January 28, 2003

Mr. Calvin R. Hastings
President and CEO
Caldon, Inc.
1070 Banksville Ave.
Pittsburgh, PA 15216

Mr. Henry Sepp
Westinghouse Electric Company
P.O. Box 355
Pittsburgh, PA 15230-0355

SUBJECT: REVIEW OF CALDON ENGINEERING REPORT ER-262, REVISION 0, "EFFECTS OF VELOCITY PROFILE CHANGES MEASURED IN-PLANT ON FEEDWATER FLOW MEASUREMENT SYSTEMS" AND WESTINGHOUSE ELECTRIC COMPANY TOPICAL REPORTS WCAP-15689, REVISION 0 AND REVISION 1, "EVALUATION OF TRANSIT-TIME AND CROSS-CORRELATION ULTRASONIC FLOW MEASUREMENT EXPERIENCE WITH NUCLEAR PLANT FEEDWATER FLOW MEASUREMENT" (TAC NO. MB4073)

Dear Mr. Hastings and Mr. Sepp:

By letter dated January 10, 2002, Caldon, Inc. submitted Engineering Report ER-262, Revision 0, for information. Subsequently, by letter dated February 12, 2002, Caldon, Inc. requested staff review of this engineering report. Caldon, Inc. developed this engineering report in response to recent occurrences of Caldon leading edge flow meter (LEFM) Check and LEFM Check Plus systems velocity profile alarms in nuclear power plants. Caldon, Inc. concluded that the velocity profile change was transient in nature and the potential calibration error introduced by the profile change resulted in slightly lower indicated flow, which is conservative. The engineering report relates to velocity profile changes that influence feedwater flow measurement uncertainties of Caldon's LEFM, LEFM Check Plus, and LEFM External systems. Caldon, Inc. considered this report non-proprietary and placed it on Caldon's web site. In this engineering report, Caldon, Inc. determined that variation in swirl velocity was the principal cause of velocity profile changes at those power plants.

Caldon, Inc. stated that while the velocity profile changes do not significantly alter the calibration of LEFM Check and LEFM Check Plus (spool piece) systems, they will produce significant calibration changes in LEFM External (clamp-on) and cross-correlation (clamp-on) flowmeters. The cross-correlation flowmeter, called Crossflow, was developed by Combustion Engineering, which is now owned by Westinghouse Electric Company (WEC). The staff approved several applications for measurement uncertainty recapture (MUR) power uprates using Crossflow, LEFM Check, or LEFM Check Plus systems for feedwater flow measurement. The LEFM External system is not credited for power uprates.

WEC submitted their response to Caldon’s concerns regarding crossflow vulnerability to swirl velocities in Topical Reports WCAP-15689-P and WCAP-15689-NP. The enclosed safety evaluation (SE) documents the staff’s review of the ER-262 and WCAP-15689 reports, and includes only the non-proprietary information of the WEC topical report.

Based on the enclosed SE, the staff concludes that ER-262 and WCAP-15689 (-P and -NP) are acceptable for use by licensees. The details of the staff's conclusions on the reports are in Section 4.0 of the SE. If the staff’s criteria or regulations change so that its conclusion in this letter is invalidated, Caldon, Inc., WEC and/or the licensees referencing the engineering report and/or topical report will be expected to revise and resubmit its respective documentation, or submit justification for the continued applicability of the engineering report and/or topical report without revision of the respective documentation.

The staff requests that Caldon, Inc. and WEC, as applicable, publish an accepted version within 3 months of receipt of this letter. The accepted version shall incorporate (1) this letter and the enclosed SE between the title page and the abstract, (2) all requests for additional information from the staff and all associated responses, and (3) a "-A" (designating "accepted") following the report identification symbol.

We do not intend to repeat our review of the matters described in the subject report, and found acceptable, when the report appears as a reference in license applications, except to ensure that the material presented applies to the specific plant involved. Our acceptance applies only to matters approved in the report.

Normally, a safety evaluation on a proprietary topical report is withheld from the public for 10 days to give the owner of the proprietary information an opportunity to verify the safety evaluation does not contain proprietary information. However, in this case, the safety evaluation was written to provide a combined response to two vendors of competing systems. Therefore, this issue was discussed with Mr. Charles Molnar of Westinghouse on January 24, 2003. Mr. Molnar agreed that the best course of action was to release the safety evaluation as quickly as possible and there will not be a 10-day hold on this safety evaluation.

In the event that any comments or questions arise, please contact Drew Holland at (301) 415-1436.

Sincerely,

***/RA/***

William H. Ruland, Director
Project Directorate IV
Division of Licensing Project Management
Office of Nuclear Reactor Regulation

Project No. 700

Enclosure: Safety Evaluation

cc: See next page

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cc:
Mr. Gordon Bischoff, Project Manager
Westinghouse Owners Group
Westinghouse Electric Company
Mail Stop ECE 5-16
P.O. Box 355
Pittsburgh, PA 15230-0355

# SAFETY EVALUATION BY THE OFFICE OF NUCLEAR REACTOR REGULATION

# CALDON ENGINEERING REPORT ER-262, REVISION 0

# "EFFECTS OF VELOCITY PROFILE CHANGES MEASURED

# IN-PLANT ON FEEDWATER FLOW MEASUREMENT SYSTEMS" AND

# WESTINGHOUSE ELECTRIC COMPANY

# TOPICAL REPORTS WCAP-15689, REVISIONS 0 AND 1

# "EVALUATION OF TRANSIT-TIME AND CROSS-CORRELATION ULTRASONIC

# FLOW MEASUREMENT EXPERIENCE WITH NUCLEAR PLANT

# FEEDWATER FLOW MEASUREMENT"

# PROJECT NO. 700

## 1.0 INTRODUCTION

By letter dated January 10, 2002 ( Reference 1), Caldon, Inc. (Caldon) submitted Engineering Report ER-262, Revision 0, "Effects of Velocity Profile Changes Measured In-plant on Feedwater Flow Measurement Systems" for information only. Subsequently, by letter dated February 12, 2002 (Reference 2), Caldon requested staff review of this report. Caldon developed this report in response to recent occurrences of Caldon leading edge flow meter (LEFM) Check and LEFM Check Plus system velocity profile alarms in nuclear power plants. The report identifies the effects of velocity profile changes on feedwater flow measurement uncertainties of Caldon LEFM, LEFM Check Plus, and LEFM External systems, and concludes that the calibration of LEFM External meters and cross-correlation flow meters called Crossflow, will be adversely affected by the velocity profile changes.

By letter dated April 3, 2002 (Reference 3), Westinghouse Electric Company (WEC), the supplier of the Crossflow meter, submitted proprietary and non-proprietary versions of Topical Report (TR) WCAP-15689, "Evaluation of Transit-Time and Cross-Correlation Ultrasonic Flow Measurement Experience With Nuclear Plant Feedwater Flow Measurement," Revision 0. In these reports, WEC addressed the Caldon concerns regarding Crossflow vulnerability to velocity profile changes. In response to the staff's request for additional information, WEC submitted Revision 1 of the TR by letter dated September 12, 2002 (Reference 4). This report is the staff's safety evaluation (SE) of Caldon Engineering Report ER-262 and Westinghouse TR WCAP-15689, and includes only the nonproprietary information of the Westinghouse TR.

## 2.0 REGULATORY BASIS

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 and emergency core cooling system analyses assume continuous reactor operation at least 102 percent of licensed thermal power to allow for uncertainties such as instrument error. This regulation did not require demonstration of power measurement uncertainty and mandated a 2-percent power margin. In the year 2000, the NRC published a final rule which allows licensees to justify a smaller margin using more accurate instrumentation. The accuracy of thermal power calculation depends primarily upon the accuracy of feedwater flow and temperature measurement. Of the two instruments, the most important in terms of calibration sensitivity is the feedwater flow instrument (1 percent flow error in flow instrumentation calibration produces a corresponding 1 percent error in the nuclear instrumentation calibration).

After publication of the final rule, Caldon developed the LEFM Check and LEFM Check Plus systems, and WEC (formerly ABB-CE) developed the Crossflow system. Several power plants have been and are being allowed measurement uncertainty recapture (MUR) power uprates for using either one of these three instruments to measure feedwater flow. Caldon LEFM External System is not credited for power uprate. However, several power plants use Caldon LEFM External System as an alternate or in conjunction with the venturi measurement of feedwater flow to provide an indication of feedwater flow. In this application, the LEFM External system indicates whether or not the feedwater flow measurement is accurate enough to conform with the plant's current licensing basis with respect to calorimetric accuracy (the external system is not subject to "fouling" that causes the venturi to read conservatively). As such, the Caldon LEFM External system is used to recover megawatts that would be lost due to venturi fouling.

## 3.0 EVALUATION

Caldon LEFM Check and LEFM Check Plus chordal flowmeters include an alarm (benchmark velocity alarm) that annunciates when the measured fluid velocity differs from a reference value by more than a preset amount. The purpose of the alarm is to alert the LEFM user of a velocity profile change from that of the calibrated value. Recently two operating power plants (Susquehanna and Watts Bar) experienced a change in the feedwater flow velocity profile, activating a benchmark velocity alarm. Caldon's analysis of these events in the subject engineering report indicated that the change in the velocity profile was caused by a decrease in the relative wall roughness of the upstream feedwater piping system. Caldon believes that a feedwater chemistry transient caused a decrease in the feedwater piping wall roughness which, in turn, caused an increase in the swirl velocity. The change in swirl velocity induced a change in the axial velocity profile which initiated the benchmark velocity alarm. Caldon's evaluation of the LEFM Check and LEFM Check Plus systems calibration data from 18 separate installations in nuclear feedwater systems indicated that the feedwater velocity profile changes due to a change in swirl velocity. Caldon stated that, in locations meeting commonly used criteria for locating the flow elements, swirl velocity is noted to vary from 1 percent to over 10 percent of the axial velocity changing the axial velocity profile from nominal "roundness" to a shape flatter than that for fully-developed flow in a smooth pipe. The Caldon engineering report includes analyses to demonstrate that the effects of these variations on the calibration of Caldon LEFM

Check and LEFM Check Plus flowmeters is less than 0.1 percent flow, which is negligible. However, a change in the alarm logic and/or threshold is necessary to prevent nuisance alarms.

The Caldon evaluation of the events concluded that the profile changes were transient in nature and the temporary calibration error introduced by the profile change was not greater than 0.1 percent flow and was, in fact, conservative. That is, the true flow was probably 0.1 percent lower than the indicated flow during the period when the profile was altered. Caldon recommended changing the setting of the benchmark velocity alarm at Susequehanna and Watts Bar. Caldon concluded that, while the axial profile changes evident from the chordal data do not significantly alter the calibration of four and eight path chordal instruments (LEFM Check and LEFM Check Plus systems), they will produce significant calibration changes in instruments that measure velocity along one or more diametral paths, such as external transit-time instruments or cross correlation instruments. These conclusions are based on the LEFM Check and LEFM External systems velocity profile data from various operating power plants included in ER-262. The data indicated change in the calibration of an external system installed at an average location for fully-developed flow to be 0.7 percent. Greater than 1 percent to a maximum of 1.8 percent flow change would be experienced at other locations. Caldon stated that while an analysis of the effects of the measured profile changes on cross correlation meters is beyond the scope of ER-262, the axial velocity profile projected onto the diametral paths of a cross correlation meter is necessarily a determinant in its calibration and the variability of the calibration of external transit-time flow meters would be expected to apply to cross correlation instruments.

In response to ER-262, WEC and Advanced Measurement and Analysis Group (AMAG) performed a technical review to address the relevance of the ER-262 conclusions with respect to the Crossflow system performance and documented their findings in WCAP-15689, Revisions 0 and 1. In the TR, WEC summarized ER-262 and provided a detailed comparison of transit-time and cross-correlation technologies, Crossflow and LEFM systems sensitivity to various transients, and each meter’s installation and calibration procedure.

A transit-time flowmeter measures fluid velocity in a pipe by measuring the difference in the time that it takes for an ultrasonic beam pulse in a chordal path to travel upstream against the direction of flow versus the time that it takes for a similar pulse to travel downstream with the flow. The fluid velocity is proportional to this time difference. The cross-correlation flowmeter determines the velocity of the fluid by measuring velocity of eddies within the fluid using a mathematical process called cross-correlation. As the upstream ultrasonic beam, perpendicular to the axis of the pipe, passes through the fluid, the eddies impart a phase shift to the ultrasonic signals that form a unique pattern. When the eddies pass through the downstream ultrasonic beam, they also impart a similar pattern of phase shifts to this ultrasonic beam. Each of these patterns are removed from the ultrasonic signal, digitized and then analyzed to determine how many milliseconds (ms) one pattern must be shifted with respect to the other so that the two patterns can be aligned. By knowing the physical distance between the two sets of ultrasonic transducers and the time that it took for the eddies to travel between the two beams, the velocity of the fluid can be calculated. WEC stated that this time delay is on the order of 50 ms, which is 10,000 times greater than the time delay measured by a transit-time flowmeter. As such, the measured flow is not sensitive to the same conditions that can challenge a transit-time flowmeter (i.e., electronic noise, cable lengths, change in temperature, transducer beam orientation, etc.)

In the TR, WEC stated that due to the proprietary restrictions necessary to provide the continued commercial protection of Crossflow, some flow engineers and transit-time specialists have limited knowledge of cross-correlation technology, and assume that all clamp-on flowmeters are subject to similar reliability and performance issues. WEC determined that the conclusions presented in ER-262 regarding cross-correlation technology are not applicable to Crossflow and that the Crossflow technology is not subject to the specific technical issues associated with the Caldon transit-time type flow meters. The WEC TR stated that actual plant data and computational fluid dynamics calculations demonstrate that transit-time flowmeters are much more sensitive to upstream flow disturbances than are cross-correlation flowmeters. WEC/AMAG's extensive experience indicates that changes in flow profiles are due to a realignment of upstream equipment rather than an abrupt change in pipe wall roughness.

The WEC TR stated that the transit-time clamp-on system has encountered reliability and repeatability problems due to complex mounting of the transducers on pipe surfaces to inject the ultrasonic signal at an angle. The TR further stated that the holes drilled at an angle into the sides of the pipe in a transit-time chordal meter introduce turbulence into the flow that adds an additional random velocity component to the velocity measurement that must be corrected through a laboratory calibration. This turbulence is dependent on the Reynolds Number which increases several fold under plant operating conditions from that achievable in a laboratory. As such, the laboratory calibration of a transit-time meter is to be extrapolated for a much higher Reynolds Number without any empirical formula for predicting the corresponding change in turbulence. WEC stated that the ability to accurately predict how this calibration changes, as the Reynolds Number is increased to plant operating conditions, can be challenging; and thus, it would be prudent to validate the meter's accuracy under operating conditions rather than only under the laboratory conditions. WEC/AMAG have elected to use in-situ calibration whenever there is a question about the velocity profile being fully developed at the flow meter installation location. This approach allows the Crossflow calibration to be performed under operating conditions which minimizes the uncertainty of extrapolating a laboratory calibration to plant operating conditions.

WEC stated that the presence of any upstream flow disturbance(s) must be evaluated from the standpoint of whether or not the effects of a disturbance will have dissipated prior to reaching the flowmeter. For this evaluation, the number of pipe L/D units (L is the pipe length from the upstream device causing disturbance to the point where the disturbance is completely dissipated and D is the internal diameter of the pipe) is known. This knowledge is based on experience, model tests, and from the technical literature. Figure 2 of WCAP-15689 shows the difference in the flow velocity profile factor for horizontal and vertical orientation of single-beam transit-time and the cross-correlation flowmeters downstream of a 90 degree bend. For the cross-correlation meter, the difference between the horizontal and vertical meter readings was found to be less than 0.5 percent flow, while the corresponding differences in the transit-time meter readings were more than 8 percent at a distance of 10 pipe diameters downstream of the elbow and close to 5 percent at 50 pipe diameters downstream of the elbow. In Figure 3 of WCAP-15689, flow readings of five transit-time clamp-on meters from different vendors and the Crossflow meter were compared with the weigh tank data at the National Institute of Standards Technology (NIST) hydraulic laboratory for four different installations and three different Reynolds numbers. The results show all transit-time meters to be biased high by approximately 2 percent flow while the Crossflow meters showed a deviation of 0.05 percent from the weigh tank data. WEC stated that these dramatic differences in meter behavior can be explained by two factors. First, the cross-correlation meter is not sensitive to radial and tangential velocity components. Second, the cross-correlation meter measures the velocity of the same eddies, independent of whether the meter is mounted in the vertical or horizontal plane of the elbow.

The staff review of WCAP-15689 indicated that a cross-correlation flowmeter is not as sensitive to flow perturbation as a transit-time flowmeter. Among the transit-time flowmeters, the Caldon single beam diametrical clamp-on flowmeter is more sensitive to changes in velocity profile than the multi-path chordal flowmeter (LEFM Check and LEFM Check Plus systems) where the overall measurement variation is reduced due to four or eight measurements. The reason for the lower sensitivity is that the cross-correlation meter only tracks the axial velocity component of the fluid, while the transit-time meter is impacted by the axial as well as the tangential and the radial components of the fluid velocity that are induced by swirl. For a transit-time meter, these swirl-related velocity components may add to or get subtracted from the axial component of the fluid velocity indicating an increase or a decrease in flow. In the case of the Crossflow, these radial and tangential velocity components will only reduce the correlation between the upstream and downstream phase shift patterns near the pipe surface and the meter will track the fluid velocities near the central regions of the pipe resulting in an indication of a conservative higher mass flow. As such, an abrupt change in swirl or pipe wall roughness, as described in ER-262, would cause the shift in Crossflow output in a conservative direction. Additionally, as stated in WCAP-15689, the velocity profile correction factor for Crossflow is based on smooth pipe, which eliminates the possibility of a reduction in pipe wall roughness and the resulting increase in the swirl velocity.

## 4.0 CONCLUSION

Based on the staff's review of ER-262, the staff agrees with Caldon’s conclusions that the feedwater velocity profile change at Susquehanna Unit 2 was transient in nature, the installed LEFM Check system performed as designed, and the (temporary) potential calibration error introduced by the profile change was in fact conservative as the true flow was slightly lower than the indicated flow. ER-262 established that any upstream flow disturbance can cause much higher calibration changes of an external LEFM than that of LEFM Check or LEFM Check Plus systems. This is not a safety issue for power uprates because no External LEFM system has been credited for power uprates. The staff's review of WCAP-15689 indicated that the cross-correlation (Crossflow) flowmeter is not as sensitive to upstream flow perturbations as a clamp-on transit-time flowmeter (External LEFM). As such, the concerns identified in ER-262 are not applicable to "Crossflow" ultrasonic flowmeter measurements.

## 5.0 REFERENCES

1. Letter from Calvin R. Hastings (Caldon, Inc.) to NRC transmitting Engineering Report ER-262, Revision 0, "Effects of Velocity Profile Changes Measured In-Plant on Feedwater Flow Measurement Systems," dated January 10, 2002.

2. Letter from Calvin R. Hastings (Caldon, Inc.) to NRC, "NRC Review of Caldon Engineering Report: ER-262," February 12, 2002.

3. Letter from Ian C. Rickard (Westinghouse) to NRC transmitting Westinghouse Topical Report WCAP-15689, Revision 0, "Evaluation of Transit-Time And Cross-Correlation Ultrasonic Flow Measurement Experience With Nuclear Plant Feedwater Flow Measurement," dated April 3, 2002.

4. Letter from Ian C. Rickard (Westinghouse) to NRC transmitting Westinghouse Topical Report WCAP-15689, Revision 1, "Evaluation of Transit-Time And Cross-Correlation Ultrasonic Flow Measurement Experience With Nuclear Plant Feedwater Flow Measurement," dated September 12, 2002.

Principal Contributor: I. Ahmed

Date: January 28, 2003