Westinghouse Non-Proprietary Class 3

WCAP-15940

September 2002

Power Calorimetric Uncertainty for the 1.4-Percent Uprating of Indian Point Unit 3

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POWER CALORIMETRIC UNCERTAINTY FOR THE 1.4-PERCENT UPRATING OF INDIAN POINT UNIT 3

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M. D. Coury
C. R. Tuley

Westinghouse Electric Company LLC
4350 Northern Pike
Monroeville, Pennsylvania 15146-2886

TABLE OF CONTENTS

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I. INTRODUCTION

The purpose of this analysis is to determine the uncertainty in the daily power calorimetric for the 1.4% uprating. Reactor power is monitored by the performance of a secondary-side heat balance (power calorimetric) at least once every 24 hours. The daily power calorimetric uncertainty must be a value small enough to account for the increase in nominal operating power.

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., Millstone Unit 3, Diablo Canyon, Farley, and others. The second approach is now utilized for the determination of all instrumentation uncertainties for the Revised Thermal Design Procedure (RTDP) parameters and protection functions.

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 that 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 above, and has been endorsed by the NRC staff(5,6,7,8) and various industry standards.(9,10)

The relationships between the error components and the channel instrument error allowance are variations of the basic Westinghouse setpoint approach(11) and are based on Indian Point Unit 3 specific procedures and processes. These relationships are defined as follows.

For parameter indication utilizing the plant process computer:

$$\begin{aligned} CSA = \{&(PMA)^2 + (PEA)^2 + (SMTE + SCA)^2 + (SPE)^2 + (STE)^2 + (SRA)^2 + (PS)^2 + \\ &(SMTE + SD)^2 + (RMTE + RCA)^2 + (RTE)^2 + (RMTE + RD)^2 + (COMPREF)^2 + \\ &(COMPMTE + COMPCAL)^2 + (COMPTE)^2 + (COMPMTE + COMPDRIFT)^2\}^{1/2} + \\ &BIAS \end{aligned} \quad \text{Eq. 1}$$

Where the acronyms are defined as:

CSA = Channel Statistical Allowance
PMA = Process Measurement Accuracy
PEA = Primary Element Accuracy
SMTE = Sensor Measurement and Test Equipment accuracy
SCA = Sensor Calibration Accuracy
SPE = Sensor Pressure Effects
STE = Sensor Temperature Effects
SRA = Sensor Reference Accuracy
PS = Power Supply Effect
SD = Sensor Drift
RMTE = Rack Measurement and Test Equipment accuracy
RCA = Rack Calibration Accuracy
RTE = Rack Temperature Effects
RD = Rack Drift
COMPREF = Plant Computer Reference accuracy

COMPMTE = Plant Computer Measurement and Test Equipment accuracy
COMPCAL = Plant Computer Calibration accuracy
COMPTE = Plant Computer Temperature Effects
COMPDRIFT = Plant Computer Drift

Many of the parameters above are defined in Reference 11 and are based on ANSI/ISA 51.1-1979 (Reaffirmed 1993).(12) However, for ease in understanding, they are paraphrased below:

CSA -	Uncertainty as defined by Equation 1
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
SMTE -	Measurement and test equipment used to calibrate a sensor/transmitter
SCA -	Calibration tolerance for a sensor/transmitter
SPE -	Change in input-output relationship due to a change in static pressure for a differential pressure (Δp) cell
STE -	Change in input-output relationship due to a change in ambient temperature for a sensor or transmitter
SRA -	Reference accuracy for a sensor/transmitter
PS -	Change in input-output relationship due to a change in power supply voltage for a sensor or transmitter
SD -	Change in input-output relationship over a period of time at reference conditions for a sensor or transmitter
RMTE -	Measurement and test equipment used to calibrate rack modules
RCA -	Calibration accuracy for all rack modules in loop or channel assuming the loop or channel is string calibrated, or tuned, to this accuracy
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
COMPREF -	Allowance encompassing the effects of linearity, hysteresis, and repeatability for the plant computer
COMPMTE -	Measurement and test equipment used to calibrate the plant computer
COMPCAL -	Calibration accuracy for the plant computer in the loop or channel, assuming the loop or channel is string calibrated, or tuned, to this accuracy

COMPTE - Change in input-output relationship due to a change in ambient temperature for the plant computer

COMPDRIFT - Change in input-output relationship over a period of time at reference conditions for the plant computer

BIAS - A one-directional uncertainty for a sensor/transmitter or a process parameter with a known magnitude

A more detailed explanation of the Westinghouse approach noting the interaction of several parameters is provided in Reference 11.

III. INSTRUMENTATION UNCERTAINTIES

In this section, the reactor power measurement algorithm will be discussed first, followed by the results of the power calorimetric uncertainty calculations.

Reactor Power Measurement

The daily power measurement is based on the measurement of the feedwater (FW) flow using the Caldon Leading Edge Flow Meter (LEFM) system.

Assuming that the primary and secondary sides are in equilibrium, the core power is determined by:

- Summing the thermal output of the steam generators (SGs)
- Subtracting the reactor coolant pump (RCP) heat addition
- Adding the primary-side system losses
- Dividing by the core Btu/hr at rated full power

The equation for this calculation is:

$$RP = \frac{\{(\Sigma Q_{SG}) + Q_L - Q_P\}(100)}{H} \qquad \text{Eq. 2}$$

Where:

RP = Core power (% rated thermal power -- RTP)

Q_{SG} = Steam generator thermal output (Btu/hr)

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

Q_P = RCP heat addition (Btu/hr)

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:

$$Q_{SG} = [(h_s - h_f)W_f] - [(h_s - h_{bd})W_{bd}] \qquad \text{Eq. 3}$$

Where:

Q_{SG}	=	Steam generator thermal output (Btu/hr)
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 steam pressure, assuming saturated liquid conditions. The feedwater enthalpy is based on the measurement of feedwater temperature and feedwater pressure. Steam generator blowdown enthalpy is based on the measurement of steam generator outlet steam pressure, assuming saturated conditions. The measurement of steam generator blowdown flow is made with an orifice plate and Δp transmitter.

The feedwater flow is determined by a single LEFM device in each of four feedwater lines and the following calculation:

$$W_f = (C_o)(A_p)(\rho_{fw})(L/\Delta t) \qquad \text{Eq. 4}^*$$

Where:

W_f	=	Feedwater loop flow (lb/hr)
C_o	=	Caldon flow profile correction factor
A_p	=	Cross-sectional area of pipe flow path
ρ_{fw}	=	Feedwater density (lb/ft^3)
L	=	Length of pipe between transducer points
Δt	=	Time required for signature to travel length of L
*		Provided by Caldon

Additional details associated with the Caldon system include:

- The feedwater flow profile correction factor is the product of several constants including as-built dimensions of the Caldon system and calibration tests performed by the vendor.
- Feedwater density is based on the measurement of feedwater temperature and feedwater pressure.
- The pipe length between transducer points is a fixed value once the Caldon system is installed.

- Time required for the signature to travel between transducers is obtained from the Caldon system electronics.

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

- Steamline pressure (P_s)
- Feedwater temperature (T_f)
- Feedwater pressure (P_f) (at LEFM spool piece)
- Steam generator blowdown flow (W_{bd})
- Feedwater flow (W_f) (from Caldon system)
- Moisture carryover (affects h_s)

The power measurement is also based on the following calculated values:

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

Power Calorimetric Uncertainties

The secondary-side uncertainties are in four principal areas: feedwater flow, feedwater enthalpy, steam enthalpy, and steam generator blowdown flow. These areas are identified in Tables 1 through 3.

For the measurement of feedwater flow, the Caldon LEFM has a stated accuracy of [$]^{+a,c}$, which the utility provided to Westinghouse to use in the calculations. Since the calculated steam generator thermal output is proportional to feedwater flow, the flow coefficient uncertainty is expressed as [$]^{+a,c}$.

An allowance of [$]^{+a,c}$ was used for the steam generator blowdown orifice plate flow coefficient. This resulted in an uncertainty of [$]^{+a,c}$.

The uncertainty applied to the steam generator blowdown orifice plate thermal expansion correction (F_a) is based on the uncertainties of the temperature and the coefficient of thermal expansion for the orifice plate material, type 304 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 uncertainty of 5.0% in F_a for type 304 stainless steel is used in this analysis. This results in an additional uncertainty bounded by [ ]$^{+a,c}$. This allowance is included to account for the variations in material composition that could exist for the orifice plate.

Using the NBS/NRC steam tables, it is possible to determine the sensitivities of various parameters to changes in feedwater temperature and pressure. Table 1 notes the instrument uncertainties for the hardware used to perform the parameter measurements. Table 2 lists the various parameter sensitivities. Both feedwater temperature and feedwater pressure uncertainties have an effect on feedwater density and feedwater enthalpy.

Steam generator blowdown orifice plate Δp uncertainties are converted to % steam generator blowdown flow using the following conversion factor:

$$\% \text{ flow} = (\Delta p \text{ uncertainty})(1/2)(\text{transmitter span} / 100)^2 \qquad \text{Eq. 5}$$

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 1 notes the uncertainty in steam pressure and Table 2 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 in Table 2.

With respect to primary-side uncertainties, 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 a 4-loop plant as follows:

System heat losses	- 2.0 MWt
Component conduction and convection losses	- 1.4 MWt
Pump heat adder	+ 17.4 MWt
Net heat input to reactor coolant system	+ 14.0 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 less than [ ]$^{+a,c}$ of core power.

The calorimetric power measurement determination is performed using a computerized formulation or a manual calculation. As noted in Table 3, Westinghouse has determined the dependent sets in the calculation and the direction of interaction.

Using the power uncertainty values noted in Table 3, the 4-loop uncertainty equation is:

$$\varepsilon = \left[\qquad \qquad \qquad \qquad \right]^{+a,c} \quad \text{Eq. 6}$$

Where:

ε = Power calorimetric uncertainty

$SGBF_V$ = Steam generator blowdown flow orifice (basic accuracy)

$SGBF_{\Delta p}$ = Steam generator blowdown flow Δp

h_{SP} = Steam enthalpy (as a function of pressure)

Fa_t = Steam generator blowdown flow F_a (as a function of temperature, inferred from steam pressure)

h_{SG_LIQ} = Steam generator blowdown flow enthalpy (as a function of steam pressure)

ρ_{SG_P} = Steam generator blowdown flow density (as a function of steam pressure)

Fa_m = Steam generator blowdown flow F_a (as a function of material)

ρ_P = Feedwater flow density (as a function of pressure)

h_P = Feedwater flow enthalpy (as a function of pressure)

N = Number of primary-side loops

LEFM = Feedwater flow (mass flow accuracy of Caldon system)

NPHA = Net pump heat addition

$h_{s\ moist}$ = Steam enthalpy (as a function of moisture)

$$\varepsilon = \Big[\qquad \Big]^{+a,c} \qquad \text{Eq. 7}$$

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

Number of loops	Power Uncertainty (% RTP)
4	[ ] $^{+a,c}$

TABLE 1
POWER CALORIMETRIC INSTRUMENTATION UNCERTAINTIES

+a,c

	FW Temp. °F	FW Press. % Span ***	FW Header % Mass Flow	SG Blowdown % Δp Span	Steam Press. % Span
LEFM					
SRA					
SCA					
SMTE					
SPE					
STE					
SD					
PS					
BIAS					
COMPREF					
RCA					
COMPCAL					
RMTE					
COMPMTE					
RTE					
COMPTE					
RD					
COMPDRFT					
SQRTEXTR					
CSA					
# Instruments Used					
Units	°F	psig	Mass Flow	% Δp	psig
Instrument Span	480	1500		100,000 lbm/hr	1400
Instrument Uncertainty (Random)					
Nominal	427.8°F	862 psia		69,600 lbm/hr	762 psia

+a,c

* Provided by the utility

** Provided by Caldon

*** Rosemount transmitter

TABLE 2
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
    Δp

* * Effects included in feedwater flow uncertainty provided by the utility

TABLE 3
SECONDARY-SIDE POWER CALORIMETRIC MEASUREMENT UNCERTAINTY

+a,c

Component	Instrument Uncertainty	Power Uncertainty (% power)
Feedwater Flow		
SG Blowdown Flow		
Orifice ($SGBF_V$)		
Thermal Expansion Coefficient		
Temperature (Fa_t)		
Material (Fa_m)		
Density		
Pressure (ρ_{SG_P})		
Δp ($SGBF_{\Delta p}$)		
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)		
4-Loop Uncertainty		

* *, * * * Indicates sets of dependent parameters

* * * * Effects included in feedwater flow uncertainty provided by the utility

IV. RESULTS/CONCLUSIONS

The preceding sections provide the methodology to account for the power calorimetric uncertainties for the 1.4% uprating. The uncertainty calculations have been performed for Indian Point Unit 3 utilizing plant-specific instrumentation and calibration procedures. A power calorimetric uncertainty value of [ ]$^{+a,c}$ will be used in the Indian Point Unit 3 safety analysis.

REFERENCES

1. Westinghouse letter NS-CE-1583, C. Eicheldinger to J. F. Stolz, NRC, dated 10/25/77.
2. Westinghouse letter NS-PLC-5111, T. M. Anderson to E. Case, NRC, dated 5/30/78.
3. Westinghouse letter NS-TMA-1837, T. M. Anderson to S. Varga, NRC, dated 6/23/78.
4. Westinghouse letter NS-EPR-2577, E. P. Rahe Jr. to C. H. Berlinger, NRC, dated 3/31/82.
5. NRC letter, S. A. Varga to J. Dolan, Indiana and Michigan Electric Company, dated 2/12/81.
6. NUREG-0717 Supplement No. 4, Safety Evaluation Report Related to the Operation of Virgil C. Summer Nuclear Station Unit No. 1, Docket 50-395, August, 1982.
7. Regulatory Guide 1.105 Rev. 3, "Instrument Setpoints for Safety-Related Systems," dated 12/99.
8. NUREG/CR-3659 (PNL-4973), "A Mathematical Model for Assessing the Uncertainties of Instrumentation Measurements for Power and Flow of PWR Reactors," 2/85.
9. ANSI/ANS Standard 58.4-1979, "Criteria for Technical Specifications for Nuclear Power Stations."
10. ANSI/ISA-67.04.01-2000, "Setpoints for Nuclear Safety-Related Instrumentation."
11. 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.
12. ANSI/ISA-51.1-1979 (Reaffirmed 1993), “Process Instrumentation Terminology.”