WESTINGHOUSE CLASS 3

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RCS FLOW UNCERTAINTY
FOR
SHEARON HARRIS UNIT 1

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C. R. Tuley
W. H. Moomau

Westinghouse Electric Corporation
Energy Systems
P.O. Box 355
Pittsburgh, Pennsylvania 15230

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WESTINGHOUSE RCS FLOW CALORIMETRIC MEASUREMENT UNCERTAINTY METHODOLOGY

I. INTRODUCTION

RCS flow is a monitored parameter via the performance of a precision flow calorimetric at the beginning of each cycle and the normalization of the RCS Cold Leg elbow taps against the calorimetric (used for monthly surveillance with a small increase in uncertainty).

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",(1,2,3) which is based on the conservative assumption that the uncertainties can be described with uniform probability distributions. Another approach (for McGuire and Catawba) 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 errors for both Improved Thermal Design Procedure (ITDP) parameters, of which RCS Flow is one, 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 of those groups of components which are statistically independent. Those errors 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. 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[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 defined as follows:

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

$$CSA = \{(SCA + SMTE + SD)^2 + (SPE)^2 + (STE)^2 + (RDOUT)^2\}^{1/2}$$

Eq. 1

2. For parameter indication utilizing the plant process computer;

$$CSA = \{(SCA + SMTE + SD)^2 + (SPE)^2 + (STE)^2 + (RCA + RMTE + RD)^2 + (RTE)^2 + (ID)^2 + (A/D)^2\}^{1/2}$$

Eq. 2

where:

CSA	=	Channel Allowance
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 (DVM or gauge)

ID = Computer Isolator Drift

A/D = Analog to Digital Conversion Accuracy

The parameters above are as defined in references 5 and 12 and are based on SAMA Standard PMC 20.1, 1973[13]. However, for ease in understanding they are paraphrased below:

SCA - reference (calibration) accuracy for a sensor/transmitter,

SMTE- measurement and test equipment accuracy for calibration of sensor/transmitter, assumed to be less than 10 % of the calibration accuracy (and therefore neglected) unless otherwise stated.

SPE - change in input-output relationship due to a change in static pressure for a d/p cell,

STE - change in input-output relationship due to a change in ambient temperature for a sensor/transmitter,

SD - change in input-output relationship over a period of time at reference conditions for a sensor/transmitter,

RCA - reference (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 accuracy for calibration of the racks modules, assumed to be less than 10 % of the calibration accuracy (and therefore neglected) unless otherwise stated.

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 it's most accurate applicable range for the parameter measured,

ID - change in input-output relationship over a period of time at reference conditions for a control/protection signal isolating device,

A/D - allowance for conversion accuracy of an analog signal to a digital signal for process computer use, A more detailed explanation of the Westinghouse methodology noting the interaction of several parameters is provided in references 5 and 12.

III. INSTRUMENT UNCERTAINTIES

Technical Specifications, and ITDP, requires an RCS Flow measurement with a high degree of accuracy. It is assumed for this error analysis, that this flow measurement is performed within the calibration (or guaranteed accuracy) period for the measurement instrumentation, usually thirty to ninety days. Therefore, except where necessary due to sensor location, drift effects are not included. It is also assumed that the calorimetric flow measurement is performed at the beginning of a cycle, i.e., no allowances have been made for Feedwater venturi fouling, and above 70% RTP.

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.,

$$W_{RCS} = N(W_L). \qquad \text{Eq. 3}$$

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:

$$W_L = \frac{(A)(Q_{SG} - Q_P + (Q_L/N))(V_C)}{(h_H - h_C)} \qquad \text{Eq. 4}$$

where;

W_L = Loop flow (gpm)

A = 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 precision secondary side calorimetric measurement, which is defined as:

$$Q_{SG} = (h_s - h_f)W_f \qquad \text{Eq. 5}$$

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 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 is determined by multiple measurements and the following calculation:

$$W_f = (K)(F_a)\{(p_f)(d/p)\}^{1/2} \qquad \text{Eq. 6}$$

where;

K	=	Feedwater venturi flow coefficient
F_a	=	Feedwater venturi correction for thermal expansion
p_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 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 Pressurizer pressure. The Cold Leg specific volume is based on measurement of the Cold Leg temperature and 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)
Feedwater venturi differential pressure (d/p)
Hot Leg temperature (T_H)
Cold Leg temperature (T_C)
Pressurizer pressure (P_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)
- Hot Leg enthalpy (h_H)
- Cold Leg enthalpy (h_C).

These measurements and calculations are presented schematically on Figure 1.

Starting off with the Equation 6 parameters, the derivation of the measurement errors is noted below.

Secondary Side

The secondary side uncertainties are in four principal areas, Feedwater flow, Feedwater enthalpy, Steam enthalpy and RCP heat addition. These four areas are specifically identified on Table 3. It should be noted that Table 3 provides flow uncertainties that are specifically calculated, or are bounding values, for the hardware at the plant. This document is thus specific for the Shearon Harris plant, as opposed to generic (based on generic calculations). The plant must insure that the parameters are measured as accuractly as specified in Table 1 for this analysis to be valid.

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,b,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 loop 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, it's 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, usually 304 stainless steel. For this material, a change of ± 1 °F in the nominal Feedwater temperature range changes F_a by ± 0.002 % 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 Feedwater flow. Westinghouse uses the conservative value of [ ]$^{+a,c}$.

Using the 1967 ASME 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 measurements. Table 2 lists the various sensitivities. As can be seen on Table 2, 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:

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

Typically, the Feedwater flow transmitter span is [ ]^{a,c} nominal flow.

Using the 1967 ASME Steam Tables again, 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 on Table 2.

The net pump heat uncertainty is derived from the combination of the primary system net heat losses and pump heat addition and are summarized for a four loop plant as follows:

System heat losses	-2.0 MWt
Component conduction and convection losses	-1.4
Pump heat adder	+18.0
Net Heat input to RCS	+14.6 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 II and by input power measurements from several 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 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. 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 1, the sensitivities are provided on Table 2.

Based on Westinghouse evaluation of Hot Leg circumferential temperature data from several plants, the Hot Leg streaming uncertainty is split into random (loop independent) and systematic (loop dependent) components. For plants with direct immersion RTDs located in RTD bypass manifolds fed by scoops in the legs, the streaming uncertainty is [ ]$^{+a,c}$ for both random and systematic components. For plants with RTDs located in thermowells placed in the scoops (bypass manifolds eliminated), the streaming uncertainty is, [ ]$^{+a,c}$ random and [ ]$^{+a,c}$ systematic.

The Cold Leg enthalpy and specific volume uncertainties are impacted by T_C and Pressurizer pressure. Table 1 notes the T_C instrument uncertainty and Table 2 provides the sensitivities.

Noted on Table 3 is the plant specific RTD cross-calibration systematic allowance. When necessary, an allowance is made for a systematic temperature error due to the RTD cross-calibration procedure. No allowance was determined to be necessary for this plant.

Parameter dependent effects are identified on Table 3. 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, the N loop uncertainty equation (with biases) is as follows:

[ ]+a,c

Depending on the number of loops, number, type and measurement method of RTDs, and the vessel Delta-T, the flow uncertainty can vary by a significant amount. The equation noted above and Tables 1, 2 and 3 are for Shearon Harris only and result in an uncertainty of [ ]+a,c. Using an expected set of measurement uncertainties, a three loop plant would be expected to have a precision flow calorimetric measurement uncertainty of [ ]+a,c. Thus Shearon Harris has a more accurate measurement than a generic Westinghouse calculation.

As noted earlier, the precision flow calorimetric is used as the reference for the normalization of the Cold Leg elbow taps. Assuming that the elbow tap d/p transmitters are used to feed the plant process computer, it is a simple matter to perform Technical Specification required surveillance. Table 4 notes the instrument uncertainties for normalization of the elbow taps, assuming one elbow tap per loop. Included as one of the uncertainties is the impact of [ ]+a,c. The d/p transmitter uncertainties are converted to % flow on the same basis as the Feedwater venturi d/p. The elbow tap uncertainty is then combined with the precision flow calorimetric uncertainty. This combination of uncertainties results in a total flow uncertainty of ± 2.0 % flow. The typical total uncertainty expected for a three loop plant is [ ]+a,c, thus the Shearon Harris total uncertainty is better than the typical value.

TABLE 1

FLOW CALORIMETRIC INSTRUMENTATION UNCERTAINTIES

(% SPAN)	FW TEMP	FW PRES	FW d/p	STM PRESS	T_H	T_C	PRZ PRESS	
SCA =								+a,c
M&TE=								
SPE =								
STE =								
SD =								
R/E =								
RDOT=								
BIAS=								
CSA =								
# OF INST USED					1	1	3 **	
	°F	psia	% d/p	psia	°F	°F	psia	
INST SPAN =	568.	1200.	120.	2000.	100.	100.	800.	
INST UNC. (RANDOM) =								+a,c
INST UNC. (BIAS) =								
NOMINAL =	435.	1064.		964.	620.2	557.4	2250.	

* [

]+a,c

** Number of Hot Leg and Cold Leg RTDs used for measurement in each loop and the number of Pressurizer Pressure transmitters used overall, i.e., one per loop.

TABLE 2
FLOW CALORIMETRIC SENSITIVITIES

FEEDWATER FLOW			
F_a			
TEMPERATURE	=		+a,c
MATERIAL	=		
DENSITY			
TEMPERATURE	=		
PRESSURE	=		
DELTA P	=		
FEEDWATER ENTHALPY			
TEMPERATURE	=		
PRESSURE	=		
h_s	=	1194.2 BTU/LBM	
h_f	=	414.0 BTU/LBM	
Dh(SG)	=	780.2 BTU/LBM	
STEAM ENTHALPY			
PRESSURE	=		+a,c
MOISTURE	=		
HOT LEG ENTHALPY			
TEMPERATURE	=		
PRESSURE	=		
h_H	=	643.3 BTU/LBM	
h_C	=	556.4 BTU/LBM	
Dh(VESS)	=	86.9 BTU/LBM	
$Cp(T_H)$	=	1.565 BTU/LBM-^{o}F	
COLD LEG ENTHALPY			
TEMPERATURE	=		+a,c
PRESSURE	=		
$Cp(T_C)$	=	1.262 BTU/LBM-^{o}F	
COLD LEG SPECIFIC VOLUME			
TEMPERATURE	=		+a,c
PRESSURE	=		

TABLE 3

CALORIMETRIC RCS FLOW MEASUREMENT UNCERTAINTIES

COMPONENT	INSTRUMENT ERROR	FLOW UNCERTAINTY
FEEDWATER FLOW		+a,c
VENTURI		
THERMAL EXPANSION COEFFICIENT		
TEMPERATURE		
MATERIAL		
DENSITY		
TEMPERATURE		
PRESSURE		
DELTA P		
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		
RTD CROSS-CAL SYSTEMATIC ALLOWANCE		

*, **, +, ++ INDICATE SETS OF DEPENDENT PARAMETERS

TABLE 3 CONTINUED

CALORIMETRIC RCS FLOW MEASUREMENT UNCERTAINTIES

COMPONENT		FLOW UNCERTAINTY
BIAS VALUES		+a,c
FEEDWATER PRESSURE	DENSITY	
	ENTHALPY	
STEAM PRESSURE	ENTHALPY	
PRESSURIZER PRESSURE	ENTHALPY - HOT LEG	
	ENTHALPY - COLD LEG	
	SPECIFIC VOLUME - COLD LEG	
FLOW BIAS TOTAL VALUE		

		+a,c
SINGLE LOOP UNCERTAINTY	(WITHOUT BIAS VALUES)	
N LOOP UNCERTAINTY	(WITHOUT BIAS VALUES)	
N LOOP UNCERTAINTY	(WITH BIAS VALUES)	

TABLE 4
COLD LEG ELBOW TAP FLOW UNCERTAINTY

INSTRUMENT UNCERTAINTIES

	% d/p SPAN	% FLOW	
PMA =			+a,c
PEA =			
SCA =			
SPE =			
STE =			
SD =			
RCA =			
M&TE=			
RTE =			
RD =			
ID =			
A/D =			
RDOT=			
BIAS=			
FLOW CALORIM. BIAS =			
FLOW CALORIMETRIC =			
INSTRUMENT SPAN =			

SINGLE LOOP ELBOW TAP FLOW UNC =		+a,c
N LOOP ELBOW TAP FLOW UNC =		
N LOOP RCS FLOW UNCERTAINTY (WITHOUT BIAS VALUES) =		
N LOOP RCS FLOW UNCERTAINTY (WITH BIAS VALUES) =	2.0	

IV. CONCLUSIONS

The preceding sections provide the methodology for what Westinghouse believes is a reasonable means of accounting for instrument uncertainties for the measurement of RCS Flow. As noted in this document, the calculations presented are specific for the Shearon Harris plant. Also noted are the expected results for a typical three loop plant. The results indicate that the Shearon Harris plant measurement uncertainty for RCS Flow is better than the typical expected value. This is due to the lower instrument uncertainties for the hardware used by the plant staff.

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FIGURE 1

RCS FLOW CALORIMETRIC SCHEMATIC