Enclosure 13
to NRC-13-0004

Fermi 2 NRC Docket No. 50-341
Operating License No. NPF-43

License Amendment Request for Measurement Uncertainty Recapture (MUR) Power Uprate

Fermi 2 Calculation DC-6443, Volume I DCD 1, Revision A, "Reactor Core Thermal Power Uncertainty with Feedwater Flow Measured by LEFM CheckPlus C System"

50 Pages

DESIGN CALCULATION COVER SHEET

PART 1: DESIGN CALCULATION IDENTIFICATION		
A) **Design Calculation Number** DC-6443		B) **Volume Number** I DCD 1
C) **Revision** A	D) **PIS Number** B2100/C1100/C3200/G3300	E) **QA Level** ☐ Non-Q ☐ 1 ☒ 1M
F) **ASME Code Classification** ☒ NA		G) **Certification Required** ☐ Yes ☒ No
H) **Lead Discipline** I&C		I) **Incorporation Code** F

J) **Title – Reactor Core Thermal Power Uncertainty with Feedwater Flow Measured by LEFM CheckPlus C System**

K) **Design Change Documents Incorporated (Number and Revision)**
None

L) **Design Calculations Superseded (Number and Revision)**
DC-6443 Volume I DCD 1 Revision 0.

M) **Revision Summary**
DCD 1 Revision A changes the title, incorporates new values for feedwater temperature uncertainty (for both fully functional and maintenance mode LEFM CheckPlus C) and feedwater flow uncertainty (maintenance mode LEFM CheckPlus C) from Cameron report ER-781 Revision 2. Added References 6.27 – 6.29. The QA Level is changed to 1M, and it is now identified as a Key Calculation. All pages are reprinted, including attachments and appendices. Revision bars indicate content changes.

N) **Review of Assumptions, Methods, and Inputs Completed (Step 4.3.2)**
☐ Standard review, completed in revision ______
☒ Key calculation review, completed in revision A
☐ N/A (For Non-Q)

O) **Key Calculations Review Incorporated in Revision** A
☐ N/A, Not a Key Calculation

P) **PPRNs are required:** ☐ Yes ☒ No
Issuing DCD EDP 36969 ☐ N/A

Q) **Key Calculation:** ☒ Yes ☐ No
Justification for Yes or No: Technical Specifications – supports licensed core thermal power limit

PART 2: PREPARATION, REVIEW, AND APPROVAL

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D) Design Calculation Utility has been updated ☒ Yes ☐ N/A AJ Banek / 1-8-2013 / 00045194
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Table of Contents

Section Page Number

1.0 Purpose/Objective 3
2.0 Summary of Results and Conclusion 3
3.0 Method of Analysis 4
3.11 Boundary Conditions and Methodology Limitations 9
4.0 Design Inputs 9
5.0 Assumptions 12
5.1 Verified Assumptions 12
5.2 Unverified Assumptions 13
6.0 References 14
7.0 Calculation Details 17
8.0 Acceptance Criteria 31

Appendices
A RWCU Flow Loop Error 32
B CRD Flow Loop Error 35
Attachments
1. NIST Data on Thermophysical Properties of Water 39
2. Excerpt from ASME Fluid Meters 40
3. Excerpt from ANSI/ASME PTC-6 41
4. Excerpts from NUREG/CR-3659 42

1.0 Purpose/Objective

The purpose of this calculation is to determine the uncertainty in the reactor core thermal power (heat balance) calculation when using the Cameron Leading Edge Flow Meter (LEFM) CheckPlus System as the source for feedwater flow and temperature values. This calculation will evaluate the contribution of the uncertainties of the different instrument channel loops that provide the inputs that are used to calculate core thermal power (CTP). CTP is normally calculated in the Integrated Plant Computer System (IPCS), but may also be calculated manually. This calculation will determine the overall uncertainty of the CTP calculation at the proposed Measurement Uncertainty Recapture (MUR) rated power when done either by the IPCS or manually, and with the LEFM CheckPlus in both fully functional and maintenance mode. Use of the term LEFM or LEFM CheckPlus within this calculation specifically refers to the Cameron LEFM CheckPlus C.

2.0 Summary of Results and Conclusion

Results

In terms of the Current Licensed Thermal Power (CLTP) rated power of 3430 MWt (Design Input 4.1) and the MUR rated power of 3486 MWt (Design Input 4.1), the total uncertainty to a 2σ, or 95.5% confidence level, associated with the reactor thermal power (heat balance) calculation is:

	Core Thermal Power Calculation Method	Associated Uncertainty		
		MWt	% CLTP	% MUR CTP
1.	IPCS with LEFM CheckPlus Fully Functional:	± 12.373	± 0.361	± 0.355
2.	IPCS with LEFM CheckPlus in Maintenance Mode:	± 19.358	± 0.564	± 0.555
3.	Manual Calculation with LEFM CheckPlus Fully Functional:	± 12.384	± 0.361	± 0.355
4.	Manual Calculation with LEFM CheckPlus in Maintenance Mode:	± 19.364	± 0.565	± 0.555

Conclusion

For Case 1 (Core thermal power calculated by IPCS with LEFM CheckPlus Fully Functional), the uncertainty is ± 12.373 MWt (or ± 0.361% CLTP). Per the Case 1 acceptance criterion in Section 8.0, the proposed MUR CTP (3486 MWt) plus the total positive uncertainty in MWt must remain bounded by 1.02% (3499 MWt) of Current Licensed Thermal Power (CLTP, at 3430 MWt).

3486 MWt + 12.373 MWt = 3498.373 MWt, which is less than 3499 MWt (1.02% of CLTP)

Thus, the Case 1 results are acceptable and support the proposed MUR rated power of 3486 MWt, or 101.64% of CLTP.

As stated in Section 8.0, for the remaining three cases there are no specific acceptance criteria and the uncertainties are simply stated in the table above.

3.0 Method of Analysis

The determination of reactor core thermal power (CTP) is based on the net heat output from the reactor vessel, which is based on the energy balance of heat flows into and out of the reactor vessel. The following figure is a simplified representation of the reactor energy balance (Ref. 6.6, 6.19, 6.23 and 6.24).

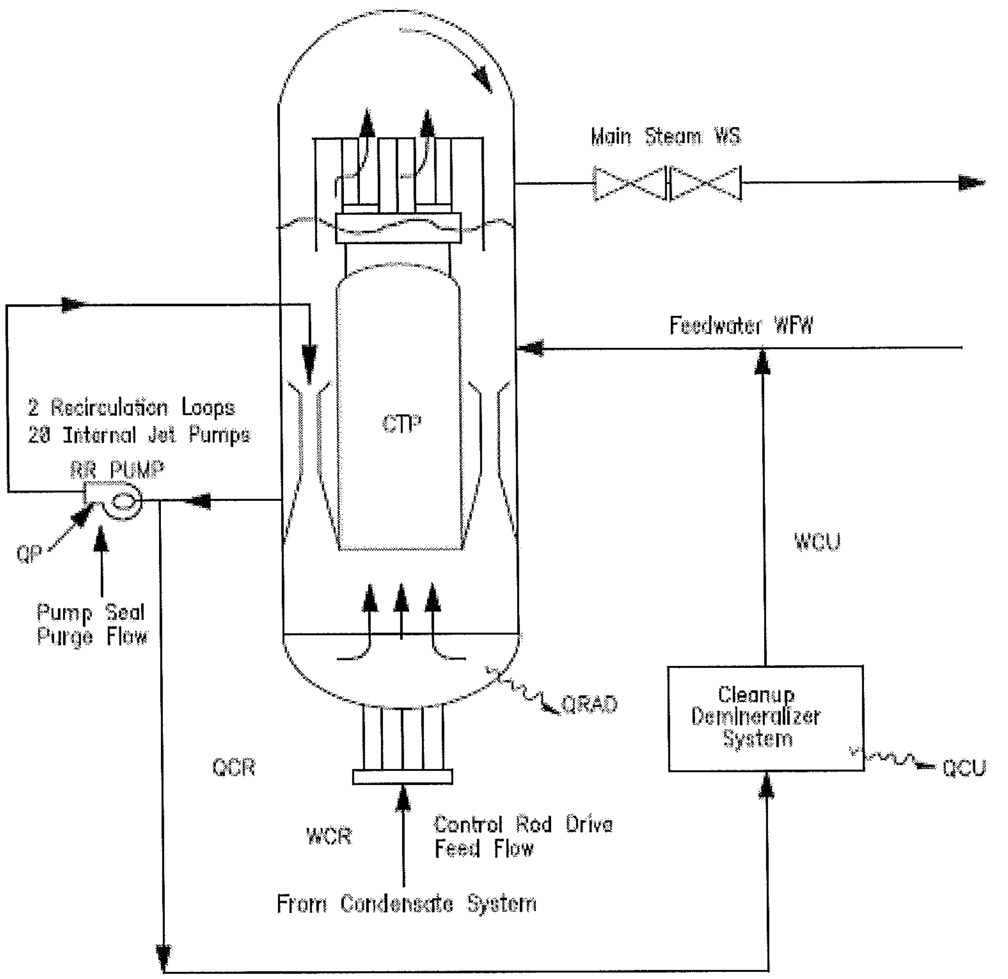


Figure 1 Reactor Energy Balance Schematic

3.1. The equation used to calculate core thermal power is (References 6.2, 6.4 & 6.19):

$$CTP = Q_{FW} + Q_{CR} + Q_{CU} + Q_{RAD} - Q_{P} \qquad \textbf{[Equation 3.1]}$$

where:

CTP = Core Thermal Power

Q_{FW} = net power transferred to feedwater (MWt)

Q_{CR} = net power transferred to Control Rod Drive (CRD) cooling water (MWt)

Q_{CU} = net power transferred to the Reactor Water Clean Up system (MWt)

Q_{RAD} = net power radiated to the Drywell and other thermal losses (MWt)

Q_{P} = net power input to the reactor coolant from the Reactor Recirculation (RR) pumps (MWe)

3.2. Utilizing BTU/hr to MWt conversion constant C1, the individual energy terms for Q_{FW}, Q_{CR} and Q_{CU} in Equation 3.1 can be expressed in terms of mass flow (W) and enthalpy (h) as:

Q_{FW} = [WFW * ((hg – FM * hfg) – hFW)]/C1 **[Equation 3.2-1]**

Q_{CR} = [WCR * ((hg – FM * hfg) – hCR)]/C1 **[Equation 3.2-2]**

Q_{CU} = [WCU * hCU1 – (WCU –WCUbd) * hCU2]/C1 **[Equation 3.2-3]**

Where: WFW is Feedwater Mass Flow Rate (Mlbm/hr)

hg is Saturated Steam Enthalpy (BTU/lbm)

FM is Moisture Carryover Fraction

hfg is Latent Heat of Vaporization (BTU/lbm).

hfg = hg – hf, where hf is saturated water enthalpy.

hFW is Feedwater Enthalpy (BTU/lbm)

hCR is Control Rod Drive Water Enthalpy (BTU/lbm)

WCR is CRD Mass Flow Rate (Mlbm/hr)

WCU is RWCU Mass Flow Rate (Mlbm/hr)

WCUbd is RWCU Blowdown Mass Flow Rate (Mlbm/hr)

hCU1 is RWCU Suction Enthalpy (BTU/lbm)

hCU2 is RWCU Discharge Enthalpy (BTU/lbm)

Substituting hg – hf for hfg, Equation 3.2-1 can be re-written as:

Q_{FW} = [WFW * (hg * (1 – FM) + hf * FM – hFW)]/C1 **[Equation 3.2-4]**

Substituting hg – hf for hfg, Equation 3.2-2 can be re-written as:

Q_{CR} = [WCR * (hg * (1 – FM) + hf*FM – hCR)]/C1 **[Equation 3.2-5]**

Per Section 5.1.4, RWCU blowdown flow is considered to be zero during steady state operation. Thus Equation 3.2-3 reduces to:

Q_{CU} = [WCU * (hCU1 – hCU2)]/C1 **[Equation 3.2-6]**

Substituting Equations 3.2-4, 3.2-5 and 3.2-6 into Equation 3.1, core thermal power can be calculated as:

CTP = [WFW * (hg * (1 – FM) + hf * FM – hFW)]/C1
+ [WCR * (hg * (1 – FM) + hf*FM – hCR)]/C1
+ [WCU * (hCU1 – hCU2)]/C1 + Q_{RAD} - Q_P **[Equation 3.2-7]**

3.3. The energy input to the reactor coolant by the RR Pumps is not measured directly but is calculated by multiplying the measured electrical power consumption of the RR pump motors by their efficiency. As a result Q_P = QPelec * ETA where ETA is the RR pump motor efficiency.

3.4. All mass flows and fluid temperatures are measured via independent instruments. As such, all input variables are modeled as independent. Only the calculated enthalpy pressure effects are dependent since the steam dome pressure measured from the same instrument is applied in each calculation. However, considering the very small dependence of enthalpy on pressure and small uncertainty in steam dome pressure, this dependency is not expected to significantly affect the results (Section 5.1.9).

3.5. The determination of CTP uncertainty is based on the mathematical methodology of NUREG/CR-3659 (Ref. 6.20). Although Ref. 6.20 was written for Pressurized Water Reactors (PWRs), it details a mathematical methodology of determining instrumentation measurement uncertainty for power and flow. This mathematical methodology is based on a combination of measurement uncertainties in a rigorous statistical manner, and is applicable to evaluate the uncertainty of any multivariable system with measured input variables. This methodology is equally valid for either PWR or Boiling Water Reactor (BWR) power and flow measurements. As stated in the executive summary of NUREG/CR-3659 (Ref. 6.20) "While the method is directed toward PWR power and flow determination, it is suitable for generalized application to instrument measurement uncertainties."

Based on Ref. 6.20, the mathematics of determining the uncertainty in CTP are developed as follows:

For a function Y of multiple variables (x_n), such as:

$$Y = f(x_1, x_2, x_3, \ldots, x_n)$$ **Equation 3.5-1**

The change in Y due to changes in the individual x_n variables is:

$$dY = \left\langle \frac{\partial Y}{\partial x_1} * dx_1 \right\rangle + \left\langle \frac{\partial Y}{\partial x_2} * dx_2 \right\rangle + \ldots + \left\langle \frac{\partial Y}{\partial x_n} * dx_n \right\rangle$$ **Equation 3.5-2**

Using σ_n to represent the standard deviation of each variable x_n (which is the uncertainty of the individual variable x_n), as developed within Ref. 6.20, the uncertainty (U_Y) associated with multifunction variable Y may be represented as:

$$U_Y{}^2 = \sigma_Y{}^2 < \left\langle \frac{\partial Y}{\partial x_1} \right\rangle^2 * \sigma x_1{}^2 + \left\langle \frac{\partial Y}{\partial x_2} \right\rangle^2 * \sigma x_2{}^2 + \ldots$$

$$+2 \left\langle \left|\frac{\partial Y}{\partial x_j}\right| \left|\frac{\partial Y}{\partial x_k}\right| \sigma x_j \, \sigma x_k + \left|\frac{\partial Y}{\partial x_m}\right| \left|\frac{\partial Y}{\partial x_n}\right| \sigma x_m \, \sigma x_n + \ldots \right\rangle$$

where letter subscripts designate cross products of dependent terms.

If all the variables are independent, the cross product terms become zero, and this simplifies to:

$$U_Y{}^2 = \sigma_Y{}^2 = \left\langle \frac{\partial Y}{\partial x_1} \right\rangle^2 * \sigma x_1{}^2 + \left\langle \frac{\partial Y}{\partial x_2} \right\rangle^2 * \sigma x_2{}^2 + \ldots + \left\langle \frac{\partial Y}{\partial x_n} \right\rangle^2 * \sigma x_n{}^2$$

Per Section 5.1.9 all variables are considered to be independent so all of the cross product terms from the squaring operation are zero. Thus the uncertainty of multifunction Y is:

$$U_Y = \sqrt{(\frac{\partial Y}{\partial x_1} * \sigma x_1)^2 + (\frac{\partial Y}{\partial x_2} * \sigma x_2)^2 + \ldots + (\frac{\partial Y}{\partial x_n} * \sigma x_n)^2}$$ <u>Equation 3.5-3</u>

This calculation applies Equation 3.5-3 to the variables in Equation 3.2-7 to determine the overall uncertainty in core thermal power.

3.6. To complete the CTP uncertainty calculation, the enthalpy uncertainties must be computed. Since enthalpy varies with pressure and temperature, the partial differential of each enthalpy term will be taken with respect to temperature (T), pressure (P) and the enthalpy read from the steam tables (I). The results will be squared to provide a statistical average and the square root of the result taken to provide the standard deviation of the enthalpy. Per section 5.1.9 the enthalpy variables are considered independent so all of the cross product terms can be set to zero. The result of these mathematical operations is Equation 3.6-1 below and is used as the basis for determining the enthalpy uncertainties:

$$\sigma_h = \sqrt{(\frac{\partial h}{\partial T} * \sigma_T)^2 + (\frac{\partial h}{\partial P} * \sigma_P)^2 + (\frac{\partial h}{\partial I} * \sigma_I)^2}$$ **[Equation 3.6-1]**

Per sections 5.1.5, 5.1.6 and 5.1.7, the variation of enthalpy with respect to T and P is considered to be linear. Since h is enthalpy, and I is the enthalpy read from the steam table, the change in h with respect to I is constant, thus $\partial h/\partial I = 1$. Therefore Equation 3.6-1 can be expressed as:

$$\sigma_h = \sqrt{(\frac{\Delta h}{\Delta T} * \sigma_T)^2 + (\frac{\Delta h}{\Delta P} * \sigma_P)^2 + \sigma_I^2}$$ **[Equation 3.6-2]**

The calculation of uncertainty for saturated steam and water enthalpies, σ_{hg}, and σ_{hf} use a modified form of Equation 3.6-2 above since temperature input is not required to determine saturation enthalpy. Thus $\Delta H/\Delta T$ is set to 0 and the uncertainties associated with the saturated steam and water enthalpies are expressed as:

$$\sigma_{hg} = \sqrt{(\frac{\Delta hg}{\Delta P} * \sigma_P)^2 + \sigma_I^2}$$ **[Equation 3.6-3]**

$$\sigma_{hf} = \sqrt{(\frac{\Delta hf}{\Delta P} * \sigma_P)^2 + \sigma_I^2}$$ **[Equation 3.6-4]**

Where: hg is the enthalpy of saturated steam (BTU/lbm)

hf is the enthalpy of saturated water (BTU/lbm)

P is the steam dome pressure (psia).

I is the enthalpy read from the steam table.

The uncertainty associated with the control rod system water enthalpy is expressed as:

$$\sigma_{hCR} = \sqrt{(\frac{\Delta hCR}{\Delta TCR} * \sigma_{TCR})^2 + (\frac{\Delta hCR}{\Delta P} * \sigma_P)^2 + \sigma_I^{\ 2}}$$ **[Equation 3.6-5]**

Where: hCR is the enthalpy of CRD system water (BTU/lbm).

P is the steam dome pressure (psia).

TCR is the CRD water temperature (°F)

I is the enthalpy read from the steam table.

The uncertainty associated with the feedwater enthalpy is expressed as:

$$\sigma_{hFW} = \sqrt{(\frac{\Delta hFW}{\Delta TFW} * \sigma_{TFW})^2 + (\frac{\Delta hFW}{\Delta P} * \sigma_P)^2 + \sigma_I^{\ 2}}$$ **[Equation 3.6-6]**

Where: hFW is the feedwater enthalpy (BTU/lbm).

TFW is the feedwater temperature (°F).

P is the steam dome pressure (psia).

I is the enthalpy read from the steam table.

The uncertainty associated with the RWCU suction enthalpy is expressed as:

$$\sigma_{hCU1} = \sqrt{(\frac{\Delta hCU1}{\Delta TCU1} * \sigma_{TCU1})^2 + (\frac{\Delta hCU1}{\Delta P} * \sigma_P)^2 + \sigma_I^{\ 2}}$$ **[Equation 3.6-7]**

Where: hCU1 is the RWCU suction enthalpy (BTU/lbm).

TCU1 is the RWCU suction temperature (°F).

P is the steam dome pressure (psia).

I is the enthalpy read from the steam table.

The uncertainty associated with the RWCU discharge enthalpy is expressed as:

$$\sigma_{hCU2} = \sqrt{(\frac{\Delta hCU2}{\Delta TCU2} * \sigma_{TCU2})^2 + (\frac{\Delta hCU2}{\Delta P} * \sigma_P)^2 + \sigma_I^{\ 2}}$$ **[Equation 3.6-8]**

Where: hCU2 is the RWCU discharge enthalpy (BTU/lbm).

TCU2 is the RWCU discharge temperature (°F).

P is the steam dome pressure (psia).

I is the enthalpy read from the steam table.

3.7. The rated Reactor Dome Pressure value is used to calculate the different enthalpies (Section 5.1.10).

3.8. The methodology used to calculate the loop uncertainties for RWCU flow and temperature, CRD flow and RR Pump motor power in the Appendices is based on C1-4180 "Setpoint Validation Guidelines" (Reference 6.1).

3.9. These indication loops evaluated in this calculation are non-safety-related, but the indications are used to calculate Core Thermal Power, which is a licensing limit. Thus the random errors are combined via Square Root Sum of the Squares (SRSS) and taken to a 2σ value for conservatism.

3.10. An enthalpy value uncertainty of ±0.1% [2σ] will be applied in the overall enthalpy uncertainty evaluations in Section 7.1 of this calculation, based on Input 4.5.

3.11. Boundary Conditions and Methodology Limitations

Because the input values used are for normal full power operation, this calculation methodology determines the uncertainty of the reactor core thermal power only for normal operation near the rated thermal power. No attempt is made to quantify uncertainties for other modes of operation.

4.0 Design Inputs

4.1. Nominal values of the core thermal power calculation input parameters for operation of Fermi 2:

1. At 100% of current licensed thermal power (CLTP), 3430 MWt, are listed in UFSAR Figure 1.2-32, "GE Reactor System Heat Balance Rated Performance" (Reference 6.6),
2. At 101.64% of CLTP, or the proposed MUR rated power (3486 MWt), are listed in MURFTRT0100 Figure 3-2a, "Revised Reactor Heat Balance - TLTP (101.64% CLTP)" (Reference 6.26), and
3. Also per Reference 6.26, 1.02% of CLTP is 3499 MWt.

4.2. Conversion factors:

4.2.1. For MBTU/hr to MWt: C1 = 3.413 MBTU/MWt-hr (Ref. 6.2)

4.2.2. For HP to MWe: 1 HP = 0.7457 KWe = 0.0007457 MWe (Ref. 6.1)

4.3. From DC-4567 Volume I (Ref. 6.9), the uncertainty of the RWCU flow indicator is ± 11.02 gpm [$1.645\ \sigma$]. Using the density (52.363 lbm/ft^3) at the RWCU discharge temperature of 435.9°F and 1045 psia to convert this to mass flow, and taking it to 2σ:

$$\sigma_{WCU} = [(\pm\ 11.02\ \text{gpm})*(52.363\ \text{lbm/ft}^3)*(1\ \text{ft}^3/7.480519\ \text{gal})*(60\ \text{min/hr})]*2/1.645$$

$$\sigma_{WCU} = \pm\ 5627\ \text{lbm/hr} = \pm\ 0.0056\ \text{Mlbm/hr} \qquad [2\sigma]$$

4.4. From Ref. 6.14, 6.15 and 6.24 each Recirc pump motor is rated at 7500 HP. There are two pumps (Loop A and B). Converting this to MWe to get the bounding pump motor energy input:

QP = (2 * 7500 HP)*(0.0007457 MWe / HP) = 11.185 MWe

4.5. Reference 6.16 evaluates the effect of the use of enthalpy values from four major sources: Keenan & Keyes 1936, ASME 1967, NIST Version 2.2 and IAPWS-IF97. It states that the uncertainty of the enthalpy as read from any of these four sources is bounded by ± 0.1% of the value. This calculation applies the bounding ± 0.1% uncertainty to the enthalpy values. Because this bounding enthalpy uncertainty is included in the overall uncertainty determination, the calculation results are conservative as long as this calculation and the plant's core thermal power determination utilize any of these four sources. This calculation utilizes the NIST source. Per References 6.2 and 6.22, the process computer and the manual calculation both use Keenan & Keyes.

4.6. The table below lists the input parameters to the proposed MUR rated core thermal power calculation and the source of these values:

Table 4.6-1 CTP Input Parameters (at MUR conditions)

Description	Term	Nominal Value	Units	Source
Reactor Dome Pressure	P	1045.0	PSIA	Ref. 6.26
Feedwater Flow Rate	WFW	15.111	Mlbm/hr	Ref. 6.26
CRD Flow Rate	WCR	0.032	Mlbm/hr	Ref. 6.26
RWCU Flow Rate	WCU	0.133	Mlbm/hr	Ref. 6.26
Feedwater Temperature	TFW	426.5	°F	Ref. 6.26
Control Rod Drive Temperature	TCR	100.0	°F	Ref. 6.3, 6.6
RWCU Suction Temperature	TCU1	533.8	°F	Ref. 6.26
RWCU Discharge Temperature	TCU2	435.9	°F	Ref. 6.26
Radiated and Misc Thermal Losses	QRAD	2.1 *	MWt	Ref. 6.3
Recirc Pump Motor Energy Input	QPelec	11.185	MWe	Input 4.4
Recirc Pump Motor Efficiency Pump A & Pump B	ETA	95.2	%	Ref. 6.3
Saturated Steam Enthalpy (at dome pressure)	hg	1191.7	BTU/lbm	Ref. 6.7 (Att. 1)
Steam Moisture Content (at dryer exit)	FM	0.001	---	Ref. 6.19
Saturated Water Enthalpy (at dome pressure)	hf	549.87	BTU/lbm	Ref. 6.7 (Att. 1)
Feedwater Enthalpy	hFW	404.89	BTU/lbm	Ref. 6.7 (Att. 1)
CRD Enthalpy	hCR	70.834	BTU/lbm	Ref. 6.7 (Att. 1)
RWCU Suction Enthalpy	hCU1	529.17	BTU/lbm	Ref. 6.7 (Att. 1)
RWCU Discharge Enthalpy	hCU2	415.20	BTU/lbm	Ref. 6.7 (Att. 1)

* The total radiated and miscellaneous thermal losses value of 2.1 MWt is based on 1.1 MWt (Ref. 6.19) for radiative heat loss through the vessel wall, in the recirculation piping, RWCU piping, feed lines and steam lines and 1.0 MWt for the Recirc Pump Seal Purge flow from CRD (Ref. 6.3).

** The value of 100.0°F for control rod drive temperature is not changed by increasing the power level. Thus the existing 100°F value from Ref. 6.3 and 6.6 is used instead of the 97.2°F value from Ref. 6.26.

4.7. References 6.2, 6.3 & 6.25 identify the instrument or computer point displays that provide CTP input indications. The table below lists the uncertainties associated with various core thermal power input parameters and the source of these values:

Table 4.7-1 CTP Input Parameter Uncertainties (all 2σ unless noted otherwise)

Description	Term	Indication	Uncertainty	Units	Source
Reactor Dome Pressure - IPCS	σP	C32DP1732	± 18.9 [1.645σ]	PSI	DC-4556 Vol. I (Ref. 6.8)
Reactor Dome Pressure - Indicator		C32R609	± 12.7 [1.645σ]		
Feedwater Flow Rate - LEFM √Plus Fully Functional	σWFW	LEFM √Plus indication or LEFM √Plus input to IPCS N21CF6138 N21CF6035 (Loop A) N216036 (Loop B)	± 0.28% of 15.111	Mlbm/hr	ER-781 Rev. 2 (Ref. 6.11)
Feedwater Flow Rate – LEFM √Plus in Maintenance Mode			± 0.51% of 15.111		
CRD Flow Rate - IPCS	σWCR	C11CF6001 C11DF1052	± 0.0025	Mlbm/hr	Appendix B
CRD Flow Rate - Indicator		C11R800	± 0.0029		Appendix B
RWCU Flow Rate – IPCS	σWCU	G33CF6004 G33DF1055 (A716)	± 0.0022	Mlbm/hr	Appendix A
RWCU Flow Rate – Indicator		G33R609 or G33R623	± 0.0056	Mlbm/hr	Input 4.3
Feedwater Temperature - (LEFM √Plus fully functional	σTFW	LEFM √Plus indication or input to IPCS N21GT2804 N21GT2805	± 0.55	°F	ER-781 Rev. 2 (Ref. 6.11)
Feedwater Temperature - (LEFM √Plus in Maintenance Mode			± 0.58		
Control Rod Drive Temperature	σTCR	N/A	± 10	°F	Section 5.1.1
RWCU Suction Temperature – IPCS or indicator	σTCU1	G33DT2502 G33R607	± 10	°F	Section 5.1.1
RWCU Discharge Temperature – IPCS or indicator	σTCU2	G33DT2503 G33R607	± 10	°F	Section 5.1.1
Radiated and Misc Thermal Losses	σQRAD	N/A	(± 10% of nominal)	MWt	Section 5.1.2
Recirc Pump Motor Energy Input	σQP	N/A	(± 10% of nominal)	MWe	Section 5.1.8
Recirc Pump Motor Efficiency	σETA	N/A	(± 1% efficiency)	%	Section 5.1.3
Saturated Steam Enthalpy (at dome pressure)	σhg	N/A	± 1.522	BTU/lbm	Section 7.1.1
Saturated Water Enthalpy (at dome pressure)	σhf	N/A	± 3.504	BTU/lbm	Section 7.1.1
Feedwater Enthalpy - LEFM √Plus Fully Functional	σhFW	N/A	± 0.725	BTU/lbm	Section 7.1.4
Feedwater Enthalpy - LEFM √Plus in Maintenance Mode			± 0.752		
CRD Enthalpy	σhCR	N/A	± 9.947	BTU/lbm	Section 7.1.5
RWCU Suction Enthalpy	σhCU1	N/A	± 12.541	BTU/lbm	Section 7.1.2
RWCU Discharge Enthalpy	σhCU2	N/A	± 11.018	BTU/lbm	Section 7.1.3

5.0 Assumptions

5.1. Verified Assumptions

5.1.1. A conservative assumption has been made that CRD and RWCU temperature variations are bounded by ±10 °F of the nominal value based on engineering judgment. The 10% is consistent with the 10% error assigned for all non-feedwater flow related error in existing calculations DC-4568 Volumes VII and VIII (Refs. 6.12 and 6.13), which determine the overall uncertainty in the IPCS and manual calculations of core thermal power when using the feedwater flow indication from the differential pressure flow measurement system.

5.1.2. A conservative assumption has been made that the radiated and miscellaneous thermal loss value listed in Reference 6.2 is bounded by a ±10% variation. The 10% is consistent with the 10% error assigned for all non-feedwater flow related error in existing calculations DC-4568 Volumes VII and VIII (Refs. 6.12 and 6.13).

5.1.3. A conservative assumption has been made that the RR Pump motor efficiency when the Unit is operating at design basis conditions is bounded by a ±1% variation. Per Ref. 6.21 the B pump efficiency changes from 94.65% to 95.18% for a loading change from 75% to 125% of rated load. Since the core thermal power is determined for normal operating conditions near 100% loading, a 1% variation conservatively bounds any expected efficiency variation. This 1% variation is conservatively assumed to apply to both the A pump and the B pump, due to their similarity in type, size and operating characteristics (Ref. 6.14 and 6.15).

5.1.4. It is assumed that RWCU blowdown flow during steady-state normal operations is 0 gpm, because blowdown is not utilized during normal steady-state operations.

5.1.5. It is assumed that a ±1 degree variation in steam temperature is sufficiently small such that the variation of enthalpy with temperature is linear for the calculation of steam enthalpy uncertainty. This is based on engineering judgment from review of the steam tables.

5.1.6. It is assumed that a ± 5°F variation in temperature is sufficiently small such that the variation of enthalpy with temperature is linear for the calculation of liquid enthalpy uncertainty. This is based on engineering judgment from review of the steam tables.

5.1.7. It is assumed that a ± 30 psi variation in pressure is sufficiently small such that the variation of enthalpy with pressure is linear for the calculation of liquid enthalpy uncertainty. This is based on engineering judgment from review of the steam tables.

5.1.8. A conservative assumption has been made that the RR Pump motor power reading is bounded by a ±10 % variation. The 10% is consistent with the 10% error assigned for all non-feedwater flow related error in existing calculations DC-4568 Volumes VII and VIII (Refs. 6.12 and 6.13).

5.1.9. It is assumed that all variables used for calculation of the various enthalpies can be considered as independent based on engineering judgment, since enthalpies are relatively insensitive to pressure and all flow and temperature measurements are provided by different instruments.

5.1.10. It is assumed that CRD and RWCU pressures are equal to Reactor Steam Dome Pressure for the calculation of CRD and RWCU enthalpy uncertainties based on the use of this pressure for calculation of these enthalpies in Reference 6.2.

5.1.11. A conservative assumption is made that the uncertainty of the CRD flow nozzle is bounded by ±5.0%. Per Table II-V-1 of Ref. 6.17 the worst case uncertainty of a flow nozzle is ± 2.0%. Per Ref. 6.18, the worst case uncertainty of an uncalibrated flow section is ± 3.2%. The selected value of ±5.0 conservatively bounds either of these cases. Thus this assumption is conservative.

5.1.12. It is assumed that there is no significant uncertainty associated with the digital transfer of data from the LEFM to the IPCS. The LEFM has a direct digital connection to the IPCS. Per engineering judgment, no significant error is introduced to the data that is transferred via this direct connection.

5.1.13. It is assumed that there is no significant uncertainty associated with the digital calculations performed within the IPCS. Per engineering judgment, the digital calculations performed by the IPCS do not in themselves create an additional source of error.

5.2. Unverified Assumptions

None

6.0 References

DOCUMENT INTERFACE SUMMARY								
Ref #	**DTC**	**DSN or Document Type**	**Rev**	**Title**	**Ref**	**In put**	**Out put**	**How document is used in calculation**
6.1	TDPINC	C1-4180 (DECO File No. C1-4180)	C	Setpoint Validation Guidelines	☐	☒	☐	Methodology for instrument loop accuracy determination in Appendices
6.2	TRVEND	520 2311300 06E (DECO File No. M14-886)	1	IPCS - Detailed Design Manual Appendix E NSSS	☐	☒	☐	Formulas and inputs for the CTP calculation
6.3	TPNPP	57.000.02	33	Core Thermal Power Evaluation	☐	☒	☐	Inputs to CTP calculation
6.4	TCEDP	36238.A024	0	Feedwater Ultrasonic Flow Measurement System (Markups to 520-231100-06E)	☐	☒	☐	Formulas and inputs for the CTP calculation
6.5	TSICSS	G33N042-SS	A	RWCU Bottom Head Drain Temperature	☐	☒	☐	Inputs on RWCU temp instrumentation – to App. A
6.6	TDFSAR	UFSAR	18	Updated Final Safety Analysis Report Chapter 1 and Chapter 5	☐	☒	☐	Section 1.1 and Figures 1.2-32 & 5.1-1a – nominal CLTP variable inputs
6.7				Thermophysical Properties of Fluid Systems, Chemistry WebBook, NIST Standard Reference Database Number 69	☐	☒	☐	Data Retrieved October 16, 2011. Enthalpy and density data included as Attachment 1
6.8	TDPINC	DC-4556 Vol I	H	Remote Shutdown Reactor Instrumentation	☐	☒	☐	Inputs on reactor dome pressure instrumentation accuracy
6.9	TDPINC	DC-4567 Vol I	D	RWCU Differential Flow Instrumentation Surveillance Procedure Validation	☐	☒	☐	Inputs for RWCU flow instrumentation accuracy
6.10	TDPINC	DC-5924 Vol I	E	CRD Flow Instruments Calibration Specification	☐	☒	☐	Inputs on CRD flow instrumentation accuracy
6.11	TRVEND	ER 781 (DECO File No. C1-7406)	2	Bounding Uncertainty Analysis for Thermal Power Determination at Fermi Unit 2 Using the LEFM C System	☐	☒	☐	LEFM CheckPlus C measurement accuracy of FW flow and temperature
6.12	TDPINC	DC-4568 Vol VII DCD	0	Maximum Probable Error in Process Computer Calculation of Core Thermal Power	☐	☒	☐	10% uncertainty for non-FW flow parameters
6.13	TDPINC	DC-4568 Vol VIII DCD	0	Maximum probable Error in NPP-57.000.02 Manual Calculation of Core Thermal Power	☐	☒	☐	10% uncertainty for non-FW flow parameters

DOCUMENT INTERFACE SUMMARY								
Ref #	DTC	DSN or Document Type	Rev	Title	Ref	In put	Out put	How document is used in calculation
6.14	TMINSL	VMR1-39	A	General Electric 295X271 Nuclear Reactor Water Recirculating Pump Motor	☐	☒	☐	RR pump A motor rating
6.15	TMINSL	VMR1-96	0	Vertical Induction Motor for Nuclear Reactor Water Recirculating Pump "B"	☐	☒	☐	RR pump B motor rating
6.16	TDVEND	DRF A13 00461 02 (PROPRIETARY)	0	Impact of Steam Table Basis on Process Computer Heat Balance Calculations (GE Nuclear Energy)	☐	☒	☐	Uncertainty of Enthalpy as read from steam table sources
6.17				ASME Fluid Meters, Their Theory and Application, Sixth Edition, 1971	☐	☒	☐	Typical Uncertainty of flow nozzle – used for Assumption 5.1.11 (Table included as Att. 2)
6.18				ANSI/ASME PTC-6 Report 1985, Guidance for Evaluation of Measurement Uncertainty in Performance Tests of Steam Turbines	☐	☒	☐	Typical Uncertainty of uncalibrated flow sections – used for Assumption 5.1.11 (Table included as Att. 3)
6.19	TDDATA	NEDC 32805P (DECO File No. R1-7306)	1	Fermi 2 Process Computer Reactor Heat Balance Review	☐	☒	☐	Heat Balance Equation, conversion constant for BTU to MW-hr, radiative heat loss value, moisture fraction
6.20		NUREG/CR-3659		A Mathematical Model for Assessing the Uncertainties of Instrumentation Measurements for Power and Flow for PWR Reactors	☐	☒	☐	Uncertainty Methodology (applicable pages included as Attachment 4)
6.21	TDDATA	218098 (DECO File No. C1-7119)	1	Induction Motor for Nuclear Reactor Water Recirculating Pump	☐	☒	☐	RR pump motor efficiency vs. loading – used for Assumption 5.1.3
6.22	TMINSL	GEK 73527A	---	GEK 73527A	☐	☒	☐	States which steam table is used for manual calculation – used for input 4.5
6.23	TDDBD	C11-00	C	Control Rod Drive Hydraulics System	☐	☒	☐	Information on CRD flow
6.24	TDDBD	B31-00	B	Reactor Recirculation System	☐	☒	☐	Info on RR system and pumps
6.25	TRVEND	520 2311300 06A (DECO File No. M14-884)	2	IPCS - Detailed Design Manual Appendix A NSSS	☐	☒	☐	Formulas and inputs for the CTP calculation
6.26	TRVEND	MURFTRT0100	0	Project Task Report Detroit Edison Fermi-2 Thermal Power Optimization Task T0100: Reactor Heat Balance	☐	☒	☐	Proposed MUR CTP variable inputs

DOCUMENT INTERFACE SUMMARY								
Ref #	**DTC**	**DSN or Document Type**	**Rev**	**Title**	**Ref**	**In put**	**Out put**	**How document is used in calculation**
6.27	TRVEND	ER 157PA (and Rev. 8 Errata) (DECO File No. C1-7303)	8	Supplement to Caldon Topical Report ER-80P: Basis for Power Uprates with an LEFM Check or an LEFM CheckPlus System	☒	☐	☐	
6.28	TMINSL	VMC1-510	0	LEFM CheckPlus C User's Manual	☒	☐	☐	
6.29	TRVEND	SD 36238 983 01	3	Leading Edge Flow Meter (LEFM) and Integrated Plant Computer System (IPCS) Interface	☒	☐	☐	

7.0 Calculation Details

7.1. Evaluation of the Enthalpy Uncertainties. The equations in section 3.6 are used to calculate enthalpy uncertainty to a 2σ level. The largest error in steam dome pressure from Table 4.7-1 is applied for the pressure uncertainty, so the results are conservative for both manual and IPCS uncertainties. In each enthalpy uncertainty determination, the uncertainty of reading enthalpy from the steam table (Ref. 6.7) is ±0.1% = ± 0.001 per Input 4.5.

7.1.1. Saturated Steam and Water Enthalpy Error

The rated dome pressure for the heat balance calculation is 1045.0 psia, which has a saturation temperature of 550.02 °F (Ref. 6.7). Per section 5.1.5 a ±1°F variation is used to determine the variation in steam and water enthalpies with pressure. The temperatures that bound this value (549.02 °F and 551.02 °F) are used to determine the corresponding pressures at saturation per Ref. 6.7, and to establish the change in saturation steam enthalpy, hg, and saturated water enthalpy, hf, relative to the change in temperature.

Saturated Steam Enthalpy (BTU/lbm)

T \ P	1036.5	1045.0	1053.5
549.02 °F	1192.0	-	-
550.02 °F	-	1191.7	-
551.02 °F	-	-	1191.3

Using Equation 3.6-3:

$$\sigma_{hg} = \sqrt{\left\langle \frac{(1192.0 - 1191.3)\frac{BTU}{lbm}}{(1036.5 - 1053.5)\,psia} * (2 * \frac{18.9\,psi}{1.645}) \right\rangle^2 + \left\langle 0.001 * 1191.7 \frac{BTU}{lbm} \right\rangle^2}$$

$$\sigma_{hg} = \pm 1.522 \frac{BTU}{lbm}$$

Saturated Water Enthalpy (BTU/lbm)

T \ P	1036.5	1045.0	1053.5
549.02 °F	548.59	-	-
550.02 °F	-	549.87	-
551.02 °F	-	-	551.15

Using Equation 3.6-4:

$$\sigma_{hf} = \sqrt{\left\langle \frac{(548.59 - 551.15)\frac{BTU}{lbm}}{(1036.5 - 1053.5)\,psia} * (2 * \frac{18.9\,psi}{1.645}) \right\rangle^2 + \left\langle 0.001 * 549.87 \frac{BTU}{lbm} \right\rangle^2}$$

$$\sigma_{hf} = \pm 3.504 \frac{BTU}{lbm}$$

7.1.2. RWCU Suction Enthalpy Error

The conditions used in the heat balance to describe the RWCU suction enthalpy, hCU1, are a nominal pressure of 1045 psia and a rated temperature of 533.8 °F. Per Sections 5.1.6 and 5.1.7, a ±5 °F temperature variation and a ± 30 psi pressure variation are used to determine the variation of liquid enthalpy with temperature and pressure. Reference 6.7 is used to develop the entries in the following table to calculate the uncertainty in the enthalpy for the RWCU suction.

RWCU Suction Enthalpy (BTU/lbm)

T \ P	1015.0	1045.0	1075.0
528.80 °F	-	522.94	-
533.80 °F	529.22	529.17	529.12
538.80 °F	-	535.47	-

Using Equation 3.6-7:

$$\sigma_{hCU1} = \sqrt{\left(\frac{(535.47-522.94)\frac{BTU}{lbm}}{(538.80-528.80)\,^{\circ}F}*(10\,^{\circ}F)\right)^2 + \left(\frac{(529.12-529.22)\frac{BTU}{lbm}}{(1075.0-1015.0)\,psia}*(2*\frac{18.9\,psi}{1.645})\right)^2 + \left(0.001*529.17\,\frac{BTU}{lbm}\right)^2}$$

$$\sigma_{hCU1} = \pm\ 12.541\ \frac{BTU}{lbm}$$

7.1.3. RWCU Discharge Enthalpy Error

The conditions used in the heat balance to describe the RWCU discharge enthalpy, hCU2, are a nominal pressure of 1045 psia and a rated temperature of 435.9 °F. Per Sections 5.1.6 and 5.1.7, a ±5 °F temperature variation and a ±30 psi pressure variation are used to determine the variation of liquid enthalpy with temperature and pressure. Reference 6.7 will be used to develop the entries in the following table to calculate the uncertainty in the enthalpy for the RWCU discharge.

RWCU Discharge Enthalpy (BTU/lbm)

T \ P	1015.0	1045.0	1075.0
430.9 °F	-	409.71	-
435.9 °F	415.18	415.20	415.23
440.9 °F	-	420.72	-

Using Equation 3.6-8:

$$\sigma_{hCU2} = \sqrt{\left(\frac{(420.72-409.71)\frac{BTU}{lbm}}{(440.9-430.9)\ °F}*(10°F)\right)^2 + \left(\frac{(415.23-415.18)\frac{BTU}{lbm}}{(1075-1015)\ psia}*(2*\frac{18.9 psi}{1.645})\right)^2 + \left(0.001*415.20\frac{BTU}{lbm}\right)^2}$$

$$\sigma_{hCU2} = \pm\ 11.018\frac{BTU}{lbm}$$

7.1.4. Feedwater Enthalpy Error

The conditions used in the heat balance to describe the feedwater enthalpy, hFW, are a nominal pressure of 1045 psia and a rated temperature of 426.5 °F. Per Sections 5.1.6 and 5.1.7, a ± 5 °F temperature variation and a ± 30 psi pressure variation are used to determine the variation of liquid enthalpy with temperature and pressure. Reference 6.7 will be used to develop the entries in the following table to calculate the uncertainty in the enthalpy for Feedwater, hFW.

Feedwater Enthalpy (BTU/lbm)

T \ P	1015.0	1045.0	1075.0
421.5 °F	-	399.44	-
426.5 °F	404.87	404.89	404.92
431.5 °F	-	410.37	-

Using Equation 3.6-6, for LEFM fully functional:

$$\sigma_{hFW} = \sqrt{\left(\frac{(399.44-410.37)\frac{BTU}{lbm}}{(421.5-431.5)^{\circ}F}*(0.55^{\circ}F)\right)^2 + \left(\frac{(404.92-404.87)\frac{BTU}{lbm}}{(1075-1015)psia}*(2*\frac{18.9psi}{1.645})\right)^2 + \left(0.001*404.89\frac{BTU}{lbm}\right)^2}$$

$$\sigma_{hFW} = \pm\ 0.725\ \frac{BTU}{lbm}$$

Using Equation 3.6-6, for LEFM in Maintenance Mode:

$$\sigma_{hFW} = \sqrt{\left(\frac{(399.44-410.37)\frac{BTU}{lbm}}{(421.5-431.5)^{\circ}F}*(0.58^{\circ}F)\right)^2 + \left(\frac{(404.92-404.87)\frac{BTU}{lbm}}{(1075-1015)psia}*(2*\frac{18.9psi}{1.645})\right)^2 + \left(0.001*404.89\frac{BTU}{lbm}\right)^2}$$

$$\sigma_{hFW} = \pm\ 0.752\ \frac{BTU}{lbm}$$

7.1.5. CRD Enthalpy Error

The conditions used in the heat balance to describe the CRD system water enthalpy, hCR, are a nominal pressure of 1045 psia and a temperature of 100.0°F. Per Sections 5.1.6 and 5.1.7, a ± 5°F temperature variation and a ± 30 psi pressure variation are used to determine the variation of liquid enthalpy with temperature and pressure. Reference 6.7 will be used to develop the entries in the following table to calculate the uncertainty in the enthalpy for the CRD water.

CRD System Water Enthalpy (BTU/lbm)

T \ P	1015.0	1045.0	1075.0
95.0 °F	-	65.861	-
100.0 °F	70.755	70.834	70.913
105.0 °F	-	75.808	-

Using Equation 3.6-5:

$$\sigma_{hCR} = \sqrt{\left(\frac{(75.808-65.861)\,\frac{BTU}{lbm}}{(105.0-95.0)\,^{\circ}F}*(10\,^{\circ}F)\right)^2 + \left(\frac{(70.913-70.755)\,\frac{BTU}{lbm}}{(1075-1015)\,psia}*(2*\frac{18.9\ psi}{1.645})\right)^2 + \left(0.001*70.834\,\frac{BTU}{lbm}\right)^2}$$

$$\sigma_{hCR} = \pm\, 9.947\,\frac{BTU}{lbm}$$

7.2. Feedwater Flow Energy Uncertainty

7.2.1. IPCS Calculation, with LEFM CheckPlus Fully Functional

Recalling Equation 3.2-4, which represents the feedwater flow energy:

$$Q_{FW} = WFW*(hg*(1 - FM) + hf*FM - hFW)$$

Taking the partial derivatives with respect to the individual terms, to show the effect with respect to CTP:

$$\frac{\partial CTP}{\partial WFW} = hg*(1 - FM) + hf*FM - hFW \qquad \frac{\partial CTP}{\partial hg} = WFW*(1 - FM)$$

$$\frac{\partial CTP}{\partial hf} = WFW * FM \qquad \frac{\partial CTP}{\partial hFW} = -WFW$$

Based on Equation 3.5-3, the uncertainty in core thermal power due to uncertainty in feedwater flow energy (U_{FW}) is:

$$U_{FW} = \left[\left(\frac{\partial CTP}{\partial WFW} * \sigma_{WFW}\right)^2 + \left(\frac{\partial CTP}{\partial hg} * \sigma_{hg}\right)^2 + \left(\frac{\partial CTP}{\partial hf} * \sigma_{hf}\right)^2 + \left(\frac{\partial CTP}{\partial hFW} * \sigma_{hFW}\right)^2\right]^{1/2}$$

Substituting the partial derivatives from above:

$$U_{FW} = [((hg*(1 - FM) - hf*FM - hFW)* \sigma_{WFW})^2 + ((WFW*(1 - FM)) * \sigma_{hg})^2 + (WFW*FM * \sigma_{hf})^2 + (- WFW * \sigma_{hFW})^2]^{1/2}$$ **Equation 7.2-1**

Solving Equation 7.2-1 will determine the contribution of the uncertainty in the feedwater flow energy to the overall core thermal power uncertainty.

Input values from Table 4.6-1:

hg	=	1191.7 BTU/lbm
hf	=	549.87 BTU/lbm
FM	=	0.001 at dryer exit
hFW	=	404.89 BTU/lbm
WFW	=	15.111 Mlbm/hr

Uncertainties from Table 4.7-1:

σ_{WFW} = (± 0.28 %)*(15.111 Mlbm/hr) = 0.0423 Mlbm/hr [2σ]

σ_{hg} = ± 1.522 BTU/lbm [2σ]

σ_{hf} = ± 3.504 BTU/lbm [2σ]

σ_{hFW} = ± 0.725 BTU/lbm [2σ] (LEFM fully functional)

Using these values to solve Equation 7.2-1:

$$U_{FW} = \{[((1191.7\ BTU/lbm)*(1 - 0.001) - (549.87\ BTU/lbm)*0.001 - (404.89\ BTU/lbm))*(0.0423\ Mlbm/hr)]^2 + ((15.111\ Mlbm/hr)*(1 - 0.001) * (1.522\ BTU/lbm))^2 + ((15.111\ Mlbm/hr)*0.001*(3.504\ BTU/lbm))^2 + ((-15.111\ Mlbm/hr)*(0.725\ BTU/lbm))^2\}^{1/2}$$

U_{FW} = ± 41.842 MBTU/hr

Converting to MWt, with the conversion factor from Input 4.2:

U_{FW} = (± 41.842 MBTU/hr) / (3.413 MBTU/MWt-hr) = ± 12.260 MWt

No Moisture Carryover Case

The case will be run with FM = 0 (no moisture carryover) to demonstrate which case is the most conservative. For FM = 0, Equation 3.2-4 reduces to:

$$Q_{FW} = WFW*(hg - hFW)$$

The partial derivatives with respect to the individual terms reduce to:

$$\frac{\partial CTP}{\partial WFW} = hg - hFW \qquad \frac{\partial CTP}{\partial hg} = WFW \qquad \frac{\partial CTP}{\partial hFW} = -WFW$$

Based on Equation 3.5-3, the uncertainty in core thermal power due to uncertainty in feedwater flow energy (U_{FW}) is:

$$U_{FW} = \left[\left(\frac{\partial CTP}{\partial WFW} * \sigma_{WFW}\right)^2 + \left(\frac{\partial CTP}{\partial hg} * \sigma_{hg}\right)^2 + \left(\frac{\partial CTP}{\partial hFW} * \sigma_{hFW}\right)^2\right]^{1/2}$$

Substituting the partial derivatives from above:

$$U_{FW} = [((hg - hFW) * \sigma_{WFW})^2 + ((WFW * \sigma_{hg})^2 + (-WFW * \sigma_{hFW})^2]^{1/2}$$ **Equation 7.2-1a**

Solving Equation 7.2-1a will determine the contribution of the uncertainty in the feedwater flow energy to the overall core thermal power uncertainty, for the case of no moisture carryover.

Input values from Table 4.6-1:
hg = 1191.7 BTU/lbm
hFW = 404.89 BTU/lbm
WFW = 15.111 Mlbm/hr

Uncertainties from Table 4.7-1:
σ_{WFW} = (± 0.28 %)*(15.111 Mlbm/hr) = 0.0423 Mlbm/hr [2σ]
σ_{hg} = ± 1.522 BTU/lbm [2σ]
σ_{hFW} = ± 0.725 BTU/lbm [2σ] (LEFM fully functional)

Using the values from above to solve Equation 7.2-1a:

$$U_{FW} = [((1191.7 - 404.89)\ BTU/lbm*(0.0423\ Mlbm/hr))^2 + ((15.111\ Mlbm/hr)*(1.522\ BTU/lbm))^2 + ((-15.111\ Mlbm/hr)*(0.725\ BTU/lbm))^2]^{1/2}$$

U_{FW} = ± 41.913 MBTU/hr

Converting to MWt, with the conversion factor from Input 4.2:

U_{FW} = (± 41.913 MBTU/hr) / (3.413 MBTU/MWt-hr) = ± 12.280 MWt

Comparison of these values to those above for FM = 0.001 at the steam dryer outlet, shows that a slightly higher uncertainty is calculated for the case of no moisture carryover. Inclusion of the moisture carryover term reduces the total calculated uncertainty, because the uncertainty is higher when the full effect of the steam enthalpy term (1191.7 BTU/lbm) is not reduced by the influence of the water enthalpy from the moisture carryover.

7.2.2. IPCS Calculation, with LEFM CheckPlus in Maintenance Mode

When in Maintenance mode, per Table 4.7-1 the LEFM feedwater flow accuracy is ±0.51% of nominal.

Thus the input values to solve Equation 7.2-1a are:

Input values from Table 4.6-1: hg = 1191.7 BTU/lbm
hFW = 404.89 BTU/lbm
WFW = 15.111 Mlbm/hr

Uncertainties from Table 4.7-1:

σ_{WFW} = (± 0.51 %)*(15.111 Mlbm/hr) = 0.0771 Mlbm/hr [2σ]
σ_{hg} = ± 1.522 BTU/lbm [2σ]
σ_{hFW} = ± 0.752 BTU/lbm [2σ] (LEFM in Maintenance Mode)

Solving Equation 7.2-1a:

$$U_{FW} = [((1191.7 - 404.89)\ \text{BTU/lbm}*(0.0771\ \text{Mlbm/hr}))^2 + ((15.111\ \text{Mlbm/hr})*(1.522\ \text{BTU/lbm}))^2 + ((-15.111\ \text{Mlbm/hr})*(0.752\ \text{BTU/lbm}))^2\ ]^{1/2}$$

U_{FW} = ± 65.864 MBTU/hr

Converting to MWt, with the conversion factor from Input 4.2:

U_{FW} = (± 65.864 MBTU/hr) / (3.413 MBTU/MWt-hr) = ± 19.298 MWt

7.3. Control Rod Drive Flow Energy Uncertainty

Recalling Equation 3.2-5, which represents the CRD flow energy, and setting FM=0 to obtain the most conservative (largest) uncertainty:

$$Q_{CR} = WCR*(hg - hCR)$$

Taking the partial derivatives with respect to the individual terms, to show the effect with respect to CTP:

$$\frac{\partial CTP}{\partial WCR} = hg - hCR \qquad \frac{\partial CTP}{\partial hg} = WCR \qquad \frac{\partial CTP}{\partial hCR} = -WCR$$

Based on Equation 3.5-3, the uncertainty in core thermal power due to uncertainty in CRD flow energy (U_{CR}) is:

$$U_{CR} = \left[\left(\frac{\partial CTP}{\partial WCR} * \sigma_{WCR}\right)^2 + \left(\frac{\partial CTP}{\partial hg} * \sigma_{hg}\right)^2 + \left(\frac{\partial CTP}{\partial hCR} * \sigma_{hCR}\right)^2\right]^{1/2}$$

Substituting the partial derivatives from above:

$$U_{CR} = [((hg - hCR) * \sigma_{WCR})^2 + (WCR * \sigma_{hg})^2 + (-WCR * \sigma_{hCR})^2]^{1/2}$$ **<u>Equation 7.3-1</u>**

Solving Equation 7.3-1 will determine the contribution of the uncertainty in the CRD flow energy to the overall core thermal power uncertainty.

Input values from Table 4.6-1:

hg = 1191.7 BTU/lbm
hCR = 70.834 BTU/lbm
WCR = 0.032 Mlbm/hr

Uncertainties from Table 4.7-1:

σ_{WCR} = ± 0.0025 Mlbm/hr [2σ] (IPCS indication)
σ_{WCR} = ± 0.0029 Mlbm/hr [2σ] (manual indication)
σ_{hg} = ± 1.522 BTU/lbm [2σ]
σ_{hCR} = ± 9.947 BTU/lbm [2σ]

<u>Using these values to solve Equation 7.3-1, for IPCS indication:</u>

$$U_{CR} = [((1191.7 - 70.834)\ BTU/lbm*(0.0025\ Mlbm/hr))^2 + ((0.032\ Mlbm/hr)*(1.522\ BTU/lbm))^2 + ((-0.032\ Mlbm/hr)*(9.947\ BTU/lbm))^2]^{1/2}$$

U_{CR} = ± 2.821 MBTU/hr

Converting to MWt, with the conversion factor from Input 4.2:

$$U_{CR} = (\pm 2.821\ MBTU/hr) / (3.413\ MBTU/MWt\text{-}hr) = \pm 0.827\ MWt$$

<u>Using these values to solve Equation 7.3-1, for manual indication:</u>

$$U_{CR} = [((1191.7 - 70.834)\ BTU/lbm*(0.0029\ Mlbm/hr))^2 + ((0.032\ Mlbm/hr)*(1.522\ BTU/lbm))^2 + ((-0.032\ Mlbm/hr)*(9.947\ BTU/lbm))^2]^{1/2}$$

U_{CR} = ± 3.266 MBTU/hr

Converting to MWt, with the conversion factor from Input 4.2:

$U_{CR} = (\pm 3.266 \text{ MBTU/hr}) / (3.413 \text{ MBTU/MWt-hr}) = \pm 0.957 \text{ MWt}$

7.4. Reactor Water Clean Up Flow Energy Uncertainty

Recalling Equation 3.2-6, which represents the RWCU flow energy:

$Q_{CU} = WCU*(hCU1 - hCU2)$

Taking the partial derivatives with respect to the individual terms, to show the effect with respect to CTP:

$\frac{\partial CTP}{\partial WCU} = (hCU1 - hCU2)$ $\quad \frac{\partial CTP}{\partial hCU1} = WCU$ $\quad \frac{\partial CTP}{\partial hCU2} = -WCU$

Based on Equation 3.5-3, the uncertainty in core thermal power due to uncertainty in RWCU flow energy (U_{CU}) is:

$$U_{CU} = \left[\left(\frac{\partial CTP}{\partial WCU} * \sigma_{WCU}\right)^2 + \left(\frac{\partial CTP}{\partial hCU1} * \sigma_{hCU1}\right)^2 + \left(\frac{\partial CTP}{\partial hCU2} * \sigma_{hCU2}\right)^2\right]^{1/2}$$

Substituting the partial derivatives from above:

$$U_{CU} = [((hCU1 - hCU2)* \sigma_{WCU})^2 + (WCU* \sigma_{hCU1})^2 + (-WCU * \sigma_{hCU2})^2]^{1/2}$$ **Equation 7.4-1**

Solving Equation 7.4-1 will determine the contribution of the uncertainty in the RWCU flow energy to the overall core thermal power uncertainty.

Input values from Table 4.6-1:

hCU1 = 529.17 BTU/lbm
hCU2 = 415.20 BTU/lbm
WCU = 0.133 Mlbm/hr

Uncertainties from Table 4.7-1:

σ_{WCU} = ± 0.0022 Mlbm/hr [2σ] (IPCS calculation)
σ_{WCU} = ± 0.0056 Mlbm/hr [2σ] (manual calculation)
σ_{hCU1} = ± 12.541 BTU/lbm [2σ]
σ_{hCU2} = ± 11.018 BTU/lbm [2σ]

<u>Using these values to solve Equation 7.4-1, for IPCS calculation:</u>

$$U_{CU} = [((529.17 - 415.20 \text{ BTU/lbm})*(0.0022 \text{ Mlbm/hr}))^2 + ((0.133 \text{ Mlbm/hr})*(12.541 \text{ BTU/lbm}))^2 + ((-0.133 \text{ Mlbm/hr})*(11.018 \text{ BTU/lbm}))^2]^{1/2}$$

$U_{CU} = \pm 2.234 \text{ MBTU/hr}$

Converting to MWt, with the conversion factor from Input 4.2:

$U_{CU} = (\pm 2.234 \text{ MBTU/hr}) / (3.413 \text{ MBTU/MWt-hr}) = \pm 0.655 \text{ MWt}$

Using these values to solve Equation 7.4-1, for manual calculation:

$$U_{CU} = [((529.17 - 415.20\ BTU/lbm)*(0.0056\ Mlbm/hr))^2 + ((0.133\ Mlbm/hr)*(12.541\ BTU/lbm))^2 + ((-0.133\ Mlbm/hr)*(11.018\ BTU/lbm))^2]^{1/2}$$

$U_{CU} = \pm\ 2.310$ MBTU/hr

Converting to MWt, with the conversion factor from Input 4.2:

$$U_{CU} = (\pm\ 2.310\ MBTU/hr) / (3.413\ MBTU/MWt\text{-}hr) = \pm\ 0.677\ MWt$$

7.5. Radiated Heat Uncertainty

The radiated and other heat losses in Table 4.6-1are a constant of 2.1 MWt, which per Ref. 6.3, is based on 1.1 MWt radiated heat loss and 1.0 MWt heat loss to recirculation pump seal purge flow.

Because CTP varies directly with QRAD, the partial derivative of CTP with respect to QRAD is 1:

$$\frac{\partial CTP}{\partial QRAD} = 1$$

Based on Equation 3.5-3, the uncertainty in core thermal power due to radiated and other thermal losses (U_{QRAD}) is:

$$U_{QRAD} = [(\frac{\partial CTP}{\partial QRAD} * \sigma_{QRAD})^2]^{1/2}$$

Per Table 4.7-1, the uncertainty associated with this heat loss is conservatively taken as ±10 %

$$\sigma QRAD = \pm 10\% * (2.1 \text{ MWt}) = \pm 0.21 \text{ MWt}$$

Substituting the values from above:

$$U_{QRAD} = [((1 * 0.21 \text{ MWt})^2]^{1/2} = \pm 0.21 \text{ MWt}$$

7.6. Reactor Recirculation (RR) Pump Heat Uncertainty

As described in Section 3.3, the energy input to the reactor coolant by the RR Pumps is not measured directly but is calculated by multiplying the measured electrical power consumption of the RR pump motors by their efficiency (ETA).

$$Q_P = QP_{ELEC} * ETA$$

Taking the partial derivatives with respect to the individual terms, to show the effect with respect to CTP:

$$\frac{\partial CTP}{\partial ETA} = QP_{ELEC} \qquad \frac{\partial CTP}{\partial QP} = ETA$$

Based on Equation 3.5-3, the uncertainty in core thermal power due to RR Pump energy uncertainty (U_{RCP}) is:

$$U_{RCP} = \left[\left(\frac{\partial CTP}{\partial ETA} * \sigma_{ETA}\right)^2 + \left(\frac{\partial CTP}{\partial QP} * \sigma_{QP}\right)^2\right]^{1/2}$$

Substituting the partial derivatives from above:

$$U_{CU} = [(QP_{ELEC} * \sigma_{ETA})^2 + (ETA * \sigma_{QPELEC})^2]^{1/2}$$ **<u>Equation 7.6-1</u>**

Solving Equation 7.6-1 will determine the contribution of the RR pump energy uncertainty to the overall core thermal power uncertainty.

Input values from Table 4.6-1: QP_{ELEC} = 11.185 MWe (combined, for both pumps)
ETA = 95.2% = 0.952

Uncertainties from Table 4.7-1: $\sigma_{QPELEC} = \pm$ 10% (11.185 MW) = ± 1.119 MWe [2σ]
$\sigma_{ETA} = \pm$ 1% = ± 0.01 [2σ]

Using these values to solve Equation 7.6-1:

$$U_{RCP} = [((11.185\ MWe)*0.01)^2 + (0.952 *(1.119\ MWe))^2]^{1/2}$$

$$U_{RCP} = \pm 1.071\ MWe = \pm 1.071\ MWt$$

7.7. The total CTP Uncertainty is the combination of the individual uncertainties calculated in Sections 7.2 through 7.6 above. Because the individual uncertainties are independent, they are combined via the square root sum of the squares.

$$U_{CTP} = (U_{FW}{}^2 + U_{CR}{}^2 + U_{CU}{}^2 + U_{QRAD}{}^2 + U_{RCP}{}^2)^{1/2}$$

<u>Fully Functional LEFM CheckPlus, IPCS Calculation</u>

Substituting in the uncertainty values from Sections 7.2.1, and 7.3 through 7.6:

$$U_{CTP} = ((12.280\ \text{MWt})^2 + (0.827\ \text{MWt})^2 + (0.655\ \text{MWt})^2 + (0.21\ \text{MWt})^2 + (1.071\ \text{MWt})^2)^{1/2}$$

$$U_{CTP} = \pm\ 12.373\ \text{MWt}$$

In terms of percent of current licensed thermal power (CLTP) at 3430 MWt (Input 4.1):

$$P_{CLTP} = (\pm\ 12.373\ \text{MWt}) / 3430\ \text{MWt}$$

$$P_{CLTP} = \pm\ 0.361\ \%\ \text{CLTP}$$

In terms of percent of MUR rated core thermal power (CTP), at 3486 MWt (Input 4.1):

$$P_{MUR\_CTP} = (\pm\ 12.373\ \text{MWt}) / 3486\ \text{MWt}$$

$$P_{MUR\_CTP} = \pm\ 0.355\ \%\ \text{MUR CTP}$$

<u>Maintenance Mode LEFM CheckPlus, IPCS Calculation</u>

Substituting in the uncertainty values from Sections 7.2.2, and 7.3 through 7.6:

$$U_{CTP} = ((19.298\ \text{MWt})^2 + (0.827\ \text{MWt})^2 + (0.655\ \text{MWt})^2 + (0.21\ \text{MWt})^2 + (1.071\ \text{MWt})^2)^{1/2}$$

$$U_{CTP} = \pm\ 19.358\ \text{MWt}$$

In terms of percent of CLTP, at 3430 MWt (Input 4.1):

$$P_{CLTP} = (\pm\ 19.358\ \text{MWt}) / 3430\ \text{MWt}$$

$$P_{CLTP} = \pm\ 0.564\ \%\ \text{CLTP}$$

In terms of percent of MUR CTP, at 3486 MWt (Input 4.1):

$$P_{MUR\_CTP} = (\pm\ 19.358\ \text{MWt}) / 3486\ \text{MWt}$$

$$P_{MUR\_CTP} = \pm\ 0.555\ \%\ \text{MUR CTP}$$

<u>Fully Functional LEFM CheckPlus, Manual Calculation</u>

Substituting in the uncertainty values from Sections 7.2.1, and 7.3 through 7.6:

$$U_{CTP} = ((12.280\ \text{MWt})^2 + (0.957\ \text{MWt})^2 + (0.677\ \text{MWt})^2 + (0.21\ \text{MWt})^2 + (1.071\ \text{MWt})^2)^{1/2}$$

$$U_{CTP} = \pm\ 12.384\ \text{MWt}$$

In terms of percent of CLTP at 3430 MWt (Input 4.1):

$$P_{CLTP} = (\pm\ 12.384\ \text{MWt}) / 3430\ \text{MWt}$$

$$P_{CLTP} = \pm\ 0.361\ \%\ \text{CTP}$$

In terms of percent of MUR CTP, at 3486 MWt (Input 4.1):

$$P_{MUR\_CTP} = (\pm\ 12.384\ \text{MWt}) / 3486\ \text{MWt}$$

$$P_{MUR\_CTP} = \pm\ 0.355\ \%\ \text{MUR CTP}$$

Maintenance Mode LEFM CheckPlus, Manual Calculation

Substituting in the uncertainty values from Sections 7.2.2, and 7.3 through 7.6:

$U_{CTP} = ((19.298\ MWt)^2 + (0.957\ MWt)^2 + (0.677\ MWt)^2 + (0.21\ MWt)^2 + (1.071\ MWt)^2)^{1/2}$

$U_{CTP} = \pm\ 19.364\ MWt$

In terms of percent of core thermal power, for CTP = 3430 MWt (Input 4.1):

$P_{CLTP} = (\pm\ 19.364\ MWt) / 3430\ MWt$

$P_{CLTP} = \pm\ 0.565\ \%\ CTP$

In terms of percent of MUR CTP, at 3486 MWt (Input 4.1):

$P_{MUR\_CTP} = (\pm\ 19.364\ MWt) / 3486\ MWt$

$P_{MUR\_CTP} = \pm\ 0.555\ \%\ MUR\ CTP$

8.0 Acceptance Criteria

For operation at the proposed MUR CTP (3486 MWt, per Ref. 6.26), this calculation determines the uncertainty associated with the determination of core thermal power for the following four cases:

1. IPCS with LEFM CheckPlus Fully Functional,
2. IPCS with LEFM CheckPlus in Maintenance Mode,
3. Manual Calculation with LEFM CheckPlus Fully Functional, and
4. Manual Calculation with LEFM CheckPlus in Maintenance Mode.

For Case 1 (Core thermal power calculated by IPCS with LEFM CheckPlus Fully Functional), the acceptance criterion is that the proposed MUR CTP (3486 MWt) plus the total positive uncertainty in MWt remains bounded by 1.02% (3499 MWt) of Current Licensed Thermal Power (CLTP, at 3430 MWt).

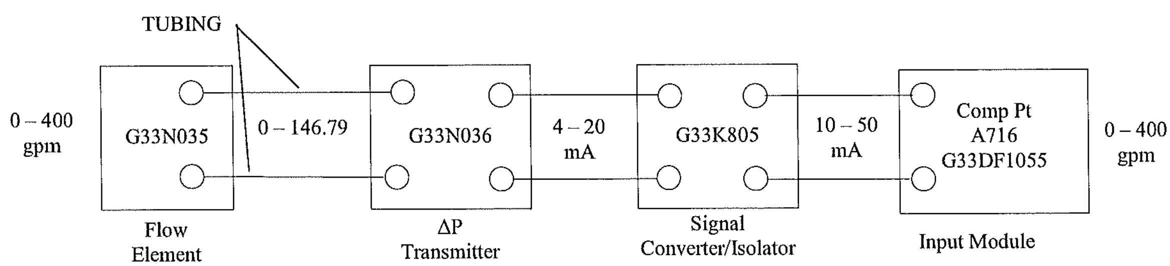
For the remaining three cases (Core thermal power determined by IPCS with LEFM CheckPlus in Maintenance Mode, Manual Calculation with LEFM CheckPlus Fully Functional, and Manual Calculation with LEFM CheckPlus in Maintenance Mode), there are no specific acceptance criteria. The uncertainty is determined and simply stated.

The purpose of this Appendix is to determine the channel instrument error (CIE) in Reactor Water Clean-Up (RWCU) mass flow rate at MUR rated conditions of 3486 MWt for insertion into Table 4.7-1 of the base calculation.

NOTE: References are listed in the main body of the calculation. Paragraph references refer to steps within this Appendix. Section references refer to steps within the main body of the calculation.

A1 Reactor Water Clean-Up (RWCU) Flow Loop Configuration

The RWCU flow input to the plant computer is addressed in calculation DC-4567 (Ref. 6.9) as Channel 7. This loop consists of a Rosemount transmitter measuring differential pressure across a flow element. The transmitter provides a 4-20 mA signal to a signal converter/isolator that sends a 10-50 mA signal to the PPC for display in the Control Room. The analyzed instrument loop may be represented as follows:



A2 Reactor Water Clean-up (RWCU) Flow Instrument Data and Uncertainty Values

Calculation DC-4567 provides the following parameters and uncertainties for the instruments in this flow loop. Page numbers are referenced from DC-4567 where the information is found.

A2.1 Flow Element (G33N035) (page 14 & App. A page 7 of 22):

Full Scale Inlet Flow: 400 gpm

dP @ Full Scale Inlet Flow: 146.79 inwc

Flow Element Uncertainty (PEA) = ± 1% of span = ± 4 gpm [2σ]

A2.2 Transmitter (G33N036):

Rosemount Model 1152DP4E22PB

Normal accuracy (page 25): t2AN = ± 0.468 inwc = ± 0.638 gpm [2σ]

Drift (page 25), adjusted for 25% late interval:

t2DDa = ± 0.575 inwc = ± 0.782 gpm [2σ]

From page 42, Calibration Error t2CC = ± 0.86 gpm [2σ]

A2.3 Signal Converter/Isolator (G33K805):

TEC Model 156L: 4-20 mA input to 10-50 mA output

Normal accuracy (page 31): i2A = ± 0.195 mA (input scale) [2σ]

Convert to gpm, at full flow of 400 gpm, per Equation 8 on p. 46 of Ref. 6.1:

i2A = (400 gpm)*((1^2 + (0.195 mA/40 mA))$^{1/2}$ - 1)

i2A = ± 0.974 gpm [2σ]

Drift (page 31): i2DD = ± 0.111 mA (input scale) [2σ]

Convert to gpm, at full flow of 400 gpm, per Equation 8 on p. 46 of Ref. 6.1:

i2DD = (400 gpm)*((1^2 + (0.111 mA/40 mA))$^{1/2}$ - 1)

i2DD = ± 0.555 gpm [2σ]

Using the methodology from page 41 and values from page 40:

Calibration equipment effect: i2CX = (xi2 * (i2CLI^2 + i2CLO^2) $^{1/2}$

i2CX = (1 * (0.275^2 + 0.350^2) $^{1/2}$

i2CX = 0.445 gpm [3σ]

From page 31: i2ALT = 0.240 mA [3σ]

Convert to gpm, at full flow of 400 gpm, per Equation 8 on p. 46 of Ref. 6.1:

i2ALT = (400 gpm)*((1^2 + (0.240 mA/40 mA))$^{1/2}$ - 1)

i2ALT = 1.198 gpm [3σ]

Per Ref. 6.1, Calibration Procedure Effect: EP = ALT if ALT > CX, otherwise, EP = CX if ALT < CX. In this case: i2ALT = ± 1.198 gpm > i2CX = ± 0.445 gpm.

Therefore since ALT > CX: i2EP = i2ALT = ± 1.198 gpm

Calibration Error, i2CC, using the methodology of page 42:

i2CC = (2/3 * (i2CX^2 + (i2CX/rt)^2 + i2EP^2) $^{1/2}$

i2CC = (2/3 * ((0.445 gpm)^2 + (0.445 gpm/2)^2 + (1.198 gpm)^2) $^{1/2}$

i2CC = ± 0.865 gpm [2σ]

A2.4 I/O card (G33DF1055):

Accuracy (page 36): ce1A = ± 0.5% of span = ± 2.0 gpm [2σ]

Drift: included in accuracy so ce1DD = 0

No calibration instrument error, CX, but per page 36, celALT = ± 3.0 gpm [3σ]. Thus per the methodology of Ref. 6.1, celEP = celALT = ± 3.0 gpm

Thus total calibration error is:

ce1CC = 2/3*(ce1EP) = 2/3*(3.0 gpm) = ± 2.0 gpm [2σ]

A3 Reactor Water Clean-up (RWCU) Flow Loop Channel Uncertainties

The total uncertainty is the SRSS of the uncertainties due to instrument accuracies, drift, and calibration. Combining the individual uncertainties:

Channel Accuracy: $LANce1 = (t2AN^2 + i2A^2 + ce1A^2)^{1/2}$

$LANce1 = ((0.638\ gpm)^2 + (0.974\ gpm)^2 + (2.0\ gpm)^2)^{1/2}$

$LANce1 = \pm\ 2.314\ gpm\ [2\sigma]$

Channel Drift: $LDce1 = (t2DDa^2 + i2DD^2 + ce1DD^2)^{1/2}$

$LDce1 = ((0.782\ gpm)^2 + (0.555\ gpm)^2 + (0)^2)^{1/2}$

$LDce1 = \pm\ 0.959\ gpm\ [2\sigma]$

Channel Calibration Error: $LCce1 = (t2CC^2 + i2CC^2 + ce1CC^2)^{1/2}$

$LCce1 = (0.86\ gpm)^2 + (0.865\ gpm)^2 + (2.0\ gpm)^2)^{1/2}$

$LCce1 = \pm\ 2.343\ gpm$

Channel Instrument Error per page 44 methodology, but taken to a 2σ confidence level:

$CIEce1 = (LANce1^2 + LDce1^2 + LCce1^2 + PEA^2)^{1/2}$

$CIEce1 = ((2.314\ gpm)^2 + (0.959\ gpm)^2 + (2.343\ gpm)^2 + (4\ gpm)^2)^{1/2}$

$CIEcel = \pm\ 5.269$ gpm to a 2σ, or 95.5% confidence level

The density at the RWCU discharge conditions (from Table 4.6-1) of 435.9 °F and 1045 psia (52.363 lbm/ft^3, from Attachment 1) is used to convert this to terms of Mlbm/hr for inclusion in the CPT determination:

$CIEcel = (\pm\ 5.269\ gpm) * (52.363\ lbm/ft^3) * (1\ ft^3/7.480519\ gal) * (60\ min/hr)$

$CIEcel = \pm\ 2213\ lbm/hr = \pm\ 0.0022\ Mlbm/hr$

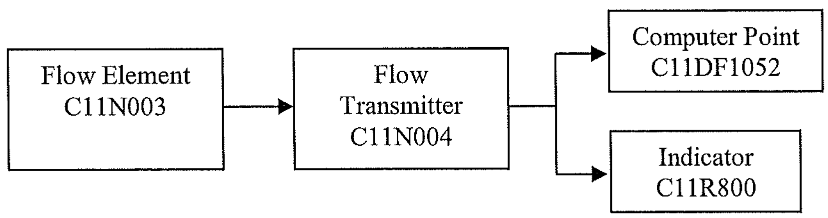
This value is entered into the Table 4.7-1 of the base calculation as the uncertainty of the RWCU Flow Rate when using the IPCS input based on G33CF6004/G33DF1055.

The purpose of this appendix is to calculate the uncertainty in the measurement of Control Rod Drive (CRD) mass flow at MUR rated conditions of 3486 MWt for input to the Table 4.7-1 of the base calculation.

NOTE: References are listed in the main body of the calculation. Paragraph references refer to steps within this Appendix. Section references refer to steps within the main body of the calculation.

B1 CRD Flow Loop Configuration (Reference Calculation DC-5924 Rev. E, Ref. 6.10)

The instrument loop consists of a differential pressure transmitter tapped across a flow element. The transmitter provides a 4-20 mA output to a computer input card. The loop is shown as:



Per Ref. 6.25 Section 4.2.2, the IPCS converts the volumetric flow input to point C11DF1052 to mass flow read at point C11CF6001.

The loop components evaluated in this document, the applicable performance specifications and process parameter data are as follows:

B2 CRD Flow Instrument Data and Uncertainty Values

Calculation DC-5924 provides the following parameters and uncertainties for the instruments in this flow loop. Page numbers are referenced from DC-5924 where the information is found.

B2.1 Flow Element (C11N003) (Design Basis Document C11-00 Rev. B Section 4.1.3.3.3, p. 4-25 & 4-26):

Maximum differential pressure: 200 inwc at 100 gpm (p. 2 & p. 9)

Flow Element Uncertainty (PEA) = ± 5 % of span = ± 5 gpm [2σ] (Sect. 5.1.11)

B2.2 Transmitter (C11N004):

Rosemount Model 3051S1CD2A2F12A1AB2 (p. 13)

Calculation DC-5924 page 14 states the following uncertainties:

Accuracy VA = ± 0.400 inwc [3σ]

Convert to gpm, at full flow of 100 gpm, per Equation 8 on p. 46 of Ref. 6.1 and take at 2σ:

$tAN = VA*(2/3) = (\pm 0.400 \text{ inwc})*(2/3) = \pm 0.267 \text{ inwc}$

$tAN = (100 \text{ gpm})*((1^2 + (0.267 \text{ inwc}/200 \text{ inwc}))^{1/2} - 1)$

$tAN = \pm 0.067 \text{ gpm } [2\sigma]$

Drift DD1 = ± 1.764 inwc [2σ]

Convert to gpm, at full flow of 100 gpm, per Equation 8 on p. 46 of Ref. 6.1:

$tDD = (100\ gpm)*((1^2 + (1.764\ inwc/200\ inwc))^{1/2} - 1)$

$tDD = \pm 0.440\ gpm$ [2σ]

Calculation DC-5924 page 26 recommends that this transmitter be calibrated with a pressure gauge of accuracy ± 0.15%, and a DMM of accuracy ±0.05 mA, or better.

Taking the error at the maximum 200 inwc, for a 0.15% accuracy, per the method on p. 29 of Ref. 6.1:

Calibration equipment effect: $tCX = (tCLI^2 + tCLO^2)^{1/2}$

$tCX = (((0.15\%*(200\ inwc)*(16\ mA/200\ inwc))^2 + (0.05\ mA)^2)^{1/2}$

$tCX = \pm 0.055\ mA$ [3σ]

Convert to gpm, at full flow of 100 gpm, per Equation 8 on p. 46 of Ref. 6.1:

$tCX = (100\ gpm)*((1^2 + (0.055\ mA/16\ mA))^{1/2} - 1)$

$tCX = \pm 0.172\ gpm$ [3σ]

From page 14: tALT = 0.400 inwc [3σ]

Convert to gpm, at full flow of 100 gpm, per Equation 8, p. 46 of Ref. 6.1:

$tALT = (100\ gpm)*((1^2 + (0.400\ inwc/200\ inwc)^{1/2} - 1)$

$tALT = 0.10\ gpm$ [3σ]

Per Ref. 6.1, Calibration Procedure Effect: EP = ALT if ALT > CX, otherwise, EP = CX if ALT < CX. In this case: tALT = ± 0.10 gpm < tCX = ± 0.172 gpm. Thus, tEP = tCX = ± 0.172 gpm

Calibration Error, tCC, per p. 30 of Ref. 6.1:

$tCC = (2/3 * (tCX^2 + (tCX/rt)^2 + tEP^2)^{1/2}$

$tCC = (2/3 * ((0.172\ gpm)^2 + (0.172\ gpm/2)^2 + (0.172\ gpm)^2)^{1/2}$

$tCC = \pm 0.172\ gpm$ [2σ]

B2.3 I/O card (C11-DF1052 with Resistor C11AR4A) (Refer to DC-5924 Page 15):

Accuracy: ceA = ± 0.5 % of span = ± 1.000 inwc [2σ]

Convert to gpm, at full flow of 100 gpm, per Equation 8, p. 46 of Ref. 6.1:

$ceA = (100\ gpm)*((1^2 + (1.000\ inwc/200\ inwc))^{1/2} - 1)$

$ceA = 0.250\ gpm$ [2σ]

Drift: included in accuracy so ce1DD = 0

No calibration instrument error, CX, but per page 15, ceALT = ±1.500 inwc [3σ].

Therefore since ALT > CX: ceEP = ceALT = ± 1.500 inwc [3σ]

Thus total calibration error is: ceCC = 2/3*(ceEP) = 2/3*(1.5 inwc) = ± 1.0 inwc

Convert to gpm, at full flow of 100 gpm:

$ceCC = (100\ gpm)*((1^2 + (1.0\ inwc/200\ inwc))^{1/2} - 1)$

$ceCC = 0.250\ gpm$ [2σ]

B2.4 CRD Indicator (C11R800)(Refer to DC-5924 Page 17):

Accuracy: i2A = ± 2% of span = ± 2.000 gpm [2σ]

Drift: included in accuracy so i2DD = 0

No calibration instrument error, CX, but per page 17, ALT4 = ±3.000 gpm [3σ]

Therefore since ALT > CX: i2EP = ALT4 = ± 3.000 gpm [3σ]

Thus total calibration error is:

i2CC = 2/3*(i2EP) = 2/3*(3.000 gpm) = ± 2.000 gpm [2σ]

B3 CRD IPCS Flow Loop Channel Uncertainties

The total uncertainty is the SRSS of the uncertainties due to instrument accuracies, drift, and calibration. Combining the individual uncertainties:

<u>Channel Accuracy</u>: $LANce = (tAN^2 + ceA^2)^{1/2}$

$LANce = ((0.067\ gpm)^2 + (0.250\ gpm)^2)^{1/2}$

$LANce = \pm 0.259\ gpm$ [2σ]

<u>Channel Drift</u>: LDce = tDD = ± 0.440 gpm [2σ]

<u>Channel Calibration Error</u>: $LCce = (tCC^2 + ceCC^2)^{1/2}$

$LCce = ((0.172\ gpm)^2 + (0.250\ gpm)^2)^{1/2}$

$LCce = \pm 0.303\ gpm$ [2σ]

<u>Channel Instrument Error</u>

$CIEce = (LANce^2 + LDce^2 + LCce^2 + PEA^2)^{1/2}$

$CIEce = ((0.259\ gpm)^2 + (0.440\ gpm)^2 + (0.303\ gpm)^2 + (5.0\ gpm)^2)^{1/2}$

CIEce = ± 5.035 gpm to a 2σ, or 95.5% confidence level

The density (from Attachment 1) at the rated conditions of 100.0°F and 1045 psia (62.188 lbm/ft^3) is used to convert this to terms of Mlbm/hr for inclusion in the CPT determination:

$CIEce = (\pm 5.035\ gpm) * (62.188\ lbm/ft^3) * (1\ ft^3/7.480519\ gal) * (60\ min/hr)$

CIEce = ± 2511 lbm/hr = ± 0.0025 Mlbm/hr

This value is entered into the Table 4.7-1 of the base calculation as the uncertainty of the CRD Flow Rate when using the IPCS input based on C11CF6001/C11DF1052.

B4 CRD Indicator Flow Loop Channel Uncertainties

The total uncertainty is the SRSS of the uncertainties due to instrument accuracies, drift, and calibration. Combining the individual uncertainties:

Channel Accuracy: $LANi = (tAN^2 + i2A^2)^{1/2}$

$LANi = ((0.067 \text{ gpm})^2 + (2.000 \text{ gpm})^2)^{1/2}$

$LANi = \pm 2.001$ gpm [2σ]

Channel Drift: $LDi = tDD = \pm 0.440$ gpm [2σ]

Channel Calibration Error: $LCi = (tCC^2 + i2CC^2)^{1/2}$

$LCi = ((0.172 \text{ gpm})^2 + (2.000 \text{ gpm})^2)^{1/2}$

$LCi = \pm 2.007$ gpm [2σ]

Channel Instrument Error

$CIEi = (LANi^2 + LDi^2 + LCi^2 + PEA^2)^{1/2}$

$CIEi = ((2.001 \text{ gpm})^2 + (0.440 \text{ gpm})^2 + (2.007 \text{ gpm})^2 + (5.0 \text{ gpm})^2)^{1/2}$

$CIEi = \pm 5.764$ gpm to a 2σ, or 95.5% confidence level

The density (from Attachment 1) at the rated conditions of 100.0°F and 1045 psia (62.188 lbm/ft^3) is used to convert this to terms of Mlbm/hr for inclusion in the CPT determination:

$CIEi = (\pm 5.764 \text{ gpm}) * (62.188 \text{ lbm/ft}^3) * (1 \text{ ft}^3/7.480519 \text{ gal}) * (60 \text{ min/hr})$

$CIEi = \pm 2875$ lbm/hr $= \pm 0.0029$ Mlbm/hr

This value is entered into the Table 4.7-1 of the base calculation as the uncertainty of the CRD Flow Rate when using the indicator input.

Attachment 1 NIST Data on Thermophysical Properties of Water

Isothermal and Isobaric Properties of Water

Temperature (F)	Pressure (psia)	Density (lbm/ft^3)	Specific Volume (ft^3/lbm)	Enthalpy (Btu/lbm)	Phase
Isothermal					
533.80	1015.0	47.044	0.021257	529.22	liquid
533.80	1045.0	47.065	0.021247	529.17	liquid
533.80	1075.0	47.086	0.021238	529.12	liquid
435.9	1015.0	52.352	0.019102	415.18	liquid
435.9	1045.0	52.363	0.019097	415.20	liquid
435.9	1075.0	52.375	0.019093	415.23	liquid
426.5	1015.0	52.775	0.018949	404.87	liquid
426.5	1045.0	52.786	0.018945	404.89	liquid
426.5	1075.0	52.796	0.018941	404.92	liquid
100.00	1015.0	62.182	0.016082	70.755	liquid
100.00	1045.0	62.188	0.016080	70.834	liquid
100.00	1075.0	62.193	0.016079	70.913	liquid
Isobaric					
538.80	1045.0	46.732	0.021398	535.47	liquid
533.80	1045.0	47.065	0.021247	529.17	liquid
528.80	1045.0	47.390	0.021102	522.94	liquid
440.90	1045.0	52.134	0.019181	420.72	liquid
435.90	1045.0	52.363	0.019097	415.20	liquid
431.50	1045.0	52.562	0.019025	410.37	liquid
430.90	1045.0	52.589	0.019015	409.71	liquid
426.50	1045.0	52.786	0.018945	404.89	liquid
421.50	1045.0	53.006	0.018866	399.44	liquid
105.00	1045.0	62.122	0.016097	75.808	liquid
100.00	1045.0	62.188	0.016080	70.834	liquid
95.000	1045.0	62.250	0.016064	65.861	liquid

Saturated Steam Properties

Temperature (F)	Pressure (psia)	Density (lbm/ft^3)	Specific Volume (ft^3/lbm)	Enthalpy (Btu/lbm)	Phase
549.02	**1036.5**	2.3337	0.42850	**1192.0**	vapor
550.02	**1045.0**	2.3553	0.42458	**1191.7**	vapor
551.02	**1053.5**	2.3770	0.42070	**1191.3**	vapor

Saturated Water Properties

Temperature (F)	Pressure (psia)	Density (lbm/ft^3)	Specific Volume (ft^3/lbm)	Enthalpy (Btu/lbm)	Phase
549.02	**1036.5**	46.017	0.021731	**548.59**	liquid
550.02	**1045.0**	45.952	0.021762	**549.87**	liquid
551.02	**1053.5**	45.887	0.021793	**551.15**	liquid

"Thermophysical Properties of Fluid Systems" by E.W. Lemmon, M.O. McLinden and D.G. Friend in **NIST Chemistry WebBook, NIST Standard Reference Database Number 69**, Eds. P.J. Linstrom and W.G. Mallard, National Institute of Standards and Technology, Gaithersburg MD, 20899, http://webbook.nist.gov, (retrieved October 06, 2011).

Table II-V-1 Tolerances for Discharge Coefficients and Flow Coefficients

Primary Element	Coefficient from	Pipe Size, D	R_d or R_D	β	Tolerance (per cent)
Square-Edged Concentric Orifices — Flange taps	Equations (II-III-1), (II-III-2) or Table II-III-2				
D & ½ D taps	Equations (II-III-3), (II-III-4) or Table II-III-3	$D \gtrsim 2.0$ in.	$R_d \gtrsim 5000\ D$	$0.20 \lesssim \beta \lesssim 0.70$ $0.11 \lesssim \beta \lesssim 0.20$ $0.70 \lesssim \beta \lesssim 0.75$	± 1.0 or less ± 2.25 to ± 1.0 linearly with β ± 1.0 to ± 2.25 linearly with β
Vena contracta taps	Equations (II-III-5), (II-III-6) or Table II-III-4			V.C. taps only $0.70 \lesssim \beta \lesssim 0.80$	± 1.0 to ± 2.5 linearly with β
As above		$1.0 < D < 2.0$ in.		As above	Above tolerances to be multiplied by a factor of 1 to 2 increasing linearly as D decreases
As above			$4000 \lesssim R_d < 5000\ D$	As above	Above tolerances to be multiplied by a factor of 1 to 2 increasing linearly as R_d decreases
Long-Radius Flow Nozzle (Fig. II-III-14) Pipe-wall taps at D & ½ D	Equation (II-III-12) or Table II-III-5	$2.0 \lesssim D \lesssim 16$ in.	$10^4 \lesssim R_d \lesssim 2.5\times10^6$	$0.2 \lesssim \beta \lesssim 0.8$	± 2.0
Long-radius Flow Nozzle (Fig. II-III-14) Taps at 1 D and nozzle throat	Calibration (See Par. II-IV-6)	$2.0 \lesssim D \lesssim 16$ in.	$R_d \lesssim 10^5$	$0.2 \lesssim \beta \lesssim 0.5$	As determined (or ± 0.3)
1932 ISA Flow Nozzle (Fig. II-III-22) Corner taps	K by Fig. II-III-23	$2 \lesssim D \lesssim 40$ in.	$2\times10^4 \lesssim R_D \lesssim 10^6$	$0.32 < \beta < 0.8$	± 1.0
Venturi Tube Rough-cast inlet cone	Par. II-III-38	$4 \lesssim D \lesssim 32$ in.	$2\times10^5 \lesssim R_D \lesssim 10^6$	$0.3 \lesssim \beta \lesssim 0.75$	± 0.75
Venturi Tube Machined inlet cone	Par. II-III-38	$2 \lesssim D \lesssim 10$ in.	$10^5 \lesssim R_D \lesssim 10^6$	$0.4 \lesssim \beta \lesssim 0.75$	± 1.0
Venturi Tube Welded sheet metal inlet cone	Par. II-III-38	$8 \lesssim D \lesssim 48$ in.	$2\times10^5 \lesssim R_D \lesssim 2\times10^6$	$0.4 \lesssim \beta \lesssim 0.7$	± 1.5
Eccentric Orifice Flange taps Vena contracta taps	Fig. II-III-9	$4 \lesssim D \lesssim 14$ in.	$10^4 \lesssim R_D \lesssim 10^6$	$0.3 \lesssim \beta \lesssim 0.8$	$D = 4$ in. ± 1.9 $D > 4$ in. ± 1.4
Segmental Orifice Flange taps Vena contracta taps	Fig. II-III-10	$4 \lesssim D \lesssim 14$ in.	$10^4 \lesssim R_D \lesssim 10^6$	$0.35 \lesssim \beta \lesssim 0.85$	± 2

Attachment 3 Excerpt from ANSI/ASME PTC-6

ANSI/ASME PTC 6 REPORT-1985
AN AMERICAN NATIONAL STANDARD

GUIDANCE FOR EVALUATION OF MEASUREMENT UNCERTAINTY
IN PERFORMANCE TESTS OF STEAM TURBINES

TABLE 4.10
BASE UNCERTAINTIES OF PRIMARY FLOW MEASUREMENT

Item	Base Uncertainty, U_B,%	Liquid: Flow Nozzle, Throat Tap	Liquid: Flow Nozzle, Pipe Wall Tap	Liquid: Orifice	Superheated Steam (at Least 25° Superheat): Flow Nozzle, Throat Tap	Superheated Steam (at Least 25° Superheat): Flow Nozzle, Pipe Wall Tap	Superheated Steam (at Least 25° Superheat): Orifice
	Group 1 — Calibrated Flow Sections						
A	Meeting Code requirements	0.15 [Note (3)]	0.25 [Note (4)]	0.25 [Note (4)]	0.25 [Note (4)]	0.35 [Note (4)]	0.45 [Note (4)]
B	Calibrated immediately before test and inspected after test, coefficient curve extrapolated	0.25	0.50	0.60	0.50	0.75	1.10
C	Calibrated before installation and inspected before and after test assuring no visible or measurable changes in the flow element	0.35	0.60	0.80	0.70	1.05	1.65
D	Calibrated before permanent installation and installed after initial flushing [Note (1)]	1.25	1.25	1.55	1.60	1.70	2.30
E	Calibrated before permanent installation [Notes (1) and (2)]	2.50	2.50	3.00	2.75	2.80	3.70
	Group 2 — Uncalibrated Flow Sections						
F	Inspected immediately before and after test	0.80	2.00	1.00	1.20	2.50	2.00
G	Inspected immediately before test	1.15	2.50	2.50	1.50	3.00	3.00
H	Inspected before permanent installation [Notes (1) and (2)]	2.60	3.20	3.20	3.00	3.70	4.20
I	No inspection and permanent installation			See Par. 4.16(a)(1), Item I			

GENERAL NOTE: Overall uncertainty of flow sections:
With no flow straightener $= \sqrt{(U_B)^2 + (U_{INS})^2 + (U_X)^2 + (U_{OS1})^2}$
With a flow straightener $= \sqrt{(U_B)^2 + (U_X)^2 + (U_{LS1})^2 + (U_{LS2})^2 + (U_{OS2})^2}$
Where U_B is from this table, U_{INS} is from Fig. 4.5, U_X is from Fig. 4.6, U_{LS1} is from Fig. 4.7, U_{LS2} is from Fig. 4.8, and U_{OSi} is from Fig. 4.9.

NOTES:
(1) Good water chemistry, no after test inspection, less than six months in service (see Par. 4.17).
(2) Reasonable assurance that minimal damage was caused to flow element during initial flushing.
(3) 0.15% pertains to flow sections located in the lower temperature part of the cycle. The 0.15% may increase to 0.25% when the flow section is located in the higher temperature part of the cycle, such as in the boiler feedwater line downstream of the top heater.
(4) Information relative to the construction, calibration, and installation of other flow-measuring devices is described in ASME PTC 19.5-1972. Although these devices are not recommended for the measurement of primary flow, they may be used if they conform to the general requirements of Par. 4.22 of the Code with the following exceptions:
  (a) For the requirement of Par. 4.22(a) of the Code, the β ratio shall be limited to the range 0.25 to 0.50 for wall tap nozzles and venturis and 0.30 to 0.60 for orifices.
  (b) For the requirement of Par. 4.22(d) of the Code, the appropriate reference coefficient for the actual device given in PTC 19.5 shall be used. The parties to a test should become familiar with the contents of PTC 19.5 regarding these devices.

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A Mathematical Model for Assessing the Uncertainties of Instrumentation Measurements for Power and Flow of PWR Reactors

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EXECUTIVE SUMMARY

Neither the power nor flow of pressurized water reactors (PWR) are measured directly. Instead, values of both are calculated from data of several other variables which are directly measured. Each of these directly measured variables has an uncertainty in its value. An assessment model was developed which gives the appropriate statistical method of combining the uncertainties in the measured variables to give the uncertainty in the power or flow measurements for use in technical specification input.

While the method is directed toward PWR power and flow determination, it is suitable for generalized application to instrument measurement uncertainties.

The method defines the parameters considered with references to reactor power and reactor coolant flow.

The report next defines the classification of errors, systematic and random, together with a discussion concerning the proper handling of each. The sources of possible errors are provided to all of which must be considered to ensure that all uncertainties are included. Sources of numerical values of the several possible errors are given.

A mathematical model is developed by which the numerical values of the measurement errors are combined to give the overall error in the desired parameter. An example calculation using the model is given.

A background section on statistics is provided giving the underlying basis for the model and the statistical implications of the results.

to be of little use because in the field different electrical leads or different lengths of electrical leads were used, and the system did not perform as expected. When possible, instrument systems should be using the total system from sensing element to the final output as shown in the previous schematic.

- Drift data are usually obtained by prior experience, in observations of how the measurements of a particular sensor change over time. Instrument drift errors can be reduced through more frequent calibration of the instrumentation and crosschecks with comparable instrumentation. Drift over a specific time interval is obtained by noting the differences between the calibration at the start of the interval and the calibration at the end of the interval. Drift uncertainty is somewhat difficult to define since intermediate values of drift are rarely obtained for the time interval desired; the assumption that drift is a linear function of time is sometimes used, which may not necessarily be valid.

- The representativeness of the data is an area of uncertainty. In many cases, a local measurement of temperature, pressure, or flux is used to represent bulk properties associated with a volume or area that is much larger than that sensed by the sensing element. The degree of uncertainty in this case may be handled by theory or additional experimental data. An example of poor representativeness would be the use of a point temperature measurement in a thermally stratified fluid, without regard to the thermal stratification.

- Detailed design analysis can also provide input into an uncertainty analysis. The analysis can calculate the effects of the geometrical configurations used, sensing locations, size, and flow blockage introduced, as well as a host of other factors associated with the physical and electrical design of a sensing system and the system into which the sensing system is placed.

- The data spread about empirical curve fits of correlation data can be used to estimate the uncertainty of the empirical correlation value.

DEVELOPMENT OF THE UNCERTAINTY METHOD

The uncertainty of a quantity is the maximum reasonably expected departure of a measurement from the true value of the quantity. It is necessary to establish a permissible percentage of time during which this error can be exceeded. For instance, a 95% uncertainty analysis permits up to 5% of the values obtained to exceed the tolerance interval calculated from the uncertainty analysis.

The following discussion develops a systematic model for estimating the uncertainty of a result.

A result, e.g., mass flow rate or power, is a value which has been computed using an equation, the terms of which are variables, each with an uncertainty in its value. The following model examines how the uncertainties in the variable propagate into the uncertainty in the desired result.

The procedure for calculating the uncertainty in any result will consist of the following two steps:

1. Obtain an estimate of the uncertainty in each of the variables, e.g., temperature, pressure. These uncertainty estimates may be calculated using the following model or may simply come from vendor specifications or other sources of uncertainty data listed in the previous section.

2. Combine the uncertainties obtained for each of the variables according to the following model to obtain the total uncertainty in the result.

This analysis assumes that any vendor-supplied uncertainties have been evaluated and are valid.

MATHEMATICS OF THE MODEL

Generally, the desired result is a function of many variables (X_i), e.g., mass flow rate, power. That is,

$$\text{Result} = R = f(X_1, X_2, X_3 \ldots X_n)$$

The change in R resulting from changes in the variables (X_i's) would be

$$dR = \frac{\partial R}{\partial X_1} dX_1 + \frac{\partial R}{\partial X_2} dX_2 \ldots \frac{\partial R}{\partial X_n} dX_n \qquad (1)$$

Each variable X_1, X_2, $\ldots X_n$ can be either negative or positive. This may be handled statistically by averaging, <()>, the square of dR.

$$\langle (dR)^2 \rangle = \langle (\frac{\partial R}{\partial X_1} dX_1)^2 \rangle + \langle (\frac{\partial R}{\partial X_2} dX_2)^2 \rangle + \ldots \langle (\frac{\partial R}{\partial X_n} dX_n)^2 \rangle$$

$$+ 2 (\langle \frac{\partial R}{\partial X_1} \frac{\partial R}{\partial X_2} dX_1\, dX_2 \rangle + \ldots \langle \frac{\partial R}{\partial X_1} \frac{\partial R}{\partial X_n} dX_1\, dX_n \rangle + \ldots \langle \frac{\partial R}{\partial X_2} \frac{\partial R}{\partial X_3} dX_2\, dX_3 \rangle$$

$$+ \ldots \langle \frac{\partial R}{\partial X_{n-1}} \frac{\partial R}{\partial X_n} dX_{n-1}\, dX_n \rangle) \qquad (2)$$

For any two independent variables X_m and X_n, the cross product is zero:

$$\langle \frac{\partial R}{\partial X_m} \frac{\partial R}{\partial X_n} dX_m \, dX_n \rangle = 0.$$

That is, the cross-product terms involving independent variables in Eq. (2) are equal to zero and may be deleted from the equation. For those variables that are dependent (correlated) the cross-product terms remain. For these dependent variables, Schwarz's inequality (Parzen 1960) shows that

$$\langle \frac{\partial R}{\partial X_i} \frac{\partial R}{\partial X_j} dX_i \, dX_j \rangle < \left|\frac{\partial R}{\partial X_i}\right| \left|\frac{\partial R}{\partial X_j}\right| \sigma_{X_i} \sigma_{X_j} \tag{3}$$

where σ_{X_i} and σ_{X_j} are the square root of the variances of X_i and X_j, e.g.,

$$\sigma_{X_i} = (\sigma_{X_i}{}^2)^{1/2} = (\langle (dX_i)^2 \rangle)^{1/2}$$

The term σ_{X_i} is sometimes referred to as the RMS (Root Mean Square) value of X_i or the standard deviation of X_i; in either case, it is the square root of the variance of X_i about X_i's mean.

Using Eq. (3) in Eq. (2) results in

$$\langle (dR)^2 \rangle = \sigma_R{}^2 < \left(\frac{\partial R}{\partial X_1}\right)^2 \sigma_{X_1}{}^2 + \left(\frac{\partial R}{\partial X_2}\right)^2 \sigma_{X_2}{}^2 + \ldots$$

$$+ 2 \left(\left|\frac{\partial R}{\partial X_j}\right| \left|\frac{\partial R}{\partial X_k}\right| \sigma_{X_j} \sigma_{X_k} + \left|\frac{\partial R}{\partial X_\ell}\right| \left|\frac{\partial R}{\partial X_m}\right| \sigma_{X_\ell} \sigma_{X_m} + \ldots \right) \tag{4}$$

where the cross products subscripted with a letter are the cross products of dependent terms.

If all the variables were independent, all the cross-product terms would be zero, and the variance of the result, $\sigma_R{}^2$, would simply equal the sum of the variable variances times their respective coefficients. Or:

$$\sigma_R{}^2 = \left(\frac{\partial R}{\partial X_1}\right)^2 \sigma_{X_1}{}^2 + \left(\frac{\partial R}{\partial X_2}\right)^2 \sigma_{X_2}{}^2 + \ldots \left(\frac{\partial R}{\partial X_n}\right)^2 \sigma_{X_n}{}^2 \text{ (for independent variables)} \tag{5}$$

Where some of the variables are dependent, Eq. (4) may be written:

$$\sigma_R^2 < \left(\frac{\partial R}{\partial X_1}\right)^2 \sigma_{X_1}^2 + \left(\frac{\partial R}{\partial X_2}\right) \sigma_{X_2}^2 + \ldots + \left[\left|\frac{\partial R}{\partial X_i}\right| \sigma_{X_i} + \left|\frac{\partial R}{\partial X_j}\right| \sigma_{X_j} + \left|\frac{\partial R}{\partial X_k}\right| \sigma_{X_k} + \ldots\right]^2$$

$$+ \left[\left|\frac{\partial R}{\partial X_m}\right| \sigma_{X_m} + \left|\frac{\partial R}{\partial X_n}\right| \sigma_{X_n} + \ldots\right]^2 \ldots \text{(for independent and dependent variables)} \tag{6}$$

where the terms subscripted by integers are independent, those subscripted by i, j, k ... are dependent one to another, and those subscripted by n, m, ... are dependent one to another. Eq. (6) provides a conservative estimate of the value of the variance of the result: that is, Eq. (6) will give a value which exceeds or equals the expected variance of the result. The RMS value of the result is simply the square root of the variance or

$$\sigma_R = (\sigma_R^2)^{1/2} < [\text{right side of Eq. (6)}]^{1/2} \tag{7}$$

The uncertainty in R may now be expressed in terms of the uncertainty of each of the variables. For instance, both sides of the equation could be multiplied by 2, giving us a value of $2\sigma_R$. Assuming that R is normally distributed,[a] a $2\sigma_R$ value infers that the probability is greater than 95% that the actual value of R lies between the measured value of $R + 2\,\sigma_R$ and $R - 2\,\sigma_R$.

Many times uncertainty is written as a ratio of the uncertainty, U_R, of the result to the value of the result, R. That is, from Eq. (7)

$$\frac{U_R}{R} < \left(\left(\frac{\partial R}{\partial X_1}\right)^2 \left(\frac{U_{X_1}}{R}\right)^2 + \left(\frac{\partial R}{\partial X_2}\right)^2 \left(\frac{U_{X_2}}{R}\right)^2 + \ldots \left[\left|\frac{\partial R}{\partial X_i}\right| \frac{U_{X_i}}{R} + \ldots\right]^2\right)^{1/2} \tag{8}$$

where U_{X_i} is the uncertainty in the variable X_i and where the numerical subscripts denote independent variables and letter subscripts denote dependent variables. Unless otherwise specified, it is assumed that U_{X_i} is equal to $2\sigma_{X_i}$.

(a) By the central limit theorem, the more variables R is a function of, the more assured we are that R is normally distributed. Also, if each of the variables were normally distributed, R would be normally distributed. If some of the variables were normally distributed and some uniformly distributed or if all were uniformly distributed, the assumption of normality of R would be conservative for the uncertainty analysis.

Many times when differentiation is difficult it is more convenient to numerically calculate the sensitivity coefficient, $\partial R/\partial X_i$, by calculating $R+\Delta R$ from an equation using $X_i + \Delta X_i$, and using the ratio $\Delta R/\Delta X_i$ in lieu of $\partial R/\partial X_i$. One must be cautious, however, to keep ΔX_i small so that $\Delta R/\Delta X_i$ represents the local slope of a curve relating R and X_i.

Eq. (8) may also be written

$$\frac{U_R}{R} < \left\{\left(\frac{\partial(\ln R)}{\partial(\ln X_1)}\frac{U_{X_1}}{X_1}\right)^2 + \left(\frac{\partial(\ln R)}{\partial(\ln X_2)}\frac{U_{X_2}}{X_2}\right)^2 + \ldots + \left[\left|\frac{\partial(\ln R)}{\partial(\ln X_i)}\right|\frac{U_{X_i}}{X_i} + \ldots\right]^2\right\}^{1/2} \quad (9)$$

Some experimentalists prefer the form of Eq. (9) because the coefficients in front of each variable uncertainty are a measure of the percentage of the amount that the result would vary for a 1% change in the uncertainty of the variable. This is sometimes useful in determining which variables cause the largest uncertainties in the result.

At this point, a value for the uncertainty of a result has been determined. If conservatism has been built into obtaining this result, such as some of the variables being dependent, having uniform density distributions, or simply that conservative estimates in the uncertainties of the variables were used, no further computation may be warranted. However, one may wish to impose a confidence limit on the uncertainty value obtained. For instance, if the uncertainty analysis were performed for the $\pm 2\sigma$ value of the result, i.e., 95% tolerance interval, one may also wish to be 95% confident that this tolerance will not be exceeded. To evaluate this confidence limit, one should use the statistics associated with the noncentral t-distribution.

It should also be noted that the analysis developed in this report assumes that the uncertainties associated with each variable act over a region which can be considered linear. If extremely large uncertainties are expected and they occur over strongly nonlinear calibration regions, then a Taylor series expansion using higher-order terms may be warranted (Golden 1982). It should also be noted that the model presented is consistent with the International Organization for Standardization Committee (1981), Kline (1953), and with NUREG/CR-2459, except that the model presented addresses the issue of dependent variables. The model presented uses a conservative form for evaluating the uncertainties associated with dependent variables. A less restrictive model should be used only if the joint frequency distribution of dependent variables is known, for which case Eq. (2) could be used directly.

Further, note that the uncertainty of a variable, e.g., temperature, can be reduced by a factor of $1/\sqrt{n}$ when taking the average of readings from n independent sensors.

An example of this would be using the mean value of temperature obtained by averaging the temperature obtained from n similar independent sensors.

$$T_{ave} = \frac{T_1 + T_1 + T_3 + \ldots T_n}{n} \tag{10}$$

From Eq. (5) the uncertainty in T_{ave}, $U_{T_{ave}}$ would be

$$U_{T_{ave}} = \left(\left(\frac{\partial T_{ave}}{\partial T_1}\right)^2 U_{T_1}{}^2 + \ldots \left(\frac{\partial T_{ave}}{\partial T_n}\right)^2 U_{T_n}{}^2 \right)^{1/2} = \frac{1}{n}\left(U_{T_1}{}^2 + U_{T_2}{}^2 + \ldots U_{T_n}{}^2\right)^{1/2} \tag{11}$$

Since the uncertainty of each similar temperature sensor would be the same, the uncertainty in the average temperature value would be

$$U_{T_{ave}} = \frac{1}{n}\sqrt{n}\, U_{T_1} = \frac{U_{T_1}}{\sqrt{n}}$$

Where U_{T_1} is the uncertainty associated with any one of the similar temperature sensors.

Summary of the Uncertainty Method

The uncertainty of a result, such as flow rate, may be computed by:

1. estimating the uncertainty of each variable
2. computing the uncertainty of the result from the equation that relates the variables to the result and using the relations given by Eq. (7), Eq. (8), or Eq. (9).

Estimating the uncertainties in the variables may itself require an uncertainty analysis. That is, the variables may be functions of other parameters; for example enthalpy, which is a variable used in computing power absorbed in a steam generator, is a function of temperature and pressure. In this case, an uncertainty analysis on the variable, enthalpy, is required to obtain the variable's uncertainty to be used in the uncertainty analysis of the final result--power transferred in a steam generator of a PWR.

Note that the equations formulated for adding variances to obtain the variance of the result are conservative when any of the variables are uniformly distributed. Also conservative is the practice of summing the RMS values of dependent variables and then squaring this sum to add to the variances of the independent variables.

Representative lists of variables that should be considered are given in Appendix E.

Example of the Uncertainty Method

Suppose that the uncertainty in the value of the power transferred in a steam generator is desired. For this case the following equation relates power (P_A), to the inlet enthalpy (h_i), outlet enthalpy (h_o), and the mass flow rate through the steam generator ($\dot{m}$), and the system losses (Q_L).

$$P_A = (h_o - h_i)\dot{m} + Q_L \qquad (13)$$

The numerical values in the example are deliberately chosen to represent no particular nuclear reactor or operating condition.

The first step in assessing the uncertainty in P_A is to determine the 2σ uncertainty in h_o, h_i, $\dot{m}$, and Q_L. For 100% power the nominal conditions are assumed to be

$\dot{m} = 15\text{x}10^6$ lbm/hr,	$Q_L = 2\text{x}10^6$ Btu/hr
$P_i = 830$ psi,	$P_o = 830$ psi,
$T_i = 434°F$,	$T_o = 522.5°F$
$h_i = 413$ Btu/lbm,	$h_o = 1195$ Btu/lbm

$P_A = (h_o - h_i)\,\dot{m} + Q_L = 1.1732\text{x}10^{10}$ Btu/hr.

DETERMINING THE 2σ UNCERTAINTIES OF THE VARIABLES

The value of h_i is a function of temperature, T, pressure, P, and the accuracy of the steam table interpolation, I. All parameters may be considered independent and thus Eq. (6) may be used, yielding:

$$\sigma_{h_i} = [(\frac{\partial h_i}{\partial T})^2 \sigma_T{}^2 + (\frac{\partial h_i}{\partial P})^2 \sigma_P^2 + (\frac{\partial h_i}{\partial I_o})^2 \sigma_{I_o}{}^2]^{1/2}$$

or

$$\sigma_{h_i} = [(\frac{\Delta h_i}{\Delta T})^2 \sigma_T{}^2 + (\frac{\Delta h_i}{\Delta P})^2 \sigma_P{}^2 + (\frac{\Delta h_i}{\Delta I_o})^2 \sigma_{I_o}{}^2]^{1/2} \qquad (14)$$