June 18, 2004

Mr. Calvin R. Hastings
President and CEO
Caldon, Inc.
1070 Banksville Ave.
Pittsburgh, PA 15216

SUBJECT: REPORT OF THE ULTRASONIC FLOW METER ALLEGATION TASK GROUP REVIEW OF CALDON ULTRASONIC FLOW METERS

Dear Mr. Hastings:

Attached is a copy of the final report of the Ultrasonic Flow Meter Allegation Task Group which documents its review of the Caldon ultrasonic flow meters. In preparing the final report, the Task Group considered the comments provided in Caldon's letter of May 10, 2004, regarding the proprietary content and technical accuracy of the draft report which was sent to Caldon by NRC letter dated May 6, 2004.

In accordance with Caldon's request, the attached final report is non-proprietary and will be available to the public.

If you have any questions, please contact George Dick at 301-415-3019.

Sincerely,

/RA/

Stephen Dembek, Chief, Section 2
Project Directorate IV
Division of Licensing Project Management
Office of Nuclear Reactor Regulation

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REPORT OF THE ULTRASONIC FLOW METER ALLEGATION TASK GROUP REVIEW OF CALDON ULTRASONIC FLOW METERS

Allegation Task Group Leader:

Jared S. Wermiel

Allegation Task Group Members:

Clifford K. Doutt

Warren C. Lyon

Abdelghani (Ghani) Zigh

June 7, 2004

Enclosure

SUMMARY AND RECOMMENDATIONS

Ultrasonic flow meters (UFM) are used to measure such items as feedwater flow, steam generator blowdown flow, and other plant flows in light water nuclear reactor power plants. In principle, application of UFMs leads to a reduction in the uncertainty associated with determining thermal power level, usually because of the increased accuracy in feedwater flow measurement. This uncertainty reduction should allow plants to be operated at increased thermal power while providing reasonable assurance that licensed thermal power is not exceeded.[1]

UFMs manufactured by Caldon, Inc. and by Westinghouse Electric Company LLC / Advanced Measurement and Analysis Group, Inc. (W/AMAG) have been installed in US nuclear power plants to measure feedwater flow. Questions were raised regarding the use of UFMs of the AMAG Crossflow design and its claimed accuracy and the Allegation Task Group was formed to answer the following questions:

1. Is the AMAG flow meter providing the accuracy intended and approved by the staff for implementation in license amendments?

2. If not, is the problem inherent to the design of the device or is it a problem associated with the device's implementation and/or application?

These questions relate to the licensee's ability to ensure that plant operation is being maintained within the power level authorized in the plant license. However, they do not represent a significant safety concern because of the large margins and conservatisms assumed in the licensing basis accident and transient analyses. They do, however, reduce the safety margin and raise questions of compliance with the plant license.

In practice, licensed thermal power has been exceeded in UFM installations that did not involve license amendments in plants equipped with Crossflow UFMs and in plants equipped with early versions of Caldon UFMs. The Task Group concluded that a broader, more inclusive assessment was required to ensure objectivity and to fully address potential issues. Consequently, the Task Group has addressed the use of Crossflow and Caldon UFMs in US nuclear power plant feedwater systems. However, the Task Group's charter was effectively to identify real or potential problems and, with respect to installations, the Task Group concentrated its assessment where problems had been recognized. The Task Group did not directly assess all plant installations. Further, the Task Group report is based on information available up to mid-April, 2004.

This report addresses the Task Group's review of UFMs produced by Caldon. The Task Group W/AMAG Crossflow UFM evaluation is provided in a separate report.

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[1]The increase in thermal power is achieved in two different applications. In one, UFMs are used to compensate for changes that occur during operation, such as venturi fouling that leads to an erroneous indication of overpower that, in turn, forces operators to unnecessarily reduce thermal power. In the other, the uncertainty improvement achieved from the perceived uncertainty of UFMs is credited for a thermal power increase that remains within the thermal power that was previously used for many of the licensing basis analyses.

In its evaluation, the Task Group considered UFM design, development, testing, application, implementation, maintenance, and UFM vendor followup. It applied these considerations to three types of installations:

1. A temporary installation to evaluate and sometimes to calibrate existing feedwater flow measurement instruments followed by removal or discontinuation of use of the UFMs,

2. Power recovery where UFMs are used to recalibrate feedwater flow instruments during operation, such as correction for venturi fouling, and

3. Measurement uncertainty recapture uprates which require license amendments that take advantage of the perceived increased flow measurement accuracy of UFMs to increase licensed thermal power.

The following Caldon UFMs were considered by the Task Group:

Designation	Typical Uncertainty, Percent	Task Group Comments
External LEFM (Several Design Generations)	<~1.2	External strap-on. Reports two diametral and two diagonal velocities. Design improvements with time.
LEFM✓™	0.4 - 0.5	Spool piece. Reports four chordal velocities.
LEFM CheckPlus™	0.3 - ~0.37	Spool piece. Reports eight chordal velocities.

The Task Group has briefly evaluated Caldon history and has reached the following conclusions:

Item	Comments
Owners group	Historically and presently active. Web site excellent with sensitive data available to authorized users.
Operational knowledge and response to problems	Fully aware of most problems and corrects them when discovered. Historical record provided from 1993. Licensee Condition Reports received from most users in March, 2004 to ensure consideration of most recent information. (Quarterly reporting started in 2003.)
Problem type experienced during operation	Mostly hardware, operator, and software problems.

Item	Comments
Installation approach	Full flow, full scale test of every LEFM✓ and LEFM CheckPlus instrument in simulated plant configurations followed by comparison to in-plant operation. Re-test if needed. Scale model parametric testing simulating plant configurations for External LEFM system.

In general terms, these instruments effectively measure average flow velocities corresponding to the number and location of sonic sampling paths. Translation of these velocities into flow rate is accomplished from laboratory testing information obtained prior to installation in a plant. Any deviation in the velocity distribution as a function of position in a plane perpendicular to direction of flow can affect the calibration. The sensitivities to these deviations are also affected by the number and location of the sonic sampling paths. The effect of the velocity profile on the fluid is critical in ultrasonic flow measurement since UFMs only measure the average fluid velocity directly and not the mass flow rate. In the case of the Caldon designs, the average flow velocity is the result of the area average velocity as determined by the transit time of ultrasonic pulses between transducer locations. Flow volume is related to the velocity distribution (velocity profile) across the flow path. UFMs typically have built-in error checks to “look” for changes in the velocity flow profile that may invalidate the calibration. The Task Group’s assessment of the effectiveness of these error checks and the ability of the Caldon UFMs to continue to provide a correct flow rate is summarized in the following table:

Designation	Sonic Paths (Velocities Measured)	UFM Response to Flow Profile Change That May Cause Flow Error	
		Automatic Recognition	Continues to Provide Correct Flow Rate
External LEFM (Several Design Generations - Not used for power uprates)	2 diagonal and 2 diametral	Poor	Poor
LEFM✓™	4 chordal	Good	Good
LEFM CheckPlus™	8 chordal	Excellent (but < 100 percent)	Good to Excellent

As a general observation, the greater the number of sampling paths, the greater the likelihood that a UFM will be insensitive to or will identify a change in flow profile. Thus, the combination of the number of flow paths and the pre-installation testing of the Caldon LEFM✓ and LEFM CheckPlus designs appears to have resulted in few unrecognized problems due to changing such items as pump configurations and valve manipulations.

Questions have arisen regarding plant installations that use AMAG and Caldon UFMs. These issues impact applications approved by the staff as well as applications that are not typically reviewed by the staff that have led to overpower operation.

The Task Group is aware of more than a dozen events that involved questions of UFM accuracy since 1999 and additional events may have occurred where the staff does not have information. The Task Group does not have specific information on licensee efforts to correct many of these past problems. Further, unlike many instruments that can be relied upon for the full range of measurement and plant conditions, UFMs are unique in that they must be installed and used within carefully defined bounds if the claimed uncertainties are to be obtained.[2] The problems include, but are not limited to, changes in plant configuration such as feedwater valve manipulations, changes in operating feedwater pumps, changes in feedwater temperature, or other flow disturbances that unacceptably impact licensed operation when UFMs are used for power uprates as reviewed by the staff or for power recovery under 10 CFR 50.59.

The Task Group believes that all licensees using UFMs must provide information to demonstrate that the devices are providing the claimed accuracy in order to ensure compliance with the licensed power level. Consequently, the Task Group recommends that the staff issue a bulletin to all licensees using Caldon LEFMs which requires that information be provided to demonstrate that the device is providing the intended accuracy consistent with the plant license.

Some licensees have used a temporary UFM installation to recalibrate venturis or they may have found that reliance on UFM feedwater flow readings would have required a plant thermal power derate. The Task Group has concluded that such venturi recalibrations or ignoring the indication of the need for a potential plant derate are unacceptable unless complete justification is available. The Task Group recommends that the generic communication identified above should obtain information regarding these practices. Further, increased thermal power operation based on these practices should not continue unless acceptably justified to the staff.

[2]The Task Group notes that Caldon claims its chordal designs (the LEFM✓ and LEFM CheckPlus designs) are capable of operating to less than 10 percent of nominal flow rate. However, the uncertainty based upon actual flow rate will increase as flow rate is reduced. For practical purposes, this reduction is not of concern because the need for UFM accuracy is limited to near-full flow rate conditions.

TABLE OF CONTENTS

APPENDICES

ABBREVIATIONS

AMAG	Advanced Measurement and Analysis Group (Manufacturer of the Crossflow UFM)
C_f	venturi correction factor
CFD	computational fluid dynamics
INPO	Institute of Nuclear Power Operations
LEFM	Leading Edge Flow Meter (Manufactured by Caldon)
LOCA	loss-of-coolant accident
M	feedwater flow rate
MUR	measurement uncertainty recapture (the10 CFR 50 Appendix K uprate)
NRC	Nuclear Regulatory Commission
NRR	NRC Office of Nuclear Reactor Regulation
PWR	pressurized water reactor
RCP	reactor coolant pump
RCS	reactor coolant system
Re	Reynolds number
RG	Regulatory Guide
SER	safety evaluation report
SG	steam generator
SRSS	square root of the sum of the squares
SRXB	NRC Reactor Systems Branch within NRR
UFM	ultrasonic flow meter
W	Westinghouse (The vendor responsible for the AMAG UFM)

1 INTRODUCTION

There has been an increasing trend in the number of events that involve UFM applications for determining feedwater flow in recent years. The problems have affected safety analysis margins and, in mid-2003, were found to result in exceeding the licensing basis analysis limits on thermal power level in some plants. In particular, the staff became aware of problems involving the W/AMAG Crossflow UFM in approximately 2001 and the staff's concern has increased as the implications became more serious. Staff involvement increased in late 2002 and early 2003 with recognition of issues at the Byron station. The Task Group believes that Byron 1 was operating at more than 2 percent over its licensed thermal power level for several years prior to August, 2003. These and related concerns led to investigations by Exelon (a root cause and an evaluation of management), by W/AMAG, by the Omaha Public Power District, and by the Institute of Nuclear Power Operations (INPO). Problems have occurred with Caldon LEFMs as well. Perhaps the most serious was operation at River Bend for an extended time at greater than 2 percent over the licensed power level.

The Task Group reviewed relevant documentation including topical reports, safety evaluations, requests for additional information, inspection reports, licensee event reports, industry advisories, industry and applicable technical literature, conference proceedings, vendor data, calibration facility data, and other material. In addition, discussions were held with cognizant staff, independent calculations were performed, and meetings were held with UFM vendors.

The Task Group's charter was to determine whether questions regarding the accuracy claims for the Crossflow UFM were valid and what, if any, action should be taken with regard to the use of the device. The initial Task Group review indicated that recommendations generic to UFM feedwater flow measurement applications were necessary and, therefore, the Task Group expanded its investigation to provide a broader, more inclusive assessment of potential problems. The Task Group review consequently covered UFMs provided by W/AMAG and Caldon in one-time only, power recovery, and power uprate applications.

This report addresses the Task Group review of Caldon UFMs. A separate report addresses the AMAG UFM review.

2 BACKGROUND

2.1 Thermal Power Measurement

A straightforward pressurized water reactor (PWR) coolant system (RCS) heat balance shows that:

$$Q_{core} = Q_{SG} - Q_P + Q_L$$

where:	Q_{core}	=	core thermal power
	Q_{SG}	=	calorimetrically-determined steam generator (SG) thermal output
	Q_P	=	reactor coolant pump (RCP) heat addition rate
	Q_L	=	RCS net heat loss rate including contributions for letdown, makeup, RCP cooling, RCP seal injection, insulation and support heat losses, control rod drive heat loss, and the pressurizer.

The term "- Q_P + Q_L" is less than one percent of Q_{SG}. Further, Q_{SG}, with small corrections for such items as steam generator (SG) blowdown and heat losses, is proportional to the SG feedwater flow rate. Thus, as an approximation, a percent change in thermal power is equal to a percent change in feedwater flow rate. For discussion purposes, the Task Group will not differentiate between percent changes in feedwater flow rate and percent changes in thermal power.

Venturis[3] were provided as original equipment in nuclear power plant feedwater systems to determine feedwater flow rates. In approximately the last ten years, ultrasonic flow meters have been increasingly used to reduce feedwater flow measurement uncertainty in three applications:

1. A one-time check of venturi performance,
2. Power recovery to correct for such effects as venturi fouling, and
3. A power uprate that credits the perceived reduced UFM uncertainty.

The staff typically does not review one-time checks and power recovery since they do not involve a license change. Power uprates require a license change and must be reviewed by the staff in response to a licensee 10 CFR 50.90 license amendment request. The Task Group notes that the Byron and Braidwood overpower conditions resulted from power recovery activities that were addressed via the requirements of the 10 CFR 50.59 process and which do not require prior staff review and approval. Overpower conditions are addressed further in Sections 2.3 and 2.6, below.

Further discussion of these applications and illustrations of the effect on uncertainty are provided in Appendix A.

2.2 One-Time Measurements

Some licensees have used temporary UFM installations to calibrate feedwater venturis in a "one-time" test, with the calibration assumed to remain valid for long-term operation. Such calibrations are based on the presumptions that the UFMs provide a more accurate feedwater flow rate than the venturis and that the venturi characteristics will not change to indicate a lower flow rate. The staff does not routinely evaluate this use of UFMs because no license amendment is involved.

The one-time UFM check outcomes and the Task Group conclusions are as follows:

[3] Other methods, such as flow nozzles and orifices may have been used. The term "venturi" as used herein is intended to encompass such other methods.

Outcome	Licensee Action	Task Group Conclusion
Reactor thermal power is less than indicated when using venturis to determine feedwater flow rate	UFMs are permanently installed and used for venturi recalibration, venturis are recalibrated based upon one-time results, or, if potential thermal power benefit is small, no action is taken.	Recalibration based upon one-time results is not acceptable absent additional proof regarding the plant condition and meter-specific uncertainty information[4].
Reactor thermal power is equal to value determined using venturis	Probably none unless there is a history of venturi fouling or similar situations that cause operation at reduced thermal power.	If the comparison is made when venturis are fouled, then an overpower condition may exist following venturi cleaning or a defouling event. See next item.
Reactor thermal power is greater than would be achieved by using UFMs	Perhaps none because the plant is perceived to be operating consistent with the existing license.	The plant, as originally licensed, may be operating above the licensed thermal power limit. This is not acceptable.

2.3 Power Recovery

Feedwater venturis are typically inspected and cleaned during refueling outages. In many plants, the venturis foul during ensuing power operation. Such fouling changes venturi flow characteristics and may reduce the effective flow area which causes the venturis to erroneously indicate an increased flow. The erroneous flow indication, in turn, causes an erroneous indication of high thermal power, necessitating a reduction in thermal power to keep the indicated thermal power within the licensed thermal power level.

Licensees often install UFMs to reduce or eliminate power production lost due to venturi fouling or other factors that erroneously affect indicated feedwater flow rate. These UFMs are perceived to reduce the uncertainty in determining thermal power, although the effect of the uncertainty reduction is not credited for an increase in licensed thermal power. However, as illustrated in Appendix A, the reduced uncertainty can lead to an actual thermal power increase in addition to the benefit of correcting for venturi fouling.

[4]Early applications typically used UFMs that were less accurate than the more recent designs. Further, to be applicable, the calibration may only be applied when venturis are in pristine condition to ensure later defouling will not lead to thermal overpower, and a complete evaluation of both combined instrument uncertainty and other potential perturbing plant conditions must be accomplished. Note similar conditions also apply to a calibration using other measurement methods, such as tracer test results.

In practice, the venturis are used for plant operation, including automatic responses to feedwater indications. Some UFMs are used to periodically or essentially continuously calculate a venturi correction factor that is defined by the following equation:

$$C_f = M_{UFM} / M_{venturi}$$

where:

C_f = venturi correction factor
M = feedwater flow rate indicated by the subscript

Thus, as venturi fouling occurs and $M_{venturi}$ increases relative to M_{UFM}, C_f decreases. Multiplying $M_{venturi}$ by C_f and using the result in place of the actual $M_{venturi}$ indication results in plant operation consistent with the UFM indication.[5] As identified above, this application has resulted in operation in excess of licensed thermal power. This is addressed in Section 2.6, below.

2.4 Appendix K Power Uprates

10 CFR 50 Appendix K requires a two percent allowance for thermal power uncertainty based upon the estimated uncertainty that would bound the feedwater flow measurement capability that existed in 1974. Development and application of UFMs was believed to reduce that feedwater flow measurement uncertainty and, in the 1990's, some licensees requested an exemption from Appendix K to allow an increase in licensed thermal power while remaining within the licensing basis analyses that were originally performed for 102 percent thermal power. Some exemptions were granted and, in June, 2000, Appendix K was changed to allow a smaller uncertainty when justified. An increase in licensed thermal power using this process is called a measurement uncertainty recapture (MUR) uprate or an Appendix K uprate, it involves a license amendment (a change in plant power level), and NRC approval is required.

2.5 Velocity Profile and Relation to Flow Rate

A UFM effectively measures different parameters to measure fluid velocity, depending on the technology type, and translates these measurements into a volumetric flow rate. Although the parameter measurements are precise, translation into a true average velocity or volumetric flow rate is a challenge. A straightforward method of translating UFM measurements to volumetric flow rate would be to calculate a correction factor by dividing an average velocity determined from laboratory timed weigh tank results by the average velocity determined by the UFM. The UFM would then be installed and used to determine flow rate by multiplying UFM-determined average velocity times the correction factor times the flow area. However, this simplistic case is not appropriate because the laboratory cannot precisely duplicate the conditions and variations encountered in actual use.

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[5] A large number of data points are necessary to obtain an average value that has a small uncertainty. In historical applications, UFMs have not been used for plant control. This operation method has the additional benefit of allowing plant operation to continue if a UFM malfunctions. Either the previously obtained C_f is used within specified constraints, or C_f is set equal to one, effectively returning control to the venturis.

A next step in translating laboratory results is to assume fully developed flow is realized in both the laboratory and the application so that the velocity profile[6] is both known and stable. If the velocity profiles in the laboratory and application are the same, then the laboratory-determined flow rate results can be used. However, for a specific plant installation, laboratory UFM tests may not always reflect the actual plant piping configuration or equipment. In these cases, plant-specific flow disturbances change the velocity profile and contribute to a potential increase in uncertainty.

In practice, fully developed flow rarely exists due to such perturbing influences as an inadequate length of straight pipe and the presence of elbows, tees, valves, or other flow disturbances. These introduce velocity changes that in some cases cause the velocity profile to be completely asymmetric. An attempt is made for some installations to account for this by simulating plant configurations in the laboratory. However, any change in a plant configuration, such as changing a feedwater pump or manipulating a valve, can perturb the velocity profile. Such changes are shown below to propagate significantly further than is traditionally assumed in fluid flow applications and in UFM installation practice can affect the velocity profile. Since velocity profile is directly related to flow rate, velocity profile considerations are extremely important.

UFMs installed in permanent feedwater applications in nuclear power plants have different capabilities to adapt to operational and configuration changes. They also have built-in analysis capabilities that attempt to recognize if a measurement error results due to such changes. As a first approximation, the greater the number of average velocities determined from the UFM measured parameters, the more flexibility it will exhibit in adequately adapting to such changes. Regardless, however, the velocity profile is essential for the UFM to properly compute volumetric flow rate. Other plant effects, such as pipe roughness, pipe vibration/system noise, bypass flow, and feedwater temperature, may affect the velocity profile and are also important to UFM performance

The Task Group performed preliminary analyses using Computational Fluid Dynamics (CFD) to provide insight into the effect of upstream perturbances on the velocity profile. Figure 1, from the analyses described in Appendix B, illustrates the results for the case of a upstream elbow that turns from vertical to horizontal in a 14 inch diameter pipe for conditions typical of a feedwater pipe. The view is from above. Note that the profile is still changing at 90 diameters downstream of the elbow. Figure 2 shows similar information for a view from the side that illustrates the skewed flow profile. Profile behavior perpendicular to the flow direction 60 pipe diameters downstream of the elbow is illustrated in Figure 3. Note that a UFM will typically measure different velocities for the same flow rate if rotated around the pipe. The Caldon LEFMs, especially the LEFM✓ and LEFM CheckPlus designs, are stated to be capable of recognizing these profile changes. The same result could occur if a plant perturbation were to occur. If two offset elbows had been assumed instead of one, the profile distortion would be greater.

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[6]Velocity profile is typically the map of velocities in a plane perpendicular to the pipe axis. Note integration over the map with respect to area will not provide the volumetric flow rate unless there are no velocity components within the plane of the map.

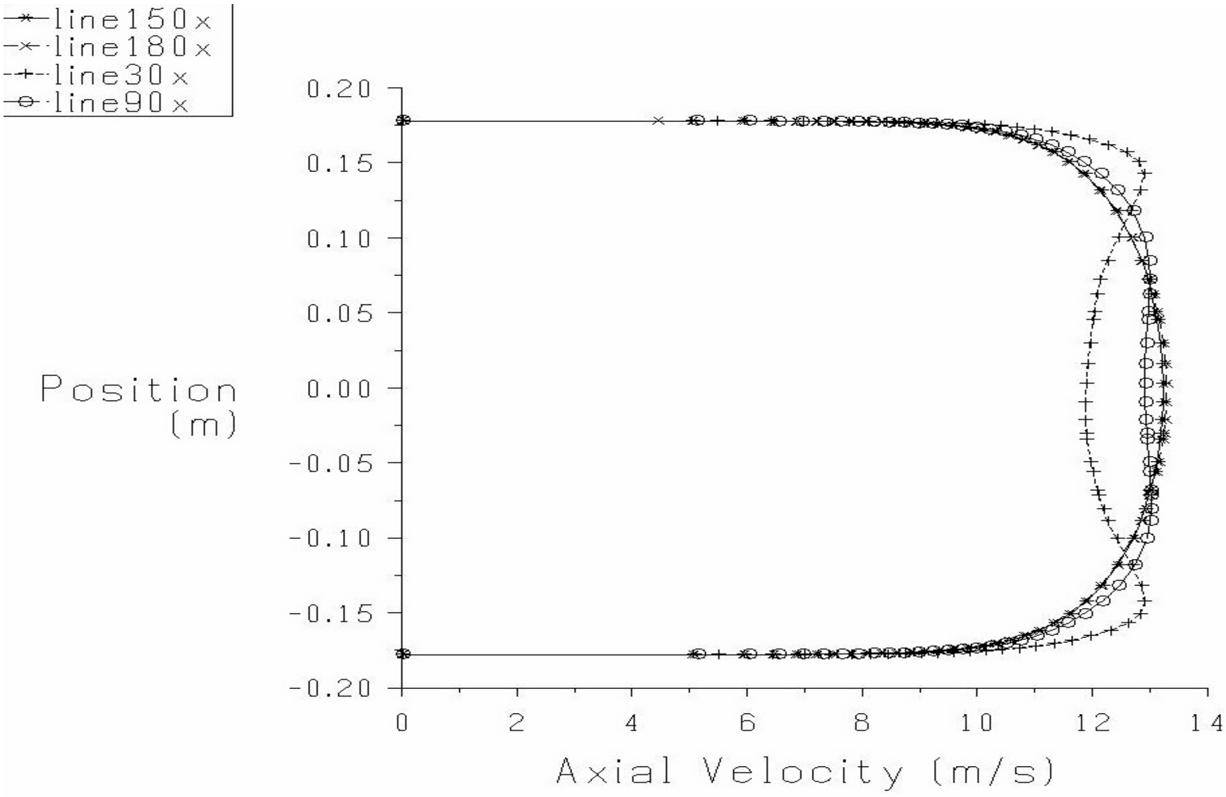

Figure 1. Velocity Profile from Above

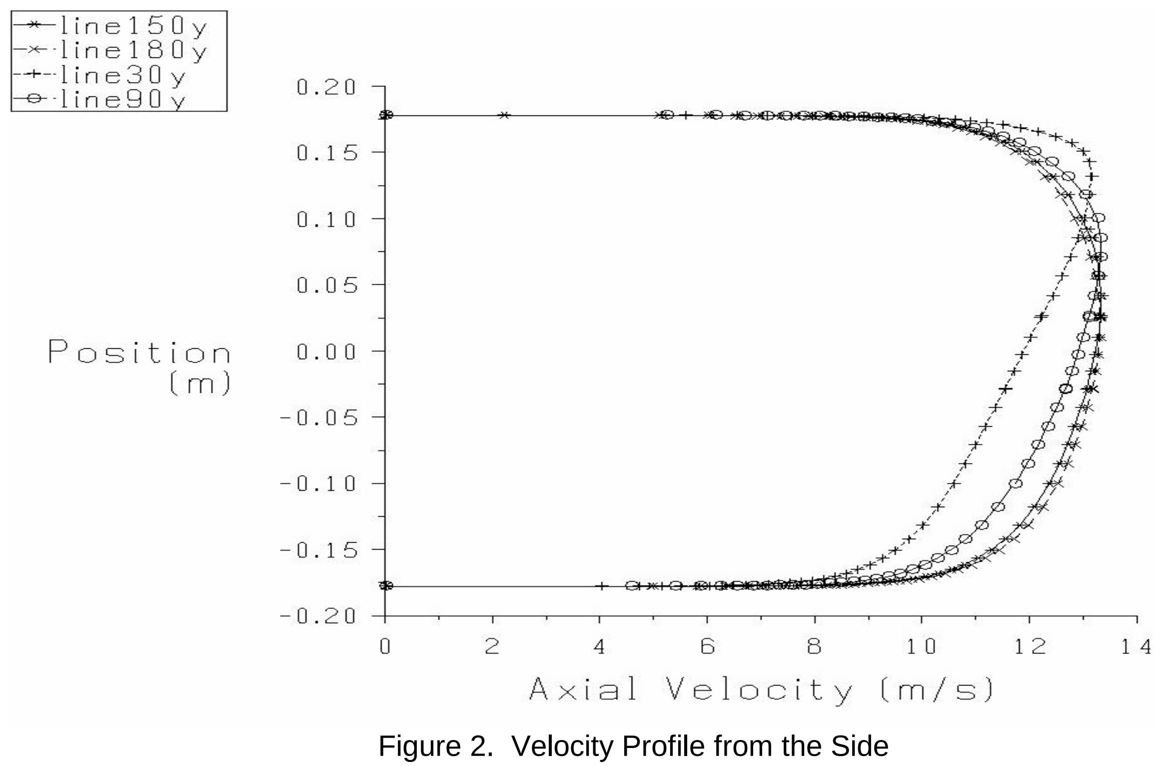

Figure 2. Velocity Profile from the Side

UFMs are often installed at less than 20 diameters downstream from flow perturbations such as elbows. Clearly, UFMs are often installed where the flow profiles are not fully developed and the translation between the measured velocities and the flow rate requires correction for the

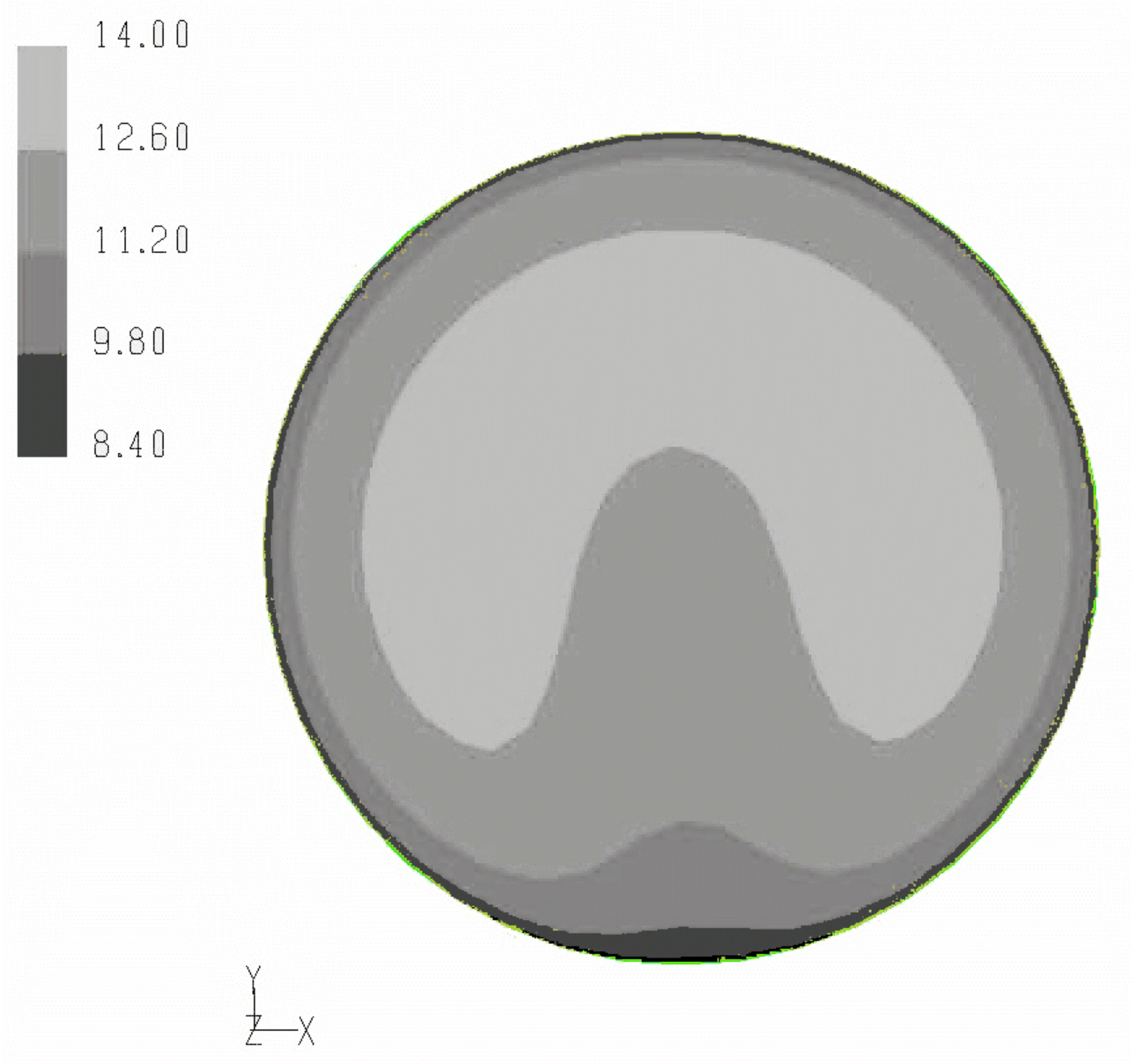

Figure 3. Illustration of Velocity Profile 60 Pipe Diameters Downstream of Elbow

profile. This correction is obtained via calibration testing in a laboratory using a representation of the plant configuration. In the case of Caldon, full scale testing of the plant configuration is performed on every LEFM✓™ and LEFM CheckPlus™ UFM prior to installation.

An upstream change, such as repositioning a valve or pumping into a header from a different pump, can change the flow profile. A UFM that is profile sensitive may provide an erroneous flow rate when such a change occurs.

2.6 Industry Experience

The Task Group did not extensively research UFM installation history to evaluate installation and operation success. Rather, it relied on readily available knowledge regarding operation at a few nuclear power plants where unanticipated problems occurred; problems that in many cases were not resolved as of the date of this Task Group report.

In August 2003, Byron 1, which was using the Crossflow UFMs, was estimated to be operating at significantly more than 2 percent over its licensed thermal power, a condition that apparently existed for several years. Byron 2 and Braidwood 1 and 2, which were also using the Crossflow UFMs, have also been found to be operating above their licensed thermal power. These performance issues and related concerns led to investigations by Exelon, W/AMAG, the Institute of Nuclear Power Operations (INPO) and the staff. Subsequent issues at Fort Calhoun caused W/AMAG to expand its evaluation of the expected accuracy and uncertainty as specified in the approved W/AMAG topical report CENPD-397-P-A. Other overpower conditions have also occurred, including, for example, the discovery in May 2003, that River Bend, which was using early Caldon External LEFMs, apparently operated at more than 2 percent over its licensed thermal power for one cycle and was above its licensed power level during additional cycles.

In its limited consideration of the operational history, the Task Group found that Caldon has an Internet site (www.caldon.net) that lists nuclear power plant installations through 2002 and provides UFM information. This site lists the following installations in US and foreign nuclear power plants:

1. 29 permanent and 20 test External LEFMs for power recovery
2. 21 chordal installations for power recovery
3. 38 (total purchased) LEFM✓ and CheckPlus for Appendix K uprates.

Caldon has an active owners group, appears to follow up on all installations to reasonably assess behavior, and actively implements improvements based upon operational experience. The operational power problems appear to be generally limited to the older External LEFM models that do not provide the accuracy of the LEFM✓ and CheckPlus spool piece designs, and to hardware and software problems in all designs that Caldon addressed as they were encountered. Caldon personnel exhibited an in-depth knowledge of operational history. The Task Group is not aware of any instrumentation problems that caused a significant overpower condition due to Caldon LEFM✓ and CheckPlus. Further, the LEFM✓ and CheckPlus models, either due to hydraulic configuration testing, chordal design, or both, do not appear to have the same apparent flow profile sensitivity that has been seen with External LEFM time-of-flight designs.

The limited LEFM operational information obtained by the Task Group was summarized above. With the above stated exceptions, the Task Group did not obtain in-depth operational information and is not able to form definitive conclusions with respect to Caldon UFM operational history in most nuclear power plants where Caldon UFMs have been installed.

3 EVALUATION OF CALDON ULTRASONIC FLOW METERS

3.1 Theory and Operation

Transit time UFMs use ultrasonic transmission techniques and may operate in the time domain or the frequency domain. Both types use ultrasonic pulses from a transmitting transducer through the flow medium to a receiving transducer. The difference in the pulse travel time of the upstream pulse and the downstream pulse is used to calculate the fluid velocity in both types.

A transit time or time-of-flight UFM uses the fact that the speed of an acoustic pulse will increase in the direction of flow and will decrease when transmitted against the flow. To determine volumetric flow rate a transit time meter transmits an acoustic pulse along a selected path and records the arrival of the pulse at the receiver. Another pulse is transmitted in the opposite direction and the time for that pulse is recorded. The difference in the upstream and downstream transit times for the acoustic pulse provides information on fluid motion (flow velocity). Once the difference in travel times is determined, the average velocity of the fluid along the acoustic path can be determined. Therefore, the difference in transit time is proportional to the velocity of the fluid.

To improve the performance of a transit time meter, chordal systems have been developed by Caldon that consist of an array of ultrasonic transducers housed in fixtures on a spool piece. The transducers are arranged such that they form parallel and precisely defined acoustic paths. Using the resulting time measurements and the known path lengths, the fluid velocity along each path length is determined. The resulting path length velocity measurements and the known path angle to the flow axis are used to find the axial fluid velocity. Using Gaussian quadrature integration, the velocities measured along the acoustic paths are combined to determine the average volumetric flow rate through the flow meter cross section. The chordal placement is intended to provide an accurate numerical integration of the axial flow velocity along the chordal paths.

To obtain the average flow velocity a meter factor is applied to the integrated average flow velocity. The meter factor is determined through meter testing at a flow calibration laboratory and is equal to the true area averaged flow velocity divided by the flow velocity averaged along the meter paths to correlate the meter readings to the average velocity and hence to the average meter volumetric flow. The mass flow rate is found by multiplying the pipe area by the average flow velocity and density. A time of flight meter constructed using a spool piece and chordal paths improves the dimensional uncertainties including the time measurement of the ultrasonic signal and enables the placement of the chordal paths at locations generally not possible with an externally mounted UFM. This allows a chordal UFM to integrate along off-diameter paths to more efficiently sample the flow cross section. In addition, a spool piece has the benefit that it can be directly calibrated in a flow facility, potentially improving measurement uncertainty compared to an externally mounted UFM.

Earlier reviews by the staff found that UFMs of the transit time (time of flight) multiple path (chordal) spool piece type can achieve uncertainties of better than 0.2 percent of flow in calibration laboratory tests. According to the literature, transit time meters can be expected to provide between 0.25 and 1.0 percent of full scale if the installation duplicates the flow lab conditions for flow above about one foot per second.

3.2 System Descriptions

There are three types of Caldon systems currently in use in nuclear power plants in the United States. The first design, the External LEFM, is a clamp-on UFM. The second type, the LEFM✓, is a UFM that utilizes a spool piece and incorporates four ultrasonic paths arranged in a chordal fashion (quadrature plane). The third type, the LEFM CheckPlus, is an eight acoustic path chordal UFM with each set of four paths crossed in quadrature planes. Each meter type has advantages and disadvantages with regard to performance and cost. The External LEFM meter is not used for uncertainty recapture uprates but has been installed in plants for power recovery purposes.

3.2.1 External LEFM

The current External LEFM is mounted to the process pipe using an external mounting fixture. According to Caldon the newer External LEFM consists of eight transducers arranged in four acoustic paths. The mounting fixture locates two sets of transducers in diagonal paths with the other two sets of transducers mounted in a crossed path configuration. The External LEFM calculates fluid temperature and density using the cross path and measures the axial fluid velocity using the diametric paths.

The External LEFM systems are used for power recovery. The idea here was to provide a measurement system that is equivalent to the uncertainty limits of the current calorimetric measurement (generally the venturis) and the two percent limit of 10 CFR 50 Appendix K. The advantage of the UFM in this application is that it is not prone to fouling, a condition which causes the venturi to overstate flow and results in overstated calorimetric power. Because the External LEFM is not sensitive to the same fouling effects as a venturi, it is used to quantify any venturi fouling that might occur and provide a corrected feedwater flow measurement.

However, in part because of the external mounting technique, the External LEFM does not achieve the stated uncertainty of the LEFM✓ or LEFM CheckPlus systems. There are several reasons for this. Among them are the dimensional variability associated with externally mounting the transducers (pipe dimensions, transducer locations, acoustic path, path angle, and time measurement). In addition, signal diffraction due to pipe mounted transducers, and the limited acoustic paths generally available for this type of meter (non chordal), contribute to increased uncertainty. The limited number of acoustic paths and their mounting arrangement also contribute to the external meter's greater sensitivity to flow profile effects with respect to a chordal transit time meter. Although the stated uncertainty for the External LEFM is adequate for power recovery applications where the intent is to quantify the fouling of the feedwater venturi, the application of the External LEFM for power uprates has not been reviewed or approved by the staff. The Task Group also notes that the use of an External LEFM for power recovery requires that the UFM be installed permanently if the venturi is being normalized to the flow indication of the External LEFM. (See also Section 2.2, above.) Finally, this type of meter has resulted in operation in excess of 2 percent above the licensed thermal limit.

3.2.2 LEFM ✓ and LEFM CheckPlus

The LEFM✓ System, as described in the staff safety evaluation for Caldon topical reports ER-80P and ER-157P, consists of a spool piece with eight transducer assemblies forming the four chordal acoustic paths in one plane of the spool piece. The system includes an electronics unit with hardware and software installed to provide flow and temperature measurements and an on-line verification of these measurements.

The LEFM CheckPlus System, both hydraulically and electronically, is made up of two LEFM✓ Systems in a single spool piece. This layout has two sets of four chordal acoustic paths in two planes of the spool piece which are perpendicular to each other. The electronics for the two subsystems, while electrically separated, are housed in a single cabinet. To ensure independence, the two measurement planes of the LEFM CheckPlus™ System have independent clocks for measuring transit times of the ultrasound pulses.

The stated advantage of the LEFM CheckPlus is that the fluid velocity measured by an acoustic path in one plane consists of the vector sum of the axial fluid velocity as projected on the path and any transverse component of the fluid velocity projected on the same path. When the net velocity measured by this acoustic path is averaged with the net velocity measured by its companion path in the second plane, the transverse components of the fluid velocity will substantially cancel and the averaging will only be of the axial velocities. Thus, the numerical integration of four axial velocities, averaged by the measurements in two planes and without the transverse component, is inherently a more accurate computation of the volumetric flow than that provided by a single plane of four acoustic paths in the LEFM✓ system. As a result, the calibration of the LEFM CheckPlus system is less sensitive to the specifics of a hydraulic configuration than that of the LEFM✓ system. Still, like other UFMs, the profile correction factor becomes a critical influence on flow meter uncertainty.

3.3 <u>System Uncertainties and Sensitivities</u>

3.3.1 <u>Overview</u>

The system uncertainties and sensitivities for the External LEFM, LEFM✓, and LEFM CheckPlus are different for each meter type. These differences relate to the External LEFM's mounting and limited number of acoustic paths, the spool piece construction and multi chord paths of the LEFM✓, and the dual crossed chordal paths of the LEFM CheckPlus. The uncertainty in feedwater flow measurement is improved with each successive LEFM design. Differences also exist in the treatment and magnitude of the uncertainties assumed for each LEFM type. In addition, the uncertainty of the calibration facility is reduced for more recent testing of the LEFM CheckPlus UFMs.

Although there are differences, the basic principles of operation are similar for each type. Because the LEFM✓ and the LEFM CheckPlus are used for power uprate applications, the uncertainties and sensitivities for these meters will be the focus of this section.

The uncertainties of a chordal LEFM can be classified as follows.

- Hydraulic uncertainties - These are uncertainties attributable to the calibration facility, the profile factor, the profile factor as it relates to a specific installation, and the uncertainties attributable to applying these uncertainties to a plant specific installation.

- Geometric uncertainties - These include uncertainties related to the manufacturing of the spool piece which include the diameter, acoustic path lengths, acoustic path angles, spool alignment, and the location of the acoustic paths with respect to the pipe (chordal paths). Based on testing each individual spool piece, the uncertainty of the spool diameter, the path angle, the path spacing, and the path length are calibrated out through the measured profile correction factor.

- Time measurement uncertainties - These comprise the uncertainties associated with measuring the transit time of the acoustic pulses. Also included here are the non-acoustic delay uncertainties that include ultrasonic signal delays attributable to the transducer interface with the fluid.

- Correlation uncertainties - Because a chordal LEFM uses ultrasonic signals to also measure temperature, there are additional uncertainties related to sound velocity and the correlation to temperature and pressure.

- Observational errors - These are attributable to the characteristics of the Chordal LEFM in that it is a system based on sampling. Since the calibration facility can only test to a limited time (typically due to the capacity of a weigh tank used to measure flow), limited samples are available during the test. This can sometimes be a problem if the flow requirement specification includes a limitation in the number of test runs to achieve a certain repeatability. No such requirement exists for feedwater flow. However, because the Chordal LEFM is sample based, a significant number of data points are generally required for accurate fluid measurements which may require multiple runs in a calibration facility and relatively long measurement periods in plant operation.

- Computational errors - These are based on the digital processing of the Chordal LEFM data.

The total error for a chordal LEFM is represented by the percent error (uncertainty) of each variable by its associated sensitivity coefficient. All errors and biases are handled per ASME-PTC-19, “Measurement Uncertainty,” and Regulatory Guide (RG) 1.105, “Setpoints for Nuclear Safety Related Instrumentation used in Nuclear Power Plants.” RG 1.105 endorsed ISA 67.04.01, “Setpoints for Safety-Related Instrumentation.” The standard, the recommended practice, and the RG are intended for the development of safety related setpoints but the basic methodology is applicable to the calculation of channel uncertainties. The RG is based on the square root sum of the squares method (SRSS) to combine random uncertainties and the algebraic combination of non-random terms with the result. PTC-19 appears to provide an option in the treatment of bias as either an SRSS or algebraic combination with random uncertainties with respect to expected uncertainty coverage. It is therefore possible with respect to the treatment of biases to obtain somewhat different uncertainty results compared to ISA 67.04.01. The staff Safety Evaluation Report (SER) to ER-80P alluded to this by stating that the methodology be based on an accepted plant setpoint methodology and applied consistently to both venturi and UFM installations. From the analyses performed by Caldon, the uncertainties in volumetric flow measurement are due to uncertainties in the profile correction factor, expansion factor (spool piece thermal expansion), time of flight measurement, and non-fluid delays.

3.3.2 <u>Profile correction factor</u>

The uncertainty of the profile factor is determined based on the stated uncertainties for the calibration facility, the Chordal LEFM electronics used in testing, modeling and Reynolds number extrapolation, observation uncertainties (uncertainties related to the test run time period and number of samples), and additional uncertainty for pre-installed spool pieces not originally installed for power uprates. The total uncertainty for the profile correction factor is the SRSS of the above uncertainties and is generally budgeted as 0.4 percent for the LEFM✓. Uncertainties for the LEFM CheckPlus are improved based on the reduction in uncertainty in the electronics, modeling, and Reynolds number extrapolation. These reductions are a direct result of the four dual paths used in the LEFM CheckPlus and the uncertainty is estimated to be 0.25 percent. The additional paths of the CheckPlus reduce random uncertainties and the impact of transverse velocity components. For the LEFM✓, the uncertainty due to modeling appears to be the biggest contributor. For the LEFM CheckPlus, the calibration facility uncertainty appears to be the biggest contributor.

3.3.3 <u>Error in time of flight measurements</u>

The uncertainty in the transit time of the acoustic pulse and the uncertainty contribution due to the pulse traveling though non-fluid media (transducer facing, cabling, etc) was found to be less that 0.12 percent and 0.09 percent for the LEFM✓ and LEFM CheckPlus, respectively.

3.3.4 <u>Spool piece dimensional errors</u>

Based on the LEFM chordal spool pieces being individually calibrated in a calibration facility, the dimensional errors for the spool piece are calibrated out and are part of the profile correction factor. Since the profile correction factor includes this uncertainty, no additional errors are carried. However, an uncertainty is budgeted to account for the fact that a spool piece diameter and other dimensional factors may change over time due to material deposition or corrosion. Caldon stated that the spool piece wall thickness is checked periodically through the inservice inspection program. The uncertainty allowance used is dependent on the spool piece inside diameter and is more significant with smaller pipe. It should be less that 0.10 percent.

3.3.5 <u>Spool piece alignment</u>

There is an uncertainty in the mounting of an LEFM spool piece based on the fact that the interface between the LEFM spool piece and system piping may create a flow disturbance that affects the calculated profile factor and / or affects the meter calibration as installed. To account for this, the chordal LEFMs for feedwater service are fabricated such that the length of the spool piece should introduce limited error. In addition, tests performed on chordal LEFMs showed that the error due to angular miss-alignment is on the order of 0.1 percent. Caldon stated that the LEFM CheckPlus based on the dual 4 chordal path arrangement is much less sensitive and alignment error should be limited.

3.3.6 <u>Spool piece thermal expansion</u>

The spool piece thermal expansion contribution to chordal LEFM uncertainty affects both the volumetric flow error, the mass flow, and the thermal power measurement since the chordal LEFM also measures temperature. (Density and enthalpy are affected). For the volumetric flow, an uncertainty of 0.07% is taken, and for the power, an uncertainty of 0.108% is budgeted.

3.3.7 <u>Time of flight measurement</u>

The following uncertainties were identified from Caldon reports and meetings with Caldon:

1. <u>Clock Accuracy</u> - Long term clock accuracy.

2. Clock Resolution - This is based on clock frequency and required sample length.

3. Random Noise - This relates to turbulence and sample size.

4. Coherent Noise - This is due to noise that is not reduced by sampling such as acoustic energy that gets transmitted along the pipe wall and not through the intended fluid. Coherent noise can be picked up by the receivers and can affect the flow measurement via signal detection and calculated transit times.

5. Non-Fluid Delays - These errors are associated with unequal delays in acoustic signal transmission and are not related to the fluid time delay. They include effects due to cables, multiplexers, and zero crossing detection.

These uncertainties are discussed below.

Clock Accuracy and Resolution. With respect to clock accuracy, the Chordal LEFM clock is compared to a standard such that clock accuracy is maintained within an uncertainty of 0.01 percent. Based on this, the uncertainty in acoustic path time measurement would be the path lengths divided by the fluid speed of sound plus the non-fluid time delays. This would represent the uncertainty for time and sound measurement. However, the Chordal LEFM calculates velocity by subtracting the upstream and downstream acoustic pulse transit times for each path. Because the Chordal LEFM samples in the millisecond range, the uncertainty in the clock calculation is essentially canceled by the differential time measurement. Therefore, the accuracy of the time measurement for the upstream/downstream time difference is found by looking at the time accuracy of the differential measurement. Based on the vendor stated clock accuracy and an assumed pipe size, time uncertainties appear for differential time measurement to be in the 0.3ns and 0.5ns range for the short and long paths, respectively. Clock resolution is controlled by the clock frequency and period. Clock resolution error may be reduced based on the designated number of Chordal LEFM measurement samples during the clock period.

The Chordal LEFM, like UFMs in general, are sample rate based systems. Each acoustic pulse fluid velocity is determined along a defined path. Because the fluid velocity will vary in time due to turbulence and other effects, a single measurement will not establish an accurate average flow rate. UFMs require that many measurement samples be taken to limit the uncertainty of the measurement. Because of variations in fluid velocity, a sample rate needs to be established along with the number of samples required per reading over a prescribed time period. For Caldon UFMs, this time is typically a number of minutes based on the installation, fluid characteristics, and measurement uncertainty desired. For a chordal LEFM, the turbulent intensity is developed based on past measurement experience. Resolution will vary with the assumed turbulence intensity, spool piece dimensions (path distances), the assumed chordal LEFM sample rate, and the Chordal LEFM clock resolution. The assumptions for turbulence intensity and plant specific characteristics need to be confirmed for plant specific installations. Based on material submitted by Caldon, the sample rate requirements are confirmed during flow meter acceptance testing.

Random Noise. The random noise contributions limit is defined as a phase displacement of the zero crossing point of the ultrasonic pulse. Zero crossing displacement will affect the transit time measurement of the ultrasonic pulse.

Coherent Noise. Coherent noise is handled similarly to random noise. However, as stated above, sampling will not improve the coherent noise signal to noise ratio. Caldon specifies a minimum coherent signal to noise ratio. This value is confirmed during acceptance testing and is designed to account for signal degradation or increases in the coherent noise signal. Coherent noise time differential uncertainty is estimated at 4.8 ns and 3.4 ns for the LEFM✓ and LEFM CheckPlus, respectively, which equates to an estimated volumetric measurement uncertainty with respect to time measurement of 0.06 percent for the LEFM✓ and 0.04 percent for the LEFM CheckPlus, again based on an assumed pipe size.

Non-Fluid Delays. Non-fluid delays are calculated using three different methods with the weighted combination of the estimated uncertainty of the three methods. The error in volumetric flow based on non-fluid delays is estimated to be 0.03 percent for the LEFM✓ and 0.02 percent for the LEFM CheckPlus. The difference is due to the eight path configuration of the LEFM CheckPlus. Note that time measurement uncertainty and non-fluid time delays are also contributors to temperature since the chordal LEFMs also measure temperature ultrasonically. These uncertainties will then also impact the measurement of density and enthalpy.

Based on the above, Caldon estimated a volumetric flow rate uncertainty of 0.43 percent and 0.27 percent for the LEFM✓ and LEFM CheckPlus, respectively.

3.3.8 Temperature measurement

The correlation uncertainty for temperature measurement is estimated to be in the range of 0.5 °F for full power operation. The justification for the temperature uncertainty is based on the fact that the temperature of a fluid can be determined if the sonic velocity and pressure are known. The correlation used by Caldon is based on empirical data with a stated accuracy of 0.02 percent. Allowing for the uncertainty in the data and the curve fit error results in the estimated temperature measurement uncertainty of 0.5 °F.

The temperature measurement is affected by the acoustic path distance due to thermal expansion. This is estimated to be 0.06 °F and 0.04 °F for the LEFM✓ and LEFM CheckPlus, respectively. In addition, temperature is also affected by the uncertainty in non-fluid time delay which is estimated to be 0.12 °F for the LEFM✓ and 0.08 °F for the LEFM CheckPlus. Since the temperature correlation also depends on pressure measurement, an uncertainty with respect to the sensitivity of the temperature/sound velocity correlation to pressure is required. Based on Caldon submitted data, the impact of pressure on the correlation is small and, assuming a nominal error in feedwater pressure measurement, the error is estimated to be 0.21 °F. This uncertainty estimate is the same for both chordal LEFM types since pressure is an independent measurement and is not reduced based on LEFM path redundancy or the calculation.

The uncertainty in chordal LEFM temperature measurement is shown to be less than that assumed for conventional RTD temperature measurement. Therefore, the improved temperature measurement associated with a chordal LEFM also contributes significantly to the improvement in feedwater mass flow rate measurement and thermal power measurement when compared to conventional venturi based calculations where temperature is determined by other means.

Based on the above uncertainties, a thermal power measurement based on chordal LEFM technology has the potential to provide a thermal power uncertainty in the 0.4 percent to 0.6 percent range. The above uncertainty estimates and sensitivities would indicate that changes in profile factors, if not accounted for in the uncertainty calculation, would have a significant impact on meter performance. If flow profiles are known to change during plant operation, it should be shown that the meter is insensitive to the profile change, the meter has diagnostic capabilities to detect any changes in profile beyond the claimed uncertainty budget, or the uncertainty analysis is bounding for the changes expected during operation. Since the claimed uncertainty for the above meters is approaching calibration laboratory results for fluid flow, it would be difficult to confirm that these uncertainties are being maintained by using conventional plant instrumentation. Therefore, diagnostic capabilities and system reliability may also play a role in maintaining the claimed uncertainty but are not evaluated here.

3.4 Laboratory Calibration

As stated by Caldon, each External LEFM, LEFM✓, or LEFM CheckPlus is calibrated against a weigh tank as a standard. As a result, the vendor has collected calibration data from more than two thousand weigh tank runs at Reynolds numbers up to five million. For this discussion, only the LEFM chordal systems (LEFM✓ and LEFM CheckPlus) are included but the overall procedure is generally applicable to the External LEFM as well.

The purpose of the LEFM✓ calibration is to develop a profile factor (meter factor) that provides a correction factor for the LEFM✓ volumetric flow rate calculation with respect to the measured velocity. The LEFM✓ is a volumetric flow rate meter and, based on the numerical integration over the four acoustic paths, its indication is in error when compared with the true volumetric flow rate. Therefore, a profile factor is required to correct the meter reading such that it corresponds to the true volumetric flow rate.

For the LEFM✓, the vendor initially sets the profile correction factor to one (no correction for profile) to model the instrument in a piping installation representative of the final meter installation in the plant. This is done to quantify the hydraulic profile at the intended installation location for the LEFM✓. In other words, a plant specific test is run at a calibration test facility using an LEFM✓ installation that models the plant specific installation including upstream piping disturbances such as elbows, tees, and valves. The model constructed is a full scale model of the intended installation but is only representative of the piping determined to be critical for the installation. Although a scaled model could be used, because the vendor also tests the actual spool piece to be installed in the plant, a full scale mock-up is required. Because the LEFM✓ flow profile correction factor is set to one, the resulting profile correction factor will be that of the intended installation. The profile correction factor is determined based on the calibration facility measured flow divided by the LEFM✓ indicated flow.

The determination of a profile correction includes with it certain uncertainties associated with the measurement. First, the stated accuracy of the test facility needs to be determined. For

Alden Labs, this uncertainty has been established at 0.25 percent. More recent tests have credited a facility uncertainty of 0.15 percent based on Alden Labs uncertainty analysis. In addition, the plant specific LEFM✓ installation has uncertainty associated with the fact that the installation is only a partial representation of the plant specific piping. The model selected is based on an evaluation of which critical piping parameters have the potential to affect the hydraulic profile and therefore the profile correction factor. Lastly, there is uncertainty associated with the LEFM✓ meter itself. These uncertainties and their relationships were discussed in Section 3.3, above.

Full scale testing provides a means to test the LEFM✓ in an installation that represents the plant installation, but the scale test still may not be fully representative of the flow conditions experienced by the LEFM✓ in the plant. The problem is that the Alden calibration facility cannot duplicate the fluid properties in a plant[7]. Although the Alden calibration facility can duplicate the flow rate, duplicating the temperature of a plant feedwater system is not generally possible. This results in a Reynolds number of one to five million instead of the approximately thirty million that is seen in the plant. Therefore, an extrapolation is required to the Reynolds number seen in the plant. To do this, multiple calibration runs are performed at various Reynolds numbers over the range capability of the calibration facility. Once the data are collected, the measured profile factors are plotted against the Reynolds number corresponding to the test. A curve fit is performed to extrapolate the profile correction factor to higher Reynolds numbers. A review of vendor supplied test data for straight pipe runs (at a single location) at Reynolds numbers from approximately 1.0E6 to 4.4E6 shows a small sensitivity to Reynolds numbers for a chordal LEFM. Based on these test results, Caldon stated that the Reynolds number extrapolation carries an uncertainty of approximately 0.1 percent. More recent assessments by the vendor use the profile correction factor as determined in the laboratory and the profile correction factor as determined by the extrapolation to higher Reynolds numbers as bounding values to determine the uncertainty of the Reynolds number extrapolation. This method can result in a lower value than stated previously (0.05 percent is referenced in some calculations).

The calibration of the LEFM✓ spool piece results in a profile correction factor that essentially calibrates out meter uncertainties related to hydraulics and dimensional uncertainties related to the manufacturing of the LEFM✓ spool piece. However, hydraulic uncertainty is still a consideration if the hydraulic profile is subject to change based on plant line-up, modifications, or operational changes that would affect the hydraulic profile seen by the LEFM✓. If the LEFM✓ is sensitive to these changes, a significant variance in the meter indicated flow rate will result with a corresponding calibration shift in the LEFM✓. To account for this, parametric tests are run on the plant specific model by introducing flow disturbances to the model. If changes are noted in the profile correction factor, this change can be used to bound the uncertainty of the model and the profile correction factor. This would also include any required mounting orientation of the meter caused by flow disturbances. (Mounting orientation of the LEFMs has been shown to affect the flow measurement depending on the flow disturbance encountered.) The total modeling uncertainty is estimated to be less than 0.25 percent based on vendor documents and test results.

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[7]Plant configurations also vary due to such variables as pump combinations, valve positions, and heater variations.

As noted above, the installation of a UFM in a plant specific installation may not represent the installation used to calibrate the UFM at a calibration facility. The additional piping configurations and flow disturbances may present a velocity profile that is different from the flow profile to which the UFM was calibrated. The potential exists for the assumed profile to change over time due to changes in the feedwater system configuration such as valve position, pump operations, bypass flow, and piping changes including roughness. Therefore, understanding how the installed meter reacts to changes in flow profile and the diagnostics available to identify these changes are important to maintain the meter calibration in the field. Changes to flow profiles either need to be identifiable through meter diagnostics or need to be quantified for the installation with respect to meter performance and accuracy. Test data presented by Caldon indicate that changes in profile correction factor are small for an upstream elbow or non-coplanar bends that are spaced apart. Additional testing has also been performed with respect to LEFM installations downstream of a header with similar results. However, testing of close coupled non-coplanar bends can introduce a significant calibration shift. The LEFM CheckPlus is less susceptible than the LEFM✓ to transverse velocity flow components such as produced by the above piping arrangements due to the crossed dual quadrature ultrasonic paths which tend to cancel the transverse flow components. Based on the above, Caldon states that for power uprate applications, calibrations are performed for both straight pipe and the plant specific installation. Once installed, path data are available to compare the profile developed during the calibration with that seen in the field. This provides some feedback that the profile seen in the field is consistent with the profile developed during calibration testing subject to profile effects not recognized by each LEFM type and model fidelity.

3.5 Installation, Implementation, and Operation

A review of Caldon documentation shows a reasonably comprehensive set of procedures for the installation of a chordal LEFM. The scope of the procedures covered functional requirements, design requirements, storage and operational specifications, inspection and test, and final documentation requirements. Procedures reviewed by the Task Group included procurement specifications, software generation, LEFM✓ and LEFM CheckPlus commissioning procedures, commissioning data and test packages, and profile calculation and accuracy assessment procedures for plant specific spool pieces. In addition, periodic testing is also specified.

Caldon also supports an annual Users Group meeting. The Task Group reviewed the presentation given at the 2003 Users Group meeting. The information presented included reliability data, deficiency reports, and customer condition reports. The Task Group noted that the information was detailed and included procedural changes to improve data collection from customers, improve evaluation times, and root cause evaluation for returned items. Extensive discussion was included for product development, including programs to improve system reliability and performance. Product upgrades and specific design changes were discussed. Overall, the Task Group determined that vendor installation, implementation, and operation support were responsive to customer issues.

The chordal LEFMs incorporate various on-line diagnostics that are used during system commissioning and normal plant operation. The diagnostic capabilities of chordal LEFM systems as stated by Caldon and described in Topical Reports and presentations made by Caldon are presented below as related to the stated uncertainties.

1. <u>Profile Factor</u> - Path velocities are measured and the “Flatness Ratio” is monitored. Values that exceed those expected during operation are alarmed.

2. <u>Spool Piece Dimensions</u> - The ratios of individual path length velocities are monitored and alarmed to provide information on changes in acoustic path dimensions.

3. <u>Clock</u> - Accuracy is monitored on-line and by periodic surveillance tests.

4. <u>Transmitter/Receiver Reciprocity</u> - Unequal delays in the multiplexer, delays in signal detection, and possible delays due to cable length are monitored and alarmed through LEFM self testing during commissioning and operation.

5. <u>Signal to Coherent Noise Ratio</u> - This value is confirmed during commissioning and is measured and alarmed through the total signal to noise ratio measurement.

6. <u>Signal to Noise Ratio</u> - This value is confirmed during commissioning and is measured and alarmed during operation.

7. <u>Non-Fluid Delays</u> - This value is confirmed during commissioning and is monitored and alarmed during chordal LEFM operation.

8. <u>Pressure</u> - For the LEFM CheckPlus, upscale and downscale alarms are provided. For redundant instruments, a differential alarm is also available. Alarms are included here because pressure instrumentation is provided.

Based on information contained in topical reports and as presented by Caldon, other parameters are not required to be monitored either because the parameter will remain bounded or are implicitly included in other parameter measurements.

Operational data provided by Caldon included deficiency and condition reports that list the failures experienced to date but did not relate these failures to whether LEFM diagnostics were able to detect them. A review of LER and other industry data did not provide additional insights into the effectiveness of the LEFM online diagnostics. An additional report published by Caldon (ER-262) discusses the effect of velocity changes on chordal LEFM systems as reported by velocity profile alarms. This report provides some feedback on the diagnostic operation of chordal LEFMs with respect to flow profiles. The Task Group also notes that the parameters monitored by the LEFM are key contributors to the LEFM uncertainty budget and the monitoring of these parameters provides a means to maintain chordal LEFM uncertainty assumptions subject to the variables discussed above.

Overall, Caldon is fully aware of most problems and corrects them when discovered. Recognized problems have mostly involved hardware, operator, and software issues. The combination of the number of flow paths and the pre-installation testing in the LEFM✓ and LEFM CheckPlus UFMs appears to have resulted in few problems due to flow disturbances from such items as pump configurations and valve manipulations.

4 CONCLUSIONS AND FINDINGS

The perceived accuracy of UFMs has been credited for a reduction in the uncertainty associated with determining thermal power level. This, in turn, has allowed licensees to operate at increased thermal power while believing that there was reasonable assurance that licensed thermal power would not be exceeded. Currently, the UFMs used for this purpose are manufactured by W/AMAG and Caldon. However, the Byron and Braidwood nuclear power plants were found to be operating in excess of their licensed thermal power when the Crossflow UFMs were used. This led to questions regarding the Crossflow UFM technology at other facilities.

Problems have occurred with Caldon UFMs as well. Perhaps the most serious was operation at River Bend for an extended time at greater than 2 percent over the licensed power level. The Task Group notes that the Caldon UFM was an early External LEFM that is not claimed to have the accuracy of the more recent LEFM✓ and LEFM CheckPlus models. This experience does, however, underscore the Task Group's concern with the Caldon models.

Tables describing the Caldon LEFMs considered by the Task Group, a summary of operational history, and the Task Group's assessment of the effectiveness of the built-in error checks and the ability of the UFMs to continue to provide a correct flow rate were provided in the SUMMARY AND RECOMMENDATIONS section, above, and will not be repeated here.

The following table provides a summary of characteristics of the Caldon LEFM✓ that is commonly used in power recovery and power uprate applications:

Item	Caldon LEFM✓
Number of velocity locations sampled	Four in one plane perpendicular to flow. (Eight are available in two planes in the LEFM CheckPlus.)
Timing	Nanoseconds. The Task Group has not identified an issue with timing.
Method	Determines velocity by difference in transit time via two perpendicular vectors for each path.
Diagnostics	Flatness Ratio, path length velocity ratios, unequal delays in the multiplexer, delays in signal detection, possible delays due to cable length, signal to noise ratio, and non-fluid delays are monitored and alarmed. Clock accuracy is monitored on-line and by periodic surveillance tests. For the LEFM CheckPlus, upscale and downscale pressure alarms are also provided.
Experimental testing	Every UFM is tested at Aldon Laboratories in a full scale test with plant configurations. Retesting is performed if the UFM behaves differently in the plant than at Aldon.
Boundary layer control	Yes - (A thinner boundary layer makes the velocity profile flatter)

Item	Caldon LEFM✓
Owners group	Active and extensive
Historical record	Yes. Updated continuously. Informative web site is available.
Reasonable assurance UFM is operating as expected	Probably. The Task Group does not have substantial data to support this conclusion but it has no information that indicates existence of current overpower problems.
Effectiveness in addressing flow profile changes	Four path method in one plane judged somewhat effective - but not fully effective for changes out-of-plane. This method appears to provide a better likelihood of recognizing a flow profile problem than the External LEFM.
Effect of built-in error detection	Uncertainty appears small unless out-of-plane flow profile changes occur that do not affect the four in-plane readings, a more unlikely condition if plant specific piping configurations are included during calibration
Control room information	Plant computer. Other displays not determined.
Adequate operator response to diagnostic indications	Probably.
Sensitivity to plant configuration changes	Appears generally small, especially for eight path chordal LEFM. Specific data not obtained.
Temperature	Sensitive. The meter provides an accurate temperature.
Configuration	~ 5 foot long spool piece
Vendor Involvement	High
Historical improvement to address problems	Yes - actively obtained feedback and used it effectively.
Uncertainty	0.4 - 0.5. LEFM CheckPlus is 0.25 - 0.30
Meter orientation impacts uncertainty	Yes. 4 chord > 8 chord. Depends on flow disturbance.

The LEFM CheckPlus appears to be an improvement over the LEFM✓ and the Task Group is reasonably confident either UFM will provide the anticipated accuracy when properly operated and maintained by trained personnel. Conversely, the Task Group is concerned with the performance of the External LEFM in nuclear power plant feedwater applications. The Task Group believes the LEFM✓ and the LEFM CheckPlus UFMs are inherently better able to recognize and are less sensitive to changes in the velocity profile than the External LEFM designs. Thus, the Task Group's concern regarding the LEFM✓ and the LEFM CheckPlus UFMs is less than with the External LEFMs.

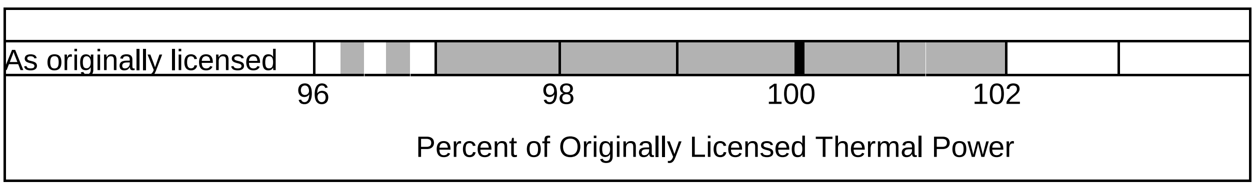
The Task Group's recommendations for further staff action were provided in the SUMMARY AND RECOMMENDATIONS section and will not be repeated here.

APPENDIX A

THE EFFECT OF ULTRASONIC FLOW METER USE IN NUCLEAR POWER PLANTS

Original safety analyses for loss-of-coolant accidents (LOCAs) were conducted at 102 percent of licensed thermal power to account for a perceived two percent instrument uncertainty that was specified in 10 CFR 50 Appendix K. Operation with an indicated power greater than 100 percent or with a bias that results in actual power being greater than 100 percent is inconsistent with the operating license.

The following sketch illustrates the actual power level generally believed to exist when operating at an indicated 100 percent power in nuclear power plants that are operating as originally licensed. The dark line is the perceived or indicated thermal power and the grey band represents the effect of instrumentation uncertainty and bias. Actual power during initial operation of the as-built plant would be expected to within ± 2 percent of the 100 percent indication. Operation with an actual power less than 98 percent could occur as feedwater venturis fouled and indicated a flow rate greater than actual, resulting in an indication of thermal power greater than actual, and causing an unnecessary power reduction so that indicated thermal power remained within the licensed limit.



Some licensees have used temporary ultrasonic flow meter (UFM) installations to calibrate feedwater venturis in a “one-time” test, with the calibration assumed to remain valid for long-term operation.[8] Reference 1 and interviews with licensee personnel indicated an average improvement of about one percent was expected. This is consistent with the experience at Dresden Unit 2, where total feedwater flow was reduced in 1996 by 1.26 percent.[9] Such calibrations are based on the presumption that the UFMs provide a more accurate feedwater flow measurement than the venturis and that the venturi characteristics will not change to indicate a lower flow rate. Such changes could occur due to venturi defouling. The staff does not traditionally evaluate this use of UFMs. As discussed in Section 2.2, above, the Task Group finds this to be an unacceptable use of UFMs unless complete justification is accomplished.

Licensees often install UFMs to reduce or eliminate power production lost due to venturi fouling. These UFMs are perceived to reduce the uncertainty in determining thermal power, although

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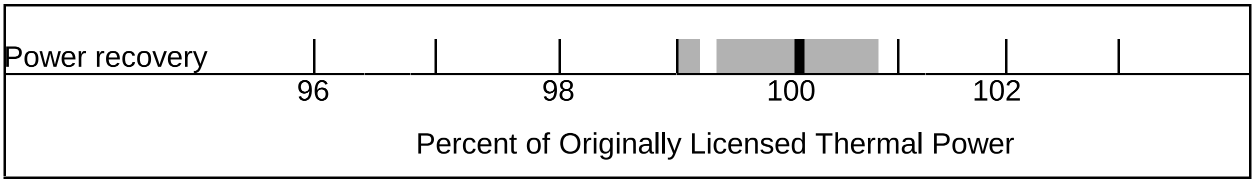
[8]The UFMs are removed following venturi calibration.

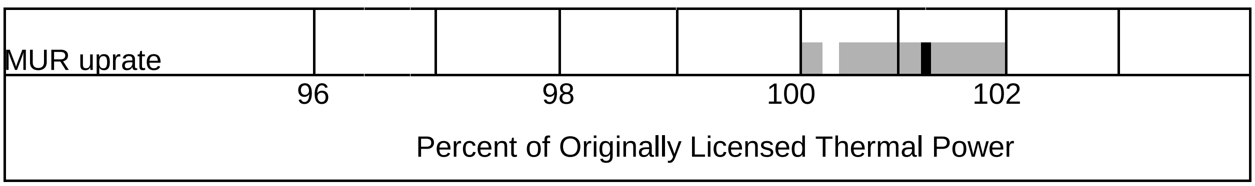
[9]This correction is still in effect. Since the plant is being operated below 98.7 percent thermal power, the licensee does not consider this to be a current concern. However, a combination of weather and condenser conditions could result in exceeding 98.7 percent thermal power in May, 2004. The licensee plans to complete an evaluation of the condition prior to exceeding 98.7 percent thermal power. (Reference 2)

the effect of the uncertainty reduction is not credited for an increase in licensed thermal power. The following sketch illustrates the effect of this use of UFMs for the case of an assumed overall 0.7 percent uncertainty achieved by the combination of UFMs and corrected venturi indications:



This UFM application is accomplished using the 10 CFR 50.59 process and does not require NRC review or approval since there is no licensing basis change (licensed power level stays the same).[10]

Licensees also increase licensed thermal power by crediting the perceived reduced uncertainty due to UFMs as illustrated in the following sketch:



This is called a measurement uncertainty recapture (MUR) uprate or an Appendix K uprate because it must, in part, be justified in accordance with the requirements of 10 CFR 50 Appendix K and, since it involves an amendment to the license (a change in plant power level), NRC approval is required. Note that the sketch is based on the assumption that continuous venturi corrections are accomplished to compensate for venturi fouling. Original use of this MUR uprate was accomplished via the exemption process because Appendix K required a two percent allowance for uncertainty. The regulation was changed in June, 2000 to allow a smaller uncertainty when justified.

Implementation of UFMs at the Byron and Braidwood plants using the Crossflow UFM to accomplish power recovery resulted in overpower conditions at the four units. The highest overpower appears to have occurred at Byron Unit 1, as illustrated in the following sketch of estimated values:

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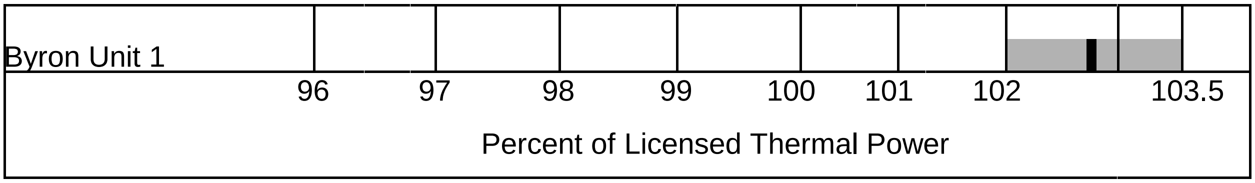
[10]The two percent allowance for uncertainty between 100 percent and 102 percent thermal power remains in place. The cause of thermal power less than the original 98 percent due to venturi fouling or other long-term instrumentation bias accumulation is essentially eliminated if this process works as planned. <u>If</u> the thermal power determined by the venturis and by the UFMs is identical during initial operation, then, neglecting uncertainty, there will be no change in initial thermal power.



Note the 102.7 percent estimate is above the licensed thermal power of 100 percent and is above the LOCA licensing basis analyses that were accomplished at 102 percent. Clearly, this result is inconsistent with the precision that is perceived to be achieved by installation of UFMs. The reasons for this error are not understood by the Task Group.

Appendix A References

1. “10 CFR 50.59 Safety Evaluation Form, Byron/1&2 Tracking No.: 6G-00-0079 Rev. 1,” RS-AA-104.04, “Effective Date: 12/27/99".

2. “Unit 2 Feedwater Flowrate Indication Based on 1996 AMAG Calibration Test,” EC #347441, Dresden, Undated but issued in late February, 2004 since it references a February 12, 2004 W publication.

APPENDIX B

THEORETICAL INVESTIGATIONS

B-1. Computational Fluid Dynamics (CFD) Investigation

Knowledge of the velocity profile is essential for the UFM to properly compute mass flow rate at a given cross section. In theory, the available velocity profiles are derived for ideal situations where fully developed flow exists. In nuclear plants, the UFM is not placed in locations where fully developed flow exists. In most cases, the measurement is made downstream of an elbow, a T-connection, or other flow configurations that perturb the symmetrical profile found in fully developed flow.

Preliminary Computational Fluid Dynamics (CFD) analyses were performed using the FLUENT[11] code to investigate the effect of upstream perturbances on the velocity profile. A steady state isothermal model was used in each simulation. The Renormalization Group Theory RNG k-epsilon model was chosen to model turbulence in the core flow, while the standard wall function was used to bridge the core flow to the laminar sublayer near the wall. A Neumann boundary condition with zero normal gradient was applied at the pipe exit. The first nodal layer near the pipe wall was carefully placed for the proper use of the RNG-k-epsilon model using the standard wall functions. Boundary layer meshing was used near the wall to achieve mesh orthogonality to reduce numerical error due to the additional tensor geometrical coefficients in the conservation equations.

Two 14 inch diameter pipe configurations were analyzed with 220 °C water at a uniform velocity entering the pipe:

1. A straight pipe that was 100 diameters long. The corresponding Reynolds number is 28E6.

2. A pipe with a 10 diameters long straight section followed by a 90 degree elbow followed by a 200 diameters long downstream section. Reynolds numbers of 3.51E5, 1.4E6, 4.21E6, 14.45E6, 21.18E6, and 28E6 were evaluated

The results from the first configuration simulation showed that the fully developed profile can be attained at a distance between 20 and 30 diameters downstream of a uniform velocity inlet and the velocity profile changes only radially and uniformly in the tangential direction.[12] The results obtained for the 90 degrees bend show that the fully developed flow is not obtained even at 100 diameters downstream of the elbow. Additionally, downstream of an elbow, the flow remains disturbed and asymmetrical. The results show that the axial velocity profiles change

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[11] FLUENT is a commercially available state-of-the-art computer program for modeling fluid flow and heat transfer in complex geometries.

[12] Numerous figures were generated during these analyses. Representative examples are provided in Section 2.5, above. The others have been omitted from this report because of the length of the files.

tangentially even at long distances from the elbow, distances that exceed those attainable in most if not all installations in nuclear power plant feedwater lines.

B-2. Caldon Approach for Feedwater Mass Flow Rate Measurement

The volumetric flow rate in a pipe is given by the integral of the axial velocity over the cross sectional area of the pipe:

$$\dot{Q} = \int_A V_a(x,y)dA$$

The External LEFM✓ and External LEFM CheckPlus UFMs perform this integration numerically by measuring the integral of V_a(x)dx at four pre-selected y positions. These preselected positions are chosen using Gaussian quadrature formulas which can lead to improved integration accuracy. This method, which is also referred to as Gauss-Legendre integration, does not necessarily use the endpoint to evaluate the integral. The fundamental theorem of Gaussian quadrature states that the optimal abscissa of the m-point Gaussian quadrature formula is precisely the roots of the orthogonal polynomial for the same interval and weighting function. Gaussian quadrature is optimal because it fits all polynomials up to degree 2m exactly. In the application of the four chordal meter, the following equation divided by two is used to obtain the above integral:

$$\dot{Q} = W_1 * D_i * \int_{y_1} V_a(x)dx + W_2 * D_i * \int_{y_2} V_a(x)dx + W_3 * D_i * \int_{y_3} V_a(x)dx + W_4 * D_i * \int_{y_4} V_a(x)dx$$

The four chordal paths are positioned at the locations y_1, y_2, y_3, and y_4. W_1, W_2, $W_{3,}$ and W_4 are the Gaussian weighing factors. For the four points integral, the four weighing factors are $W_1 = W_4 = 0.173927$ and $W_2 = W_3 = 0.326073$, and the locations y_i are y_1 / R = -0.33998104, y_2 / R = +0.33998104, y_3 / R = -0.86113631, and y_4 /R = +0.86113631 where R = D_i / 2 and D_i is the pipe inside diameter. Note the integrations are performed on four rectangular cross sections, ΔA = Δx Δy, and the area correction is used to correct for the circular cross section of the pipe.

The transit time in the fluid is a function of the average sound velocity and the average fluid velocity projected onto the path:

$$t_{down} = L_{path} / (C + V)$$

$$t_{up} = L_{path} / (C - V)$$

which lead to the following:

$$V = \frac{L_{path}}{2}\left(\frac{1}{t_{down}} - \frac{1}{t_{up}}\right)$$

$$C = \frac{L_{path}}{2}\left(\frac{1}{t_{down}} + \frac{1}{t_{up}}\right)$$

$$V_a = V / \cos\varphi$$

where: φ = axial angle

C	=	speed of sound in the running fluid
L_{path}	=	distance of the ultrasonic path
t_{down}	=	time it takes the signal to travel downstream in the flow direction
t_{up}	=	time it takes the signal to travel upstream against the direction of the flow.

The mass flow rate is:

$$\dot{W} = \rho * PF * F_{a3}(T) * (D_i / 2) \sum_{i=1}^{4} \frac{W_i L_{ffi}^2 (\Delta t_i)}{\tan(\varphi_i)(t_i + \Delta t_i/2 - \tau_i)}$$

where:

ρ	=	mean feedwater density
PF	=	profile factor
$F_{a3}(T)$	=	thermal expansion factor
L_{ffi}	=	face-to-face distance between transducer wells of path *I*
t_i	=	total indicated time of flight of pulse along path *I* in the flow direction
Δt_i	=	difference in the total transit time of pulses traveling against the flow and with the flow
τ_i	=	total of the non-fluid delays of pulses traveling along path I
T	=	mean fluid temperature

The profile factor is determined by calibration tests in a certified laboratory. The sensitivity of profile factor to variations in axial profile is measured by changes in flatness ratio, FR, defined as the ratio of the average axial velocity at the outside chords (chords 1 and 4) to the average axial velocity at the inside chords (chords 2 and 3). For the LEFM✓:

$$FR = (V_1 + V_4) / (V_2 + V_3)$$

and for the LEFM CheckPlus:

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

FR is a function of Reynolds number, pipe wall roughness, and the piping system configuration. The effect of the configuration is evaluated in laboratory tests. The effect of Reynolds number is deduced from the fully developed flow inverse power law profile.

$$\frac{V}{V_{\max}} = \left(\frac{X}{R}\right)^{1/n}$$

where the exponent *n* varies with Reynolds number.

The four path chordal flow LEFM✓ was calibrated to obtain a relationship between the profile factor PF, Flatness Ratio FR, and Reynolds number.

If the spool piece is mounted downstream of an elbow or any other flow disturbing configuration, the meter will not be able to predict the axial velocity variation in the entire cross section. A profile factor that is based solely on a flatness ratio which is derived for fully developed flow will not be adequate to correct the axial velocity in these cases. The meter takes four measurements of the axial velocities along the pipe diameter, but this is not enough to carry the integration. This is due to the continuous changes of the axial velocity and its asymmetrical velocity profile behavior. For these reasons, as expressed by the Caldon staff, experimental data are always used to deduce the profile factor, and sensitivities to changes in profile are characterized in the calibration process using flatness ratio.