Checklist Confirming the LEFM✓ and LEFM ✓+ Systems are Operating Within Design Basis

CUSTOMER INFORMATION BULLETIN

Background

Recent overpower incidents associated with the use of externally mounted ultrasonic systems for feedwater flow measurement have demonstrated the desirability of verifying, on-line, that these systems are operating within their design basis uncertainties. While there has been no experience that indicates a similar need for chordal ultrasonic systems, on-line monitoring is clearly desirable for any system whose operation can potentially affect reactor safety. Furthermore, as their names imply, the designs of Caldon's LEFM Check and CheckPlus systems lend themselves to on-line checking of key inputs to the flow computation, to a degree that no other flow measurement system can match. In general, if uncertainties in these inputs approach their design bounds, the user is alerted by an alarm.

Verification of the performance of LEFM Check and CheckPlus systems relies on internal but independent checks of those inputs that might plausibly cause the systems to operate outside their design basis. This approach to verification is made necessary by the required flow measurement accuracies of these systems, about ± 0.3% for CheckPlus systems and ± 0.5% for Check systems. A valid check using another feedwater flow measurement would require that the check system have an accuracy substantially better than these figures. There is no system for the measurement of feedwater flow that can deliver such accuracy.

This bulletin derives the requirements for on-line monitoring of the inputs to LEFM Check and CheckPlus feedwater flow computation. It does so by starting with the mass flow algorithm for these systems, describing in general terms how the uncertainties in all of the inputs to the algorithm are bounded. Those inputs whose uncertainties can plausibly change in the field are highlighted. They are tabulated in a checklist along with the means whereby their approach to a bounding condition is detected and, in selected cases, automatically alerted. It should be noted that the monitoring features of LEFM Check and CheckPlus systems described in this bulletin have, for the most part, been present in the designs since they were first offered to nuclear plant operators. The intent of this bulletin is to enhance the user's understanding of these features and to describe supplementary means whereby a user can independently monitor the inputs and apply trending to detect their approach to a bounding condition.

Summary

Inputs to the LEFM flow computation are divided into four categories: (1) hydraulic, (2) dimensions, (3) time, and (4) property functions. A tabulation is provided of the means whereby it can be verified that each independent input is within the bounds of its design basis uncertainty. Those inputs for which errors in the field can plausibly differ from those in the calibration lab are identified. Errors in some of these inputs may develop relatively quickly (e.g., meter calibration as it is affected by velocity profile, certain errors in time measurement). For such conditions, the alerts whereby the user is automatically notified are tabulated. Errors in other inputs develop more slowly (e.g. drift in the transmitter that provides pressure input to the LEFM, erosion of the internal diameter of the flow element). The means whereby the user manually monitors these inputs are specified. Table 4, at the end of this bulletin, is a checklist of the checks that are mandatory to confirm that LEFM Check and CheckPlus Systems are operating within their design bases.

The Mass Flow Algorithm

The mass flow algorithm used in LEFM Check and CheckPlus systems is derived in Appendix B of the Caldon Topical Report, ER-80P. The mass flow rate is calculated by (1) the numerical integration of the axial fluid velocity over the pipe cross section to determine the volumetric flow rate, and (2) by multiplying the result by the spatial average of the fluid density. The axial fluid velocity at each of the four chordal locations is determined from the transit times of ultrasonic pulses traveling with and against the direction of flow along the path.

Specifically, the mass flow algorithm is:

$$W_f = \rho \cdot \mathrm{PF} \cdot \mathrm{F}_{a3}(\mathrm{T}) \cdot (\mathrm{ID}/2) \sum_{i=1}^{4} \frac{\mathrm{w}_i \mathrm{L}_{ffi}^{2} (\Delta \mathrm{t}_i)}{\tan(\varphi_i)(t_i + \Delta t_i / 2 - \tau_i)^2} \quad (1)$$

Where

W_f = the mass flow rate through the chordal ultrasonic meter, (lbs/sec)

ρ = the mean feedwater density, (lbs/cu. in.)

PF = the profile (or meter) factor determined by calibration, dimensionless

$F_{a3}(T)$ = the thermal expansion factor. This factor accounts for the difference in internal diameter (ID) and transducer face-to-face distance (Lffi) at operating temperature T versus the temperature at which dimensions were measured T_0. $F_{a3}(T) = 1 + 3\alpha(T - T_0)$,

Where α is the coefficient of thermal expansion of the flow element material in (in/in/°F)

ID = the internal diameter of the flow element, normal to the chordal paths (in)

w_i = the Gaussian quadrature integration weighting factor for path i, (dimensionless)

φ_i = the angle between path i and a plane normal to the axis of the flow element (deg)

L_{ffi} = the face-to-face distance between transducer housings of path i, (in)

t_i = the total time of flight of pulse along path i in the direction of flow,(sec)

t_{upi} = the total time of flight along path i opposite the direction of flow, (sec)

Δt_i = the difference in the total transit times of pulses traveling against the flow and with the flow along path i, (sec); $\Delta t_i = t_{upi} - t_i$ (sec)

τ_i = the total of the delays, in non-fluid media, of pulses traveling along path i, (sec)

T = the mean fluid temperature, (°F)

Note that the numerical integration of the algorithm is carried out for four area segments, the number of chordal paths in an LEFM Check system. The integration over four segments also applies to an LEFM CheckPlus system, even though the number of chordal paths is eight.

This is because the average of the two velocities measured at each chordal location of a CheckPlus is used, in effect, to establish the axial fluid velocity at that location, which is the variable to be integrated over the pipe cross section.

To determine the thermal expansion, the fluid temperature is needed. To determine the density, the fluid temperature and pressure are needed. The fluid pressure is measured by a conventional pressure transmitter. The temperature is determined from a measurement of the sound velocity, averaged over the pipe cross section and the fluid pressure.

The square of the velocity c of a pressure wave propagating through a fluid at rest (the sound velocity) is related to the other state variables for the fluid by the partial derivative of fluid pressure p with respect to density ρ along a line of constant entropy, s.

$$c^2 = \partial p/\partial \rho|_s \qquad (2)$$

The precision of property tables for steam and water (for example, the 1967 ASME Steam Tables) is, however, insufficient for an accurate determination of fluid temperature from its sound velocity. Caldon measurement systems therefore rely on a proprietary algorithm, derived from experimental data and confirmed by a large number of comparisons with RTD data (see Appendix C of ER-80P).

Expressing the methods employed for determining density and temperature algebraically:

$$\rho = f_\rho\,(T, p) \qquad (3)$$

Where f_ρ is determined from the 1967 ASME Steam Tables.

$$T = f_T\,(c_{mean}, p) \qquad (4)$$

Where f_T is the proprietary Caldon algorithm.

$$c_{mean} = F_{a1}\,(T) \sum_{i=1}^{4} [w_i\, L_{ffi}]/[t_i + (\Delta t_i/2) - \tau_i] \qquad (5)$$

Where $F_{a1}(T) = 1 + \alpha\,(T - T_0)$

Note that for each set of time and pressure measurements, the procedure for determining temperature and sound velocity is iterative. This is necessary because the determination of sound velocity is itself sensitive to temperature as evidenced by the F_{a1} (T) term in the equation for the mean sound velocity, c_{mean}. This term accounts for the thermal expansion of the path lengths L_{ffi} from the temperature at which they were measured to the temperature at which the sound velocity is measured.

Inputs for the Measurement

The inputs of the LEFM mass flow measurement algorithm can be grouped in four categories as shown in Table 1 below:

The table does not list intermediate variables such as temperature and density since verification of these variables rests entirely on the sets listed in the table. It also does not include the weighting functions, w_i, for the numerical integration. These constants are defined in accordance with numerical integration rules specified by the mathematician Carl Friedrich Gauss and can be found in most mathematics handbooks (for example, the *Handbook of Mathematical Functions,* page 887, National Bureau of Standards, Applied Mathematics Series).

The outcome of the numerical integration *is* affected by the chordal path locations, which variables do not appear explicitly in the algorithm. Like other dimensions, however, errors in the path locations for a specific flow element are embedded, by the calibration process, in the Profile Factor (meter factor) for that element and do not contribute to the uncertainty of the mass flow measurement.

Table 1
Inputs to the LEFM Mass Flow Measurement

Category	Input
Hydraulics	PF, Profile Factor (meter factor)
Dimensions	ID, the internal diameter $L_{ff\,i}$, the face-to-face length of chordal path i in the fluid (4 or 8 inputs) φ_i, the angle made by chordal path i with respect to a plane normal to the axis of the flow element (4 or 8 inputs)
Times	t_i, the total transit time measured in the direction of flow along chordal path i. $t_{up\,i}$, the total transit time measured opposite the direction of flow along chordal path i. τ_i, the total time delay in non fluid media, for an energy pulse transiting path i.
Property Functions	α, the coefficient of thermal expansion of the LEFM flow element f_T, the proprietary algorithm relating fluid temperature to sound velocity and pressure f_ρ, the algorithm relating fluid density to temperature and pressure, p fluid pressure

Input Verification

Uncertainties for each of the variables in Table 1 of the previous section are estimated and budgeted, on a generic basis, in Appendix E of Topical Report ER-80P for LEFM Check systems and in Appendix A of Topical Report ER-157P for LEFM CheckPlus systems. In addition, each user of a Check of CheckPlus system has been provided with a site specific uncertainty analysis in which the budgets of the applicable topical report are modified, as appropriate, to account for the specifics of the site measurement (for example, the uncertainties in the Profile Factor arising from the calibration of the flow element(s) for that site). Verification that an LEFM Check or CheckPlus system is operating within its design basis therefore requires that the uncertainties of each of the inputs of Table 1 are within the budgets of the applicable Topical Report and the site specific uncertainty analysis.

The approaches used to verify that the individual inputs of Table 1 meet their uncertainty requirements are given in Table 2. It will be seen that verification of the uncertainties in many of the inputs rests on the analyses performed in the topical reports or on the first article flow element calibration process performed in a certified hydraulics laboratory. Consequently, verification that these elements of the uncertainties in these inputs are within their design basis does not require that measures be taken in the field. There are however elements of hydraulics, dimensional, time measurement and property function inputs that *do* require field verification. These field verification requirements are shown in bold in Table 2.

Field Verification of Input Uncertainties

From Table 2 it will be seen that a relatively small set of uncertainties in the LEFM inputs require verification in the field. The field verification requirements of these input uncertainties are listed by category and input in Table 3. This table also describes the methods by which trending of field data can be used to ensure that these uncertainties remain within their budgeted bounds. For inputs whose uncertainties can change rapidly (e.g., axial profile as it affects calibration, time measurement signal quality), the LEFMs are provided with automatic alerts to warn the user that action is required. These alerts are shown in bold in the table. For inputs whose uncertainties can change only slowly (e.g., flow element internal diameter, pressure transmitter calibration), periodic checks by the user are prescribed. These checks are underlined in the table.

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Table 2
Verification of Input Uncertainties

Field verification requirements shown in **bold**

Category	Input	Approach to Bounding Uncertainties
Hydraulics	PF	The uncertainties in the determination of the meter calibration are accounted as an uncertainty in the profile (meter) factor PF. They are determined on a flow element specific basis and documented in a unit specific engineering report, which includes data collected by the certified laboratory in which the flow element(s) were calibrated, an analysis by Caldon to determine the Profile Factor(s) appropriate for use in-plant, and an analysis to determine the uncertainties in that Profile Factor (or Factors), in-plant. The calibration process includes testing of each flow element in a full scale model of the segment of the feedwater system in which it is located. The hydraulics of the model are varied parametrically to determine the sensitivity of the meter calibration to changes in velocity profile. The uncertainties include those in the standards of the calibration lab and in the test equipment used for calibration testing, as well as the uncertainties associated with use of the laboratory calibration data in-plant. The uncertainties associated with the application of the calibration data in the field are related to the differences between the axial velocity profiles experienced in the calibration testing and those experienced in the field. **Accordingly, the velocity profiles measured by an LEFM Check or CheckPlus flow element in the field must be monitored to ensure that they remain within the design basis for the flow element calibration.**
Dimensions	ID $L_{ff\,i}$ φ_i	As regards the volumetric flow calculation, uncertainties in all dimensions (including the path spacing, not explicitly listed) are embedded in the Profile Factor PF measured in the calibration lab; they do not therefore add to the overall flow measurement uncertainty. Uncertainties in the measurements of $L_{ff\,i}$ do affect the determination of sound velocity (which in turn affects the temperature and density determinations). These uncertainties are accounted in the site specific uncertainty analysis. Only changes in dimensions from calibration lab to field conditions can introduce additional errors in the flow measurement. Uncertainties in the thermal expansion of the flow element are embedded in the uncertainties of the time measurements and the property functions and do not require separate accounting. **Changes in path lengths $L_{ff\,i}$ and internal diameter ID due to erosion corrosion or deposition of corrosion products must however be monitored to ensure that their uncertainties remain within budgeted allowances**. There is, however, no mechanism whereby the path angles can change in the field from their values during calibration.

Table 2, continued
Field verification requirements shown in **bold**

Category	Input	Requirements
Time	t_i	Errors in the transit time can arise from the clocks which measure them and from the quality of the received signals whereby the arrival of an energy pulse is detected. **Wander in the clocks and degradation of the received signal quality must be monitored in the field to ensure that the uncertainties in the time measurements remain within their design basis.**
	t_{upi}	
	τ_i	The delays in non fluid media are calculated based on the physical properties of the media through which the energy travels. They are also confirmed by measurements during commissioning in the field. Uncertainties in the calculation and in the confirmatory measurement are calculated in the applicable Topical Reports. There is no mechanism whereby the non fluid delays can change from their commissioning values by an amount exceeding their budgeted uncertainty.
Property Functions	α	The bases for the uncertainties budgeted for the thermal expansion coefficient for the flow element material, for the fluid property function relating temperature to sound velocity and pressure, and for the fluid property function relating density to temperature and pressure are described in the applicable Topical Reports. Since the material properties of the flow element and the equations of state for feedwater do not change significantly in service, there is no need for field verification that these relationships remain within their design basis uncertainties.
	f_T	
	f_p	
	p	Both the density of the fluid as determined from its temperature and the temperature as determined from its sound velocity are weak functions of pressure. **Consequently, assurance must be provided that the calibration of the pressure transmitter that provides the pressure input to the LEFM remains within its budgeted uncertainty allowance.**

Table 3
Field Verification of Input Uncertainties

Category	Input	Method of Verification Automatic alerts shown in **bold** Mandatory periodic checks shown underlined	Methods for Manual Trending (Optional)
Hydraulics	PF	The axial profile is characterized by its Flatness, measured by the ratio of the sum of the measured outside (short) chord velocities to the sum of the inside (long) chord velocities. A reference flatness is measured in the field at commissioning and the appropriate profile factor and uncertainty determined on the basis of the calibration tests that determine the sensitivity of PF to the Flatness, as well as the uncertainty in this relationship. An allowable variation in Flatness, based on the budgeted uncertainty for the effect of axial profile on PF is also determined at commissioning. **An alert, indicating meter failure, is provided if the measured Flatness changes beyond its budgeted uncertainty.**	The Flatness F can be calculated from the normalized path velocities included as a data output from the LEFM. For an LEFM Check, $F = (V1+V4)/(V2+V3)$ For an LEFM CheckPlus $F = (V1+V4+V5+V8)/(V2+V3+V6+V7)$ F can be trended over time and correlated with changes in plant water chemistry and feedwater system operating configuration, to better define the full range of profiles "seen" by the meters. Swirl velocity (the transverse velocity measured by the outer chordal paths divided by the average axial velocity) may also be monitored for information, since increases in flatness are often correlated with increases in swirl. For a Check system the swirl velocity is given by V1 – V4. For a CheckPlus System it is V1 – V4 + V8 – V5. The data for path velocities are automatically stored in the LEFM and can be retrieved on demand.
Dimensions	ID L_{ffi}	Experience in nuclear feedwater systems shows that measurable changes in internal diameter of feedwater pipes due to erosion-corrosion or deposition of corrosion products takes place slowly. Consequently, only a periodic measurement of wall thickness using an ultrasonic thickness gage is required. It is required that this measurement be incorporated in the plant's erosion corrosion surveillance program. It provides assurance that any change in ID remains within its budgeted uncertainty. Under normal operating conditions, the temperature and therefore the sound velocity of feedwater is uniform over the cross section of the flow element. **Consequently a change in path length due to deposition of corrosion products on the face of a transducer housing will be detected by an alert that occurs when the sound velocity measured by one path differs from the average of all paths by a preset amount.**	Under some operating conditions, temperature and therefore sound velocity is not uniform over a feedwater pipe cross section. Specifically, at low flow rates flow can stratify, with lower temperature fluid collecting near the bottom of the pipe. Thermal gradients can also occur if the high pressure heater bypass valve is open. For LEFM flow elements located in a horizontal pipe with their chords horizontal, such gradients can cause initiation of the sound velocity alert *when there has been no change in chordal path length.* It is therefore useful to trend the sound velocity measured at each chord for all operating conditions to determine when and under what conditions unit operations lead to these alerts. For vertically oriented LEFMs, stratification is not a concern.

Table 3, continued

Category	**Input**	**Method of Verification** Automatic alerts shown in **bold** Mandatory periodic checks shown underlined	**Methods for Manual Trending (Optional)**
Time	t_i t_{upi}	Each clock used to measure transit time in LEFM systems is continuously and automatically checked against an independent reference clock. **An alert is provided if the difference between the time measurement clock and the reference clock exceeds a preset amount.** To ensure that the quality of the received signals allows the measurement of transit times within the uncertainty bounds budgeted for these measurements, the quality of the received signals is continuously monitored. If a received signal fails to meet any one of several criteria, that signal is rejected and the time data are not used in the flow computation. **If the fraction of signals rejected on a chordal path exceeds a preset threshold, that path is considered out-or service and the condition is alerted.** The criteria on which signal rejection are based include: • Low signal/noise ratio • Non reciprocal signals in opposing directions along a path • Variations in time differences in opposing directions along a path exceeding a statistically determined threshold. An anticipatory alert on signal quality is also provided. Degradation in signal quality is usually caused by a degradation in the acoustic coupling between the transducer and the housing in which it is situated. An automatic gain control in the receiver maintains the magnitude of the signal seen by the detection logic constant; as the magnitude of the input signal degrades, receiver gain automatically increases. **An alert is provided when the receiver gain approaches the end of its effective range,** to enable the user to take measures to restore input signal before use of the path is lost An automatic check of resistance to ground on each transducer lead is provided on newer systems and may be added as an option to older systems. Low resistance of one transducer lead to ground can lead to non reciprocal time measurement errors that may not be detected by the non-reciprocal signal check. If the resistance drops below a preset threshold **the condition is automatically alerted**.	To anticipate loss of signal quality, receiver gain in the up and down directions and signal/ noise ratio should be trended over time for each chordal path. Gain will change with power (because signal strength is affected by feedwater temperature), but at full power feedwater temperature, gain should remain constant within about 3 db. An increase in gain outside this bound is indicative of a deteriorating couplant or, less likely, a defective transducer. An increasing gain will usually be accompanied by a decreasing signal noise ratio. Deteriorating signal/noise ratio in the absence of an increasing gain may be indicative of a low resistance on a transducer lead or degradation of an electronic component in the receiver. For systems without automatic resistance-to-ground checking electronics, the resistance to ground of each transducer lead should be periodically checked using a volt-ohm-multimeter. For this measurement, the LEFM should be temporarily removed from service and the transducer leads should be temporarily disconnected at the cabinet entry terminal board.

Table 3, continued

Category	**Input**	**Method of Verification** Automatic alerts shown in **bold** Mandatory periodic checks shown underlined	**Methods for Manual Trending (Optional)**
Property Functions	p	To ensure that the pressure transmitter calibration remains within its design basis uncertainty, the calibration of the transmitter should be checked biannually against a traceable standard. To establish a pass/fail criterion, the uncertainty budget allotted to this measurement should be reduced by the estimated uncertainty of the maintenance and test equipment. The difference between the as found pressure and the reference pressure should be within the reduced budget. Should the pressure transmitter fail upscale or fail downscale (due to an interruption to its power supply for example), these conditions are detected and a **pressure input error alert is automatically initiated**.	Data from multiple periodic checks of the transducer calibration can be analyzed on a statistical basis to confirm that the uncertainty for the transmitter lies within the 2 standard deviation bounds allocated for it.

Table 4
Mandatory Check List
Verification of LEFM Check and CheckPlus Inputs in the Field

Category	Input Symbol	Definition	Method of Verification	Auto/Manual
Hydraulics	PF	Profile (Meter) Factor	Alert, Profile Flatness outside Reference Flatness ± Allowance	Auto
Dimensions	ID	Internal Diameter	Periodic measurement of wall thickness using UT gage	Manual
	L_{ffi}	Chordal Path Lengths	Alert, Path Sound Velocity differs from average by more than threshold	Auto
Time	t_i t_{upi}	Total transit time for chordal path i in the direction of flow Total transit time for chordal path i against the direction of flow	(1) Fraction of signals rejected greater than threshold (low signal quality) (2) Accuracy of time measurement clock not confirmed (3) Resistance to ground of transducer leads below specification	(1) Auto (2) Auto (3) Manual (Auto optional)
Property Functions	p	Feedwater system pressure at LEFM	Periodic confirmation of calibration using a traceable standard	Manual