Docket Number 50-346
License Number NPF-3
Serial Number 3198
Enclosure 3

Enclosure 3

AREVA NP Calculation 32-5012428-08
Davis-Besse Heat Balance Uncertainty
April 2007

AREVA

CALCULATION SUMMARY SHEET (CSS)

Document Identifier 32-5012428-08

Title Davis Besse Heat Balance Uncertainty Calculation

PREPARED BY:	REVIEWED BY:
	METHOD: ☒ DETAILED CHECK ☐ INDEPENDENT CALCULATION
NAME Bret L. Boman	NAME Todd Matthews
SIGNATURE B L Boman	SIGNATURE M. Todd Matthews
TITLE Eng Mgr DATE 4/9/07	TITLE Principal Eng DATE 4/9/07
COST CENTER 41917 REF. PAGE(S) 37-38	TM STATEMENT: REVIEWER INDEPENDENCE [signature]
	NAME 04/09/07

PURPOSE AND SUMMARY OF RESULTS:

Purpose – The objective of this calculation was to calculate Davis Besse's full-power reactor core power uncertainty value, also referred to as the "heat balance uncertainty," based on the planned installation of Caldon's ultrasonic feedwater flow metering equipment. Specific objectives were: (1) determine the minimum practical full-power core thermal power uncertainty in order to define the limits of Davis Besse's MUR power uprate; (2) determine the sensitivity of the core thermal power uncertainty to the individual measurements' uncertainty. This will assist Davis Besse in making decisions regarding the maintenance and modification of the instrumentation used in the core thermal power calculation; and (3) provide an accepted core thermal power uncertainty methodology to be used in future evaluations.

Summary of Results- The ASME Performance Test Code Methodology was used to calculate the expected core thermal power uncertainty to be achieved using the Caldon CheckPlus™ System ultrasonic flow meter. The analysis concluded that using the following instrument uncertainty values, the core thermal power uncertainty would be 0.369%, thus allowing a power uprate of 1.63% to be pursued.

- Feedwater Flow Uncertainty of 0.29%
- Feedwater Pressure Uncertainty of 14.6 psi (systematic) and 1.35 psi (random)
- Steam Pressure Uncertainty of 1.42 psi (systematic) and 1.52 psi (random)
- Steam Temperature Uncertainty of 1.56°F (systematic) and 0.153°F (random)

The other parameters (makeup, letdown, RCP heat, and ambient losses) are minor contributors. Their uncertainties are defined in the body of the report.

Rev. 01 – added the case for the MVP Uprate conditions. Rev. 02 – As-tested Caldon uncertainties evaluated. Rev. 03 – removed assumption regarding random uncertainty values. Rev 04 & 05 evaluated a change in steam pressure uncertainties as directed by FENOC. Rev 06 complete revision to address comments and eliminate inconsistencies. Rev 07 incorporates the feedwater pressure uncertainty change into the MVP case. Rev 08 revised the feedwater flow uncertainty from 0.26% to 0.29%, updates References 3 and 21, and deletes Caldon proprietary attachments.

THE FOLLOWING COMPUTER CODES HAVE BEEN USED IN THIS DOCUMENT:		THE DOCUMENT CONTAINS ASSUMPTIONS THAT MUST BE VERIFIED PRIOR TO USE ON SAFETY-RELATED WORK
CODE/VERSION/REV	CODE/VERSION/REV	☐ YES
		☒ NO

RECORD OF REVISIONS

Revision	Date	Purpose
00	June 2001	Original Release
01	Oct. 2001	Define the uncertainty for the MVP operating conditions. Changed a previous assumption on steam temperature, steam pressure, and feedwater pressure to an input by referencing a Davis Besse calculation package.
02	April 2003	In the previous revision feedwater flow and temperature uncertainty values were assumed. Based on testing the assumed values have been confirmed as bounding. See assumption number 3.
03	May 2003	Based on input from FENOC the assumption regarding the validity of the random uncertainty values was removed.
04	July 2006	Removed Proprietary header. Fixed typos. Revised Uncertainties for feedwater pressure.
05	August 2006	Revised Uncertainties for feedwater pressure (case 10). Added case 11 for as-tested Caldon LEFM uncertainties.
06	September 2006	Completely revised document to redefine the base case and remove inconsistencies created by multiple revisions.
07	October 2006	Revised the MVP section for the revised feedwater pressure uncertainty (pages. 27 & 30 only).
08	April 2007	Revised the feedwater flow uncertainty from 0.26% to 0.29% based on the replacement transducers. Updated References 3 and 21 to latest revisions, deleted previous attachments 1 and 4, changed 'FRA-ANP' to 'AREVA NP' and 'Appendix K' to 'MUR'.

TABLE OF CONTENTS

Section Page

1.0 OBJECTIVES

The objective of this calculation was to calculate Davis Besse's full-power reactor core power uncertainty value, also referred to as the "heat balance uncertainty," based on the planned installation of Caldon's ultrasonic feedwater flow metering equipment. Specific objectives were:

- Determine the minimum practical full-power core thermal power uncertainty in order to define the limits of Davis Besse's MUR power uprate.
- Determine the sensitivity of the core thermal power uncertainty to the individual measurements' uncertainty. This will assist Davis Besse in making decisions regarding the maintenance and modification of the instrumentation used in the core thermal power calculation.
- Provide an accepted core thermal power uncertainty methodology to be used in future evaluations.

2.0 ASSUMPTIONS AND INPUTS

The assumptions and inputs used in these calculations are presented in this section.

2.1 ASSUMPTIONS

The following assumptions were used in these calculations. None require further verification before using the results of this calculation.

(1) The core thermal power analysis (CTPA) software uses three methods for computing core power (see Section 3.3). It is assumed that the secondary power method is being used at 100% power. This assumption is reasonable because page 5 of Reference 7 states,

> "A switch is incorporated in CTPA so that the output from the secondary side heat balance is used in the core power distribution calculation above a specified power level, and the output from the delta T method is used at or below the specified power level."
>
> "It is recommended that this power level be set at 50% (this is the initial setting). However, the switch is adjustable and may be set at any power level equal to or greater than 15% of rated power."

(2) The correspondence between the plant computer IDs and the variables used in CTPA was not formally provided to AREVA NP. Thus, the information shown is assumed.

(3) The following values were assumed. Because the results are not sensitive to these values as shown by the calculations, herein, they do not require verification.

Feedwater Pressure = 1005 psia

Makeup Temperature = 100°F
Makeup Pressure = 2250 psia
Letdown Pressure = 2250 psia

Makeup Flow Systematic Uncertainty = 5%
Makeup Flow Standard Deviation = 10%
Makeup Temperature Systematic Uncertainty = 5°F
Makeup Temperature Standard Deviation = 2°F
Makeup Pressure Systematic Uncertainty = 50 psi
Makeup Pressure Standard Deviation = 50 psi
Letdown Flow Systematic Uncertainty = 5%
Letdown Flow Standard Deviation = 10%
Letdown Temperature Systematic Uncertainty = 5°F
Letdown Temperature Standard Deviation = 2°F
Letdown Pressure Systematic Uncertainty = 50 psi
Letdown Pressure Standard Deviation = 50 psi

(4) In addressing the steam pressure instrument location effects, a ± 20 % uncertainty on the steam line pressure losses was assumed based on engineering judgment. The heat balance uncertainty is insensitive to this assumption.

(5) In calculating the steam line unrecoverable losses, the elbows were assumed to have a 1.5 diameter bend radius (R/D = 1.5) based on past experience with piping systems. The previous assumption accounts for a variation in steam line pressure loss that would encompass any variation in steam line bend radius. The heat balance uncertainty is insensitive to this assumption.

(6) Letdown flow is measured downstream of the letdown cooler and pressure reducing orifice. The conditions used for evaluating the letdown density were 120°F and 150 psia. The potential variations in these conditions would not affect the heat balance uncertainty calculation.

2.2 INPUTS

The following inputs were used to calculate the core thermal power uncertainty:

(1) The Caldon LEFM CheckPlus™ System ultrasonic feedwater flow meter provides a measurement of the feedwater flow and feedwater temperature. The uncertainty values for these measurements were not finalized at the time of the original calculation and were thus based on Revision 0 of Reference 21. The **initial** values used were:

Combined uncertainty feedwater flow and feedwater temperature = 0.32% full power

Feedwater Flow Rate Systematic Uncertainty = 0.30%

Absolute Standard Deviation of Mean Feedwater Flow Measurements = 0 (based on Caldon input, the random effects are near negligible and included in the systematic uncertainty)

Feedwater Temperature Systematic Uncertainty = 0.6°F

Absolute Standard Deviation of Mean Feedwater Temperature Measurements was determined to be 0.24728°F (see the calculation section) in order to achieve the combined uncertainty of 0.32%.

After the original calculation, the Davis Besse Caldon LEFM CheckPlus™ System ultrasonic feedwater flow meter was tested at Alden labs. Based on this testing, the following values used determined (Reference 21, Section 2, Result 4):

Combined uncertainty feedwater flow and feedwater temperature = 0.29% full power

Feedwater Flow Rate Systematic Uncertainty = 0.26%

Absolute Standard Deviation of Mean Feedwater Flow Measurements = 0 (based on Caldon input, the random effects are near negligible and included in the systematic uncertainty)

Feedwater Temperature Systematic Uncertainty = 0.10°F

Random Feedwater Temperature Uncertainty = 0.56°F. This corresponds to two standard deviations. Thus, the Absolute Standard Deviation of Mean Feedwater Temperature

Measurements = 0.28°F (i.e., 0.56/2). However, to achieve the combined uncertainty of 0.29%, this value was increased to 0.46°F (see case 3).

However, subsequently the transducers were changed and Caldon revised the feedwater flow uncertainty from 0.26% to 0.29%, Reference 22. Thus, the **final** values used were:

Feedwater flow systematic flow uncertainty = 0.29%

Feedwater Temperature Systematic Uncertainty = 0.10°F

Random Feedwater Temperature Uncertainty = 0.46°F

(2) The following random uncertainties for steam temperature, steam pressure, and feedwater pressure were provided by Davis Besse, Attachment 3. Note: that these values are based on the existing instrumentation and because they are based on plant measurement variations include both random error and some part of the systematic uncertainty. While some part of the systematic uncertainty is double-accounted, this is conservative.

Random Uncertainties

Steam Temperature = 0.153°F

Steam Pressure = 1.52 psi

Feedwater Pressure = 1.35 psi

(3) Aside from the feedwater flow uncertainty, the steam measurements have the largest impact on the core thermal power uncertainty. The following instrumentation uncertainties were used in the base calculations, References 20 and 23.

Two values are shown below: (1) “single” which refers to a single instrument, and (2) “dual” which refers to the total uncertainty based on one instrument per feedwater/steam loop. Since each loop's instruments will normally be operable, the “dual” uncertainties were used in the base analyses. The steam temperature uncertainty was also varied in the calculations to demonstrate its impact.

The rationale for using the “dual” loop uncertainties is as follows. The Caldon feedwater flow and feedwater temperature values were provided as a lumped parameter for total feedwater flow rather than on a per feedwater train basis. Thus, the heat balance uncertainty calculations were performed on a total feedwater flow basis. The uncertainties for steam temperature, steam pressure, and feedwater pressure were provided as both "single" which refers to individual measurements in each feedwater/steam train and as "dual" in which individual uncertainties were combined using the square root sum of the squares. For example, the "single" steam temperature is 2.2°F while the "dual" value is 1.56°F. The "dual" value is the "single" value divided by the square root of 2 which is equivalent to $2.2/(2.)^{0.5}$. If the heat balance had been performed on a per feedwater train basis, the "single" values would have been used but during the uncertainty calculation process the "single" values would have been statistically combined to effectively yield the "dual" values.

Note: to achieve full power operation, the loops would be operating at comparable conditions. Thus, the steam temperature, steam pressure, feedwater flow, etc. would be nearly the same for the "A" and "B" loops.

Systematic Uncertainties (Refs. 20 and 23)

Feedwater Pressure = 20.63 psi (single); 14.60 psi (dual)

Steam Temperature = 2.2°F (single); 1.56°F (dual)

Steam Pressure = 2 psi (single); 1.42 psi (dual)

(4) Nominal Letdown Flow Rate = 45 gpm (Reference 9)

= 45 gal/min ÷ 7.4805 gal/ft^3 * 61.7 lbm/ft^3 * 60 min/hr = 22,270 lbm/hr

based on a letdown density = 61.7 lbm/ft^3 (at 150, psia and 120°F).

Note: the effects of Boron on makeup and letdown water density were neglected. Due to the insensitivity of makeup and letdown flow on the total heat balance uncertainty, there is no effect of this omission.

(5) Nominal Makeup Flow Rate = 22,270 lbm/hr
(Set equal to letdown flow rate)

= 22,270 lbm/hr ÷ 62.4 lbm/ft^3 * 7.4805 gal/ft^3 ÷ 60 min/hr = 44.5 gpm

based on a makeup density = 62.4 lbm/ft^3 (at 2250, psia and 100°F)

(6) RC Pump power. From Appendix B and Reference 6,

QRCP = 0.8*6.181 Mw/RCP * 4 RCP * 1000 kw/Mw * 3413 Btu/hr/kw
= 6.75e7 Btu/hr

(7) The systematic uncertainty in RC pump heat was taken from Reference 6 as,

θ_{QRCP} = 4.928e6 Btu/hr

(8) Reference 6 provides an ambient heat loss rate of 5.12e6 Btu/hr with an uncertainty of 2.5e6 Btu/hr. However, Reference 24 uses an ambient heat loss of 0.653 MW_t (2.23e6 Btu/hr), which is used herein. Both values were shown to have a negligible effect on the core power uncertainty.

(9) Since the RCP heat input and RCS heat losses are not typically measured values and because they have a negligible effect on the core power uncertainty, no random uncertainties were used.

3.0 METHODOLOGY

A discussion of heat balance uncertainty methodology is presented herein.

3.1 Industry Standard

The ASME provides a standard methodology for estimating instrument-related uncertainties, Reference 1. Both individual instruments as well as resultants from multiple instruments are treated. Instrument uncertainties are classified as either systematic related or random errors. Systematic errors are defined as that portion of the total measurement uncertainty that remains constant in repeated measurements of the true value. Systematic errors may arise from imperfect calibration corrections, data acquisition systems, data reduction techniques, etc. Random errors are defined as that portion of the total measurement uncertainty that varies in repeated measurements of the true value. Random errors may arise from non-repeatability in the measurement system, environmental conditions, data reduction techniques, and measurement methods.

Provisions for co-dependent errors that may occur due to using the same apparatus to measure different parameters or calibrating different parameters against the same standard are also presented.

3.2 Caldon Experience

In performing MUR uprates for other plants, Caldon calculated the power uncertainties for their Check and CheckPlus™ Systems, References 2 and 3. However, neither of these reports addressed the B&W plants. Since the OTSG provides superheated steam, the equations presented therein are not applicable.

3.3 AREVA NP Experience

AREVA NP has performed secondary heat balance calculations including uncertainty calculations for secondary thermal power, core thermal power, and RCS flow for a number of B&W plants. Examples of these are References 4-6. The methodology used in these calculations is consistent with those of the ASME, Reference 1. The governing equation is presented and then differentiated with respect to the contributing measurements. The products of the partial derivatives and individual measurement uncertainties are squared, summed, and then square-rooted to solve for the core thermal power uncertainty. For example, from Reference 6, the uncertainty in steam generator "A" secondary power is:

$$E(Q_A) = [(\partial Q_A/\partial Wfw \times \varepsilon_{Wfw})^2 + (\partial Q_A/\partial Ts \times \varepsilon_{Ts})^2 + (\partial Q_A/\partial Tfw \times \varepsilon_{Tfw})^2 + (\partial Q_A/\partial Ps \times \varepsilon_{Ps})^2 + (\partial Q_A/\partial Pfw \times \varepsilon_{Pfw})^2]^{0.5}$$

Where

$E(Q_A)$ = steam generator thermal power uncertainty
Q_A= steam generator thermal power
Wfw = feedwater flow
Ts = steam temperature
Tfw = feedwater temperature
Ps = steam pressure
Pfw = feedwater pressure
ε_i = measurement uncertainty for feedwater flow, feedwater pressure, feedwater temperature, steam pressure, and steam temperature

3.4 Davis Besse Heat Balance Equations

Davis Besse plant computer software was reviewed to define core thermal power calculation methodology and corresponding input variables. The nuclear steam system (NSS) application software (NAS) software consists of data reduction, nuclear, thermal/hydraulic, and utility programs to support plant operation, performance monitoring, and fuel management. The core thermal power analysis (CTPA) module of NAS computes the core power level. The equations used to calculate core power are contained in Reference 7 and are reproduced here and Appendix B as the basis for the heat balance uncertainty calculation.

The expression for core power in terms of a secondary side heat balance is:

$$Q_{Core} = W_{FWA}(\Delta H_{SGA}) + W_{FWB}(\Delta H_{SGB}) + Q_{corr1}$$

Where W_{FWA}, W_{FWB}	Feedwater flow, OTSG A and B
ΔH_{SGA}, ΔH_{SGB}	Enthalpy change, OTSG A and B
Q_{corr1}	Correction for letdown, makeup, RC pumps, and surface heat loss

Within the code listing, formulations were provided for the heat balance. Computer code excerpts are provided in Appendix B.

The NAS software will eventually be replaced by the Fixed Incore Detector Monitoring System (FIDMS), Reference 18. This software contains core thermal power analysis algorithms, which are effectively the same as those in NAS. Some improvements to the NAS calculations have been made including an adjustment for the ΔP between the steam pressure and temperature locations (this is discussed further in Section 5). Currently FIDMS is running in parallel with NAS; results show that the calculated core thermal power from NAS and FIDMS agree within a few tenths of Mwt.

3.5 Davis Besse Heat Balance Instruments

A listing of Davis Besse computer points that are input to the current (pre-Caldon instrumentation) core thermal power calculation is provided for information. This table was provided informally to AREVA NP. "Both" refers to both the primary ("Prim") and secondary heat balance methods.

Davis-Besse Heat Balance Input Listing

Point Number	Instrument Description	Units	Range	Heat Balance Method
F673	MN FW 1 COMP FLOW, FY2B2	KPPH	0-7000	Both
F674	MN FW 1 COMP FLOW, FY2B1	KPPH	0-7000	Both
F679	MN FW 2 COMP FLOW, FY2A1	KPPH	0-7000	Both
F680	MN FW 2 COMP FLOW, FY2A2	KPPH	0-7000	Both
F718	RC LETDOWN FLOW	KPPH	0-80	Both
F738	RC MU FLOW 2 LOW RANGE	GPM	0-50	Both
F859	RC HLG TOTAL FLOW, RPS CH 1	MPPH	0-160	Prim
F861	RC HLG TOTAL FLOW, RPS CH 2	MPPH	0-160	Prim
F863	RC HLG TOTAL FLOW, RPS CH 3	MPPH	0-160	Prim
F864	RC HLG TOTAL FLOW, RPS CH 4	MPPH	0-160	Prim
P721	RC LOOP 1 HLG NR PRESS, RPS CH 1	PSIG	1700-2500	Both
P722	RC LOOP 1 HLG NR PRESS, RPS CH 3	PSIG	1700-2500	Both
P729	RC LOOP 2 HLG NR PRESS, RPS CH 2	PSIG	1700-2500	Both
P730	RC LOOP 2 HLG NR PRESS, RPS CH 4	PSIG	1700-2500	Both
P930	SG 1 MN FW NOZZLE PRESS	PSIG	0-1500	Both
P931	SG 1 OUT STM PRESS, PT12B1	PSIG	0-1200	Both
P932	SG 1 OUT STM PRESS, PT12B2	PSIG	0-1200	Both
P935	SG 2 MN FW NOZZLE PRESS	PSIG	0-1500	Both
P936	SG 2 OUT STM PRESS, PT12A1	PSIG	0-1200	Both
P937	SG 2 OUT STM PRESS, PT12A2	PSIG	0-1200	Both
T476	HPT IN TEMP FROM SG 2	Deg F	50-650	Both
T477	HPT IN TEMP FROM SG 1	Deg F	50-650	Both
T671	MN FW TEMP TO ICS, TT1-1	Deg F	0-600	Both
T672	MN FW TEMP TO ICS, TT1-2	Deg F	0-600	Both
T719	RC LOOP 1 HLG NR TEMP, RC3B1	Deg F	520-620	Prim
T720	RC LOOP 1 HLG NR TEMP,	Deg F	520-	Prim

Point Number	Instrument Description	Units	Range	Heat Balance Method
	RC3B3		620	
T721	RC LOOP 1 HLG NR TEMP, RPS CH 1	Deg F	520-620	Prim
T722	RC LOOP 1 HLG NR TEMP, RPS CH 3	Deg F	520-620	Prim
T728	RC LOOP 2 HLG NR TEMP, RC3A1	Deg F	520-620	Prim
T729	RC LOOP 2 HLG NR TEMP, RC3A3	Deg F	520-620	Prim
T730	RC LOOP 2 HLG NR TEMP, RPS CH 2	Deg F	520-620	Prim
T731	RC LOOP 2 HLG NR TEMP, RPS CH 4	Deg F	520-620	Prim
T769	RC MU TK TEMP	Deg F	0-200	Both
T780	RCP 1-1 DISCH CLG NR TEMP, RC4B1	Deg F	520-620	Prim
T800	RCP 1-2 DISCH CLG NR TEMP, RC4B3	Deg F	520-620	Prim
T820	RCP 2-1 DISCH CLG NR TEMP, RC4A1	Deg F	520-620	Prim
T840P	RCP 2-2 DISCH CLG NR TEMP, RC4A3	Deg F	520-620	Prim
Z674B	MN FW 1 STOP VLV	DS	0 or 1	Both
Z679B	MN FW 2 STOP VLV	DS	0 or 1	Both
T821	RCP 2-1 DISCH CLG WR TEMP, RC4A2	Deg F	50-650	Both

CLG : Cold Leg
COMP: Compensated
DS : Digital Scan point, On or Off
FW : Feed Water System
HPT : High Pressure Turbine
HLG : Hot Leg
ICS : Integrated Control System
LD : Let down
MU : Makeup
MN : Main
NR : Narrow Range Instrument
RC : Reactor Coolant
RCP : Reactor Coolant Pump
RPS : Reactor Protection System
SG : Steam Generator
STM : Steam
TK : Tank
WR : Wide Range Instrument

4.0 CALCULATION INPUTS

Inputs were calculated for two sets of conditions: (1) operating conditions for the MUR power uprate, and (2) operating conditions for the Maximum Value Program (MVP) uprate.

4.1 MUR POWER UPRATE CONDITIONS

Reference 1 provides step-by-step instructions for calculating the uncertainty of a result. These were implemented as follows:

(a) Define measurement process[1]

(1) Review test objectives and test duration.

The "test" objective is to continuously calculate the core thermal power and ensure the plant is operated within its licensed power.

(2) List all independent measurement parameters and their nominal levels.

The independent measurement parameters and their nominal values[2] are comprised of the following values in Table 1.

TABLE 1 - Nominal Heat Balance Parameter Values

Symbol	Description	Units	Nominal Value	Basis
WFW	Feedwater Flow Rate	lbm/hr	1.184E+07	Ref. 10
TS	Steam Temperature	F	596	Ref. 10
PS	Steam Pressure	psia	930	Ref. 10
TFW	Feedwater Temperature	F	455	Ref. 10
PFW	Feedwater Pressure	psia	1005	Assmptn 3
WMU	Makeup Flow Rate	lbm/hr	2.227E+04	Ref. 9
TMU	Makeup Temperature	F	100	Ref. 9
PMU	Makeup Pressure	psia	2250	Assmptn 3
WLD	Letdown Flow Rate	lbm/hr	2.227E+04	Ref. 9
TLD	Letdown Temperature	F	557	Ref. 10

[1] The alphanumeric heading and subheading nomenclature as well as the text (e.g., reference to "test") from the ASME Performance Test Code (Ref. 1) is used herein.

[2] "nominal" refers to the expected value at 101.7% of 2772 or 2819 Mwt core thermal power. The 101.7% value was the initial guess of the maximum achievable power. Thus, the nominal values were calculated at this power level in Reference 10.

PLD	Letdown Pressure	psia	2250	Assmptn 3
QRCP	RCP Power	Btu/hr	6.75E+07	Ref. 6
QLOSS	Ambient Heat Loss	Btu/hr	2.23E+06	Ref. 24

Water Properties:
Steam Enthalpy = 1253.356 Btu/lbm[3] at 596°F and 930 psia
Feedwater Enthalpy = 436.041 Btu/lbm at 455°F and 1005 psia
Makeup Enthalpy = 73.957 Btu/lbm at 100°F and 2250 psia
Letdown Enthalpy = 555.518 Btu/lbm at 557°F and 2250 psia

(3) List all calibrations and instrument setups that will affect each parameter. Be sure to check for uncertainties in measurement system components that affect two or more measurements simultaneously (correlated uncertainties).

Except for the Caldon ultrasonic flow meter, the other instruments (feedwater pressure, steam temperature, steam pressure, makeup: flow, pressure, temperature, letdown: flow, pressure, temperature) are maintained and calibrated by Davis Besse. An instrument uncertainty calculation should exist for each instrument.

(4) Define the functional relationship between the independent measurement parameters and the test result.

The expression for core power in terms of a secondary side heat balance is shown below. This is equivalent to the equations used by CTPA.

$$Q_C = W_{FWA}(H_{SA} - H_{FWA}) + W_{FWB}(H_{SB} - H_{FWB}) + Q_{LD} - Q_{MU} - Q_{RCP} + Q_{LOSS}$$

Where W_{FWA}, W_{FWB} — Feedwater flows in Loop A & B
H_{SA}, H_{FWA}, H_{SB}, H_{FWB} — Steam & feedwater enthalpies for Loops A & B
$Q_{LD} = W_{LD} H_{LD}$ — Heat loss due to primary side letdown flow
$Q_{MU} = W_{MU} H_{MU}$ — Heat added due to makeup and net seal injection
Q_{RCP} — Heat added due to RC pumps
Q_{LOSS} — Ambient heat losses from the RCS
W_{LD}, W_{MU} — Letdown and Makeup Flow Rates
H_{LD}, H_{MU} — Letdown and Makeup Enthalpies

(b) List Elemental Error Sources

(1) Make a complete and exhaustive list of all possible test uncertainty sources for all parameters.

---

[3] Water properties were based on STP published values.

Not needed to calculate the core thermal power uncertainty.

(c) Calculate the Systematic and Random Standard Deviation for Each Parameter

Uncertainties for each parameter are shown below:

TABLE 2 – HEAT BALANCE PARAMETER UNCERTAINTY VALUES

Symbol	Description	Units	Absolute Systematic Uncertainty		Absolute Standard Deviation Of the Mean	
			Value	Basis	Value	Basis
WFW	Feedwater Flow Rate	Lbm/hr	Initial Value = 0.30% of nominal flow Final Value = 0.29% of nominal flow	Input 1	0	Input 1
TS	Steam Temperature	F	2.2(single) 1.56 (dual)	Input 3	0.153	Input 2
PS	Steam Pressure	psia	2 (single) 1.42 (dual)	Input 3	1.52	Input 2
TFW	Feedwater Temperature	F	Initial Value = 0.6 Final Value = 0.10	Input 1	Initial Value = 0.24728 Final Value = 0.46	Input 1
PFW	Feedwater Pressure	psia	20.63 (single) 14.60 (dual)	Input 3	1.35	Input 2
WMU	Makeup Flow Rate	lbm/hr	5% of nominal flow	Assmptn 3	10% of nominal flow	Assmptn 3
TMU	Makeup Temperature	F	5	Assmptn 3	2	Assmptn 3
PMU	Makeup Pressure	psia	50	Assmptn 3	50	Assmptn 3
WLD	Letdown Flow Rate	lbm/hr	5% of nominal flow	Assmptn 3	10% of nominal flow	Assmptn 3
TLD	Letdown Temperature	F	5	Assmptn 3	2	Assmptn 3
PLD	Letdown Pressure	psia	50	Assmptn 3	50	Assmptn 3
QRCP	RCP Power	Btu/hr	4.93e6	Input 7	0	N/A
QLOSS	Ambient Heat Loss	Btu/hr	2.5e6	Input 8	0	N/A

(d) Propagate the Systematic and Random Standard Deviations

(1) The systematic and random (sample) standard deviations of the independent parameters are propagated separately all the way to the final result.

(2) Propagation of the standard deviations is done, according to the functional relationship defined in step (a)(4) above, by using the Taylor series method. This requires a calculation of sensitivity factors, either by differentiation or by computer perturbation.

The core thermal power equation was differentiated with respect to the individual measured parameters to yield the following sensitivity coefficients:

$$\theta_{Wfw} = \partial Qc/\partial W_{FW} = (H_S - H_{FW})$$

$$\theta_{Pfw} = \partial Qc/\partial P_{FW} = W_{FW}\ \partial H/\partial P_{FW}$$

$$\theta_{Tfw} = \partial Qc/\partial T_{FW} = W_{FW}\ \partial H/\partial T_{FW}$$

$$\theta_{Ps} = \partial Qc/\partial P_S = W_{FW}\ \partial H/\partial P_S$$

$$\theta_{Ts} = \partial Qc/\partial T_S = W_{FW}\ \partial H/\partial T_S$$

$$\theta_{Wmu} = \partial Qc/\partial W_{MU} = H_{MU}$$

$$\theta_{Tmu} = \partial Qc/\partial T_{MU} = W_{MU}\ \partial H/\partial T$$

$$\theta_{Pmu} = \partial Qc/\partial P_{MU} = W_{MU}\ \partial H/\partial P$$

$$\theta_{Wld} = \partial Qc/\partial W_{LD} = H_{LD}$$

$$\theta_{Tld} = \partial Qc/\partial T_{LD} = W_{LD}\ \partial H/\partial T$$

$$\theta_{Pld} = \partial Qc/\partial P_{LD} = W_{LD}\ \partial H/\partial P$$

$$\theta_{Qrcp} = \partial Qc/\partial Q_{RCPs} = 1$$

$$\theta_{Qloss} = \partial Qc/\partial Q_{LOSS} = 1$$

In order to calculate these sensitivity coefficients, the water enthalpy differentials were computed.

For steam at 930 psia:

At T = 590°F, H = 1248.264 Btu/lbm

At T = 600°F, H = 1256.687 Btu/lbm

$\partial H/\partial T_S \cong (1256.687 - 1248.264)/(600 - 590) = 0.842$ Btu/lbm/°F

For steam at 596°F:

At P = 925 psia, H = 1253.921 Btu/lbm

At P = 935 psia, H = 1252.789 Btu/lbm

$\partial H/\partial P_S \cong (1252.789 - 1253.921)/(935 - 925) = -0.1132$ Btu/lbm/psia

For feedwater at 1000 psia:

At T = 450°F, H = 430.472 Btu/lbm

At T = 460°F, H = 441.637 Btu/lbm

$\partial H/\partial T_{fw} \cong (441.637 - 430.472)/(460 - 450) = 1.117$ Btu/lbm/°F

For feedwater at 455°F:

At P = 950 psia, H = 436.015 Btu/lbm

At P = 1050 psia, H = 436.067 Btu/lbm

$\partial H/\partial P_{fw} \cong (436.015 - 436.067)/(950 - 1050) = 5.20e\text{-}4$ Btu/lbm/psia

For letdown at 2250 psia:

At T = 550°F, H = 546.774 Btu/lbm

At T = 560°F, H = 559.306 Btu/lbm

$\partial H/\partial T_{LD} \cong (559.306 - 546.774)/(560 - 550) = 1.2532$ Btu/lbm/°F

For letdown at 557°F:

At P = 2300 psia, H = 555.429 Btu/lbm

At P = 2200 psia, H = 555.609 Btu/lbm

$\partial H/\partial P_{LD} \cong (555.429 - 555.609)/(2300 - 2200) = -1.80e\text{-}3$ Btu/lbm/psia

For makeup at 2250 psia:

At T = 90°F, H = 64.075 Btu/lbm

At T = 100°F, H = 73.957 Btu/lbm

$\partial H/\partial T_{MU} \cong (73.957 - 64.075)/(100 - 90) = 0.9882$ Btu/lbm/°F

For makeup at 100°F:

At P = 2300 psia, H = 74.087 Btu/lbm

At P = 2200 psia, H = 73.826 Btu/lbm

$\partial H/\partial P_{MU} \cong (74.087 - 73.826)/(2300 - 2200) = 2.61e-3$ Btu/lbm/psia

The water property derivatives are summarized in Table 3 below.

TABLE 3 - Water Property Derivatives

	∂H/∂T, Btu/(lbm°F)	∂H/∂P, Btu/(lbm psi)
Steam (596°F, 930 psia)	0.842	-0.1132
Feedwater (455°F, 1000 psia)	1.117	5.20e-4
Letdown (557°F, 2250 psia)	1.2532	-1.80e-3
Makeup (100°F, 2250 psia)	0.9882	2.61e-3

Sensitivity Coefficients and Uncertainty Contributions

The sensitivity coefficients and the uncertainty contributions were calculated using the values in Tables 2 and 3 as follows:

Feedwater Flow Rate

The sensitivity coefficient, θ_{Wfw}, was calculated using the previously defined partial derivative:

$\theta_{Wfw} = \partial Qc/\partial W_{FW} = (H_S - H_{FW}) = 1253.356 - 436.041 = 817.315$ Btu/lbm

Using the systematic uncertainty of $B_{Wfw} = (0.30/100) * 11.84e6 = 3.552e4$ lbm/hr, the systematic uncertainty contribution is:

$[\theta_{Wfw} * B_{Wfw}/2]^2 = [817.315 * 3.552e4/2]^2 = 2.107e14$ (Btu/hr)^2

Using the random standard deviation $S_{x,Wfw}$ = 0.0, the random uncertainty contribution is:

$[\theta_{Wfw} * S_{x,Wfw}]^2 = [817.315 * 0.0]^2 = 0.0\ (Btu/hr)^2$

Feedwater Pressure

The sensitivity coefficient, θ_{Pfw}, was calculated using the previously defined partial derivative:

$\theta_{Pfw} = \partial Qc/\partial P_{FW} = W_{FW}\ \partial H/\partial P_{FW} = (11.84e6)(5.20e\text{-}4) = 6.157e3$ Btu/hr/psi

Using the **single instrument**, systematic uncertainty of B_{Pfw} = 20.63 psi, the systematic uncertainty contribution is:

$[\theta_{Pfw} * B_{Pfw}/2]^2 = [6.157e3 * 20.63/2]^2 = 4.033e9\ (Btu/hr)^2$

Using the **dual instrument**, systematic uncertainty of B_{Pfw} = 14.60 psi, the systematic uncertainty contribution is:

$[\theta_{Pfw} * B_{Pfw}/2]^2 = [6.157e3 * 14.60/2]^2 = 2.020e9\ (Btu/hr)^2$

Using the random standard deviation $S_{x,Pfw}$ = 1.35, the random uncertainty uncertainty contribution is:

$[\theta_{Pfw} * S_{x,Pfw}]^2 = [6.157e3 * 1.35]^2 = 6.908e7\ (Btu/hr)^2$

Feedwater Temperature

The sensitivity coefficient, θ_{Tfw}, was calculated using the previously defined partial derivative:

$\theta_{Tfw} = \partial Qc/\partial T_{FW} = W_{FW}\ \partial H/\partial T_{FW} = (11.84e6)(1.117) = 1.323e7$ Btu/hr/°F

Using the systematic uncertainty of B_{Tfw} = 0.6 °F, the systematic uncertainty contribution is:

$[\theta_{Tfw} * B_{Tfw}/2]^2 = [1.323e7 * 0.6/2]^2 = 1.574e13\ (Btu/hr)^2$

Using the random standard deviation $S_{x,Tfw}$ = 0.24728°F, the random uncertainty uncertainty contribution is:

$[\theta_{Tfw} * S_{x,Tfw}]^2 = [1.323e7 * 0.24728]^2 = 1.070e13\ (Btu/hr)^2$

Steam Pressure

The sensitivity coefficient, θ_{Ps}, was calculated using the previously defined partial derivative:

$$\theta_{Ps} = \partial Qc/\partial P_S = W_{FW}\ \partial H/\partial P_S = (11.84e6)(-0.1132) = -1.340e6\ Btu/hr/psi$$

Using the **single instrument**, systematic uncertainty of B_{Ps} = 2.0 psi, the systematic uncertainty contribution is:

$$[\theta_{Ps} * B_{Ps}/2]^2 = [-1.340e6 * 2.0/2]^2 = 1.796e12\ (Btu/hr)^2$$

Using the **dual instrument**, systematic uncertainty of B_{Ps} = 1.42 psi, the systematic uncertainty contribution is:

$$[\theta_{Ps} * B_{Ps}/2]^2 = [-1.340e6 * 1.42/2]^2 = 9.056e11\ (Btu/hr)^2$$

Using the random standard deviation $S_{x,Ps}$ = 1.52, the random uncertainty uncertainty contribution is:

$$[\theta_{Ps} * S_{x,Ps}]^2 = [-1.340e6 * 1.52]^2 = 4.150e12\ (Btu/hr)^2$$

Steam Temperature

The sensitivity coefficient, θ_{Ts}, was calculated using the previously defined partial derivative:

$$\theta_{Ts} = \partial Qc/\partial T_S = W_{FW}\ \partial H/\partial T_S = (11.84e6)(-0.842) = -9.969e6\ Btu/hr/°F$$

Using the **single instrument**, systematic uncertainty of B_{Ts} = 2.2°F, the systematic uncertainty contribution is:

$$[\theta_{Tsa} * B_{Tsa}/2]^2 = [-9.969e6 * 2.2/2]^2 = 1.203e14\ (Btu/hr)^2$$

Using the **dual instrument**, systematic uncertainty of B_{Ts} = 1.56°F, the systematic uncertainty contribution is:

$$[\theta_{Tsa} * B_{Tsa}/2]^2 = [-9.969e6 * 1.56/2]^2 = 6.047e13\ (Btu/hr)^2$$

Using the random standard deviation $S_{x,Ts}$ = 0.153°F, the random uncertainty uncertainty contribution is:

$$[\theta_{Psa} * S_{x,Psa}]^2 = [-9.969e6 * 0.153]^2 = 2.327e12\ (Btu/hr)^2$$

Makeup Flow Rate

The sensitivity coefficient, θ_{Wmu}, was calculated using the previously defined partial derivative:

$\theta_{Wmu} = \partial Qc/\partial W_{MU} = H_{MU} = 73.96$ Btu/lbm

Using the systematic uncertainty of $B_{MU} = 0.05 * 2.227e4$ lbm/hr = 1.114e3 lbm/hr, the systematic uncertainty contribution is:

$[\theta_{MU} * B_{MU}/2]^2 = [73.96 * 1.114e3/2]^2 = 1.696e9\ (Btu/hr)^2$

Using the random standard deviation $S_{x,MU} = 0.10 * 2.227e4$ lbm/hr = 2.227e3 lbm/hr, the random uncertainty uncertainty contribution is:

$[\theta_{MU} * S_{x,MU}]^2 = [73.96 * 2.227e3]^2 = 2.713e10\ (Btu/hr)^2$

<u>Makeup Temperature</u>

The sensitivity coefficient, θ_{TMU}, was calculated using the previously defined partial derivative:

$\theta_{TMU} = \partial Qc/\partial T_{MU} = W_{MU}\ \partial H/\partial T_{MU} = (2.227e4)(0.9882) = 2.201e4$ Btu/hr/°F

Using the systematic uncertainty of $B_{TMU} = 5.0$ °F, the systematic uncertainty contribution is:

$[\theta_{TMU} * B_{TMU}/2]^2 = [2.201e4 * 5.0/2]^2 = 3.027e9\ (Btu/hr)^2$

Using the random standard deviation $S_{x,TMU} = 2.0$, the random uncertainty uncertainty contribution is:

$[\theta_{TMU} * S_{x,TMU}]^2 = [2.201e4 * 2.0]^2 = 1.937e9\ (Btu/hr)^2$

<u>Makeup Pressure</u>

The sensitivity coefficient, θ_{PMU}, was calculated using the previously defined partial derivative:

$\theta_{PMU} = \partial Qc/\partial P_{MU} = W_{MU}\ \partial H/\partial P_{MU} = (2.227e4)(2.61e-3) = 5.813e1$ Btu/hr/psi

Using the systematic uncertainty of $B_{PMU} = 50.0$ psi, the systematic uncertainty contribution is:

$[\theta_{PMU} * B_{PMU}/2]^2 = [5.813e1 * 50.0/2]^2 = 2.112e6\ (Btu/hr)^2$

Using the random standard deviation $S_{x,PMU} = 50.0$, the random uncertainty uncertainty contribution is:

$[\theta_{PMU} * S_{x,PMU}]^2 = [5.813e1 * 50.0]^2 = 8.446e6\ (Btu/hr)^2$

Letdown Flow

The sensitivity coefficient, θ_{WLD}, was calculated using the previously defined partial derivative:

$\theta_{WLD} = \partial Qc/\partial W_{LD} = H_{LD} = 555.52$ Btu/lbm

Using the systematic uncertainty of $B_{LD} = 0.05 * 2.227e4$ lbm/hr = 1.114e3 lbm/hr, the systematic uncertainty contribution is:

$[\theta_{LD} * B_{LD}/2]^2 = [555.52 * 1.114e3/2]^2 = 9.566e10\ (Btu/hr)^2$

Using the random standard deviation $S_{x,LD} = 0.10 * 2.227e4$ lbm/hr = 2.227e3 lbm/hr, the random uncertainty uncertainty contribution is:

$[\theta_{LD} * S_{x,LD}]^2 = [555.52 * 2.227e3]^2 = 1.531e12\ (Btu/hr)^2$

Letdown Temperature

The sensitivity coefficient, θ_{TLD}, was calculated using the previously defined partial derivative:

$\theta_{TLD} = \partial Qc/\partial T_{LD} = W_{LD}\ \partial H/\partial T_{LD} = (2.227e4)(1.2532) = 2.791e4$ Btu/hr/°F

Using the systematic uncertainty of $B_{TLD} = 5.0$ °F, the systematic uncertainty contribution is:

$[\theta_{TLD} * B_{TLD}/2]^2 = [2.791e4 * 5.0/2]^2 = 4.868e9\ (Btu/hr)^2$

Using the random standard deviation $S_{x,TLD} = 2.0$, the random uncertainty uncertainty contribution is:

$[\theta_{TLD} * S_{x,TLD}]^2 = [2.791e4 * 2.0]^2 = 3.116e9\ (Btu/hr)^2$

Letdown Pressure

The sensitivity coefficient, θ_{PLD}, was calculated using the previously defined partial derivative:

$\theta_{PLD} = \partial Qc/\partial P_{LD} = W_{LD}\ \partial H/\partial P_{LD} = (2.227e4)(-1.80e-3) = -4.009e1$ Btu/hr/psi

Using the systematic uncertainty of $B_{PLD} = 50.0$ psi, the systematic uncertainty contribution is:

$[\theta_{PLD} * B_{PLD}/2]^2 = [-4.009e1 * 50.0/2]^2 = 1.004e6\ (Btu/hr)^2$

Using the random standard deviation $S_{x,PLD} = 50.0$, the random uncertainty uncertainty contribution is:

$[\theta_{PLD} * S_{x,PLD}]^2 = [-4.009e1 * 50.0]^2 = 4.017e6\ (Btu/hr)^2$

RCP Power

The sensitivity coefficient, θ_{Qrcp}, was calculated using the previously defined partial derivative:

$\theta_{Qrcp} = \partial Qc/\partial Q_{RCPs} = 1$

Using the systematic uncertainty of $B_{Qrcp} = 4.93e6$ Btu/hr, the systematic uncertainty contribution is:

$[\theta_{Qrcp} * B_{Qrcp}/2]^2 = [1 * 4.93e6/2]^2 = 6.076e12\ (Btu/hr)^2$

Using the random standard deviation $S_{x,Qrcp} = 0.0$, the random uncertainty uncertainty contribution is:

$[\theta_{Qrcp} * S_{x,Qrcp}]^2 = [1 * 0.0]^2 = 0.0\ (Btu/hr)^2$

Ambient Heat Loss

The sensitivity coefficient, θ_{Qloss}, was calculated using the previously defined partial derivative:

$\theta_{Qloss} = \partial Qc/\partial Q_{LOSSs} = 1$

Using the systematic uncertainty of $B_{Qloss} = 2.50e6$ Btu/hr, the systematic uncertainty contribution is:

$[\theta_{Qloss} * B_{Qloss}/2]^2 = [1 * 2.50e6/2]^2 = 1.563e12\ (Btu/hr)^2$

Using the random standard deviation $S_{x,Qloss} = 0.0$, the random uncertainty contribution is:

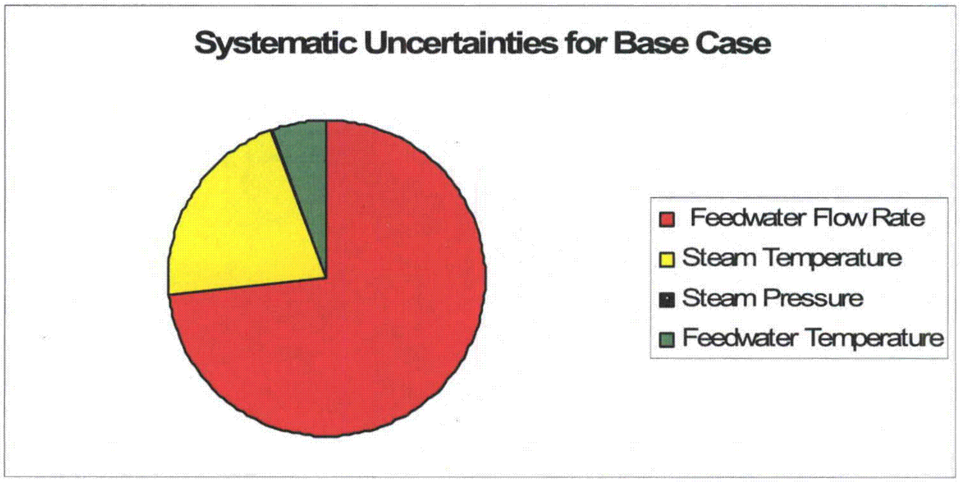
$[\theta_{Qloss} * S_{x,Qloss}]^2 = [1 * 0.0]^2 = 0.0\ (Btu/hr)^2$

The uncertainty contributions are summarized below in Table 4.

TABLE 4 – HEAT BALANCE PARAMETER UNCERTAINTY CONTRIBUTIONS

Symbol	Description	Systematic Uncertainty Contribution		Random Uncertainty Contribution	
		Absolute $(Btu/hr)^2$	Relative	Absolute $(Btu/hr)^2$	Relative
WFW	Feedwater Flow Rate	2.107e14	71.29%	0.0	0.00%
TS	Steam Temperature	6.047e13	20.46%	2.327e12	12.41%
PS	Steam Pressure	9.056e11	0.31%	4.150e12	22.15%
TFW	Feedwater Temperature	1.574e13	5.33%	1.070e13	57.09%
PFW	Feedwater Pressure	2.020e9	0.00%	6.908e7	0.00%
WMU	Makeup Flow Rate	1.696e9	0.00%	2.713e10	0.14%
TMU	Makeup Temperature	3.027e9	0.00%	1.937e9	0.01%
PMU	Makeup Pressure	2.112e6	0.00%	8.446e6	0.00%
WLD	Letdown Flow Rate	9.566e10	0.03%	1.531e12	8.17%
TLD	Letdown Temperature	4.868e9	0.00%	3.116e9	0.02%
PLD	Letdown Pressure	1.004e6	0.00%	4.017e6	0.00%
QRCP	RCP Power	6.076e12	2.06%	0.0	0.00%
QLOSS	Ambient Heat Loss	1.563e12	0.53%	0.0	0.00%
Totals		2.956e14	100%	1.873e13	100%

Note: the systematic uncertainty contribution is an order of magnitude greater than the random uncertainty contribution. Thus, the significant contributors to the systematic uncertainty are the most important for defining the uncertainty. The values shown in Table 4 are presented graphically in the figure below to show the most significant uncertainty parameters.



(e) Calculate uncertainty

(1) Combine the systematic and random uncertainties to obtain the total uncertainty.

Reference 1 shows that the total uncertainty on the core thermal power is calculated using the following equation.

Result Uncertainty = 2*[(Absolute Systematic Uncertainty)^2 + (Absolute Random Uncertainty)^2]$^{0.5}$

Absolute Systematic Uncertainty, B_R = 2*(Absolute Systematic Uncertainty Contribution)$^{0.5}$

$B_R = 2(2.956e14)^{0.5} = 3.4386e7$ Btu/hr

Absolute Random Uncertainty , $2S_R$ = 2*(Absolute Random Uncertainty Contribution)$^{0.5}$

$2S_R = 2(1.873e13)^{0.5} = 8.6566e6$ Btu/hr

Thus, the Core Thermal Power Uncertainty = $[(3.4386e7)^2 + (8.6556e6)^2]^{0.5}$ = 3.546e7 Btu/hr

On a percentage basis, Core Thermal Power Uncertainty = 3.546e7/(2819*3413*1000) = 3.685e-3 = 0.369%

(f) Report

Reference 1 provides a standard format for the uncertainty calculations. This format has been used for each of the cases analyzed (see Appendix A for the spreadsheet tables).

4.2 MVP POWER UPRATE CONDITIONS

The preceding calculations were modified for the MVP power uprate conditions. From Reference 19, the new operating conditions at a core thermal power of 3016 MWt are:

- Feedwater flow rate, WFW = 12.72e6 lbm/hr
- Steam Temperature = 591°F

The feedwater pressure (1005 psia), feedwater temperature (455°F), and steam pressure (930 psia) were unchanged from the MUR uprate conditions.

The affected parameters are those impacted by steam enthalpy and feedwater flow rate. These consist of:

1. Steam enthalpy, H_s
2. $\partial H/\partial P_S$
3. $\theta_{Wfw} = \partial Qc/\partial W_{FW} = (H_S - H_{FW})$
4. $\theta_{Pfw} = \partial Qc/\partial P_{FW} = W_{FW}\ \partial H/\partial P_{FW}$
5. $\theta_{Tfw} = \partial Qc/\partial T_{FW} = W_{FW}\ \partial H/\partial T_{FW}$
6. $\theta_{Ps} = \partial Qc/\partial P_S = W_{FW}\ \partial H/\partial P_S$
7. $\theta_{Ts} = \partial Qc/\partial T_S = W_{FW}\ \partial H/\partial T_S$

Steam Enthalpy = 1249.121 Btu/lbm at 591°F and 930 psia

For steam at 591°F:

At P = 925 psia, H = 1249.704 Btu/lbm

At P = 935 psia, H = 1248.535 Btu/lbm

$\partial H/\partial P_S \cong (1248.535 - 1249.704)/(935 - 925) = -0.1169$ Btu/lbm/psia

Sensitivity Coefficients and Uncertainty Contributions

The sensitivity coefficients and the uncertainty contributions were calculated using the values in Tables 2 and 3 and in this section as follows:

Feedwater Flow Rate

The sensitivity coefficient, θ_{Wfw}, was calculated using the previously defined partial derivative:

$\theta_{Wfw} = \partial Qc/\partial W_{FW} = (H_S - H_{FW}) = 1249.121 - 436.041 = 813.080$ Btu/lbm

Using the systematic uncertainty of $B_{Wfw} = (0.30/100) * 12.72e6 = 3.816e4$ lbm/hr, the systematic uncertainty contribution is:

$[\theta_{Wfw} * B_{Wfw}/2]^2 = [813.080 * 3.816e4/2]^2 = 2.407e14$ $(Btu/hr)^2$

Using the random standard deviation $S_{x,Wfw} = 0.0$, the random uncertainty uncertainty contribution is:

$[\theta_{Wfw} * S_{x,Wfw}]^2 = [813.080 * 0.0]^2 = 0.0$ $(Btu/hr)^2$

Feedwater Pressure

The sensitivity coefficient, θ_{Pfw}, was calculated using the previously defined partial derivative:

$\theta_{Pfw} = \partial Qc/\partial P_{FW} = W_{FW}\ \partial H/\partial P_{FW} = (12.72e6)(-5.20e-4) = -6.614e3$ Btu/hr/psi

Using the **single instrument**, systematic uncertainty of $B_{Pfw} = 20.63$ psi, the systematic uncertainty contribution is:

$[\theta_{Pfw} * B_{Pfw}/2]^2 = [6.614e3 * 20.63/2]^2 = 4.654e9$ $(Btu/hr)^2$

Using the **dual instrument**, systematic uncertainty of $B_{Pfw} = 14.60$ psi, the systematic uncertainty contribution is:

$[\theta_{Pfw} * B_{Pfw}/2]^2 = [6.614e3 * 14.60/2]^2 = 2.331e9$ $(Btu/hr)^2$

Using the random standard deviation $S_{x,Pfw} = 1.35$, the random uncertainty uncertainty contribution is:

$[\theta_{Pfw} * S_{x,Pfw}]^2 = [6.614e3 * 1.35]^2 = 7.973e7$ $(Btu/hr)^2$

Feedwater Temperature

The sensitivity coefficient, θ_{Tfw}, was calculated using the previously defined partial derivative:

$\theta_{Tfw} = \partial Qc/\partial T_{FW} = W_{FW}\ \partial H/\partial T_{FW} = (12.72e6)(1.117) = 1.421e7$ Btu/hr/°F

Using the systematic uncertainty of B_{Tfw} = 0.6 °F, the systematic uncertainty contribution is:

$[\theta_{Tfw} * B_{Tfw}/2]^2 = [1.421e7 * 0.6/2]^2 = 1.817e13\ (Btu/hr)^2$

Using the random standard deviation $S_{x,Tfw}$ = 0.24728°F, the random uncertainty uncertainty contribution is:

$[\theta_{Tfw} * S_{x,Tfw}]^2 = [1.421e7 * 0.24728]^2 = 1.235e13\ (Btu/hr)^2$

Steam Pressure

The sensitivity coefficient, θ_{Ps}, was calculated using the previously defined partial derivative:

$\theta_{Ps} = \partial Qc/\partial P_S = W_{FW}\ \partial H/\partial P_S = (12.72e6)(-0.1169) = 1.487e6$ Btu/hr/psi

Using the **single instrument**, systematic uncertainty of B_{Ps} = 2.0 psi, the systematic uncertainty contribution is:

$[\theta_{Ps} * B_{Ps}/2]^2 = [1.487e6 * 2.0/2]^2 = 2.211e12\ (Btu/hr)^2$

Using the **dual instrument**, systematic uncertainty of B_{Ps} = 1.42 psi, the systematic uncertainty contribution is:

$[\theta_{Ps} * B_{Ps}/2]^2 = [1.487e6 * 1.42/2]^2 = 1.115e12\ (Btu/hr)^2$

Using the random standard deviation $S_{x,Ps}$ = 1.52, the random uncertainty uncertainty contribution is:

$[\theta_{Ps} * S_{x,Ps}]^2 = [1.487e6 * 1.52]^2 = 5.109e12\ (Btu/hr)^2$

Steam Temperature

The sensitivity coefficient, θ_{Ts}, was calculated using the previously defined partial derivative:

$\theta_{Ts} = \partial Qc/\partial T_S = W_{FW}\ \partial H/\partial T_S\ \ (12.72e6)(-0.842) = 1.071e7$ Btu/hr/°F

Using the **single instrument**, systematic uncertainty of B_{Ts} = 2.2°F, the systematic uncertainty contribution is:

$[\theta_{Tsa} * B_{Tsa}/2]^2 = [1.071e7 * 2.2/2]^2 = 1.388e14$ (Btu/hr)^2

Using the **dual instrument**, systematic uncertainty of B_{Ts} = 1.56°F, the systematic uncertainty contribution is:

$[\theta_{Tsa} * B_{Tsa}/2]^2 = [1.071e7 * 1.56/2]^2 = 6.979e13$ (Btu/hr)^2

Using the random standard deviation $S_{x,Ts}$ = 0.153°F, the random uncertainty uncertainty contribution is:

$[\theta_{Psa} * S_{x,Psa}]^2 = [1.071e7 * 0.153]^2 = 2.685e12$ (Btu/hr)^2

The uncertainty contributions are summarized below in Table 5.

TABLE 5– HEAT BALANCE PARAMETER UNCERTAINTY CONTRIBUTIONS REVISED FOR MVP CONDITIONS

Symbol	Description	Systematic Uncertainty Contribution	Random Uncertainty Contribution
		Absolute (Btu/hr)^2	Absolute (Btu/hr)^2
WFW	Feedwater Flow Rate	2.407e14	0.0
TS	Steam Temperature	6.979e13	2.685e12
PS	Steam Pressure	1.115e12	5.109e12
TFW	Feedwater Temperature	1.817e13	1.235e13
PFW	Feedwater Pressure	2.331E+09	7.973e7

Note: there are some insignificant round-off differences between these values and those shown in the Appendix A spreadsheets.

5.0 CASES ANALYZED

The preceding heat balance uncertainty equations were input into a spreadsheet and the following cases were analyzed:

1) Definition of "Random" Feedwater Temperature Uncertainty
2) Base Case (Dual Loop P_{FW}, T_S, P_S Uncertainties)
3) Definition of "Random" Feedwater Temperature Uncertainty to match the as-tested Caldon LEFM uncertainties
4) Revised Case 2 using the Revised Feedwater Flowmeter Transducer Uncertainty
5) Reduced Steam Temperature Uncertainty
6) Single Loop P_{FW}, T_S, P_S Uncertainties
7) Instrument Location Effects
8) Instrument Locations Effects (continued)
9) Alternate Steam Pressure Location
10) Insensitivity to Assumed Values for Makeup Flow, Letdown Flow, RCP Power, Ambient Losses
11) MVP Base Case (Dual Loop P_{FW}, T_S, P_S Uncertainties)

Case 1 - Definition of "Random" Feedwater Temperature Uncertainty

The Caldon CheckPlus™ System equipment was originally specified with a combined 0.32% feedwater flow-temperature uncertainty. This is a systematic uncertainty that includes the random effects. The equations derived herein treat the feedwater flow and feedwater temperature as separate uncertainties. To account for the combined uncertainty, the individual feedwater flow and temperature uncertainties were input to the equations and then an additional "random" feedwater temperature uncertainty was varied until the combined uncertainty was obtained. Specifically, the 0.30% feedwater flow and 0.6°F feedwater temperature uncertainties were input to the spreadsheet and the "random" feedwater temperature uncertainty was varied until the 0.32% total heat balance uncertainty was achieved (all the other uncertainties were set to zero). The resulting value of the random uncertainty is 0.24728°F as shown in Appendix A.

Case 2 - Base Case Using Initial Caldon Uncertainties and Dual Loop P_{FW}, T_S, P_S Uncertainties

The base case core thermal power uncertainty was determined using the dual loop uncertainties for feedwater pressure, steam pressure, and steam temperature, where "dual loop" refers to a single instrument in each steam line. The resulting core thermal power uncertainty is 0.369%.

Note: the values provided in this spreadsheet serve as the spreadsheet benchmark since the values agree with the calculations shown in Section 4.

Case 3 Definition of "Random" Feedwater Temperature Uncertainty to Match the as-tested Caldon LEFM uncertainties

After the original calculation, the Davis Besse Caldon LEFM CheckPlus™ System ultrasonic feedwater flow meter was tested at Alden labs. Based on this testing, the following values were determined (Reference 21, Section 2):

> Combined uncertainty feedwater flow and feedwater temperature = 0.29% full power
>
> Feedwater Flow Rate Systematic Uncertainty = 0.26%
>
> Feedwater Temperature Systematic Uncertainty = 0.10°F
>
> Random Feedwater Temperature Uncertainty = 0.56°F. This corresponds to two standard deviations. Thus, the Absolute Standard Deviation of Mean Feedwater Temperature Measurements = 0.28°F (i.e., 0.56/2).

However, to achieve the combined uncertainty of 0.29%, this random feedwater temperature uncertainty value was increased to 0.46°F.

Case 4 Revised Case 2 with New Transducer Uncertainty

After the flowmeter testing, the transducers were changed and Caldon revised the feedwater flow uncertainty from 0.26% to 0.29%, Reference 22. Case 1 was re-run using the following flowmeter uncertainties:

> Feedwater flow systematic flow uncertainty = 0.29%
>
> Feedwater Temperature Systematic Uncertainty = 0.10°F
>
> Random Feedwater Temperature Uncertainty = 0.46°F

When combined with the other heat balance uncertainties, the total heat balance uncertainty is 0.367%, which is marginally less than Case 2 that used the pre-test uncertainties.

Case 5 - Reduced Steam Temperature Uncertainty

To determine whether further reductions in the heat balance uncertainty are possible through the reduction of the steam temperature uncertainty, a case was analyzed with a steam temperature uncertainty of 1.1°F which corresponds to $(2)^{-0.5}$ times the base case uncertainty of 1.56°F (this would be representative of adding a second independent temperature transducer to each steam line). The resulting core themal power uncertainty value is 0.349%.

Case 6 - Single Loop P_{FW}, T_S, P_S Uncertainties

In the event that only instrumentation from a single loop were available, the heat balance uncertainty would be 0.401% based on the following systematic uncertainties: feedwater pressure = 20.6 psi, steam pressure = 2 psi, steam temperature = 2.2 °F.

Cases 7 and 8 – Instrument Location Effects

Feedwater pressure, feedwater temperature, steam pressure, and steam temperature are used to calculate the feedwater and steam enthalpies used in the heat balance calculation. Ideally, these measurements would be conducted at the steam generator inlet and outlet nozzles to achieve a heat balance free from instrument location errors. Since this is not possible, the instrument location effects should be factored into the heat balance calculation and heat balance uncertainty calculation. The new FIDMS CTPA software provides a means where the ΔP can be included in the heat balance calculation.

The temperature change between the steam generator and the instrument location will be immeasurable. Thus, the effects of temperature location errors are perceived as negligible.

There will be appreciable pressure differences between the measurement locations and the steam generator. For the feedwater pressure, this is not significant as evidenced by the small systematic uncertainty contribution of feedwater pressure as shown in Table 4. Steam pressure, however, does have an impact and should be addressed.

OTSG outlet pressure is sensed in the 26" steam lines downstream of the steam generator. From Appendix C, there is a 3 psi unrecoverable pressure loss between the outlet nozzle and the pressure transducer location. It is recommended that this pressure loss be taken into account in FIDMS' CTPA software.

If the adjustment is made, then the only addition to the uncertainty is the uncertainty on the ΔP calculation. Assuming, that the line loss has a calculational uncertainty of 20% (assumption no. 4), the additional steam pressure uncertainty factor is 0.2*3, or 0.6 psi. The line loss uncertainty can be considered independent of the instrumentation uncertainty and thus combined in a square-root-sum-of-the-squares method.

Steam pressure uncertainty = $[(2.0)^2 + (0.6)^2]^{0.5}$ = 2.09 psi

Using two pressure instruments, the uncertainty = $2.09 * 2^{-0.5}$ = 1.48 psi

The resulting core thermal power uncertainty for this Case 7 is 0.367% and is unchanged from the base case.

If the pressure difference adjustment is not made within the heat balance calculation and/or plant computer software, then the addition to the uncertainty is the uncertainty on the ΔP calculation plus the ΔP itself. Assuming, that the line loss has a calculational uncertainty of 20%,

Steam pressure uncertainty = $[(2.0)^2 + (3*1.2)^2]^{0.5}$ = 4.12 psi

Using two pressure instruments, the uncertainty = $4.12 * 2^{-0.5}$ = 2.91 psi

The resulting core thermal power uncertainty for this Case 8 is 0.369%.

<u>Case 9 - Alternate Steam Pressure Location</u>

In the event that turbine header pressure instruments were used instead of the steam generator outlet pressures, pressure adjustments would be required in the FIDMS CTPA software (i.e., 15 or 20 psi would need to be added to account for the steam line losses between the two locations). These values are based on the line loss calculations shown in Appendix C. Assuming, that the line loss has a calculational uncertainty of 20%, an additional steam pressure uncertainty factor must be considered. The line loss uncertainty can be considered independent of the instrumentation uncertainty and thus combined in a square-root-sum-of-the-squares method.

Steam pressure uncertainty = $[(2.0)^2 + (0.2*20.0)^2]^{0.5}$ = 4.47 psi

Steam pressure uncertainty = $[(2.0)^2 + (0.2*15.0)^2]^{0.5}$ = 3.61 psi

Using both steam lines, the uncertainty = $[(4.47/2)^2 + (3.61/2)^2]^{0.5}$ = 2.87 psi

The resulting core thermal power uncertainty for this case is 0.369%.

Case 10 - Insensitivity to Assumed Values for Makeup and Letdown Flow, Pressure, and Temperature

To demonstrate the core thermal power uncertainty to the assumed uncertainties relative to makeup and letdown flow, pressure, and temperature, a case was analyzed in which each of the uncertainties were doubled. The resulting uncertainty only increased from 0.367% to 0.370%, thus demonstrating the insensitivity of these values.

Case 11 – MVP Base Case (Dual Loop P_{FW}, T_S, P_S Uncertainties)

To determine the effects of the larger MVP uprate on the heat balance uncertainty, case 2 was repeated for at the 3016 Mwt feedwater flow and steam temperature conditions. Even though there are differences in the secondary operating conditions at the larger power uprate, no significant effect on the heat balance uncertainty was observed as the resulting core thermal power uncertainty is 0.367% (which matches Case 4 to three significant figures).

6.0 SUMMARY OF RESULTS

The ASME Performance Test Code Methodology was used to calculate the expected core thermal power uncertainty to be achieved using the Caldon CheckPlus™ System ultrasonic flow meter. The analysis concluded that using the following instrument uncertainty values, the core thermal power uncertainty would be 0.367%, thus allowing a power uprate of 1.63% to be pursued. This is based on:

- Feedwater Flow Uncertainty of 0.29%
- Feedwater Temperature Uncertainty of 0.1°F (systematic) and 0.46°F (random*)
- Feedwater Pressure Uncertainty of 14.6 psi (systematic) and 1.35 psi (random)
- Steam Pressure Uncertainty of 1.42 psi (systematic) and 1.52 psi (random)
- Steam Temperature Uncertainty of 1.56°F (systematic) and 0.153°F (random)

The other parameters (makeup, letdown, RCP heat, and ambient losses) are minor contributors. Their uncertainties are defined in the body of the report.

This result is valid for both the MUR and MVP uprates.

* "Random" as described herein corresponds to one standard deviation as opposed to two standard deviations. The Caldon published random uncertainty of 0.56°F corresponds to two standard deviations or 0.28°F. The 0.28°F value was increased to 0.46°F to match the Caldon published combined flow uncertainty (see Case 3).

7.0 REFERENCES

(1) ASME PTC 19.1-1998, Test Uncertainty, Instruments and Apparatus, American Society of Mechanical Engineers, NY, NY, 1998.

(2) Caldon, Inc. Engineering Report-80P Revision 0 (Proprietary Version), Topical Report - "Improving Thermal Power Accuracy and Plant Safety While Increasing Operating Power Level Using the LEFM✓™ System," March 1997. **(For Information Only)**

(3) Caldon Topical Report Caldon, Inc. Engineering Report-157P Revision 5 (Proprietary Version), Topical Report - "Supplement to Topical Report ER-80P: Basis for a Power Uprate With the LEFM✓™ or LEFM CheckPlus™ System.". **(For Information Only)**

(4) AREVA NP Document 32-1119395-00, Calculated Uncertainty in Qprimary," May 1980.

(5) AREVA NP Document 32-1142654-00, "Error Equations for RC Flow Calculation," May 1983.

(6) AREVA NP Document 32-5001078-01, "CR-3 Heat Balance Uncertainty Calc," March 1998.

(7) AREVA NP Document 75-1103982-02, "Core Thermal Power Analysis Module (CTPA), 1983.

(8) AREVA NP Document 32-5007853-01, "DAVIS-BESSE CYCLE 13 OLC DBU," May 2000

(9) AREVA NP Document 51-5005750-00, "DBNPS Design Basis Validation for the Makeup and Purification System," October 1999.

(10) AREVA NP Document 32-5011757-00, "DB App. K Power Uprate – New Operating Conditions," March 2001.

*(11) Bechtel Drawing M-203A Rev. 20, "Piping Isometric Main Steam System Ctmt. Bldg. Steam Gen. 1-1."

*(12) Bechtel Calculation No. 1.38 Rev. 0.

(13) Idelchik, I.E., Handbook of Hydraulic Resistance, Second Edition, Hemisphere Publishing Co., Washington DC, 1986.

(14) Ladish General Catalog No. 55, "Forged and Seamless Welding Pipe Fittings, Cudahy, WI, 1971.

(15) Crane Technical Paper No. 410, "Flow of Fluids Through Valves, Fittings, and Pipe," 24th Printing, King of Prussia, PA, 1988.

*(16) Bechtel Drawing M-203B Rev. 16, "Piping Isometric Main Steam System Ctmt. Bldg. Steam Gen. 1-2."

*(17) Bechtel Drawing M-203C Rev. 11, "Piping Isometric Main Steam System Turbine Building."

(18) AREVA NP Document 51-5003544-00, "FIDMS Methodology," September 1999.

(19) AREVA NP Document 32-5013080-00, "DB 3016 Mwt Power Uprate – New Operating Conditions," June 2002.

*(20) Davis Besse Calculation No. C-ICE-083.01-004 Rev. 01, "Loop Uncertainty for Main Feedwater & High Pressure Turbine Main Steam Temperature & Pressure."

*(21) Caldon, Inc. Engineering Report: ER-202 Revision 2, "Bounding Uncertainty Analysis for Thermal Power Determination at Davis Besse Nuclear Power Station Using the LEFM✓+ System," July 2004.

*(22) Letter from Ed Madera (Cameron) to Tim Laurer (Davis Besse), "Cameron Measurement Systems Response to Transducer Replacement Sensitivity," dated March 8, 2007. (Attachment 2)

*(23) Davis Besse Calculation No. C-ICE-083.01-004 Rev. 03 Addendum No. 2, "DB Loop Uncertainty for Main Feedwater & High Pressure Turbine Main Steam Temperature & Pressure."

(24) AREVA NP 38-5038413-00, "Revision of NAS QHTRS Variable."

* Retrievable from Davis-Besse records center and thus acceptable references for this calculation.

Dallas P. Scott 4/7/09

APPENDIX A – Heat Balance Spreadsheets

The methodology developed in Section 5 was programmed in Excel for ease of evaluating various inputs. The Excel spreadsheet was verified by comparing the results of Case 2 with those listed in Section 5.

Case 1 - Definition of "Random" Feedwater Temperature Uncertainty

All uncertainties except feedwater flow and feedwater temperature set to zero.

Symbol	Description	Units	Nominal Value	Absolute Systematic Uncertainty	Absolute Std. Dev. of the Mean	Absolute Sensitivity	Absolute Systematic Uncertainty Contribution	Absolute Random Uncertainty Contribution	Relative Systematic Uncertainty Contribution	Relative Random Uncertainty Contribution
WFW	Feedwater Flow Rate	lbm/hr	1.18E+07	3.55E+04	0	8.170E+02	2.105E+14	0.000E+00	93.05%	0.00%
TS	Steam Temperature	F	596	0	0	9.969E+06	0.000E+00	0.000E+00	0.00%	0.00%
PS	Steam Pressure	Psia	930	0	0	-1.340E+06	0.000E+00	0.000E+00	0.00%	0.00%
TFW	Feedwater Temperature	F	455	0.6	0.24728	-1.323E+07	1.574E+13	1.070E+13	6.96%	100.00%
PFW	Feedwater Pressure	Psia	1005	0	0	-6.157E+03	0.000E+00	0.000E+00	0.00%	0.00%
WMU	Makeup Flow Rate	lbm/hr	2.23E+04	0.00E+00	0.00E+00	7.396E+01	0.000E+00	0.000E+00	0.00%	0.00%
TMU	Makeup Temperature	F	100	0	0	2.201E+04	0.000E+00	0.000E+00	0.00%	0.00%
PMU	Makeup Pressure	Psia	2250	0	0	5.812E+01	0.000E+00	0.000E+00	0.00%	0.00%
WLD	Letdown Flow Rate	lbm/hr	2.23E+04	0.00E+00	0.00E+00	5.555E+02	0.000E+00	0.000E+00	0.00%	0.00%
TLD	Letdown Temperature	F	557	0	0	2.791E+04	0.000E+00	0.000E+00	0.00%	0.00%
PLD	Letdown Pressure	Psia	2250	0	0	-4.009E+01	0.000E+00	0.000E+00	0.00%	0.00%
QRCP	RCP Power	Btu/hr	6.75E+07	0.00E+00	0	1.000E+00	0.000E+00	0.000E+00	0.00%	0.00%
QLOSS	Ambient Heat Loss	Btu/hr	0.00E+00	0.00E+00	0	1.000E+00	0.000E+00	0.000E+00	0.00%	0.00%
							2.263E+14	1.070E+13	100.00%	100.00%

Symbol	Description	Units	Nominal Value	Absolute Systematic Uncertainty	Absolute Random Uncertainty	Absolute Uncertainty Btu/hr	Relative Uncertainty %
Qc	Core Thermal Power	Btu/hr	9.621E+09	3.009E+07	6.541E+06	3.079E+07	**0.32**

HSB	Steam Enthalpy	Btu/lbm	1250	DHS/DT	0.842	DHS/DP	-0.1132
HFWB	Feedwater Enthalpy	Btu/lbm	433	DHFW/DT	-1.117	DHFW/DP	-5.20E-04
HMU	Makeup Enthalpy	Btu/lbm	73.96	DHMU/DT	0.9882	DHMU/DP	2.61E-03
HLD	Letdown Enthalpy	Btu/lbm	555.52	DHLD/DT	1.2532	DHLD/DP	-1.80E-03

Case 2 - Base Case Using Dual Loop Instrument Uncertainties

Symbol	Description	Units	Nominal Value	Absolute Systematic Uncertainty	Absolute Std. Dev. of the Mean	Absolute Sensitivity	Absolute Systematic Uncertainty Contribution	Absolute Random Uncertainty Contribution	Relative Systematic Uncertainty Contribution	Relative Random Uncertainty Contribution
WFW	Feedwater Flow Rate	lbm/hr	1.18E+07	3.55E+04	0	8.173E+02	2.107E+14	0.000E+00	71.29%	0.00%
TS	Steam Temperature	F	596	1.56	0.153	9.969E+06	6.047E+13	2.327E+12	20.46%	12.42%
PS	Steam Pressure	psia	930	1.42	1.52	-1.340E+06	9.056E+11	4.150E+12	0.31%	22.15%
TFW	Feedwater Temperature	F	455	0.6	0.24728	1.323E+07	1.574E+13	1.070E+13	5.33%	57.09%
PFW	Feedwater Pressure	psia	1005	14.6	1.35	-6.157E+03	2.020E+09	6.908E+07	0.00%	0.00%
WMU	Makeup Flow Rate	lbm/hr	2.23E+04	1.11E+03	2.23E+03	7.396E+01	1.696E+09	2.713E+10	0.00%	0.14%
TMU	Makeup Temperature	F	100	5	2	2.201E+04	3.027E+09	1.937E+09	0.00%	0.01%
PMU	Makeup Pressure	psia	2250	50	50	5.812E+01	2.112E+06	8.446E+06	0.00%	0.00%
WLD	Letdown Flow Rate	lbm/hr	2.23E+04	1.11E+03	2.23E+03	5.555E+02	9.566E+10	1.531E+12	0.03%	8.17%
TLD	Letdown Temperature	F	557	5	2	2.791E+04	4.868E+09	3.116E+09	0.00%	0.02%
PLD	Letdown Pressure	psia	2250	50	50	-4.009E+01	1.004E+06	4.017E+06	0.00%	0.00%
QRCP	RCP Power	Btu/hr	6.75E+07	4.93E+06	0	1.000E+00	6.076E+12	0.000E+00	2.06%	0.00%
QLOSS	Ambient Heat Loss	Btu/hr	2.23E+06	2.50E+06	0	1.000E+00	1.563E+12	0.000E+00	0.53%	0.00%
							2.956E+14	1.873E+13	100.00%	100.00%

Symbol	Description	Units	Nominal Value	Absolute Systematic Uncertainty	Absolute Random Uncertainty	Absolute Uncertainty Btu/hr	Relative Uncertainty %
Qc	Core Thermal Power	Btu/hr	9.621E+09	3.438E+07	8.657E+06	3.546E+07	**0.36852537**

HSB	Steam Enthalpy	Btu/lbm	1253.356	DHS/DT	0.842	DHS/DP	-0.1132
HFWB	Feedwater Enthalpy	Btu/lbm	436.041	DHFW/DT	1.117	DHFW/DP	-5.20E-04
HMU	Makeup Enthalpy	Btu/lbm	73.96	DHMU/DT	0.9882	DHMU/DP	2.61E-03
HLD	Letdown Enthalpy	Btu/lbm	555.52	DHLD/DT	1.2532	DHLD/DP	-1.80E-03

Case 3 – Definition of Randon Feedwater Temperature Uncertainty for As-Tested Caldon Flowmeter
All other terms set to zero

Symbol	Description	Units	Nominal Value	Absolute Systematic Uncertainty	Absolute Std. Dev. of the Mean	Absolute Sensitivity	Absolute Systematic Uncertainty Contribution	Absolute Random Uncertainty Contribution	Relative Systematic Uncertainty Contribution	Relative Random Uncertainty Contribution
WFW	Feedwater Flow Rate	lbm/hr	1.18E+07	3.08E+04	0	8.173E+02	1.583E+14	0.000E+00	99.72%	0.00%
TS	Steam Temperature	F	596	0	0	9.969E+06	0.000E+00	0.000E+00	0.00%	0.00%
PS	Steam Pressure	psia	930	0	0	-1.340E+06	0.000E+00	0.000E+00	0.00%	0.00%
TFW	Feedwater Temperature	F	455	0.1	0.46	1.323E+07	4.373E+11	3.701E+13	0.28%	100.00%
PFW	Feedwater Pressure	psia	1005	0	0	-6.157E+03	0.000E+00	0.000E+00	0.00%	0.00%
WMU	Makeup Flow Rate	lbm/hr	2.23E+04	0.00E+00	0.00E+00	7.396E+01	0.000E+00	0.000E+00	0.00%	0.00%
TMU	Makeup Temperature	F	100	0	0	2.201E+04	0.000E+00	0.000E+00	0.00%	0.00%
PMU	Makeup Pressure	psia	2250	0	0	5.812E+01	0.000E+00	0.000E+00	0.00%	0.00%
WLD	Letdown Flow Rate	lbm/hr	2.23E+04	0.00E+00	0.00E+00	5.555E+02	0.000E+00	0.000E+00	0.00%	0.00%
TLD	Letdown Temperature	F	557	0	0	2.791E+04	0.000E+00	0.000E+00	0.00%	0.00%
PLD	Letdown Pressure	psia	2250	0	0	-4.009E+01	0.000E+00	0.000E+00	0.00%	0.00%
QRCP	RCP Power	Btu/hr	6.75E+07	0.00E+00	0	1.000E+00	0.000E+00	0.000E+00	0.00%	0.00%
QLOSS	Ambient Heat Loss	Btu/hr	0.00E+00	0.00E+00	0	1.000E+00	0.000E+00	0.000E+00	0.00%	0.00%
							1.587E+14	3.701E+13	100.00%	100.00%

Symbol	Description	Units	Nominal Value	Absolute Systematic Uncertainty	Absolute Random Uncertainty	Absolute Uncertainty Btu/hr	Relative Uncertainty %
Qc	Core Thermal Power	Btu/hr	9.621E+09	2.519E+07	1.217E+07	2.798E+07	**0.29080499**

HSB	Steam Enthalpy	Btu/lbm	1253.356	DHS/DT	0.842	DHS/DP	-0.1132
HFWB	Feedwater Enthalpy	Btu/lbm	436.041	DHFW/DT	1.117	DHFW/DP	-5.20E-04
HMU	Makeup Enthalpy	Btu/lbm	73.96	DHMU/DT	0.9882	DHMU/DP	2.61E-03

Case 4 – Base Case Using New Feedwater Flowmeter Transducer Uncertainty

Symbol	Description	Units	Nominal Value	Absolute Systematic Uncertainty	Absolute Std. Dev. of the Mean	Absolute Sensitivity	Absolute Systematic Uncertainty Contribution	Absolute Random Uncertainty Contribution	Relative Systematic Uncertainty Contribution	Relative Random Uncertainty Contribution
WFW	Feedwater Flow Rate	lbm/hr	1.18E+07	3.43E+04	0	8.173E+02	1.969E+14	0.000E+00	73.89%	0.00%
TS	Steam Temperature	F	596	1.56	0.153	9.969E+06	6.047E+13	2.327E+12	22.69%	5.16%
PS	Steam Pressure	psia	930	1.42	1.52	-1.340E+06	9.056E+11	4.150E+12	0.34%	9.21%
TFW	Feedwater Temperature	F	455	0.1	0.46	1.323E+07	4.373E+11	3.701E+13	0.16%	82.15%
PFW	Feedwater Pressure	psia	1005	14.6	1.35	-6.157E+03	2.020E+09	6.908E+07	0.00%	0.00%
WMU	Makeup Flow Rate	lbm/hr	2.23E+04	1.11E+03	2.23E+03	7.396E+01	1.696E+09	2.713E+10	0.00%	0.06%
TMU	Makeup Temperature	F	100	5	2	2.201E+04	3.027E+09	1.937E+09	0.00%	0.00%
PMU	Makeup Pressure	psia	2250	50	50	5.812E+01	2.112E+06	8.446E+06	0.00%	0.00%
WLD	Letdown Flow Rate	lbm/hr	2.23E+04	1.11E+03	2.23E+03	5.555E+02	9.566E+10	1.531E+12	0.04%	3.40%
TLD	Letdown Temperature	F	557	5	2	2.791E+04	4.868E+09	3.116E+09	0.00%	0.01%
PLD	Letdown Pressure	psia	2250	50	50	-4.009E+01	1.004E+06	4.017E+06	0.00%	0.00%
QRCP	RCP Power	Btu/hr	6.75E+07	4.93E+06	0	1.000E+00	6.076E+12	0.000E+00	2.28%	0.00%
QLOSS	Ambient Heat Loss	Btu/hr	0.00E+00	2.50E+06	0	1.000E+00	1.563E+12	0.000E+00	0.59%	0.00%
							2.664E+14	4.505E+13	100.00%	100.00%

Symbol	Description	Units	Nominal Value	Absolute Systematic Uncertainty	Absolute Random Uncertainty	Absolute Uncertainty Btu/hr	Relative Uncertainty %
Qc	Core Thermal Power	Btu/hr	9.621E+09	3.265E+07	1.342E+07	3.530E+07	**0.36687916**

HSB	Steam Enthalpy	Btu/lbm	1253.356	DHS/DT	0.842	DHS/DP	-0.1132
HFWB	Feedwater Enthalpy	Btu/lbm	436.041	DHFW/DT	1.117	DHFW/DP	-5.20E-04
HMU	Makeup Enthalpy	Btu/lbm	73.96	DHMU/DT	0.9882	DHMU/DP	2.61E-03

Case 5 - Reduced Steam Temperature Uncertainty

Symbol	Description	Units	Nominal Value	Absolute Systematic Uncertainty	Absolute Std. Dev. of the Mean	Absolute Sensitivity	Absolute Systematic Uncertainty Contribution	Absolute Random Uncertainty Contribution	Relative Systematic Uncertainty Contribution	Relative Random Uncertainty Contribution
WFW	Feedwater Flow Rate	lbm/hr	1.18E+07	3.43E+04	0	8.173E+02	1.969E+14	0.000E+00	83.41%	0.00%
TS	Steam Temperature	F	596	1.1	0.153	9.969E+06	3.006E+13	2.327E+12	12.74%	5.16%
PS	Steam Pressure	psia	930	1.42	1.52	-1.340E+06	9.056E+11	4.150E+12	0.38%	9.21%
TFW	Feedwater Temperature	F	455	0.1	0.46	1.323E+07	4.373E+11	3.701E+13	0.19%	82.15%
PFW	Feedwater Pressure	psia	1005	14.6	1.35	-6.157E+03	2.020E+09	6.908E+07	0.00%	0.00%
WMU	Makeup Flow Rate	lbm/hr	2.23E+04	1.11E+03	2.23E+03	7.396E+01	1.696E+09	2.713E+10	0.00%	0.06%
TMU	Makeup Temperature	F	100	5	2	2.201E+04	3.027E+09	1.937E+09	0.00%	0.00%
PMU	Makeup Pressure	psia	2250	50	50	5.812E+01	2.112E+06	8.446E+06	0.00%	0.00%
WLD	Letdown Flow Rate	lbm/hr	2.23E+04	1.11E+03	2.23E+03	5.555E+02	9.566E+10	1.531E+12	0.04%	3.40%
TLD	Letdown Temperature	F	557	5	2	2.791E+04	4.868E+09	3.116E+09	0.00%	0.01%
PLD	Letdown Pressure	psia	2250	50	50	-4.009E+01	1.004E+06	4.017E+06	0.00%	0.00%
QRCP	RCP Power	Btu/hr	6.75E+07	4.93E+06	0	1.000E+00	6.076E+12	0.000E+00	2.57%	0.00%
QLOSS	Ambient Heat Loss	Btu/hr	0.00E+00	2.50E+06	0	1.000E+00	1.563E+12	0.000E+00	0.66%	0.00%
							2.360E+14	4.505E+13	100.00%	100.00%

Symbol	Description	Units	Nominal Value	Absolute Systematic Uncertainty	Absolute Random Uncertainty	Absolute Uncertainty Btu/hr	Relative Uncertainty %
Qc	Core Thermal Power	Btu/hr	9.621E+09	3.073E+07	1.342E+07	3.353E+07	**0.34851553**

HSB	Steam Enthalpy	Btu/lbm	1253.356	DHS/DT	0.842	DHS/DP	-0.1132
HFWB	Feedwater Enthalpy	Btu/lbm	436.041	DHFW/DT	1.117	DHFW/DP	-5.20E-04
HMU	Makeup Enthalpy	Btu/lbm	73.96	DHMU/DT	0.9882	DHMU/DP	2.61E-03

Case 6 - Single Loop Uncertainties

Symbol	Description	Units	Nominal Value	Absolute Systematic Uncertainty	Absolute Std. Dev. of the Mean	Absolute Sensitivity	Absolute Systematic Uncertainty Contribution	Absolute Random Uncertainty Contribution	Relative Systematic Uncertainty Contribution	Relative Random Uncertainty Contribution
WFW	Feedwater Flow Rate	lbm/hr	1.18E+07	3.43E+04	0	8.173E+02	1.969E+14	0.000E+00	60.19%	0.00%
TS	Steam Temperature	F	596	2.2	0.153	9.969E+06	1.203E+14	2.327E+12	36.76%	5.16%
PS	Steam Pressure	psia	930	2	1.52	-1.340E+06	1.796E+12	4.150E+12	0.55%	9.21%
TFW	Feedwater Temperature	F	455	0.1	0.46	1.323E+07	4.373E+11	3.701E+13	0.13%	82.15%
PFW	Feedwater Pressure	psia	1005	20.63	1.35	-6.157E+03	4.033E+09	6.908E+07	0.00%	0.00%
WMU	Makeup Flow Rate	lbm/hr	2.23E+04	1.11E+03	2.23E+03	7.396E+01	1.696E+09	2.713E+10	0.00%	0.06%
TMU	Makeup Temperature	F	100	5	2	2.201E+04	3.027E+09	1.937E+09	0.00%	0.00%
PMU	Makeup Pressure	psia	2250	50	50	5.812E+01	2.112E+06	8.446E+06	0.00%	0.00%
WLD	Letdown Flow Rate	lbm/hr	2.23E+04	1.11E+03	2.23E+03	5.555E+02	9.566E+10	1.531E+12	0.03%	3.40%
TLD	Letdown Temperature	F	557	5	2	2.791E+04	4.868E+09	3.116E+09	0.00%	0.01%
PLD	Letdown Pressure	psia	2250	50	50	-4.009E+01	1.004E+06	4.017E+06	0.00%	0.00%
QRCP	RCP Power	Btu/hr	6.75E+07	4.93E+06	0	1.000E+00	6.076E+12	0.000E+00	1.86%	0.00%
QLOSS	Ambient Heat Loss	Btu/hr	0.00E+00	2.50E+06	0	1.000E+00	1.563E+12	0.000E+00	0.48%	0.00%
							3.271E+14	4.505E+13	100.00%	100.00%

Symbol	Description	Units	Nominal Value	Absolute Systematic Uncertainty	Absolute Random Uncertainty	Absolute Uncertainty Btu/hr	Relative Uncertainty %
Qc	Core Thermal Power	Btu/hr	9.621E+09	3.617E+07	1.342E+07	3.858E+07	**0.40102689**

HSB	Steam Enthalpy	Btu/lbm	1253.356	DHS/DT	0.842	DHS/DP	-0.1132
HFWB	Feedwater Enthalpy	Btu/lbm	436.041	DHFW/DT	1.117	DHFW/DP	-5.20E-04
HMU	Makeup Enthalpy	Btu/lbm	73.96	DHMU/DT	0.9882	DHMU/DP	2.61E-03
HLD	Letdown Enthalpy	Btu/lbm	555.52	DHLD/DT	1.2532	DHLD/DP	-1.80E-03

Case 7 - Instrument Location Effects (Adjustment Incorporated)

Symbol	Description	Units	Nominal Value	Absolute Systematic Uncertainty	Absolute Std. Dev. of the Mean	Absolute Sensitivity	Absolute Systematic Uncertainty Contribution	Absolute Random Uncertainty Contribution	Relative Systematic Uncertainty Contribution	Relative Random Uncertainty Contribution
WFW	Feedwater Flow Rate	lbm/hr	1.18E+07	3.43E+04	0	8.173E+02	1.969E+14	0.000E+00	73.87%	0.00%
TS	Steam Temperature	F	596	1.56	0.153	9.969E+06	6.047E+13	2.327E+12	22.69%	5.16%
PS	Steam Pressure	psia	930	1.48	1.52	-1.340E+06	9.837E+11	4.150E+12	0.37%	9.21%
TFW	Feedwater Temperature	F	455	0.1	0.46	1.323E+07	4.373E+11	3.701E+13	0.16%	82.15%
PFW	Feedwater Pressure	psia	1005	14.6	1.35	-6.157E+03	2.020E+09	6.908E+07	0.00%	0.00%
WMU	Makeup Flow Rate	lbm/hr	2.23E+04	1.11E+03	2.23E+03	7.396E+01	1.696E+09	2.713E+10	0.00%	0.06%
TMU	Makeup Temperature	F	100	5	2	2.201E+04	3.027E+09	1.937E+09	0.00%	0.00%
PMU	Makeup Pressure	psia	2250	50	50	5.812E+01	2.112E+06	8.446E+06	0.00%	0.00%
WLD	Letdown Flow Rate	lbm/hr	2.23E+04	1.11E+03	2.23E+03	5.555E+02	9.566E+10	1.531E+12	0.04%	3.40%
TLD	Letdown Temperature	F	557	5	2	2.791E+04	4.868E+09	3.116E+09	0.00%	0.01%
PLD	Letdown Pressure	psia	2250	50	50	-4.009E+01	1.004E+06	4.017E+06	0.00%	0.00%
QRCP	RCP Power	Btu/hr	6.75E+07	4.93E+06	0	1.000E+00	6.076E+12	0.000E+00	2.28%	0.00%
QLOSS	Ambient Heat Loss	Btu/hr	0.00E+00	2.50E+06	0	1.000E+00	1.563E+12	0.000E+00	0.59%	0.00%
							2.665E+14	4.505E+13	100.00%	100.00%

Symbol	Description	Units	Nominal Value	Absolute Systematic Uncertainty	Absolute Random Uncertainty	Absolute Uncertainty Btu/hr	Relative Uncertainty %
Qc	Core Thermal Power	Btu/hr	9.621E+09	3.265E+07	1.342E+07	3.530E+07	**0.36692518**

HSB	Steam Enthalpy	Btu/lbm	1253.356	DHS/DT	0.842	DHS/DP	-0.1132
HFWB	Feedwater Enthalpy	Btu/lbm	436.041	DHFW/DT	1.117	DHFW/DP	-5.20E-04
HMU	Makeup Enthalpy	Btu/lbm	73.96	DHMU/DT	0.9882	DHMU/DP	2.61E-03
HLD	Letdown Enthalpy	Btu/lbm	555.52	DHLD/DT	1.2532	DHLD/DP	-1.80E-03

Case 8 - Instrument Location Effects
(Adjustment Not Incorporated)

Symbol	Description	Units	Nominal Value	Absolute Systematic Uncertainty	Absolute Std. Dev. of the Mean	Absolute Sensitivity	Absolute Systematic Uncertainty Contribution	Absolute Random Uncertainty Contribution	Relative Systematic Uncertainty Contribution	Relative Random Uncertainty Contribution
WFW	Feedwater Flow Rate	lbm/hr	1.18E+07	3.43E+04	0	8.173E+02	1.969E+14	0.000E+00	73.10%	0.00%
TS	Steam Temperature	F	596	1.56	0.153	9.969E+06	6.047E+13	2.327E+12	22.45%	5.16%
PS	Steam Pressure	psia	930	2.91	1.52	-1.340E+06	3.803E+12	4.150E+12	1.41%	9.21%
TFW	Feedwater Temperature	F	455	0.1	0.46	1.323E+07	4.373E+11	3.701E+13	0.16%	82.15%
PFW	Feedwater Pressure	psia	1005	14.6	1.35	-6.157E+03	2.020E+09	6.908E+07	0.00%	0.00%
WMU	Makeup Flow Rate	lbm/hr	2.23E+04	1.11E+03	2.23E+03	7.396E+01	1.696E+09	2.713E+10	0.00%	0.06%
TMU	Makeup Temperature	F	100	5	2	2.201E+04	3.027E+09	1.937E+09	0.00%	0.00%
PMU	Makeup Pressure	psia	2250	50	50	5.812E+01	2.112E+06	8.446E+06	0.00%	0.00%
WLD	Letdown Flow Rate	lbm/hr	2.23E+04	1.11E+03	2.23E+03	5.555E+02	9.566E+10	1.531E+12	0.04%	3.40%
TLD	Letdown Temperature	F	557	5	2	2.791E+04	4.868E+09	3.116E+09	0.00%	0.01%
PLD	Letdown Pressure	psia	2250	50	50	-4.009E+01	1.004E+06	4.017E+06	0.00%	0.00%
QRCP	RCP Power	Btu/hr	6.75E+07	4.93E+06	0	1.000E+00	6.076E+12	0.000E+00	2.26%	0.00%
QLOSS	Ambient Heat Loss	Btu/hr	0.00E+00	2.50E+06	0	1.000E+00	1.563E+12	0.000E+00	0.58%	0.00%
							2.693E+14	4.505E+13	100.00%	100.00%

Symbol	Description	Units	Nominal Value	Absolute Systematic Uncertainty	Absolute Random Uncertainty	Absolute Uncertainty Btu/hr	Relative Uncertainty %
Qc	Core Thermal Power	Btu/hr	9.621E+09	3.282E+07	1.342E+07	3.546E+07	**0.36858151**

HSB	Steam Enthalpy	Btu/lbm	1253.356	DHS/DT	0.842	DHS/DP	-0.1132
HFWB	Feedwater Enthalpy	Btu/lbm	436.041	DHFW/DT	1.117	DHFW/DP	-5.20E-04
HMU	Makeup Enthalpy	Btu/lbm	73.96	DHMU/DT	0.9882	DHMU/DP	2.61E-03
HLD	Letdown Enthalpy	Btu/lbm	555.52	DHLD/DT	1.2532	DHLD/DP	-1.80E-03

Case 9 - Use of Turbine Header Pressure Instruments

Symbol	Description	Units	Nominal Value	Absolute Systematic Uncertainty	Absolute Std. Dev. of the Mean	Absolute Sensitivity	Absolute Systematic Uncertainty Contribution	Absolute Random Uncertainty Contribution	Relative Systematic Uncertainty Contribution	Relative Random Uncertainty Contribution
WFW	Feedwater Flow Rate	lbm/hr	1.18E+07	3.43E+04	0	8.173E+02	1.969E+14	0.000E+00	73.13%	0.00%
TS	Steam Temperature	F	596	1.56	0.153	9.969E+06	6.047E+13	2.327E+12	22.46%	5.16%
PS	Steam Pressure	psia	930	2.87	1.52	-1.340E+06	3.699E+12	4.150E+12	1.37%	9.21%
TFW	Feedwater Temperature	F	455	0.1	0.46	1.323E+07	4.373E+11	3.701E+13	0.16%	82.15%
PFW	Feedwater Pressure	psia	1005	14.6	1.35	-6.157E+03	2.020E+09	6.908E+07	0.00%	0.00%
WMU	Makeup Flow Rate	lbm/hr	2.23E+04	1.11E+03	2.23E+03	7.396E+01	1.696E+09	2.713E+10	0.00%	0.06%
TMU	Makeup Temperature	F	100	5	2	2.201E+04	3.027E+09	1.937E+09	0.00%	0.00%
PMU	Makeup Pressure	psia	2250	50	50	5.812E+01	2.112E+06	8.446E+06	0.00%	0.00%
WLD	Letdown Flow Rate	lbm/hr	2.23E+04	1.11E+03	2.23E+03	5.555E+02	9.566E+10	1.531E+12	0.04%	3.40%
TLD	Letdown Temperature	F	557	5	2	2.791E+04	4.868E+09	3.116E+09	0.00%	0.01%
PLD	Letdown Pressure	psia	2250	50	50	-4.009E+01	1.004E+06	4.017E+06	0.00%	0.00%
QRCP	RCP Power	Btu/hr	6.75E+07	4.93E+06	0	1.000E+00	6.076E+12	0.000E+00	2.26%	0.00%
QLOSS	Ambient Heat Loss	Btu/hr	0.00E+00	2.50E+06	0	1.000E+00	1.563E+12	0.000E+00	0.58%	0.00%
							2.692E+14	4.505E+13	100.00%	100.00%

Symbol	Description	Units	Nominal Value	Absolute Systematic Uncertainty	Absolute Random Uncertainty	Absolute Uncertainty Btu/hr	Relative Uncertainty %
Qc	Core Thermal Power	Btu/hr	9.621E+09	3.282E+07	1.342E+07	3.546E+07	**0.36852064**

HSB	Steam Enthalpy	Btu/lbm	1253.356	DHS/DT	0.842	DHS/DP	-0.1132
HFWB	Feedwater Enthalpy	Btu/lbm	436.041	DHFW/DT	1.117	DHFW/DP	-5.20E-04
HMU	Makeup Enthalpy	Btu/lbm	73.96	DHMU/DT	0.9882	DHMU/DP	2.61E-03
HLD	Letdown Enthalpy	Btu/lbm	555.52	DHLD/DT	1.2532	DHLD/DP	-1.80E-03

Case 10 - Insensitivity of Makeup and Letdown
Uncertainty Assumptions

Symbol	Description	Units	Nominal Value	Absolute Systematic Uncertainty	Absolute Std. Dev. of the Mean	Absolute Sensitivity	Absolute Systematic Uncertainty Contribution	Absolute Random Uncertainty Contribution	Relative Systematic Uncertainty Contribution	Relative Random Uncertainty Contribution
WFW	Feedwater Flow Rate	lbm/hr	1.18E+07	3.43E+04	0	8.173E+02	1.969E+14	0.000E+00	73.81%	0.00%
TS	Steam Temperature	F	596	1.56	0.153	9.969E+06	6.047E+13	2.327E+12	22.67%	4.68%
PS	Steam Pressure	psia	930	1.42	1.52	-1.340E+06	9.056E+11	4.150E+12	0.34%	8.34%
TFW	Feedwater Temperature	F	455	0.1	0.46	1.323E+07	4.373E+11	3.701E+13	0.16%	74.41%
PFW	Feedwater Pressure	psia	1005	14.6	1.35	-6.157E+03	2.020E+09	6.908E+07	0.00%	0.00%
WMU	Makeup Flow Rate	lbm/hr	2.23E+04	2.23E+03	4.45E+03	7.396E+01	6.782E+09	1.085E+11	0.00%	0.22%
TMU	Makeup Temperature	F	100	10	4	2.201E+04	1.211E+10	7.749E+09	0.00%	0.02%
PMU	Makeup Pressure	psia	2250	100	100	5.812E+01	8.446E+06	3.378E+07	0.00%	0.00%
WLD	Letdown Flow Rate	lbm/hr	2.23E+04	2.23E+03	4.45E+03	5.555E+02	3.826E+11	6.122E+12	0.14%	12.31%
TLD	Letdown Temperature	F	557	10	4	2.791E+04	1.947E+10	1.246E+10	0.01%	0.03%
PLD	Letdown Pressure	psia	2250	100	100	-4.009E+01	4.017E+06	1.607E+07	0.00%	0.00%
QRCP	RCP Power	Btu/hr	6.75E+07	4.93E+06	0	1.000E+00	6.076E+12	0.000E+00	2.28%	0.00%
QLOSS	Ambient Heat Loss	Btu/hr	2.23E+06	2.50E+06	0	1.000E+00	1.563E+12	0.000E+00	0.59%	0.00%
							2.668E+14	4.974E+13	100.00%	100.00%

Symbol	Description	Units	Nominal Value	Absolute Systematic Uncertainty	Absolute Random Uncertainty	Absolute Uncertainty Btu/hr	Relative Uncertainty %
Qc	Core Thermal Power	Btu/hr	9.621E+09	3.267E+07	1.411E+07	3.558E+07	**0.36981424**

HSB	Steam Enthalpy	Btu/lbm	1253.356	DHS/DT	0.842	DHS/DP	-0.1132
HFWB	Feedwater Enthalpy	Btu/lbm	436.041	DHFW/DT	1.117	DHFW/DP	-5.20E-04
HMU	Makeup Enthalpy	Btu/lbm	73.96	DHMU/DT	0.9882	DHMU/DP	2.61E-03
HLD	Letdown Enthalpy	Btu/lbm	555.52	DHLD/DT	1.2532	DHLD/DP	-1.80E-03

Case 11 - MVP Base Case Using Dual Loop Instrument Uncertainties (Based on Case 2)

Symbol	Description	Units	Nominal Value	Absolute Systematic Uncertainty	Absolute Std. Dev. of the Mean	Absolute Sensitivity	Absolute Systematic Uncertainty Contribution	Absolute Random Uncertainty Contribution	Relative Systematic Uncertainty Contribution	Relative Random Uncertainty Contribution
WFW	Feedwater Flow Rate	lbm/hr	1.27E+07	3.69E+04	0	8.131E+02	2.249E+14	0.000E+00	73.97%	0.00%
TS	Steam Temperature	F	591	1.56	0.153	1.071E+07	6.979E+13	2.685E+12	22.95%	5.16%
PS	Steam Pressure	psia	930	1.42	1.52	-1.487E+06	1.115E+12	5.108E+12	0.37%	9.81%
TFW	Feedwater Temperature	F	455	0.1	0.46	-1.421E+07	5.047E+11	4.272E+13	0.17%	82.03%
PFW	Feedwater Pressure	psia	1005	14.6	1.35	-6.614E+03	2.331E+09	7.973E+07	0.00%	0.00%
WMU	Makeup Flow Rate	lbm/hr	2.23E+04	1.11E+03	2.23E+03	7.396E+01	1.696E+09	2.713E+10	0.00%	0.05%
TMU	Makeup Temperature	F	100	5	2	2.201E+04	3.027E+09	1.937E+09	0.00%	0.00%
PMU	Makeup Pressure	psia	2250	50	50	5.812E+01	2.112E+06	8.446E+06	0.00%	0.00%
WLD	Letdown Flow Rate	lbm/hr	2.23E+04	1.11E+03	2.23E+03	5.555E+02	9.566E+10	1.531E+12	0.03%	2.94%
TLD	Letdown Temperature	F	557	5	2	2.791E+04	4.868E+09	3.116E+09	0.00%	0.01%
PLD	Letdown Pressure	psia	2250	50	50	-4.009E+01	1.004E+06	4.017E+06	0.00%	0.00%
QRCP	RCP Power	Btu/hr	6.75E+07	4.93E+06	0	1.000E+00	6.076E+12	0.000E+00	2.00%	0.00%
QLOSS	Ambient Heat Loss	Btu/hr	2.23E+06	2.50E+06	0	1.000E+00	1.563E+12	0.000E+00	0.51%	0.00%
							3.040E+14	5.207E+13	100.00%	100.00%

Symbol	Description	Units	Nominal Value	Absolute Systematic Uncertainty	Absolute Random Uncertainty	Absolute Uncertainty Btu/hr	Relative Uncertainty %
Qc	Core Thermal Power	Btu/hr	1.029E+10	3.487E+07	1.443E+07	3.774E+07	**0.36665809**

HSB	Steam Enthalpy	Btu/lbm	1249.121	DHS/DT	0.842	DHS/DP	-0.1169
HFWB	Feedwater Enthalpy	Btu/lbm	436.041	DHFW/DT	-1.117	DHFW/DP	-5.20E-04
HMU	Makeup Enthalpy	Btu/lbm	73.96	DHMU/DT	0.9882	DHMU/DP	2.61E-03
HLD	Letdown Enthalpy	Btu/lbm	555.52	DHLD/DT	1.2532	DHLD/DP	-1.80E-03

APPENDIX B – Excerpts from CTPA

Within the code listing, formulations were provided for the heat balance. Computer code excerpts are provided below. Some of these values are considered constants whose values are defined in Reference 8 (and shown below). For the core power based on the secondary heat balance:

QCOR1=(QSECA+QSECB+QLOSS-QCDT0-QCDT1-QCDT2-QCDT3)/(WMBTU*RCSCL)

Where:

QSECA = CORE THERMAL POWER FROM SECONDARY SIDE HEAT BALANCE (STEAM GENERATOR-A-)

QSECB = CORE THERMAL POWER FROM SECONDARY SIDE HEAT BALANCE (STEAM GENERATOR-B-)

QLOSS = ENERGY LOSS BETWEEN MAKE UP AND LETDOWN FLOW

QCDT0, QCDT1, QCDT2, QCDT3 are terms for RC pump heat and ambient losses. For the case of four RC pumps operating, QCDT1 and QCDT3 are equivalent to two RC pumps. QCDT1 also accounts for the ambient losses in the form "QHTRS" shown below.

WMBTU = Conversion from kilowatts to Btu/hr = .34121E+04

RCSCL = Conversion from Mw to kw 1.0E+3

For the steam generator heat balance terms:

QSECA=WFIDA*(HSTM(TSTA,PSTA)-HFID(TFWA,PFIDA))

QSECB=WFIDB*(HSTM(TSTB,PSTB)-HFID(TFWB,PFIDB))

Where:

WFIDA = CORRECTED FEEDWATER FLOW TO STEAM GENERATOR A

WFIDB = CORRECTED FEEDWATER FLOW TO STEAM GENERATOR B

HSTM IS A FUNCTION THAT YIELDS ENTHALPY STEAM FOR A GIVEN TEMPERATURE AND PRESSURE

HFID IS A FUNCTION THAT YIELDS ENTHALPY FEEDWATER FOR A GIVEN TEMPERATURE AND PRESSURE

For the makeup and letdown heat balance:

QLOSS = QLTDN – QMKUP

Where:

QLTDN = ENERGY OF THE LETDOWN FLOW

QMKUP = ENERGY OF THE MAKEUP FLOW

QLTDN=WLTDN*HAVE(TLTDN,PRESS)

WLTDN = SIX-MINUTE AVERAGE OF LET DOWN FLOW RATE

TLTDN = SIX-MINUTE AVERAGE OF LET DOWN TEMP (DEG F)

PRESS = PRIMARY SYSTEM PRESSURE (PSIA)

PRESS = SIX-MIN. AVERAGE OF SPCRA,SPCRB (PSIA)

SPCRA = 30 SEC RC PRESSURE AT LOOP A (PSIA)

SPCRB = 30 SEC RC PRESSURE AT LOOP B (PSIA)

QMKUP = WMKUP*HAVE(TMKUP,PRESS)

WMKUP = SIX-MINUTE AVERAGE OF MAKE-UP FLOW RATE

TMKUP = SIX-MINUTE AVERAGE OF LET DOWN TEMP (DEG F)

For the RC pump heat and ambient loss terms:

If both pumps in the A loop are operating:

QCDT3=(2.0*QPUMP+QHTRS)*WMBTU

If both pumps in the B loop are operating:

QCDT1=2.0*QPUMP*WMBTU

QPUMP = ETA*QMOTR

ETA = RC Pump/Motor Efficiency

QMOTR = RC Pump Motor Power

QHTRS = ADDITIONAL ENERGY CREDITS OR LOSSES TO THE REACTOR COOLANT SYSTEM. NOTE CTPA ARE INPUT AS NEGATIVE QUANTITIES IN KILOWATTS

From Reference 8, constants for Davis Besse's version of CTPA are:

QHTRS = 0.0

QMOTR = 6181.0 kw

ETA = .80000E+00

Rev 05

From Reference 24, QHTRS = -653.0 Kw

APPENDIX C - Steam Line Pressure Losses

Calculations of the pressure losses between the OTSG outlet nozzles and the pressure transducers are presented herein. Both the outlet pressure transducers and turbine header pressure transducers are considered. Because steam density is small elevation and momentum pressure changes were ignored.

Losses to the Outlet Pressure Transducers

SG1-1 to PT SP12B2

From Reference 11, line losses consist of a 26" X 24" reducer, straight pipe, and three long radius elbows (R/D = 1.5 assumed). The straight pipe length was determined from Reference 11 to be:

L = [(12'3-1/16") – (5'6-5/8")]÷cos(40°) + 10'2-3/16" + 18'0-1/16" + 9' = 46.0 ft

From Reference 12, pipe ID = 24.476", friction factor = 0.0115 for the 26" pipe. The flow area = $(\pi/4)*(24.476/12)^2 = 3.2674\ ft^2$. For the 24" pipe, ID = 22.062".

$$fL/D = 0.0115*46/(24.476/12) = 0.26$$

From Reference 13, Diagram 6-1, form loss for a 90°, circular cross section elbow = $0.21/(R/D)^{0.5} = 0.21/(1.5)^{0.5} = 0.17$,

For three elbows, K = 3*0.17 = 0.51

From Reference 14, the length of a 26" X 24" reducer = 24"

Therefore the expansion angle, θ, $= \tan^{-1}\{[(24.476 - 22.062)/2]/24\} = 5.74°$

From Reference 15, the loss factor based on the larger pipe (26") is

$$K = 2.6(\sin\theta/2)(1-\beta^2)^2/\beta^4$$

$$\beta = 22.062/24.476 = 0.90$$

$$K = 2.6(\sin(5.74/2))(1-0.90^2)^2/0.9^4 = 0.01$$

Total form loss = 0.01 + 0.26 + 0.51 = 0.78 based on $3.2674\ ft^2$

The pressure loss was calculated as:

$$\Delta P = \frac{W^2\,\Sigma(K + fL/D)}{\rho\, A^2\, 2\, g_c}$$

where,

W = steam flow rate = 5.92e6 lbm/hr/per OSTG (Ref. 10)
Since there are two 26" lines, W = 2.96e6 lbm/hr = 822.2 lbm/s

ρ = 1.788 lbm/ft^3 (P = 930 psia, T = 596°F)

A = 3.2674 ft^2

$\Sigma(K + fL/D) = 0.78$

$$\Delta P = \frac{(822.2)^2 \text{ lbm}^2/\text{s}^2 * 0.78}{1.788 \text{ lbm/ft}^3 * (3.2674)^2 \text{ ft}^4 * 64.4 \text{ lbmft/(lbf s}^2) * 144 \text{ in}^2/\text{ft}^2}$$

ΔP = 3.0 psi

<u>SG 1-1 to PT SP12B1</u>

From Reference 11, line losses consist of a 26" X 24" reducer, straight pipe, and three long radius elbows (R/D = 1.5 assumed). The straight pipe length was determined from Reference 11 to be:

L = [(12'3-1/16") – (5'6-5/8")]÷cos(40°) + 13'8-3/16" + 12'2-15/16" + 7' = 41.7 ft

Thus,

$\Sigma(K + fL/D) = 0.01 + 0.51 + 0.0115*41.7/(24.476/12) = 0.76$

$$\Delta P = \frac{(822.2)^2 \text{ lbm}^2/\text{s}^2 * 0.76}{1.788 \text{ lbm/ft}^3 * (3.2674)^2 \text{ ft}^4 * 64.4 \text{ lbmft/(lbf s}^2) * 144 \text{ in}^2/\text{ft}^2}$$

ΔP = 2.9 psi

<u>SG 1-2 to SP12A2</u>

From Reference 16, the hydraulic characteristics match those from SG 1-1 to SP12B2. Thus, the ΔP = 3.0 psi.

<u>SG 1-2 to SP12A1</u>

From Reference 16, the hydraulic characteristics match those from SG 1-1 to SP12B1. Thus, the ΔP = 2.9 psi.

Losses to the Turbine Header Pressure Transducers

SG 1-1

Parallel 26" Lines from OTSG to 36" Tee

SP12B2 Side

From Reference 11, line losses consist of a 26" X 24" reducer, straight pipe, five long radius elbows (R/D = 1.5 assumed), a 26" X 36" reducer, and a 36"X36" Tee. The straight pipe length was determined from Reference 11 to be:

To SP12B2 = 46.0'

From SP12B12 = (16'0-1/2" – 9') + 19'6-11/16" + *7'5-1/2" = 34.1'

Total Length = 46.0 + 34.1= 80.1'

* maximizes ΔP since part of length is 36" pipe

For five elbows, K = 5*0.17 = 0.85

From Reference 14, the length of a 36" X 26" reducer = 24" (based on other reducers)

The 36" pipe ID = 33.89" (Ref. 12). $A = \pi/4 * (33.89/12)^2 = 6.264\ ft^2$

Therefore the expansion angle, θ, $= \tan^{-1} \{[(33.89 - 24.476)/2]/24\} = 11.1°$

From Reference 15, the loss factor based on the smaller pipe (26") is

$$K = 2.6(\sin\theta/2)(1-\beta^2)^2$$

$$\beta = 24.476/33.89 = 0.72$$

$$K = 2.6(\sin(11.1/2))(1-0.72^2)^2 = 0.06$$

For the Tee, Diagram 7-4 of Reference 13, shows for a 50% flow split and Fs/Fc = 1.0, K = 0.77 based on the 36" pipe. Adjusting for the area difference $K = 0.77*(3.2674/6.264)^2 = 0.21$ based on 26" pipe.

$\Sigma(K + fL/D) = 0.01 + 0.06 + 0.85 + 0.21 + 0.0115*80.1/(24.476/12) =$ 1.58 based on 3.2674 ft^2

$$\Delta P = \frac{(822.2)^2 \text{ lbm}^2/\text{s}^2 * 1.58}{1.788 \text{ lbm/ft}^3 * (3.2674)^2 \text{ ft}^4 * 64.4 \text{ lbmft/(lbf s}^2) * 144 \text{ in}^2/\text{ft}^2}$$

$\Delta P = 6.0$ psi

SP12B1 Side

From Reference 11, line losses consist of a 26" X 24" reducer, straight pipe, four long radius elbows (R/D = 1.5 assumed), a 26" X 36" reducer, and a 36"X36" Tee. The straight pipe length was determined from Reference 11 to be:

To SP12B1 = 41.7'

From SP12B1 = (20' – 7') + *38'3-11/16" = 51.3'

* maximizes ΔP since part of length is 36" pipe

Total Length = 41.7 + 51.3 = 93.0'

For four elbows, K = 4*0.17 = 0.68

From Reference 14, the length of a 36" X 26" reducer = 24" (based on other reducers)

The 36" pipe ID = 33.89" (Ref. 12). $A = \pi/4 * (33.89/12)^2 = 6.264 \text{ ft}^2$

Therefore the expansion angle, θ, $= \tan^{-1} \{[(33.89 - 24.476)/2]/24\} = 11.1°$

From Reference 15, the loss factor based on the smaller pipe (26") is

$K = 2.6(\sin\theta/2)(1-\beta^2)^2$

$\beta = 24.476/33.89 = 0.72$

$K = 2.6(\sin(11.1/2))(1-0.72^2)^2 = 0.06$

For the Tee, Diagram 7-4 of Reference 13, shows for a 50% flow split and Fs/Fc = 1.0, K = 0.53 based on the 36" pipe. Adjusting for the area difference $K = 0.53*(3.2674/6.264)^2 = 0.14$ based on 26" pipe.

$\Sigma(K + fL/D) = 0.01 + 0.06 + 0.68 + 0.14 + 0.0115*93.0/(24.476/12) = 1.41$ based on 3.2674 ft^2

$$\Delta P = \frac{(822.2)^2 \text{ lbm}^2/\text{s}^2 * 1.41}{1.788 \text{ lbm/ft}^3 * (3.2674)^2 \text{ ft}^4 * 64.4 \text{ lbmft/(lbf s}^2) * 144 \text{ in}^2/\text{ft}^2}$$

ΔP = 5.4 psi

Since the ΔPs to the common location differ, the flow will not be evenly split.

$W2/W1 = (1.58/1.41)^{0.5} = 1.06$

W2 = 1.06W1

Since W1 + W2 = 2*822.2, W1 + 1.06*W1 = 2*822.2

W1 = 798.3 lbm/s

$$\Delta P = \frac{(798.3)^2 \text{ lbm}^2/\text{s}^2 * 1.58}{1.788 \text{ lbm/ft}^3 * (3.2674)^2 \text{ ft}^4 * 64.4 \text{ lbmft/(lbf s}^2) * 144 \text{ in}^2/\text{ft}^2}$$

ΔP = 5.7 psi

From Tee to PI109

From References 11 and 17, line losses consist of two check valves, straight pipe, and eight long radius elbows (R/D = 1.5 assumed). The straight pipe length was determined from References 11 and 17 to be:

L = 4'7-13/16" + 32'11-1/8" + *36.36' + 9'6" + 104'11" + 64' + 85' + (24'7" – 5'1" – 4'6") + 50'6" + 5'6" + 18" + 16'4" + (23'11" – 3'9" – 12") = 445.3'

*Note: 34'11-5/16" of length has a diameter of 33.625" vs. typical 33.89". The equivalent length = $34.943*(33.89/33.625)^5 = 36.34'$

For eight elbows, K = 8*0.17 = 1.36

Two check valves = 50L/Ds each (Ref. 12)
Area = $\pi/4 * (33.89/12)^2 = 6.2643 \text{ ft}^2$

$\Sigma(K + fL/D) = 1.36 + 0.01075*(445.3 + 100)/(33.89/12) = 3.44$ based on 6.2643 ft^2

$$\Delta P = \frac{(2*822.2)^2 \text{ lbm}^2/\text{s}^2 * 3.44}{1.788 \text{ lbm/ft}^3 * (6.2643)^2 \text{ ft}^4 * 64.4 \text{ lbmft/(lbf s}^2) * 144 \text{ in}^2/\text{ft}^2}$$

ΔP = 14.3 psi

Total ΔP from SG 1-1 to PI 109 = 5.7 + 14.3 = 20.0 psi

SG 1-2

From SG 1-2 to Tee

ΔP = 5.7 psi since geometry is the same as SG 1-1

From Tee to PI273

From References 16 and 17, line losses consist of two check valves, straight pipe, two 45° elbows and four 90° long radius elbows (R/D = 1.5 assumed). The straight pipe length was determined from References 16 and 17 to be:

L = 4'7-3/16" + 32'11-1/8" + *38.42' + 9'6" + 31'11" + 10' + 5'6" + (32'5" – 5'1") + 50'6" + 5'6" + 18" + 16'4" + (23'11" – 3'9" – 12") = 253.2'

*Note: 36'11-5/16" of length has a diameter of 33.625" vs. typical 33.89". The equivalent length = $36.943*(33.89/33.625)^5$ = 38.42'

For four 90° elbows, K = 4*0.17 = 0.68

For two 45° elbows, K = 2*0.17*0.9sin(45) = 0.22
(See Ref. 13, Dia 6-1)

Two check valves = 50L/Ds each (Ref. 12)
Area = $\pi/4 * (33.89/12)^2 = 6.2643\ ft^2$

Σ(K + fL/D) = 0.68 + 0.22 + 0.01075*(253.2 + 100)/(33.89/12) = 2.24 based on $6.2643\ ft^2$

$$\Delta P = \frac{(2*822.2)^2\ lbm^2/s^2 * 2.24}{1.788\ lbm/ft^3 * (6.2643)^2\ ft^4 * 64.4\ lbmft/(lbf\ s^2) * 144\ in^2/ft^2}$$

ΔP = 9.3 psi
Total ΔP from SG 1-2 to PI 109 = 5.7 + 9.3 = 15.0 psi

ATTACHMENT 1 – CALDON Uncertainty Inputs – Telecon with Herb Estrada

Note: the values shown in this attachment were superceded by those in Reference 21. The information used herein was the description of how to treat the Caldon "lumped" feedwater flow-temperature uncertainty treatment, rather than the values themselves.

Telecon Memo

Date: April 12, 2001

Person calling: Bret Boman, Framatome Technologies

Person called: Herb Estrada

Subject: LEFM Interface and Reconciliation Document, Davis Besse, dated 4/12/01

Bret called after having read the subject document. He understood that the value given for the "AB" term is a bounding value and covers thermal power uncertainties in both mass flow and enthalpy. However, the analysis that he is preparing for Davis Besse carries these terms separately and he would like to retain this format. I suggested that, in lieu of simply increasing the temperature error from 0.6 ^{0}F until the aggregate uncertainty due to mass flow and feedwater enthalpy is 0.31% (the value given for AB in the table), he retain the 0.6 ^{0}F error, but treat a portion of it as systematic (to be summed with the mass flow error) and a portion of it as random (to be combined as the root sum square with the mass flow and systematic temperature term). This process in fact represents the nature of the errors. Bret understood and said he will iterate to find the fraction of the temperature related enthalpy error that should be treated as systematic, while treating the remainder randomly, to obtain the same bottom line. I told him I believed the fraction was about 0.3. [I have since calculated the fraction; it is 0.313. That is, the 0.08% should be divided into two parts: a systematic part $S = 0.313 \times 0.08$, which should be summed with the 0.28% mass flow error, and a random part $R= (1 - 0.313) \times 0.08$, which should be combined with $(0.28 + S)$ as the root sum square.]

I noted that the LEFM uncertainties listed in the subject document do not support an uprate of 1.7%. I said that, if the 1.7% figure is a firm objective, the final LEFM uncertainty analysis will probably support it. This is because the final analysis incorporates the actual profile factor uncertainty, which is usually in the 0.20 to 0.22% range. I also told him it would be good if the analysis submitted to the NRC shows some margin because they are looking for it.

We discussed briefly the methodology of our analysis. I told him that we followed PTC 19.1. He noted that that document discusses both random errors and biases. I told him that in fact we have both kinds and they are incorporated in AB—no additional random errors should be included. I told him that to bound time dependent random errors, due both to time measurements and turbulence, the analysis assumes a two minute (minimum) average of the data.

Bret asked, and I confirmed, that we considered the effect of the two (loop) feedwater measurements that will be incorporated at Davis Besse. I said that while a number of terms are reduced by the random combination of the uncertainties in the two loop measurements, these terms are small. Furthermore some of the starting points for time measurement and length errors are a little larger than the analyses of ER 157P because the two Davis Besse pipes are individually smaller than the single 157 pipe. The random combination of these slightly larger errors for two pipes brings the aggregate result to a level equal to or slightly below that in 157. I noted that the biggest LEFM uncertainty—profile factor—is treated as systematic, because both spools are usually calibrated in the same hydraulic model in the same facility, one after the other.

I told Bret that I used what I believed to be conservatively accurate values for feed and steam conditions in calculating the Davis Besse numbers. Specifically:

- Total feedwater flow: 11.8 million pounds per hour (actual, 12 million)
- Steam conditions: 900psia, 590 ^{0}F (actual, 900, 596)
- Final feed conditions: (1050 psia, 460 ^{0}F (actual ~1100, 455)

The net effect of all of the above discrepancies is to make the Davis Besse numbers in the subject document very slightly conservative (their effects probably will not show in the bottom line).

I told Bret that if he or any of the Framatome people would like to discuss our analysis in detail we would be happy to oblige.

<u>Distribution</u>:

Bret Boman, Framatome Technologies
Leeanne Jozwiak
Ernie Hauser
Ed Madera
Jenny Regan

ATTACHMENT 2 - Revised CALDON Flow Uncertainty Values

The attached file presents the revised feedwater flow uncertainty for the replacement transducers.

CAMERON

Measurement Systems

Caldon® Ultrasonics Technology Center
1000 McClaren Woods Drive
Coraopolis, PA 15108
Tel: 724-273-9300
Fax: 724-273-9301
www.c-a-m.com

March 8, 2007

Tim Laurer
Nuclear Staff Engineer
Davis-Besse Nuclear Power Station
5501 North State Route 2
Oak Harbor, OH 43449
Attn: Tim Laurer

Telephone Number: 419-321-7764

Reference: First Energy Nuclear Operation Corp. Order No. 7048503
Cameron Measurement Systems Contract No. CO-22776

Subject: Cameron Measurement Systems Response to Transducer Replacement Sensitivity

Dear Tim,

At the request of the NRC, Cameron conducted transducer replacement testing to create an empirical, statistical evaluation of the uncertainty involved in replacing LEFM CheckPlus transducers in the field. The results of these tests reveals a spread on the same order as the uncertainty in the testing itself. In addition, uncertainties already accounted for in the analysis could be the source of parts of the spread in the raw results.

As a conservative measure, however, Cameron has elected to create a new uncertainty term in all analyses going forward explicitly to address the transducer replacement uncertainty. The term will actually appear both in the calibration uncertainty and in the installed system uncertainty as it applies to both instances. The amount of this uncertainty term for Davis Besse's two 18 inch pipe case is 0.1%. Applying this term in both calibration and installation uncertainty cases results in a change in overall mass flow uncertainty from 0.26% to 0.29%.

It is planned that no changes will be backfit to existing analyses, but that all analyses going forward will contain these additional terms. However, as Davis Besse is in the unusual position of having an old analysis being submitted for a new approval, an exception to this plan seems to be required. Therefore, Cameron proposes to revise Davis Besse's analysis to reflect the new terms. We will deliver the revised analysis in 90 days. In the meantime, Cameron will continue with our plans to schedule a general meeting with the NRC to discuss the particulars of the issue and the proposed plan.

Please do not hesitate to give me a call if you have any questions.

CAMERON

Measurement Systems

Caldon® Ultrasonics Technology Center
1000 McClaren Woods Drive
Coraopolis, PA 15108
Tel: 724-273-9300
Fax: 724-273-9301
www.c-a-m.com

Sincerely,

Ed Madera
Cameron Measurement Systems Sr. Project Engineer

Ernie Hauser
Director of Sales
Cameron Measurement Systems
(formerly Caldon Inc.)

ATTACHMENT 3 - Davis Besse Instrument Uncertainty Values

The attached file presents the basis for the random uncertainty values for steam temperature, steam pressure, and feedwater pressure.

FirstEnergy

Davis-Besse Nuclear Power Station
5501 North State Route 2
Oak Harbor, Ohio 43449-9760

PRS-03-00016
April 28, 2003

Mr. Bret Boman
Framatome ANP
3315 Old Forest Road
PO Box 10935
Lynchburg, VA 24506-0935

Subject: Calculation 32-5012428, Heat Balance Uncertainty

Dear Bret,

In regards to assumption (4) of the subject calculation, please consider the data provided as Attachment 3 to the calculation to be valid input for random uncertainties used for steam temperature = 0.153°F, steam pressure = 1.52 psi and feedwater pressure = 1.35 psi. This data was obtained at steady state, 100% power, at 30 second intervals for 24 hours on August 25, 2000. The plant computer Data Acquisition Display System analyzed this data collection and calculated a standard deviation for these computer points. This process has been reviewed and is considered to be representative of the random error for these instrument strings.

Please use the above to provide verification of assumption (4) in the Heat Balance Uncertainty Calculation.

Sincerely,

John P. Hartigan

John P. Hartigan,
Senior Consultant

JPH/sas

cc: Nuclear Records Management

Caldon Flow Errors

$Q_{Sec} = W_{Fw} \cdot (H_{Stm} - H_{Fw})$

$dQ_{Sec} = dW_{Fw} \cdot (H_{Stm} - H_{Fw}) + (W_{Fw} \cdot dH_{Stm}) + (W_{Fw} \cdot dH_{Fw})$

The instrument string uncertainty was obtained from instrument data packages and the mean and standard deviation was obtained from data collected on 8/25/00 at a 30 second sample rate for the entire day. Values were calculated by DADS.

Mean	Process Standard Deviation	Instrument String Accuracy	Total Uncertainty	
$p481 := 871.7$ Psig	$\delta_{p481} := 1.47$	$d_{p481} := 4.38$	$d\delta_{p481} := \sqrt{\delta_{p481}^2 + d_{p481}^2}$	$d\delta_{p481} = 4.62$
$p482 := 880.6$ Psig	$\delta_{p482} := 1.52$	$d_{p482} := 4.38$	$d\delta_{p482} := \sqrt{\delta_{p482}^2 + d_{p482}^2}$	$d\delta_{p482} = 4.636$
$p930 := 924.4$ Psig	$\delta_{p930} := 1.32$	$d_{p930} := 10.6$	$d\delta_{p930} := \sqrt{\delta_{p930}^2 + d_{p930}^2}$	$d\delta_{p930} = 10.682$
$p935 := 926.0$ Psig	$\delta_{p935} := 1.35$	$d_{p935} := 10.6$	$d\delta_{p935} := \sqrt{\delta_{p935}^2 + d_{p935}^2}$	$d\delta_{p935} = 10.686$
$t476 := 589.9$ Deg F	$\delta_{t476} := .148$	$d_{t476} := 4.3$	$d\delta_{t476} := \sqrt{\delta_{t476}^2 + d_{t476}^2}$	$d\delta_{t476} = 4.303$
$t477 := 590.5$ Deg F	$\delta_{t477} := .153$	$d_{t477} := 4.3$	$d\delta_{t477} := \sqrt{\delta_{t477}^2 + d_{t477}^2}$	$d\delta_{t477} = 4.303$
$t671 := 454.8$ Deg F	$\delta_{t671} := .183$	$d_{t671} := 4.32$	$d\delta_{t671} := \sqrt{\delta_{t671}^2 + d_{t671}^2}$	$d\delta_{t671} = 4.324$
$t672 := 455.5$ Deg F	$\delta_{t672} := .184$	$d_{t672} := 4.32$	$d\delta_{t672} := \sqrt{\delta_{t672}^2 + d_{t672}^2}$	$d\delta_{t671} = 4.324$
$f673 := 5853$ KPPH	$\delta_{f673} := 26.7$	$d_{f673} := 46.46$	$d\delta_{f673} := \sqrt{\delta_{f673}^2 + d_{f673}^2}$	$d\delta_{f673} = 53.586$
$f674 := 5826$ KPPH	$\delta_{f674} := 26.7$	$d_{f674} := 46.46$	$d\delta_{f674} := \sqrt{\delta_{f674}^2 + d_{f674}^2}$	$d\delta_{f674} = 53.586$
$f675 := 671.3$ In H_2O	$\delta_{f675} := 6.18$	$d_{f675} := 5.34$	$d\delta_{f675} := \sqrt{\delta_{f675}^2 + d_{f675}^2}$	$d\delta_{f675} = 8.167$
$f676 := 666.6$ In H_2O	$\delta_{f676} := 6.10$	$d_{f676} := 5.29$	$d\delta_{f676} := \sqrt{\delta_{f676}^2 + d_{f676}^2}$	$d\delta_{f676} = 8.074$
$f679 := 5782$ KPPH	$\delta_{f679} := 22.7$	$d_{f679} := 46.46$	$d\delta_{f679} := \sqrt{\delta_{f679}^2 + d_{f679}^2}$	$d\delta_{f679} = 51.709$
$f680 := 5810$ KPPH	$\delta_{f680} := 23.0$	$d_{f680} := 46.46$	$d\delta_{f680} := \sqrt{\delta_{f680}^2 + d_{f680}^2}$	$d\delta_{f680} = 51.841$
$f681 := 655.0$ In H_2O	$\delta_{f681} := 5.17$	$d_{f681} := 5.30$	$d\delta_{f681} := \sqrt{\delta_{f681}^2 + d_{f681}^2}$	$d\delta_{f681} = 7.404$
$f682 := 652.8$ In H_2O	$\delta_{f682} := 5.20$	$d_{f682} := 5.28$	$d\delta_{f682} := \sqrt{\delta_{f682}^2 + d_{f682}^2}$	$d\delta_{f682} = 7.411$

Of note, the string accuracy for t476 and t477 are different but the actual hardware is identical.

Feedwater temperature is obtained from T671 and T672 which are physically located in the same thermowell and as such, the temperature at that location and the temperature error are as follows.

$$t_{Feed} := \frac{t671 + t672}{2} \qquad t_{Feed} = 455.15$$

$$d\delta_{tFeed} := \frac{\sqrt{d\delta_{t671}^{\ 2} + d\delta_{t672}^{\ 2}}}{\sqrt{2}}$$

$$d\delta_{tFeed} = 4.324$$

The following Densities were calculated based on International Association for the Properties of Water (IAPS 1984)

$$\rho_{p930tFeed} := 51.4259$$

$$\rho_{p935tFeed} := 51.4265$$

Feedwater flow is determined by the following methods

$$W_{Feed} = C\cdot\sqrt{\frac{\rho_{Feed}}{\rho_{Ref}}\cdot DP_{Feed}}$$

$$W_{f681} := 225900\cdot\sqrt{\frac{\rho_{p930tFeed}}{51.4933}\cdot f681} \qquad W_{f681} = 5.778\times 10^{6}$$

$$W_{f682} := 226300\cdot\sqrt{\frac{\rho_{p930tFeed}}{51.4933}\cdot f682} \qquad W_{f682} = 5.778\times 10^{6}$$

$$W_{f675} := 225200\cdot\sqrt{\frac{\rho_{p935tFeed}}{51.4933}\cdot f675} \qquad W_{f675} = 5.831\times 10^{6}$$

$$W_{f676} := 226100\cdot\sqrt{\frac{\rho_{p935tFeed}}{51.4933}\cdot f676} \qquad W_{f676} = 5.834\times 10^{6}$$

$$W_{Feed1} := \frac{W_{f675} + W_{f676}}{2} \qquad W_{Feed1} = 5.832\times 10^{6}$$

$$W_{Feed2} := \frac{W_{f681} + W_{f682}}{2} \qquad W_{Feed2} = 5.778\times 10^{6}$$

The following Enthalpies were calculated based on International Association for the Properties of Water (IAPS 1984)

HPT Inlet from OTSG 1

$h_{p482t477} := 1252.26$

$h_{Stm1} := h_{p482t477}$

$h_{Stm1} = 1252.26$

HPT Inlet from OTSG 2

$h_{p481t476} := 1252.78$

$h_{Stm2} := h_{p481t476}$

$h_{Stm2} = 1252.78$

OTSG 1 Inlet

$h_{p930tFeed} := 436.13$

$h_{Feed1} := h_{p930tFeed}$

$h_{Feed1} = 436.13$

OTSG 2 Inlet

$h_{p935tFeed} := 436.13$

$h_{Feed2} := h_{p935tFeed}$

$h_{Feed2} = 436.13$

The following calculates enthalpy errors for the above parameters.

$$dh = \sqrt{\left[\left(\frac{\delta h}{\delta p}\right)\cdot dp\right]^2 + \left(\frac{\delta h}{\delta t}\cdot dt\right)^2}$$

$$\frac{\delta h}{\delta p} = \frac{\Delta h}{\Delta p} = \frac{h(p-10,t) - h(p+10,t)}{20}$$

$dp = pressureuncertainty$

$$\frac{\delta h}{\delta t} = \frac{\Delta h}{\Delta t} = \frac{h(p,t+5) - h(p,t-5)}{10}$$

$dt = temperatureuncertainty$

$$\Delta h_{p482t477} := \sqrt{(0.1142\cdot d\delta_{p482})^2 + (0.82969\cdot d\delta_{t477})^2} \qquad \Delta h_{p482t477} = 3.609$$

$$\Delta h_{Stm1} := \Delta h_{p482t477} \qquad \Delta h_{Stm1} = 3.609$$

$$\Delta h_{p481t476} := \sqrt{(0.11389\cdot d\delta_{p481})^2 + (0.82506\cdot d\delta_{t476})^2} \qquad \Delta h_{p481t476} = 3.589$$

$$\Delta h_{Stm2} := \Delta h_{p481t476} \qquad \Delta h_{Stm2} = 3.589$$

$\Delta h_{p930tFeed} := \sqrt{(-0.0005 \cdot d\delta_{p930})^2 + (1.11835 \cdot d\delta_{tFeed})^2}$ $\Delta h_{p930tFeed} = 4.836$

$\Delta h_{Feed1} := \Delta h_{p930tFeed}$ $\Delta h_{Feed1} = 4.836$

$\Delta h_{p935tFeed} := \sqrt{(-0.0005 \cdot d\delta_{p935})^2 + (1.11833 \cdot d\delta_{tFeed})^2}$ $\Delta h_{p935tFeed} = 4.836$

$\Delta h_{Feed2} := \Delta h_{p935tFeed}$ $\Delta h_{Feed2} = 4.836$

$Q_{Sec} := W_{Feed1} \cdot (h_{Stm1} - h_{Feed1}) + W_{Feed2} \cdot (h_{Stm2} - h_{Feed1})$

$Q_{Sec} = 9.479 \times 10^9$

The new CALDON flow sensor will have a Feedwater temperature uncertainty of 0.5 Deg F and the flow sensor will have <0.28% mass flow error

$$dQ_{Sec} = \sqrt{[dW_{Fw} \cdot (H_{Stm} - H_{Fw})]^2 + (W_{Fw} \cdot dH_{Stm})^2 + (W_{Fw} \cdot dH_{Fw})^2}$$

$dW_{Fw1} := W_{Feed1} \cdot \frac{.28}{100}$

$dW_{Fw1} = 1.633 \times 10^4$

$dW_{Fw2} := W_{Feed2} \cdot \frac{.28}{100}$

$dW_{Fw2} = 1.618 \times 10^4$

$\delta W_{Fw1} := \sqrt{\frac{\delta_{f673}{}^2 + \delta_{f674}{}^2}{2}} \cdot 10^3$

$\delta W_{Fw1} = 2.67 \times 10^4$

$\delta W_{Fw2} := \sqrt{\frac{\delta_{f679}{}^2 + \delta_{f680}{}^2}{2}} \cdot 10^3$

$\delta W_{Fw2} = 2.285 \times 10^4$

$d\delta W_{Fw1} := \sqrt{\delta W_{Fw1}{}^2 + dW_{Fw1}{}^2}$

$d\delta W_{Fw1} = 3.13 \times 10^4$

$d\delta W_{Fw2} := \sqrt{\delta W_{Fw2}{}^2 + dW_{Fw2}{}^2}$

$d\delta W_{Fw2} = 2.8 \times 10^4$

$$dt_{Fw} := 0.5 \qquad \delta t_{Fw} := \sqrt{\frac{\delta_{t671}{}^2 + \delta_{t672}{}^2}{2}} \qquad d\delta t_{Fw} := \sqrt{\delta t_{Fw}{}^2 + dt_{Fw}{}^2} \qquad d\delta t_{Fw} = 0.533$$

$$dH_{Fw1} := \sqrt{(-0.0005 \cdot d\delta_{p935})^2 + (1.11833 \cdot dt_{Fw})^2} \qquad dH_{Fw2} := \sqrt{(-0.0005 \cdot d\delta_{p930})^2 + (1.11835 \cdot dt_{Fw})^2}$$

$$dH_{Fw1} = 0.559 \qquad dH_{Fw2} = 0.559$$

$$dQ_{Sec1} := \sqrt{\left[d\delta W_{Fw1} \cdot (h_{Stm1} - h_{Feed1})\right]^2 + (W_{Feed1} \Delta h_{Stm1})^2 + (W_{Feed1} \cdot dH_{Fw1})^2}$$

$$dQ_{Sec1} = 3.326 \times 10^7$$

$$ERR_1 := \frac{dQ_{Sec1}}{W_{Feed1} \cdot (h_{Stm1} - h_{Feed1})} \cdot 100$$

$$ERR_1 = 0.699$$

$$dQ_{Sec2} := \sqrt{\left[d\delta W_{Fw2} \cdot (h_{Stm2} - h_{Feed2})\right]^2 + (W_{Feed2} \Delta h_{Stm2})^2 + (W_{Feed2} \cdot dH_{Fw2})^2}$$

$$dQ_{Sec2} = 3.103 \times 10^7$$

$$ERR_2 := \frac{dQ_{Sec2}}{W_{Feed2} \cdot (h_{Stm2} - h_{Feed2})} \cdot 100$$

$$ERR_2 = 0.658$$

$$ERR := \sqrt{\frac{ERR_1{}^2 + ERR_2{}^2}{2}}$$

$$ERR = 0.679$$