August 11, 2005

Mr. James A. Gresham, Manager
Regulatory Compliance and Plant Licensing
Westinghouse Electric Company
P.O. Box 355
Pittsburgh, PA 15230-0355

SUBJECT: FINAL SAFETY EVALUATION FOR TOPICAL REPORT (TR) WCAP-16260-P, "THE SPATIALLY CORRECTED INVERSE COUNT RATE (SCICR) METHOD FOR SUBCRITICAL REACTIVITY MEASUREMENT" (TAC NO. MC3065)

Dear Mr. Gresham:

By letter dated April 30, 2004, as supplemented by letters dated January 20, March 28, and April 18, and e-mail dated August 10, 2005, Westinghouse Electric Company (Westinghouse) submitted Topical Report (TR) WCAP-16260-P, "The Spatially Corrected Inverse Count Rate (SCICR) Method for Subcritical Reactivity Measurement," to the U.S. Nuclear Regulatory Commission (NRC) staff for review. By letter dated June 10, 2005, an NRC draft safety evaluation (SE) regarding our approval of WCAP-16260-P was provided for your review and comments. By letter dated June 29, 2005, Westinghouse commented on the draft SE. The staff accepted all of Westinghouse's comments, which were proprietary or grammatical in nature.

The NRC staff has found that WCAP-16260-P is acceptable for referencing in licensing applications for Westinghouse 2-, 3-, and 4-loop nuclear steam supply system design; and the CE 217-assembly type plant only. Applicability of the SCICR methodology to other types of plants, for which no data were provided for in this TR, will require that the data be submitted to the NRC staff for review/audit before implementation to confirm that they are consistent with the constraints and requirements of the benchmark data in the TR. The final SE defines the basis for acceptance of the TR.

Our acceptance applies only to material provided in the subject TR. We do not intend to repeat our review of the acceptable material described in the TR. When the TR appears as a reference in license applications, our review will ensure that the material presented applies to the specific plant involved. License amendment requests that deviate from this TR will be subject to a plant-specific review in accordance with applicable review standards.

In accordance with the guidance provided on the NRC website, we request that Westinghouse publish accepted proprietary and non-proprietary versions of this TR within three months of receipt of this letter. The accepted versions shall incorporate this letter and the enclosed final SE after the title page. Also, they must contain historical review information, including NRC requests for additional information and your responses. The accepted versions shall include a "-A" (designating accepted) following the TR identification symbol.

The document transmitted herewith contains proprietary information. When separated from the proprietary SE, this document is decontrolled.

If future changes to the NRC's regulatory requirements affect the acceptability of this TR, Westinghouse and/or licensees referencing it will be expected to revise the TR appropriately, or justify its continued applicability for subsequent referencing.

Sincerely,

/RA/
Herbert N. Berkow, Director
Project Directorate IV
Division of Licensing Project Management
Office of Nuclear Reactor Regulation

Project No. 700

Enclosures: 1. Non-Proprietary Safety Evaluation
2. Proprietary Safety Evaluation

cc w/encl:
Mr. Gordon Bischoff, Manager
Owners Group Program Management Office
Westinghouse Electric Company
P.O. Box 355
Pittsburgh, PA 15230-0355

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SAFETY EVALUATION BY THE OFFICE OF NUCLEAR REACTOR REGULATION

TOPICAL REPORT WCAP-16260-P, REVISION 0,

"THE SPATIALLY CORRECTED INVERSE COUNT RATE (SCICR) METHOD FOR

SUBCRITICAL REACTIVITY MEASUREMENT"

WESTINGHOUSE ELECTRIC COMPANY

PROJECT NO. 700

1.0 INTRODUCTION AND BACKGROUND

By letter dated April 30, 2004, (Reference 1) as supplemented by letters dated January 20 (Reference 2), March 28 (Reference 3), and April 18, 2005 (Reference 4), Westinghouse Electric Company (Westinghouse) submitted WCAP-16260-P, "The Spatially Corrected Inverse Count Rate (SCICR) Method for Subcritical Reactivity Measurement," to the Nuclear Regulatory Commission (NRC) for review and approval.

This report describes the SCICR methodology for subcritical reactivity measurement, which determines the negative reactivity of a core for any static subcritical core condition and control rod configuration using a combination of ex-core detector signal measurements and advanced subcritical core condition prediction methods.

The theory of the method is to use the ALPHA/PHOENIX/ANC (APA) (or PARAGON in place of PHOENIX) (References 5, 6, and 7), core-design code system to calculate three-dimensional spatial correction factors for the measured inverse count rate ratio (ICRR) data such that the corrected ICRR becomes linear as a function of the magnitude of the core subcriticality.

The specific steps of applying this methodology are prescribed to process the ICRR data that are routinely available in the normal process of operating a subcritical core. The outcome of this is a linearly regressed line of corrected ICRR versus core subcriticality, which can be used to determine the corresponding core negative reactivity for any measured and corrected ICRR.

Data of thirteen operating cycles from eight plants have been analyzed to demonstrate and qualify the SCICR methodology. The database covers pressurized-water reactor (PWR) cores of Westinghouse Type 2-loop, 3-loop, and 4-loop and Combustion Engineering (CE) 217-assembly Type. Six of the eight plants have and two do not have a secondary source. All the data show good results, aimed at confirming the applicability of SCICR methodology to real measurements.

In support of affirming that the SCICR methodology is working appropriately, Westinghouse conducted sensitivity analyses using a three-dimensional (3-D) core simulation to assess if the dependency of SCICR on the spatial correction factors could have any appreciable non-conservative impact on the SCICR results in the sense of "masking" the discrepancy between measurement and prediction.

SCICR is a methodology to measure the Total Rod Worth of the Control and Shutdown Banks at subcritical conditions using ex-core neutron detector measurements provided by the plant Nuclear Instrumentation System (NIS) at subcritical reactor conditions. This methodology is used to verify the core is constructed and operates as the core designers intended.

In Mode 3, a subcritical rod worth measurement data acquisition system will be connected to the installed plant NIS. Baseline SCICR data will be collected at the reactor conditions that exist at the time, with all control (or regulating) and shutdown banks inserted. NIS signals, and other core condition parameters, are measured as the control rods are being withdrawn.

The predicted subcritical neutron source distribution is generated for the core conditions present at each point where NIS data is collected. The SCICR methodology is used to remove the spatial effects that introduce non-linearity in the ICRR determined from the measured NIS data. The rod worth of the banks can then be measured from the changes in the spatially corrected measured linear ICRR relationship. Deviations between the intended core behavior and the actual core behavior can be identified from the linearity of the spatially corrected ICRR relationship.

SCICR provides for a continuous on-line monitoring of changes to K-effective once the subcritical baseline conditions for the reactor are modeled and a baseline K-effective has been calculated. The on-line monitoring system will track changes from the baseline conditions, and by applying the SCICR methodology, will trend the changes in K-effective of the reactor. As part of an on-line continuous monitoring system, changes in K-effective will be available to Plant Operations personnel for information and action as required.

The SCICR methodology, when applied and used in conjunction with updated reactor condition information, can provide continuous estimated critical positions and estimated critical boron projections based on the current measured K-effective value. The continuous online availability of critical condition information will assist the operators in performing a safe and controlled startup.

2.0 <u>REGULATORY EVALUATION</u>

Section 50.34 of Title 10 of the *Code of Federal Regulations* (10 CFR), "Contents of applications; technical Information," requires that safety analysis reports be submitted that analyze the design and performance of structures, systems, and components provided for the prevention of accidents and the mitigation of the consequences of accidents. As part of the core-reload-design process, licensees (or vendors) perform reload safety evaluations to ensure that their safety analyses remain bounding for the design cycle. To confirm that the analyses remain bounding, licensees confirm that key inputs to the safety analyses (such as the critical power ratio) are conservative with respect to the current design cycle. If key safety analysis parameters are not bounded, a reanalysis or reevaluation of the affected transients or accidents is performed to ensure that the applicable acceptance criteria are satisfied.

TR WCAP-16260-P, Revision 0, describes the vendor's methodology for implementing a spatially corrected factor-to-detector signal measurement. The NRC staff review of WCAP-16260-P, focused on methodology for determining and obtaining the 3-D spatial factors. Specifically, the staff review focused on the fundamental physics and mathematics as well as the implementation of the methodology to Westinghouse and CE plants. Therefore, the staff review was based on the evaluation of technical merit and compliance of the revisions with any applicable regulations.

3.0 TECHNICAL EVALUATION

3.1 The Theory Behind the Spatially Corrected Inverse Count Rate

As stated in the introduction above, WCAP-16260-P describes and applies the methodology of SCICR for subcritical reactivity measurement, which determines the negative reactivity of a core for any static subcritical core condition and control rod configuration using a combination of ex-core detector signal measurements and advanced subcritical core condition prediction methods.

Spatial correction factors obtained from 3-D neutronic and thermal-hydraulic code combinations are applied to the detector signal measurements such that the inverse of the corrected signal has a linear relationship with respect to the magnitude of subcriticality of a core. This linear relationship can be used to measure the negative reactivity of the subcritical core corresponding to any given spatially corrected ex-core detector signal measurement.

Data from thirteen operating cycles obtained from eight different operating plants have been analyzed by Westinghouse to demonstrate and qualify the SCICR methodology. Sensitivity analyses using 3-D core simulations were performed to determine if the dependency of SCICR on the spatial correction factors (SCF) could have any appreciable masking (biasing) effect on the SCICR results.

The SCICR methodology will be applied to measure the negative reactivity of any subcritical static core condition with any possible control rod configuration. The SCICR methodology can also be used to measure the core shutdown margin, the total rod worth, and forecast the combination of rod configuration and/or reactor boron concentration that will result in criticality.

The SCICR method can also be used to accurately measure small variations in reactivity changes, caused by such things as reactor temperature changes, when the core is nearly critical and the ex-core detector signal levels are high and not subject to poor signal-to-noise characteristics.

3.2 Core Physics

The existence of neutron flux in a subcritical core is maintained by the extraneous neutron sources in the core, which consist of the implanted primary or secondary neutron source and the spontaneous fission source due to certain isotopes that are generated in the process of fuel burn-up. For a point core model, the inverse of the core flux level varies linearly with the magnitude of subcriticality of the core. This linear relationship is the basis of the ICRR method that has been used by reactor operators to help estimate the onset of criticality in a subcritical core. In this simple point core model, the negative reactivity of a subcritical core can be readily determined if the core flux level is known. Except for the case when the reactor is very close to criticality, the ICRR behavior is radically non-linear and irregular.

Information about this complicated relationship is not provided by typical core-design codes. Currently, the lack of a method to determine the expected subcritical core ICRR behavior that accounts for the influences of the changes in the spatial distributions of the extraneous neutron sources prevents the proper interpretation of the measured changes in the ex-core detector responses. Consequently, it has not been possible to measure the reactivity of a subcritical commercial core.

The modern core-design code system, such as the Westinghouse neutronic codes SPNOVA and the APA suite, can calculate the extraneous neutron source distribution in a core and perform subcritical diffusion calculations in the presence of extraneous neutron sources, and also simulate the corresponding ex-core detector signals. With this capability, spatial correction factors can be determined and applied to the measured detector signals such that the spatially corrected ICRR does vary linearly with the magnitude of the core subcriticality. Consequently it becomes possible to determine the negative reactivity of a subcritical core from spatially corrected measured detector signals.

The application of the SCICR methodology is immediately feasible without the need of any ex-core detector hardware changes or any methodology modification. For example: (1) The SCICR methodology can be used to measure reactivity changes of a subcritical core due to programmed core condition changes. Thus, one is able to verify the consistency of the operating core with the predicted core-design model. An example of this is the reactivity change due to rod movement or temperature change. (2) The SCICR methodology can be used to continuously provide accurate forecasts of the combination of temperature, boron concentration, and control rod position needed for criticality using subcritical condition measurements. The improved knowledge of the reactor critical conditions will help speed up the process of approaching criticality. (3) The SCICR methodology can be applied to periodically measure and verify the core shutdown margin that is predicted by core-design and assumed in the safety analysis. (4) The SCICR methodology, when incorporated in a core monitoring system, can be used for on-line continuous monitoring of the negative reactivity of a subcritical core. If the core in question is equipped with the Westinghouse BEACON™ continuous monitoring system, the process will be much faster since the APA code system is an inherent part of the BEACON™ system.

3.3 Methodology

The methodology of implementing the theory outlined in Section 3.2, to carry out the SCICR process, is provided in chapter 3 of Reference 1. The process is typical of that followed for the current inverse count rate measurement. The difference is that, for the SCICR, additional steps are needed to account for the selection of the chosen states (i.e., Rods In or Rods Out, the inclusion of boron, etc.) and accessing of the APA code system to perform the 3-D simulations, capturing the spacial effects and disposition of the core. Westinghouse will develop plant-specific procedures consistent with the documentation contained in this safety evaluation.

4.0 DEMONSTRATION OF THE SCICR METHODOLOGY USING PLANT DATA

To demonstrate and qualify SCICR, Westinghouse analyzed data from thirteen operating cycles from eight different plants. The core geometry selected is intended to cover the Westinghouse Type 2-loop, 3-loop and 4-loop PWR cores and the CE Type 217-assembly PWR core. Six of the plants (eleven cycles) contain secondary sources, while the other two plants (two cycles) do not. Data from cores without a secondary source or from cores with very deep subcriticality have lower detector signals, and hence provide a more severe test of the SCICR method.

Specifically, Westinghouse analyzed plant data from eleven cycles of six different plants that have cores containing secondary sources. The six plants are 2-loop, 3-loop and 4-loop type PWRs built by Mitsubishi Heavy Industries (MHI) and Westinghouse. Westinghouse categorized the data available from these plants into three categories. Namely,

a) cores with both rod pull and dilution data available,
b) cores with only rod pull data available, and
c) cores with both rod pull and rod drop data available.

Typically, these categories cover the normal process of core startup; i.e., rod pull followed by boron dilution. The data is from eight cycles of four MHI PWR plants; two cycles of one 2-loop plant (Cycles 8 and 9 of Plant 1), three cycles of one 3-loop plant (Cycles 4 to 6 of Plant 2), and three cycles of two 4-loop plants (Cycles 3 and 5 of Plant 3, and Cycle 8 of Plant 4). All of the data stops at the condition of all control banks in, but shutdown banks being out, except for Cycle 8 of Plant 4, which does cover all the rods-in condition. The cores are very heavily borated such that some of the data cover deeply subcritical conditions. In particular, for two cycles of the 3-loop plant the core is more than 10 percent subcritical. The detector signals become very low at these deeply subcritical conditions. The results of SCICR analyses for these eight cycles' data are presented in Figures 4-1 to 4-8 of Reference 1. The Figures referenced indicate that the original ICRR data, before the spatial correction, show very strong non-linear behavior versus the core subcriticality. After spatial corrections, all the data line up linearly as the theory of SCICR predicts.

The SCICR method can determine the state of a subcritical reactor, as well as measure the total rod worth. For individual bank worth measurements, where the reactivity changes are much smaller, the signal measurement statistics are not, in general, stable enough to demonstrate generically accurate results. Ex-core detector signals obtained from near critical conditions, where the signals are high, result in accurate individual control bank worth measurements. This means that when applying the SCICR method to measure smaller reactivity changes, such as temperature reactivity coefficients or individual bank worth measurements, either special care must be taken to ensure the ex-core detector response data are collected properly, or the measurements should be carried out closer to core criticality.

5.0 STATISTICAL AND SENSITIVITY ANALYSIS ASSOCIATED WITH THE SCICR METHODOLOGY

The SCICR method was developed to enhance the conventional method for estimating core subcriticality. SCICR is built around a system of measurements that account for all available parameters, thus yielding a more accurate and more precise state of core subcriticality. As the graphs in Reference 1 clearly show, the accuracy increases as the subcriticality increases (criticality decreasing) where SCICR's deviation from the conventional method is very substantial.

SCICR's applicability is demonstrated in a variety of plants, cycles, and other parameters. The main statistical objective of this study is to assure that SCICR provides an unbiased (or of small bias) estimate of subcriticality. To that end, the ratio of the mean deviation (MD) to the root mean square is constructed, as given at the bottom of Page 3 of Reference 3:

[

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Unfortunately, the distribution of MD/RMS is not known. Thus, the percentiles of the distribution cannot be ascertained. Westinghouse addresses this problem by recognizing that MD/RMS is similar, in structure, to the standard normal variable, commonly denoted as "Z." Using a standard normal table, one finds that the probability that Z lies between **[**

]

The statistic MD/RMS can be shown not to be smaller than -1.00 or larger than +1.00, **[ ]**. The Westinghouse staff agreed to the NRC staff suggestion that the critical point for testing for bias be set at **[ ]**. Indeed, all runs where no bias was present, MD/RMS fell well below the **[ ]** threshold. Conversely, in every case where a bias was present (introduced deliberately), the corresponding MD/RMS was considerably above the **[ ]** mark.

The data collection for this study was guided by the chi-square criterion with N–1 degrees of freedom. This criterion calculated as $\chi^2_{N-1} = \frac{\sum_{i=1}^{N} \frac{(x-\overline{x})^2}{N-1}}{\overline{x}}$, where $\overline{x} = \frac{1}{N}\sum_{l=1}^{N} x_i$ and x_i is the measured source range, based on a one-second count rate, and is the total number of counts. If the calculated chi-square statistic is not within the 5 percent and 95 percent table values for N minus one degree of freedom, the data set is not included in the study as "unrepresentative." In summary, the staff does not have any issues with the statistics that Westinghouse used in their study.

In addition, Westinghouse conducted sensitivity studies to determine if a bias existed in the predictive capability of the SCICR methodology and in which direction (i.e., conservative or non-conservative direction). Westinghouse's concern was in regard to the magnitude of the bias and the sensitivity of the core model to this bias, since it is this measurement on which the calculated SCF is based. To address this concern, Westinghouse performed a series of sensitivity studies to assure that this sensitivity is either easily identifiable, small, or is in the conservative direction, in the sense of enlarging the difference between measurement and the prediction. Enlarging the difference is referred to as "unmasking." Minimizing the difference between measured and predicted is referred to as "masking." The NRC staff reviewed the results of the sensitivity studies provided in Reference 1, in light of the statistical methodology provided above, and concluded that the sensitivity issues were appropriately addressed, and thus concurs with the results.

6.0 LIMITATIONS AND CONDITIONS

The NRC staff accepts the methodology described in WCAP-16260-P, subject to the following conditions:

1. The SCICR methodology is applicable to the Westinghouse 2-, 3-, and 4-loop NSSS design; and the CE 217-assembly type plant only. Applicability of the SCICR methodology to other types of plants, for which no data were provided for in this TR, will require that the data be submitted to the NRC staff for review/audit before implementation to confirm that they are consistent with the constraints and requirements of the benchmark data in the TR.

2. Reactivity-sensitivity analyses must be conducted and submitted to the NRC staff for review/audit on a plant-specific basis to predetermine the masking effect (biases) so that they can be accounted for in SCICR applications to the plant.

3. The SCICR methodology can be applied for the following measurements:

    - The negativity of any subcritical static PWR core condition and configuration.
    - The PWR core shutdown margin.
    - The total rod worth.
    - The estimated criticality forecast.
    - To measure reactivity changes due to temperature changes while the core is close to criticality. This application needs to be demonstrated with measurement data and submitted to the NRC staff for review/audit.

4. At this time, sufficient data does not exist to apply this methodology to measure individual rod worth.

7.0 CONCLUSION

The NRC staff reviewed the analyses and results presented in WCAP-16260-P and determined that the analyses and results are in accordance with the guidance and limitations specified in 10 CFR 50.34, and the applicable sections of NUREG-0800. In addition, review of the presented plant data analysis and the sensitivity analysis conducted by Westinghouse, and as provided in Reference 1, confirm that the proposed SCICR methodology can be applied to a subcritical core. Therefore, on the basis of the above review and justification, the staff concludes that the Westinghouse WCAP-16260-P, the SCICR methodology, is acceptable.

8.0 REFERENCES

1. Letter from J. A. Gresham, Manager, Westinghouse to the NRC, Transmitting 4 copies of WCAP-16260-P, "The spatially corrected inverse count rate (SCICR) method for subcritical reactivity measurement," dated April 30, 2004, ADAMS Accession No. ML041280253.

2. Letter from J. A. Gresham, Manager, Westinghouse to the NRC, "Responses to NRC request for additional information on WCAP-16260-P," dated January 20, 2005, ADAMS Accession No. ML050310306.

3. Letter from J. A. Gresham, Manager, Westinghouse to the NRC, "Responses to NRC request for additional information on WCAP-16260-P, Revision 0, 'The spatially corrected inverse count rate (SCICR) method for subcritical reactivity measurement'," dated March 28, 2005, ADAMS Accession No. ML051100331.

4. Letter from J. A. Gresham, Manager, Westinghouse to the NRC, "Responses to NRC request for additional information on WCAP-16260-P, Revision 0, 'The spatially corrected inverse count rate (SCICR) method for subcritical reactivity measurement'," dated April 18, 2005, ADAMS Accession No. ML051150308.

5. Liu, Y.S., et. al., "ANC: A Westinghouse Advanced Nodal Computer Code," WCAP-10965-P-A (Proprietary) and WCAP-10966-A (Non-proprietary), September 1986.

6. Nguyen, T.Q., et. al., "Qualification of the PHOENIX-P/ANC Nuclear Design System for Pressurized Water Reactor Cores," WCAP-1 1596-P-A (Proprietary) and WCAP-1 1579-A (Nonproprietary), June 1988.

7. Mayhue, L., et.al., "Qualification of Two-Dimensional Transport Code PARAGON," WCAP-16045-P-A (Proprietary) and WCAP-16045-NP-A (Non-Proprietary), August 2004.

Principal Contributor: Tony Attard

Date: August 11, 2005