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BEACON™

Core Monitoring and Operation Support System, Addendum 4

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BEACON^{TM}

Core Monitoring and Operation Support System, Addendum 4

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1.0 Introduction and Purpose

Westinghouse has developed an improved analysis process for evaluating thermocouple behavior and uncertainties for the BEACON™[1] core monitoring system. The new method is based on the original generic methodology, but uses plant/cycle specific thermocouple data in the evaluation. The BEACON core monitoring system has been in use for over 20 years by Westinghouse, and is well known to the USNRC.

The Best Estimate Analyzer for Core Operation – Nuclear (BEACON™) system[(1)] was developed to improve the operational support for pressurized water reactors. It is an advanced core monitoring and support package which uses current instrumentation in conjunction with a fully analytical methodology for an on-line generation of 3D power distributions. The system provides core monitoring of the power limits delineated in the Technical Specifications, core measurement reduction, core follow, core analysis and core predictions. The methodology for calculating and applying measurement uncertainties was reviewed and approved by the USNRC in the BEACON topical report[(1)].

The updated thermocouple uncertainty evaluation method presented in this report is based on the licensed methodology in the BEACON topical report but uses the current plant/cycle data in the evaluation process to generate cycle specific uncertainty constants. There are no new methods being developed for the BEACON system; this update is a change in the application of the approved method. This uncertainty methodology is only applied to plants with movable incore detectors that are using thermocouples to determine the measured power distribution as described in WCAP-12472-P-A.

The purpose of this BEACON topical report addendum is the following:

a) Provide the information needed to review and approve the updated thermocouple uncertainty analysis process that will be applied in the BEACON on-line core monitoring system. The uncertainty methodology for BEACON was previously documented and approved. This report will reference the previously approved document and in many cases the referenced information is reproduced in this report to provide detail for convenience of review.

b) Affirm the continued use of the USNRC approved Westinghouse design model methodology, currently PHOENIX-P/ANC, PARAGON/ANC and NEXUS/ANC, in the BEACON system. This methodology can be updated in the future without making a separate BEACON addendum.

In 2000, the BEACON system was approved to use the PHOENIX-P/ANC code system in Addendum 1 to the BEACON topical report[2]. In 2004, the PARAGON code was approved in the PARAGON topical report[3] and was considered by the USNRC to be a replacement for the PHOENIX-P code. Most recently, in February 2007, the NEXUS/ANC code system was approved in Addendum 1 to the PARAGON topical report[4] and is considered to be a replacement for the PARAGON/ANC code system.

c) Establish that the uncertainties applied to power distribution monitoring using fixed incore self-powered detectors continue to be valid using higher order polynomial fits of the detector measurement variability and the fraction of inoperable detectors.

   The uncertainty methodology is implemented such that the polynomials can have more terms than those defined in equations (3) and (4) of Addendum 1[2], as described and shown for equations (7) and (8) of Addendum 3[5], for improved fitting results depending on the shape and data range needed to bound the uncertainties.

Section 2 will provide background information on the licensing and operational status of the BEACON system. Section 3 will review the BEACON systems basic core monitoring methodology. Section 4 will present the updated thermocouple uncertainty analysis process and the impact on the uncertainty results. Section 5 will provide information on the plant specific Technical Specification changes needed to implement the updated uncertainty process. Section 6 will discuss the plant specific application requirements for using the updated uncertainty process in the BEACON system.

2.0 Background

A topical report on the "BEACON™ Core Monitoring and Operations Support System," was submitted to the USNRC in April 1990 and was approved in February 1994[1]. The key aspects of the report are: 1) the methodology used to obtain the measured power distribution from the Westinghouse standard instrumentation system, i.e., the movable incore detectors, core exit thermocouples and excore detectors, and 2) the methodology for assessing uncertainties to be applied to the measured power distribution and Technical Specifications with the BEACON system as the source of the measured power distribution.

An addendum to the topical report was submitted to the USNRC in May 1996 and was approved in September 1999[2]. The key aspects of this addendum are: 1) the new optional methodology in BEACON to predict the Rhodium self-powered neutron detector (SPD) responses, 2) the methodology to assess uncertainties to be applied to the measured power distribution and Technical Specifications for SPD plants using BEACON as the source of the measured power distribution, and 3) the use of the PHOENIX-P/ANC methodology including cross-section generation, NEM solution technique, and pin power reconstruction for the 3D nodal solution.

A second addendum to the topical report was submitted to the USNRC in March 2001 and was approved in February 2002[6]. The key aspect of this addendum is the new optional methodology in BEACON to predict Platinum or Vanadium SPD responses for application in obtaining the measured power distribution for SPD plants using BEACON as the source of measured power distribution.

A third addendum to the topical report was submitted to the USNRC in October 2004 and was approved in November 2005[5]. The key aspects of this addendum are: 1) the new optional BEACON-COLSS product level for monitoring the PWR core conditions, 2) a new methodology to assess uncertainties to be applied to the measured power distribution for SPD plants using BEACON-COLSS as the source of the measured power distribution, and 3) the use of the CETOP-D code as a DNBR calculator in the BEACON system.

The BEACON system is in operation at approximately 60 plants around the world with movable and fixed incore detector designs. There are 27 plants in the US using the BEACON system of which 15 have licensed BEACON for on-line monitoring of the Technical Specification LCOs.

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3.0 BEACON Monitoring Methodology

The BEACON system has the capability of inferring the measured core power distribution with the methods defined in Section 3.4 of WCAP-12472-P-A. The BEACON core monitoring power distribution methodology with movable incore detectors consists of three distinct steps. A summary of these steps is provided below.

Step 1: Calibration Factor Update by Incore Flux Map

The incore maps are used to determine calibration factors for the nodal code, thermocouples, and the excore detectors. The calibration factor associated with the nodal code is defined as the ratio of the measured to predicted reaction rate in the incore detector. The best estimate power distribution is obtained by multiplying the predicted power distribution by the model calibration factors. These calibration factors are extended to the non-instrumented assemblies using a surface spline fit method.

The thermocouple calibration factors (mixing factors) are defined as the ratio of the best estimate power to the relative enthalpy rise measured by the assembly outlet temperature.

The excore detector calibration factors are defined to relate the axial offset and power level of the assemblies near the excore detectors to the excore detector readings. The best estimate core axial behavior is obtained from the calibrated nodal code calculation.

Step 2: Nodal Model Update

The 3D nodal model is updated frequently by following the core operation history. The model is adjusted to reproduce the axial offset measured at this condition. The model calibration factors determined in Step 1 are then applied to the calculated 3D power distribution. The radial power distribution is further corrected by core exit thermocouple measurement. The corrections are extended to non-instrumented assemblies, again using the surface spline fit. This correction is necessary because the real reactor condition may or may not be the same as the input reactor condition to the calculational model. This power distribution will serve as a reference for the frequent power distribution updating in Step 3.

Step 3: Power Distribution Update by Thermocouple and Excore Detector

The reference power distribution in Step 2 is adjusted to the current reactor condition as measured by the core exit thermocouples for the radial power distribution adjustment and excore detectors for the axial power distribution adjustment. The radial power distribution is adjusted such as to reproduce the assembly-wise enthalpy rise measured by the thermocouple, assuming the mixing factors retain their same values as under the Step 2 conditions. Again an interpolation process is used to determine the adjustment for the non-instrumented assemblies. The axial power distribution is adjusted by adding a sinusoidal harmonic term to preserve the axial offset measured by the excore detectors.

The power distribution monitoring process is depicted in Figure 1. In the BEACON system, the power distribution updating by thermocouples and excore detectors (Step 3) is performed on a continuous basis without any interruption. Generation of a new reference power distribution (Step 2) is performed as a parallel operation without hindering Step 3 operation. As soon as generation of the power shape of Step 2 is completed, the reference power distribution is replaced.

4.0 Thermocouple Uncertainty Methodology

4.1 Current Method

As mentioned above, a key component in the BEACON topical report is the methodology to apply uncertainties to the BEACON measured powers. The measured power uncertainty methodology for BEACON has been described in Section 5 of WCAP-12472-P-A for plants using movable incore detectors. A component of the measurement uncertainty is the variability of the thermocouple calibration factors (mixing factors). The components of the thermocouple mixing factor uncertainty are described in Section 4.3 of WCAP-12472-P-A and are summarized below.

The method for evaluation of the thermocouple calibration data accounts for the power dependence of the mixing factor standard deviation by accounting for two effects independently. These effects are: (1) the increased percentage of variability in the thermocouple measured power due to the decreased temperature difference at lower powers, and (2) the changes in the cross flow patterns as the power is reduced. This is generically expressed in equation 4-1 in Section 4.3.1 of WCAP-12472-P-A. Evaluation of the plant data documented in the WCAP-12472-P-A demonstrated that mixing factor variability is [ ] a, c. This relationship is quantified in equation 4-4 of WCAP-12472-P-A which is shown below.

[ ] a, c (1)

where:

$\sigma^{o}_{T/C}$ = average percentage deviation at HFP for the thermocouples

The [ ] a, c as discussed in Section 4.3.1 and in the response to the RAI question 26 in WCAP-12472-P-A.

The uncertainty methodology described in Section 4 of WCAP-12472-P-A is based on the average thermocouple deviation at HFP ($\sigma^{o}_{T/C}$), being determined from the past performance of the thermocouples. This approach results in some limitations in determining accurate thermocouple uncertainties. When evaluating thermocouple performance from the previous cycle, the typical changes to the hardware from a refueling outage to operate in the current cycle are not considered. These changes include disconnection of the thermocouple electrical connectors, possible repair or damage to the detectors, re-connection of the thermocouple electrical connectors - with the possibility of a loose connection or a cross connection. Any of these possibilities can lead to a change in the thermocouple response signal and statistical behavior which can cause inaccuracies in the BEACON on-line monitoring of the power distribution. While the overall behavior and characteristics of the thermocouple set would remain applicable, some individual thermocouples may have changed behavior.

The approval of WCAP-12472-P-A allowed plants using the BEACON system for on-line monitoring of LCOs to operate up to six months between taking a flux map for calibration. In this operating mode, the typical three or four flux maps taken per year would not provide enough data to determine an accurate HFP thermocouple deviation, consistent with the licensed methodology, for use in the uncertainty calculation. Even double this number would not be sufficient, as it would result in an overly conservative thermocouple standard deviation due to the small sample size.

These limitations in the current thermocouple evaluation process of using previous cycle behavior can require operable thermocouples to be removed from the core monitoring input data set because of changes in the signal characteristics caused during the refueling outage. This can potentially result in an inaccuracy or increase in the average thermocouple uncertainty deviation used to determine the measured power uncertainties.

4.2 Updated Method

To address these issues the updated thermocouple evaluation process uses thermocouple temperature and power data from the current cycle collected during the initial startup power ascension following the refueling. The analysis of the thermocouple mixing factors is performed as described in Section 4 of WCAP-12472-P-A. Any planned or unplanned changes to the characteristics of the thermocouple behavior are in place and measured during the initial power ascension. This process of using power dependent mixing factor data was discussed in Section 6.2.3 of WCAP-12472-P-A when evaluating the behavior of the thermocouple mixing factor standard deviation during a load follow maneuver and the results compared with equation 4-4.

By collecting and evaluating power dependent thermocouple mixing factor data from a long power ramp, the two effects of the power dependence on the mixing factor standard deviation are captured simultaneously in one function, eliminating the independent treatment. [

]$^{a, c}$.

The core average mixing factor standard deviation is the average value over all of the thermocouples at a given core power.

$$\left[\qquad \right]^{a,c} \qquad (2)$$

where:

[ ] a, c
[ ] a, c

This function represents the plant/cycle specific power dependent thermocouple deviation while equation (1) represents the plant specific HFP average thermocouple deviation with an independent, conservative power dependent cross flow deviation term added. Both of the thermocouple standard deviation functions (equations (1) and (2)) [ ] a, c and can provide the same behavior trends, which demonstrate that the components of the thermocouple mixing factor uncertainty described in Section 4.3 of WCAP-12472-P-A and generically expressed in equation 4-1 are also captured in the form of equation (2).

The uncertainty on radial assembly power is discussed in Section 5.3.4 of WCAP 12472-P-A and is calculated using equation 5-7 of WCAP 12472-P-A which includes the power dependent thermocouple deviation function defined in equation (1) as shown below.

$$\left[\qquad \right]^{a,c} \qquad (3)$$

In the updated thermocouple evaluation process, equation (2) is used in equation (3) instead of equation (1) and the radial assembly uncertainty function becomes:

$$\left[\qquad \right]^{a,c} \qquad (4)$$

where:

$\overline{\sigma_{T/C}(AP)}$ = the average thermocouple deviation as a function of assembly power at a given core power level.

In this form the radial assembly uncertainty is a function of the plant/cycle specific power dependent thermocouple deviation. At full power conditions the average thermocouple deviation ($\overline{\sigma_{T/C}(AP)}$) will be equal to the average deviation for the thermocouples ($\sigma^{o}_{T/C}$) if it were calculated from multiple flux maps near HFP conditions at the start of the current cycle. Hence, if assuming only full power conditions, equations (3) and (4) would be equivalent. At reduced power levels the trends of the thermocouple mixing factor standard deviations and the radial assembly uncertainties will be different [

]$^{a, c}$.

4.3 Application of Updated Method

The updated BEACON method of analyzing the thermocouple mixing factor data is unchanged from the licensed method in WCAP-12472-P-A. What has changed in the update is the use of current plant/cycle thermocouple data in the analysis to generate a plant/cycle specific power dependent thermocouple deviation function that replaces the function defined in equation 4-4 of WCAP-12472-P-A.

This change is implemented with the following process steps:

- [

  ]$^{a, c, f}$.
- [

  ]$^{a, c, f}$.
- [

  ]$^{a, c, f}$.
- [

  ]$^{a, c, f}$.

- [

]$^{a, c, f}$.

An example of the results from an on-line analysis is shown in Table 1 from Plant X. These results are from a Westinghouse 4 loop plant with 197 fuel assemblies and 57 thermocouples. The average thermocouple mixing factor standard deviation at HFP conditions was determined to be [ ]$^{a, c}$, indicating very good thermocouple behavior at full power conditions. The fitting coefficients determined for the thermocouple deviation function, equation (2), were determined to be [ ]$^{a, c}$.

Table 1 also provides a comparison of the thermocouple power dependent deviations and uncertainties using the original method of WCAP-12472-P-A and the updated method discussed above. Columns 2 and 3 of the table show the power dependent average thermocouple deviation results using equation (1) (equation 4-4 of WCAP-12472-P-A) with $\sigma^{o}_{T/C}$ = [ ]$^{a, c}$ and results from the analysis based on using equation (2) to determine the deviation for each thermocouple then averaging for the core value. The radial assembly uncertainty (U_{AS}) results from using equation (3) and using the updated equation (4) are also shown in the table in columns 5 and 6. The difference between the original method and the updated method for the average standard deviation and assembly uncertainty is shown in columns 4 and 7, respectively. As the core average power is [

]$^{a, c}$ for this particular plant and cycle.

A second example of results from an on-line analysis is shown in Table 2 for Plant Y, with greater variability in the thermocouple behavior. These results are from a Westinghouse 4 loop plant with 197 fuel assemblies with 65 thermocouples. The average thermocouple mixing factor standard deviation at HFP conditions was determined to be [ ]$^{a, c}$, indicating greater variability in the thermocouple behavior at full power conditions. The fitting coefficients determined for the thermocouple deviation function (equation (2)) were determined to be [ ]$^{a, c}$.

Table 2 also provides the same comparison of the thermocouple power dependent deviations and uncertainties using the original method of WCAP-12472-P-A and the updated method discussed above. Columns 2 and 3 of the table show the power dependent average thermocouple deviation results using equation (1) (equation 4-4 of WCAP-12472-P-A) with $\sigma^{o}_{T/C}$ = [ ]$^{a, c}$ and results from the analysis based on using equation (2) to determine the deviation for each thermocouple then averaging for the core value. The radial assembly uncertainty (U_{AS}) results from using equation (3) and using the updated equation (4) are also shown in the table in columns 5 and 6. The difference between the original method and the updated method for the average standard deviation and assembly uncertainty is shown in columns 4 and 7, respectively.

These results clearly show that the benefit from the updated analysis process is plant/cycle specific and can be relatively small depending on the cycle specific thermocouple behavior.

The total peaking factor uncertainty values resulting from using either equation (3) or (4) does not impact the reload safety analysis because valid ranges of the on-line surveillance uncertainties are considered in the plant specific safety analysis using approved methodologies.

5.0 Technical Specification Modifications

The updated thermocouple analysis process will not require any changes in the limits being monitored. Therefore there are no Technical Specification changes required for plants with the Westinghouse type movable incore detector system that are currently licensed to use the BEACON on-line monitoring system for surveillance of Technical Specification LCOs.

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6.0 Plant Specific Applications

The BEACON on-line thermocouple data analysis process is dependent on the BEACON system being operable with thermocouple data being supplied to the system from the plant computer during the initial startup power ascension. Plants that use the updated thermocouple evaluation process will activate the BEACON system data collection option typically before 25% power to collect data during the entire startup period up to approximately 100% power. The HFP flux map will be processed with the collected thermocouple data to generate fitting coefficients for the plant/cycle specific power dependent thermocouple deviation function.

During the initial startup before the new fitting coefficients are applied, the thermocouple deviation will be determined using equation (1) (equation 4-4 of WCAP-12472-P-A) with the default for $\sigma^{o}_{T/C}$ set to [ ]^{a,c} or a value determined from the previous cycle.

The plant/cycle specific application eliminates the need for the off-line analysis of previous cycle data for determination of thermocouple deviation behavior.

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7.0 Conclusion

Westinghouse has updated the thermocouple analysis process to collect and evaluate the thermocouple mixing factor standard deviation data during the cycle startup power ascension. Using this process eliminates the need to use previous cycle thermocouple data, which can be problematic due to insufficient data or changing thermocouple characteristics between refueling.

The updated method evaluates and combines the effects of the temperature dependent variability and the power dependent cross flow effect on the thermocouple into one function that replaces the overly conservative function defined in the original BEACON topical report, which treats these effects independently. This change results in a plant/cycle specific power dependent thermocouple deviation function that is applied in the uncertainties. The thermocouple deviation is unchanged at HFP conditions since the power dependence is removed at HFP conditions. The thermocouple deviation will typically be lower at reduced powers due to the analysis providing combined power dependent results that are plant/cycle specific. As a result, the updated method will result in more accurate and reliable thermocouple uncertainties.

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8.0 References

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3. Ouisloumen, K., et. al., "Qualification of the Two-Dimensional Transport Code PARAGON," WCAP-16045-P-A, March 2003.

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Table 1
Comparison of Thermocouple
Power Dependent Deviations and Uncertainties
(Plant X)

Core Rel Power	TC Average Std. Dev. % (1)	Updated TC Avg Std. Dev. % (2)	Std. Dev. Diff (1) - (2)	Assm Uncert U_{AS} % (3)	Updated Assm Uncert U_{AS} % (4)	U_{AS} Diff (3) - (4)
1						
0.9						
0.8						
0.7						
0.6						
0.5						
0.4						
0.3						

a, c

Measured thermocouple HFP mixing factor standard deviation = [ ]$^{a, c}$

1) From equation (1) (equation 4-4 of WCAP-12472-P-A)
2) From equation (2) using plant/cycle specific core power distribution
3) From equation (3) (equation 5-7 of WCAP-12472-P-A)
4) From equation (4)

Table 2
Comparison of Thermocouple
Power Dependent Deviations and Uncertainties
(Plant Y)

Core Rel Power	TC Average Std. Dev. % (1)	Updated TC Avg Std. Dev. % (2)	Std. Dev. Diff (1) - (2)	Assm Uncert U_{AS} % (3)	Updated Assm Uncert U_{AS} % (4)	U_{AS} Diff (3) - (4)
1						
0.9						
0.8						
0.7						
0.6						
0.5						
0.4						
0.3						

a, c

Measured thermocouple HFP mixing factor standard deviation = [ ] a, c

1) From equation (1) (equation 4-4 of WCAP-12472-P-A)
2) From equation (2) using plant/cycle specific core power distribution
3) From equation (3) (equation 5-7 of WCAP-12472-P-A)
4) From equation (4)

Figure 1
BEACON Power Distribution Monitoring Process