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BOUNDING UNCERTAINTY ANALYSIS FOR THERMAL POWER DETERMINATION AT INDIAN POINT UNIT 2 NUCLEAR POWER STATION USING THE LEFM✓ SYSTEM

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NON-PROPRIETARY VERSION

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1.0 INTRODUCTION

The LEFM✓ is an advanced ultrasonic system that accurately determines the mass flow and temperature of feedwater in nuclear power plants. Using feedwater pressure signal input to the LEFM✓; its mass flow and temperature outputs are used along with other plant data to compute reactor core thermal power. The technology underlying the LEFM✓ ultrasonic instruments and the factors affecting their performance are described in a topical report, Reference 1, and a supplement to this topical report, Reference 2. The exact amount of the uprate allowable under a recent revision to 10CFR50 Appendix K depends not only on the accuracy of the LEFM✓ output but also on the uncertainties in other inputs to the thermal power calculation.

It is the purpose of this document to provide an analysis of the uncertainty contribution of the LEFM✓ System in its normal operation to the overall thermal power uncertainty of Indian Point Unit 2 Nuclear Power Station. The total uncertainty contribution is documented in the Interface and Reconciliation document (included with this document as Appendix C) as the term AB. This uncertainty is the aggregate power uncertainty due to the feedwater flow, temperature and pressure measurements.

The uncertainties in mass flow and feedwater temperature are also provided. If desired, these data may be used in the calculation of the overall thermal power uncertainty. If this method is used, a special procedure is required for combining the mass flow uncertainty and the uncertainty in feedwater enthalpy due to temperature. The procedure is necessary because some elements of the temperature uncertainty are systematically related to elements of the mass flow uncertainty and others are not. For plants that require the LEFM✓'s contribution to plant thermal power uncertainty be presented in just the feedwater temperature and mass flow terms, a systematic and random temperature calculation of feedwater temperature uncertainty is also provided.

Finally, this report utilizes actual dimensions for the spool piece(s), as well as system measurements for full power mass flow, final feedwater temperature and steam conditions. Bounding values for the uncertainties in length measurements, time measurements and calibration coefficient (profile factor) are employed. The commissioning tests for the LEFM✓, performed following its installation in the plant, confirmed that in fact, the time measurement uncertainties are within the bounding values used in the analysis.

2.0 SUMMARY

For the Indian Point Unit 2 Nuclear Power Station, Revision 1 results are as follows:

1. The mass flow uncertainty approach is documented in Reference 3. The uncertainty in the LEFM✓'s mass flow of feedwater is as follows:
    - LEFM✓ system mass flow uncertainty is [ ].
2. The uncertainty in the LEFM✓ feedwater temperature is as follows:
    - LEFM✓ system temperature uncertainty is [ ]
3. The thermal power uncertainty approach is documented in Reference 3. The uncertainty in the LEFM✓'s thermal power of feedwater is as follows:
    - LEFM✓ system thermal power uncertainty is [ ].

    Note: Because some elements of the temperature uncertainty are systematic, the total power uncertainty due to the LEFM✓ is *not* the root sum squares of the uncertainties due to items 1 and 2 above.
4. For an overall thermal power uncertainty analysis in which mass flow and temperature errors are to be treated separately (i.e., the thermal power uncertainty above is not used), the bounding mass flow and temperature errors must be [

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3.0 APPROACH

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4.0 OVERVIEW

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Appendix A.1, LEFM✓ Inputs

- - - This Appendix is Proprietary in its Entirety - - -

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Appendix A.2, LEFM✓ Mass Flow and Temperature Uncertainties

- - - This Appendix is Proprietary in its Entirety - - -

This appendix calculates the uncertainties in mass flow and temperature as computed by the LEFM✓ using the methodology described in Appendix E of Reference 1 and Appendix A of Reference 3[1], with uncertainties in the elements of these measurements bounded as described in both references[2]. [

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This appendix utilizes the results of the spool piece calibration test and analysis for the uncertainty in the profile factor (calibration coefficient). The engineering calculation for the spool piece calibration test is referenced in Appendix A.3 of this report.

Appendix A.3, Profile Factor (Calibration and Analysis) Uncertainties

As noted above, the calibration test report and analysis for the spool piece(s) establishes the overall uncertainty in the profile factor of the LEFM✓. [

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[1] Reference 3 (ER 157P) develops the uncertainties for the LEFM ✓ system. Because this system uses two measurement planes, the structure of its uncertainties differs somewhat that of an LEFM✓.

[2] [

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Appendix A.4, Uncertainties in the Measurement of Time Differences (Δt's)

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Appendix A.5, Uncertainties in the Measurement of Transit Times (t's)

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Appendix A.6, Systematic and Random Temperature Uncertainties

This appendix calculates the systematic and random temperature uncertainties as related to mass flow. This appendix considers that the LEFM✓ temperature errors are systematic when used to compute enthalpy as well as density. It is understood that most nuclear power plant thermal power uncertainty analysis do not have the term AB, the total thermal power uncertainty due to the LEFM✓ that is defined as term AB and described in Appendix C. Therefore, Appendix A.6 computes the random and systematic feedwater temperature uncertainty in order to facilitate the nuclear power plants uncertainty analysis.

Appendix B, Total Thermal Power Uncertainty due to the LEFM✓

The total thermal power uncertainty due to the LEFM✓ is calculated in this appendix, [

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Appendix C, Interface and Reconciliation Document

For completeness, an Interface and Reconciliation Document for this project is included as Appendix C. An interface and reconciliation document is provided to each LEFM✓ and LEFM✓ customer. This document breaks down the uncertainties that Caldon will calculate and justify for a specific uprate project, as well as those outside Caldon's scope. It provides a set of uncertainties for use by the customer or the customer's agent in establishing the amount of the power uprate. Appendix C also reconciles the results of this analysis with the uncertainties calculated in the Topical Report and its supplements (References 1, 2, and 3).

5.0 REFERENCES

1) Caldon Topical Report ER-80P, "Improving Thermal Power Accuracy and Plant Safety While Increasing Operating Power Level Using the LEFM Check System", Rev. 0.

2) Caldon Engineering Report ER-160P, "Supplement to Topical Report ER 80P: Basis for a Power Uprate with the LEFM System", May 2000

3) Caldon Engineering Report ER-157, "Supplement to Caldon Topical Report ER-80P: Basis for Power Uprates with an LEFM Check or an LEFM CheckPlus", dated October 2001, Revision 5

4) ASME PTC 19.1-1985, Measurement Uncertainty

5) ISA-RP67.04.02-2000, Methodologies for the Determination of Set Points for Nuclear Safety-Related Instrumentation

6) MPR Engineering Report MPR-1614 Rev. 0 "Feedwater Flow Measurement with LEFM Chordal Systems at Indian Point Unit 2 Configuration and Uncertainty Analysis", dated October 1995

7) Alden Research Laboratory Report No. 106-79/C91, "Calibration Report of Indian Point 2 18" Ultrasonic Flowmeters Serial Nos. WMP No. 2 & 3."

Appendix A

Appendix A.1, - - - Proprietary to Caldon in its Entirety - - -

Appendix A.2, - - - Proprietary to Caldon in its Entirety - - -

Appendix A.3, Profile Factor (Calibration) Uncertainties

Appendix A.4, - - - Proprietary to Caldon in its Entirety - - -

Appendix A.5, - - - Proprietary to Caldon in its Entirety - - -

Appendix A.6, - - - Proprietary to Caldon in its Entirety - - -

Appendix A.1 is Proprietary to Caldon in its Entirety

Appendix A.2 is Proprietary to Caldon in its Entirety

Appendix A.3
LEFM✓ Spool Piece(s) Profile Factor and Profile Factor Uncertainty

Refer to:

1. MPR-1614 Rev. 0, Proprietary to Caldon

2. Alden Research Laboratory Report No. 106-79/C91, "Calibration Report of Indian Point 2 18" Ultrasonic Flow Meters Serial Nos. WMP No. 2 & 3."

Appendix A.4 is Proprietary to Caldon in its Entirety

Appendix A.5 Proprietary to Caldon in its Entirety

Appendix A.6 Proprietary to Caldon in its Entirety

Appendix B Proprietary to Caldon in its Entirety

Appendix C
LEFM✓ + Interface and Reconciliation Documents, Calorimetric Uncertainties with the LEFM✓ and LEFM✓ +

LEFM Interface and Reconciliation Document
Calorimetric Uncertainties with the LEFM✓ and LEFM✓+
Indian Point 2

I. Purpose

It is the purpose of this document to define precisely the uncertainties that Caldon will calculate and justify for a specific Appendix K uprate project. The uncertainties that are outside Caldon's scope are also defined, as well as the method for combining all uncertainties to obtain a power uncertainty. This document also breaks down the relationship between the uncertainties tabulated in Caldon reports covering the operation of the LEFM✓ and LEFM✓+ instruments and the data that Caldon will provide for a specific uprate project.

II. Background

Reports covering the operation of the LEFM✓ and LEFM✓+ instruments describe how the use of these instruments reduces the uncertainties in feedwater mass flow and feedwater enthalpy.[1] In combination with the uncertainties in the determination of other variables (steam enthalpy, for example), the uncertainties in feedwater mass flow and enthalpy establish the uncertainty in the core thermal power. The amount of a power increase allowable under an Appendix K uprate is directly dependent on achieving a thermal power uncertainty within bounds defined by the reports cited above.

The uncertainty in the mass flow, which is measured by an LEFM✓ (LEFM✓+), and the uncertainty in the feedwater enthalpy, which is derived from the LEFM✓'s temperature and pressure outputs, are made up of several elements. These elements relate to the LEFM✓+'s measurements of time, to its dimensions, to the hydraulics of the installation and to correlations relating fluid temperature and density to sound velocity and pressure. With respect to the correlations and the measurements of time and dimensions, some of the uncertainties in mass flow are systematically related to the uncertainties in feedwater enthalpy while others are not. The structure and combination methods for power uncertainties are described in Section III below.

III. Structure of the Thermal Power Uncertainties

The core thermal power as determined by a heat balance around the steam supply is given by:

(1) $Q_{RX} = W_{FW} (h_S - h_{FW}) + Q_{LOSS\ NET}$

Where Q_{RX} is the core thermal power

W_{FW} is the mass flow rate of the feed to the steam supply, the product of feedwater volumetric flow rate and feedwater density,

[1] Caldon Engineering Reports ER-80P, ER-160P and ER-157P

h_S is the enthalpy of the steam delivered by the steam supply, a function of its pressure and moisture content for saturated steam supplies and its pressure and temperature for superheated steam supplies,
h_{FW} is the enthalpy of the feedwater, a function of its temperature and pressure, and
$Q_{LOSS\ NET}$ is the net loss or gain in power from coolant pump heating, blowdown and/or reactor water purification, component cooling, convective and radiant losses, etc.

The contributing uncertainties to the thermal power computation are defined by differentiating equation (1):

(2) $$dQ_{RX} = dW_{FW} (h_S - h_{FW}) + W_{FW}\, dh_S - W_{FW}\, dh_{FW} + dQ_{LOSS\ NET}$$

The contributors can be expressed per unit by dividing equation (2) by Q_{RX}.

(3) $$dQ_{RX}/Q_{RX} = dW_{FW}/W_{FW} [1 - (Q_{LOSS\ NET}/Q_{RX})] + [dh_S/ (h_S - h_{FW})] [1 - (Q_{LOSS\ NET}/Q_{RX})] - [dh_{FW} / (h_S - h_{FW})] [1 - (Q_{LOSS\ NET}/Q_{RX})] + dQ_{LOSS\ NET}/ Q_{RX}$$

Since the net gains and losses term is typically less than 1% of the reactor thermal power, the term $[1 - (Q_{LOSS\ NET}/Q_{RX})]$ may be taken as approximately 1.0. Hence,

(4) $$dQ_{RX}/Q_{RX} = dW_{FW}/W_{FW} + [dh_S/ (h_S - h_{FW})] - [dh_{FW}/ (h_S - h_{FW})] + dQ_{LOSS\ NET}/ Q_{RX}$$

It should be pointed out that equation (4) applies algebraically only if all error contributors are systematically related to each other. Most of these components are *not* systematically related. If all of the components were random errors or biases the power uncertainty of equation (4) would be the square root of the sum of the squares of the individual terms on the right hand side of the equation. In fact, a combination of the two procedures is appropriate as described below.

The feedwater enthalpy is a function of its temperature and pressure. Likewise, the density of the feedwater, which the LEFM✓ (LEFM✓+) combines with volumetric flow to compute mass flow, is also a function of temperature and pressure. Because of this and other factors, certain elements of the uncertainty in feedwater enthalpy are combined systematically with the mass flow uncertainty, while other elements, unrelated to the mass flow measurement, are combined randomly. For convenience in defining the combination of terms, the feedwater enthalpy will be related to its temperature and pressure by the following:

(5) $$h_{FW} = \delta h/\delta p\,|_T (p_{FW} - p_0) + \delta h/\delta T\,|_p (T_{FW} - T_0) + h_0$$

The computation of feedwater enthalpy from temperature and pressure by the plant computer—part of the thermal power computation—may be carried out by a more complex algorithm than that of equation (5), or the enthalpy may be determined from a look up table. Equation (5) is used here simply as a convenience for developing the elements of the error contributors to feedwater enthalpy. Using equation (5), the uncertainty in feedwater enthalpy is:

(6) $$dh_{FW} = \delta h/\delta p\,|_T\, dp_{FW} + \delta h/\delta T\,|_p\, dT_{FW} + dh_0$$

Here dh_0 represents the potential bias in the enthalpy algorithm of the plant computer.

Rewriting equation (4) to incorporate equation (6), and rearranging terms:

(7) $$dQ_{RX}/Q_{RX} = \underbrace{\{dW_{FW}/W_{FW}\}}_{A} - \underbrace{\{[1/(h_S - h_{FW})]\,[\delta h/\delta p\,|_T\, dp_{FW} + \delta h/\delta T\,|_p\, dT_{FW}]\}}_{B}$$

$$+ \underbrace{\{[1/(h_S - h_{FW})]\, dh_0\}}_{C} + \underbrace{\{[1/(h_S - h_{FW})]\, dh_S\}}_{D} + \underbrace{\{dQ_{LOSS\ NET}/Q_{RX}\}}_{E}$$

In the determination of overall thermal power uncertainty, terms **A** and **B** will be provided by Caldon, based in part on the uncertainty in the analog feedwater pressure signal provided to the LEFM✓ (LEFM✓+) by the utility. Unless otherwise specified, this pressure will be assumed to represent the feedwater pressure at the LEFM✓ spool piece(s) within ± 11 psi (two standard deviations or 95% confidence limits). The utility will be expected to certify the accuracy of the feedwater pressure input to the LEFM✓. To ensure that terms **A** and **B** are computed on the correct bases, the utility will also provide Caldon with thermodynamic data characterizing the operation of the nuclear steam supply at full power, pre-uprate. These data include: mass flow, final feedwater temperature and pressure, and steam enthalpy.

Terms **C**, **D**, and **E** are outside of Caldon's scope, are based on other plant instruments, and are to be provided by others.

Caldon will provide a single uncertainty, **AB**, expressed as a percentage of the rated thermal power, that encompasses terms **A** and **B**. They will also provide the thermodynamic coefficients (e.g., the elements of term **B**) used to compute terms **A** and **B** for the utility's review and records. Under normal circumstances, there will not be a systematic relationship between term **AB**, on the one hand, and terms **C**, **D**, and **E**, on the other. Likewise, there will normally not be systematic relationships among terms **C**, **D**, and **E**. Therefore, the utility will normally compute the total thermal power uncertainty from the following.

(8) $$dQ_{RX}/Q_{RX} = [(AB)^2 + (C)^2 + (D)^2 + (E)^2]^{1/2}$$

IV. Reconciliation of Uncertainties with the Uncertainties Quoted in Caldon Engineering Reports

Table 1 below compares the site-specific bounding uncertainties for Indian Point 2 to the following Caldon Engineering Reports:

- ER-80P, Rev. 0 (1997), the original Caldon topical report that requested a 1% power uprate based on an accuracy of the LEFM✓ system bounded by ± 0.6% (two standard deviations) thermal power accuracy.
- ER-160P, Rev. 0, which presents instrument uncertainties identical to those in ER-80P. ER-160P recognizes that, in accordance with NRC Rulemaking in June 2000, a power uprate up to and including 1.4% power can be requested for the LEFM✓ (LEFM✓ +) System (since ER-80P demonstrates that its accuracy supports a thermal power uncertainty of ± 0.6%).
- ER-157P, Rev. 5, which describes Caldon's next generation LEFM✓ +. ER-157P revises the uncertainty analyses of ER-80P to reflect actual LEFM✓ data as applied to a typical single flow measurement application. ER-157P demonstrates that the LEFM✓ + can support power uncertainties as small as ± 0.3%. It also shows that the LEFM✓ system can achieve power uncertainties as low as ± 0.5% thermal power accuracy.

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