Notes on NRC SER on ER-262
Dated February 5, 2003
Revision 7

Purpose

The purpose of this document is to describe and clarify the inconsistencies that appear in WCAP-15689 REV 1 and are subsequently quoted in the SER dated January 28, 2003. It is provided at the request of the Steve Alexander in the Office of Inspection on January 29, 2003.

Summary

In January 2002, Caldon provided important new information to the NRC on the behavior of velocity profiles in feedwater piping that had been developed as a result of the study of measured velocity profiles in plant conditions. The information was provided to the NRC and to our customers because of the effect that these velocity profile changes have on our LEFM External and LEFM Check/CheckPlus instruments. In the report, ER-262, Caldon did not evaluate the effects of the observed velocity profile changes on Cross Correlation technology available from Westinghouse as it is outside our area of expertise. Caldon did, however, draw the conclusion that it should be evaluated in light of the new profile data.

Westinghouse submitted a review of the impact on the Crossflow meter accuracy in April 2002. Their response included conclusions that stated:

1) Velocity profiles do not change in plant, except when plant line-up changes.
2) The Crossflow meter is insensitive to changes in velocity profile.

The basis for the first conclusion provided in the report is that in the many years of experience with the Crossflow meter, changes in velocity profile have not been observed. However, the report goes on to explain that the Crossflow meter does not measure velocity profiles. This is confirmed in the Westinghouse response on page ii of the Executive Summary and page 14 of the report where it states that the Crossflow meter senses only axial velocities, and does not sense tangential or radial velocities. It would therefore not seem surprising that velocity profile changes have not been observed with the Crossflow meter, but the lack of observation evidence would not lead to the conclusion that profiles do not change. The data provided in ER-262 provides measurements of these components and shows that the velocity profiles do change over time.

In ER-262, Caldon cited a technical paper from the developers of the Crossflow meter, which stated that it is more sensitive than external transit time meters. The data in ER-262 show that the average change in velocity profile, owing

largely to swirl, among the 18 pipes studied would cause a 0.7% change in an external transit time meter profile. The Westinghouse submittal supports this conclusion. In Appendix B of the report, Westinghouse states, "Specifically, for a swirl generating pair of out-of-plane 90^{O} 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 quotation clearly suggests that the sensitivity of the Crossflow meter to swirl generated changes in velocity profile is greater than the average sensitivity of an external meter. More than one data point is required to confirm a 95% confidence interval bound, but the interval must be larger than 1%. The Westinghouse report takes comfort in the fact that the data shows that the swirl case flow profile correction factor is less than the fully developed case and therefore the 1% error is conservative.

However, it should be noted that once a Crossflow meter is calibrated in-situ, a change in profile may have either a conservative or non-conservative effect, depending on the velocity profile prevailing at the calibrated meter at the time of calibration. Since Westinghouse confirms that the Crossflow meter does not measure velocity profiles, it cannot be known what profile conditions exist at any particular time in the plants. Because a sensitivity to profile shape exists, it is a critical parameter that is unmeasured. An unmeasured parameter cannot be made traceable to national standards, as required by NRC Inspection Procedure 61706, "Core Thermal Power Determination", Section 03.01b Inspection Requirement 02.01c. The Crossflow meter fails to meet this requirement. As the data from ER-262 show, these velocity profile characteristics change over time, and are unpredictable. The conclusion is that a critical parameter is untraceable and leads to uncertainties that are unquantified. The one piece of data referenced indicates that the uncertainty can be at least as high as 1%.

Swirl is not the only thing that changes profile shape. Westinghouse has provided data publicly and within the Topical Report that documents the sensitivity to profile shape without swirl. These data are plotted versus Reynolds number, and they reveal a 2-1/2% change over a Reynolds number range from 400,000 to 25 million. These data are interesting because the profiles represented by these Reynolds numbers represent the entire range of profiles encountered in Nuclear feedwater lines and reported in ER-262.

The important conclusions drawn from the Westinghouse report are:

1) The Crossflow meter does not measure velocity profiles or the changes in velocity profiles that occur in feedwater piping.
2) The Crossflow meter carries at least a 1% sensitivity to profile shape (the case presented is a swirl case).
3) Errors due to changes in swirl, after a Crossflow meter have been calibrated in-situ, may be either conservative or non-conservative.

4) The Crossflow meter is sensitive to velocity profiles and the assumption of a velocity profile is an unbounded, untraceable assumption that can lead to errors of 2-1/2%.

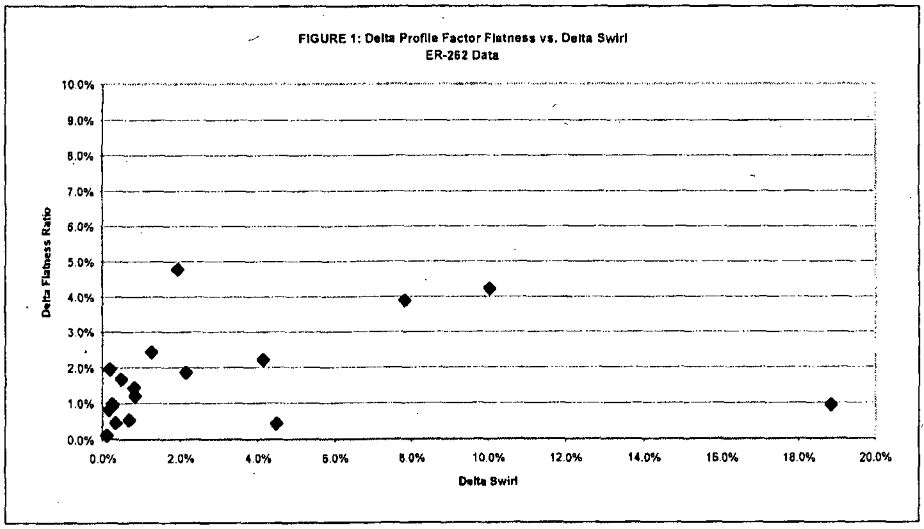
The WCAP containing these conclusions raise a question about accuracies claimed to be 0.5% and have been used to justify uprates at seven nuclear power stations, and have been requested for two others.

Detailed Review of SER dated January 28, 2003

1. Section 1.0 Introduction
   a. Caldon ER-262 does not conclude that the Crossflow meter will be adversely affected by the velocity profile changes observed, but specifically states that the Crossflow meter effects were not included in this report. Rather, ER-262 quoted the vendor, WEC, who had publicly stated in technical literature that the Crossflow meter is more sensitive to velocity profile than transit time meters. Based upon these published positions, the conclusion that the Crossflow meter should be analyzed seems prudent.

2. Regulatory Basis
   a. The LEFM Check and CheckPlus Systems were developed prior to the final rule being published, and the accuracy of those instruments was a matter of record prior to the final rule being published. The Crossflow System was also developed prior to the publishing of the final rule. WEC is now claiming accuracies of less than 0.3% for this meter.

3. Evaluation
   a. Caldon's evaluation does not conclude that all 18 pipe profiles changed only because of swirl as implied here. In fact the data provided indicates that profiles change without changes in swirl also. Figure 1 below plots delta Profile Flatness versus delta Swirl. Since there is a poor correlation it is clear that there are other causes, for example roughness, for profile shape change.



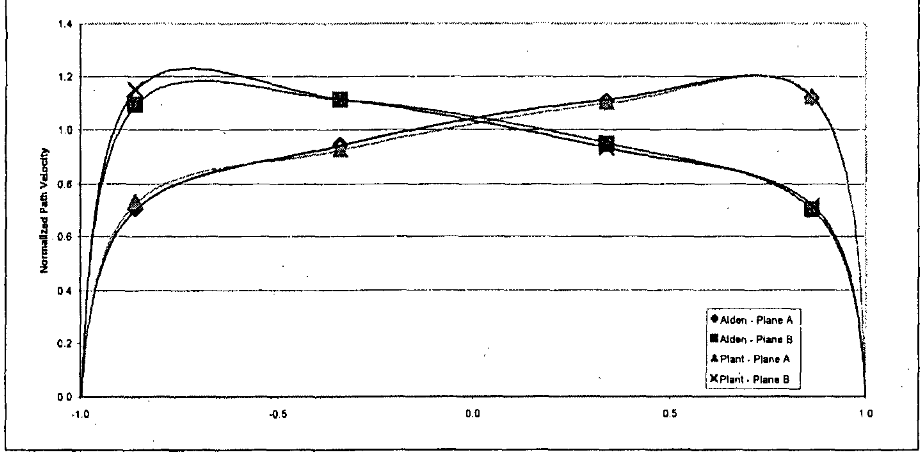
b. It does not logically follow that since the measured time delay for the Crossflow meter is in ms and the time difference in transit time meters is in ns, that the Crossflow meter is not sensitive to profile changes that are the topic of ER-262, nor does it follow that it is insensitive to noise, cable lengths, (see **Attachment 1**, "Installation and Initial Operating Experience with the Crossflow Ultrasonic Flow and Temperature Systems At SONGS Units 2 and 3", dated July 2002 for a discussion on noise and cable length effects), temperature and transducer beam orientation (See **Attachment 2**, Hope Creek LER 2002-005-00 dated 7/25/02). The reference documents state that the Crossflow meter is sensitive to effects in these areas. These effects are quantified for one case as -0.47% (non-conservative) in LER 2002-005-00.

c. The SER quotes WEC **"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 flowmeters."** This statement seems to contradict other statements and data provided by WEC. ER-262 addresses sensitivity to velocity profiles. WEC published data (**Attachment 3**, Flomeko '98) provides quantitative data on sensitivity of the Crossflow technology to profile shape (2.5%). The ABB CENP Topical Report CENPD-397-NP states that Crossflow is sensitive to flow profile, and WCAP-15689 provides a quantitative sensitivity to swirl, another, but separate, profile effect (1%). The statement that the Crossflow meter is not subject to this technical issue (profile sensitivity) is inconsistent with the very basis for the profile factor determination as a function of Reynolds number, the statement in the ABB CENP Topical Report CENPD-397-NP, and the statement that test data shows a 1 percent change owing to swirl. See **Attachment 4**, "Sensitivities of Crossflow (and LEFM) External Systems to Profile Shape", for a detailed discussion of the Flomeko data.

d. WEC cites reliability and repeatability problems for transit time clamp on systems. The WEC report and the SER is silent on transducer mounting errors experienced and reported in the Hope Creek LER 2002-005-00 due to mounting considerations. The WEC report further states "**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.**" This statement is apparently contradicted in STP SER dated April 12, 2002, which sites three transducer failures since 1999.

e. The SER quotes the WEC TR as stating "**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 the 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. 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 laboratory conditions.**" These statements are misleading and demonstrate a lack of knowledge of test data that has been published by both Westinghouse and Caldon. (It is noted that the LEFM product line was developed by Westinghouse). Caldon has provided the NRC with justification for extrapolation of lab results to plant Reynolds numbers and has confirmed the results directly by comparing profiles throughout the full power range. An example is shown in Figure 2. The data is from the Beaver Valley 2 Plant and Alden Labs. Caldon applies an uncertainty for this extrapolation. The extrapolation uncertainty is expressly treated and included and is typically +/-0.05%.

FIGURE 2: Beaver Valley Unit 2 vs. Alden Labs



f. The SER quotes that "**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.**" As previously noted, WEC points out that no measurement of velocity profile is possible with the Crossflow meter. ER-262 records non-fully developed flow profiles in seven pipes at ≥ 13 L/D from a bend, including one at greater than 45 L/D from a bend. The technical literature records that swirl can persist for over 100 L/D. The presence of swirl is impossible if the flow is fully developed. The obvious question in light of these measurement facts is "how does WEC determine if there is a question about whether the flow profile is fully developed without any measurement of the flow profile".

g. The SER quotes that "**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**." Eventually the calibration of the meter must be tied to traceable standards. There is no reduction in extrapolation uncertainty in this process if a second Crossflow meter is used to calibrate the first. The calibration uncertainty is simply shifted from the first to the second Crossflow meter, which must in turn be tied to a lab calibration. Therefore, the logic that the extrapolation uncertainty is reduced seems to be flawed. WEC states that the Crossflow meter is not sensitive to radial or tangential velocity components. It clearly follows that velocity profiles cannot be measured with the Crossflow meter. Without knowledge of the actual velocity profile, an assumption of fully developed flow cannot be made traceable to any standard as required in NRC Inspection Procedure 61706

"Core Thermal Power Determination". Therefore, there can be no reduction in uncertainty in an extrapolation credited and the uncertainty allowed should be shown to bound the range of profiles that would be encountered. Using ER-262 measurements for the range of profile shapes encountered, and using the published sensitivity to profiles for the Crossflow meter, this uncertainty would be 2.5%.

h. WEC asserts that the evaluation of the dissipation of effects of upstream disturbances is based upon experience, model tests, and the technical literature. This is curious. WEC/AMAG conclusions that flow is fully developed 15 L/D from 90-degree bends disagree with Schlichting, Brown, and the ASME nozzle standards, so it seems odd to list them as part of the basis. Figure 2 of the WCAP-15689 is used as justification for the conclusion that the Crossflow meter is less sensitive to flow profiles. This argument seems flawed. The transit time data is reportedly based upon a CFD model but no details of the model or its assumptions are provided so cannot be evaluated on its own merit. In fact the curve for transit-time meters is inconsistent with Caldon's experience from traceable calibration laboratory testing. Data from 25 tests is provided in Figure 3.

(b)(4)

The difference between horizontal and vertical measurements as a function of L/D from the 90 degree bend shows a pattern with scatter, as one would expect in a reasonable sample size. It is noted that it is impossible to determine scatter with the three data points that WEC provides for the Crossflow meter. The Caldon data shows that flow is not fully developed even at 25 diameters from the bend. If it were fully developed, no difference between vertical and horizontal measurements could exist by definition.

The 1% difference in the delta between horizontal and vertical measurements (at 10 and 58 L/D) for the Crossflow meter is instructive. It means that the Crossflow meter is measuring the velocity of eddies near the center of the pipe. WEC makes the same conclusion when they explain "**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 logic behind this conclusion may be tested by the example that if the meter measured the exact center velocity, the vertical and horizontal paths would read exactly the same velocity, because they would be measuring the same point. In fact, the 0.5% difference between the two at any given point indicates that they are not measuring precisely the same point, but certainly measuring less of the profile than is measured by a transit time meter. It is also instructive that even at 58 diameters the flow cannot be fully developed for this test, which is consistent with the literature but rejected by WEC/AMAG. The data actually indicate another error term of at least 0.5% even for distances 58 L/D from a bend.

i. WEC provides data in Figure 3 from a NIST report on testing of external ultrasonic meters. The SER quotes the WEC TR as stating that "**...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% from the weigh tank data**. " This conclusion is taken from a small sample of data from the report and is misleading. Figure 2 of the TR shows that at Re=2.9M the Crossflow meter contained a bias low of approximately –0.8% (non-conservative). The time varying standard deviation of this number is shown in Figure 2 of the TR to be +/-1% for the Crossflow meter. The data not provided by WEC but included in the NIST report shows changes in the error for the Crossflow meter from test to test of 1%. The figure cited is only one of many in the NIST report. The report fails to include the other data in the thorough NIST report and results in misleading conclusions.

j. The SER quotes WEC that "**The reason for the lower sensitivity of (of the Crossflow meter) 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**." The conclusion that the change in meter factor of the external meter is associated with the impact of radial and tangential velocities is an overstatement. For swirl to have the effect that is described here, it would have to be off-center, as Westinghouse notes. What is not noted is that the off-centered swirl conditions are rarely seen more than 5 diameters from bends, as measured by a large number of LEFM Check and CheckPlus systems. External Systems are not installed closer than 5 diameters from a bend. ER-262 provided a proof and demonstration that there are effects due to profile shape, or flatness, and therefore manifest themselves as an "integration error", or more appropriately, a "profile correction factor" error, independent of a velocity measurement error. A velocity measurement error in actual Caldon LEFM External meters is eliminated or reduced significantly by the bounce path geometry used and the fact that the tangential velocity is perpendicular to a diametral path and therefore has no projection onto the measured velocity path. The conclusion that the Crossflow meter is not sensitive to these velocity vectors and that somehow this fact insulates it from effects due to profile shape does not follow. WEC goes on to contradict their own conclusion by observing that the abrupt change in swirl or pipe wall roughness as described in ER-262 would cause a shift in the Crossflow output in the conservative direction. This implies that WEC believes that the profile shape is affected by pipe wall roughness and swirl, and that the Crossflow meter has a sensitivity to these changes. Appendix B of the TR later goes on to quantify one example where the sensitivity to a swirl condition is 1%. The published data on profile shape, as expressed by Re for fully developed smooth pipe flow, sets the sensitivity at 2½ %. These two conclusions seem self-contradictory.

4. Conclusion

a. The WCAP contained a statement that the sensitivity to swirl was observed to be at least 1%. Published data on meter factor as a function of profile shape as expressed by Re reveals that the sensitivity would be 2 ½%. The conclusion that the Crossflow meter is less sensitive than the External LEFM is not supported by these facts.
b. Table 2 of the WEC Report contains information from an NIST simulation that is not supported by test and field data with the LEFM External meter, shown in Figure 3 above. Gregor Brown of NEL has done extensive work comparing simulations to actual test results for a large variety of installations. His work also contradicts the validity of the data presented by WEC and ascribed to NIST.
c. Table 2 of the TR provides actual test data for work done at the full flow lab at Ontario Hydro. Work is reported at Re of 1 million. The data clearly shows a change in the relationship between vertical and horizontal measurements of 1 percent (-0.5% to +0.5%) from 10 L/D to 58 L/D. It also clearly shows that for this test the flow profile could not be considered to be fully developed at 58 L/D, as

evidenced that the horizontal and vertical readings differ. This is *inconsistent with WEC's assertions that flow is fully developed at 15* L/D from a bend. While this data do show that the profile was not fully developed, they do not speak to the flow profile sensitivity. They simply show that the profile effect is systematic for both paths and not random per path.

d. WEC reported in technical papers that the Crossflow meter was more sensitive to velocity profile than external meters. They explain the increased sensitivity by the theory that the Crossflow meter detects eddies at the center of the pipe and not at the wall, and therefore changes in velocities at the wall are not detected and accounted for, and the correction factor changes. In WCAP-15689, WEC claims that conclusion was erroneous. It follows that the theory that supports the conclusion is flawed in some way. *However, in WCAP-15689, the same theory is used to explain the* 1% change in profile factor owing to swirl. This argument is inconsistent. The Crossflow meter either measures velocities at the center of the pipe and is more sensitive to profile shape, or it does not measure velocities at the center of the pipe and the effects of swirl need to be explained by a different theory.