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Evaluation of Transit-Time and Cross-Correlation Ultrasonic Flow Measurement Experience with Nuclear Plant Feedwater Flow Measurement

Westinghouse

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WCAP-15689-NP, REVISION 1

EVALUATION OF TRANSIT-TIME AND CROSS-CORRELATION ULTRASONIC FLOW MEASUREMENT EXPERIENCE WITH NUCLEAR PLANT FEEDWATER FLOW MEASUREMENT

EXECUTIVE SUMMARY

Caldon, Inc. recently issued a technical report titled "Effects of Velocity Profile Changes Measured In-Plant on Feedwater Flow Measurement Systems" (Report Number ER-262). Caldon states that the purpose of the report was to discuss the effects of velocity profile changes measured in-plant on feedwater flow measurement systems using Caldon's LEFM Check and LEFM CheckPlus ultrasonic flow measurements systems and provide "new information that could affect the design bases for these instruments". According to the Caldon report, fluid velocity profiles are very dynamic and flow swirl can vary as much as 10% and more of the axial velocity measurement in these systems, which in turn can impact feedwater flow measurement accuracy.

In ER-262, Caldon also chose not to limit their technical evaluation to their own product line or their own area of expertise but went on to comment about what effects these issues might have on cross-correlation ultrasonic flow measurement technology. ER-262 notes that "Obviously, any external system in service for the determination of calorimetric power should be evaluated in light of this new data." Westinghouse Electric Company LLC (WEC) and Advanced Measurement and Analysis Group, Inc. (AMAG) subsequently performed a technical review to address the relevance of the conclusion(s) drawn in ER-262 with respect to the performance of the CROSSFLOW Ultrasonic Flow Measurement System, which is a clamp-on cross-correlation flowmeter. ER-262 offers the following key points:

(1) The Caldon multi-path transit-time chordal spool piece indicates changes in flow profile during power transients.

(2) These changes in flow profile are hypothesized to be due to spontaneous changes in feedwater pipe wall roughness that subsequently induce swirl.

(3) The consequent changes in flow profile have resulted in flow measurement errors associated with Caldon's clamp-on transit-time flowmeter. It is further speculated that this would also probably be true of all clamp-on ultrasonic flowmeters, including cross-correlation flowmeters.

(4) Based on the performance of the spool piece design, they (Caldon) should be using a flow profile factor for their clamp-on transit-time flowmeter of 0.96 (which corresponds to the factor assumed for a smooth walled feedwater pipe).

The WEC/AMAG review of ER-262 indicates that:

(1) Although ultrasonic transit-time and cross-correlation flowmeters both measure fluid velocity, there is a significant difference in the physics underlying each flowmeters operating principals and, therefore, the response of each to flow disturbances will be different. The ER-262 suggestion that what is true of clamp-on transit-time flowmeters is also true of a clamp-on cross-correlation flowmeter is not based on a full evaluation of the cross-correlation technology and the manner in which theory is translated to operational hardware and software for field implementation.

(2) 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. Thus, when installing a LEFM clamp-on,

Check or CheckPlus transit-time flowmeter using the approach described in ER-262, it would be expected that a shift in the transit-time flowmeter reading could occur during a plant transient (e.g., a power transient). Based on a review of the plant specific upstream realignment of operating equipment for events where problems have been reported, WEC/AMAG believes that these transients are due more to flow profile changes caused by the upstream realignment of operating equipment rather than abrupt changes in pipe wall roughness.

(3) Throughout WEC/AMAG's extensive experience in both ultrasonic flow measurement systems and nuclear plant operation, flow profile changes, as observed by Caldon, and attributed to abrupt changes in pipe wall roughness, have not been experienced. Changes in flow profiles have been seen due to the realignment of upstream equipment. For this reason, WEC/AMAG have strict guidelines on the calibration, operation and installation procedures for the CROSSFLOW cross-correlation ultrasonic flowmeter. It is appropriate that Caldon now plans to assess more rigorously the effect of upstream geometry in their installation procedures.

(4) ER-262 reports that the profile correction factor for their transit-time meter should have been using a value of 0.96 rather than 0.94. Although not noted in the report, this corresponds to a more conservative assumption that the interior surfaces of the feedwater pipe are smooth. WEC/AMAG have always made this assumption, thus ER-262 is now validating CROSSFLOW's long time approach.

In addition, as part of the Westinghouse/AMAG review, the following issues are discussed in detail along with supporting technical data:

- The CROSSFLOW cross-correlation based ultrasonic flowmeter is not as sensitive to flow perturbations as clamp-on the transit-time flowmeters. The reasons for the lower sensitivity is that the cross-correlation meter only tracks the axial velocity component of the fluid, while the transit-time technology is impacted by all of the velocity components including not only the axial, but the radial and tangential components as well. If swirl were to occur as hypothesized in ER-262, a cross-correlation flowmeter will behave in a predictable manner, while transit-time measurements may be biased high, low or remain unaffected, depending on the assumptions used to account for the radial and tangential flow components. Although abrupt changes in swirl or pipe wall roughness, as described in ER-262, have never been encountered in our operating experience, if these conditions were to occur, the shift in meter output would always be to increase measured flow which would be in the conservative direction. Furthermore, the velocity profile correction factor is already based on smooth pipe, so the possibility of encountering a situation where the pipe is smoother does not exist.

- The inherent limitations of model testing should be considered for all types of calibrations including calibrations that compensate for manufacturing tolerance of a multi-path chordal spool piece. WEC/AMAG have elected to use in-situ calibrations whenever there is a question about the velocity profile being fully developed at the flowmeter installation location. This approach allows the calibration to be performed under operating conditions, which eliminates the need for most laboratory calibrations. Hence, the uncertainty of having to extrapolate a laboratory calibration to plant operating conditions is minimized.

Furthermore, any local flow disturbances in the velocity profile can also be accounted for. Consequently, the CROSSFLOW Ultrasonic Flowmeter System provides outstanding flow measurement accuracy under operating plant conditions.

- Conclusions presented in ER-262 are based on Caldon's operating experience with transit-time technology and the limited information that is available in the public domain regarding cross-correlation technology. Due to the proprietary restrictions necessary to provide the continued commercial protection of CROSSFLOW, most flow measurement experts, in general, are not in a fully informed position to provide objective technical evaluations and public presentations or reports that accurately reflect the state-of-the-art in cross-correlation technology. It is, therefore, understandable why 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 problem with drawing conclusions from old information is illustrated by the attached letter AMAG recently received from Dr. David Zobin of Ontario Power Generation (OPG). Dr. David Zobin (OPG) notes, in part of his greater input that:

  > "The Caldon report specifically referenced a 1992 paper[1] by Jim Sherin, and myself and concluded that *'the sensitivity of a cross correlation meter to the axial velocity profile may be somewhat greater than that of an externally mounted transit time meter.'*

  Dr. Zobin goes on to point out that while the Caldon quote is correct as a snapshot in time (circa 1992), it is incorrect as a current interpretation of the state-of-the-art as it has evolved since that time. Dr. Zobin writes,

  > "Originally it was believed that the flow profile factor strongly depends on the fluid velocity. The statement was based on the best fit to the laboratory test data collected in 1990. *This conclusion turned out to be erroneous* (emphasis added) since the observed dependence is later proved to be due to the test loop characteristic behavior and not due to any flow profile changes."

- Both the clamp-on LEFM and the multi-path chordal systems are subject to similar issues with the electronics and ultrasonic transducer technology. While design improvements have likely been implemented over the years, utilities have continued to experience non-conservative drift or transducer failures that have led to overpower events. With CROSSFLOW's proven and unique technology, to date there have been no reliability problems in either ultrasonic transducers or the associated electronics. The permanent transducers are designed to perform indefinitely and thus far have never experienced a design or operating failure.

In summary, WEC/AMAG technical experts have completed a review of ER-262, to determine whether there is validity to Caldon's new concerns which would be pertinent to the performance of the CROSSFLOW Ultrasonic Flowmeter System. Based on this review, it has been 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 Caldon's transit-time flowmeter as documented in their report.

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Acronyms

ABB CENP	ABB Combustion Engineering Nuclear Power
AMAG	Advanced Measurement and Analysis Group, Inc.
ARL	Alden Research Laboratory
ASME	American Society of Mechanical Engineers
INPO	Institute for Nuclear Power Operations
L/D	Pipe Length/Pipe Diameter
LEFM	Leading Edge Flowmeter
LER	License Event Report
NIST	National Institute of Standards and Technology
NRC	Nuclear Regulatory Commission
OPG	Ontario Power Generation
Re	Reynolds Number
SER	Safety Evaluation Report
WEC	Westinghouse Electric Company LLC

EVALUATION OF TRANSIT-TIME AND CROSS-CORRELATION ULTRASONIC FLOW MEASUREMENT EXPERIENCE WITH NUCLEAR PLANT FEEDWATER FLOW MEASUREMENT

1.0 INTRODUCTION

Caldon, Inc. recently issued Engineering Report ER-262, "Effects of Velocity Profile Changes Measured In-Plant On Feedwater Flow Measurement Systems" (Reference 1). ER-262 concludes that under certain conditions, ultrasonic flowmeters based on the cross-correlation technology, that has been licensed by the Nuclear Regulatory Commission (NRC) for 10 CFR 50, Appendix K power uprates, may fail to meet their stated accuracy. Caldon's conclusions are based on it's operating experience with transit-time technology and the limited information that is available in the public domain regarding cross-correlation technology.

Similar concerns were raised by Caldon on February 15, 2000 in a letter to the NRC (Reference 2) where they stated "Based on our own analyses, and a review of information developed by others, Caldon is concerned that instruments measuring flow by means of cross correlating ultrasonic signals affected by eddies in the flow stream may not support a significant reduction in the 2-percent power margin of Appendix K." In response to this letter, the NRC held a public meeting on March 8, 2000 to permit Caldon to further express their concerns.

Westinghouse (formerly ABB Combustion Engineering Nuclear Power) subsequently issued a response letter (Reference 3, see Appendix A). In this letter, WEC/AMAG noted that Caldon gave a reasonable assessment of the state-of-the-art of cross-correlation technology as it existed many years ago. It was also noted that while it was understandable why the public and transit-time specialists would have limited practical application knowledge of CROSSFLOW, disclosing further information would require WEC/AMAG to "share the intellectual property that gives cross-correlation a clear technical and commercial advantage over transit-time technologies." The NRC subsequently issued the CROSSFLOW Safety Evaluation Report (SER) on March 20, 2000 with notice to Caldon (Reference 4).

One example of the problem with drawing conclusions from old information is illustrated by a letter AMAG recently received (Reference 5, see Appendix B) from Dr. David Zobin of Ontario Power Generation (OPG). Dr. David Zobin notes, in part of his greater input that:

> "The Caldon report specifically referenced a 1992 paper[1] by Jim Sherin, and myself and concluded that *'the sensitivity of a cross correlation meter to the axial velocity profile may be somewhat greater than that of an externally mounted transit time meter.'* This is based on our statement in the paper that reads: 'The flow profile correction factor has also been observed to be dependent on the flow velocity, varying between 0.92 and 0.94 over 3.5 to 4.5 m/s range."

[1] J. R. Sherin, D. Zobin, "Feedwater Flow Measurements Using Ultrasonic Cross-Correlation Flow Meter", Presented at the Nuclear Plant Performance Seminar, Miami, February 24-25, 1992

Dr. Zobin goes on to point out that while the Caldon quote is correct as a snapshot in time (circa 1992), it is incorrect as a current interpretation of thestate-of-the-art as it has evolved since that time. Again, Dr. Zobin:

> "Originally it was believed that the flow profile factor strongly depends on the fluid velocity. The statement was based on the best fit to the laboratory test data collected in 1990. *This conclusion turned out to be erroneous* (emphasis added) since the observed dependence is later proved to be due to the test loop characteristic behavior and not due to any flow profile changes."

Dr. Zobin continues:

> "More recent theoretical analysis and calibration work indicates that the value of the flow profile correction factor, although lower than that for a transit time meter, is only weakly dependent on the Reynolds number. This dependence has been validated in several tests under actual operating conditions."

As demonstrated by Dr. Zobin's observation referred to above, the fact that WEC/AMAG have guarded the release of cross-correlation/CROSSFLOW intellectual property, makes it difficult for most individuals outside of the two companies that do not have full access to the technical details provided to the NRC to meaningfully comment on CROSSFLOW Ultrasonic Flowmeter System performance.

WEC/AMAG technical experts have completed a review of ER-262, to determine whether there is validity to Caldon's new concerns, which would be pertinent to the performance of the CROSSFLOW Ultrasonic Flowmeter System. This report documents the results of the WEC/AMAG technical review; which demonstrate 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 Caldon's transit-time flowmeter as documented in their report. As noted previously , much of the technical information on cross-correlation technology is proprietary due to the large technical and commercial value associated with the intellectual property. It is, therefore, necessary that the response provided herein be treated similarly.

This report first provides a brief review of the fundamental differences between the transit-time and cross-correlation technologies. Next, the installation and operating features of the CROSSFLOW system that are designed to prevent and/or protect the system from situations similar to that encountered by the Caldon system are described. Finally, in-plant operating data that validates the accuracy and repeatability of the CROSSFLOW meter are provided.

1.1 SUMMARY OF CALDON ENGINEERING REPORT ER-262

ER-262, "Effects of Velocity Profile Changes Measured In-Plant On Feedwater Flow Measurement Systems" (Reference 1) provides Caldon's own evaluation of technical issues with their Leading Edge Flowmeter (LEFM) Check; CheckPlus and LEFM clamp-on systems that have been encountered during plant operations. These issues manifest themselves by activating the Benchmark Alarm in the LEFM Check and LEFM CheckPlus systems when the ratio of the inner to outer chordal flow velocities exceed a preset limit; indicating that a change in the velocity flow profile has occurred. The alarm has been triggered at a number of nuclear power stations, including Watts Bar, Beaver Valley and Susquehanna, where the LEFM Check or LEFM CheckPlus systems have been installed. Based on the operating experience at these plants, Caldon undertook a study to review the operating experience of the LEFM clamp-on systems. This review indicated that similar events had also occurred with the clamp-on system , but that they had gone undetected, since the errors were small typically "only 1 to 2%". It was also noted that the clamp-on system was more sensitive to flow perturbations, because of its use of a single diametrical ultrasonic beam to measure the fluid velocity. Based on these observations, Caldon speculated that a cross-correlation ultrasonic flowmeter would also be subject to the same problems associated with a changing flow profile as are their LEFM systems.

For Susquehanna and Watts Bar, the stated reason for the change in the flow profile, and, hence, the activation of the Benchmark Alarm, was a abrupt decrease in feedwater pipe wall roughness that in turn introduced swirl into the flow stream; which had been suppressed prior to the change in roughness. The Susquehanna flowmeter immediately started to return to it original readings while the Watts Bar flowmeter remained in its shifted state for about three months before it too abruptly returned to its original output. Based on these observations, Caldon concluded that swirl induced by spontaneous changes in feedwater pipe wall roughness are a potential challenge to accurate flow measurement, particularly for a clamp-on LEFM.

2.0 COMPARISON OF TRANSIT-TIME AND CROSS-CORRELATION TECHNOLOGIES

2.1 WESTINGHOUSE BACKGROUND WITH ULTRASONIC FLOW MEASUREMENT

During the 1980's, the challenge to remain cost competitive with alternate forms of power production increased the need to understand and improve nuclear plant performance. Companies began to look for new ways to measure feedwater flow (and hence plant power output) more accurately. In response to market demand, in the late 1980's WEC designed and sponsored the LEFM ultrasonic measurement technology based on "time-of-flight" or transit-time technology. Over time, this product was not considered to have long term viability and the technology was sold to a small company, Caldon, Inc.

In parallel, ABB Combustion Engineering Nuclear Power (ABB CENP) was developing their own product called FLOWTRAC, which was also based on transit-time technology. The performance of FLOWTRAC was adequate but, like WEC, ABB CENP engineers also had doubts about its long term technical and commercial viability. In the early 1990's, ABB CENP became aware of cross-correlation technology and its associated capabilities, while performing feedwater flow testing using chemical tracers at the Pickering Station in Ontario, Canada. The close agreement between the tracer and cross-correlation meter readings and the ease with which the system could be installed, convinced ABB CENP to team with AMAG.

During the mid-1990's the relationship evolved into an exclusive agreement for ABB CENP to provide the CROSSFLOW technology to the nuclear industry. This agreement was based on the principle that ABB CENP, "as a major supplier of goods and services to the nuclear power industry with an established nuclear licensing and marketing infrastructure, and activities in conducting thermal performance testing of nuclear power plants", recognized "the AMAG CROSSFLOW Equipment and Related Services as the best commercially available for the ultrasonic measurement of NPP coolant flow rates".

WEC/AMAG subsequently worked together to achieve NRC approval as a licensed technology to support 10 CFR 50, Appendix K power uprates. As noted earlier, during this time, significant technical proprietary information was generated that was, and commercial reasons. Due to the proprietary restrictions necessary to provide the continued commercial protection of CROSSFLOW, the industry, including flow measurement experts, are in general not in a fully informed position to provide objective technical evaluations and public presentations or reports that accurately reflect the state-of-the-art in cross-correlation technology and in particular for the CROSSFLOW Ultrasonic Flow Measurement System. It is, therefore, understandable why 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 The NRC was fully aware of these industry misperceptions when they heard technical concerns expressed by Caldon and other flow experts in a public forum on March 8, 2000, and, subsequently, decided that issuance of their SER for CROSSFLOW on March 20, 2000 was still appropriate. Today, the collective WEC/AMAG technical experience with both transit-time and cross-correlation flowmeters provides a sound technical base for understanding and comparing the performance of both technologies.

2.2 FUNDAMENTALS OF TRANSIT-TIME TECHNOLOGY

Both transit-time and cross-correlation flowmeters measure fluid velocity, however, they are based on entirely different underlying physical phenomena and hence, respond differently to various flow disturbances and operational conditions (e.g., fluid temperature).

The transit-time technology measures a local fluid velocity within a pipe by measuring the difference in the time that it takes a narrow ultrasonic beam pulse to travel upstream against the direction of flow versus the time that it takes a similar pulse to travel downstream with the flow; the velocity of the fluid is proportional to the difference in these times. Since this measured velocity includes axial, radial and tangential components, when the flow is not fully developed, the meter must be calibrated to compensate for these components in order to obtain the correct fluid axial velocity.

The transit-time clamp-on system has encountered both transducer reliability and repeatability problems due to the complex mounting of the transducer crystals on the surface of the pipe in order to inject the ultrasonic signal at an angle to the axis to the pipe. To avoid this problem, the chordal meter includes holes drilled at an angle into the sides of the pipe. The holes allow the ultrasonic transducers to be mounted so that opposing transducers face each other. Unfortunately, the presence of these holes introduce turbulence into the flow that adds an additional random velocity component to the velocity measurement that must be corrected for through a laboratory calibration. This is one reason why each chordal meter must be calibrated in the laboratory; to correct for this random error. However, as will be discussed under Section 2.5.1 "Model Testing", the ability to accurately predict how this calibration changes as the Reynolds number is increased to plant operating conditions can be challenging. Since this laboratory calibration is on the order of 0.7%, as noted in a Caldon publication describing the calibration of their meter for the Beaver Valley piping configuration, and the claimed accuracy of the meter is 0.3%, it would be prudent to validate the meter's accuracy under operating conditions rather than under only laboratory conditions.

The difference in the measured transit-time delay with and against the flow is a small number (≈1 μsec) calculated from two larger numbers (≈500 μsec). Therefore, the potential to introduce inaccuracy is not insignificant and must be carefully addressed in the measured fluid velocity (temperature changes, electronic noise, cable lengths, etc.). Installing the ultrasonic transducers on a machined spool piece helps to control some of these measurement uncertainties. Both the clamp-on LEFM flowmeter and the multi-path chordal spool piece flowmeters use identical technology to determine the fluid velocity within the confines of the ultrasonic beam.

One difference between the various types of transit-time flowmeters is the number of ultrasonic beams that are used to measure the flow. The clamp-on flowmeter utilizes a single ultrasonic beam that passes through the diametrical center of the pipe, while the chordal multi-path spool piece flowmeters use four (4) or eight (8) ultrasonic beams to measure the flow velocity along each of the chordal beams.

This approach has the benefit of making the chordal system less sensitive to velocity profile perturbations. It is, however, still affected by velocity profile perturbations as documented by the Watts Bar, Susquehanna and Beaver Valley incidents.

A second difference between transit-time meters is the manner in which the flowmeter determines the bulk fluid velocity. The clamp-on flowmeter must assume that the velocity profile is known in order for a single ultrasonic beam to measure the flow. If the velocity profile is not known, the only way it can be determined is by calibration. A chordal multi-path flowmeter is more flexible than the clamp-on meter in that it is less sensitive to distortions in the flow profile due to the multiple beam measurements. However, certain assumptions about velocity profiles or hydraulic calibrations and conditions of the calibration should be maintained during field operation in order achieve the expected accuracy.

2.3 FUNDAMENTALS OF CROSS-CORRELATION TECHNOLOGY

The cross-correlation flowmeter determines the velocity of the fluid by measuring the velocity of eddies within the fluid using a mathematical process called cross-correlation. The measurements are performed by passing an ultrasonic beam through the fluid perpendicular to the axis of pipe. As the ultrasonic beam passes through the fluid, the eddies impart a phase shift to the ultrasonic signals that form a unique pattern. A second set of transducers is located a known distance downstream, which performs the same function. As the pattern of eddies pass through the second ultrasonic beam, they also impart a similar pattern of phase shifts to the second ultrasonic beam. Each of these patterns are removed from the ultrasonic signal, digitized and then analyzed to determine how many milliseconds 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 in the pipe can be calculated.

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. Therefore, the measured flow is not sensitive to the same conditions that can challenge transit-time technology flowmeters (i.e., electronic noise, cable lengths, changes in temperature, transducer beam orientation, etc.). A schematic showing the difference in the orientation of the cross-correlation and the clamp-on transit-time meter is shown in Figure 1.

2.4 DIFFERENCES IN SENSITIVITY BETWEEN THE TRANSIT-TIME AND CROSS-CORRELATION TECHNOLOGIES

The transit-time flowmeter measures the speed of sound in water both with and against the flow in the pipe. This is used to calculate the velocity of the fluid within the confines of the narrow ultrasonic beam. As a result, any component of fluid velocity including not only the axial velocity component of the fluid, but also the radial and tangential velocity components are all superimposed on the measurement. It is precisely because these additional components are captured, that the single beam clamp-on diametrical flowmeter is more sensitive to changes in the velocity profile. The chordal multi-path flowmeter is also impacted in the same manner, but because four (4) or eight (8) measurements are taken, the overall variation in the fluid velocity measurement is somewhat reduced.

The difference in sensitivity due to upstream flow disturbances between cross-correlation and transit time clamp-on meters can be seen in Figure 2. In this figure, the difference in velocity profile factor for horizontal and vertical orientation of single-beam transit time and cross-correlation transducers is shown downstream of a 90^0 bend. The transit-time meter data was generated by NIST using a numerical simulation and a Reynolds number of 3 million. The cross-correlation meter data was obtained during hydraulic laboratory tests at Ontario Hydro, where the Reynolds number equaled 1 million. For the cross-correlation meter, the difference between the horizontal and vertical meter readings was ≤0.5%, while the corresponding differences in the transit-time meter readings were about 8% at a distance of 10 pipe diameters downstream of the elbow and still had a 4% difference at 50 pipe diameters downstream of the elbow.

These dramatic differences in meters 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.

Another example of the difference in sensitivity to changes in the velocity profile is illustrated in Figure 3. Flow readings of five transit-time clamp-on meters from different vendors (Sections A-D and F) and the CROSSFLOW meter (Section E) were compared with weigh tank data at the NIST hydraulic Laboratory for four different installations and three different Reynolds numbers. Vendor meters A, B, C and F (Vendor meter D had more significant deviations) are all biased high by approximately 2%. At the same time, the cross-correlation meter has an average deviation of only 0.05% from the weigh tank data. All meters were installed assuming that the velocity profile in the pipe was fully developed. It was later determined using Laser-Doppler flow measurements, that there was a small non-symmetry in the velocity profile, which affected the transit-time meters significantly more than the cross-correlation meter.

2.4.1 Sensitivity to Swirl

If swirl were to occur as hypothesized in ER-262, the transit-time flowmeter may be biased high, low or remain unaffected, depending on the orientation of the radial and tangential velocity components. If the swirl happened to be perfectly centered about the axis of the pipe, the tangential velocity components would be cancelled out. However, under most conditions, this is not the case, so the impact of the swirl is difficult to predict.

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2.4.2 Effects of Temperature Transients

For transit-time flowmeters, a change in temperature can affect the flow measurement. Changes in pipe and water temperature, especially for clamp-on transit-time flowmeters, can result in a change in the angle of transmission of the ultrasound beam that may bias the measurement. For this reason, clamp-on transit-time flowmeters must be adjusted to reflect the plant's normal operating conditions.

This difficulty is avoided with the cross-correlation flowmeter, since the ultrasonic transducers are mounted perpendicular to the pipe, thus avoiding the miss-alignment of the transducers due to the thermal growth of the pipe.

2.4.3 Electronics and Transducer Technology

Both the clamp-on LEFM and the multi-path chordal systems are subject to similar issues with the electronics and ultrasonic transducer technology. While design improvements have likely been implemented over the years, utilities have continued to experience non-conservative drift or transducer failures that have led to overpower events. One such overpower event occurred at Comanche Peak where an error was introduced in the phase relationship between the ultrasonic transducers, when they were changed out during an outage. In turn, this caused the transit-time flowmeter to read low, which would have resulted in an overpower event if it had not been detected before the plant reached full power. Information concerning this event can be found in the Institute for Nuclear Power Operations (INPO) Report No. 50-445.

Similarly, a failure at the Point Beach station resulted in a low flow indication of between 1.25% and 2%, which did lead to an overpower condition of between 101.25% and 102%. The problem was traced to a degradation in the ultrasonic transducer signal. Unfortunately, this problem was not caught before the overpower condition had occurred. The initial replacement of the ultrasonic transducers also failed due to a high signal to noise ratio. Ultimately, the ultrasonic transducers and push rod assemblies had to be replaced and the electrical alignment adjusted, before the system could again be declared operational. The event was reported as required by 10 CFR 50.73(a)(2)(i)(A), "The completion of any nuclear plant shutdown required by the plant's Technical Specifications." Information on the Point Beach event can be found in License Event Report (LER) No. 94-001-01, dated September 29, 1994.

A more recent event occurred at St Lucie Unit 2 where an overpower event was caused by a gradual drift in the transit-time flowmeter, which was ultimately traced to a degraded ultrasonic transducer (Reference 6). These are not isolated events in that other utilities using transit-time based flowmeters have also recently experienced step changes in flow indication following ultrasonic transducer replacement.

With CROSSFLOW's proven and unique technology, to date there have been *No* reliability problems in either ultrasonic transducers or the associated electronics. The permanent transducers are designed to perform indefinitely and thus far have *NEVER* experienced a failure. [

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2.5 INSTALLATION CONSIDERATIONS

As with all flowmeters, it is important that the upstream flow conditions be evaluated during the selection of a location for an ultrasonic flowmeter. Thus, 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 installation location. Knowledge concerning the number of pipe diameters (i.e., L/Ds) required for dissipation of a disturbance is based on experience, model tests and from the technical literature.

2.5.1 Model Testing

Hydraulic laboratory model testing is used very sparingly because of its limitation for ultrasonic flowmeters. It is often assumed that a full-scale model of a piping installation is the ultimate means for calibrating a flowmeter. The bases for this assumption is that all venturis, orifice plates and nozzles are calibrated in this manner, therefore, it should be appropriate for ultrasonic flowmeters as well. This is not necessarily a fully valid assumption.

A good example of this limitation for model testing was demonstrated a few years ago, when a full-scale model of the feedwater piping configuration at a nuclear power plant was replicated at the Alden Research Laboratory in order to calibrate a clamp-on transit-time flowmeter. When the flowmeter was later installed in the plant, it indicated that the feedwater flow was 2.6% lower than the plant instrumentation. Fortunately, the performance engineer at the plant questioned the results of the transit-time meter and requested additional testing.

A cross-correlation flowmeter was then installed in the same location as the transit-time meter, but it was assumed that the velocity profile was fully developed and that the pipe walls were smooth. The cross-correlation meter readings were within 0.1% of the venturi readings. To further support the accuracy of the venturis, chemical tracer tests were also performed that again confirmed that the venturis were operating properly. Finally, the venturis were actually cut out of the piping and sent to the Alden Research Laboratory, where again their accuracy was confirmed through weigh tank tests. Thus, the utility was able to avoid an overpower incident of 102.6%.

This example demonstrates how important it is to understand the limitations of laboratory tests. Most likely, the laboratory tests were conducted using pipe with an interior surface roughness that was greater than what existed in the plant and the velocity profiles were not fully developed during the laboratory tests. ER-262 confirms that the vendor has recently become aware of one of these limitations. The report states on page 11, "Another conclusion can be drawn from Table 2. The mean profile factor for external transit-time meters in all hydraulic locations of this table is 0.964 – nearly 2% above the profile factor of an external transit time meter for fully developed flows in commercial steel pipe at feedwater Reynolds number".

In contrast, to avoid this particular problem, the CROSSFLOW meter was calibrated using smooth plastic pipe, which more closely corresponds to the internal surface of feedwater pipes.

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It should be noted that while laboratory calibrations for ultrasonic flowmeters have to be conducted more carefully, they are quite appropriate for pressure differential devises such as venturis and orifices, which are not as sensitive to profile changes due to pipe wall roughness and upstream flow disturbances. This is because most venturis that are installed in power plants have a beta ratio (venturi throat diameter to the upstream pipe diameter) that is in the range of 0.5. A review of the literature will show that the sensitivity of a venturi to upstream flow disturbances increases as the beta ratio is increased. The reason for this change is the ability of the venturi to dominate the flow streams as the fluid passes through the venturi throat. As the beta ratio is increased, the venturi has a decreasing influence over the incoming flow profile, making it more sensitive to any distortions in the upstream flow. For an ultrasonic flowmeter, the effective beta ratio is one (1), since there is no change in the pipe diameter, thus the profile is totally dependent on the upstream flow conditions.

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Caution should be exercised when using model testing for ultrasonic flowmeters, for all types of calibrations including calibrations that compensate for manufacturing tolerances of a multi-path chordal spool piece. For example, the chordal meter includes holes drilled into the sides of the pipe to allow the transducer crystals be aligned. These cavities introduce turbulence into the flow stream that must be calibrated out through laboratory testing. Furthermore, it is known that the turbulence within these cavities, which is in-line with the ultrasonic beam, is dependent on the Reynolds number. Since the Reynolds number is significantly different for laboratory calibrations and plant conditions, an adjustment must be made to compensate for this difference. This can be a significant challenge, since as noted above, there is no empirical formula for predicting how this turbulence will change. The approach that assures the correction has been done correctly and is validation of the meter accuracy under plant operating conditions.

2.5.2 In-situ Calibrations

To minimize reliance on laboratory calibrations, WEC/AMAG have elected to use in-situ calibrations, when there is a question about the velocity profile being fully developed at the preferred flowmeter installation location. In this situation, a second CROSSFLOW meter can be used at a location where there is no question about the condition of the flow profile to validate the assumption of fully developed flow. This approach allows the calibration to be performed under operating conditions, which eliminates need for laboratory calibration. Hence, the uncertainty of having to extrapolate the calibration to a higher Reynolds number is eliminated.

2.6 CROSSFLOW ON-LINE MONITORING PROTECTION

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Another software feature provides protection not only for rapid venturi defouling events but also protects against abrupt changes in pipe swirl, if it were to occur. However, in all the CROSSFLOW operating experience to date, an abrupt shift in swirl has never been encountered, but if it were to occur, the system would detect the change and alert the operator, even though the shift would be in the conservative direction.

2.7 VERIFICATION OF METER ACCURACY

The ultimate proof of any flowmeter's accuracy is its verification under actual field conditions. As noted earlier, records of ultrasonic flowmeter accuracy, which are based entirely on laboratory tests, are of questionable value because of the challenges associated with accurately extrapolating a laboratory calibration that is not performed under fully developed flow conditions, to actual plant operating conditions. Hence, if a calibration must be performed to compensate for spool piece manufacturing tolerances, for example, the extrapolated calibration should be verified under actual plant operating conditions to maximize the accuracy of the flow measurement. The basis for this recommendation is that the distortion in the flow profile may not represent a fully developed flow condition, thus it is likely subject to change as the Reynolds number is increased.

In general, verification is difficult, since existing plant instrumentation is not capable of providing the same level of flow measurement accuracy that is claimed for ultrasonic flowmeters. [

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The fact that the average difference between the cross-correlation and plant flow instrumentation in Table 1 is only 0.04%, confirms the accuracy not only of the ultrasonic flowmeters used in these tests, but the belief that the plant instrumentation was also accurate at the time of the tests. The fact that two independent means of measuring the same flow (ultrasonic and differential pressure instruments), provide close agreement, each with it's own unique uncertainties, is strong evidence that both instruments are measuring the flow correctly.

These tests also support another point: that the interior walls of feedwater pipes are quite smooth. The bases for this conclusion is again the close agreement between the ultrasonic flowmeter readings and the plant instrumentation. The ultrasonic flowmeter was calibrated using plastic piping, in order to assure that the calibration would be conservative, since a calibration based on rough wall pipe and then used in an application were the pipe wall was smooth would create a non-conservative measurement. However, based on these results, it must be concluded that the assumption of smooth wall pipe is also valid for the interior surface of feedwater pipes. If this were not the case, there would be a bias between the cross-correlation and plant instrumentation readings, with the ultrasonic flowmeter reading tending to be higher. This observation provides further evidence that the interior surfaces of the piping are always smooth and that abrupt changes to a smoother surface that is already smooth is not possible.

There are technical reasons why the feedwater piping interior wall surface is generally considered to be smooth. In any piping system there are two forces at work, general corrosion and flow assisted corrosion (FAC); sometimes referred to as corrosion-erosion. Because of well documented experiences with corrosion and FAC in feedwater piping, utilities take great care to minimize its occurrence. General corrosion occurring in feedwater systems is minimized by utility control of water chemistry (e.g., of oxygen and pH) following established industry guidelines (e.g., EPRI). General corrosion results in a uniform and very slow dissolution of material and, therefore, is not a process that would be a likely source of abrupt changes in pipe wall roughness. Under nominal feedwater chemical conditions, localized forms of corrosion, such as pitting, which can produce roughened surfaces, do not occur. On the other hand, FAC has occurred in feedwater piping systems (as well as other secondary side systems). In areas where FAC has occurred, the pipe inside diameter surfaces can become roughened. Such areas, however, have been limited to piping locations where diameter or directional changes are present (e.g., elbows) and result in increased flow turbulence. Otherwise, FAC has been minimal and, in conjunction with general corrosion, has had the effect of producing a smooth pipe wall interior surface with only very minor wall loss.

Again, FAC is not a process that would be a likely source of abrupt changes in pipe wall roughness.

3.0 CONCLUSIONS

3.1 FLOW PERTURBATION SENSITIVITY

The information presented in this report demonstrates why the CROSSFLOW, cross-correlation based, ultrasonic flowmeter is not as sensitive to flow perturbations as clamp-on transit-time flowmeters. 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 technology is impacted by all of the velocity components including not only the axial, but the radial and tangential components.

3.2 AVOIDANCE OF AN OVERPOWER CONDITION

Although the explanation for the appearance of swirl, suggested in ER-262, as being due to an abrupt change in pipe wall roughness is questionable, if it were to occur, its impact on a cross-correlation based flowmeter would be to increase the flow reading. This would be a conservative rather than non-conservative error as suggested in ER-262, thereby, it would preclude the potential for creating an overpower condition such as have occurred in plants employing transit-time technology. Furthermore, there are software features that provide protection from not only a change in swirl, but also other changes in the flow stream, such as from upstream disturbances. [

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3.3 INFLUENCE OF UPSTREAM DISTURBANCES ON FLOWMETER PERFORMANCE

Closer examination of the Caldon data presented in ER-262 Tables 1 and 2 indicates that the reported events of an abrupt flow profile change occurred when the ultrasonic transducers were apparently located too close to a source of an upstream disturbance, that can change with operational realignment of equipment. The CROSSFLOW system location/installation procedure does not allow for locating the flowmeter where such upstream disturbances could be detrimental to its accurate performance.

3.4 CALIBRATION FACTOR DETERMINATION

It appears from ER-262 that Caldon has come to the conclusion, based on experience with their multi-path choral spool-piece design, that the appropriate flow profile factor for their clamp-on transit-time system should be 0.96 rather than 0.94. A flow profile factor of 0.96 for a transit-time flowmeter is appropriate for smooth wall pipe. This corroborates the WEC/AMAG claim that the interior surfaces of feedwater pipes are smooth.

3.5 CONFIRMATION OF FLOWMETER ACCURACY

This report documents the only true verification of a flowmeter's accuracy – one where the accuracy is confirmed under actual plant operating conditions using independent and diverse measurement techniques. As noted in this report, verification of a flowmeter's accuracy under laboratory conditions, while acceptable for differential pressure devises, can be questionable for ultrasonic flowmeters due to the uncertainty of extrapolating the calibration to plant operating conditions, unless the laboratory calibration is performed under fully developed flow conditions.

In summary, the CROSSFLOW ultrasonic flowmeter, using cross-correlation technology, continues to provide robust and accurate measurement of feedwater flow in nuclear power plants world wide. The technical speculation suggested by Caldon in ER-262 is not applicable to cross-correlation ultrasonic flow measurement technology in general and CROSSFLOW in particular.

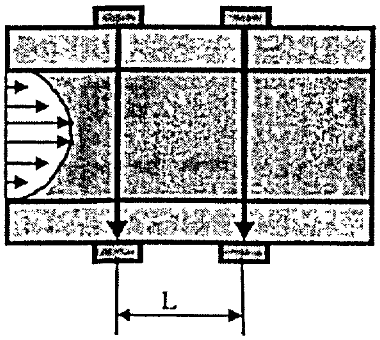
4.0 REFERENCES

1. Caldon Letter, C. R. Hastings (Caldon) to J. A. Zwolinski (NRC), "Caldon Engineering Report: ER-262, Effects of Velocity profile Changes Measured In-Plant on Feedwater Flow Measurement Systems", January 10, 2002
2. Caldon Letter, Calvin R. Hastings to USNRC, "Information on Ultrasonic Flow Measurement Instrumentation, dated February 15, 2000.
3. ABB CENP Letter, I. C. Rickard to USNRC Document Control Desk, "ABB CENP General Response to Public Meeting Regarding Caldon, Inc. Ultrasonic Flow Measurement Representation of Cross-Correlation Flowmeters Technology", LD-2000-0018, March 13, 2000
4. NRC Letter, Stuart A. Richards to Calvin R. Hastings, "Caldon Letter dated March 17, 2000, Regarding ABB Response to the March 8, 2000, Meeting with NRC", dated April 6, 2000.
5. OPG Letter, Dr. D. Zobin (OPG) to Dr. Y. Gurevich (AMAG), "Comments on Caldon Report – ER 262", February 28, 2002
6. FPL Letter, Rajiv. S. Kundalkar (FPL) to USNRC Document Control Desk, "St Lucie Unit 2 Follow-Up Report, License Condition 2.F", L-2000-221, October 16, 2000

Table 1 Comparison of Cross -Correlation Meter with Plant Instrumentation						
Plant Number	Meter Location	Reynolds Number	X-Correlation (K#/Hr)	Plant (K#/Hr)	Difference (%)	Comments
1	Common Header	25,000,000	14850 0	14854.0	-0 03	Venturi calibrated prior to test at Alden
2	Loop B	15,000,000	4047.0	4051.0	-0 10	Venturi accuracy confirm at Alden
2	Loop C	15,000,000	4107.0	4104.0	0.07	Venturi accuracy confirm at Alden
3	Loop A	20,000,000	7463.1	7463.1	0.00	Venturi defouled prior to test
3	Loop B	20,000,000	7479.9	7478.9	0.01	Venturi defouled prior to test
4	Loop A	20,000,000	7409.3	7404.9	0.06	Venturi defouled prior to test
4	Loop B	20,000,000	7374.6	7373.6	0.01	Venturi defouled prior to test
5	Loop B	11,000,000	5471.2	5487.9	-0 30	Venturi calibrated prior to test at Alden
6	Loop B	13,000,000	3675.0	3665.0	0.27	Verified using nozzle with wall rather than throat tap
7	Loop 2A	11,000,000	3073.0	3065.0	0.26	Verified using tracer test
7	Loop 2B	11,000,000	3151.4	3147.4	0.13	Verified using tracer test
8	Common Header	14,500,000	3988.5	3983.8	0.12	Verified using orifice plate
			Average Difference =		0.04	

FIGURE 1

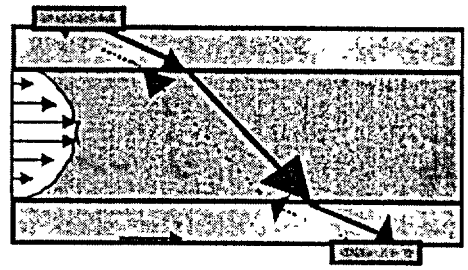
Comparison of Cross-Correlation vs. Transit-Time



$V_m = L/\tau^*$

$\tau^* \approx 50\text{ms}$

CROSS-CORRELATION FLOWMETER



$V_m = \Delta T C^2/(2L\cos\alpha)$
$V_m = L(T_1-T_2)/(2T_1T_2\cos\alpha)$
$\Delta T \approx 1\mu s$

TRANSIT-TIME FLOWMETER

Figure 2
Difference In Flow Profile Factor Between Vertical and Horizontal Oriented Transducers Downstream of Elbow for CROSSFLOW and Transit time meter

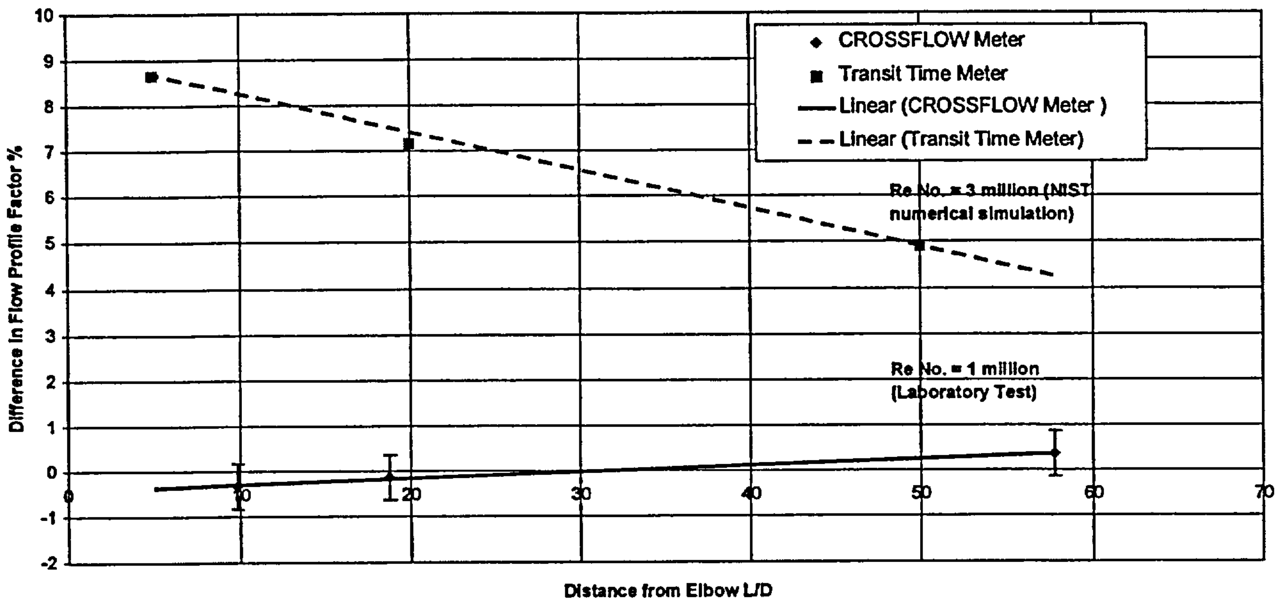


Figure 3

Response of Clamp-on Transit-Time Meters and A Cross-Correlation Meter Due to Slightly Non-Fully Developed Flow Profile

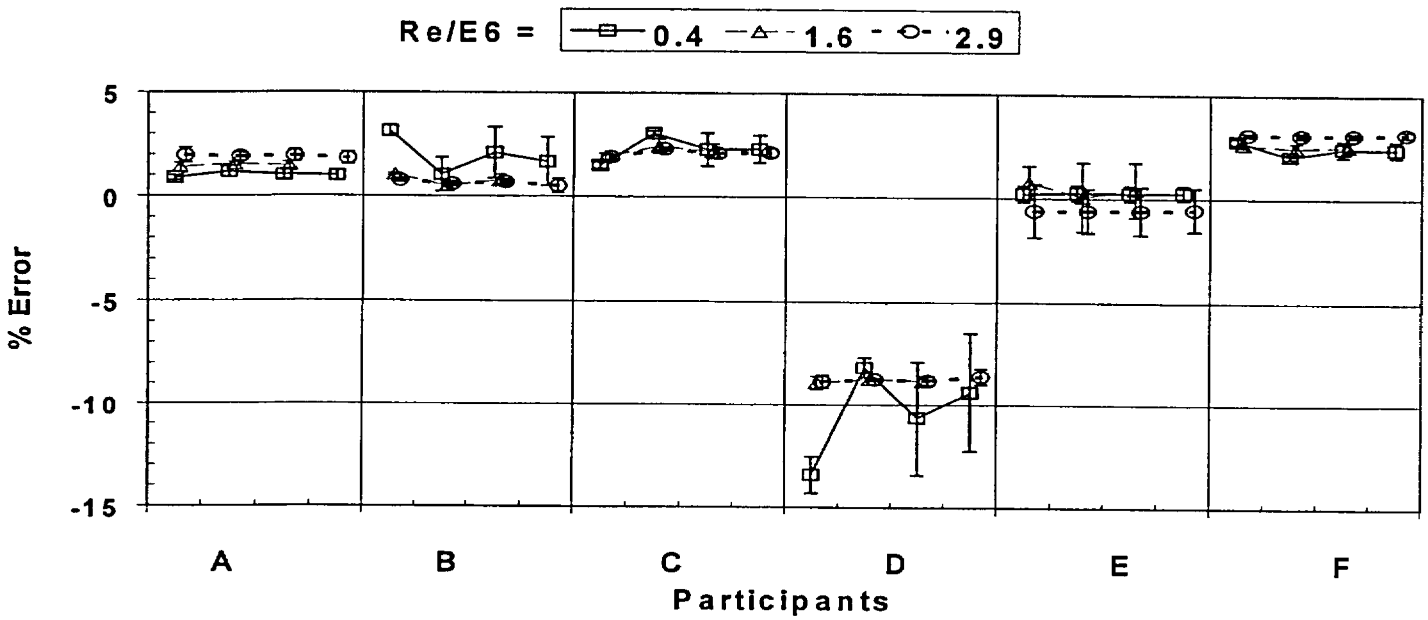


FIGURE 4
RESPONSE OF CROSSFLOW BEFORE AND AFTER A SIGNIFICANT POWER TRANSIENT

FIGURE 5

Comparison of CROSSFLOW Data with Plant Instrumentation

APPENDIX A

ABB CENP LETTER, IAN C. RICKARD TO USNRC, LD-2000-0018

"ABB CENP GENERAL RESPONSE TO PUBLIC MEETING REGARDING CALDON, INC. ULTRASONIC FLOW MEASUREMENT REPRESENTATION OF CROSS-CORRELATION FLOWMETERS TECHNOLOGY"

ASEA BROWN BOVERI

13 March, 2000
LD-2000-0018

U. S. Nuclear Regulatory Commission
Attn: Document Control Desk
Washington, D.C. 20555

SUBJECT: **ABB CENP GENERAL RESPONSE TO PUBLIC MEETING REGARDING CALDON, INC. ULTRASONIC FLOW MEASUREMENT REPRESENTATION OF CROSS-CORRELATION FLOWMETERS TECHNOLOGY**

References:
1) Letter, C. R. Hastings (Caldon) to USNRC Document Control Desk, "Information on Ultrasonic Flow Measurement Instrumentation", February 15, 2000
2) Letter I. C. Rickard (ABB CENP) to USNRC Document Control Desk, "Submittal of CENPD-397-P, Rev. 01 – Improved Flow Measurement Accuracy Using CROSSFLOW Ultrasonic Flow Measurement Technology", LD-2000-0002, January 6, 2000 {Contains Proprietary Information}

On March 8, 2000, the Nuclear Regulatory Commission (NRC) held a public meeting with Caldon, Inc. The purpose of the meeting was to provide Caldon an opportunity to discuss the state-of-the-art of ultrasonic flow measurement (UFM) technology, as a follow-up to Caldon's submittal made on February 15, 2000 (Reference 1). Caldon indicated in its submittal that certain factors may be relevant to NRC's ongoing review of cross-correlation technology. Although the Caldon letter did not specifically mention ABB C-E Nuclear Power, Inc. (ABB CENP), Advanced Measurement and Analysis Group, Inc. (AMAG) or the CROSSFLOW UFM System by name, the ongoing NRC review activities are associated with the ABB CENP topical report CENPD-397-P, Rev. 01, "Improved Flow Measurement Using CROSSFLOW Ultrasonic Flow Measurement Technology" (Reference 2). Following the public meeting, the NRC verbally requested that ABB CENP provide a general response to the issues raised at the meeting. This letter provides the requested response.

GENERAL COMMENTS:

The topics discussed by Caldon and its consultants that participated in the public meeting are well know to ABB CENP and AMAG and we believe are effectively addressed in Reference 2. Much of the information provided by Caldon gives a reasonable assessment of the state of the art as it existed a number of years ago. In reviewing the Caldon submittal, it is interesting to note that many papers were authored by either current AMAG employees or users of the cross-correlation and CROSSFLOW technology. However, there is a balance of significant, proprietary information missing from the presentation. This information includes cross-correlation technology knowledge

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gained by Canadian General Electric in the early 1970's, continued research and development by Ontario Power Generation (formerly Ontario Hydro) through the 1980's and further development by AMAG since the early 1990's. AMAG was founded and is presently led by individuals who played key roles in development of cross-correlation technology for Ontario Power Generation and Canadian General Electric. AMAG has advanced the development and application of CROSSFLOW technology with financial support from the Canadian government, commercial contracts and its partnership with ABB CENP.

ABB CENP has also invested in the continued development of cross-correlation technology since its relationship with AMAG was initiated in the early 1990's. As a designer of light water reactor Nuclear Steam Supply Systems (NSSS) and provider of nuclear services and fuel world wide, ABB CENP has performed multiple and rigorous multi-disciplined expert reviews of the CROSSFLOW technology including hardware design, software, data acquisition, ultrasonics, thermal hydraulics and uncertainty analyses. ABB CENP promotes the CROSSFLOW solution to the nuclear industry because the product meets the high standards of quality, technical excellence and integrity that we insist upon as a reputable supplier to the nuclear industry.

Based on the meeting with the NRC Staff on March 8, 2000, it is understandable why the public and transit time specialists would have limited practical application knowledge of a cross-correlation based ultrasonic flow measurement system. However, disclosing this type of information to the public would require ABB CENP and AMAG to share the intellectual property that gives cross-correlation a clear technical and commercial advantage over transit time technologies. Although cross-correlation technology have been understood for years, the required data processing necessary to perform the statistical averaging in an accurate, timely and cost-effective manner was not commercially viable until the past decade. Today's enhanced computing power together with AMAG's advancements in ultrasonic cross-correlation application and sophisticated acoustical design, have allowed AMAG and ABB CENP to significantly evolve, validate and verify the technology. We believe it is the technology for the present and for the future and that the many potential applications and opportunities across many industries are yet to be identified and realized.

SPECIFIC COMMENTS:

ABB CENP is confident that the information already provided in the base topical report and in responses to the NRC Request for Additional Information (RAI) addresses all issues of interest to the NRC Staff as part of its comprehensive review effort. However, we would like to respond publicly to selected issues raised during the March 8, 2000 meeting to assist the public in understanding the current state of cross-correlation technology.

- Theoretical Basis of Cross-Correlation Technology

  The theory of flow measurement in a pipe using ultrasonic cross-correlation technology for single-phase flow originated in the 1970's as an empirical relationship. It was further developed into a theoretical relationship and verified by AMAG in the

1990's. This issue is addressed in the topical report, Sections 2 and 4, and again in the RAI's and Supplementary Record documents.

- Effect of Upstream Disturbance on Flow Measurement

  All flow measurement devices, including venturis, clamp-on transit time, chordal multi-path transit time, cross-correlation etc., are affected by upstream disturbance. To provide accurate flow measurement, the effect of this upstream disturbance must be accounted for and established via installation criteria that have to be met to achieve the specified accuracy. For example, the specific flow meter has to be installed at a certain distance downstream of the disturbance. This issue is addressed in the topical report, Section 5.6.

- Influence of Acoustical Noise

  The influence of acoustical noise on cross-correlation feedwater flow measurements has been investigated in detail by Canadian General Electric, Ontario Power Generation and AMAG starting in the 1970's. During the last five years, AMAG has performed a comprehensive analysis of this effect. This resulted in a new system design and methodology that has reduced the effect of acoustical noise to a minimum to achieve the specified accuracy. This issue is addressed in the topical report, Section 3.

- Percentage of Flow Stream Measured with Cross-Correlation Technology

  The CROSSFLOW ultrasonic beam interacts with the turbulence in the flow over the whole pipe diameter. The distribution of this effect varies depending on the design and methodology used to extract the required information related to flow measurement. CROSSFLOW monitors all eddies that are required for the determination of accurate feedwater flow. This is addressed in the topical report, Section 2.3, and in the RAI document.

- Accuracy of Clamp-on Ultrasonic Flowmeters

  During the March 8 presentation, Dr. George Mattingly, from the National Institute of Standards and Technology (NIST), stated that none of the five ultrasonic flow meters that NIST had tested had an accuracy of less than 1%.

  This conclusion is based on making an instantaneous comparison of the flow measurements by the CROSSFLOW system with the weigh tank results. As discussed in the topical report, Section 3.2.4.6, CROSSFLOW was designed to accurately measure flow as an average of a number of readings, which is appropriate in feedwater flow applications.

  An ABB CENP and AMAG analysis of the NIST weigh tank test results (obtained from NIST) demonstrates that the CROSSFLOW flow measurement accuracy is consistent with the accuracy specified in the topical report.

SUMMARY/CONCLUSIONS

ABB CENP and AMAG have carefully reviewed the non-proprietary portion of Caldon's submittal (Reference 1) as well as the transcripts and handouts from the March 8, 2000 public meeting. Our review has not uncovered any new technical issues that would prevent the NRC from issuing an SER for CENPD-397-P, Rev. 01. We believe the appropriate technical information to support our conclusion is provided in Reference 2 and the associated RAI responses.

If you have any remaining questions concerning this matter, please do not hesitate to call me or Chuck Molnar of my staff at (860) 285-5205 if we may be of further assistance.

Very truly yours,
ABB C-E NUCLEAR POWER, INC.

Ian C. Rickard, Director
Nuclear Licensing

xc: J. A. Calvo (NRC)
J. S. Cushing (NRC)
J. E. Donoghue (NRC)
E. C. Marinos (NRC)

APPENDIX B

ONTARIO POWER GENERATION COMMENTS ON CALDON REPORT - ERL-262

ONTARIO POWER GENERATION

700 University Avenue Toronto, Ontario M5G 1X6

February 28, 2002

Dr. Y. Gurevich
Senior Engineering Scientist
Advanced Measurement & Analysis Group, Inc.
2396 Dunwin Drive
Mississauga, Ontario L5L 1J9

Subject: Comments on Caldon Report – ERL 262

Dear Yuri:

Since Ontario Power Generation has used the cross-correlation technology for ultrasonic flow measurements for nearly 20 years (over 300 unit-years of operating experience) and since the above report addresses issues that adversely reflect on the accuracy of feedwater flow calibration, I would like to offer the following comments:

1. General Comments

a) We have not observed the sudden changes in pipe roughness/swirl that were detected by the LEFM plus during power coast down. If the alarm were due to changing plant conditions (e.g. specifically changes in pipe roughness) that result in flow profile changes, one would expect many more alarms over many system-years of operation. The fact that Caldon's experience has only three alarms on all 18 installations makes hardware/software problems a much more likely cause.

b) Without access to Appendices A and B it is impossible to comment on the statement "...the operational transient appears to have brought a sudden decrease in pipe wall roughness". In general, there has been no indication from any type of data that feedwater pipes have significant roughness. In fact, the common opinion among plant engineers is that they are quite smooth due to the magnetite layer formed on the pipe inner surface. Although the above scenario of sudden change in roughness is not likely, it will be hard to prove or disprove since measurement of hydraulic roughness is a non-trivial exercise.

c) It has been stated in previous publications that the CROSSFLOW calibration is done on smooth pipes precisely because it gives a conservative value of the flow profile correction factor. In other words, CROSSFLOW reading on a rough pipe having the same piping configuration as a smooth pipe will be higher. If the pipe roughness decreases, the CROSSFLOW reading will drop but will still be higher than the value for a smooth pipe. Over the years we have done extensive comparison of ultrasonic cross-correlation feedwater flow measurements with the results of modified PTC-6 tests, chemical tracing, and ASME nozzle data. The comparison has unambiguously shown that the assumption of smooth pipe is valid in the case of feedwater pipes in CANDU plants.

d) Deviation of the flow profile from the fully developed value for the CROSSFLOW has been studied extensively for an upstream single 90° bend, an upstream T-junction, and for a pair of out-of-plane 90° bends. It has been demonstrated that the value of the flow profile correction factor approaches that for the fully developed flow at distances from the upstream disturbance, which are much shorter than for transit-time meters. (typically between 15 and 40 L/D, depending on Reynolds number and the type of disturbance). Specifically, for a swirl generating pair of out-of-plane 90° bends, our recent tests showed that the flow profile correction factor is about 1% lower than the fully developed value at distances between 10 and 30 L/D. This means that for a typical CROSSFLOW installation downstream of a pair of out-of-plane 90° bends the flow measurement will be conservative (higher) if one uses the fully developed flow profile correction factor.

2. Comments on CROSSFLOW vs. Caldon Installation

Table 1 in the Caldon report lists hydraulic geometry, i.e. piping configuration, for a number of Caldon installations. Only one hydraulic geometry in the Table 1 would qualify for a CROSSFLOW installation.

Our experience indicates that except for that one location, the measurement accuracy would be dependent on upstream conditions. In these cases, either an alternative location would be selected or an in-situ calibration would be performed. If the shape of the flow profile in a CROSSFLOW installation is in doubt, readings would be collected in an more favorable location and compared to the data collected in the primary location.

3. CROSSFLOW Sensitivity to the Velocity Profile

The Caldon report specifically referenced a 1992 paper[1] by Jim Sherin, and myself and concluded that "*the sensitivity of a cross correlation meter to the axial velocity profile may be somewhat greater than that of an externally mounted transit time meter.*" This is based on our statement in the paper that reads: "The flow profile correction factor has also been observed to be dependent on the flow velocity, varying between 0.92 and 0.94 over 3.5 to 4.5 m/s range."

Originally it was believed that the flow profile strongly depends on the fluid velocity. The statement was based on the best fit to the laboratory test data collected in 1990. This conclusion turned out to be erroneous since the observed dependence is later proved to be due to the test loop characteristic behavior and not due to any flow profile changes.

[1] J. R. Sherin, D. Zobin, "Feedwater Flow Measurements Using Ultrasonic Cross-Correlation Flow Meter", Presented at the Nuclear Plant Performance Seminar, Miami, February 24-25, 1992

More recent theoretical analysis and calibration work indicates that the value of the flow profile correction factor, although lower than that for a transit time meter, is only weakly dependent on the Reynolds number. This dependence has been validated in several tests under actual operating conditions.

Last year a detailed test was performed at Pt. Lepreau NGS, where feedwater flows in four loops were measured using CROSSFLOW at power levels between 86%FP and 95%FP and were compared to the corresponding venturi readings. The results of these tests disproved our earlier conclusion about the sensitivity of the flow profile to axial velocity and validated the dependence of the flow profile correction factor on the Reynolds number currently used in CROSSFLOW measurements

4. Conclusions

4.1 We have been using cross-correlation technology for the last 20 years and our extensive experience does not support the Caldon conclusions. During the last five years, we have purchased CROSSFLOW systems, which are based on a significantly improved design compared to what we had earlier and have used them extensively in all our nuclear plants for measuring feedwater flows, coolant flows and other flows such as service water and reheater drains.

4.2 The report presents no supporting evidence for the assumption that changes in the swirl velocity can take place after certain plant transients due to sudden changes in pipe roughness and are responsible for the LEFM chordal meter alarms. Even if this assumption were correct, the underlying physics behind CROSSFLOW operation is such that the effect of the swirl velocity will either be small or the meter readings will be conservative under similar conditions.

4.3 In our experience with CROSSFLOW, we have not observed sudden changes in flow profile during transients, both large and small. However, we are aware that if the transducer location is chosen inappropriately, such as in the table provided by Caldon, the system could result in a bias due to a change in the upstream conditions (e.g. valve position). The point is that ultrasonic flowmeters are susceptible to upstream disturbances to a degree and it is important to install the transducer at specific distance from the disturbance.

4.4 Caldon's conclusion based on our outdated paper is in error since we have proved in a planned in-situ test at a CANDU plant under actual operating condition that the flow profile factor for CROSSFLOW is a very weak function of Reynold's number.

Dr. David Zobin
Senior Scientist
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Nuclear Analysis Department
Ontario Power Generation

APPENDIX C

RESPONSES TO NUCLEAR REGULATORY COMMISSION

RAIs REGARDING WCAP-15689-P

[These responses were originally submitted via letter LTR-NRC-02-036, July 17, 2002.]

Nuclear Regulatory Commission RAIs Regarding WCAP-15689-P

Question No. 1

With respect to WCAP-15689-NP, Page ii, last paragraph:

a) How does WEC/AMAG perform an in-situ calibration?

b) How do we establish the fully developed flow location?

Response

1a) If there is a question concerning whether or not the flow can be accurately measured, an in-situ calibration can be used to answer this question. A second CROSSFLOW meter is installed at an alternative location, where it is known that an accurate measurement can be obtained. The readings from the two meters can be compared. If there is no difference, the flow measurements at the preferred CROSSFLOW meter installation are also accurate and no additional action is required. However, if there is a difference in the meter readings, the reading from the second CROSSFLOW meter can be used to determine a flow profile correction factor for the meter installed at the preferred location.

Westinghouse/AMAG prefer to use in-situ calibration instead of laboratory calibrations whenever it is feasible. The clamp-on characteristic of the CROSSFLOW meter provides for an economical and flexible in-situ calibration. In-situ calibrations provide an accurate VPCF for non-standard piping configurations and remove uncertainties and/or questions associated with extrapolation of a low Re number laboratory calibration to an operating plant environment.

1b) Fully developed flow conditions can be identified in several ways. For example, high temperature laboratory tests have been run in the past, which demonstrate that under plant operating conditions, the flow is fully developed for 15 or more diameters downstream of a 90° elbow. Multiple installations at different axial locations and different orientations about the pipe can also be used if necessary to further determine the condition of the flow. Finally, hydraulic laboratory tests can also be used to determine the number of diameters downstream of a flow disturbance that the flow becomes fully developed.

Validation of this process is demonstrated in WCAP-15689-P, Table 1. Over the years, WEC/AMAG have undertaken comparisons, where the utility believed that plant instrumentation was accurate. For example, one such comparison was performed immediately after an ASME venturi and flow straightener test section had been returned from being calibrated at the Alden Research Laboratory. Table 1 provides the data from not only this test, but also others on different piping configurations. The fact that the average difference between the cross-correlation and plant flow instrumentation in Table 1 is only 0.04%, confirms not only the accuracy of the ultrasonic flowmeters used in these tests, but also that the plant instrumentation was accurate at the time of the tests. Furthermore, the fact that the two independent means of measuring the same flow (ultrasonic and differential pressure instruments) provide close agreement, each with their own unique uncertainties, is strong evidence that both instruments are measuring the flow correctly.

This type of comparison is the ultimate confirmation of a meter's ability to accurately measure flow, where the accuracy of the meter is demonstrated under actual field conditions. This standard provides a higher degree of confidence than laboratory tests and eliminates the uncertainties encountered when extrapolating laboratory calibrations to field conditions.

Question No. 2

With respect to WCAP-15689-NP, Page 6, Section 2.4, 2nd paragraph and Figure 2:

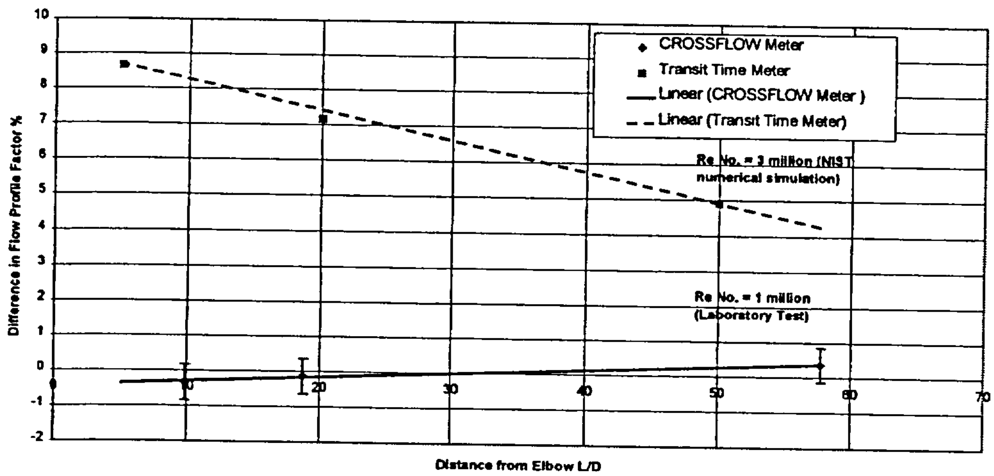
> This figure is marked proprietary in its entirety, however, the corresponding discussion of the figure is non-proprietary. Please provide a non-proprietary version of the figure, if possible, to facilitate writing of the NRC's ER-262 evaluation report which will be in the public domain. Additionally, the lines drawn on the figure are indistinguishable from one another since the figure is not in color. Use of different line types would facilitate understanding the figural presentation.

Response

The proprietary classification of Figure 2 has been removed so that the figure can be referenced in the NRC evaluation report. To facilitate the presentation, the sensitivity curve for the transit-time meter has been replaced by a dashed line to delineate it from the corresponding curve for the CROSSFLOW meter. The revised figure is shown below and has been downgraded from its former proprietary status to facilitate NRC use.

Figure 2

Difference in Flow Profile Factor Between Vertical and Horizontal Oriented Transducers Downstream of Elbow for CROSSFLOW and Transit time meter



Question No. 3

With respect to WCAP-15689-NP, Page 6, last sentence:

a) What caused the non-symmetry in the velocity profile?

b) What does symmetry mean?

Response

3a) Due to the large number of pipe diameters required for the flow to reach fully developed flow conditions, the NIST laboratory attempted to reduce the number of diameters by introducing specially prepared perforated plates upstream of the test section that were intended to facilitate the development of the velocity profile. It was learned after the tests, these perforated plates were not been completely successful in achieving a fully developed velocity profile.

As a result, when the readings were taken with the transit-time and cross-correlation meters assuming fully developed flow, the accuracy of the transit-time meters were affected more than the cross-correlation meter, since the cross-correlation meter was less sensitive to distortion in the velocity profile.

3b) Symmetry refers to the shape of the velocity profile. For a symmetrical profile, the shape of the profile is independent of the tangential position. For example, if a flow profile is symmetrical, the profile will appear to be the same in both the horizontal and vertical planes.

Question No. 4

With respect to WCAP-15689-P, Page 7, 2nd paragraph, 1st sentence, also on Page 14, Section 3.1, 2nd sentence and with respect to CENPD-397-P, Page 2-2, Section 2.2.2, paragraph starting just below Equation 2-6:

Explain the apparent discrepancy between the radial and axial component statements in the two topical reports.

Response

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Question No. 5

With respect to WCAP-15689-NP, Page 2, last sentence on page:

What is meant by "velocity profile" in this sentence?

Response

The velocity profile is normally thought of as a set of velocity vectors that form a certain distribution across the pipe cross-section. For fully developed turbulent flow, velocity profile is represented as a set of axial velocity vectors that form a well-known distribution across the diameter of the pipe. This distribution depends only on distance from pipe axis and is typically approximated by a logarithmic curve. However, when a flow disturbance occurs, additional velocity components are superimposed on the profile, that may include both radial and tangential vectors.

For the transit-time technology, these radial and tangential components may add or subtract from the chordal velocities that are being measured by the meter. This results in an apparent shift in the velocity of fluid, which may be different for the inner and outer chordal measurements. When this occurs, an alarm may be triggered, indicating that the flow measurements may no longer be valid.

Question No. 6

With respect to WCAP-15689-P, Page 8, Section 2.4, middle of last paragraph:

What is meant by "...if the signal were to degrade..."?

Response

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Question No. 7

With respect to WCAP-15689-P, Page 20, Figure 4, explain what this figure is meant to demonstrate.

Response

Figure 4 compares flow measurements at a plant by both the CROSSFLOW meter and the plant's venturi. The significant disturbance in the flow measurement was caused by a plant down-power event. The figure is provided to demonstrate CROSSFLOW's ability to accurately track the perturbation throughout the duration of the event.

Question No. 8

With respect to WCAP-15689-NP, Page 11, 2nd paragraph:

a) Was this feature described in CENPD-397-P-A?

b) What is pipe swirl?

Response

a) No. This software feature is typically employed in those installations where CROSSFLOW is tied to the Plant Computer. This feature alerts the operator to a potential problem with the CROSSFLOW measurement, which requires investigation prior to using it for venturi calibration.

b) Pipe swirl refers to the presence of a tangential velocity component within the fluid, where the fluid rotates about the central axis of the pipe. If the swirl is not symmetrical, it will also introduce a radial velocity component. For the transit-time technology, these components may either add or subtract from the axial component, resulting in a potentially unpredictable response that may indicate that the flow is either increasing or decreasing. However, for the cross-correlation technology, the imposition of radial and tangential velocity components will only reduce the correlation between the upstream and downstream phase shift patterns near the surface of pipe. As a result, the meter will tend to track the fluid velocities near the central region of the pipe resulting in a conservatively higher mass flow.

Question No. 9

With respect to WCAP-15689-NP, Page 19, Figure 3, shows several gradations within the individual participants meter responses.

Response

The gradations within the individual participant's responses are a demonstration of the meter's repeatability. For each meter, measurements were made for three (3) Reynolds numbers (shown as the vertical separations for each meter). The meter was then removed from the test section and then reinstalled on the pipe and another set of measurements taken. This process was repeated four (4) times as shown in Figure 3, leading to the four (4) gradations for each RE measurement (seen as the horizontal separations).

Question No. 10

Regarding the Zobin letter+ provided in Appendix B to WCAP-15689-NP, on Page 2, Item d of General Comments, provide a clearer explanation of the discussion therein.

+ Dr. D. Zobin (OPG) to Y. Gurevich (AMAG), "Comments on Caldon Report – ERL (sic) 262", February 28, 2002

Response

Item d makes the point that the value of the velocity profile correction factor (VPCF) for a cross-correlation meter approaches the value for fully developed flow at distances from an upstream disturbance which are shorter than other tests provided for transit-time technology. To arrive at this conclusion, Dr. Zobin compared test data obtained in OPG's high temperature laboratory, plant data from feedwater installations in Canada downstream of a single 90^0 elbow using cross-correlation technology, and results published by Caldon(1) of experiments with a similar 90^0 elbow in Alden Laboratory using transit time technology.

The test data from the cross-correlation meter shows that at the length of approximately 15L/D downstream of the elbow, the VPCF has the same value as for long straight pipe. The transit time test data shows that even on a distance of 30L/D downstream of the elbow the VPCF deviates from its value for long straight pipe by 1% - 2%.

The verification of the cross-correlation test data is provided by the substantial CROSSFLOW independent field validation discussed in response to Question 1(b). Westinghouse is not aware of any similar independent field validation of the transit-time laboratory test data at actual plant operating conditions.

(1) D. E. Mazzola (MPR Associates) and D. R. Augenstein (Caldon), "Hydraulic Testing of External Mount Ultrasonic Flow", presented at the EPRI Nuclear Plant Performance Improvement Seminar, Albuquerque, NM, August 23-24, 1995

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Question No. 11

Regarding the Zobin letter+ provided in Appendix B to WCAP-15689-NP, on Page 3, the 2nd paragraph and Item 4.4 of the Conclusions section, the discussions seem to conflict with one another, explain in further detail.

+ Dr. D. Zobin (OPG) to Y. Gurevich (AMAG), "Comments on Caldon Report – ERL (sic) 262", February 28, 2002

Response

As noted in Dr. Zobin's letter, Ontario Power Generation (OPG) originally believed that the velocity profile correction factor (VPCF) was strongly dependent on the fluid velocity. It was later confirmed during in-plant testing at Point Lepreau that this assumption was not correct. The Point Lepreau tests demonstrated that the VPCF was only a function of the Reynolds number as shown in CENPD-397-P-A Revision 01, Section 4.1, Equation 4-3.

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