March 16, 2000

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MEMORANDUM TO: Steve Dembek, Section Chief
Project Directorate Section IV-2
Project Directorate IV
Division of Licensing Project Management, NRR

FROM: Evangelos C. Marinos, Section Chief
Instrumentation and Controls Section
Electrical & Instrumentation and Controls Branch
Division of Engineering, NRR

SUBJECT: REVIEW OF ABB-CENP TOPICAL REPORT CENPD-397-P, "IMPROVED FLOW MEASUREMENT ACCURACY USING CROSSFLOW ULTRASONIC FLOW MEASUREMENT TECHNOLOGY"

By letter dated August 23, 1999, as supplemented by letters dated January 6, January 25, and March 8, 2000, ABB-CE Nuclear Power, Inc. (ABB CENP) submitted the subject topical report for staff review. This topical report documents the theory, design, and operating features of the crossflow ultrasonic flow meter (UFM) and its ability to achieve increased accuracy of flow measurement, which is generically applicable to nuclear power plants.

The staff review of the topical report indicated that the Crossflow UFM can achieve the accuracy stated in the topical report when the plant-specific operating conditions and flow measurement uncertainty determination strictly follow the guidelines in the topical report. The attached safety evaluation documents the staff's acceptability of the topical report and provides additional guidelines for the licensees who want to use the Crossflow UFM for a power uprate. The staff has determined that the acceptance of this topical report does not involve any new staff position or interpretation. This completes EEIB action for TAC NO. MA6452.

Attachment: As stated

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SAFETY EVALUATION BY THE OFFICE OF NUCLEAR REACTOR REGULATION
ABB COMBUSTION ENGINEERING NUCLEAR POWER (ABB-CENP) TOPICAL REPORT
CENPD-397-P, REVISION 01
"IMPROVED FLOW MEASUREMENT ACCURACY USING CROSSFLOW ULTRASONIC FLOW MEASUREMENT TECHNOLOGY"

1.0 INTRODUCTION

By letter dated August 23,1999, (Reference 1), ABB Combustion Engineering Nuclear Power (ABB-CENP) submitted Topical Report CENPD-397-P, Revision 00, "Improved Flow Measurement Accuracy Using Crossflow Ultrasonic Flow Measurement Technology." This report documents the theory, design, and operating features of the "Crossflow" ultrasonic flow meter (UFM) and its ability to achieve increased accuracy of flow measurement, which is generically applicable to nuclear power plants. ABB-CENP stated that this meter provides at least 50 percent improvement in feedwater flow measurement accuracy as compared to the currently installed venturi-type flow meters in most nuclear power plants. This reduction in flow measurement uncertainty will allow a nuclear power plant licensee to achieve the following:

(1) Use the increased accuracy of the UFM to support a reduction in the power level margin used in the plant emergency core cooling system (ECCS) evaluation. The licensee may then seek a license amendment to operate the power plant at higher power levels. This power level margin is 2 percent of the licensed reactor power required by the Code of Federal Regulations, 10 CFR Part 50, Appendix K,"ECCS Evaluation Model," to account for power measurement uncertainty.

(2) Apply the reduced instrumentation uncertainty to gain benefits other than power uprate.

(3) Have an in-plant capability to periodically recalibrate the feedwater venturi for the effect of fouling, thereby allowing recovery of the lost generating capacity while staying within the plant's licensed operating power level.

The staff's review of the topical report resulted in a request for additional information (Reference 2), to which ABB-CENP responded in its letter dated December 17, 1999, (Reference 3). ABB-CENP also submitted Revision 01 to the topical report by letter dated January 6, 2000, (Reference 4), and submitted supplemental information on the topical report by letters dated January 25, 2000, (Reference 5), March 8, 2000, (Reference 6), and March 13, 2000. The ABB-CENP topical report contains mostly proprietary information, except for headings and general introduction of the Crossflow technology, including development and capability of the Crossflow UFM. Therefore, the staff safety evaluation report includes only the nonproprietary information of the topical report that describes the Crossflow UFM and its ability to measure feedwater flow with an uncertainty of 0.5 percent or less at a 95 percent confidence interval.

ATTACHMENT

2.0 BACKGROUND

Nuclear power plants are licensed to operate at a specified core thermal power, and the uncertainty of the calculated values of this thermal power is a factor in determining the probability of exceeding the power levels assumed in the design basis transient and accident analyses. In this regard, Appendix K to 10 CFR Part 50 requires that loss of coolant accident (LOCA) and ECCS analyses assume continuous reactor operation of at least 102 percent of licensed thermal power with the maximum peaking factor allowed by the plant Technical Specifications to allow for uncertainties such as instrument error. This reactor thermal power is continuously indicated by the neutron flux instrumentation, which must be periodically calibrated to accommodate the effects of fuel burnup, flux pattern changes, and instrumentation setpoint drift.

The neutron flux instrumentation is calibrated to the core thermal power, which is determined by an automatic or manual calculation of energy balance around the plant nuclear steam supply system. This calculation is called a "secondary calorimetric," in the case of a pressurized water reactor, and a "heat balance," in the case of a boiling water reactor. The accuracy of this calculation depends primarily upon the accuracy of feedwater flow and feedwater net enthalpy measurements. As such, an accurate measurement of feedwater flow and temperature is necessary for an accurate calibration of the nuclear instrumentation. Of the two instruments (flow and temperature), the most important in terms of calibration sensitivity is the feedwater flow (1 percent error in flow instrumentation calibration produces a corresponding 1 percent error in the nuclear instrumentation calibration).

The typical elements used for measuring feedwater flow are an orifice plate, a venturi meter, or a flow nozzle, which generate a differential pressure proportional to the feedwater velocity in the pipe. Of the three differential pressure devices, the venturi meter is the most widely used for feedwater flow measurement in nuclear power plants. The major advantage of the venturi meter is the relatively low head loss as the fluid passes through the device. However, fouling of the device is the major disadvantage of this meter or any other nozzle-based flow meter. Fouling is a metallic plating on the throat area of the meter, which causes the meter to indicate a higher differential pressure and thus a higher than actual flow rate. This result leads plant operators to calibrate nuclear instrumentation high. Calibrating nuclear instrumentation high is conservative with respect to reactor safety, yet it causes the electrical output to be proportionally low when the plant is operated at its thermal power rating In addition to fouling, the transmitter and the analog-to-digital converter of the venturi meter introduce errors in the flow measurement thus necessitating removal, cleaning, and recalibration of the flow device. Because of the desire to improve flow instrumentation uncertainty and to operate the plant closer to the license rating, the industry assessed alternate flow measurement techniques and found the UFM to be a viable alternative. The UFM is an electronic transducer that is controlled by computer and is not susceptible to fouling because it does not have differential pressure elements.

There are many ultrasonic techniques for measuring flow. The following four techniques are identified in NUREG/CR-5501,"Advanced Instrumentation and Maintenance

Technologies for Nuclear Power Plants" (Reference 7), as major UFM types commonly used for industrial applications, including nuclear power plants.

(1) Transit time (contrapropagation)
(2) Doppler frequency
(3) Vortex shedding
(4) Cross-correlation (tag time-of-flight)

The installation of the first two UFM types (transit time and doppler frequency) is either intrusive or clamp-on while the third (vortex shedding) is only intrusive and the fourth (cross-correlation) is only clamp-on. (Clamp-on refers to the method of attaching ultrasonic transducers used in the flow measuring process by means of a clamp device mounted external to the pipe.) The transit time technology injects an ultrasonic signal diagonally through the fluid and then measures the difference in the time it takes the signal to travel upstream versus downstream. The difference in these times is proportional to the velocity of the fluid in the pipe. The cross-correlation technique measures the velocity of the fluid by determining the time taken by a unique pattern of eddies in the fluid to pass between two sets of transducers, each set at a certain known distance apart, injecting ultrasonic signals perpendicular to the pipe axis.

The cross-correlation UFM was first developed by the Canadian General Electric for Ontario Hydro. However, the system was not optimized for application over a wide range of flow velocities and pipe diameters. The task of optimizing the cross-correlation technique was carried out by the Advanced Measurement Analysis Group, Inc. (AMAG), and ABB CENP. This work resulted in an improved cross-correlation flow meter called "Crossflow." These new flow meters have been installed to measure reactor coolant flow and steam generator feedwater flow in several nuclear power plants (more than 40 plants) in the United States, Canada, South America, and Europe. However, licensees have not taken credit for the Cross Flow UFM in regulatory applications.

3.0 EVALUATION

The ABB-CENP topical report, CENPD-397-P, provided a detailed description of the cross-correlation theory, the Crossflow UFM system, instrumentation uncertainties, instrumentation testing and calibration, and field implementation of the UFM.

3.1 Theory, Development, and Testing of the Crossflow UFM

Flow meters measure the velocity of the fluid flowing in the pipe. Also, the velocity profile of a fluid flowing through a pipe is dependent upon the inertial force of the fluid in the pipe and the fluid viscosity. The inertial force makes the fluid flow through the pipe, while the viscous force makes the flow slow down as the fluid passes over the pipe wall. The ratio between the inertial force and the viscous force is a dimensionless number called the Reynolds (Rd) number. Rd numbers greater than 4000 are generally accepted as being in the turbulent flow region (where eddies are formed). In the feedwater system of a typical nuclear power plant, Rd numbers are as high as approximately 30 million.

The operation of a cross-correlation UFM is based on the fact that when an ultrasonic beam travels across fluid flowing in a pipe, the ultrasonic beam is affected (modulated) by the turbulence (eddies) present in the flowing liquid. When this modulated signal is processed, a random signal, which is a signature of the flowing eddies, can be obtained. The cross-correlation meter measures the time a unique pattern of eddies takes to pass between two sets of ultrasonic transducers. The upstream transducer injects an ultrasonic signal perpendicular to the pipe axis. The eddies in the fluid modulate the ultrasonic signal, creating a phase shift, which is unique to the eddies passing through the ultrasonic signal at that moment. The same eddies pass through a second ultrasonic signal injected by the downstream transducer at a known distance from the upstream transducer. These eddies modulate the second ultrasonic signal in the same manner as they modulated the first (upstream) ultrasonic signal. Both modulated signals are then demodulated to obtain two wave forms that are the unique signatures of the eddies. The cross-correlation algorithm calculates the time the eddies took to pass the two signals by mathematically shifting the downstream signal wave form backwards in time to a point at which there is a maximum correlation between the two demodulated signals. The known distance between the two sets of transducers is then divided by the calculated time to obtain the flow velocity. This measured velocity is not an average velocity (highest velocity is at the center of the pipe) and must be multiplied by a factor called the velocity profile correction factor (VPCF) to obtain the average velocity of the fluid flowing in the pipe.

The topical report includes the AMAG-developed numerical techniques, algorithm, and formulae for calculating the time the eddies take to pass through the two ultrasonic signals and for finding the values of VPCF as a function of the Rd number with a fully developed turbulent flow in a straight pipe. The Topical Report also includes a VPCF versus Rd number curve developed for VPCF as a function of only Rd number. This curve assumed that the velocity profile is fully developed and that the pipe wall friction is small. Formulae and guidelines are provided for determining the additional correction factors to be applied to the VPCF for the piping configuration where the flow is not fully developed, such as downstream of an elbow. These formulae were used to calculate the VPCF for the entire spectrum of pipe Rd numbers in a typical nuclear power plant. The Crossflow UFM was calibrated at the Alden Research Laboratory (ARL) for Rd numbers ranging from [0.8 million to 7 million,] using plastic pipe. This calibration involved using the theoretical VPCF and fitting it to ARL experimental data (weigh tank data) using statistical techniques. The ARL extrapolated the experimental data to the Rd numbers of up to 30 million and developed the VPCF versus the Rd number curve. A close agreement was found between the theoretical and experimental VPCF curves. The result of this comparison is included in the topical report, and the differences between the measured and the predicted VPCF are well within the uncertainty of the ARL weigh tank test accuracy of ±0.25 percent with a repeatability uncertainty of ±0.1percent. Therefore, the calibrated VPCF accuracy is the same as the ARL weigh tank test VPCF accuracy, with a 95 percent confidence interval. The VPCF curve developed in the topical report assumes that the velocity profile is fully developed, and the curve compared favorably to experimental data from the tests using smooth pipe. The low pipe wall friction of smooth pipe, relative to the friction expected in a typical feedwater pipe of a nuclear power plant, provides a limiting condition that maximizes the velocity measured by the Crossflow UFM. This limiting condition provides confidence that the velocity measured by the UFM will be equal to or greater than the actual flow velocity.

In addition to the ARL tests, the [Everest Laboratory (Chatou, France) conducted tests for Rd numbers 0.7 million to 1.3 million] on the Crossflow UFM and showed the same values of uncertainty and repeatability of the test results as those at the ARL (Reference 8). The National Institute of Standards and Technology conducted tests on six different UFMs from different developers, at an Rd number of 0.4 million, and found the Crossflow UFM to contain nearly zero errors (Reference 8).

Since the laboratory tests cannot create the Rd numbers normally present in a nuclear power plant, the AMAG collected Crossflow UFM feedwater flow measurement data from two operating nuclear power plants in the United States where the accuracy of the in-plant flow instrumentation was independently confirmed through weigh tank tests at ARL. Those data, which range up to a 25 million Rd number, were used to calculate the corresponding VPCF in the same way as was done for the ARL tests. These calculated VPCFs were found to compare with the ARL experimental VPCF curve. This comparison sufficiently demonstrates that the low Rd number calibration curve, which is extrapolated to the higher Rd numbers, can be used to determine the VPCFs for a nuclear power plant feedwater flow.

Based on its review of the theory and test data provided, the staff concludes that the Crossflow UFM approach is suitable for nuclear power plant applications.

3.2 System Components

The Crossflow UFM consists of four ultrasonic transducers (two transmitters and two receivers) mounted to a support frame (M/TSF), which is externally attached to the pipe in which the flow is to be measured. The ultrasonic transducers are connected to a signal conditioning unit (SCU) and a data processing computer (DPC). There are two transducer designs in use: one with the aluminum box-type M/TSF and the other with the carbon steel saddle-type M/TSF. The box-type M/TSF is field assembled and is no longer offered. Currently, the saddle-type M/TSF is used, in which the transducer holes are bored in one run on a computerized numerical control machine. This frame provides an exceptionally accurate alignment of the transducers, and no field adjustments are needed. The DPC, with its Crossflow software, performs digital signal processing on the demodulated ultrasonic signals and calculates the delay time for use in the flow calculation. The Crossflow software verification and validation are performed in accordance with the ABB-CENP quality and implementing procedure manuals. To ensure the accuracy claimed for the Crossflow system, the report listed several techniques (proprietary) for verification and diagnostics. Verification is normally carried out at a predetermined periodic interval, and the diagnostics are performed if a system failure occurs. The report provided details of the system hardware, software, operation verification and diagnostics, and component classification (proprietary) to establish that the Crossflow UFM will perform its function as an in-plant instrument for updating the calibration of the feedwater venturi. The Crossflow hardware and software do not perform a safety function and are therefore classified non-safety-related. The topical report stated that the Crossflow software does not interact with the plant computer or with any safety-related systems, and the UFM hardware and software development, tests, and calculation data are maintained as quality records.

3.3 Flow Measurement Uncertainties

The topical report provided a methodology for determining measurement uncertainty of the Crossflow UFM. This methodology uses specific guidelines and equations for determining uncertainty values of the Crossflow input parameters with a 95 percent confidence interval. The parameters that contribute to feedwater flow measurement uncertainty are pipe inside diameter, transducer spacing, feedwater density, Crossflow time delay, pipe wall roughness, and the VPCF. The topical report included typical uncertainties for each of the input parameters, except for the pipe wall roughness, and overall flow measurement uncertainty of the Crossflow UFM for a typical feedwater loop (straight pipe, fully developed flow). Actual uncertainties will be determined on a plant-specific basis by using the guidelines and equations provided in the topical report. Most of these uncertainties are affected by temperature change and, therefore, the topical report recommended improving the accuracy of the feedwater temperature instrumentation to reduce the total uncertainty of the feedwater flow measurement. The accuracy of the Crossflow time delay is confirmed monthly in the field for a specified acceptable value, and the power plant licensee is advised in the topical report to accurately measure the feedwater temperature. The methodology specified additional correction factors to be applied to the VPCF of a fully developed flow in a straight pipe when determining the VPCF for plant-specific conditions and pipe configuration.

As stated in the topical report, the Crossflow UFM and its associated hardware and software is able to achieve flow measurement uncertainty of 0.5 percent or better, with a 95 percent confidence interval for a fully developed flow. A staff review of the Crossflow UFM design and test results indicates that this meter can achieve the accuracy stated in the topical report when the plant-specific operating conditions and flow measurement uncertainty determination strictly follow the guidelines in the topical report. Ultrasonic flow meters have shown significant improvement in recent years, with calibration laboratory test results showing accuracies better than 0.2 percent of flow (straight pipe, fully developed flow) and commercially available systems claiming accuracies of better than 0.5 percent of flow (including Crossflow UFM).

3.4 Crossflow UFM Field Implementation

As described in the topical report, the Crossflow UFM is simple to install and operate. The installation of the UFM follows a standard procedure identified in the topical report. The installation procedure requires documentation of key installation/setup steps and important parameter values. The topical report stated that a trained representative from ABB-CENP or AMAG will perform a preinstallation survey to identify the installation location on the basis of piping configuration and will also determine the pipe's outside diameter and pipe material. This information will be used to custom fabricate the transducer mounting hardware (M/TSF) for the specific feedwater pipe. Since the support frame is mounted externally on the pipe surface, the feedwater pressure boundary is not affected, and the installation and commissioning can be performed while the plant is in operation. Additionally, if the piping configuration is such that the velocity profile is not fully developed at the desired location for permanent installation of the UFM, a second UFM can be installed at a location where the velocity profile is fully developed and the second meter can be used to calibrate the permanent meter on-line at the desired location.

In addition to the guidelines outlined in Topical Report CENPD-397-P, the following criteria shall be addressed by licensees referencing this topical report in their request for license amendment:

1. The licensee should discuss the development of maintenance and calibration procedures that will be implemented with the Crossflow UFM installation. These procedures should include process and contingencies for an inoperable Crossflow UFM and the effect on thermal power measurement and plant operation.

2. For plants that currently have the Crossflow UFM installed, the licensee should provide an evaluation of the operational and maintenance history of the installed UFM and confirm that the instrumentation is representative of the Crossflow UFM and is bounded by the requirements set forth in Topical Report CENPD-397-P.

3. The licensee should confirm that the methodology used to calculate the uncertainty of the Crossflow UFM in comparison to the current feedwater flow instrumentation is based on accepted plant setpoint methodology (with regard to the development of instrument uncertainty). If an alternative methodology is used, the application should be justified and applied to both the venturi and the Crossflow UFM for comparison.

4. The licensee of a plant at which the installed Crossflow UFM was not calibrated to a site-specific piping configuration (flow profile and meter factors not representative of the plant-specific installation) should submit additional justification. This justification should show that the meter installation is either independent of the plant-specific flow profile for the stated accuracy, or that the installation can be shown to be equivalent to known calibration and plant configurations for the specific installation, including the propagation of flow profile effects at higher Reynolds numbers. Additionally, for previously installed and calibrated Crossflow UFM, the licensee should confirm that the plant-specific installation follows the guidelines in the Crossflow UFM topical report.

4.0 CONCLUSION

On the basis of review of Topical Report CENPD-397-P, Revision 01 (Proprietary and Non-Proprietary), the staff concludes that the Crossflow UFM is designed and tested to achieve the flow measurement uncertainty of 0.5 percent or better, with a 95 percent confidence interval. This level of accuracy is achievable only when the plant-specific operating conditions and flow uncertainty parameters strictly follow the guidelines in the Crossflow UFM topical report. Additionally, the guidelines and the equations provided in the report were sufficiently clear for incorporating plant-specific pipe configurations and plant operating conditions in the flow measurement uncertainty calculations. The staff agrees with the statement in the topical report that the report is generically suitable for reference by utilities employing the Crossflow UFM to pursue plant operation at a higher power level, within the limitations of the license.

5.0 REFERENCES

1. ABB-CENP Topical Report CENPD-397-P, Revision 00, "Improved Flow Measurement Accuracy Using Crossflow Ultrasonic Flow Measurement Technology" dated August 1999, transmitted to NRC by Ian C. Rickard (ABB-CENP) letter dated August 23, 1999.

2. J. Cushing (NRC) letter to I. C. Rickard (ABB-CENP), dated November 19, 1999, "Request for Additional Information (RAI) on Topical Report CENP-397P, Revision 00."

3. Ian C. Rickard (ABB-CENP) letter to NRC, dated December 17, 1999, "Response to NRC RAI on Topical Report CENPD-397P, Revision 00."

4. ABB-CENP Topical Report CENPD-397-P, Revision 01, "Improved Flow Measurement Accuracy Using Crossflow Ultrasonic Flow Measurement Technology," dated January 2000, transmitted to NRC by Ian C. Rickard (ABB-CENP) letter dated January 6, 2000.

5. ABB-CENP Topical Report CENPD-397-P, Revision 01 "Supplemental Information", transmitted to NRC by Ian C. Rickard (ABB-CENP) letter dated January 25, 2000.

6. Ian C. Rickard (ABB-CENP) letter to NRC,"Response to Verbal Request For Additional Information," dated March 8, 2000.

7. NUREG/CR-5501,"Advanced Instrumentation and Maintenance Technologies for Nuclear Power Plants," dated July 1998.

8. Ian C. Rickard (ABB-CENP) letter to NRC, "Non-Proprietary Meeting Presentation Material," dated February 25, 1999.