Journal of the Korean Nuclear Society
Volume 30, Number 6, pp.592~608, December 1998

<Technical Note>

Several Problems in Reactor Coolant System Flow Rate Measurement

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(Received July 28, 1998)

Abstract

Inspection of RCS flow measurements for the domestic pressurized water reactors has been performed by the Korea Institute of Nuclear Safety (KINS) as one of the authorized periodical inspection activities. The inspection results for the Westinghouse-type plants reveal that 1) the RCS flow instrumentation has been calibrated by using the initial design and commissioning test result, without reflecting the cycle specific reference flow measurements, 2) the loop-to-loop flow variation in the actual flow measurement which has not been considered in the safety analysis affects the asymmetric flow transient results, and 3) the measured RCS flows in Kori 3 and 4, Yonggwang 1 and 2 do not support the definition of the best estimate RCS flow, approaching the RCS flow limit. In this study, the revealed problems were discussed with review of the design and the RCS flow measurement uncertainty evaluation, and the technical approaches and recommendations for resolving these problems were proposed.

1. Introduction

The Reactor Coolant System (RCS) flow rate is a major parameter in the design of the system and its components of a nuclear reactor. Accurate measurement of the RCS flow rate is important to obtain maximum allowable operating power. Due to the technical difficulties in directly measuring the flow through large diameter pipings, indirect measurements which are known to be less accurate have been used historically. Well-known indirect flow measurement methods are the ones using Reactor Coolant Pump (RCP) differential pressure (d/p), RCS elbow tap d/p and Precision Calorimetric Heat Balance (PCHB). In these methods, the RCS flow rate is obtained from physical relationships or calculated from other parameters.

For the domestic Westinghouse (W)-type plants, the RCS flow rate commonly is measured by the latter two methods of elbow tap d/p and PCHB. The RCS elbow tap d/p flow measurement is performed by measuring the pressure difference between two taps in both sides of the inner wall of the RCS elbow, and then by using the functional relationship between the RCS flow and the elbow tab d/p, where the d/p is proportional to the square of the flow velocity. The proportional coefficient can be determined from the reference design and flow measurement. Major factors affecting this coefficient are the geometry conditions such as the inside diameter and the radius of curvature, etc., and the coefficient value may differ for each operating cycle due to the change of the geometry condition by crud or fouling, etc. Due to a possibility that the elbow tap d/p flow measurement will bring a biased value for each cycle of the operating plant, the PCHB flow measurement is performed to provide the reference values for normalization of the elbow tap d/p transmitters. In the PCHB flow measurement, the cold and hot leg temperatures of each loop and the thermal power of the corresponding steam generator are measured, and then the RCS flow rate is calculated by considering the heat balance between the RCS and the secondary system.

Inspection of RCS flow measurements for the domestic pressurized water reactors has been performed by the Korea Institute of Nuclear Safety (KINS) as one of the authorized periodical inspection activities. The inspection results for the W-type plants reveal that 1) the RCS flow instrumentation has been calibrated by using the initial design and commissioning test result, without reflecting the cycle specific reference flow measurements, 2) the loop-to-loop flow variation in the actual flow measurement which has not been considered in the safety analysis affects the current asymmetric flow transient results, and 3) the measured RCS flows in Kori 3 and 4, Yonggwang 1 and 2 do not support the definition of the best estimate RCS flow, approaching the RCS flow limit. In this study, the revealed problems were discussed with review of the design and the RCS flow measurement uncertainty evaluation, and the technical approaches and recommendations for resolving these problems were proposed.

2. Design Considerations

2.1. Definitions and Applications

W has traditionally identified three RCS flow rates for various design considerations, Best Estimate Flow (BEF), Thermal Design Flow (TDF) and Mechanical Design Flow (MDF). In earlier 1970, the Minimum Measured Flow (MMF) has been proposed to improve reactor operating margin (also called thermal margin). The definitions of these flows are described below and Fig. 1 shows how these flows can be determined.

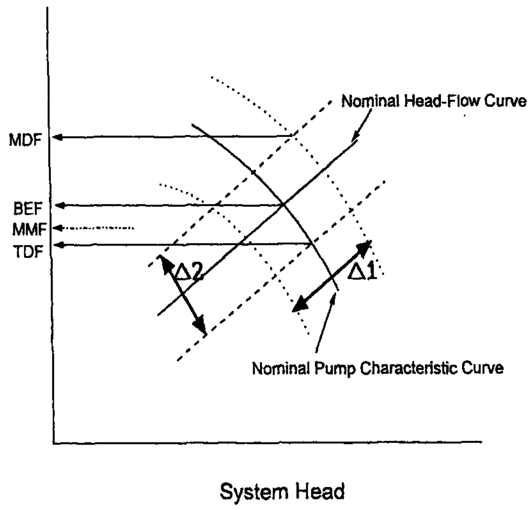

Fig. 1. Determination of RCS Flow Rates
(Δ1 : Head-to-Flow Uncertainty Band,
Δ2 : Pump Characteristic Curve Uncertainty Band)

The Best Estimate Flow (BEF) is the most likely value for the actual plant operating condition. This flow is based on the best estimates of the reactor vessel, steam generator and piping flow resistances, and the best estimate of the reactor

Table 1. Design Flows for Domestic Westinghouse-Type Plants

Plant \ Flow	Mechanical Design Flow	Best Estimate Flow	Minimum Measured Flow	Thermal Design Flow	Ave.SGTP Level, %
Kori 1	200,400 gpm	178,400 gpm	176,400 gpm	172,400 gpm	15
Kori 2	213,000 gpm	201,600 gpm	N/A	189,000 gpm	5
Kori 3	320,700 gpm	307,200 gpm	293,700 gpm	286,800 gpm	5
Kori 4	320,700 gpm	307,200 gpm	293,700 gpm	286,800 gpm	5
Yonggwang 1	320,700 gpm	307,200 gpm	294,800 gpm	286,800 gpm	5
Yonggwang 2	320,700 gpm	307,200 gpm	294,800 gpm	286,800 gpm	5
Ulchin 1	70,920 m3/hr	65,985 m3/hr	63,843 m3/hr	61,254 m3/hr	10
Ulchin 2	70,920 m3/hr	65,985 m3/hr	63,843 m3/hr	61,254 m3/hr	10

(note) N/A: Not Applicable, Ave. SGTP: Average SG Tube Plugging

pump head-flow capacity, with no uncertainties assigned to either the system flow resistances or the pump head. The BEF is used to calculate the fuel assembly pressure drop and lift force in the typical operating conditions such as hot full power and pump overspeed conditions, etc. For each condition, flow maldistribution bias and uncertainty are considered in a conservative fashion. The Thermal Design Flow (TDF) is the basis for the reactor core thermal performance, the steam generator thermal performance, and the nominal plant parameters used throughout the design. To provide the required margin, the TDF accounts for the uncertainties in reactor vessel, steam generator and piping flow resistance, RCP head, and the methods used to measure the flow rate. The combination of these uncertainties is equivalent to increasing the best estimate RCS flow resistance, and the intersection of this conservative flow resistance with the best estimate pump curve establishes the TDF. The TDF is used for both the conventional thermal design and for the Loss of Coolant Accident (LOCA) analysis. The conventional thermal design includes the Departure from Nucleate Boiling (DNB) analysis for non-LOCA accidents of the plants where statistical treatment of the flow is not applied. The Mechanical Design Flow (MDF) is a conservatively high flow used in the mechanical design of the reactor vessel internals and fuel assemblies. It is also used to evaluate the rod vibration and wear. To assure that a conservatively high flow is specified, the MDF is based on a reduced system resistance and on increased pump head capability. The intersection of this flow resistance with the higher pump curve establishes the MDF. The Minimum Measured Flow (MMF) is the lowest predicted by the expected flow measurement range and is the nominal flow used in reactor core DNB analyses for plants applying the statistical thermal design methods. The expected flow measurement range is defined as the statistical combination of the hydraulics and measurement uncertainties such that there is a 95 percent probability with 95 percent confidence that the actual measured flow will be equal to or greater than the MMF. For reference, the values of the four design flows which are used in domestic W-type plants are presented in Table 1. The MMF is not applicable to Kori 2 where the conventional thermal design method is used. The values of the design flows for Ulchin 1 and 2 are the ones which have been recently determined by Westinghouse with the fuel change from the JDFA (KAERI and KWU Joint-Designed Fuel Assembly) to the Vantage-5H fuel assembly.

2.2. RCS Flow Rate-LSSS and LCO

The LCO' s (Limiting Conditions for Operation) mean the lowest functional capability or performance levels of equipment required for safe plant operation. They are imposed on selected operating parameters which must be observed to preclude exceeding a safety limit based on the plant safety analysis. The LSSS' s (Limiting Safety System Settings) are the setpoints for automatic protective devices related to the process variables having significant safety functions. Therefore the LSSS' s are determined such that automatic protective action will be actuated to prevent a safety limit from being exceeded.

The RCS flow rate-LSSS and LCO are described in the Technical Specification (T/S) of each plant, based on MMF or TDF aforementioned. Table 2 shows the comparison of the RCS flow rate-LSSS' s and LCO' s of the domestic W-type plants and Westinghouse Standard Technical Specification (W-STS). The low flow trip setpoint is expressed by a fraction of the loop design flow. The loop design flow equals to MMF (for statistical thermal design) or TDF (for conventional thermal design) which are divided by the number of the loops because the symmetric loop flow is assumed in the safety analysis. The RCS flow rate-LCO is equal to TDF plus flow measurement uncertainty, which commonly equals to MMF in the plants using the statistical thermal design method. In each T/S of six Westinghouse supplied plants, the RCS flow rate is considered as the parameter which is to be periodically checked with the surveillance frequency of 1 month (Kori 1 and 2) or 12 hours (Kori 3 and 4, Yonggwang 1 and 2). Surveillance requirements are intended to provide adequate monitoring to detect possible flow reduction. In Ulchin 1 and 2 plants supplied by Framatome the RCS flow rate-LCO was not described in the original T/S, which has been recently revised to involve the contents of Table 1. The W-STS helps us understanding the basis of the RCS flow rate-LCO surveillance with a separate subsection for surveillance of three DNB-related safety parameters: RCS flow rate, pressure and average coolant temperature. It also requires that surveillance of the DNB-related parameters should be performed periodically with the interval of 12 hours, based on operating practice to be sufficient to assess potential degradation and to verify operation within the bounds of design and safety analyses.

Based on the W-STS, surveillance for RCS flow measurement is summarized as follows: 1) performance of the PCHB flow measurement once every cycle is required to provide the reference for normalization of the installed RCS flow instrumentation, 2) the RCS flow rate is monitored and checked once per 12 hours by the RCS flow instrumentation in order to confirm that the measured RCS flow is above the flow assumed in the safety analysis. The installed RCS flow instrumentation is represented by the elbow tap flow transmitter, transmitting the pressure difference between both sides in the inner wall of the elbow by the electrical current signal, which is converted to the voltage unit which is inputted to both the flow indicators and the reactor trip bistable. Resultantly, the actual RCS flow can be directly monitored by the flow indicators or the plant process computer which are fed by the elbow tap d/p transmitters, to perform the required surveillance of every 12 hours.

2.3. Calibration of Elbow Tap d/p Transmitter

Calibration of the elbow tap d/p transmitter resets the relationship between the d/p and the electrical current to the desired one, by adjusting the zero point or the span and then by checking the linearity over the full span according to the

Table 2. Comparison of RCS Flow Rate-LSSS and LCO in T/S

Item / Plant	LSSS	LCO Surveillance Requirement	LCO Basis
K1	T 16.2.2-1 LDF*1=88,200 (gpm/loop) LFT*2=90% LDF	16.4.2.3.1. PDL*3 for RCS Flow & R - measured flow ≥178,500 gpm(K1) - measured flow ≥196,000 gpm(K2) - Combination of RCS flow and R_1 a.Prior to operation ≧ 75% RTP b. At least once per 31 EFPD. - FI*4 subjected to Channel Calibration once per 18 months. - Flow measurement by PCHB once per 18 months and ≧90 % RTP	16B.3/4.2.3.1 The limits on heat flux hot channel factor, RCS flow rate, and nuclear hot enthalpy rise channel factor ensure 1) the design limits on peak LPD and minimum DNBR -------.
K2	T 16.2.2-1 LDF=94,500 (gpm/loop) LFT=90% LDF		
K3/4	T 16.2.2-1 LDF=97,900 (gpm/loop) LFT=90% LDF	16.4.2.3.1. PDL for RCS Flow & R -measured flow 293,700 gpm(K3/4) -measured flow 294,800 gpm(Y1/2) -Combination of RCS flow and R1 a.Prior to operation 75% RTP b. At least once per 31 EFPD. - FI subjected to Channel Calibration once per 18 months. - Flow measurement by PCHB once per 18 months and 90 % RTP - Periodic verification of RCS flow with frequency of 12 hrs.	16B.3/4.2.3.1 Measurement errors of 3.5 % for RCS total flowrate and ------ . The 12-hour periodic surveillance of indicated RCS flow is sufficient to detect ------.
Y1/2	T 16.2.2-1 LDF=97,900 (gpm/loop) LFT=90% LDF		
U1/2	T 16.2(2/5) LDF=21,281 (m3/hr/loop) LFT=91.8%LDF	16.5.3.1.d) total RCS Flowrate - measured flow 63,843 m3/hr - Periodic verification of RCS flow with frequency of 1 month. - Flow Measurement by PCHB once every 18 months and Calibration of Instrumentation	16.5.3.2.d): frequency of 18 months reflects the importance of verifying flow after a refueling outage when the core has been altered
W-STS	T 3.3.1-1 LFT=[90%]	3.4.1.RCS Pressure,Temperature, Flow DNBR Limits SR3.4.1.3: Periodic verification of RCS flow with frequency of 12 hrs. SR3.4.1.3: Flow measurement by PCHB once per 18 months and 90 % RTP (Not Required until 24 hrs after 90% RTP)	-SR3.4.1.3: 12-hour frequency performed using installed RCS instrumentation. 12 hr--- by operating practice ----. -SR3.4.1.4: Measurement of RCS total flowrate by PCHB once every 18 months allows installed flow instrumentation to be calibrated and verifies the actual RCS flow minimum required RCS flow.

*1LDF=loop design flow, *2 LFT=low flow trip setpoint, *3 PDL=power distribution limit *4FI=flow nacator predetermined function:

$$I = a \Delta P + b \quad (1)$$

Here, the b value depends on the zero point setting, (which is set typically at 4 mA) and the a value is determined from the design and reference flow measurement. The RCS flow instrumentation span equivalent to the electrical current of 4 mA to 20 mA is usually zero to 120 % of the RCS flow. The value of the elbow tap d/p equivalent to the nominal design flow can be obtained from the design and reference flow measurement result, because the elbow tap d/p is related fo the RCS flow rate, $\dot{m}$, as:

$$d/p = k \times \dot{m}^2, \quad (2)$$

where k, from the physical consideration, depends on the diameter of piping and the radius of curvature, and Reynolds number, etc and is determined from the reference flow measurement. A typical example is shown in Fig. 2-a, 2-b and 2-c. If the elbow tap d/p is 472 inch H_2O at the nominal design flow of 30,000 gpm, the a and b values in Eq. (1) become 0.0282 and 4.000 respectively. Then calibration of the elbow tap d/p transmitter is made to the solid line of Fig. 2-a. Note that 100 percents of the transmitter span, 17.3 mA, 30,000 gpm and 472 inch H_2O are used as the equivalent quantity. The value of k in Eq. (2) can be obtained because the elbow tap d/p equivalent to the nominal design flow is known. The calibration leads to the physical relationships between the elbow tap d/p and the nominal design flow as represented by the solid line of Fig. 2-b and between the absolute and the relative RCS flows as represented by the solid line of Fig. 2-c. The RCS flow used in the safety analysis, 30,000 gpm is then converted to the relative value, 100

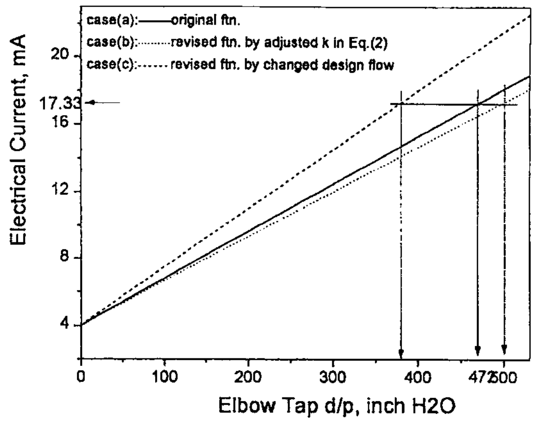

Fig. 2-a. Linearity Equation Used for Calibration of Elbow Tap d/p Transmitter

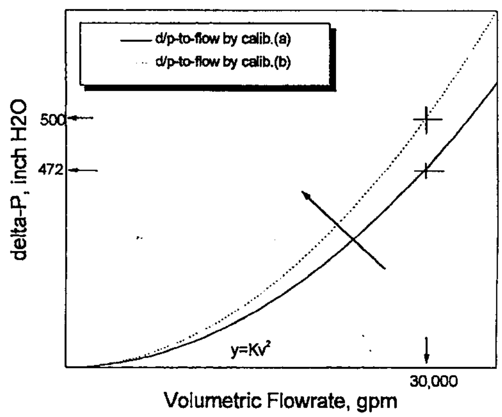

Fig. 2-b. Physical Relationship Between Elbow Tap d/p and RCS Volumetric Flow Rate

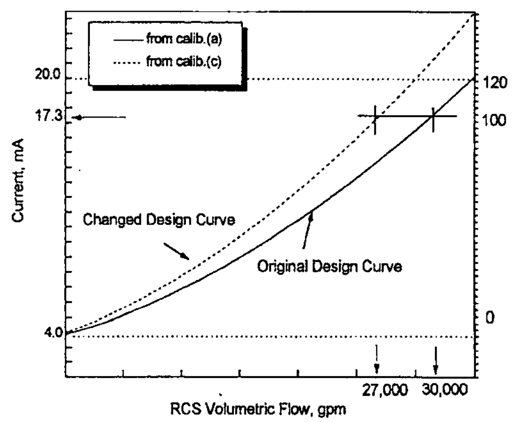

Fig. 2-c. Relationship Between Absolute and Relative RCS Flow Rates Obtained Through Calibration

percents of the flow indicator span, in Fig. 2-c. As the number of operating cycles increases, the k value can become higher due to crud or fouling, etc., tending to move the solid line to an arrow direction in Fig. 2-b. In case where the PCHB flow measurement result for a specific cycle indicates that the flow-to-d/p relationship is represented by the dotted line of Fig. 2-b (with adjusted k), a calibration should be made according to the dotted line of Fig. 2-a, in order to maintain the relationship of the two RCS flows which is represented by the solid line of Fig. 2-c. Meanwhile, the nominal design flow can be changed by the intent of the designer. If the changed nominal design flow is assumed to be 27,000 gpm, the desired relationship between the absolute and the relative RCS flows is changed to the dashed line from the solid line of Fig. 2-c. In this case the revised linearity function represented by the dashed line of Fig. 2-a should be used for calibration of the elbow tap d/p transmitter.

3. RCS Flow Measurement and Uncertainty Evaluation

3.1. Mathematical Models for Error Evaluation

Errors are, generally, classified as bias (systematic) errors and precision (random) errors. Bias errors are relatively fixed during test. Large bias errors are removed during calibration. If all bias errors were known, the errors could be added directly. However, in general, there are many small bias errors of which the magnitude and the sign are unknown, and the probability that they are all plus or all minus is very small. Thus the unknown values of these bias errors are embedded in the calibration and will be combined in the same fashion that the precision errors will be combined. Precision errors occur because of numerous small effects which cause repeated measurements to differ in value. A precision error causes random variations from the true measurement value. A statistical measure of this random variation is the standard deviation. The larger the standard deviation, the larger the spread in the data. Fig. 3 shows classified measurement errors.

The procedure for evaluating the errors usually consists of two steps: obtaining an estimate of the uncertainty in each of the variables, x_i, and then combining the uncertainties according to the following model. The desired quantity generally is a function of many measured and calculated variables, i.e.,

$$R=f(x_1, x_2, x_3, \cdots, x_n), \tag{3}$$

where R is the RCS flow and x_i' s are the variables participating in the measurement, i.e., feedwater flow coefficient, hot leg and cold leg temperatures and steam enthalpy, etc. The change in R resulting from the changes in the variables would be:

$$dR=\frac{\partial R}{\partial x_1}dx_1+\frac{\partial R}{\partial x_2}dx_2+\cdots+\frac{\partial R}{\partial x_n}dx_n. \tag{4}$$

Each variable x_1, x_2, x_n $\cdots$ can be either negative or positive. This may be handled statistically by averaging, $<()>$, the square of dR.

$$\begin{aligned}<(dR)^2> = &<(\frac{\partial R}{\partial x_1}dx_1)^2>+<(\frac{\partial R}{\partial x_2}dx_2)^2>+\cdots<(\frac{\partial R}{\partial x_n}dx_n)^2>\\ &+2\Big\{<\frac{\partial R}{\partial x_1}\frac{\partial R}{\partial x_2}dx_1dx_2>+\cdots<\frac{\partial R}{\partial x_1}\frac{\partial R}{\partial x_n}dx_1dx_n>\\ &+\cdots<\frac{\partial R}{\partial x_2}\frac{\partial R}{\partial x_3}dx_2dx_3>+\cdots<\frac{\partial R}{\partial x_{n-1}}\frac{\partial R}{\partial x_n}dx_{n-1}dx_n>\Big\}\end{aligned} \tag{5}$$

For any two independent variables x_m and x_n, the cross product is zero. That is, the cross product terms involving independent variables in Eq. (5) are equal to zero and may be deleted from the equation. For those variables that are dependent the cross product terms remain. For these

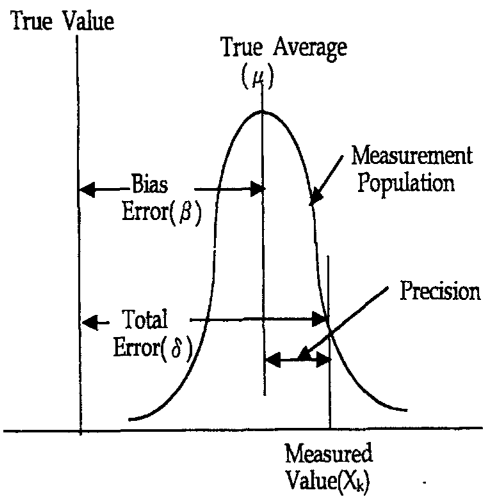

Fig. 3. Classification of Measurement Errors

dependent variables, Schwarz' s inequality shows that

$$< \frac{\partial R}{\partial x_i} \frac{\partial R}{\partial x_j} dx_i dx_j > \leq \left| \frac{\partial R}{\partial x_i} \right| \left| \frac{\partial R}{\partial x_j} \right| \sigma_{x_i} \sigma_{x_j} \quad (6)$$

where σ_{x_i} and σ_{x_j} are the square root of the variances of σ_{x_i} and σ_{x_j}, i.e.,

$$\sigma_{x_i} = (\sigma_{x_i}^2)^{1/2} = (<(dx_i)^2>)^{1/2}.$$

The term σ_{x_i} is sometimes referred to as the RMS (Root Mean Square) value of x_i or the standard deviation of x_i. The variance of the result, σ_R^2, can conservatively be estimated as the sum of the variable variances times their respective coefficients:

$$\sigma_R^2 = \left(\frac{\partial R}{\partial x_1}\right)^2 \sigma_{x_1}^2 + \left(\frac{\partial R}{\partial x_2}\right)^2 \sigma_{x_2}^2 + \cdots + \left[\left|\frac{\partial R}{\partial x_i}\right| \sigma_{x_i} + \left|\frac{\partial R}{\partial x_j}\right| \sigma_{x_j} + \cdots\right]^2 + \left[\left|\frac{\partial R}{\partial x_m}\right| \sigma_{x_m} + \left|\frac{\partial R}{\partial x_n}\right| \sigma_{x_n} + \cdots\right]^2 \cdots, \quad (7)$$

where the terms subscripted by integers are independent, those subscripted by i, j, m and n are dependent one to another. If all the variables were independent, the variance of the result, σ_R^2, would simply equal to the sum of the variable variances times their respective coefficients. In many cases, uncertainty is written as a ratio of the uncertainty, U_R, of the result to the value of the result, R. In this case, Eq. (7) may also be written as:

$$\left(\frac{\sigma_R}{R}\right)^2 = S_{x_1}^2 \left(\frac{\sigma_{x_1}}{x_1}\right)^2 + S_{x_2}^2 \left(\frac{\sigma_{x_2}}{x_2}\right)^2 + \cdots + \left[S_{x_i}\left(\frac{\sigma_{x_i}}{x_i}\right) + S_{x_j}\left(\frac{\sigma_{x_j}}{x_j}\right) + \cdots\right]^2 + \left[S_{x_m}\left(\frac{\sigma_{x_m}}{x_m}\right) + S_{x_n}\left(\frac{\sigma_{x_n}}{x_n}\right) + \cdots\right]^2 + \cdots, \quad (8)$$

where $S_{x_i} = \frac{(\partial R/R)}{(\partial x_i/x_i)}$. For all variables independent, a ratio of the uncertainty of the result to the value of the result, $(\sigma_R/R)^2$, is:

$$\left(\frac{\sigma_R}{R}\right)^2 = S_{x_1}^2 \left(\frac{\sigma_{x_1}}{x_1}\right)^2 + S_{x_2}^2 \left(\frac{\sigma_{x_2}}{x_2}\right)^2 + \cdots + S_{x_N}^2 \left(\frac{\sigma_{x_N}}{x_N}\right)^2, \quad (9)$$

where the subscript, N denotes the number of variables.

3.2. RCS Flow Measurement Uncertainty

The RCS flow rate by the PCHB method is measured by determining the corrected Steam Generator (SG) thermal output for RCP heat input, system heat losses/gains and the enthalpy rise of primary coolant. A heat balance equation for each loop is given by:

$$W_L = \frac{(A)\{Q_{SG} - Q_P + (Q_L/N)\}(V_C)}{(h_H - h_C)}, \quad (10)$$

where N = the number of loops, W_L = volumetric loop flow rate, A= conversion factor, QL = primary system net heat losses, Q_{SG} = thermal power per one SG, Q_P = RCP heat addition and Vc= specific volume of the cold leg. Primary system net heat losses are determined by calculation, considering the following heat inputs and 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, control rod drive mechanism (CRDM) heat losses. The hot and cold leg enthalpy are based on the measurement of the resistance temperature detector (RTD) temperatures, and pressurizer pressure. The cold leg specific volume is based on the measurement of cold leg temperature and pressurizer pressure. The thermal power per one SG is given by:

$$Q_{SG} = (h_s - h_f)W_f. \tag{11}$$

The steam enthalpy, h_s is based on measurement of SG outlet steam pressure, assuming saturated conditions, and the feedwater enthalpy, h_f, on the measurement of feedwater temperature and pressure. The feed water flow is given by:

$$W_f = (K)(F_a)\{(\rho_f)(d/p)\}^{1/2}, \tag{12}$$

where K, F_a, and d/p are the flow coefficient, the correction for thermal expansion, and the pressure drop (inches H_2O) of the feed water venturi respectively. The feedwater venturi flow coefficient is the product of a number of constants, based on the as-built dimension and calibration test. The feedwater venturi correction is based on the thermal expansion coefficient of material and difference between feedwater temperature and calibration temperature. The feedwater density, ρ_f is based on the feedwater temperature and pressure. In summary, the PCHB flow measurement is based on both the plant measurements (for example, steamline pressure, feedwater temperature, pressure and venturi differential pressure, hot and cold leg temperature) and the calculations (for example, feedwater venturi flow coefficient and thermal expansion coefficient, feedwater density, hot and cold leg enthalpy). In uncertainty evaluation, uncertainty of each variable is estimated based on purchase and manufacturing specification and calibration and drift data, etc., and then the RCS flow measurement uncertainty is evaluated by considering the uncertainty of each variable. Table 3 shows a typical example of uncertainty for the PCHB RCS flow measurement. If the mathematical model of section 3.1. is used for the variables independent or dependent, the flow measurement uncertainty (one standard deviation, 1σ) is:

$$\begin{aligned} Uncertainty(1\sigma) = {} & [\{0.500^2 + (-0.004+0.090+0.291)^2 + 0.060^2 \\ & + (0.023-0.006)^2 + 0.805^2 + 0.141^2 + 0.210^2 \\ & + 0.085^2 + 0.983^2 + 1.254^2 + (0.807+0.075)^2\}/3^{*} \\ & + (0.114-0.031-0.020)^2/4^{**} + 1.254^2]^{1/2} = \pm 1.6\%, \end{aligned} \tag{13}$$

where one mark (*) indicates the number of the RCS loops and the other mark(**), the number of the pressure taps. The systematic error of the hot leg enthalpy due to streaming effect (1.25 percents of flow) is directly considered in the design and is not included in this calculation. In this example, the various biases including the sensor and rack drifts are not considered.

Flow measurement by the elbow tap d/p method can be performed after the transmitter has been normalized based on the PCHB flow measurement. Then, the elbow tap d/p flow measurement uncertainties without considering the PCHB flow measurement error are simply a statistical combination of subcomponents such as rack drift, calibration, sensor drift, etc. Without normalization based on the PCHB flow measurement the elbow tap d/p can bring the bias of the RCS flow rate which is not considered in the uncertainty evaluation. The RCS flow measurement uncertainty can be finally determined by statistically combining the elbow tap d/p transmitter uncertainty and the PCHB flow measurement uncertainty.

Table 3. Typical Uncertainties of PCHB Flow Measurement and Instrumentation Calibration

Component		Instrument Error	Flow Calorimetric Sensitivity	Flow Uncertainty, % Flow
Feedwater Flow(Wf)				
K		0.5 %K	1.0 %/%K	0.500
F	Temperature	2.0 F	0.002 %/F	0.004
	Material	5.0 %	0.006 %	0.060
Density	Temperature	2.0 F	0.044 %/F	0.090
	Pressure	60.0 psi	0.00038 %/F	0.023
d/p		1.1 %d/p	0.720 %/%d/p	0.805
Remainder of Calculation of S/G				
Thermal Power(QS/G)				
hf	Temperature	2.0 F	0.143 %/F	0.291
	Pressure	60.0 psi	0.000096 %/psi	0.006
hs	Pressure	30.1 psi	0.0047 %/psi	0.141
	Moisture	0.25 %Moisture	0.210%/0.25 %Mois.	0.210
Net Pump Head Additoin		20.0 %		0.085
Remainder of Calculation of Loop Flowrate(WL)				
hH	Temperature	0.5 F	1.929 %/F	0.983
	Streaming (Random)	0.6 F		1.254
	Streaming (Systematic)	0.6 F		1.254
	Pressure	12.7 psi	0.0090 %/psi	0.114
hC	Temperature	0.5 F	1.582 %/F	0.807
	Pressure	12.7 psi	0.0025 %/psi	0.031
VC	Temperature	0.5 F	0.146 %/F	0.075
	Pressure	12.7 psi	0.0016 %/psi	0.020

(Note) K, F and h represent for feedwater venturi loss coefficient, correction factor for venturi thermal expansion and enthalpy respectively. Also, subscripts, f, s, h, and c indicates feedwater, steam, hot leg and cold leg respectively.

4. Inspection Results and Discussion

4.1. RCS Flow Measurements and Calibration

Review of Current Procedure

In the domestic W-type plants, the RCS flow measurement and the instrument calibration have been performed independently without correlating each other. The current procedure for *doing* these is summarized in Table 4. The calibration in STEP 1 is meaningless so far as the physical quantity of the actual RCS flow is concerned, because the original linearity function is not usually correct for each cycle. STEP 1 does not go beyond checking the linearity between the input and the output, without considering the cycle specific reference flow measurement. In STEP 2, the RCS flow measurement is made by using the elbow tap d/p transmitter, calibrated by the imperfect method of STEP 1. As a result, a comparison is made between the imperfectly measured RCS flow and the T/S flow limit. Also, the indicated RCS flow at higher power level often can be other than 100 percents of the full span by adjusting the span at hot zero power. How can it be explained that after the measurement, the span of the d/p transmitter is so adjusted that the indicated RCS flow becomes 100 percents of the full span? Again, this adjustment indicates that STEP 1 is meaningless except for the transmitter performance itself based on the initial commissioning test. In STEP 3, the only objective of the PCHB measurement is to verify that the RCS flow is above the T/S flow limit criteria. It is a duplication of STEP 2 in a sense that the elbow tap d/p flow measurement, if it were accurate, would be also applicable at higher power level. Inconsistency and errors in the whole steps are simply due to misunderstanding of the use of the elbow tap d/p transmitter. It feeds continuously the relative RCS flow to the flow indicator, the plant process computer and the reactor trip bistable during plant operation, and can not provide the actual RCS flow without proper cycle-to-cycle calibration. The actual RCS flow is measured by the PCHB flow measurement and the elbow tap d/p transmitter should be calibrated based on this measurement. Then, the correct RCS flow can be fed to the flow indicator and the reactor trip bistable.

Proposed Approach

To resolve this problem, the above procedure can be changed as in the following: In STEP 1, the output electrical currents are adjusted to specified values against the input elbow tap d/p signals, where the specified values are determined from the linearity function based on the PCHB flow measurement of the previous cycle and the corresponding elbow tap d/p value. STEP 2 can be skipped or performed. In STEP 3, the PCHB flow measurement result is not used only for verifying the measured RCS flow is above the T/S flow limit criteria but also for providing the reference for normalization of the elbow tap d/p transmitter. If the measurement result is different from that of the previous cycle, the span of the elbow tap d/p transmitter is adjusted so that 100 percents of the span be equivalent to the design flow. Then, the coefficient of the linearity function defining the relationship of the d/p and the electrical current, i.e., a value in Eq. (1) is changed

Table 4. Current Procedure for RCS Flow Measurement and Instrumentation Calibration

STEP 1	Calibration of d/p Transmitter Below Hot Shutdown (No RCP running). - The output electrical currents are compared with the preset values against the input elbow tap d/p signals. The preset values are obtained from the linearity equation based on the initial design and the commissioning test result.
STEP 2	Measurement by d/p Transmitter at Hot Zero Power and RCP Running - It is assumed that only if the measured RCS flow is above the T/S flow limit, further surveillance is not performed until the PCHB flow measurement is performed. Regardless of the measured RCS flow, the span of the d/p transmitter is readjusted so that the indicated RCS flow become 100 % of the full span.
STEP 3	PCHB Flow Measurement at Hot Full Power - It is verified that the RCS flow is above the T/S flow limit criteria.

for the next cycle STEP 1 calibration. If the result of the PCHB flow measurement for each loop is almost same as that of the previous cycle, no additional calibration is necessary. It is also noted that the PCHB measurement should be performed as soon as the plant reaches the stable condition at the full power.

Throughout the proposed flow measurement and calibration, the actual RCS flow for each loop is indicated by the percent of the design flow, the low flow trip setpoint described in the T/S is consistent with the actual reactor trip bistable setting, and LCO surveillance can be easily performed, i.e., the RCS flow rate-LCO' s are met if the total elbow tap d/p RCS flow expressed by the percent unit is above 200 percents (for 2-loop) or 300 percents (for 3-loop) in the plants employing the statistical design method and above 207.2 percents (considering two times of RCS flow measurement uncertainty, 3.6 percents) in Kori 2.

Safety Analysis and Calibration

Two approaches are often proposed for calibration of the elbow tap d/p transmitter: 100 percents of the span is determined against the design flow (proposed above), or indicated flow of the flow measurement (same as the last step of the current procedure). It is often said that the latter approach is more acceptable than the former because it makes the actual reactor trip time comparable to that in the safety analysis of the asymmetric flow transients such as partial loss of flow and RCP locked rotor, etc: The average design flow is assumed for each loop in the safety analysis, while loop-to-loop flow variation exists in the actual flow measurements; If the asymmetric flow transients occurs in the loop indicating a higher flow, the actual reactor trip time will be delayed by the former approach while not by the latter approach. This assertion is agreeable because the latter approach has an effect of averaging the loop flows without loop-to-loop variation. However, the low flow trip setpoint is given with the absolute value for each loop in the current T/S LSSS. If the latter approach is used, the current T/S should be changed. Moreover, the RCS flow rate-LCO surveillance per 12 hours seems not to be possible with the current flow indicators even when the absolute RCS flow equal to 100 percents of the span has been determined: the scale marks of the flow indicators are the units of 2 percents (W-supplied plants) or 5 percents (Ulchin 1 and 2) where careful reading and calculation are required.

So far as LCO surveillance is concerned, the actual RCS flow (expressed by the unit of gpm or m3/hr) should be easily recognized by the plant operator. This is the reason why the former approach (100 percents of the span is determined against the design flow) is recommended for the current flow indication system where the relative value of the RCS flow against the reference value is indicated on the coarse scale mark. The latter approach (100 percents of the span is determined against the indicated flow of the flow measurement), however, will be favored if the actual RCS flow can be directly indicated with the flow indicator or the plant computer. It is because the latter approach makes the current safety analysis results become valid for any loop-to-loop flow variation.

4.2. RCS Flow Measurement Data Evaluation

The RCS flow uncertainty is evaluated, based on the flow measurement data. There exist two RCS flow uncertainties: one is the RCS flow measurement uncertainty which is composed of the errors in each of the components which are used in obtaining a flow measurement, as

Table 5. PCHB Flow Measurement Results for Kori 1

Cycle	Measured RCS Flow, gpm			S/G Plugging, %			Expected	T/S Flow
No.	Loop A	Loop B	Total	A	B	Total	Flow*, gpm	Limit ** ,gpm
7	94,995	89,287	184,282	8.7	14.5	23.2	179,929	178,500
8	91,885	90,935	182,820	9.3	15.3	24.6	179,612	
9	93,838	90,734	184,572	1.5	1.9	3.4	184,535	
10	89,593	93,939	183,532	1.8	3.1	4.9	184,178	
11	89,887	88,864	178,751	2.0	4.0	6.0	183,917	
12	93,558	91,972	185,530	3.3	4.9	8.2	183,397	
13	92,958	89,564	182,522	5.0	7.7	12.7	183,343	
14	91,965	91,676	183,641	10.2	10.3	20.5	180,543	
15	90,667	91,357	182,024	10.9	11.5	22.4	180,111	

(Note) * Based on the best estimate flow of 178,500 gpm at average SG tube plugging of 15 percents
** thermal design flow plus flow measurement uncertainty

described in section 3.2, and the other, the RCS flow prediction uncertainty which means the error of the code prediction against the measured RCS flow. The former is difference between the TDF and the minimum allowed RCS flow whose periodic surveillance is required in each plant T/S. The latter can be obtained through comparison between the predicted and the measured RCS flows if the effect of the measurement error is subtracted from the overall error in the predicted and measured flows. Because the sufficient number of the RCS flow measurements covering the effect the measurement error are currently unavailable, the overall error of the predicted flow against the measured flow can be considered as a conservative measure of the RCS flow prediction uncertainty.

Table 5 shows the results of the PCHB flow measurements for Kori 1. The BEF, 178,400 gpm, has been determined based on the average SG tube plugging (SGTP) level of 15 percents. It can be assumed that there will be the flow reduction of about one percent per average SGTP of 4 percents, based on evaluation of the design data. Considering that the BEF is defined as the most likely value for the actual plant operating condition, the expected RCS flow can be estimated for each cycle: for example, the expected RCS flow for cycle 7 (with 23.2 percents total SGTP) is 179,929 gpm (=178,400/(1-(0.300-0.232)/2/4)). The measured RCS flow for each cycle can then be normalized against the expected RCS flow. Fig. 4 shows the histogram of the normalized RCS flow data for 9 cycles, whose mean is close to the expected value showing the justification of the BEF.

The 14 data for both Ulchin 1 and 2 is also selected to observe the accuracy of the predicted RCS flow. Table 6 shows the results of the PCHB flow measurements for Ulchin 1 and 2. Assuming the flow reduction effect of the SGTP in the similar way to Kori-1 case, the expected RCS flow for earlier cycles of almost zero SGTP is 67,677 m^3/hr which is calculated from the BEF (65,955 m^3/hr). The expected RCS flow is close to the mean of the measured RCS flows (68,436 m^3/hr). Because the measured data for Kori-1 and Ulchin 1 and 2 are well expected with the BEF, comparison of the measured and the predicted RCS flows for the total 23 data is made to see the data distribution of the predicted flows against the measured flows. Fig. 5 shows percent difference in

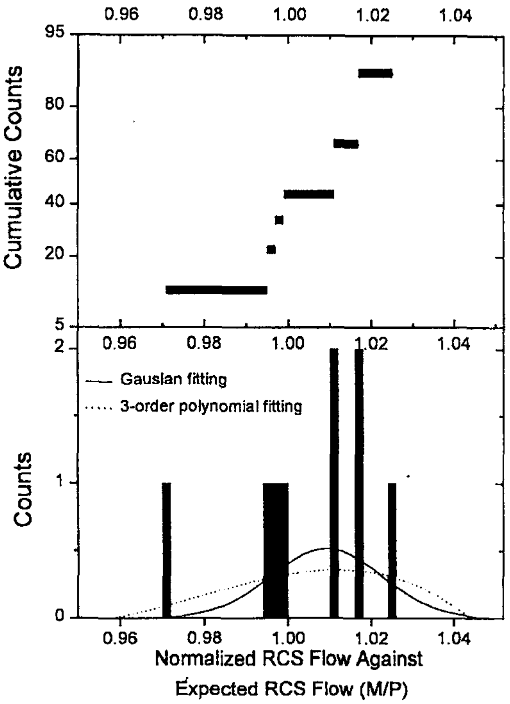

Fig.4. Normalized RCS Flow Measurement Data for Kori 1

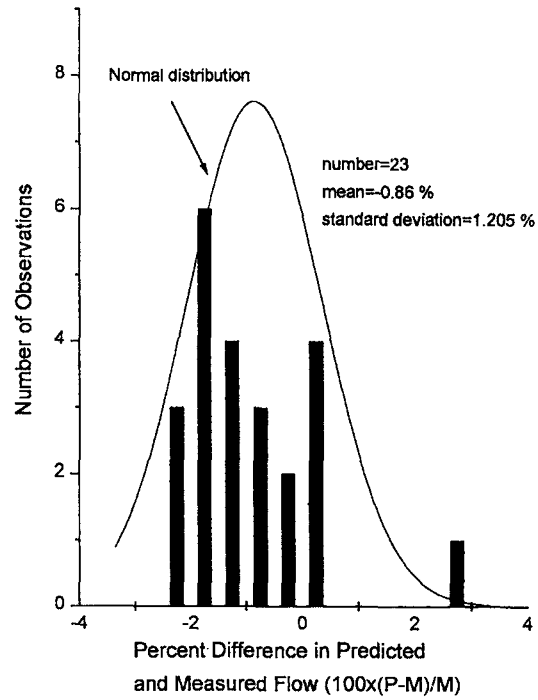

Fig.5. Measured-to-Predicted RCS Flow Comparison for Kori 1 and Ulchin 1 and 2 Plants

the predicted and measured RCS flows. The percent difference leads to a standard deviation of 0.012. A 95 percent upper confidence level value of 0.016 for the population standard deviation is obtained by using the statistics table that x^2 values are tabulated in terms of the confidence level and the degree of freedom. The one standard deviation value, 0.016, is lower than the RCS flow measurement errors (one standard deviations of 0.0175 for Kori 1 and 0.0212 for Ulchin 1 and 2), which are used in the statistical thermal designs of Kori 1 and Ulchin 1 and 2. Therefore, it seems that the prediction error is sufficiently small compared with the measurement error even when the prediction error is assumed to be the only source of the overall error.

There are six RCS flow measurement data which are currently avaliable for Kori 3 and 4 and Yonggwang 1 and 2. The average SGTP were below 0.5 percents when the flow measurements were performed. The BEF, MMF and TDF for all the four plants are 307,200, 293700, and 286,800 gpm respectively which are determined at average SGTP level of 5 percents, as presented in Table 1. The minimum allowed RCS flow rates of Yonggwang 1 and 2 (294,800 gpm) are higher than those of Kori 3 and 4 (293,700 gpm) because the flow measurement uncertainties of the former (2.8 percents) are larger than those of the latter (2.4 percents). Fig. 6 shows direct comparison of the measured flows (at SGTPs below 0.5 percents) and the BEF (at 5 percents). In the figure, the measured RCS flows are significantly lower than the BEF, and approach the MMF. The measured flows in Yonggwang 1 and 2, therefore, are observed barely above the

Table 6. PCHB Flow Measurement Results for Ulchin 1 and 2

Cycle No.	Measured RCS Flow, m^3/hr Loop A	Loop B	Loop B	Total	Expected Flow*, m^3/hr	T/S Flow Limit **, m^3/hr
Ulchin 1						
2	23,008	22,921	23,182	69,112		
3	22,684	22,775	22,608	68,068		
4	22,417	22,834	22,520	67,772		
5	22,409	23,153	22,455	68,018	67,677	21,960/loop
6	22,819	22,810	23,040	68,671		
7	23,466	22,089	23,110	68,667		
8	22,851	23,419	22,884	69,155		63,843 (total)
Ulchin 2						
2	22,612	23,459	22,751	68,822		
3	22,500	23,320	23,054	68,874		
4	22,696	23,257	22,899	68,846		
5	22,849	23,149	22,917	68,915	67,677	21,960/loop
6	22,662	22,970	22,562	68,194		
7	22,541	22,547	22,300	67,388		
8	22,413	22,878	22,305	67,596		63,843(total)

(Note) * expected flow for zero SG plugging based on the best estimate flow of 65,955 m3/hr at average SG tube plugging of 10 percents.

** BEF divided by the number of loops, 3, for cycles 2 to 7 and thermal design flow plus flow measurement uncertainty for cycle 8.

minimum allowed RCS flow. Although the number of the data is small, it seems that there is a significant bias of the RCS flow prediction from the measured RCS flow, considering that the measured flows at SGTPs below 0.5 percents will have to be close to or rather above the BEF which is considered as the most likely value at SGTP level of 5 percents. Possible causes of this overprediction are the errors of the modelled RCS flow resistances, RCP characteristic or head-to-flow curves, but further investigation is needed.

5. Concluding Remarks

In this note the inspection results of RCS flow measurements for the domestic W-type reactors were presented with short description of the design, safety analysis and technical specification related to the RCS flow. Based on the current study the following technical approaches and recommendations are proposed:

1) In the current flow indication system where the relative RCS flow against the reference value is indicated on the coarse scale mark, the following calibrations are recommended:

a. At any conditions below hot zero power, the output electrical currents are adjusted to the specified values against the input elbow tap d/p signals, and the specified values are obtained from the linearity function, based on the PCHB flow measurement of the last cycle.

b. The PCHB measurement should be performed as soon as the plant reaches the

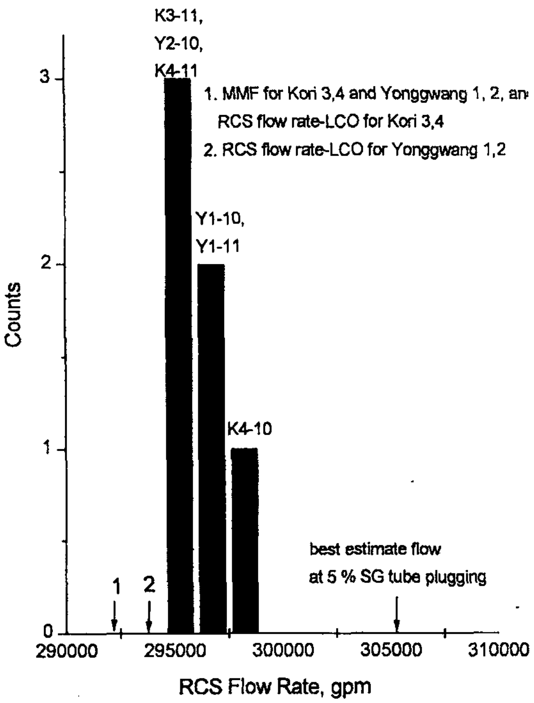

Fig.6. RCS Flow Measurement Data for Kori 3, 4 and Yonggwang 1,2

stable condition at the full power. If the results of the PCHB flow measurements of the last and current cycles is within the calibration error bound, no additional calibration is required. Otherwise, the linearity function of 1) is changed, based on this measurement and it is used for calibration of the elbow tap d/p transmitter for the current cycle and below zero power calibration of the next cycle.

2) The loop-to-loop flow variation in the actual flow measurement which has not been considered in the safety analysis can affect the asymmetric flow transient results. Therefore, the asymmetric RCS loop flow condition should be considered in the safety analysis.

3) If modification of the flow indication system is made so that the absolute RCS flow be easily recognized by the plant operator, the calibration that 100 percents of the span is determined against indicated flow of the flow measurement can be more desirable. The latter approach makes the current safety analysis results become valid for any loop-to-loop flow variation by giving an effect of averaging the loop flows without loop-to-loop variation.

4) Further investigation is needed to find out the cause that the measured RCS flows in Kori 3 and 4, and Yonggwang 1 and 2 do not support the best estimate prediction. Possible causes are the errors of the modelled RCS flow resistances, RCP characteristic or head-to-flow curves.

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