
h_f	=		
Δh (SG)	=		
STEAM ENTHALPY			
PRESSURE	=		
MOISTURE	=		
SG BLOWDOWN FLOW			
F_a			
TEMPERATURE	=		
MATERIAL	=		
DENSITY			
PRESSURE	=		
DELTA P	=		
SG BLOWDOWN ENTHALPY			
PRESSURE	=		

TABLE 9
SECONDARY SIDE POWER CALORIMETRIC MEASUREMENT UNCERTAINTY

+a,c

COMPONENT	INSTRUMENT UNCERTAINTY	POWER UNCERTAINTY
		% POWER
FEEDWATER FLOW		
VENTURI (FW_v)		
THERMAL EXPANSION COEFFICIENT		
TEMPERATURE (Fa_t)		
MATERIAL (Fa_m)		
DENSITY		
TEMPERATURE (ρ_t)		
PRESSURE (ρ_p)		
DELTA P ($F_{\Delta p}$)		
FEEDWATER ENTHALPY		
TEMPERATURE (h_t)		
PRESSURE (h_p)		
STEAM ENTHALPY		
PRESSURE (h_{sp})		
MOISTURE ($h_{s\ moist}$)		
NET PUMP HEAT ADDITION (NPHA)		
SG BLOWDOWN FLOW		
ORIFICE (Or)		
THERMAL EXPANSION COEFFICIENT		
TEMPERATURE (SG_{FAT})		
MATERIAL (SG_{Fam})		
DENSITY		
PRESSURE ($SG\rho_p$)		
DELTA P ($SG_{\Delta p}$)		
SG BLOWDOWN ENTHALPY		
PRESSURE (SG_h)		
SINGLE LOOP UNCERTAINTY		
3 LOOP UNCERTAINTY		

*, * *, * * *, INDICATES SETS OF DEPENDENT PARAMETERS

Reactor Power Measurement Using a Caldon LEFM Measurement

The daily power measurement assumes the measurement of the feedwater flow using the Caldon Leading Edge Flow Meter (LEFM) System placed in the feedwater header. The results of this measurement are used in place of the feedwater venturi measurement in the plant process computer.

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, 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 given on page 23, Equation 9, but is repeated here for convenience:

$$RP = \frac{\{(\sum Q_{SG}) + Q_L - Q_P\}(100)}{H}$$

where;

RP	= Core power (% RTP)
Q_{SG}	= Steam generator thermal output (BTU / hr) as defined earlier
Q_P	= RCP heat addition (BTU / hr) as defined earlier
Q_L	= Primary system net heat losses (BTU / hr) as defined earlier
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.

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

$$Q_{SG} = (h_s - h_f)W_f - (h_s - h_{bd})W_{bd} \qquad \text{Eq. 13}$$

where;

h_s	=	Steam enthalpy (BTU/lb)
h_f	=	Feedwater enthalpy (BTU/lb)
W_f	=	Feedwater flow (lb/hr)

h_{bd} = Steam generator blowdown enthalpy (BTU/lb)
W_{bd} = Steam generator blowdown flow (lb/hr).

The Steam enthalpy is based on the measurement of Steam Generator outlet pressure assuming saturated conditions. The Feedwater enthalpy is based on the measurement of Feedwater temperature and Feedwater pressure. Blowdown enthalpy is based on the measurement of steam generator outlet pressure assuming saturated conditions.

The feedwater flow and feedwater temperature are determined by a single (system) measurement utilizing the LEFM in the feedwater header. The steam generator blowdown flows are read from local indicators and manually entered into computer address points.

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 flow (W_f) (from LEFM)
Steam generator blowdown flow (W_{bd});

and on the following calculated values:

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

Secondary Side

The secondary side uncertainties are in four principle areas; feedwater flow, feedwater enthalpy, steam enthalpy, and net pump heat addition. These areas are specifically identified in Table 12.

For the measurement of feedwater flow, the LEFM has a stated accuracy of [ ]$^{+a,c}$ which FirstEnergy Nuclear Operating Company provided to Westinghouse to use in these calculations.

An allowance of [ ]$^{+a,c}$ was used for the steam generator blowdown (orifice) flow coefficient. Based on the small ratio of blowdown flow to feedwater flow, this results in an uncertainty of [ ]$^{+a,c}$ power.

The allowance applied to the steam generator blowdown orifice thermal expansion correction (F_a) is based on the uncertainties of the measured steam generator outlet pressure converted to temperature (Tsat) and the coefficient of thermal expansion for the orifice material, stainless steel. For this material, a change of ± 1.0 °F in the nominal temperature range changes F_a by [ ]$^{+a,c}$ but the change in steam generator thermal output is negligible.

An allowance of ± 5.0 % in F_a for the material variance of the composition of 304 stainless steel is used in this analysis. Based on the small ratio of blowdown flow to feedwater flow, this results in no additional uncertainty in power.

Using the NBS/NRC 1984 Steam Tables, it is possible to determine the sensitivities of various parameters to changes in feedwater temperature and pressure. Table 10 notes the instrument uncertainties for the hardware used to perform the measurements. Table 11 lists the various sensitivities. Feedwater pressure uncertainties have an affect on Feedwater density and feedwater enthalpy.

Steam generator blowdown d/p uncertainties are converted to % steam generator blowdown flow using the following conversion factor:

$$\% \text{ flow} = (\text{d/p uncertainty})(1/2)(\text{transmitter span} / 100)^2. \qquad \text{Eq. 14}$$

(Refer to page 13 for the discussion on moisture carryover and net pump heat addition.)

Since it is necessary to make this determination daily, the plant computer is used for the calorimetric power measurement. As noted in Table 12, Westinghouse has determined the dependent sets in the calculation and the direction of interaction.

Using the power uncertainty values noted on Table 12, the 3 loop uncertainty equation is as follows:

$$\text{Power} = \left[\qquad \right]^{+a,c} \quad \text{Eq. 15}$$

$$\text{Power} = \left[\qquad \right]^{+a,c}$$

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 (% RTP)
3	$\left[\quad \right]^{+a,c}$

TABLE 10

POWER CALORIMETRIC INSTRUMENTATION UNCERTAINTIES (USING AN LEFM ON FEEDWATER HEADER)

	FW TEMP °F	FW PRES % SPAN	FW ** (header) % FLOW	STM PRESS % SPAN	SG BLOWDOWN FLOW % FLOW
					+a,c,g
LEFM =					
SRA =					
SCA =					
SMTE =					
SPE =					
STE =					
SD =					
BIAS =					
RCA =					
RMTE =					
RTE =					
RD =					
RCA_{comp} =					
$RMTE_{comp}$ =					
RTE_{comp} =					
RD_{comp} =					
RCA_{IND} =					
$RMTE_{IND}$ =					
RTE_{IND} =					
RD_{IND} =					
$READ_{IND}$ =					
CSA =					
NUMBER OF INSTRUMENTS USED	1	1	1	3/Loop	1/Loop
INST SPAN =		1500 psi		1400 psi	2.5 % rated feedwater flow

* Effects are included in the FENOC supplied feedwater mass flow uncertainty.

** Provided by FENOC

TABLE 10 (continued)
POWER CALORIMETRIC INSTRUMENTATION UNCERTAINTIES
(USING AN LEFM ON FEEDWATER HEADER)

	FW TEMP	FW PRES	FW ** (header)	STM PRESS	SG BLOWDOWN FLOW
	°F	psi	% Flow	psi	% Flow
INST UNC. (RANDOM) =	[				]$^{+a,c,g}$
INST UNC. (BIAS) =					]
NOMINAL =	439.3 °F	906 psia	100.0 % Flow	806 psia	20000 lb/hr

* Effects are included in the FENOC supplied feedwater mass flow uncertainty.

** Provided by FENOC

*** [ ]$^{+a,c}$

TABLE 11
POWER CALORIMETRIC SENSITIVITIES

+a,c

FEEDWATER FLOW	=
FEEDWATER DENSITY	
TEMPERATURE	=
PRESSURE	=
FEEDWATER ENTHALPY	
TEMPERATURE	=
PRESSURE	=
h_s	=
h_f	=
Δh (SG)	=
STEAM ENTHALPY	
PRESSURE	=
MOISTURE	=
SG BLOWDOWN ENTHALPY	
PRESSURE	=
SG BLOWDOWN FLOW	
Fa	
TEMPERATURE	=
MATERIAL	=
DENSITY	
PRESSURE	=
DELTA P	=

* Supplied by FENOC

** Incorporated into feedwater flow uncertainty supplied by FENOC

TABLE 12
SECONDARY SIDE POWER CALORIMETRIC MEASUREMENT UNCERTAINTY

COMPONENT	INSTRUMENT UNCERTAINTY	POWER UNCERTAINTY
FEEDWATER FLOW		+a,c
LEFM		
SG BLOWDOWN FLOW		
ORIFICE ($SGBF_V$)		
THERMAL EXPANSION COEFFICIENT		
TEMPERATURE (Fa_t)		
MATERIAL (Fa_m)		
DENSITY		
PRESSURE (ρ_{SG-P})		
DELTA P ($SGBF\Delta_P$)		
SG BLOWDOWN LIQUID ENTHALPY		
PRESSURE (h_{SG-LIQ})		
FEEDWATER DENSITY		
TEMPERATURE (ρ_t)		
PRESSURE (ρ_p)		
FEEDWATER ENTHALPY		
TEMPERATURE (h_t)		
PRESSURE (h_p)		
STEAM ENTHALPY		
PRESSURE (h_{sp})		
MOISTURE ($h_{s\ moist}$)		
NET PUMP HEAT ADDITION (NPHA)		
3 LOOP UNCERTAINTY		

*, ** Indicates sets of dependent parameters

*** Effects included in feedwater flow uncertainty provided by FENOC

IV. 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 BVPS 1 utilizing plant specific instrumentation and calibration procedures. The following or more conservative values are used in the BVPS 1 safety analysis.

+a,c

[ ]

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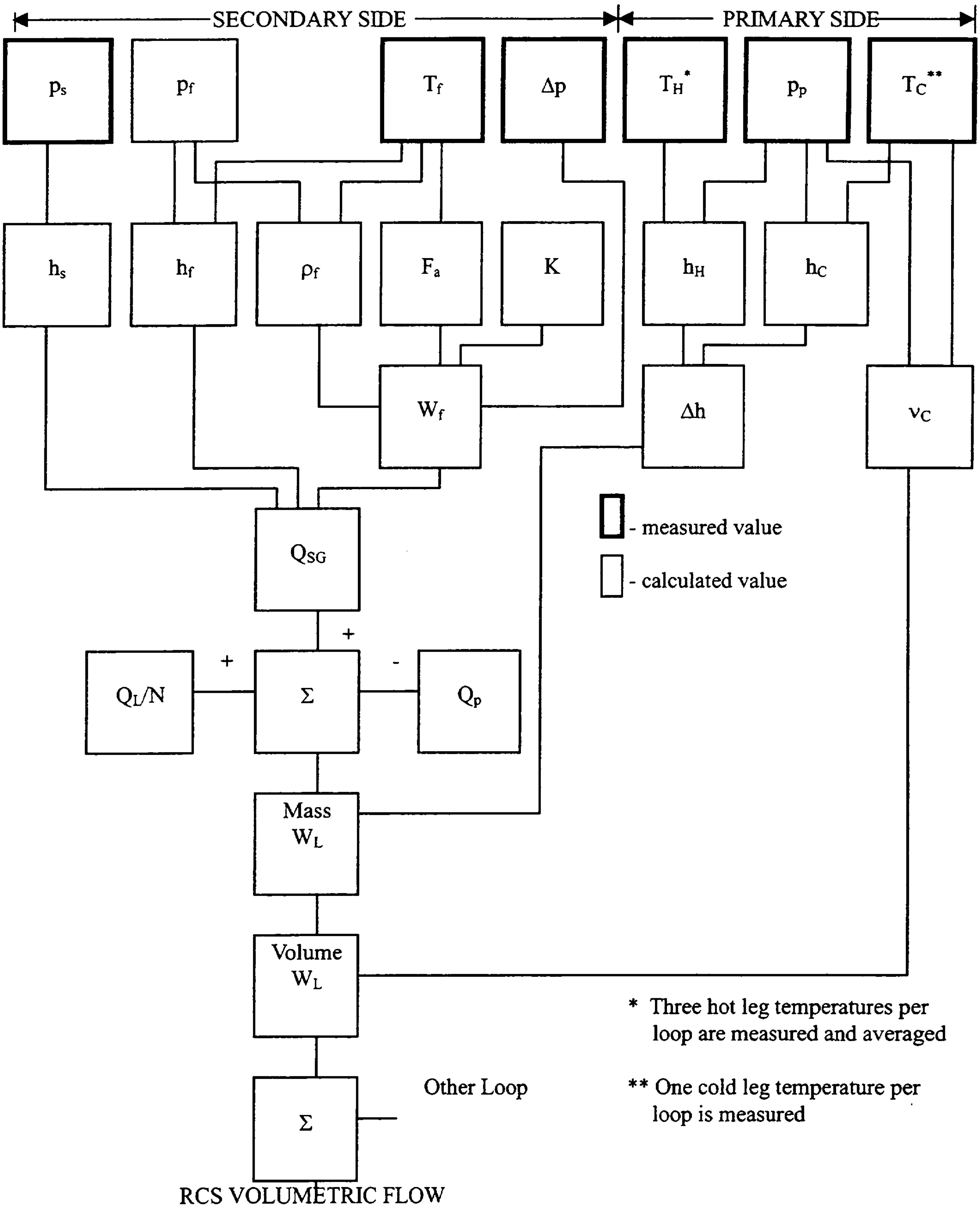

Figure 1 Calorimetric RCS Flow Measurement (Using Feedwater Venturi Secondary Side)

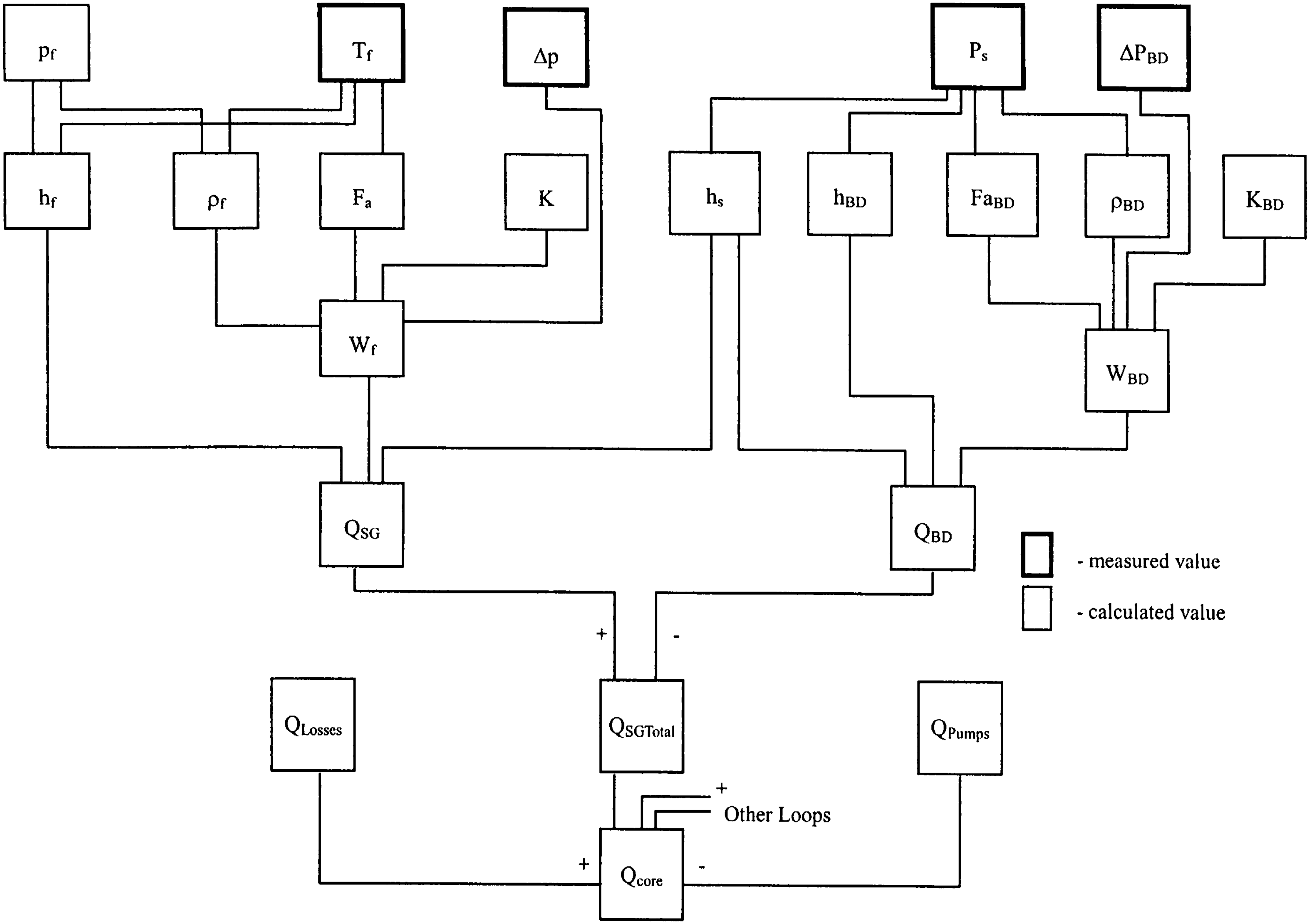

Figure 2 Calorimetric Power Measurement (Using Feedwater Venturi)

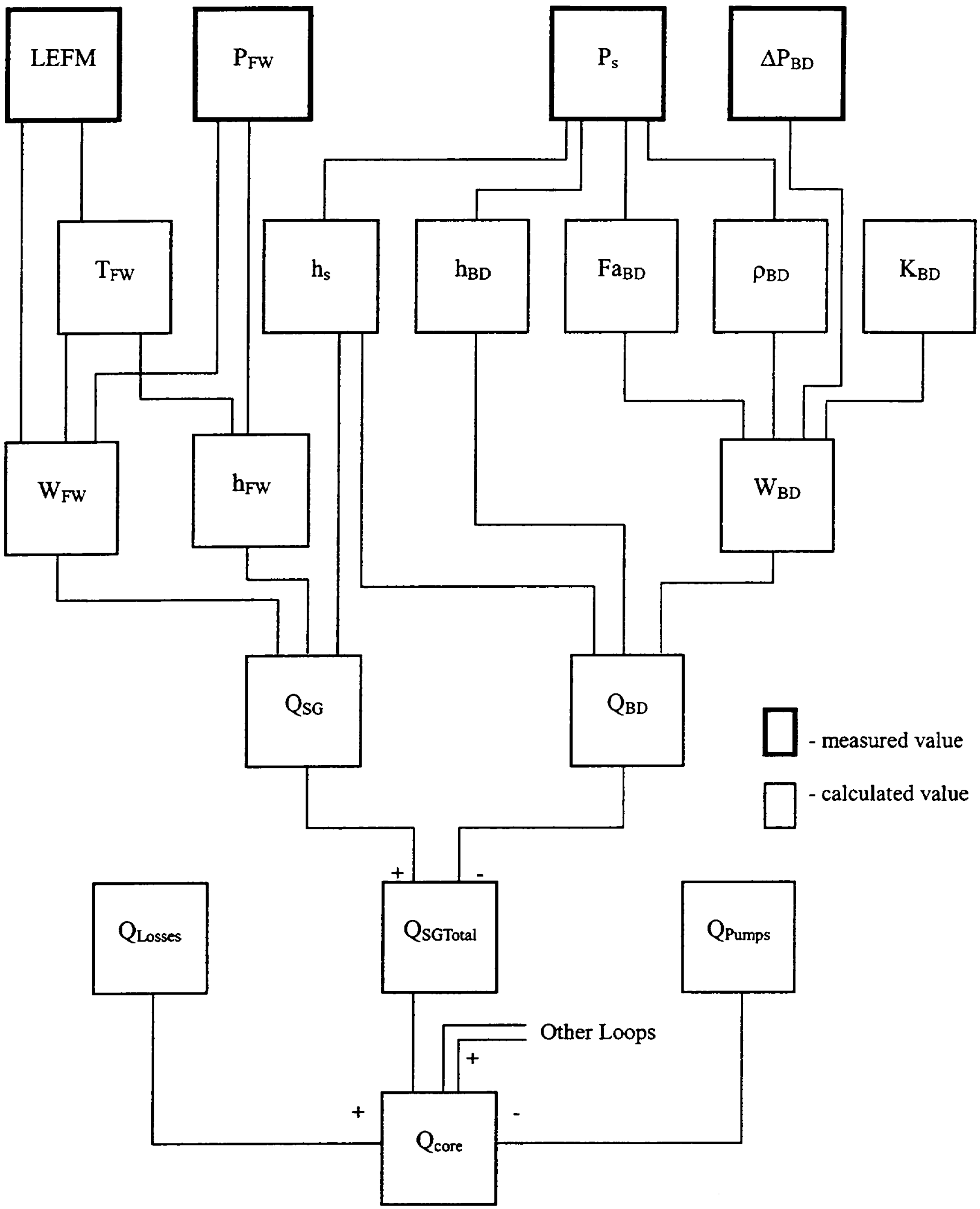

Figure 3 Calorimetric Power Measurement (using LEFM)