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A Study on the Reduction of the Reactor Power Measurement Uncertainty for Use in the RCS Flow Measurement of KSNP

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Abstract

For the RCS flow measurement by the heat balance method, the reactor power uncertainty of 2% has been used, which includes much conservatism to cover all the operating conditions expected during the plant operation and is used for safety analyses. The reactor power uncertainty for the flow measurement purpose is believed to be reduced to below 2% with the stabilized plant conditions during the RCS flow measurement period. In this paper, a study on the reduction of the reactor power measurement uncertainty has been conducted to be used in the RCS flow measurement of KSNP. All the process parameters relevant to the reactor power have been examined for the plant conditions during the RCS flow measurements. The results of this analysis indicate that the maximum uncertainty is less than 1.4% for all steam generator blowdown conditions, and that the uncertainty can be lowered to below 1% if the high capacity blowdown is not allowed during the RCS flow measurement. From a sensitivity study, it is found that the reactor power measurement uncertainty is most significantly influenced by the blowdown flow uncertainty for the high capacity blowdown, and by the feedwater venturi differential pressure uncertainty for both normal and abnormal blowdown. It is also found that all the parameters which could be directly affected by the venturi fouling have influence on the reactor power measurement uncertainty.

1. Introduction

One of concerns for the Reactor Coolant System (RCS) flow measurements of the Korea Standard Nuclear Power Plant (KSNP) is that the measured RCS flow rate is too close to the upper limit of the allowable operating band. It is attributed to the fact that the RCS flow rate is actually near the high end of the allowable band. Some improvement schemes were proposed to resolve this problem by broadening the allowable band for the flow measurements, which could be achieved by reducing the flow measurement uncertainty[1]. In the present work, one of those schemes is further investigated.

The uncertainties related with the secondary calorimetric heat balance flow rate measurement method (hereafter, the heat balance method) are instrumentation uncertainties for the cold and hot leg coolant temperatures and system pressure, the uncertainty for the reactor power measurement, and the uncertainty for the hot leg temperature correction offset for the thermal stratification in the hot leg. Among these uncertainty parameters, the uncertainties of the hot leg temperature correction offset and reactor power measurement are the major contributors to the overall uncertainty[2]. In this paper, the efforts are focused on the reactor power measurement uncertainty - one of these two important parameters.

The reactor power measurement uncertainty has been historically assumed to be 2% of the licensed power in the design and analysis, whether it is safety-related or not. The origin is the Section I of Appendix K to 10 Code of Federal Regulations (CFR) 50[3], where it reads "For the heat sources ... it shall be assumed that the reactor has been operating continuously at a power level at least 1.02 times the licensed power level (to allow for such uncertainties as instrumentation error) ... ". This guidance is to specify the heat sources during a Loss of Coolant Accident (LOCA) for the Emergency Core Cooling System (ECCS) evaluation models including some conservatism. Therefore, the 2% uncertainty should include all the uncertain sources anticipated in normal and transient operations.

On the other hand, the RCS flow measurement test has the specific purposes of all its own : These are the periodic verifications by a precise measurement of the RCS flow rate before or during commercial operations (1) that the measured flow is within the allowable bands and (2) that the calculated flow in Core Operating Limit Supervisory System (COLSS) and Core Protection Calculator System (CPCS) is conservative. To achieve the goal of precise measurement, it needs the verifications before the test that all the related instrumentation devices have been adjusted according to the calibration guidelines, and that the plant condition is stabilized. Under the circumstances, the 2% power measurement uncertainty is deemed to be too big for the flow measurement purpose. The United States Nuclear Regulatory Commission (USNRC) also has recently amended the rule to allow the reduction of an unnecessarily burdensome regulatory requirement; that is, the licensees are allowed to use a less than 2% uncertainty if they can justify the uncertainties associated with power measurement instrumentation errors are smaller than 2%[4].

The reactor power uncertainty for the flow measurement purpose is believed to be reduced to below 2% with the stabilized plant conditions during the RCS flow measurement period. In this paper, the following works are carried out for the reactor power measurement uncertainty to be used in the RCS flow measurement of KSNP : (1) All the process parameters relevant to the reactor power are examined for the RCS flow measurement purpose. (2) A reduced reactor power measurement uncertainty is proposed for each steam generator (SG) blowdown condition. (3) A sensitivity study is performed to see the degrees of sensitivity of relevant parameters.

2. Analysis

2.1 Reactor Power

In the KSNP, the secondary calorimetric reactor power, named BSCAL, is continuously monitored by the COLSS. This thermal power generated in the reactor core is determined by measuring the SG thermal power and incorporating some correction factors as follows :

$$BSCAL = E_{SG1} + E_{SG2} - Input + Output \quad (1a)$$

The SG thermal power is the heat transferred from the primary side to the secondary side of SG. The energy gains to the RCS control volume, denoted as *Input*, include the heat and/or mass addition by reactor coolant pump, charging flow, pressurizer heater, seal injection heat exchanger. The energy losses, denoted as *Output*, include the heat and/or mass loss by letdown flow, component cooling water system, surface heat loss, coolant leakage. If the net energy input, *NET*, is defined as the energy gains minus the energy losses, Eq. (1a) can be expressed as follows :

$$BSCAL = E_{SG1} + E_{SG2} - NET \quad (1b)$$

Thermal powers of SG 1 and 2 are mutually independent, and the net energy input can be treated as an independent variable. Therefore, the reactor power is expressed as a function of three independent variables, i.e., SG 1 and 2 thermal power, and net energy input :

$$BSCAL = f(E_{SG1}, E_{SG2}, NET) \quad (2)$$

The thermal power of each SG is calculated from the mass and energy balance. The main steam flow is determined by the measured feedwater flow minus the blowdown flow in SG thermal power calculation.

Mass balance : $M_{MS} = M_{FW} - M_{BD}$ (3)

Energy balance : $M_{FW} h_{FW} + E_{SG} = M_{MS} h_{MS} + M_{BD} h_{BD}$ (4)

where the main steam enthalpy and blowdown enthalpy are

$$h_{MS} = x_{MS} h_g + (1 - x_{MS}) h_f , \quad (5)$$

$$h_{BD} = x_{BD} h_g + (1 - x_{BD}) h_f . \quad (6)$$

By substituting Eqs. (3), (5), and (6) into Eq. (4) and solving for the SG thermal power,

$$E_{SG} = M_{FW}\{x_{MS} h_g + (1 - x_{MS}) h_f - h_{FW}\} - M_{BD}(x_{MS} - x_{BD})(h_g - h_f). \quad (7)$$

From the Eq. (7), the SG thermal power is a function of seven variables.

$$E_{SG} = f(M_{FW}, M_{BD}, h_{FW}, h_g, h_f, x_{MS}, x_{BD}) \quad (8a)$$

Feedwater enthalpy is a function of feedwater temperature and pressure. Feedwater flow rate is also a function of feedwater temperature and pressure as shown in Eqs. (9) and (10b). So, the feedwater enthalpy and flow rate are not independent variables. However, as shown in Table 4, the feedwater flow rate uncertainty is much less sensitive to the feedwater temperature and pressure uncertainties than to the venturi differential pressure (DP) transmitter uncertainty. Therefore, the feedwater enthalpy and flow rate can be treated as independent variables in calculating the SG thermal power. The saturated liquid and vapor enthalpy are only a function of SG pressure of saturation condition. Consequently, the SG thermal power is a function of six independent variables, i.e., feedwater flow rate, blowdown flow rate, feedwater enthalpy, SG pressure, main steam quality, and blowdown quality :

$$E_{SG} = f(M_{FW}, M_{BD}, h_{FW}, P_{SG}, x_{MS}, x_{BD}) \tag{8b}$$

The feedwater mass flow rate can be expressed as follows[5] :

$$M_{FW} = C\left\{\frac{C_d F_a d^2}{\sqrt{1-\beta^4}}\right\}\sqrt{\frac{DP_{FW}}{v_{FW}}} \tag{9}$$

In Eq. (9), the feedwater flow rate is expressed as a function of six variables, which are venturi discharge coefficient, venturi thermal expansion factor, venturi throat diameter, the ratio of throat to pipe diameter of venturi, measured DP, and feedwater specific volume :

$$M_{FW} = f(C_d, F_a, d, \beta, DP_{FW}, v_{FW}) \tag{10a}$$

The venturi thermal expansion factor is a function of the feedwater temperature. The ratio of throat to pipe diameter of venturi is a function of the venturi throat and pipe diameter. Specific volume is a function of feedwater temperature and pressure. Thus, the Eq. (10a) can be modified as follows :

$$M_{FW} = f(C_d, d, D, DP_{FW}, T_{FW}, P_{FW}) \tag{10b}$$

The reactor power, BSCAL, can be calculated by using Eqs. (1b), (7), (9), and the measured net RCS thermal input.

2.2 Uncertainty of Reactor Power

From Eq. (2), the uncertainty of reactor power can be obtained as follows :

$$\sigma^2_{BSCAL} = \left(\frac{\partial BSCAL}{\partial E_{SG1}}\right)^2 \sigma^2_{E_{SG1}} + \left(\frac{\partial BSCAL}{\partial E_{SG2}}\right)^2 \sigma^2_{E_{SG2}} + \left(\frac{\partial BSCAL}{\partial NET}\right)^2 \sigma^2_{NET} \tag{11}$$

where σ_I represents the uncertainty of each subscript I. The partial derivative terms are obtained from the Eq. (1b) as $\frac{\partial BSCAL}{\partial E_{SG1}} = \frac{\partial BSCAL}{\partial E_{SG2}} = 1$, $\frac{\partial BSCAL}{\partial NET} = -1$. Therefore,

$$\sigma^2_{BSCAL} = \sigma^2_{E_{SG1}} + \sigma^2_{E_{SG2}} + \sigma^2_{NET} \ . \tag{12}$$

Since the quantitative calculation of the net energy input uncertainty, σ_{NET}, is very complicated, the uncertainty is not calculated but conservatively assumed. The uncertainty of SG thermal power can be obtained using Eq. (8b) in the following form :

$$\begin{aligned}\sigma^2_{E_{SG}} = &\left(\frac{\partial E_{SG}}{\partial M_{FW}}\right)^2 \sigma^2_{M_{FW}} + \left(\frac{\partial E_{SG}}{\partial M_{BD}}\right)^2 \sigma^2_{M_{BD}} + \left(\frac{\partial E_{SG}}{\partial h_{FW}}\right)^2 \sigma^2_{h_{FW}} \\ &+ \left(\frac{\partial E_{SG}}{\partial P_{SG}}\right)^2 \sigma^2_{P_{SG}} + \left(\frac{\partial E_{SG}}{\partial x_{MS}}\right)^2 \sigma^2_{x_{MS}} + \left(\frac{\partial E_{SG}}{\partial x_{BD}}\right)^2 \sigma^2_{x_{BD}}\end{aligned} \tag{13}$$

From Eq. (7), the partial derivative terms for each independent variable are expressed as follows :

$$\frac{\partial E_{SG}}{\partial M_{FW}} = x_{MS} h_g + (1 - x_{MS}) h_f - h_{FW} \tag{14a}$$

$$\frac{\partial E_{SG}}{\partial M_{BD}} = -(x_{MS} - x_{BD})(h_g - h_f) \tag{14b}$$

$$\frac{\partial E_{SG}}{\partial h_{FW}} = -M_{FW} \tag{14c}$$

$$\frac{\partial E_{SG}}{\partial P_{SG}} = \frac{\partial E_{SG}}{\partial h_f}\ \frac{\partial h_f}{\partial P_{SG}} + \frac{\partial E_{SG}}{\partial h_g}\ \frac{\partial h_g}{\partial P_{SG}} \tag{14d}$$

$$\frac{\partial E_{SG}}{\partial x_{MS}} = (M_{FW} - M_{BD})(h_g - h_f) \tag{14e}$$

$$\frac{\partial E_{SG}}{\partial x_{BD}} = M_{BD}(h_g - h_f) \tag{14f}$$

where, $\frac{\partial E_{SG}}{\partial h_g} = x_{MS}(M_{FW} - M_{BD}) + x_{BD} M_{BD}$

$$\frac{\partial E_{SG}}{\partial h_f} = (1 - x_{MS}) M_{FW} + (x_{MS} - x_{BD}) M_{BD}$$

Among the uncertainties in Eq. (13), the uncertainties of the blowdown flow, SG pressure, main steam quality, and blowdown quality are input values which can be determined from appropriate assumptions or instrument vendor data. The uncertainty of the feedwater enthalpy is calculated as follows :

$$\sigma_{h_{FW}}{}^2 = \left(\frac{\partial h_{FW}}{\partial T_{FW}}\right)^2 \sigma_{T_{FW}}{}^2 + \left(\frac{\partial h_{FW}}{\partial P_{FW}}\right)^2 \sigma_{P_{FW}}{}^2 \tag{15}$$

The partial derivatives for the enthalpy in Eqs. (14d) and (15) are obtained from steam table. The uncertainties of the feedwater temperature and pressure in Eq. (15) are determined from each instrument vendor data.

The uncertainty of the feedwater flow is calculated using Eq. (10b) :

$$\sigma^2_{M_{FW}} = \left(\frac{\partial M_{FW}}{\partial C_d}\right)^2 \sigma^2_{C_d} + \left(\frac{\partial M_{FW}}{\partial d}\right)^2 \sigma^2_d + \left(\frac{\partial M_{FW}}{\partial D}\right)^2 \sigma^2_D + \left(\frac{\partial M_{FW}}{\partial DP_{FW}}\right)^2 \sigma^2_{DP_{FW}} + \left(\frac{\partial M_{FW}}{\partial T_{FW}}\right)^2 \sigma^2_{T_{FW}} + \left(\frac{\partial M_{FW}}{\partial P_{FW}}\right)^2 \sigma^2_{P_{FW}} \quad (16)$$

For calculational purpose, it is convenient to rearrange Eq. (9) by applying logarithmic function in the following form :

$$\ln(M_{FW}) = \ln C + \ln C_d + 2\ln d + \ln(F_a) + \frac{1}{2}\{\ln(DP_{FW}) - \ln(v_{FW}) - \ln(1-\beta^4)\} \quad (17)$$

Then, the partial derivative terms for each variable are converted to

$$\frac{\partial M_{FW}}{\partial X_i} = M_{FW} \frac{\partial \ln M_{FW}}{\partial X_i} \quad . \quad (18)$$

Substituting Eq. (18) into Eq. (16) gives

$$\frac{\sigma^2_{M_{FW}}}{M_{FW}^2} = \left(\frac{\partial \ln M_{FW}}{\partial C_d}\right)^2 \sigma^2_{C_d} + \left(\frac{\partial \ln M_{FW}}{\partial d}\right)^2 \sigma^2_d + \left(\frac{\partial \ln M_{FW}}{\partial D}\right)^2 \sigma^2_D + \left(\frac{\partial \ln M_{FW}}{\partial DP_{FW}}\right)^2 \sigma^2_{DP_{FW}} + \left(\frac{\partial \ln M_{FW}}{\partial T_{FW}}\right)^2 \sigma^2_{T_{FW}} + \left(\frac{\partial \ln M_{FW}}{\partial P_{FW}}\right)^2 \sigma^2_{P_{FW}} \quad . \quad (19)$$

Using Eq. (17), the partial derivative terms for each independent variable are

$$\frac{\partial \ln M_{FW}}{\partial C_d} = \frac{1}{C_d} \quad , \quad (20a)$$

$$\frac{\partial \ln M_{FW}}{\partial d} = \frac{2}{d(1-\beta^4)} \quad , \quad (20b)$$

$$\frac{\partial \ln M_{FW}}{\partial D} = -\frac{2\beta^4}{D(1-\beta^4)} \quad , \quad (20c)$$

$$\frac{\partial \ln M_{FW}}{\partial DP_{FW}} = \frac{1}{2\,DP_{FW}} \quad , \quad (20d)$$

$$\frac{\partial \ln M_{FW}}{\partial P_{FW}} = -\frac{1}{2\,v_{FW}} \frac{\partial v_{FW}}{\partial P_{FW}} \quad , \quad (20e)$$

$$\frac{\partial \ln M_{FW}}{\partial T_{FW}} = \frac{1}{F_a}\frac{\partial F_a}{\partial T_{FW}} - \frac{1}{2\, v_{FW}}\frac{\partial v_{FW}}{\partial T_{FW}} \ . \tag{20f}$$

The uncertainties in Eq. (19) can be determined from feedwater venturi or instrument vendor data. The partial derivative of the thermal expansion factor in Eq. (20f) can be calculated by first-order linear approximation with respect to feedwater temperature. And the partial derivatives of feedwater specific volume in Eqs. (20e) and (20f) can be obtained from steam table.

Using Eqs. (12), (13), (14), (15), (19), (20), and the input data described in the next section, the uncertainty of the reactor power can be determined.

2.3 Input Data

All input data in this analysis are the same as those used for the YGN 3&4 analysis. The bases for nominal values and uncertainties for each parameter are discussed below and summarized in Tables 1 and 2.

Blowdown Flow

Two blowdown nozzles are provided for each SG; one at cold side and the other at hot side of SG secondary side tube sheet region. SG blowdown system is designed to flow, during normal operation, continuously 0.2% of Maximum Steaming Rate (MSR) for the control of the secondary chemical condition, which is called the normal blowdown operation. If the secondary chemical condition is not acceptable, the blowdown flow rate is increased to about 1% of MSR, which is called the abnormal blowdown operation. A high capacity blowdown operation is also designed to perform once a week for a short period to eliminate the sludge accumulated on the SG tube sheet. During the high capacity blowdown on one SG, the continuous normal or abnormal blowdown is being done on the other SG. Since the blowdown flow rate can not be measured directly, the blowdown flow uncertainty is assumed conservatively. For normal and abnormal blowdown conditions, 50% of the blowdown flow is assumed as the uncertainty. For high capacity blowdown condition, 10% of the blowdown flow is assumed as the uncertainty. The blowdown flow rates and uncertainties for all blowdown conditions are summarized in Table 1, which were used in YGN 3&4 analysis.

Blowdown Quality

The state of blowdown flow is expected to be either slightly subcooled or saturated at the cold side nozzle, and saturated with small amount of vapor at hot side nozzle. It may also vary with the blowdown flow rate. Therefore, it is very difficult to exactly estimate the blowdown fluid conditions for each blowdown operating condition and location. Since there is much conservatism on the blowdown flow rate, the blowdown flow is assumed to be saturated with quality zero.

Others

The design value of the main steam quality is 0.9975. However, the measured steam quality during startup test is much greater than the design value. Therefore, the uncertainty of the main steam quality is expected to be very small. In uncertainty analysis, the nominal value of the main steam quality is set to 0.9975 and the uncertainty value is conservatively set to 0.0025. The venturi thermal expansion factor is approximated as a first order equation with respect to feedwater temperature ($F_a = A + B\, T_{FW}$, where A and B are constant). The uncertainties of the constant A and B can be neglected. The sub-items of net energy input (NET) for uncertainty analysis are determined during startup test periods. Since the quantitative calculation of the net energy input uncertainty is very complicated, the uncertainty is conservatively assumed to be 50% of the net energy input. The parameters related with the feedwater venturi and instrumentation can be determined from vendor data.

3. Results and Discussion

The analysis results of reactor power measurement uncertainty at 100% power are summarized for various blowdown conditions in Table 3 and Figure 1, where the uncertainties are 2σ values because all the element uncertainties of instrumentation and process parameters used in this analysis are 2σ values.

The uncertainties for normal and abnormal blowdown conditions are slightly increased compared with that of zero blowdown condition. But for the high capacity blowdown condition, the uncertainty increases considerably. The maximum uncertainty for all blowdown conditions is less than 1.4%. If the high capacity blowdown operation which is not allowed during the RCS flow measurement tests is excluded, the maximum reactor power uncertainty decreases to below 1%.

The contributions of each parameter to the total uncertainties of reactor power are also listed in Table 3. For the high capacity blowdown condition, the blowdown flow rate is the most influential and the feedwater flow rate is the next. However, for the normal and abnormal blowdown conditions, the feedwater flow rate becomes the most influential factor. The feedwater flow uncertainty and their contributors are provided in Table 4, where it is shown that the feedwater flow uncertainty is attributed mostly to the venturi DP uncertainty.

Sensitivity Study

The sensitivity of each independent variable to the reactor power uncertainty is investigated and the results are shown in Figures 2 to 12.

Figure 2 shows the variations in the reactor power uncertainties with various normal/abnormal blowdown uncertainties. It is found that the blowdown uncertainties have little influence on the reactor power uncertainty for normal and abnormal blowdown cases. Therefore, the conservative assumption of 50% uncertainty for these cases is acceptable. While as shown in Figure 3, the uncertainty of high capacity blowdown has very sensitive influence on the reactor power uncertainty. For the RCS flow measurement purpose, however, the consideration of this parameter is not necessary since the high capacity blowdown case can be excluded.

Figure 4 shows the effect of the measurement uncertainty of the feedwater venturi DP transmitter. It is found that the measurement uncertainty of the feedwater venturi DP transmitter is one of sensitive parameters. Reducing the measurement channel uncertainty is difficult without hardware change. If other feedwater flow measurement device with good accuracy is adopted, the reactor power uncertainty can be reduced considerably.

The uncertainties of feedwater temperature (Figure 7), venturi throat diameter (Figure 9), venturi discharge coefficient (Figure 11), and net energy input (Figure 12) are found to be somewhat sensitive parameters. The uncertainties of feedwater pressure (Figure 5), SG pressure (Figure 6), main steam quality (Figure 8), and feedwater venturi pipe diameter (Figure 10) are found to be less sensitive to the reactor power uncertainty.

It should be noted that the parameters which may be affected by venturi fouling such as the venturi throat diameter, venturi discharge coefficient, and DP transmitter measured output are all sensitive parameters for the reactor power uncertainty.

4. Conclusion

A study on the reduction of the reactor power measurement uncertainty has been conducted to be used in the RCS flow measurement of KSNP. All the process parameters relevant to the reactor power have been examined for the plant conditions during the RCS flow measurements. Based on the uncertainty and sensitivity analysis for the reactor power, it can be summarized as follows :

1) The maximum uncertainty is less than 1.4% for all blowdown conditions.
2) The uncertainty can be lowered from 2% to below 1% if the high capacity blowdown is excluded.
3) The reactor power measurement uncertainty is the most significantly influenced by the blowdown flow uncertainty for the high capacity blowdown, and by the feedwater venturi differential pressure for both normal and abnormal blowdown conditions.
4) The parameters which could be directly affected by venturi fouling have influence on the reactor power measurement uncertainty.

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Nomenclature

BSCAL : Reactor thermal power calculated by COLSS using the secondary heat balance
C : Constant
C_d : Venturi discharge coefficient
d : Venturi throat diameter
D : Venturi pipe diameter
DP : Differential Pressure
E : Thermal power

F_a : Venturi thermal expansion factor
h : Enthalpy
Input : Energy gains to the control volume
M : Mass flow rate
NET : Net energy input to control volume = Input - Output
Output : Energy losses from the control volume
P : Pressure
T : Temperature
x : Quality
X_i : i-th variable

Greek Symbols

β : Ratio of venturi throat to pipe diameter = d/D
v : Specific volume
σ : Uncertainty or standard deviation

Subscripts

BD : Blowdown
f : Saturated liquid
FW : Feedwater
g : Saturated vapor
MS : Main steam
SG : Steam generator
1 or 2 : Steam generator 1 or 2

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[3] Appendix K to 10 CFR 50, ECCS Evaluation Models.
[4] SECY-00-0057, Revision of Part 50, Appendix K, "ECCS Evaluation Models", March 3, 2000.
[5] Instruction Manual for Venturi Flow Meters for YGN 3&4, Sep. 12, 1991.

Table 1. Blowdown Flow Rate and Uncertainty

Blowdown Condition	Blowdown Mass Flow Rate, M_{BD} lbm/hr/SG	Uncertainty, $\sigma_{M_{BD}}$	
		lbm/hr/SG	%
zero blowdown	0	0	±0
normal blowdown	12,600	±6,300	±50
abnormal blowdown	64,080	±32,040	±50
high capacity blowdown	1,061,280	±106,128	±10

Table 2. Input Data List

Parameter	Description	Nominal Value	Uncertainty	Remark
Cd	discharge coefficient	0.9987	0.25 %	constant
F_a	thermal expansion factor	1)	-	variable
d	venturi throat diameter	10.25 in	0.005 in	constant
D	venturi pipe diameter	17.25 in	0.01 in	constant
DP_{FW}	venturi DP	475.635 inH_2O	9.3 inH_2O	100% power condition
T_{FW}	feedwater temperature	450 ˚F	3.89 ˚F	100% power condition
P_{FW}	feedwater pressure	1070 psia 2)	250 psi	100% power condition
P_{SG}	SG pressure	1070 psia	50 psi	100% power condition
x_{MS}	main steam quality	0.9975	0.0025	constant
x_{BD}	blowdown quality	0.0	0.0	constant
NET	net energy input	17 MW	8.5 MW	constant

* Note : 1) F_a = 0.9986 + 0.000019 T_{FW}, F_a = 1.00715 at T_{FW} = 450 °F

2) feedwater pressure is assumed to be the same as the SG pressure in uncertainty analysis.

Table 3. BSCAL Uncertainty and Contributors

Blowdown Condition	Uncertainties and Contributors, % of reactor power @ 2σ								
	Contributors to SG Power Uncertainty						Contributors to BSCAL Uncertainty		BSCAL uncertainty
	M_{BD}	M_{FW}	h_{FW}	x_{MS}	x_{BD}	P_{SG}	E_{SG1} or E_{SG2}	NET	
zero	0.0	**0.519**	0.287	0.105	0.0	0.134	0.617	0.302	**0.923**
normal	0.042			0.105		0.132	0.619		**0.924**
abnormal	0.212			0.104		0.127	0.651		**0.969**
high capacity	**0.702**			0.088		0.029	0.924		**1.341**

Table 4. Feedwater Flow Uncertainty and Contributors

Uncertainty and Contributors, % of feedwater flow @ 2σ						
Contributors to Feedwater Flow Uncertainty						Feedwater Flow Uncertainty
Cd	d	D	DP_{FW}	T_{FW}	P_{FW}	
0.25	0.111	0.017	**0.978**	0.171	0.092	1.034

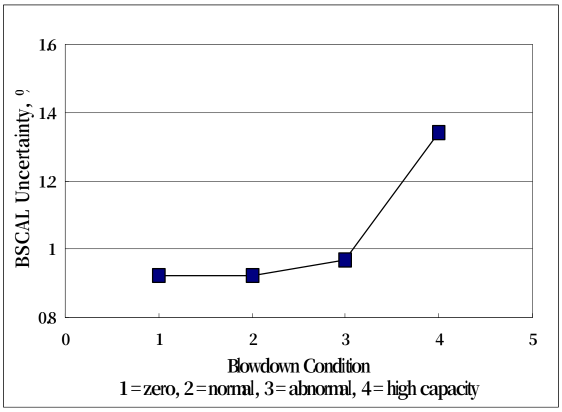


Figure 1. BSCAL Uncertainty at 100% Power

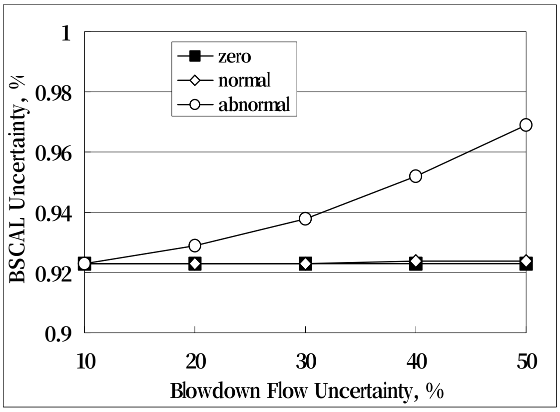


Figure 2. Sensitivity to Blowdown Flow Uncertainty

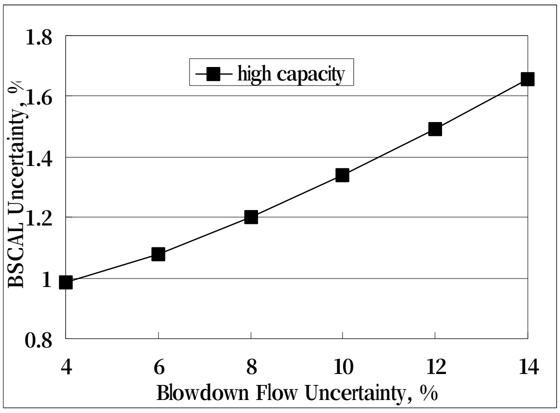


Figure 3. Sensitivity to High Capacity Blowdown Flow Uncertainty

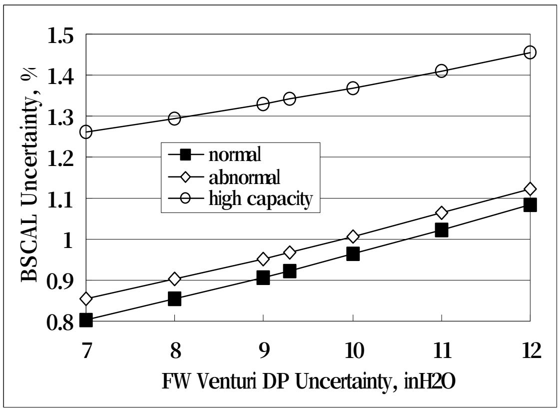


Figure 4. Sensitivity to Feedwater Venturi DP Transmitter Uncertainty

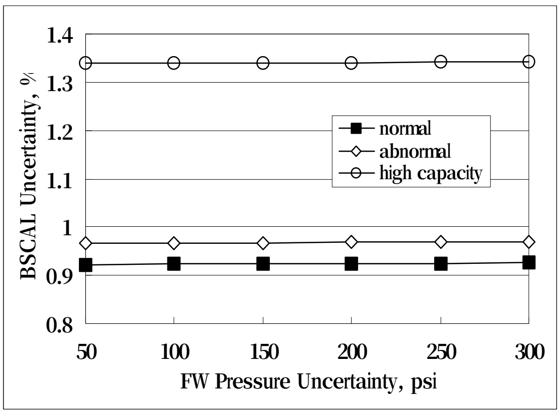


Figure 5. Sensitivity to Feedwater Pressure Uncertainty

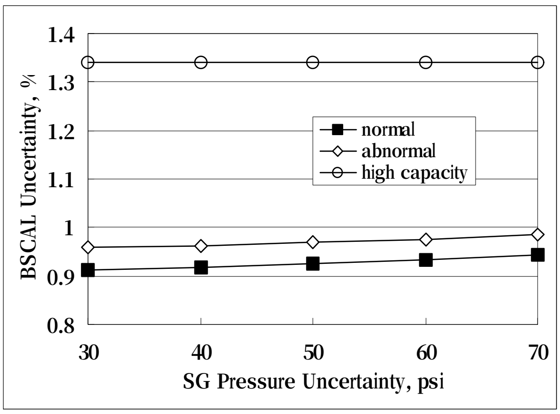
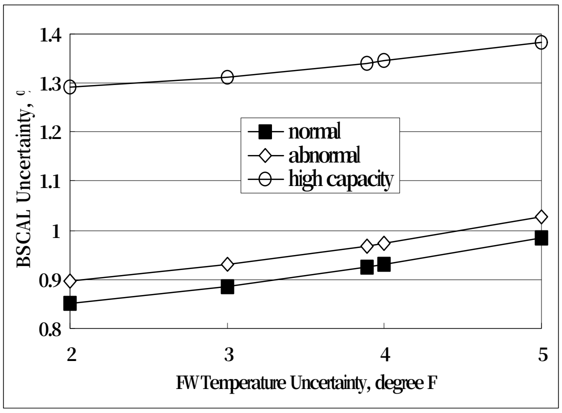


Figure 6. Sensitivity to SG Pressure Uncertainty



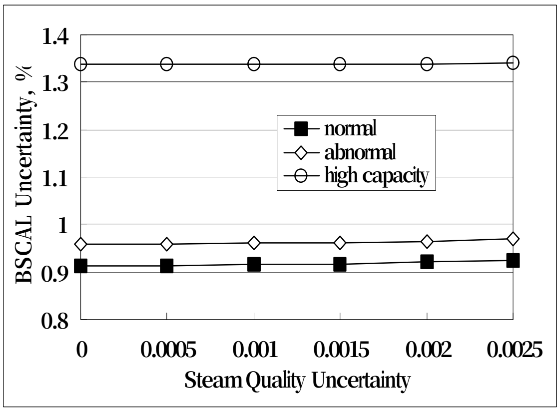
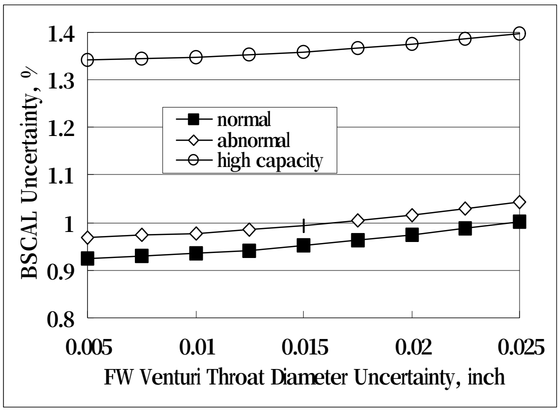


Figure 7. Sensitivity to Feedwater Temperature Uncertainty

Figure 8. Sensitivity to Main Steam Quality Uncertainty



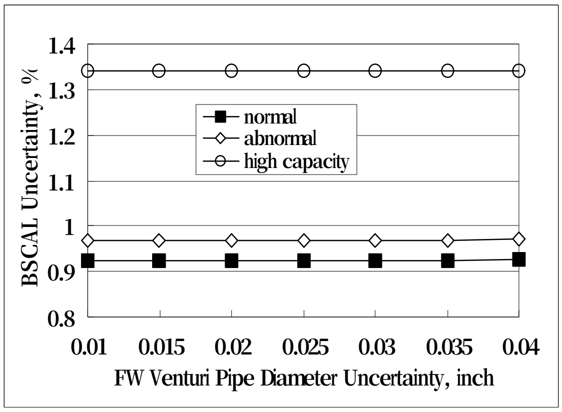
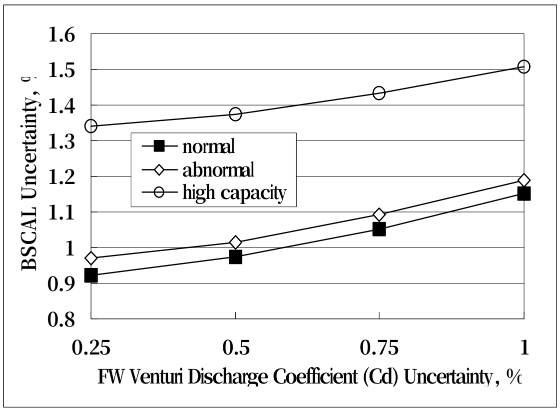


Figure 9. Sensitivity to Feedwater Venturi Throat Diameter Uncertainty

Figure 10. Sensitivity to Feedwater Venturi Pipe Diameter Uncertainty



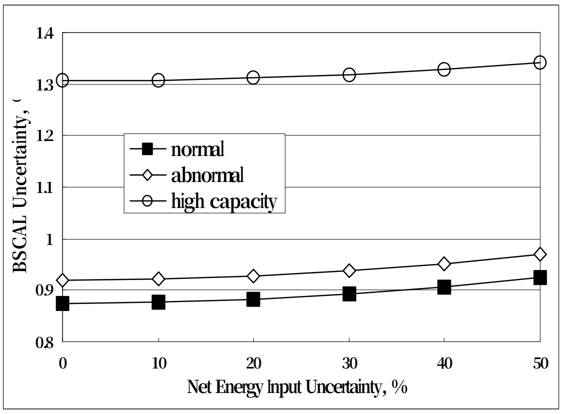


Figure 11. Sensitivity to Feedwater Venturi Discharge Coefficient Uncertainty

Figure 12. Sensitivity to Net Energy Input Uncertainty