July 5, 2006

Mr. Ernest M. Hauser, President
Caldon, Inc.
1070 Banksville Avenue
Pittsburgh, PA 15216

SUBJECT: EVALUATION OF THE HYDRAULIC ASPECTS OF THE CALDON LEADING EDGE FLOW MEASUREMENT (LEFM) CHECK AND CHECKPLUS™ ULTRASONIC FLOW METERS (UFMs) (TAC NO. MC6424)

Dear Mr. Hauser:

Caldon Topical Reports (TRs) ER-80P, Revision 0, "Improving Thermal Power Accuracy and Plant Safety While Increasing Operating Power Level Using the LEFM™ System," and ER-157P, Revision 5, "Supplement to Topical Report ER-80P: Basis for a Power Uprate with the LEFMT™ or LEFM CheckPlus™ System," were approved by the U.S. Nuclear Regulatory Commission (NRC) staff in 1997 and 2001, respectively, for the Caldon Check and CheckPlus UFMs. However, in 2002 numerous issues were found associated with UFMs of all vendors and their use in nuclear power plants for the determination of thermal power. The findings of the NRC Task Group established to investigate these issues led the NRC staff to completely re-examine the hydraulic aspects of UFM operation.

The NRC staff has completed the subject evaluation for Caldon LEFM UFMs as part of the generic assessment of the hydraulic aspects of UFM application to increase licensed thermal power. As described in the enclosed safety evaluation (SE), the NRC staff finds that the Caldon Check and CheckPlus UFMs' performance is consistent with the Caldon TRs ER-80P, Revision 0, and ER-157P, Revision 5, previously approved by the NRC staff. Caldon has reviewed the material in the enclosed SE and found it to be non-proprietary.

If you have any questions, please contact Mr. Girija Shukla at 301-415-8439.

Sincerely,

**/RA/**

Brian E. Thomas, Acting Deputy Director
Division of Policy and Rulemaking
Office of Nuclear Reactor Regulation

Project No. 1311

Enclosure: SE

July 5, 2006

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| NAME | GShukla | DBaxley | JPeralta | JNakoski | BThomas |
| DATE | 7/5/06 | 6/26/06 | 6/27/06 | 6/8/06 | 7/5/2006 |

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SAFETY EVALUATION BY THE OFFICE OF NUCLEAR REACTOR REGULATION

THE HYDRAULIC ASPECTS OF THE CALDON LEADING EDGE FLOW MEASUREMENT

(LEFM) CHECK AND CHECKPLUS™ ULTRASONIC FLOW METERS

CALDON, INC.

PROJECT NO. 1311

## 1.0 INTRODUCTION

Serious ultrasonic flowmeter (UFM) operational problems became a focus of the U.S. Nuclear Regulatory Commission (NRC) staff in 2002 due to inconsistencies between UFMs and all other indications that provided insight into thermal power level at the Byron and Braidwood nuclear power plants. Initial investigation by the NRC identified that the licensee's management and the UFM vendor were inappropriately concluding that the UFMs were correct and something was wrong with opposing conclusions being drawn in regard to all other indications. This NRC involvement was followed by establishment of an NRC Task Group that determined there were numerous issues associated with UFM use in nuclear power plants for the determination of thermal power (Reference 1 addressed the Caldon designs). The Task Group findings led the NRC staff to completely re-examine the hydraulic aspects of UFM operation. This report describes the NRC staff re-examination of the Caldon Check and CheckPlus UFMs.

Topical Reports (TRs) ER-80P, Revision 0, and ER-157P, Revision 5 (References 2 and 3), were approved by the NRC staff in 1997 and 2001, respectively, for the Caldon Check and CheckPlus UFMs. The hydraulic aspects of these TRs and more recent information from References 4 through 8 were included in the review that is described below. The review scope included the theoretical bases, pre-delivery testing at Alden Research Laboratory (ARL), and representative plans for installation, certification, and long-term operation. The NRC staff also audited the hydraulic aspects of the Check and CheckPlus UFMs that have been installed in nuclear power plant feedwater pipes to obtain additional insight into expected behavior following installation.

## 2.0 REVIEW OF THE CHECK AND CHECKPLUS ULTRASONIC FLOW METER

### 2.1 Check and CheckPlus Characteristics

The basic objective of a UFM is to compute an estimate of the average bulk fluid velocity, $\mathbf{v_B}$, in the equation:

$$W = \rho * A_p * C_{cal} * \mathbf{v_B} \tag{1}$$

where: W = feedwater mass flowrate
$\rho$ = fluid density
$A_p$ = pipe cross-sectional area
$C_{cal}$ = calibration correction factor

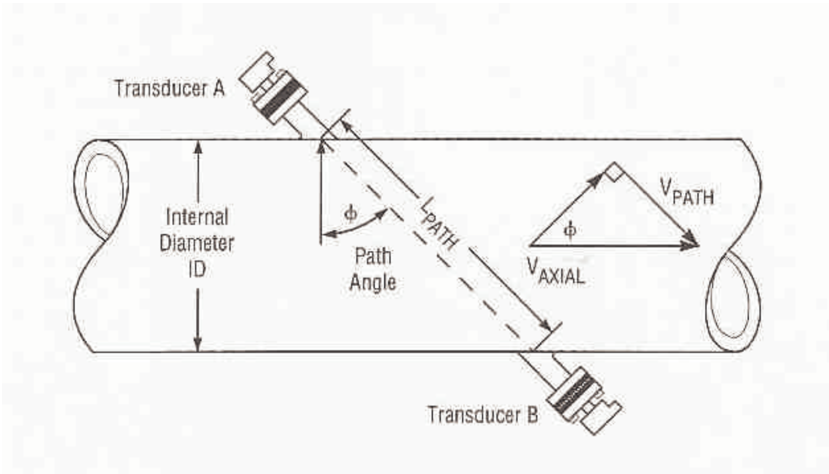
If the UFM were “perfect” and directly indicated the correct $\mathbf{v_B}$, then $C_{cal}$ would equal one. But UFMs are subject to errors that are potentially significant in light of the small uncertainties claimed for feedwater flowrate determination in nuclear power plants. Therefore, it is necessary to perform calibrations to determine $C_{cal}$.

The one thing many UFM designs have in common is that they use one or more transducers to generate and receive an acoustic wave. The way the wave interacts with the fluid and the method used to process the results of the interaction may be completely different with no relationship between various UFM designs.

Caldon has been associated with a number of UFM installations in nuclear power plants. Caldon does not recommend the older external UFM for Measurement Uncertainty Recapture (MUR) applications and these UFMs will not be addressed here other than to observe that they are not as accurate as the LEFM Check and LEFM CheckPlus designs. Both the Check and the CheckPlus are provided as spool pieces designed for each application. They are typically about five feet long. Installation typically requires that a section be cut out of the feedwater pipes and the UFM spool piece be welded in place. Twelve Check and 19 CheckPlus UFMs have been installed in nuclear power plants. Some of the early installations encountered hardware difficulties but these appear to have been addressed. The early installation difficulties will not be addressed further since it is not pertinent to the present assessment of the interaction between the acoustic wave and the flowing fluid.

Although Caldon has provided data that compared the LEFMs and venturi indications for its installations, and such data provide an approximate knowledge of behavior, Caldon did not depend upon such data, has stated that “the difference cannot be used to justify the accuracy of any of the meters,” and one “must establish actual credentials of at least one of the meters we are comparing” (Reference 6). Caldon justifies the accuracy of the LEFMs on the traceable accuracy as documented in its uncertainty analyses of record. It does not base the justification on comparisons to plant instrumentation.

The basic Caldon methodology that applies to the LEFMs is illustrated in the following sketch:




In operation, an acoustic wave is transmitted diagonally across the pipe in the A-to-B direction and in the B-to-A direction. The velocity component of the acoustic wave in the direction of flow will take less time to travel to the receiving transducer than the velocity component of the acoustic wave transmitted in the opposite direction. Reference 9 and other references describe these times by the following equations[1]:

$$t_{AB} = L_{path} / (C_{path} + V_{path}) + t_{del\ AB} \quad \text{and} \quad t_{BA} = L_{path} / (C_{path} - V_{path}) + t_{del\ BA}$$

where: $C$ = speed of sound
$V$ = velocity projected onto the acoustic path, $L_{path}$
$t_{del}$ = time due to non-fluid delays

Each sonic pulse traverses the same path in non-fluid media and the same transmitter / detector combination produces and detects each pulse. Therefore, $t_{del\ AB} = t_{del\ BA}$. Subtracting one of the above equations from the other provides the time difference between the two paths:

$$\Delta t = t_{BA} - t_{AB} = [L_{path} / (C_{path} - V_{path})] - [L_{path} / (C_{path} + V_{path})]$$

Which can be rewritten as:

$$\Delta t = 2\ L_{path}\ V_{path} / (C_{path}^2 - V_{path}^2)$$

Since $V_{path}$ is much smaller than $C_{path}$, about 15 ft/sec and 4000 ft/sec respectively, the above can be simplified as:

$$V_{path} = \Delta t\ C_{path}^2 / (2\ L_{path})$$

---

[1]Part of this derivation is repeated later in the discussion. The duplication is provided for continuity and ease of reading.

and the projection of the axial fluid velocity onto the acoustic path is described by:

$$V_{path} = V_{axial} \sin \varphi$$

Adding the starting two equations rather than subtracting them and noting that:

$$2\ t_{del} = t_{del\ AB} + t_{del\ BA}$$

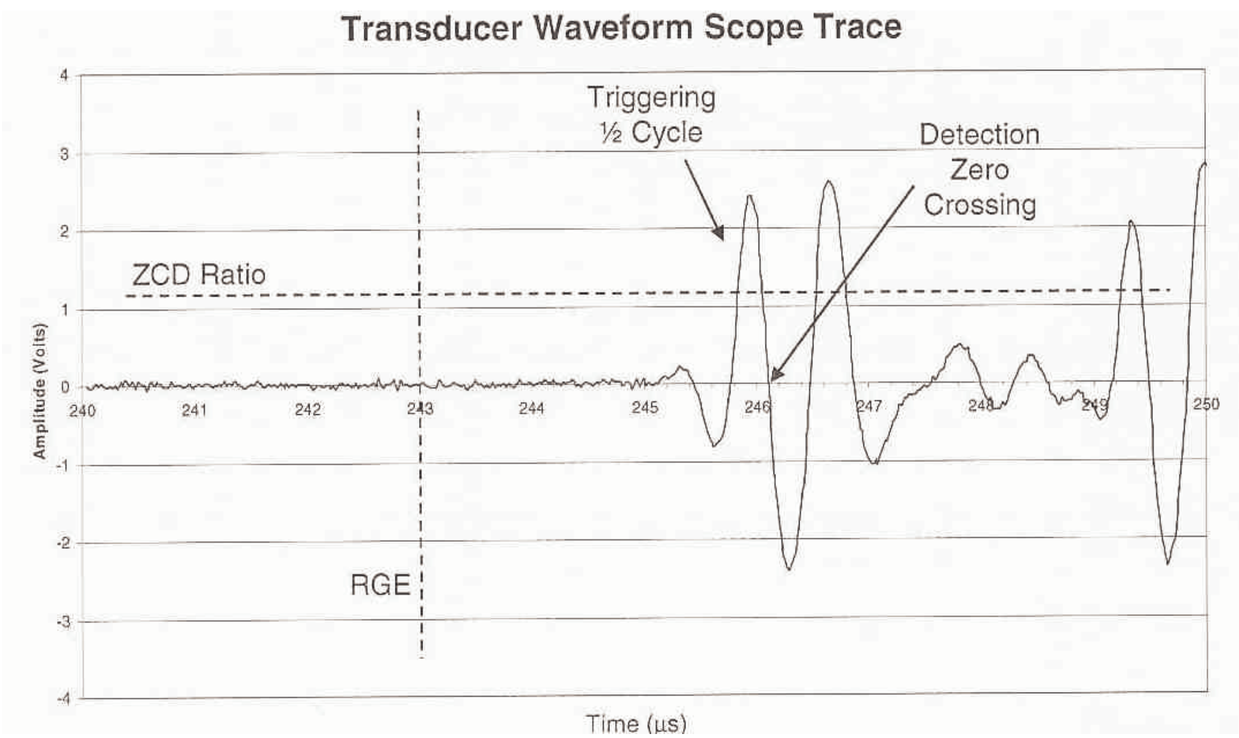
provides:

$$t_{AB} + t_{BA} = 2\ L_{path}\ C_{path} / (C_{path}^2 - V_{path}^2) + 2\ t_{del}$$

This can be solved for $C_{path}$. $V_{path}$ and $V_{axial}$ can then be determined from the above relationships.

$C_{path}$ is a function of temperature and a weak function of pressure. With $C_{path}$ and pressure known, temperature and the physical properties of the flowing fluid, can be determined. Feedwater flowrate follows from Equation 1.

The method used to determine the time is illustrated in the following sketch:

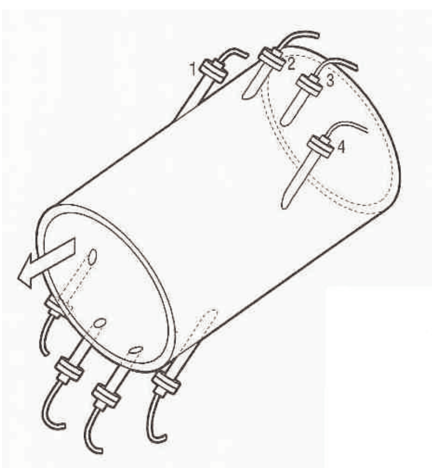


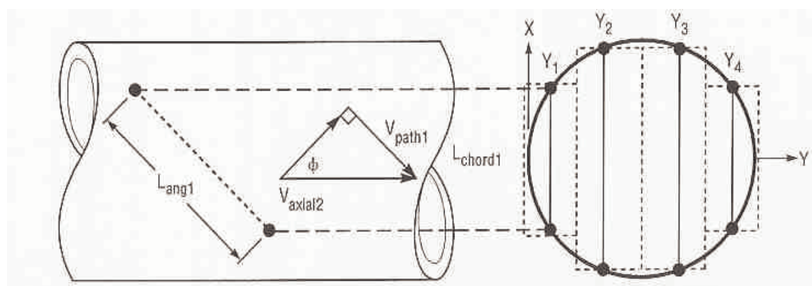

“Noise” has been a source of error in several UFM applications and has led to plants being operated in excess of the licensed thermal power level. Caldon has analyzed the potential for noise to affect accuracy through aliasing or other mechanisms and it applies a number of on-line assessments to evaluate pressure pulsations, beam diffraction, and scattering. For example, according to Reference 6, a path is entered into the “failed” mode if approximately

30 percent of the transmitted pulses are not detected, if approximately 30 percent of the time differences fail to pass statistical tests of typically three standard deviations, if approximately 30 percent of the received signals fail to correlate with the opposite received signal, and if approximately 30 percent of the received signals fail to pass signal to noise tests. This was also the topic of a Caldon Customer Information Bulletin provided as followup to discovery of noise contamination at Byron and Braidwood Nuclear Plants (Reference 10). The NRC staff briefly addresses noise further in discussing commissioning, below.

The velocity determined by the UFM illustrated above will be an estimate since it is for one acoustic path and it will not be the average velocity that provides the flowrate. It must be multiplied by $C_{cal}$ to calculate flowrate and $C_{cal}$ must be determined by experiment. The correction will typically be about 1 to 10 percent for the illustrated single path UFM. Further, the single path information, by itself, will provide little insight regarding changes in the flow profile from the flow profile that existed in the experiment and such changes, if they occur in the application, would likely invalidate the $C_{cal}$ determination when the claimed uncertainty is small.

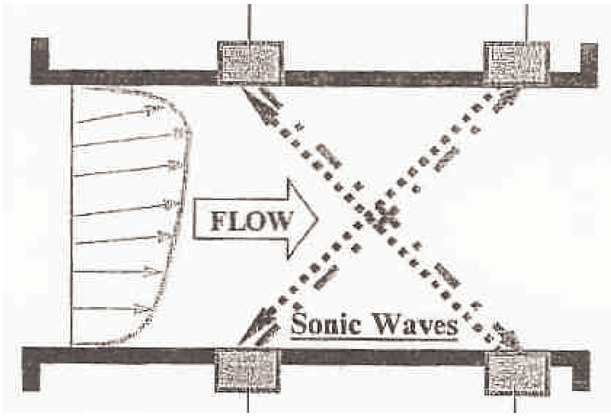
Caldon obtains additional information in the Check design by using four transducer sets as shown in the following two sketches:

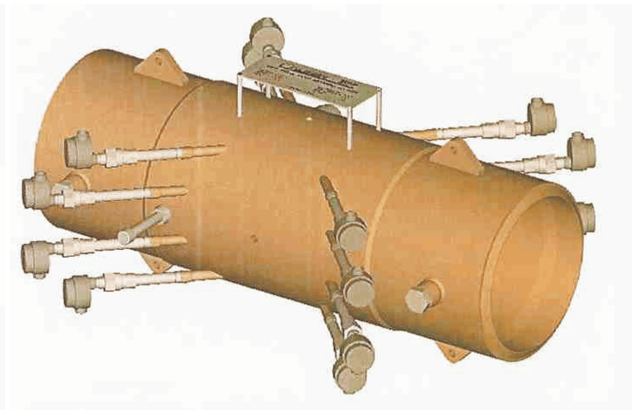



The left sketch shows the configuration with the transducers in the pipe. The right sketch shows the four paths through the pipe. Path locations are selected to correspond to the four-point Gauss quadrature formula that provides curve fit benefits for determination of the average velocity as discussed later in this section. In this design, transverse velocity vector projections cancel if swirl exists and the swirl is centered since these projections are essentially equal and opposite on paired acoustic paths (Reference 5). However, swirl will seldom be centered and an off-centered swirl may introduce additional error into the Check flowrate indication if the swirl differs from the calibration conditions. Regardless of the shape of the swirl profile, Check will provide information to identify the presence of swirl and can provide some compensation for determination of flowrate. Caldon has stated that the four path Check integrates moderately asymmetric axial profiles within approximately 0.1 percent (Reference 5).

In the CheckPlus design, a second set of four transducers is installed as illustrated below:



The NRC staff provides the following observations:

- Swirl is basically cancelled from the velocity determination since the rotational (or transverse) velocity vector projections are close to equal and of opposite sign on paired acoustic paths although swirl does affect axial profile (Reference 5).

- Swirl can be determined by examining behavior in each of the planes. This will be addressed further when the ARL test results are examined below.

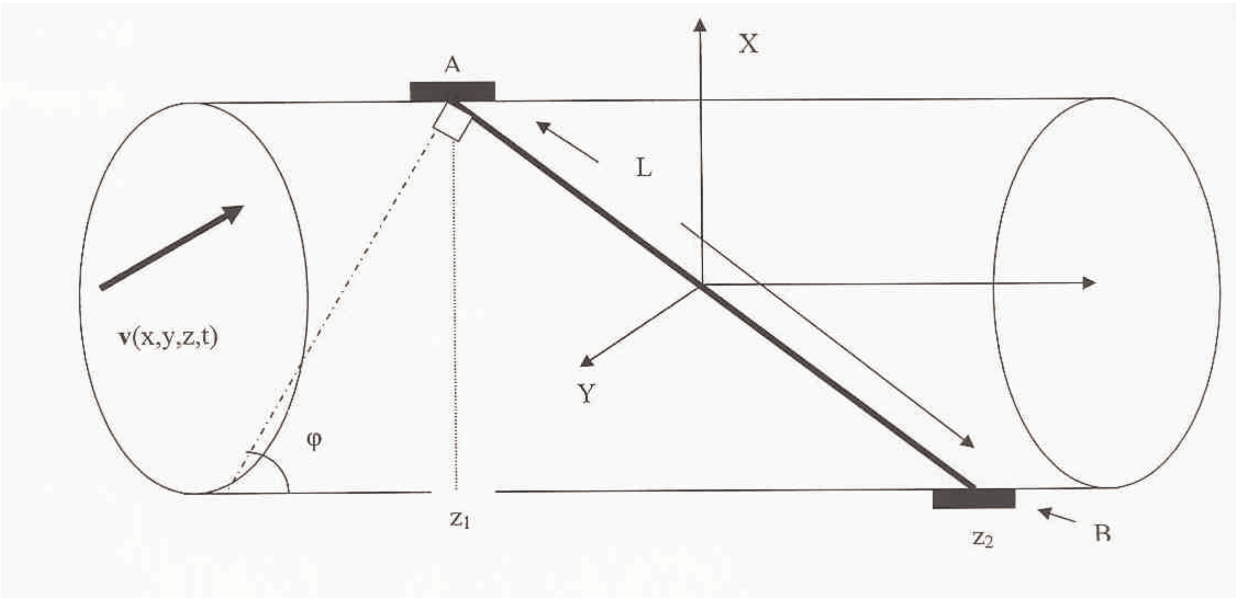
- The processing of differential times provided by the transducers to obtain CheckPlus characteristics such as velocities and flowrates is more complex than summarized above but the principle is the same.

In the following discussion, the NRC staff focuses only on the issues associated with the interaction of the vector valued random fluid velocity field and the acoustic pulse generated at the transducer. Errors introduced in the measurement of the time-of-flight of the acoustic pulse, the temperature and pressure variation of the velocity of sound, and geometric effects due to temperature are addressed separately by Caldon/each licensee and will not be covered further here.

In a feedwater pipe the fluid is in a state of turbulent flow. The velocity of the fluid is therefore a time-dependent random vector field. This can be represented in a vector field in cartesian coordinates as:

$$\mathbf{v}(x,y,z,t) = v_x(x,y,z,t)\,\mathbf{e_x} + v_y(x,y,z,t)\,\mathbf{e_y} + v_z(x,y,z,t)\,\mathbf{e_z} \quad (2)$$

The basic CheckPlus elements are illustrated in the following sketch:




The two transducers A and B are separated by the chordal distance L along which the ultrasonic pulse travels from one transducer to the other. The cartesian coordinates are oriented with the z axis along the length of the feedwater pipe. Thus, transducer A is located at $z_1$ and transducer B at $z_2$. The perpendicular to the chordal distance L forms an angle φ with the z axis. The one-point one-time realization of the random velocity field associated with the turbulent feedwater flow is shown as **v(**x,y,z,t**)**. The mean bulk velocity, $\mathbf{v_B}$, is given by the following expression:

$$\mathbf{v_B} \equiv \frac{1}{A_p}\iint_{A_p} dxdy\left[\frac{1}{T}\int_t^{t+T}\mathbf{v}\,(x,y,z,t)\bullet\mathbf{e}_z\,dt\right] \qquad (3)$$

The task is to evaluate the right-hand side of this expression in terms of the measured transit time $t_{AB}$ and $t_{BA}$ of an ultrasound pulse along the chordal path L between transducers A and B and vice versa.

First of all, the integrand of the time integral reduces to $v_z(x,y,z,t)$, the axial component of the velocity field **v**(x,y,z,t), since only the axial component contributes to the bulk flow velocity. Two further assumptions are required:

1. $v_z(x,y,z,t)$ is statistically homogeneous in the axial coordinate. That is, the density distribution function of $v_z(x,y,z,t)$ is unchanged if (x,y,z,t) is replaced by (x,y,z + Z,t).

2. The z component of the velocity field is a stationary time series. That is, all statistics of $v_z(x,y,t)$ are invariant under a shift in time (i.e. t to t + T). This assumption allows the spatial distribution of the flow to be characterized by the time averaged value:

$$< v_z(x,y) >_T \equiv \frac{1}{T}\int_t^{t+T} \mathbf{v}_z(x,y,t)\,dt \qquad (4)$$

Under these assumptions Equation 3 for the bulk velocity in the feedwater pipe reduces to:

$$v_B = \frac{1}{A_p}\iint_{A_p} v_z(x,y)\,dxdy \qquad (5)$$

The coefficient of the integral consists of readily measurable quantities whose uncertainty is not under consideration at this point in the discussion. It remains to relate the integrand to the measured transit times of the acoustic pulse.

The derivation of the necessary relationship between $v_z(x,y)$ and the transit times is given in Reference 2. The Caldon UFM consists of multiple paths across the feedwater pipe. It is sufficient to derive the required analytic relationship for only one, such as the one shown in the above sketch. The derivation was reviewed with an eye to identifying those assumptions and approximations that need to be accounted for through calibration for a high precision measurement.

The transit times can be expressed in terms of the path length L, the *mean* acoustic propagation velocity $C_L$ along L, and the *mean* fluid velocity component $v_L$ along L by the expressions:

$$t_{AB} = \frac{L}{c_L + v_L} \qquad (6a)$$

and:

$$t_{BA} = \frac{L}{c_L - v_L} \qquad (6b)$$

If Δt is defined by $\Delta t = t_{BA} - t_{AB}$, and Equations 6a and 6b are combined, the following expression is obtained:

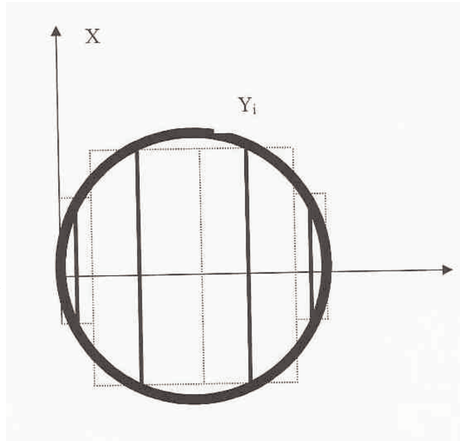
$$\Delta t = \frac{2L\,v_L}{c_L^2 - v_L^2} \qquad (7)$$

Since $c_L^2 \gg v_L^2$, the following approximation is appropriate:

$$\Delta t = \frac{2L\, v_L}{c_L^2} \qquad (8)$$

A numerical estimate of the error incurred in a feedwater pipe through this approximation can be obtained for typical values of $v_L$ ~15 ft/sec and $c_L$ ~4000 ft/sec by computing:

$$\left(1 - \frac{v_L^2}{c_L^2}\right)^{-1} = 1.000014.$$




Clearly, this error is small.

To obtain a value for the bulk fluid velocity in the feedwater pipe it is necessary to evaluate the integral in Equation 5. The figure to the right provides a schematic view of a pipe in the axial direction with four chordal paths. The i-th path is at $Y_i$:

The general expression for the bulk velocity can then be written as:

$$v_B = \int_0^{2R} dy \int_0^{L(y)\cos\phi(y)} dx\ v_z(x, y), \qquad (9)$$

where R is the radius of the pipe. If the four-point Gauss quadrature formula to the integral in Equation 9 is formally applied over the y coordinate, the following expression is obtained (Reference 11):

$$v_B = \sum_{i=1}^{4} \omega_i \int_i^{L_i\cos\phi_i} dx\, v_z(x, y_i), \qquad (10)$$

where the $\omega_i$ are the tabulated Gauss quadrature weights and $v_z(x, y_i)$ is the value of the z-component of the velocity field evaluated at the positions $y_i$ on the y axis that are known and determined by the rules associated with the application of the Gauss quadrature formula. In the xy-plane, the integral over $v_z(x, y_i)$ is related to the mean fluid velocity along the chordal distance $L_i$ by:

$$\int_0^{L_i \cos\phi_i} dx \; v_z(x, y_i) = \frac{v_{L_i}}{\sin\phi_i} \int_0^{L_i \cos\phi_i} dx \qquad (12)$$

$$= \frac{v_{L_i} L_i \cos\phi_i}{\sin\phi_i}, \qquad (13)$$

where $v_{Li}$ is the *mean* fluid velocity along chordal path $L_i$ and $\varphi_i$ is the angle associated with the i-th chordal path as illustrated above. If the expression $v_{Li}$ $L_i$ from Equation 8 is substituted into Equation 13, and the resulting equation is substituted into Equation 10, the desired expression is obtained:

$$v_B = \sum_{i=1}^{4} \omega_i \left[ \frac{\Delta t_i c_{L_i}^2}{2 \tan\phi_i} \right] \qquad (14)$$

This expression relates the measured time-of-flight $\Delta t_i$ at each of the four chords to the fluid bulk velocity.

The time-of-flight is a random variable due to the turbulence in the fluid velocity field. The probability density distribution of this fluid velocity field was assumed above to be stationary in time. Thus, in practice, a large number of measurements are made and the average of this time series, together with its standard error, are computed to give an estimate of the *mean* bulk velocity and a component of the error.

The systematic errors incurred by the use of this algorithm have two basic origins:

1. The application of the Gauss quadrature formula to the integration along the y-axis in Equation 5, for a four chord system, is equivalent to an integration over a seventh order polynomial approximation to the axial fluid velocity distribution along the y-axis (Reference 11). This should be adequate to represent most of the sharp gradient in the velocity field near the wall of the pipe.

2. The numerical approximation to the volumetric flow in the pipe is given by the sum of the flow contribution through the four rectangles shown in the above cross section of the feedwater pipe. Reference 9 noted that, with a flat velocity profile, the four path Gaussian path spacing and weighting factors do not integrate the circular area perfectly and it is necessary to multiply the sum of the intergration elements by 0.994 to correct for this.

According to Caldon, calibration experience has shown that the systematic errors are small in that the uncalibrated measured value of the bulk flow is within approximately 0.1 percent of the value of the standard for moderately asymmetric axial profiles for a four path Caldon instrument (Reference 5). (Comparisons with plant installations are tabulated below.) As discussed below,

during tests at ARL between January 16 and 18, 2006, the CheckPlus uncalibrated error for a wide range of axial profiles was less than 0.05 percent.

The velocity profile effect must be taken into account for high precision bulk velocity measurements in a feedwater pipe. The Caldon Check and CheckPlus address this issue by not only taking multiple spatially distributed measurements, but also by taking those measurements at positions dictated by the Gauss quadrature formula. This leads to a *mean* bulk velocity based on a velocity profile of higher order than would be obtained by a straightforward interpolation of four measurements. Furthermore, it allows a direct estimate of an in-situ calibration coefficient, and thereby, measurement control with regard to variation of the velocity profile and thus, the *mean* bulk fluid velocity during reactor operation.

With the basic operational principles examined, the NRC staff next further reviewed behavior with changes in fluid characteristics such as flowrate and Reynolds number (Re) which are not always directly bounded by the ARL test data. Caldon uses the characteristics of the Check and CheckPlus by defining a flatness ratio (FR) as the ratio of the average axial velocity at the outside chords to the average axial velocity at the inside chords. For the CheckPlus, this is given by:

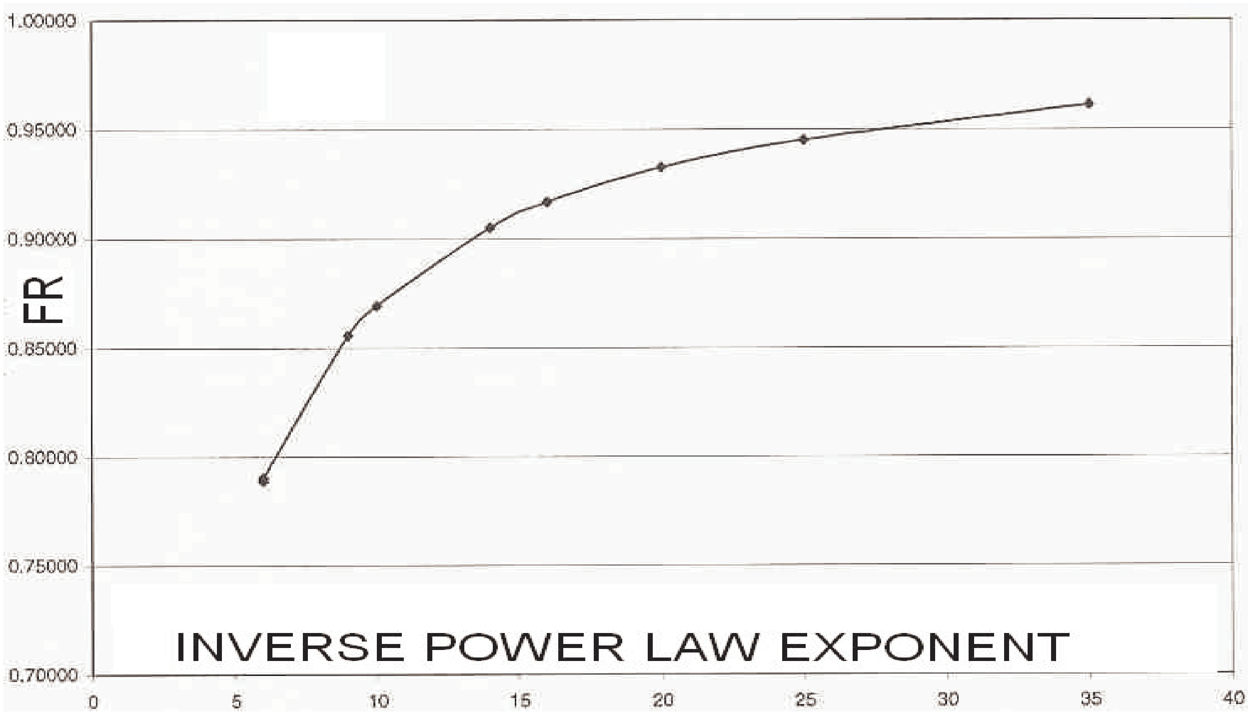
$$FR = (V_1 + V_4 + V_5 + V_8) / (V_2 + V_3 + V_6 + V_7)$$

Caldon then observes that the inverse power law:

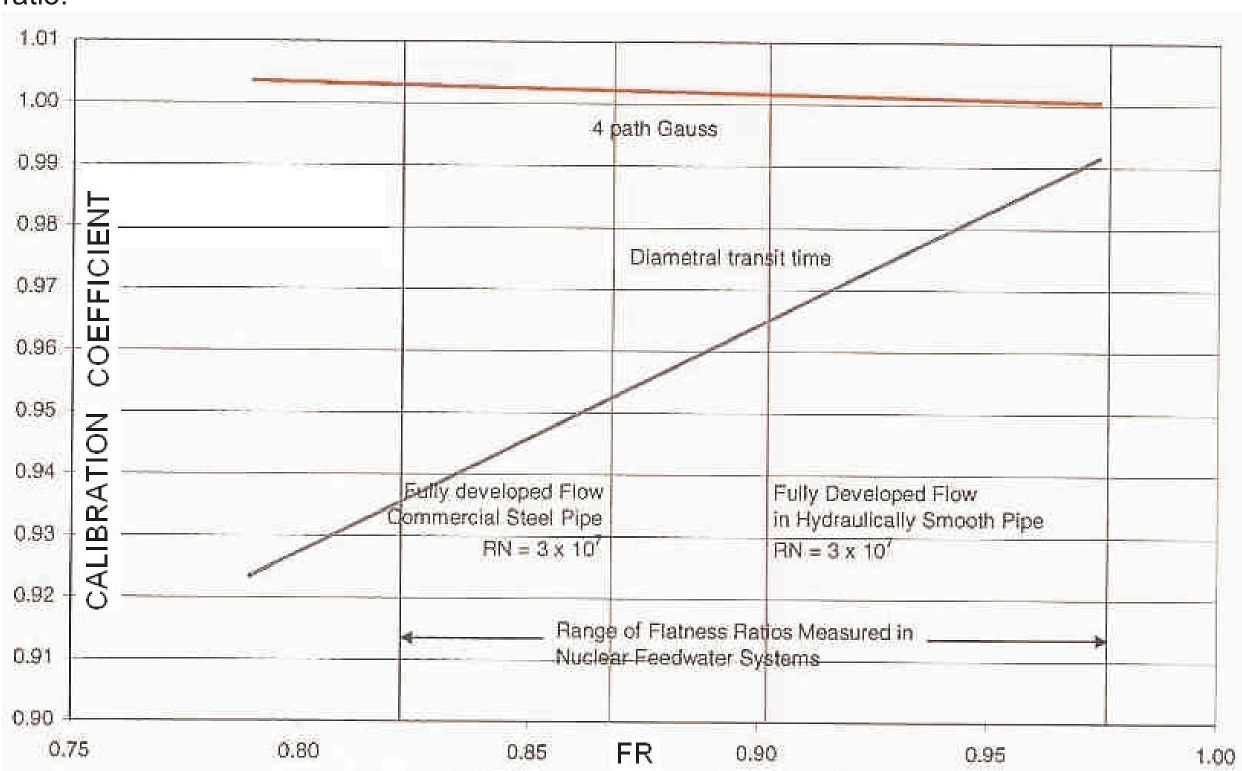
$$V(r) = V_{MAX} (r) / R)^{1/n}$$

where: r = Radial distance from pipe centerline
R = Pipe radius
n = Power law exponent

can be used to characterize a nominally symmetrical axial profile regardless of the Re or the degree of profile development, and that flatness ratio can be related to n since the positions of each of the acoustic paths, the $V_i$ and hence r for i = 1 to 4 or 1 to 8 for the Check or CheckPlus, respectively, are known. Caldon provided the following example for a Check UFM in Reference 6:




Caldon then provided the following curve of the calibration coefficient[2] as a function of Flatness ratio:




[2] Caldon often uses "profile factor" for this term.

The upper line shows a variation of about 0.4 percent over the range of flatness ratio for the Check UFM. The lower line, provided for comparison, shows a significant variation in calibration coefficient for a single path external UFM that uses the Caldon acoustic path measurement method. Also provided is an indication of the flatness ratio range encountered in feedwater systems. Caldon uses flatness ratio for correlation of the calibration coefficient and does not rely upon a Re extrapolation to extend from ARL test data to in-plant conditions. Further, since flatness ratio is provided by the LEFM, the flowmeter will provide its own variation in calibration coefficient if desired. In practice, for the CheckPlus, an allowable variation of ±0.05 percent in flatness ratio is established at commissioning and this is rarely exceeded in plant installations (Reference 5).

Where feedwater enters a common header upstream of the UFM, there is a possibility that temperature will not be uniform at the UFM location. In some cases with off-normal feedwater heater operation, a temperature difference of as much as 30° F or 40° F may occur. Reference 5 stated that CheckPlus would continue to measure bulk average feedwater flowrate within its design basis accuracy because the sound velocity is integrated over the pipe cross section.

Based on the above NRC staff evaluation, the NRC staff finds the theoretical basis for the Check and the CheckPlus to be acceptable for nuclear power plant feedwater applications. Application of the principles developed above to Check and CheckPlus operation is reviewed below.

## 2.2 Calibration Considerations

Caldon defines traceability as a process whereby a measurement can be related to a standard via a chain of comparisons. It continues with the following requirements that apply:

- The standard must be acceptable to all parties with an interest in the measurement and is usually a standard maintained by a national laboratory such as the National Institute of Standards and Technology (NIST).

- The chain of comparisons must be unbroken - the field measurement must be connected, by one or more links, directly to the standard.

- Every link in the chain involves a comparison that not necessarily carries with it an uncertainty. Hence the total uncertainty of the measurement must reflect the aggregate uncertainties of each line of the comparison chain.

- There can be no unverified assumptions in the chain of comparisons; it is clearly not possible rationally to assign an uncertainty to an assumption that has no quantitative basis.

In Reference 6, Caldon traces the variables associated with UFM operation and the uncertainties. Twenty contributors are listed of which only one, the calibration coefficient, is directly associated with the hydraulic aspects being addressed here. The generic uncertainty associated with the calibration coefficient is stated as ±0.4 percent for the Check and ±0.25 percent for the CheckPlus.

Reference 12 provided a compilation of calibration data for 35 CheckPlus and 9 Check UFM flow elements. The NRC staff understands that all were calibrated at ARL using full scale models of the plant and with the UFMs that were to be installed in the respective plants.

The theoretical relationship between meter correction factor (MF) and flatness ratio (FR) is, from Reference 13:

$$MF = 1.0167 - 0.0167\ FR$$

The mean FR measured for different hydraulic configurations with 44 different UFM flow elements is 0.868. The theoretical relationship would predict an MF of 1.0022 for this FR. The mean MF is 1.0034, a difference of 0.09 percent. The uncertainty of the MF data is ±0.75 percent, probably due to inherent difficulty in controlling certain flow element dimensions such as path angles and lateral spacing of the paths. Caldon states that this uncertainty supports the need to calibrate individual UFMs if uncertainties of ±0.3 percent are to be achieved.

There are several considerations applicable to the uncertainty associated with hydraulic behavior. These include:

- Pre-delivery: The LEFM characteristics, such as individual path velocities, flatness ratios, and the calibration coefficient, are measured over a wide range of flowrates and flow configurations in a full scale model using the spool piece and transducers that will be installed in the plant. The test facility flow methodology uses certified standards that are traceable to NIST. The uncertainties are bounded by analysis of test results.

- Commissioning: A complete comparison of test and in-plant results is accomplished to validate accuracy. Comparisons are also made with other plant parameters as a check and to provide insights relative to plant operation although these are not considered necessary to the uncertainty validation. The NRC staff notes that keys to the success of this step are the ability of the LEFM to analyze the flow profile and to provide the flatness ratio to cover flow conditions that were not enveloped by pre-delivery testing.

- Operation: LEFM characteristics are monitored and annunciated if changes occur that are greater than ascribable to normal condition changes.[3] An additional check is obtained by comparing LEFM predictions with other plant parameters consistent with good operating procedures applicable to any instrumentation.

Each of these items is addressed further in the following subsections.

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[3] Reference 13 identified three installations where a substantial change occurred in swirl velocity that affected the flow profile after months of service. In a followup evaluation of 18 installations, Caldon found that “profile changes, particularly due to changes in swirl velocity, are not uncommon.” The worst observed case “would have produced a change of 1.8% in the calibration of a Caldon externally mounted LEFM installed at that location.” In this case, an operational transient reduced wall roughness, flattened the velocity profile, and “caused swirl to increase from 2% to 10% of the axial velocity.”

Based on the above, the NRC staff finds the calibration approach that is traceable to standards and to ARL tests is acceptable.

2.3 Calibration

A CheckPlus System that was manufactured for installation at the Seabrook Station was calibrated at ARL between January 16 and 18, 2006, and selected tests were monitored by the NRC principal reviewer (Reference 7)[4]. These tests included straight pipe testing, plant piping modeling and parametric variations of those models, and extreme swirl tests. Calibration data, determined by comparing laboratory reference standards to the flow as measured by CheckPlus, were collected for each configuration at various flowrates. Measurements of flatness ratio were also collected for each test at each flowrate. Calibration values were plotted against flatness ratio for all tests and compared to analytically derived expected performance curves for quality control purposes. These data provide a quantitative measure of calibration coefficient vs. actual velocity profile encountered.

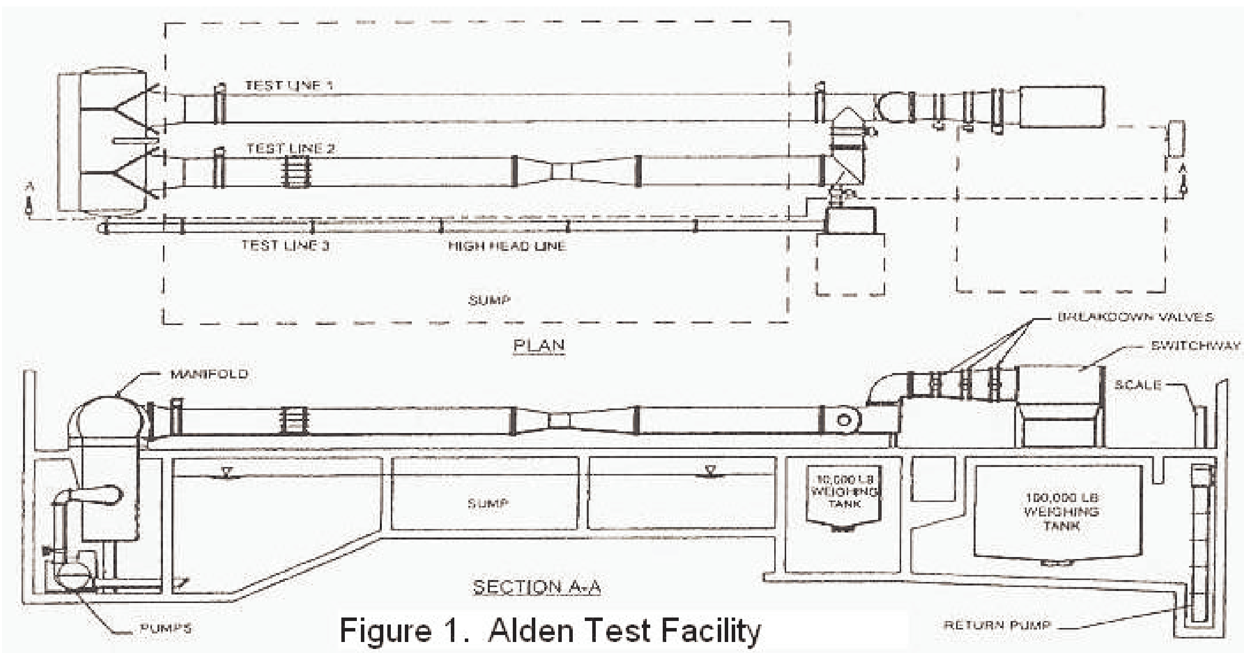


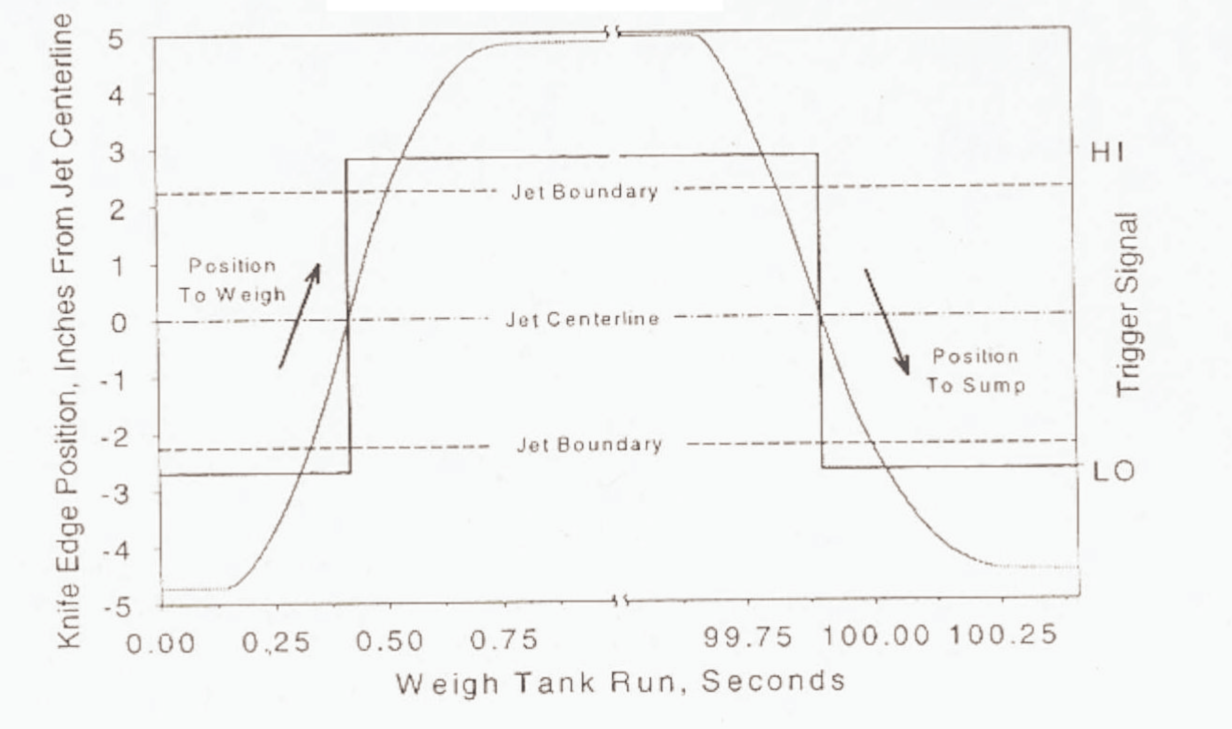

Figure 1. Alden Test Facility

Figure 1 is a generic sketch of the ARL test facility used for the UFM testing. Flow in the test sections starts with a pair of pumps in the lower left, passes through the testsections, through the breakdown (throttle) valves, through the switchway (diverter), and either into the weighing tank or into the sump. The outlet from the breakdown valves is at atmospheric pressure with the flow falling downward as an unrestrained waterfall under the influence of gravity. As a result, activities in the switchway have no influence on flowrate. The switchway consists of a manifold where water drops vertically onto a knife edge diverter plate that sends flow to the weighing tank or to the sump. During steady state operation, the knife edge is out of the flow stream. During switching, the knife edge accelerates to a constant rate prior to entering the flow stream and decelerates after leaving the flow stream as illustrated in Figure 2. This

[4] Much of the information provided in Reference 7 is reproduced here.

restricts diverter interaction with the flowstream during diverter movement to times when diverter movement is constant. Hence, by recording time in the center of the diverter movement for both initiation and termination of weighing tank fill, in the ideal sense, error due to switching is eliminated as is illustrated in Figure 2. In practice, the standard deviation due to the diverter is 0.0100 percent, a small contribution to the overall standard deviation of 0.044 percent (uncertainty of 0.088 percent or two standard deviations). The other contributors to uncertainty are controlled by NIST-certified standards (mass, time, and temperature), transfer standards, and determination of such variables as water density and buoyancy due to air.

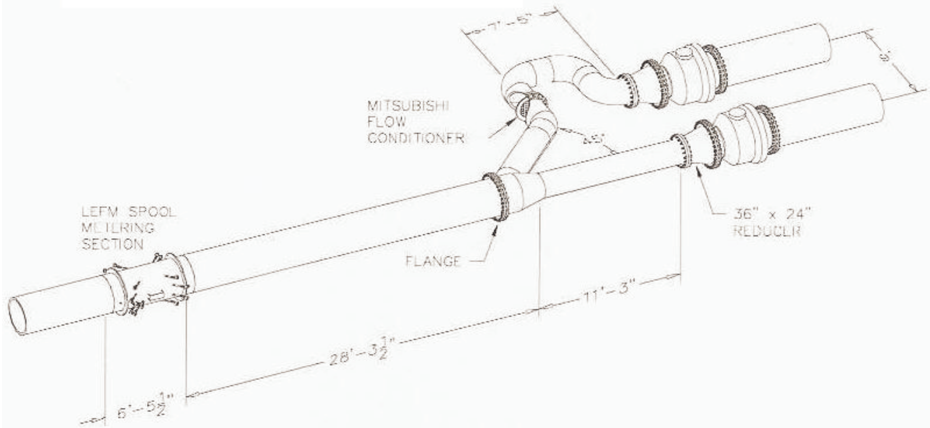
Figure 2. Diverter Operation




Flow from the pumps into the manifold and from the manifold into the two test sections occurs over a short path with abrupt turns. This introduces the possibility of noise, poorly developed flow profiles, and swirl in the test sections; all items of concern with UFMs.

The ARL test configuration for the tests is shown in Figure 3. Flow is from right to left with two 24 inch pipes connecting to a 36 inch pipe that contains the CheckPlus UFM.

Figure 3. Seabrook Test Configuration




Reference 5 stated that the standard deviation of each flow sample due to turbulence is approximately 2 percent and the standard deviation of the average flow reading for a weigh tank run is reduced by the large number of flow samples. However, the reduction is not as great as $1/(N)^{1/2}$ because the periods of some of the turbulent frequencies are only one order shorter than the weigh tank fill time. The reference went on to conclude that the uncertainties due to these statistics are accounted as the observational uncertainty contributor to the calibration factor uncertainty.

The following table summarizes the ARL test results (Reference 8):

| Test | Average Correction Factor | Number of Points | Flatness Ratio | Absolute Swirl Rate | Absolute Swirl Angle, degrees |
|---|---|---|---|---|---|
| 1. Feeds #1 (50%), #2 (50%/0) | 1.0028 | 25 | 0.897 | *0.5%* | 0.3 |
| 2. Feeds #1 (25%), #2 (75%/0) | 1.0033 | 25 | 0.900 | 0.6% | 0.4 |
| 3. Feeds #1 (75%), #2 (25%) | 1.0024 | 25 | 0.924 | 1.1% | 0.6 |
| 4. Feeds #1 (50%), #2 (50%) Mitsubishi Flow Straightener Removed | 1.0031 | 25 | 0.892 | 0.9% | *0.5* |
| 5. Feeds #*1* (50%), #2 (50%) with "Half Moon" Orifice | 1.0025 | 25 | 0.890 | 2.0% | 1.2 |
| 6. Feeds #1 (100%), #2 (0%) with 'Half Moon" Orifice | 1.0012 | 15 | 0.943 | 54.8% | 28.6 |
| 7. Straight Pipe | 1.0033 | 25 | 0.857 | *0.5%* | 0.3 |

| Test | Average Correction Factor | Number of Points | Flatness Ratio | Absolute Swirl Rate | Absolute Swirl Angle, degrees |
|---|---|---|---|---|---|
| 8. Straight Pipe/Transducer Change Out Test | 1.0035 | 10 | 0.864 | 0.7% | 0.4 |
| Average of Tests 1 - 5 | 1.0028 | - | 0.901 | 1.0% | 0.6 |

The average correction factor for the uncalibrated CheckPlus for tests 1 - 5 is 0.28 percent, indicating that the uncalibrated CheckPlus provides close to actual flowrate.

The above test results are generally consistent with other CheckPlus experience as is illustrated in the following table (Reference 14):

| Plant | Loop | Initial Percent Difference |
|---|---|---|
| Asco 1 | Header | -1.00 |
| Beaver Valley 2 | Header | -1.50 |
| Cofrentes | A | 2.52 |
| | B | 1.34 |
| DC Cook 1 | Header | 0 |
| DC Cook 2 | Header | 0.10 |
| Grand Gulf | A | 0.40 |
| | B | -0.70 |
| Peach Bottom 2 | A | 0.60 |
| | B | -0.10 |
| | C | -0.90 |
| Peach Bottom 3 | A | 0.40 |
| | B | 0.20 |
| | C | -0.75 |
| River Bend | A | -0.23 |
| | B | -0.35 |
| HB Robinson | A | -0.19 |
| | B | 0.58 |

| Plant | Loop | Initial Percent Difference |
|---|---|---|
| | C | 0.15 |
| Vandelios 2 | Header | -0.80 |
| Waterford 3 | A | 0.40 |
| | B | 0.30 |
| Average of Absolute Values | | 0.40 |

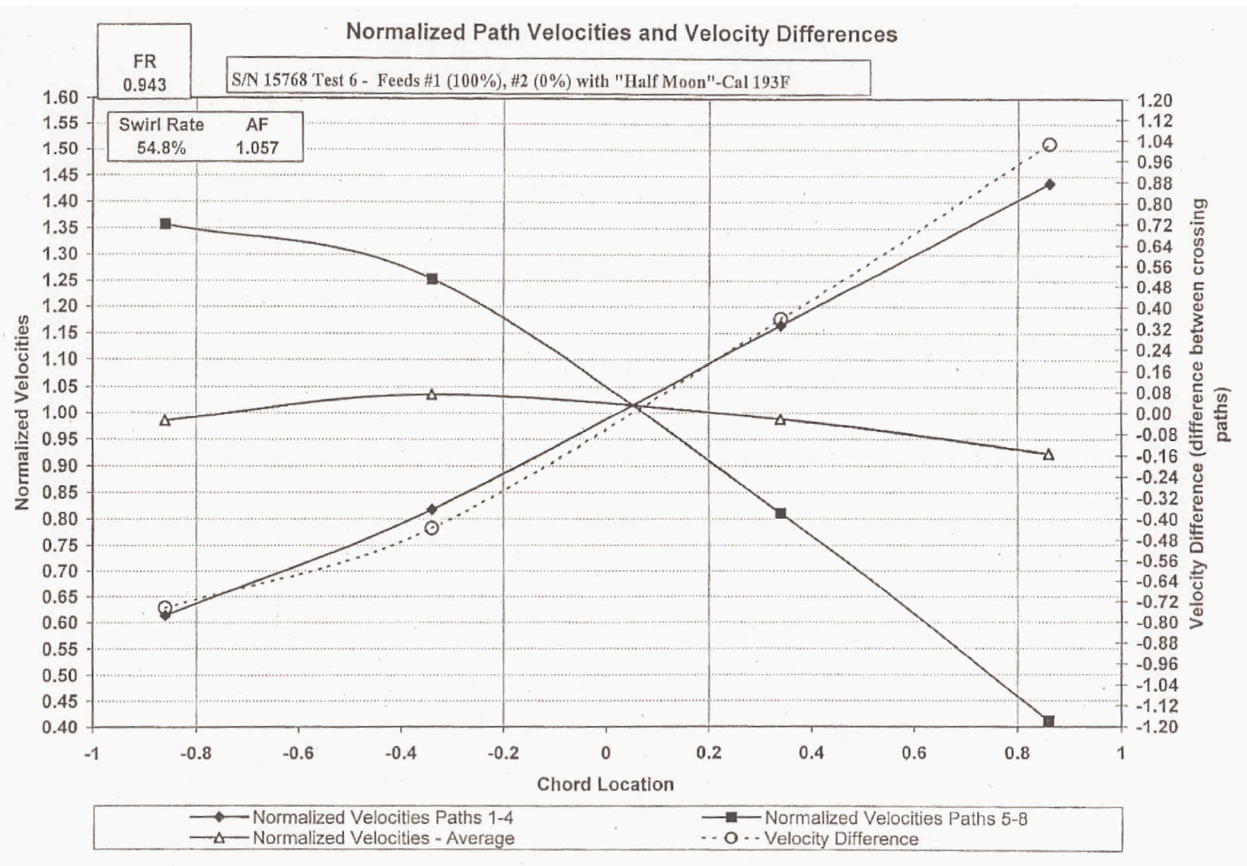
It is also informative to list the Check system experience from Reference 14:

| Plant | Loop | Initial Percent Difference |
|---|---|---|
| Beaver Valley 1 | Header | 0.30 |
| Comanche Peak 1 | Header | 0.80 |
| Comanche Peak 2 | Header | 0.60 |
| Indian Point 2 | 21 | 0.50 |
| | 22 | 0.50 |
| | 23 | 0.50 |
| | 24 | 0.50 |
| Indian Point 3 | 31 | 1.04 |
| | 32 | 1.04 |
| | 33 | 1.04 |
| | 34 | 1.04 |
| Point Beach 1 | Header | -1.00 |
| Point Beach 2 | Header | -1.00 |
| Sequoyah 1 | Header | -0.89 |
| Sequoyah 2 | Header | -0.46 |
| Susquehana 1 | A | -0.40 |
| | B | 0.40 |
| | C | 0.80 |
| Susquehana 2 | A | 0.70 |
| | B | 0.50 |

| Plant | Loop | Initial Percent Difference |
| --- | --- | --- |
| | C | -.50 |
| Watts Bar | Header | -0.46 |
| Average of Absolute Values | | 0.68 |

As expected, the Check, on average shows a greater average difference, but it still does not require a substantial correction factor.

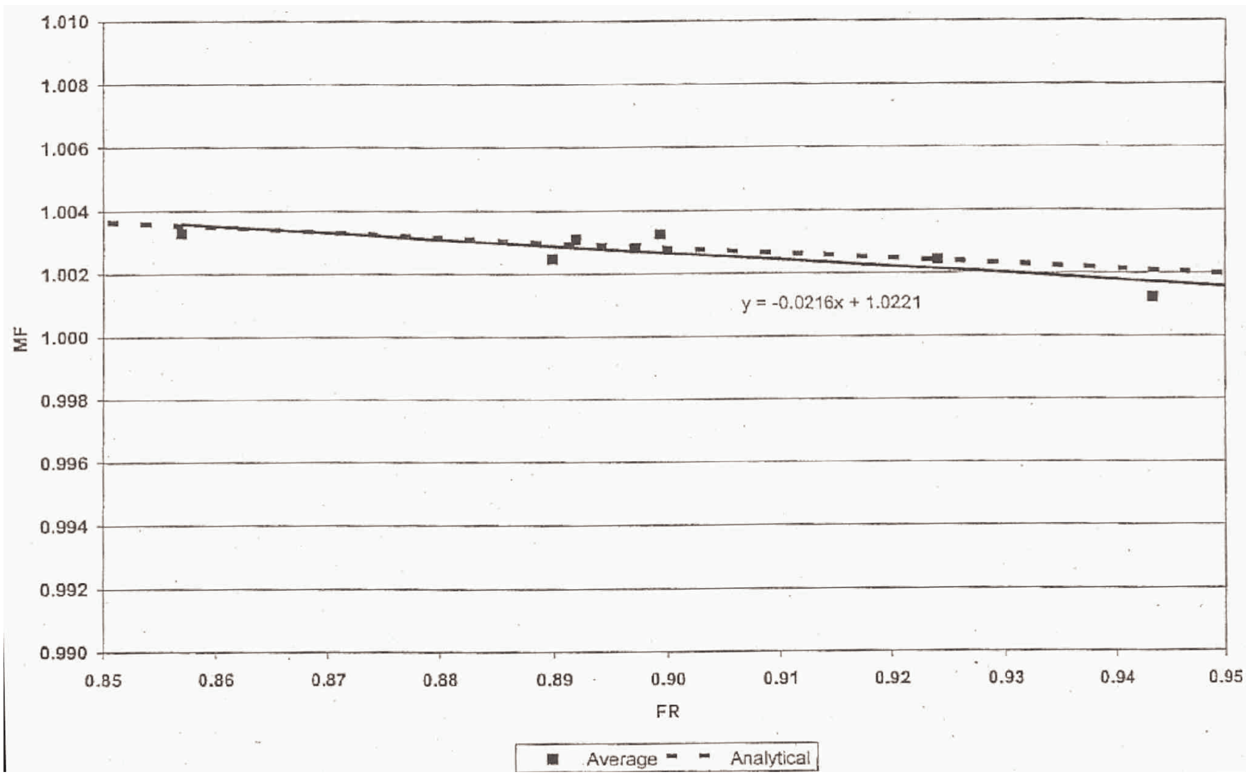
Response to swirl is also of interest. Insertion of a half moon orifice into the test pipe showed in the above CheckPlus table that the CheckPlus is relatively unaffected by a significant perturbation to the velocity profile. This is further illustrated in the following figure that illustrates the profile determined by CheckPlus for test 6:




The normalized velocities for paths 1-4 clearly show the skewed profile and the behavior shown for paths 5-8 is essentially the reverse, as expected. One may also conclude from this figure that the Check system may be more sensitive to swirl since either paths 1-4 or paths 5-8 are representative of a Check system. However, the Check system output would be a weighted average of each of the four points on the respective path curves that would reduce the effect of

the swirl and the Check system clearly is capable of providing sufficient information to identify that significant swirl is present.

Flatness ratio for the ARL tests is illustrated in the following figure where the NRC staff refers to Caldon's "MF" or meter factor as the correction factor:




This figure[5] shows that changes in flatness ratio between 0.85 and 0.95 could change the correction factor by 0.08 percent from the correction factor corresponding to a flatness ratio of 0.90. This shows that minor MF changes for the different hydraulic configurations are in general accord with the analytical calculation.

Based on the NRC staff's evaluation of the information described above, this calibration process is acceptable. The NRC staff concludes that, since Caldon conducts a similar test series for all of its Check and CheckPlus systems prior to installation, such calibration processes will also be acceptable.

2.4 Commissioning and Operation

The NRC staff evaluated the planned commissioning and operation of the CheckPlus system that is planned for installation at Seabrook Station and found these to be acceptable as reported in Reference 16. This evaluation is summarized here as an example of an acceptable commissioning and operation process.

[5] The equation for the analytical line is derived in Reference 13.

Following installation of CheckPlus at Seabrook Station, the commissioning and operation process requires, as stated in Reference 5 for the Seabrook Station licensee, that flatness ratio will be measured for each four path acoustic plane and for the eight path system as a whole. It will then establish:

- the appropriate correction factor for operation in the eight path (CheckPlus) and four path modes (the latter for use if one plane is out of service, a condition termed "maintenance mode"),

- the range of acceptable flatness ratio changes to obtain the settings for high and low flatness ratio alarms so that the determined correction factor remains applicable, and

- the allowable variation in individual path acoustic velocity versus average acoustic velocity from all paths.

The Seabrook Station licensee stated in Reference 4 that CheckPlus measurements of velocity profile will be compared to the reference measurements collected during the ARL calibration. The licensee expects that the range of velocity profiles encountered during calibration at ARL will envelope the velocity profiles encountered in the plant and will require no extrapolation. However, in the event that the ARL velocity profile data does not completely envelope the installation velocity profile data, the licensee expects the range of extrapolation will be small and, since the meter factor vs. flatness ratio calibration curve is linear, extrapolation uncertainties should also be small. However, for purposes of its Reference 8 report, the bounding uncertainty is stated to be a 5 percent maximum change in flatness ratio as the bound in differences between the ARL tests and the plant. This is stated to produce an extrapolation uncertainty of 0.08 percent.

A preliminary estimate of the uncertainty associated with applying the calibration data in the plant is to be made as part of the calibration test report. The Seabrook Station further stated that a final verification of this uncertainty will be made following installation and commissioning of the meter in the plant based on in-plant measurements of the profile flatness. These data are to be collected and the comparison to ARL data made consistent with Caldon Engineering Field Procedure EFP-61 that was provided to NRC in Reference 15.

Transducers are removed following the ARL tests, in part to avoid transportation damage since they protrude outside of the diameter of the CheckPlus flanges. They are then replaced as part of the installation process. Further, occasional transducer replacement may be necessary. Caldon addresses many aspects of the transducer-to-spool piece contributions to uncertainty but it has not provided sufficient data to substantiate that the uncertainty considerations envelope transducer replacement effects. (The effect of transducer replacement was tested during test 8 of the Seabrook Station ARL tests discussed above but the results were limited since only two spare transducers were available.) The NRC staff found that such data and an assessment of the contribution to uncertainty should be provided as part of the commissioning process and it considered this to be a confirmatory item since, in part, the ARL tests indicate the effect is small. However, future proposed applications should provide this information as part of a licensee's application.

Noise is known to potentially affect time measurements. Consequently, "during commissioning, the magnitudes of the received signals, coherent noise, and random noise are measured in

each direction for each acoustic path, to ensure that potential errors from these sources are within the uncertainty budget. The magnitude of the received signals is continuously monitored during subsequent operation of the LEFM. If the signal strength on any acoustic path falls below the level at which the signal/coherent noise ratio is acceptable (from the standpoint of the budgeted uncertainty) that signal is rejected. Continuous rejections cause a path to be declared ‘out of service’ and the meter will enter the ‘maintenance mode’ with increased uncertainty (and therefore a lower allowable thermal power). In addition, a diverse back up, the ratio of signal strength to the aggregate noise (coherent plus random) is used as a measure of signal acceptability.” (Reference 5. See also Reference 10.)

ARL test runs were typically between about 40 seconds and 3 minutes and, according to Reference 5, a sample time of greater than 2 minutes will generally reduce uncertainties due to turbulence to approximately 0.1 percent. However, operation in the plant may involve changes in feedwater valve positions and thermal equilibrium between the reactor coolant system, the steam generators, and the power conversion system. Consequently, a sample time of about 5 minutes may be needed. Plant-specific sampling times will be defined in licensee applications. For example, Seabrook Station will use an LEFM rolling average of 30 seconds to be consistent with the 4 minute, 1 hour, and 8 hour rolling averages currently used at the plant.

Reference 5 stated that an examination of the database comparison between profiles encountered in laboratory calibration and in the plants that was provided in References 12 and 13 led to the following observations:

- Plant profiles cannot be precisely predicted in the laboratory.
- Profiles are subject to change over time and in fact, change in 100 percent of the cases.
- Therefore, an allowance must be maintained to account for meter factor change commensurate with profile changes observed. The ±0.1 percent accounted for in modeling uncertainty covers this effect for LEFM CheckPlus Systems.

## 2.5 Other Considerations

Caldon has historically had a program of active followup with licensees who use its UFMs and has documented operating history, UFM failures, and corrective actions. (See, for example, Reference 14.) The only failure of concern to the NRC staff’s hydraulic aspects review was eight transducer failures of an old design that were attributed to thermal cycling that caused transducer coupling failure. Data reported in 2003 showed signal strength variation with the number of thermal cycles with the old design. Similar tests showed no significant variation or trending with the new design and no further problems have been encountered. The NRC staff considers an active followup that covers experience to be a necessity based on the operational history of UFMs and the benefits that have resulted from such interchanges of information. The NRC staff further considers that the Caldon process meets such expectations.

## 3.0 CONCLUSIONS

As a result of this review, the NRC staff finds that the hydraulic aspects of Check and CheckPlus systems have been accurately described in applicable Caldon documentation, that there is a firm theoretical and operational understanding of behavior, and, with one exception, there is no further need to re-examine the hydraulic bases for use of the Check and CheckPlus systems in nuclear power plant feedwater applications. The exception, which should be followed up by Caldon for generic purposes, is to establish the effect of transducer replacement on the Check and CheckPlus system uncertainties.

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Principal Contributor: W. Lyon

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