ABSTRACT

LEFM CheckPlus chordal ultrasonic flowmeters typically provide nuclear and fossil feedwater mass flow measurements with uncertainties of about ± 0.3% at a 95% confidence level. The largest contributor to this uncertainty is the uncertainty in meter factor—typically in the ± 0.2 to ± 0.25% range.

The meter factor and its uncertainty are established, for each CheckPlus system, by a series of calibration tests in a certified hydraulic facility. The test series is extensive. The hydraulic configuration of the intended plant installation is modeled in full scale, then varied parametrically, thereby establishing a “base” meter factor and characterizing variations in that meter factor with variations in hydraulic geometry. The parametric tests also provide a basis for extrapolating calibration results to plant conditions. This process utilizes quantitative measures of the velocity profile made during the calibration tests and in the plant to ensure that the pertinent characteristics of the plant profile have been captured by the calibration tests.

Over 100 chordal flowmeters have been calibrated using this process. Meter factors have been established in nearly 500 hydraulic geometries. This paper examines both the variations in the meter factor from one flow element to another and the variations of the meter factor of individual flow elements from one hydraulic configuration to another. Both kinds of variations are characterized statistically, allowing the quantification of variations due to flow element dimensional tolerances and of the variations as functions of a broad spectrum of upstream hydraulic configuration.

Using these data, an approach to standardizing the LEFM CheckPlus calibration process is described.

1. INTRODUCTION

The Caldon Ultrasonics group of Cameron’s Measurement Systems Division has been furnishing chordal ultrasonic meters for the measurement of feedwater flow in nuclear power plants for many years. Since 1999 these meters have been used to support nuclear plant power...
uprates (called Measurement Uncertainty Recapture or MUR uprates), under a revision to the applicable regulations [1], which allows a reduction in the margin for uncertainty in the thermal power measurement contingent on the demonstration of a reduction in the actual uncertainty of that measurement. The uncertainty in the mass rate of feedwater flow is the principal contributor to the thermal power uncertainty.

In late 2000, the LEFM CheckPlus was introduced. The CheckPlus is an eight chord meter that addresses a significant source of uncertainty in the earlier chordal meters: swirl. As shown in Figure 1, the acoustic paths that form the eight chords are arranged in two planes, which are at right angles to each other and at 45° with respect to the nominal flow axis. With this arrangement, transverse fluid velocity components, including swirl, produce equal and opposite projections in the chords of each plane, thereby cancelling.

![Figure 1: An LEFM CheckPlus Flow Element (Uninsulated)](image)

The acoustic paths in the two planes are numbered from top to bottom. Plane A is formed by paths 1, 2, 3 and 4 made up of the transducers on the left front and partially visible in the right rear of the flow element. Plane B is made up of paths 5 through 8, transducers for which are visible in the right forefront of the figure and partially visible in the left rear.

Each LEFM CheckPlus is calibrated at a certified hydraulic laboratory against traceable standards. Because a CheckPlus system performs a numerical integration of the axial velocity profile, the calibration process is carried out in a hydraulic model of the segment of the feedwater system in which the meter will ultimately be installed. The intent of the model is to produce inertial forces on the fluid that duplicate the inertial forces that the fluid will experience in the plant. Pipe size limits the extent of the model—the lines in which the meters are installed range from 14 inches to 36 inches in diameter. Because of this limitation, one or two of the principal upstream features are typically included in the model. To ensure that model tests embrace the possible impact of features not modeled, parametric tests are performed in which, for example, the velocity profile at the entrance to the model is intentionally distorted, and the change in calibration recorded. The extent of parametric testing has varied, the number of tests depending on the specifics of the eventual installation, but on average four parametric tests have been included in each calibration.

In this paper, the calibration data for 125 CheckPlus flow elements have been used to draw some general conclusions regarding the response of CheckPlus chordal meters to a spectrum of hydraulic configurations. Specifically the data have been used to characterize what has been called the “modeling sensitivity” of CheckPlus flow elements—the variation of meter factor $1$ about its mean, brought about by parametric changes to the hydraulic model of

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$1$ The term “meter factor” is used throughout this report to describe the ratio of the measurement of volumetric flow rate as determined by a traceable standard to the volumetric flow rate measurement of the LEFM—the instrument’s calibration coefficient. In Candalone reports ER-157 and ER-80, as well as other papers in the open literature, this term has been referred to as “Profile Factor”. “Meter factor” is more generally
the application. The data have also been used to characterize the dependence of the absolute values of the meter factors for these flow elements on the attributes of the upstream hydraulic configuration. Finally the data have been used in support of analyses to determine the effect on meter factor of the viscous forces on the profile, as characterized by Reynolds Number, and, inferentially, the relative roughness of the connecting piping.

2. SUMMARY

The calibration data for 125 flow elements for the measurement of feedwater flow in nuclear power plants are analyzed. In all of these calibrations the hydraulic geometry upstream of the flow elements has been modeled and varied parametrically. As a consequence, the data for the 125 flow elements includes nearly 500 separate hydraulic configurations. The uncertainties in the determination of the meter factors for these flow elements are defined and quantified, including the uncertainties associated with applying the meter factors in the field, where the viscosity of the fluid will differ from that in the calibration lab and where the relative roughness of the upstream piping may differ as well.

The aggregate meter factor uncertainties for two nuclear flow elements are calculated in a sample typifying the application of the data. It is shown that the meter factor uncertainty thus determined is consistent with a mass flow measurement uncertainty, in the plant, of ±0.25%, a figure that makes possible an overall power measurement uncertainty of ±0.3%.

3. DISCUSSION OF RESULTS

3.1 Meter Factor Data; Causes of Variability

Figure 2 is a plot of all the data used in this analysis.² The average meter factor for all calibration configurations for all of the flow elements whose data are included in this analysis is 1.0007. This figure is within 0.05% of the average of two theoretical-empirical meter factor correlations for developed profiles in the range of Reynolds Numbers for which calibrations were performed: 0.5 × 10⁶ to 3 × 10⁶. These correlations will be discussed further in a later paragraph. It should be noted however that most of the velocity profiles for the hydraulic configurations in which the meter factor measurements were made were not fully developed.

The gap in calibration data of Figure 2 between the latter half of 2004 and the beginning of 2006 corresponds to a hiatus in Measurement Uncertainty Recapture uprates due to questions about ultrasonic technology. These questions were resolved in an extensive investigation by the staff of the Nuclear Regulatory Commission, which issued an SER generally confirming the accuracy of the LEFM CheckPlus early in 2006.

The meter factors of Figure 2 vary from one flow element to another, by as much as ±0.8%, even though the average is close to 1.000. Nevertheless, it will be shown that the meter factor for a specific flow element is not very sensitive to the upstream hydraulic configuration, or to Reynolds Number, or to relative roughness. Instead, the variations in meter factors from one CheckPlus flow element to another are due in large part to differences between the geometric properties input for that flow element and the actual geometric

² Each data point in the figure is the average of all the meter factors measured for a particular hydraulic configuration. It should be noted that for each configuration, measurements are made at 4 or 5 different flow rates over a 5:1 range. At each flow rate five separate measurements of meter factor are made.
properties. The most important of these parameters (and the most difficult to measure and control) are the angles of the acoustic paths. The path angles are affected by:

- The angles the housing bores make with the axis of the flow element, but also
- The positioning of the housings in the bores (which in turn is affected by the housing-bore threads, the closure weld, and the configuration of the housing itself), and
- The position of the transducer in the housing and the center of action for the acoustic energy leaving and entering the transducers.

Support for the assertion of the preceding paragraph is found in Figure 3. The ability to control the dimensions that set the meter factor has improved over time. The figure plots the meter factors for each flow element in two groups: (1) those constructed in the 2000 to 2004 time frame, and (2) those constructed in 2005 and thereafter. There is a small difference in the average meter factor (1.0016 early and 0.9994 late). But more important, there is also a difference in the 95% confidence bounds on these meter factors: ± 0.8% for 2001 through 2004 and ± 0.5% for 2005 and later.

Figure 2: Meter Factor, 125 Flow Elements
509 Hydraulic Configurations

Figure 3: Meter Factors Measured for 125 CheckPlus Flow Elements
3.2 Meter Factor Uncertainty Contributors

The aggregate uncertainty in meter factor is the principal contributor to the uncertainty in the mass flow measurement of an LEFM CheckPlus system. The elements of this uncertainty are accounted as described in Table 1. The nomenclature is not different in its essentials from that of the topical report ER-157; however, as the table shows, the specificity of individual contributors is enhanced by separating the uncertainty contributions of the inertial forces in the plant versus the model (“modeling sensitivity”) and the differences in profile produced by differences in fluid viscosity and the relative roughness of the upstream piping in the calibration facility as against the plant (“allowance for profile variations due to viscosity and relative roughness”).
### Table 1
LEFM CheckPlus Uncertainty Definitions

<table>
<thead>
<tr>
<th>Term</th>
<th>Description</th>
<th>Relationship to Topical Report ER-157P Rev 8</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Facility Uncertainty</strong></td>
<td>This term captures the uncertainty of the weigh tank apparatus and is established by the facility operator. For multiple loop flow elements calibrated sequentially or concurrently, this term is treated systematically among the several elements, since several of the main contributors may be systematically related (e.g., scale calibration bias, deflector position/time detection).</td>
<td>Changed</td>
</tr>
<tr>
<td><strong>Measurement Uncertainty</strong></td>
<td>The aggregate time measurement uncertainties of the electronics used for the calibration tests as well as a term characterizing the uncertainty in the placement of transducers in their housings. The latter term is the square root of the sum of the squares of placement uncertainties characterizing (a) the installation of transducers for the calibration and (b) the removal of the transducers following calibration and reinstallation after the flow element is welded into the plant system. This term is treated as random among multiple loop flow elements.</td>
<td>Changed from Rev 8. The placement uncertainty was not explicitly considered in Rev 5.</td>
</tr>
<tr>
<td><strong>Modeling Sensitivity</strong></td>
<td>Differences in the hydraulic configuration of the plant versus that in the lab can cause differences in the inertial forces to which the fluid is subjected, thereby altering the velocity profile. This term captures the uncertainties in meter factor produced by configuration differences between plant and calibration facility. In past calibrations such differences have been quantified by the scatter among parametric tests of the model for the application. In the future these estimates will be augmented using data from past calibrations of flow elements in hydraulically similar geometries, as described later in this paper. This term is treated as random among multiple loop flow elements if the geometries of the loops differ.</td>
<td>This uncertainty is captured in the “Modeling and Reynolds Number” term. The ER-157P term also captured the uncertainties associated with differences in viscosity and relative roughness between calibration and the plant.</td>
</tr>
<tr>
<td><strong>Allowance for Profile Variations Due to Viscosity and Relative Roughness</strong></td>
<td>This term allows for differences in meter factor because the profiles that the meters may see in the plant can differ from profiles experienced in the calibration facility due to the differences in the viscous forces on the plant fluid versus those in the lab (characterized by the difference in the Reynolds Numbers) or to the differences, between plant and lab, in the relative roughness of the upstream piping. This term is treated as systematic among multiple loop flow elements, since the factors that affect viscosity and roughness—feedwater temperature and chemistry—are the same for all loops.</td>
<td>As noted in the preceding entry, this term is captured in the “Modeling and Reynolds Number” term of ER-157P.</td>
</tr>
<tr>
<td><strong>Mean Meter Factor Uncertainty</strong></td>
<td>The meter factor for a flow element is the average (mean) of all of the meter factor measurements made for that flow element—no data are excluded. This term characterizes the 95% confidence limits on the uncertainty in that mean. Each set of data at a given flow rate is treated as a separate datum, since in fact the profile varies with flow rate (i.e., Reynolds Number varies with flow rate). Furthermore, all hydraulic configurations are included whether or not they closely resemble the in-plant configuration, since data show that, on average, meter factor is insensitive to upstream hydraulic configuration (See discussion elsewhere in this document). For multiple loop flow elements, term is treated as random.</td>
<td>For past flow element calibrations, The uncertainty in the mean meter factor was included in the “Modeling and Reynolds Number” term.</td>
</tr>
</tbody>
</table>
3.3 Effect of Hydraulic Configuration on Meter Factor

Table 2 below summarizes the analyses of the data of Figures 2 and 3, categorized according to the hydraulic features upstream of the flow elements. One outlier from the set of Figures 2 and 3 has been eliminated—an 11 inch ID flow element for a fossil power plant whose meter factor was beyond the 99.5% confidence limits for the 2005-to-present data set. Additionally, the data for meters downstream of plate-type flow conditioners are excluded, because the data for this configuration are too sparse (3 configurations) for meaningful analysis.

Table 2
Summary of Meter Factor Measurement Data,
121 CheckPlus Meters, 427 Hydraulic Configurations

<table>
<thead>
<tr>
<th>Upstream Hydraulic Feature</th>
<th>Straight Pipe</th>
<th>Reducing Tee / Header Discharge</th>
<th>One or More Planar Bends</th>
<th>Compound Non-Planar Bends</th>
<th>Venturi</th>
<th>Tubular Flow Conditioners</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Configurations</td>
<td>72/31(1)</td>
<td>33</td>
<td>154</td>
<td>54</td>
<td>25</td>
<td>54</td>
</tr>
<tr>
<td>Minimum Proximity, Flow Element to Feature, Diameters</td>
<td>(3)</td>
<td>8</td>
<td>5</td>
<td>5</td>
<td>3</td>
<td>10.5</td>
</tr>
<tr>
<td>Mean Meter Factor</td>
<td>1.00058</td>
<td>0.99958</td>
<td>1.00146</td>
<td>1.00025</td>
<td>0.99932</td>
<td>1.0023</td>
</tr>
<tr>
<td>95% Confidence Limits Meter Factor</td>
<td>± 0.87%</td>
<td>± 0.45%</td>
<td>± 0.74%</td>
<td>± 0.69%</td>
<td>± 0.21%</td>
<td>± 0.59%</td>
</tr>
<tr>
<td>Average Flatness Ratio(4)</td>
<td>0.83</td>
<td>0.87</td>
<td>0.89</td>
<td>0.93</td>
<td>0.87</td>
<td>0.84</td>
</tr>
<tr>
<td>Standard Deviation of Variations in Meter Factor About Mean in Parametric Tests, &quot;Model Sensitivity&quot;(2)</td>
<td>± 0.00122</td>
<td>± 0.00106</td>
<td>± 0.00095</td>
<td>± 0.00077</td>
<td>± 0.00054</td>
<td>± 0.00119</td>
</tr>
<tr>
<td>95% Confidence Limits for Parametric Variations(2)</td>
<td>± 0.25%</td>
<td>± 0.22%</td>
<td>± 0.19%</td>
<td>± 0.15%</td>
<td>± 0.11%</td>
<td>± 0.24%</td>
</tr>
<tr>
<td>Average of &quot;Model Sensitivity&quot; Variations</td>
<td>0.00000</td>
<td>0.00003</td>
<td>0.00015</td>
<td>0.00022</td>
<td>-0.00010</td>
<td>-0.00011</td>
</tr>
</tbody>
</table>

(1) Straight pipe measurements were made on 72 flow elements, but on only 31 were multiple measurements made so that a “model sensitivity” term could be determined.

(2) When multiple parametric tests are performed with the model of an application, the “model sensitivity” characterizes the 95 % confidence limits for the variations in meter factor about its mean.

(3) Typically the LEFM is more than 20 D downstream of the flow conditioner used in straight pipe tests at the Alden Research Laboratory facility

(4) The flatness ratio is the quotient of the average velocities measured by the 4 outer paths of a CheckPlus and the average velocities measured by the 4 inner paths.

Note that the average meter factor for each hydraulic configuration of Table 2 is within 0.2% of the overall average meter factor for the data set—1.0003—despite the fact that the axial velocity profiles for the configurations differ significantly.

The chordal configuration of the LEFM CheckPlus flow measurement system provides a quantitative metric for the axial velocity profile: the flatness ratio. This term is defined as
ratio of the sum of the velocities measured by the 4 outer chords divided by the sum of the velocities measured by the 4 inner chords (If the profile is perfectly flat, the flatness ratio is 1.00). The flatness ratio for an LEFM CheckPlus system is insensitive to swirl and other transverse velocity components because such components project equally and oppositely on the acoustic paths of the two planes (refer again to Figure 1).

Figure 4 plots the average of the meter factors measured for each hydraulic configuration of Table 2 against the average of the flatness ratios measured for that configuration. It should be noted that the spread of the flatness ratios for each configuration is broad—for some configurations as much as ± 0.08 (two standard deviations). Nevertheless Figure 4 clearly demonstrates that, on average, the CheckPlus meter factor for the range of hydraulic configurations covered by Table 2 is not very sensitive to the shape of the axial profile produced by those configurations.

![Figure 4: Average Meter Factor for a Selection of Upstream Hydraulic Features vs. Profile Flatness](image)

### 3.4 Effect of Swirl on Meter Factor

The calibration data on which Figures 2 through 4 and Table 2 are based also demonstrate that CheckPlus meter factors are insensitive to swirl and other transverse velocity effects. The non coplanar bend and, to a lesser extent, the planar bend configurations produce significant transverse velocities. The chordal arrangement of the LEFM CheckPlus allows the tangential velocity at the pipe wall, VT in per unit to be computed as follows:

\[
VT = \frac{1}{2} \left\{ \frac{1}{2} \left[ \frac{(V1-V5)/2 + (V8-V4)/2}{Y_{OUT}} \right] + \frac{1}{2} \left[ \frac{(Y2-Y6)/2 + (Y7-Y3)/2}{Y_{IN}} \right] \right\} 
\]

(1)

Here V1, V2, etc, are the measured chordal velocities normalized to the average axial velocity and Y_{OUT} and Y_{IN} are the distances from the centerplane of the outer chords (1, 4, 5, and 8) and inner chords (2, 3, 6, and 7) respectively.

The tangential velocity near the pipe wall in some of the non coplanar bend calibrations was very high—in the range of 25% to 30% of the mean axial velocity. For some of the planar bend configurations the tangential velocity was as high as 13%. Yet on the average the meter factors for these configurations are not significantly different from those of configurations that produce little or no swirl.
3.5 Effect of Asymmetry in Axial Velocity Profile on Meter Factor

Additionally, the model sensitivity data of Table 2 includes many asymmetric axial velocity profiles. As with swirl, the chordal arrangement of the LEFM CheckPlus allows a quantitative measurement of axial asymmetry, ASYM as follows:

\[
ASYM = 1 - \frac{W_{OUT}(V1 + V5) + W_{IN}(V2 + V6)}{W_{OUT}(V4 + V8) + W_{IN}(V3 + V7)}
\]  (2)

Here \(W_{OUT}\) and \(W_{IN}\) are weighting factors for the outer and inner chordal velocities respectively, reflecting the product of path length and the prescribed weighting for the numerical integration.

Note that the quotient on the right of the above equation is the ratio of the axial velocity for the top half of the flow element to the axial velocity for the bottom half. The difference between the quotient and 1 reflects the amount of asymmetry.

In the data used to formulate the modeling sensitivity of Table 2, some parametric variations for some configurations generated substantial asymmetry. Some configurations involving planar bends, for example, produced asymmetries as large as 9%. For most of the others, asymmetries were no larger than 4%. But the largest parametric variations do not appear to be particularly correlated with asymmetry; the 4 chord numerical integration appears to deal with it effectively.

3.6 Application of Modeling Sensitivity to Meter Factor Uncertainty Analysis

If future calibration tests of LEFM CheckPlus flow elements include 3 or 4 parametric tests, the data of these tests could be used to formulate a “modeling sensitivity”. However, because a calculation of “modeling sensitivity” using the 95% confidence limits for the applicable configuration—the modeling sensitivity in Table 2 (shown in bold) — embraces a more comprehensive data set, this approach is considered more rigorous. Further confirmation would be obtained by demonstrating that the spread of the parametric test data for the flow element is consistent with the more general figure.

3.7 Uncertainty Allowance for Differences in Viscosity and Relative Roughness between Calibration Lab and Plant

The difference between the viscosity of the fluid of the calibration facility (typically around 1 centiStoke) and the viscosity of the feedwater (typically 0.1 to 0.2 centiStokes at full power feedwater temperatures) manifests itself as change in the axial velocity profile seen by the meter, owing to the thinning of the boundary layer with decreasing viscosity. There are two commonly used semi-empirical descriptions of fully developed velocity profiles: (1) the inverse power law, originally proposed by Nikuradse, and (2) the logarithmic formulation of Reichardt which was used by Moody to describe friction losses in smooth pipe as a function of Reynolds Number [2]. Moody also used the data to describe the dependence of friction losses on relative roughness [3]. Relative roughness can essentially override the effect of viscosity on friction losses by causing eddy formation at irregularities in the pipe wall. In the late 1960s the Reichardt-Moody formulation was modified by Whirlow to provide a zero velocity prediction at the pipe wall (the original formulation was discontinuous at the wall) [4]. Whirlow’s work was for the purpose of evaluating the effectiveness of various chordal arrangements in ultrasonic transit time flow measurements.

Figure 5 plots the profile flatness predicted by the inverse power law and the Reichardt-Moody-Whirlow formulations, as functions of Reynolds Number. Both formulations show increasing flatness with increasing Reynolds Number in the range of interest (roughly 106 in
the lab to 107 in the field). For an increase in Reynolds Number of a factor of 10 (the difference between lab and field), the increase in flatness for both formulations is about 0.02.

It should be emphasized that the changes in profile predicted in Figure 5 are the result of viscosity changes only. These changes can be offset or even reversed depending on the relative roughness of the pipe in the plant versus the pipe in the calibration test—a rough pipe in the plant vis-à-vis a smooth pipe in the test will lead to flatness ratio for the plant installation lower than in the laboratory. So, to ensure the meter factor uncertainty analysis reflects potential changes in viscosity and roughness between calibration laboratory and plant, changes in flatness in either direction must be considered.

![Figure 5: Flatness Ratio for Fully Developed Turbulent Flow in Straight Pipe as a Function of Reynolds Number](image)

Fortunately the effect of a change in flatness on meter factor is very small. This assertion is supported not only by the meter factor data shown in Figure 4 for the various hydraulic configurations, but also by the predictions of meter factor of the theoretical-empirical correlations of the inverse power law and of Reichardt-Moody-Whirlow. These predictions are shown in Figure 6, along with the hydraulic configuration data. Above a flatness ratio of 0.84 both correlations predict a small decrease in meter factor with increasing flatness. Below flatness ratios of about 0.84, the Reichardt-Moody-Whirlow formulation predicts a small increase in meter factor with increasing flatness, while the inverse power law predicts a small decrease. Using the average of the two predictions, also shown in the figure, the change in meter factor with increasing flatness is essentially zero below a flatness of 0.84.

Note that the meter factors for all but two of the hydraulic configurations fall close (within 0.05%) to the average of the two correlations. The two configurations showing the greatest deviation from the average—the average meter factors for LEFMs downstream of flow nozzles and downstream of headers—are 0.15% below the average of the empirical correlations.

In most feedwater installations, the profile flatness is 0.84 or higher. As noted above, above this flatness both empirical formulations predict a small decrease in meter factor with increasing flatness. For the factor of 10 increase in Reynolds Number, and a corresponding change in flatness of 0.02 the predicted decrease in meter factor is 0.03% for both the inverse power law and the Whirlow formulations. Note that this is a decrease. If the flatness in the plant is 0.02 lower than that in the laboratory (implying the relative roughness of the pipe in the plant is the same as the pipe at calibration), use of the meter factor determined at calibration is conservative by 0.03%.
The meter factor versus flatness ratio characteristics of Figure 6 can be used to determine the magnitude of the allowance, in the meter factor uncertainty accounting, for profile changes due to changes in viscosity and/or relative roughness. For example:

Suppose the average Flatness Ratio during calibration is 0.88. Further suppose it is desired to limit the meter factor uncertainty owing to viscosity or roughness-caused profile changes to ± 0.05%. Using the correlations of Figure 5, a variation in flatness of ± 0.03 will produce a meter factor change of ±/− 0.05%. Thus if the flatness measured in the field is 0.88, flatness alarms set at 0.91 increasing and 0.85 decreasing will ensure that the actual meter factor remains within ± 0.05% of that established in the calibration lab. Suppose the flatness measured in the field is, say, 0.90 (as would be projected due to the change in viscosity, with comparable roughness in plant and lab). The meter factor established in the lab is conservative by about 0.03%. Thus flatness alarms set at 0.93 increasing and 0.87 decreasing will ensure that the true meter factor is within + 0.015%− 0.075% of that established by the lab calibration. Given the conservativeness of these boundaries, it may be desirable to broaden the flatness ratio alarm settings in this situation. Alternatively, in the more unusual situation where the flatness in the field is less than that in the lab, narrower flatness limits may be required to ensure the potential meter factor variations remain within the desired limits.

3.8 Meter Factor Uncertainty Based on Actual Calibration Data

The application of the data analyzed in the foregoing discussion is best illustrated by a sample determination of meter factor uncertainty based on actual calibration data. The data in Table 3 for two 20-inch-OD nuclear flow elements below summarizes this calculation. Nomenclature is as described in Table 1. In the plant feedwater flow to each of two steam generators is measured by these LEFMs. The LEFM CheckPlus measuring the feed to steam generator A (Loop A) is about 24 diameters downstream of close-coupled non co-planar bends. Loop B is about 24 diameters downstream of a pair of planar bends.
Table 3

Typical Meter Factor Uncertainties for a 2-Loop PWR Feedwater Flow Measurement

<table>
<thead>
<tr>
<th>Uncertainty Contributor</th>
<th>Loop A</th>
<th>Loop B</th>
<th>Total Feedwater Flow</th>
<th>Basis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Facility Uncertainty</td>
<td>0.09%</td>
<td>0.09%</td>
<td>0.09%</td>
<td>Per an analysis, by the laboratory, of the uncertainty of the weigh tank apparatus used for the calibration test.</td>
</tr>
<tr>
<td>Measurement Uncertainty</td>
<td>0.12%</td>
<td>0.12%</td>
<td>0.08%</td>
<td>Per measurements of coherent noise and other contributors to the uncertainty in the transit time measurements for the calibration tests, plus an allowance based on generic tests for the uncertainty in transducer locations in their housings.</td>
</tr>
<tr>
<td>Modeling Sensitivity</td>
<td>0.15%</td>
<td>0.19%</td>
<td>0.12%</td>
<td>From the “modeling sensitivity” entries for the applicable upstream geometries in Table 2. The scatter in the parametric tests for the flow elements falls within these bounds.</td>
</tr>
<tr>
<td>Allowance for Profile Variations Due to Viscosity and Relative Roughness</td>
<td>0.05%</td>
<td>0.05%</td>
<td>0.05%</td>
<td>The average flatness ratio for the loop A tests was 0.88. The average flatness ratio for the loop B tests was 0.91. For flatness ratios in the field equal to or greater than these numbers, flatness alarms for Loop A set at 0.85 falling and 0.91 rising and for Loop B set at 0.88 falling and 0.91 rising will ensure that the viscosity and roughness in the field do not cause actual meter factors to vary from the calibration result by more than ± 0.05%.</td>
</tr>
<tr>
<td>Mean Meter Factor Uncertainty</td>
<td>0.09%</td>
<td>0.08%</td>
<td>0.06%</td>
<td>See note (2) below</td>
</tr>
<tr>
<td>Total</td>
<td>0.24%</td>
<td>0.26%</td>
<td>0.19%</td>
<td>Each of the total uncertainties is the square root of the sum of the squares of its contributors in the column above.</td>
</tr>
</tbody>
</table>

Notes for Table 3

(1) The uncertainty in total feedwater flow is found by combining, as appropriate, the uncertainties in the individual loop flows. If the uncertainty contributors in the loop flows in a specific category are systematically related (as for example are the facility uncertainties) the uncertainty in total flow in per unit, $\partial W/W$, associated with that contribution category is found as follows:

$$\partial W/W = \partial W_A/W_A (W_A/W) + \partial W_B/W_B (W_B/W)$$

Here $\partial W_A/W_A$ and $\partial W_B/W_B$ are the uncertainties in the loop flows associated with the contributor category, in per unit, and $(W_A/W)$ and $(W_B/W)$ are the sensitivity coefficients for the loop flows (equal to $\frac{1}{2}$ in this case).

If the uncertainty contributors in the loop flows in a specific category are not systematically related (as for example are the measurement uncertainties) the uncertainty in total flow in per unit, $\partial W/W$, associated with that contribution category is found as follows:

$$\partial W/W = \left\{ \left[ \partial W_A/W_A (W_A/W) \right]^2 + \left[ \partial W_B/W_B (W_B/W) \right]^2 \right\}^{1/2}$$
(2) The Loop A Meter Factor is determined from the 13 meter factor measurements consisting of 5 weigh tank runs each and the Loop B Meter Factor from the 8 measurements consisting of 5 weigh tank runs each. The uncertainty of the mean is determined as follows:

(a) One standard deviation of the meter factor data set for the flow element is determined. This figure is combined with one standard deviation of the “observational uncertainty”—the 2 standard deviation scatter—for each data set that determines the meter factor for a given flow rate
(b) The 95% confidence limits for the meter are calculated using the student’s t formulation. For the A and B flow elements, the t multiplier is based on 12 and 7 degrees of freedom, respectively.

For the example of Table 3, the bottom line contribution to the uncertainty in the total feedwater flow measurement is ± 0.19%. Given this contribution, a typical total uncertainty in mass flow, as measured in the plant, is given in Table 4 below.

<table>
<thead>
<tr>
<th>Contributor</th>
<th>Uncertainty</th>
<th>Basis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Meter Factor</td>
<td>± 0.19%</td>
<td>From Table 3 above</td>
</tr>
<tr>
<td>Measurement Uncertainties</td>
<td>± 0.12%</td>
<td>Time measurement uncertainties in the field and allowances for transducer replacement in the field</td>
</tr>
<tr>
<td>Dimensional Uncertainties</td>
<td>± 0.09%</td>
<td>Errors in measurements at room temperature are embedded in the meter factor. This term accounts for uncertainties in thermal expansion and dimensional changes due to erosion or corrosion</td>
</tr>
<tr>
<td>Density Uncertainty</td>
<td>± 0.06%</td>
<td>This term accounts for uncertainties in density due to the LEFM temperature determination and in the measurement of feedwater pressure, as well steam table uncertainties</td>
</tr>
<tr>
<td>Total Mass Flow Uncertainty</td>
<td>± 0.25%</td>
<td>The root sum squares of the individual contributions</td>
</tr>
</tbody>
</table>

4 CONCLUSION

Calibrations of over 100 chordal flowmeters with over 500 upstream hydraulic geometries have provided extensive data for use in characterizing and quantifying variations in individual meter factors. Analysis of the data allows for bounding meter factor uncertainties associated with individual flowmeters and ensures that pertinent characteristics of the plant profile have been captured by calibration tests performed on the meter(s) to be installed. The data also demonstrates that meters using the 8-path chordal arrangement are insensitive to upstream hydraulics and that calibration removes any meter-to-meter variations based on manufacturing differences.
REFERENCES

[1] Part 10 of Title 10 of the Code of Federal Regulations, Appendix K