

Caldon, Inc.

May 10, 2004

Mr. Stephen Dembeck
Chief, Section 2
Project Directorate IV
Division of Licensing Project Management
Office of Nuclear Reactor Regulation
United States Nuclear Regulatory Commission
Washington, D.C. 20555-0001

Subject: Caldor Comments on May 4, 2004 Draft Report entitled "Report of the Ultrasonic Flow Meter Allegation Task Group Review of Caldor Ultrasonic Flow Meters"

Dear Mr. Dembeck:

Per your request, Caldor has reviewed the subject report for to identify proprietary content and for technical accuracy and clarity. Please find attached Caldor's comments and suggestions contained in a marked up copy of the report. Caldor has decided that the contents of the report should be declared non-proprietary for the benefit of clarity for the industry.

Each of the comments and recommendations was discussed by conference call between Ernie Hauser of Caldor and Jared Wermiel, Cliff Douth, and Warren Lyon of the NRC on Monday, May 10, 2004. However, if there are further questions or explanations required surrounding the comments, please do not hesitate to contact me directly at 412-341-9920.

Caldor appreciates the effort put forth by the staff in their review and reflected in a high quality report.

Sincerely,

Ernest Hauser
President, Nuclear Division
Caldor

4601

May 10, 2004

Caldon's Comments on
NRC Draft Report of the Ultrasonic
Flow Meter Task Group, dated May 6, 2004

Line	Revision
99	Designation Column – “External LEFM (Several Design Generations)” Task Group Comments Column – change “one” to “two diametral and two diagonal velocities.” delete “velocity”
100	Task Group Comments Column – add “chordal”
101	Task Group Comments Column – add “chordal”
108 & 109	Comments column – delete “ – to be accomplished quarterly starting now.” add “(Quarterly reporting began in 2003)”
112	Comments column – add “Scale model parametric testing simulating plant configuration for External LEFM.”
114 & 115	Revise sentence to read as follows: “In general terms, these instruments effectively measure average flow velocities corresponding to the number and location of sonic sampling paths.”
118	Add following sentence after <i>calibration</i> : “The sensitivities to these deviations is also affected by the numbers and location of the sonic sampling paths.”
128 & 129	Designation Column - “External LEFM (Several Design Generations)” Sonic Paths Column – “2 diametral & 2 diagonal”
130	Sonic Paths Column – add “chordal”
131	Sonic Paths Column – add “chordal”
139	Revise sentence to read as follows: “Questions have arisen in plant installation that use AMAG and Caldon External UFM’s.”
140	Add “External” before <i>UFMs</i>
150	Add sentence after <i>obtained</i> “(Chordal UFM designs are capable of accurately operating to less than 10% of nominal flow.)
A	#3 footer: Delete “UFM output is noisy and”
B	#3 footer: Delete “The corresponding UFM response time is too slow to be used for plant control.”
378	Revise sentence to read “ Then one can compute an axial velocity profile.”
387	“.” after word <i>tees</i> should be “,”
393	Delete “and in UFM installation practice”
395	add “.”
403	delete “pipe vibration/system noise,”
469	Replace “clamp on” with “the External”
481 - 487	Suggested deleting this section 3.1.1
510	Move entire sentence to after line 516
511	Original line 511 change “chordal path” to “chordal paths”
515	add “rate” after <i>volumetric flow</i>
518	Replace “acoustic path” with “integrated”
540	add “External” before <i>Leading Edge Flow Meter</i>
576 & 577	Replace “is not supported by the Task Group or the vendor.” with “has not been reviewed or approved by the staff.”

May 10, 2004

Caldon's Comments on
NRC Draft Report of the Ultrasonic
Flow Meter Task Group, dated May 6, 2004

Line	Revision
776 & 777	Revise sentence to read "For Caldon UFM's, this time is typically several minutes based on the installation, fluid characteristics, and measurement uncertainty desired."
854	add "External" before <i>LEFM</i>
1029	Replace "strap-on" with "External"
1032	Replace "strap-on" with "external"
1057	Replace "clamp-on" with "External"
1079	add "External" before <i>LEFM</i>
1081	Replace "adapt" with "are less sensitive"
1081	Replace "LEFM clamp-on types.." with "External UFM's types."
1228 - 1230	Delete this entire Proprietary Note
1244	Entire equation must be multiplied by 1/2
1245	Change "chordals" to "chordal paths"
1246 & 1247	Change "W ₂ " to "W ₄ " Change "0.55555555" to "0.173927" Change "W ₃ " to "W ₂ " Change "W ₄ " to "W ₃ " Change "0.65214515" to "0.326073"
1301	add "A" before <i>Profile</i>
1305 & 1306	Revise sentence to read as follows: " 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."

May 6, 2004

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

SUBJECT: DRAFT REPORT OF THE ULTRASONIC FLOW METER TASK GROUP

Dear Mr. Hastings:

Enclosed for Caldon's review and comment is a copy of the staff's draft report of the Ultrasonic Flow Meter Task Group (hereafter referred to as the Report) which includes information related to the ultrasonic flow measurement (UFM) device manufactured by Caldon. During the evaluation, the Task Group met with members of Caldon and reviewed documents related to the development and performance of the Caldon UFM.

In completing the documentation of the evaluations, we have concluded that the enclosed Report does contain some proprietary information. We request that you review the Report for technical accuracy and for identification of proprietary information and provide the results of your review to the NRC within 10 working days of the date of this letter. With regard to your review of the Report for proprietary information, please identify such information line-by-line and define the basis pursuant to the criteria of Section 2.390 of Title 10 of the *Code of Federal Regulations* (10 CFR). The staff's disposition of your comments on the draft Report will be discussed in the final Report.

To facilitate the staff's review of your comments, please provide a marked-up copy of the draft Report showing proposed changes. Number the lines in the marked-up Report sequentially and provide a summary table of the proposed changes.

A similar Report, containing information related to the other UFM was sent to the UFM owner requesting that they do a similar review of their information.

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

Enclosure: Draft Report

DRAFT

PREDECISIONAL, CONTAINS PROPRIETARY INFORMATION

HIGHLIGHT IDENTIFIES POTENTIAL CALDON PROPRIETARY INFORMATION

**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. Doult

Warren C. Lyon

Abdelghani (Ghani) Zigh

**May 4, 2004
DRAFT**

SUMMARY AND RECOMMENDATIONS

Ultrasonic flow meters (UFM) are used to measure such items as feedwater flow, steam generator blowdown flow, and steam flow in light water nuclear reactor power plants. In principle, application of UFM's 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.

UFMs manufactured by Westinghouse / Advanced Measurement Analysis Group (W / AMAG) have been installed in US nuclear power plants to measure feedwater flow. Questions arose regarding this use of UFM's with the AMAG CrossFlow design and CrossFlow accuracy became an issue. Although 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, they do not represent a significant safety concern because of the large margins and conservatism 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. As a result, the Ultrasonic Flow Meter Allegation Task Group was formed to address 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?

In practice, licensed thermal power has been exceeded in UFM installations that did not involve license amendments in plants equipped with CrossFlow UFM's. Consequently, the Task Group concluded that a broader, more inclusive assessment was required to ensure objectivity and to fully address potential issues. Therefore, the Task Group has addressed the use of CrossFlow and Caldon UFM's in US nuclear power plant feedwater systems. This report addresses the Task Group's review of UFM's produced by Caldon. The Task Group W/AMAG Crossflow UFM evaluation is provided in a separate report.

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 of the UFM's,
2. Power recovery where UFM's 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 UFM's to increase licensed thermal power.

The following Caldon UFM's were considered by the Task Group:

	Designation	Typical Uncertainty, Percent	Task Group Comments
99	External LEFM (Several Designs Generations)	<~1.2	External strap-on. Reports <u>one-two diametral and two diagonal velocities</u> velocity. Design improvements with time.
100	LEFM [✓] ™	0.4 - 0.5	Spool piece. Reports four <u>chordal</u> velocities.
101	LEFM CheckPlus™	0.3 - ~0.37	Spool piece. Reports eight <u>chordal</u> 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.
108 109	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. <u>to be accomplished quarterly starting now. (Quarterly reporting began in 2003)</u>
	Problem type experienced during operation	Mostly hardware, operator, and software problems.
112	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. <u>Scale model parametric testing simulating plant configurations for External LEFM.</u>

114 In general terms, these instruments effectively measure average flow velocities at the number
 115 of locations 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
 118 plane perpendicular to direction of flow can affect the calibration. The sensitivities to these
deviations is 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 UFM's 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. UFM's 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 UFM's 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
128 <u>External</u> LEFM (Several Designs 129 <u>Generations</u> - Not used for power uprates)	4 <u>2</u> <u>diametral</u> & 2 <u>diagonal</u>	Poor	Poor
130 LEFM [✓] TM	4 <u>chordal</u>	Good	Good
131 LEFM CheckPlus TM	8 <u>chordal</u>	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.

139 ~~Accuracy questions-Questions~~ have arisen in plant installations that use AMAG and Caldon
140 ~~External~~ UFM^s and, ~~in some cases, there are questions regarding the basic design of the~~
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 it believes that additional events 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
148 full range of measurement and plant conditions, External UFM^s are unique in that they must be
150 installed and used within carefully defined bounds if the claimed uncertainties are to be obtained. (Chordal UFM designs are capable of accurately operating to less than 10% of nominal flow.) The problems include, but are not limited to, changes in plant configuration such as feedwater valve manipulations, changes in operating feedwater pumps or other flow disturbances that unacceptably impact licensed operation when UFM^s 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 UFM^s 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 LEFM^s 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.

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SUMMARY AND RECOMMENDATIONS

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B-1. Computational Fluid Dynamics (CFD) Investigation

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

ACRONYMS

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 (the 10 CFR 50 Appendix K update)
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
<u>W</u>	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 were found to result in exceeding the licensing basis analysis limits on thermal power level in some plants in mid-2003. In particular, the staff became aware of problems involving the W/AMAG Crossflow device in approximately 2001 and the staff's concern has increased as the implications became more serious. Staff involvement increased significantly in late 2002 and early 2003 with recognition of significant issues at the Byron station. Byron 1 was found to be operating at more than 2 percent over its licensed thermal power level in August, 2003. These and related concerns led to investigations by Exelon (a root cause and an evaluation of management) and by W/AMAG (starting in August, 2003). 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.

Although the Task Group's charter was to determine whether questions regarding the accuracy claims for the AMAG flow meter were valid and what, if any, action should be taken with regard to the use of the device the Task group also included Caldon LEFMs in its review for completeness. This report addresses the Task Group review of Caldon UFM's. 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:

$$Q_{\text{core}} = Q_{\text{SG}} - Q_{\text{P}} + Q_{\text{L}}$$

where:

Q_{SG}	Q_{core}	=	core thermal power
		=	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.

- $Q_{\text{P}} + Q_{\text{L}}$ 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.

Venturis¹ 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 appear to be based on the presumption that the UFM's 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 UFM's because no license amendment is involved.

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

¹Other 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 ² .
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.

²Early 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. UFM's 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.³ 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 UFM's 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 velocities at one or more locations and translates these measurements into a flow rate. It is able to precisely measure velocity, but translating measured velocity to a true average velocity or flow rate is a challenge. A straightforward method of translating UFM-measured velocities to 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 indicated by the UFM. The UFM would then be installed and used to determine flow rate by multiplying UFM-indicated 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.

A ³UFM output is "noisy" and a large number of data points are necessary to obtain an
B average value that has a small uncertainty. ~~The corresponding UFM response time is too slow to be 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.

378 A next step in translating laboratory results is to assume fully developed flow is realized in both
the laboratory and the application. Then one can compute an axial velocity profile. ~~velocities in a
plane perpendicular to the direction of flow; a velocity profile.~~ The velocity profile can then be
used to provide a correction factor to account for such changes as fluid property and Reynolds
number variations. However, for a specific plant installation, UFM tests performed at laboratory
facilities may not always reflect the actual plant piping configuration or equipment. In these
cases, the velocity profile becomes a potentially greater source of uncertainty due to variations
in velocity profile from the laboratory calibration.

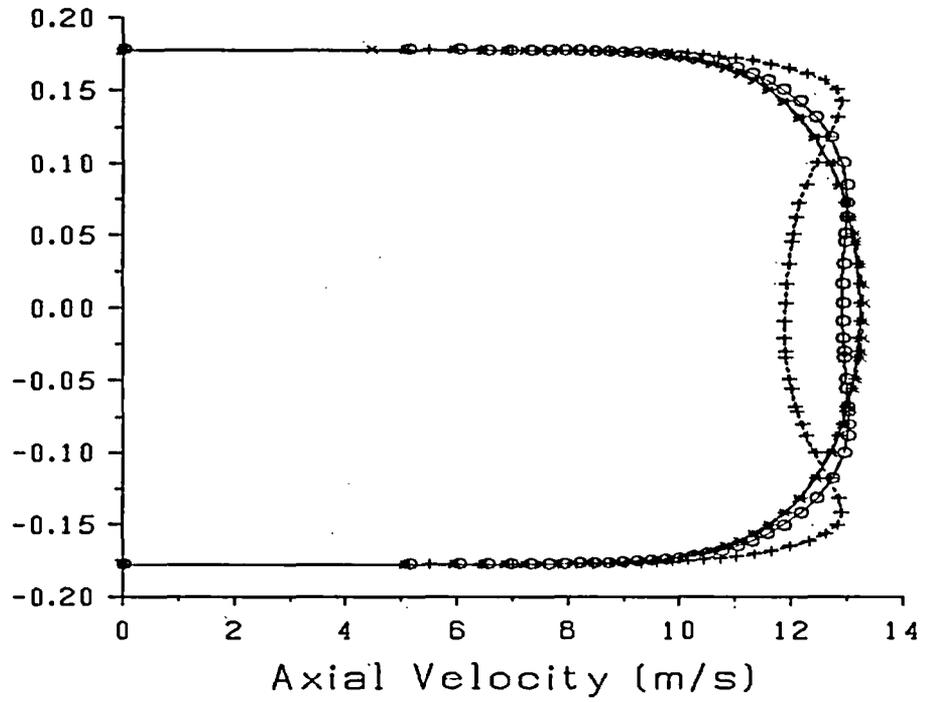
387 In practice, fully developed flow rarely exists due to such perturbing influences as an inadequate
length of straight pipe and the presence of elbows, tees, valves or other flow disturbances.
These introduce velocity changes that in some cases cause the velocity profile to be completely
asymmetric. 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
393 flow applications ~~and in UFM installation practice~~, and can affect the velocity profile. Since
velocity profile is directly related to flow rate, velocity profile considerations are extremely
395 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 individual velocities sampled within the velocity
profile by a UFM, 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 flow rate.
403 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
investigate 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 LEFM,
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, the profile distortion would be greater.

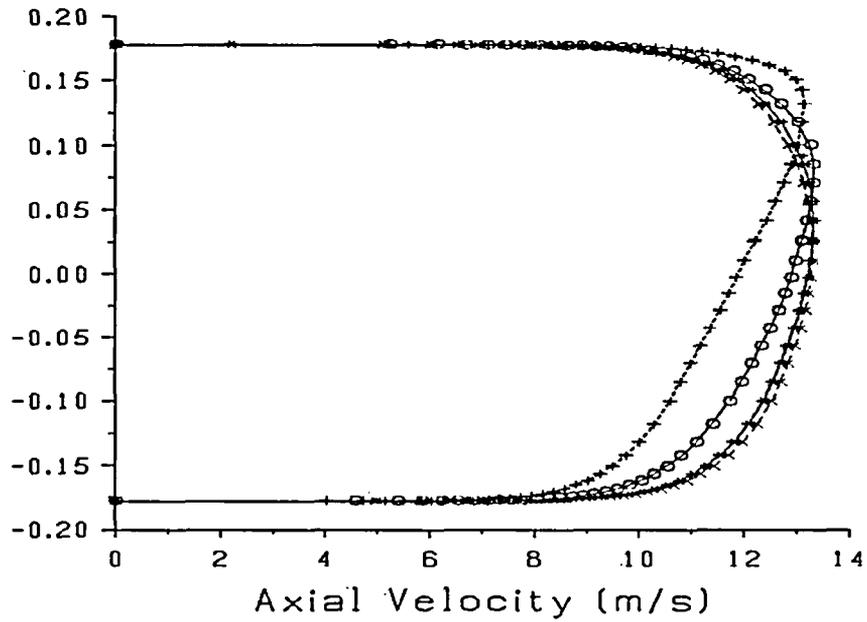
* line150x
 x line180x
 + line30x
 o line90x

Position (m)



* line150y
 x line180y
 + line30y
 o line90y

Position (m)



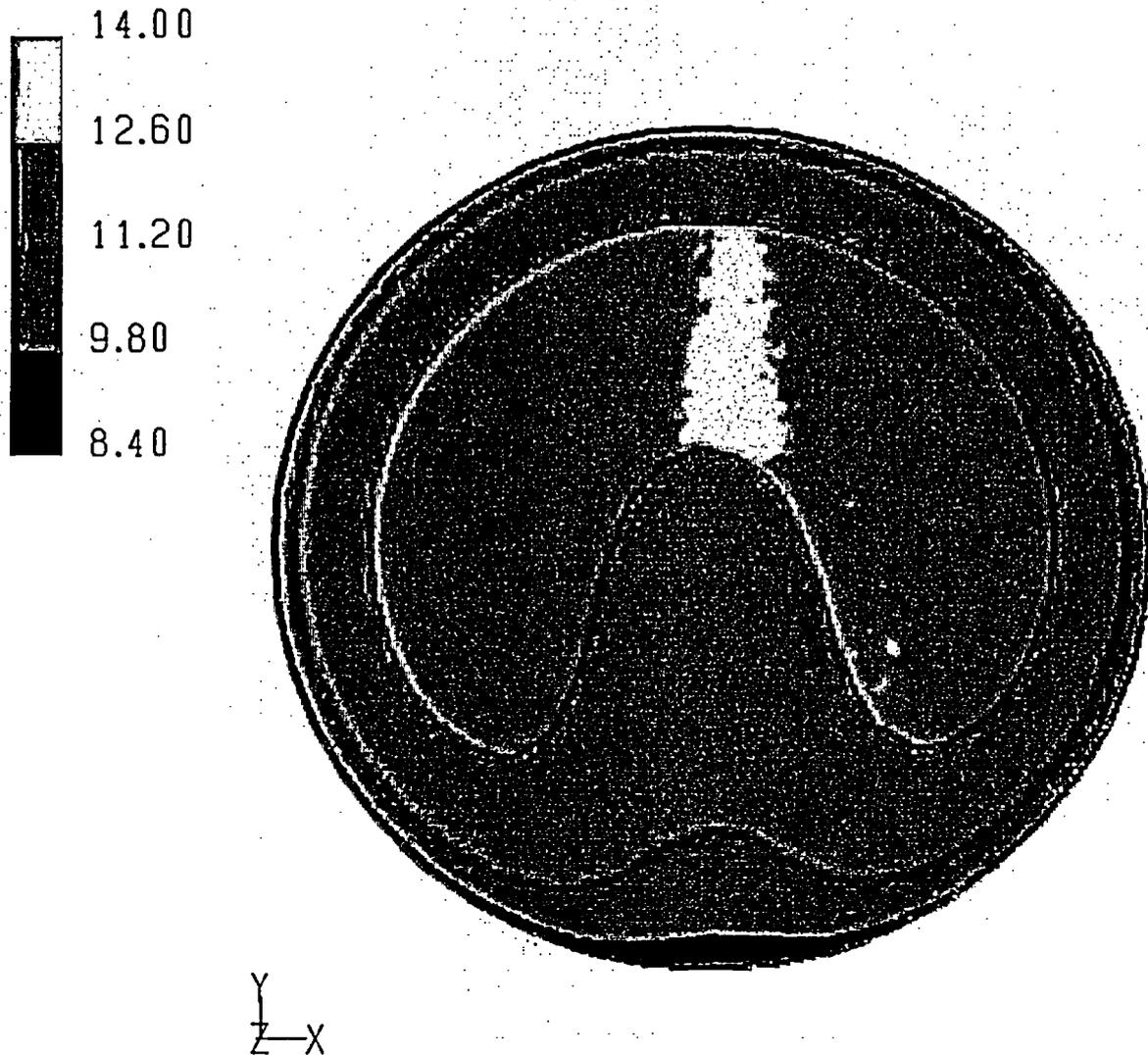


Figure 3. Illustration of Velocity Profile 60 Pie Diameters Downstream of Elbow

UFMs are often installed at less than 20 diameters downstream from flow perturbations such as elbows. Clearly, UFMs are installed where the flow profiles are not fully developed and the translation between the measured velocities and the flow rate requires correction for the 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 AMAG Crossflow UFM, was found to be operating at 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 AMAG Crossflow UFM, were also found to be operating above their licensed thermal power. These 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 AMAG to expand its evaluation of the expected accuracy and uncertainty as specified in the approved 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 LEFMs of an externally mounted design, 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 LEFM for power recovery
2. 21 chordal installations for power recovery
3. 38 (total purchased) LEFM✓ and CheckPlus for Appendix K updates.

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 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 ~~clamp-on~~ the External LEFM time-of-flight designs.

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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 UFM have been installed.

3 EVALUATION OF CALDON ULTRASONIC FLOW METERS

3.1 Theory and Operation

3.1.1 General principle of UFM operation

481 Ultrasonic flow meters use acoustic waves to detect flow through a pipe. Ultrasonic energy is
482 coupled to the fluid in the pipe through transducers that are either wetted or unwetted. Wetted
483 transducers are in contact with the fluid and non-wetted are not. Ultrasonic meters may be
484 considered as separated into two basic types, ultrasonic transmission and scattering, based on
485 how the ultrasonic signal reacts with the fluid being measured. Suggested Deleting this section.
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3.1.2 Transit time

Transit time UFM's 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 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. ~~The chordal placement is intended to provide an accurate numerical integration of the axial flow velocity along the chordal path.~~ 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.

518 To obtain the average flow velocity a meter factor is applied to the acoustic-path-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 UFM's 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

540 There are three types of Caldon systems currently in use in nuclear power plants in the United States. The first design, the External Leading Edge Flow Meter (LEFM), is an externally mounted 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 updates but has been installed in plants for power recovery purposes.

3.2.1 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 externally mounted 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 externally mounted 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

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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 is ~~not supported by the Task Group or the vendor.~~ 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 external UFM be installed permanently if the venturi is being normalized to the flow indication of the 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 UFM's, the profile correction factor becomes a critical influence on flow meter uncertainty.

3.3 System Uncertainties and Sensitivities

3.3.1 Overview

The system uncertainties and sensitivities for the LEFM, LEFM ✓, and LEFM CheckPlus are different for each meter type. These differences relate to the LEFM's external 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 UFM's.

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.

As stated in topical report ER-80P 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." Regulatory Guide (RG) 1.105, "Setpoints for Nuclear Safety Related Instrumentation used in Nuclear Power Plants," endorsed ISA 67.04.01, "Setpoints for Safety-Related Instrumentation." The endorsed standards 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 Profile correction factor

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 Error in time of flight Measurements

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

3.3.4 Spool piece Dimensional Errors

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 ISI program. The uncertainty allowance used is dependent on the spool inside diameter and is more significant with smaller pipe. It should be less than 0.10 percent.

3.3.5 Spool Piece Alignment

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 immeasurable 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 minimal.

3.3.6 Spool Piece Thermal Expansion

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 Time of Flight Measurement

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

1. Clock Accuracy - 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

3 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.

776 The Chordal LEFM, like UFM's in general, are sample rate based systems. Each acoustic pulse
777 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. UFM's 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 UFM's, this time is typically several minutes ~~can be anywhere from a couple of minutes
to hours~~-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 Caldor, 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. Caldor 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 LEFM's also measure temperature ultrasonically. These uncertainties will then also impact the measurement of density and enthalpy.

Based on the above, Caldor estimated a volumetric flow 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 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

854 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 model as well.

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

For the LEFM \checkmark , 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 \checkmark . In other words, a plant specific test is run at a calibration test facility using an LEFM \checkmark 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 \checkmark 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 \checkmark 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 \checkmark 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 \checkmark 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 \checkmark in the plant. The problem is that the Alden calibration facility cannot duplicate the fluid properties in a plant⁴. 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, Caldor stated that the Reynolds number

⁴Plant configurations also vary due to such variables as pump combinations, valve positions, and heater variations.

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 \checkmark 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 \checkmark 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 \checkmark . If the LEFM \checkmark is sensitive to these changes, a significant variance in the meter indicated flow rate will result with a corresponding calibration shift in the LEFM \checkmark . 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.

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 \checkmark 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, LEFM path data are available to provide assurance that the profile assumed in the calibration is what the LEFM is seeing in the field.

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 Caldor and described in Topical Reports and presentations made by Caldor are presented below as related to the stated uncertainties.

1. Profile Factor - Path velocities are measured and the "Flatness Ratio" is monitored. Values that exceed those expected during operation are alarmed.
2. Spool Piece Dimensions - The ratios of individual path length velocities are monitored and alarmed to provide information on changes in acoustic path dimensions.
3. Clock - Accuracy is monitored on-line and by periodic surveillance tests.
4. Transmitter/Receiver Reciprocity - 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. Signal to Coherent Noise Ratio - This value is confirmed during commissioning and is measured and alarmed through the total signal to noise ratio measurement.
6. Signal to Noise Ratio - This value is confirmed during commissioning and is measured and alarmed during operation.
7. Non-Fluid Delays - This value is confirmed during commissioning and is monitored and alarmed during chordal LEFM operation.
8. Pressure - 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. 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 UFM's appears to have resulted in few problems due to flow disturbances from such items as pump configurations and valve manipulations.

4 CONCLUSIONS AND FINDINGS

1029 The perceived accuracy of UFM's has been credited for a reduction in the uncertainty associated
1032 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. The UFM's used for this purpose are manufactured by
Caldon, Inc. and by W/AMAG. However, the Byron and Braidwood nuclear power plants have
been found to be operating in excess of their licensed thermal power when the AMAG UFM's
were used. This led to questions regarding the AMAG design and AMAG accuracy. Further
consideration of the Byron and Braidwood situation led to questions regarding use of AMAG
UFM's at other licensee facilities. Problems have occurred with Caldon UFM's 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 ~~strap-on~~
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 ~~strap-on~~ external models.

Tables describing the Caldon LEFM's 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 UFM's 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)
Owners group	Active and extensive
Historical record	Yes. Updated continuously. Informative web site is readily 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 clamp-on 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.

1057

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.

1079 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
1081 performance of the External LEFM in nuclear power plant feedwater applications. The Task
Group believes the LEFM✓ and the LEFM CheckPlus UFM types are inherently better able to
recognize and adapt are less sensitive to changes in the velocity profile than the ~~LEFM-clamp-on~~
~~types.~~ External UFM types.

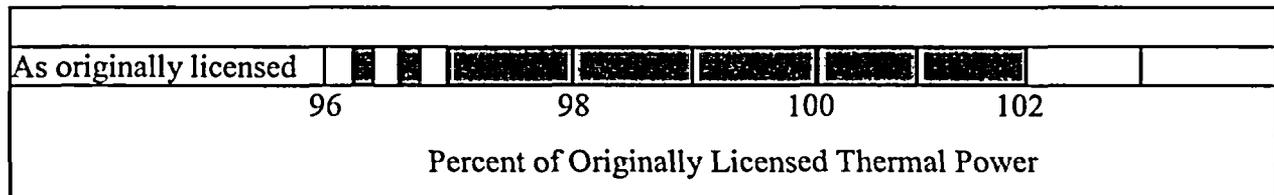
The Task Group's recommendations for further staff action were provided in the SUMMARY AND CONCLUSIONS section, above, and will not be repeated here.

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.

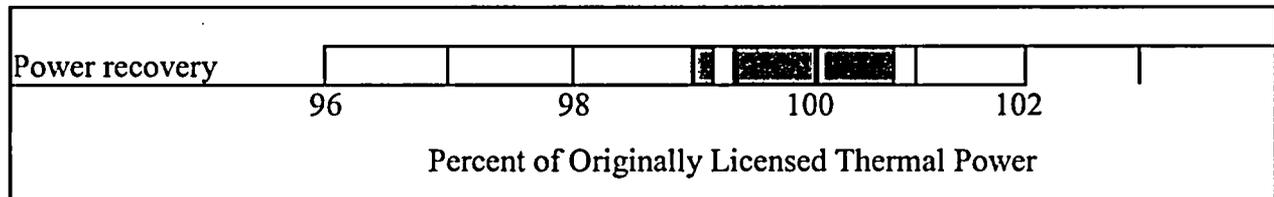


Some licensees have used temporary ultrasonic flow meter (UFM) installations to calibrate feedwater venturis in a "one-time" test, with the calibration assumed to remain valid for long-term operation.⁵ Reference 1 and interviews with licensee personnel indicated an average improvement of about one percent was expected. This is consistent with the experience at Dresden Unit 2, where total feedwater flow was reduced in 1996 by 1.26 percent.⁶ Such calibrations appear to be based on the presumption that the UFM's 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 UFM's. As discussed in Section 2.2, above, the Task Group finds this to be an unacceptable use of UFM's unless complete justification is accomplished.

⁵The UFM's are removed following venturi calibration.

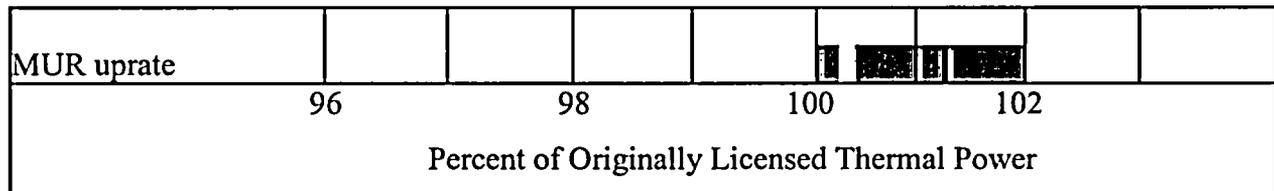
⁶This correction is still in effect. Since the plant is being operated below 98.7 percent thermal power, the licensee does not consider this to be a current concern. However, a combination of weather and condenser conditions could result in exceeding 98.7 percent thermal power in May, 2004. The licensee plans to complete an evaluation of the condition prior to exceeding 98.7 percent thermal power. (Reference 2)

Licensees often install UFM's to reduce or eliminate power production lost due to venturi fouling. These UFM's 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. The following sketch illustrates the effect of this use of UFM's for the case of an assumed overall 0.7 percent uncertainty achieved by the combination of UFM's 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).⁷

Licensees also increase licensed thermal power by crediting the perceived reduced uncertainty due to UFM's 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 UFM's at the Byron and Braidwood plants using the W AMAG, a Crossflow UFM design, 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:

⁷The 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. If the thermal power determined by the venturis and by the UFM's is identical during initial operation, then, neglecting uncertainty, there will be no change in initial thermal power.

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 FLUENT⁸ 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. Simulation results for the first configuration (i.e. straight pipe at Reynolds number of 28.25 million) and two simulation results for the second configuration corresponding to Reynolds number of 28.25 million and 1.4 million were obtained.

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

⁸ FLUENT is a commercially available state-of-the-art computer program for modeling fluid flow and heat transfer in complex geometries.

the velocity profile changes only radially and uniformly in the tangential direction.⁹ 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 the velocity profile changes only radially and uniformly in the tangential direction.¹⁰ 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 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

1228 ~~PROPRIETARY NOTE: THIS ENTIRE SECTION, INCLUDING EQUATIONS, IS~~
1229 ~~CONSIDERED TO BE PROPRIETARY UNTIL REVIEWED BY CALDON. (NOTE THE~~
1230 ~~HIGHLIGHT PROCESS HAS NOT IDENTIFIED THE EQUATIONS AS PROPRIETARY.)~~

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

The LEFM[✓] and LEFM CheckPlus UFM's 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 also referred to it 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 are 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 is used to obtain the above integral:

1244 The entire equation must be multiplied by $1/2$

1245 The four chordals 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
1246 the Gaussian weighing factors. For the four points integral, the four weighing factors are $W_1 =$
1247 $W_2, W_4 = 0.5555555555 \cdot 0.173927$ and $W_3, W_2 = W_4, W_3 = 0.65214515 \cdot 0.326073$, and the locations y_i
are $y_1 / R = -0.33998104, y_2 / R = +0.33998104, y_3 / R = -0.86113631, \text{ and } y_4 / R = +0.86113631$
where $R = D_i / 2$ and D_i is the pipe inside diameter. Note the integrations are performed on four
rectangular cross sections, $\Delta A = \Delta x \Delta y$, and the area correction is used to correct for the circular
cross section of the pipe.

⁹Numerous 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.

¹⁰Numerous 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.

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

which lead to the following:

where:

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:

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
T	=	total of the non-fluid delays of pulses traveling along path i
	=	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 LFM 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.

where the exponent n varies with Reynolds number.

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

1301 If the spool piece is mounted downstream of an elbow or any other flow disturbing
1302 configuration, the meter will not be able to predict the axial velocity variation in the entire cross
1303 section. A Pprofile factor that is based solely on a flatness ratio which is derived for fully
1304 developed flow will not be adequate to correct the axial velocity in these cases. The meter takes
1305 four measurements of the axial velocities along the pipe diameter, but this is not enough to carry
1306 the integration. This is due to the continuous changes of the axial velocity and its asymmetrical
velocity profile behavior. ~~In this situation, as expressed by the Caldon staff, experimental data
are used to deduce the profile factor.~~ 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.