July 1, 2004

Mr. James A. Gresham, Manager
Regulatory and Licensing Engineering
Westinghouse Electric Company
P.O. Box 355
Pittsburgh, PA 15230-0355

SUBJECT: NON-PROPRIETARY VERSION OF THE FINAL REPORT OF THE ULTRASONIC FLOW METER ALLEGATION TASK GROUP REGARDING THE WESTINGHOUSE/AMAG CROSSFLOW ULTRASONIC FLOW METER

Dear Mr. Gresham:

Enclosed is a copy of the non-proprietary final report of the Ultrasonic Flow Meter Allegation Task Group which documents its review of the Westinghouse/AMAG Crossflow ultrasonic flow meters (UFMs). The difference between the enclosed report and the one forwarded to you by Nuclear Regulatory Commission (NRC) letter dated June 22, 2004, is that information determined to be proprietary has been removed from the enclosed version.

The Task Group's charter was to identify real or potential problems with the use of the Westinghouse/AMAG Crossflow UFM with respect to measurement of feedwater flow rate. Consequently, the Task Group concentrated its assessment on identified problems, in particular how Crossflow UFM performance could result in plant overpower conditions such as what has occurred at the Byron and Braidwood sites. Information used in the review was obtained from Westinghouse/AMAG and other sources. The Task Group concluded that the Crossflow UFM may be capable of providing the claimed accuracy when operated by well trained operators in conjunction with a carefully controlled plant configuration. Because the review was intended to be conducted within a specific period of time, the report's conclusions are based on information that was available to the Task Group through mid-April 2004. The Task Group did not have information that would permit it to conclude that the problems identified were limited to Byron and Braidwood. Therefore, the Task Group could not conclude that such problems did not exist at other facilities.

We are aware that subsequent to the initiation of the Task Group effort, Westinghouse and Westinghouse Owners Group (WOG) undertook an effort to develop an action plan to evaluate operating experience, flow profile and signal contamination, installation criteria, and process root cause analysis related to Crossflow UFM performance. Although the action plan is not yet complete, the status and some preliminary technical information from the action plan has been provided to the NRC staff. Successful completion and implementation of the action plan should provide further information to support licensee installation and use of the Crossflow UFM. WOG, in its letter of June 8, 2004, informed the NRC that, while they concluded that the performance indications are plant-specific, the WOG formed a Crossflow Task Force to closely monitor the ongoing activities and work with Westinghouse and AMAG to implement any generic lessons learned from the plant-specific occurrences. In a letter dated June 18, 2004 (ML041740370), Westinghouse concluded that reasonable assurance exists that current

Crossflow installations are performing properly, safely and within the licensing basis, and described a number of lessons learned that can be applied to the use of Crossflow instruments. We encourage Westinghouse and the WOG to continue to keep the NRC appraised of the progress and results of these efforts to implement the lessons learned.

Although it appears that beneficial information will be forthcoming from Westinghouse's efforts regarding past Crossflow UFM performance issues and criteria that need to be applied to the use of the Crossflow UFM, the NRC needs assurance that licensees are meeting their licensed power levels. Therefore, the Task Group recommended that the NRC issue a generic communication to all licensees who rely upon the Crossflow UFMs for power level determination. The generic communication would require that information be provided to the NRC to demonstrate that the device is providing the intended accuracy, so that the plant operation will be consistent with the terms of the license. The NRC staff will discuss the recommended generic communication and the rational for it in a public meeting scheduled for July 1, 2004.

If you have 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: As stated

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REPORT OF THE ULTRASONIC FLOW METER ALLEGATION TASK GROUP REGARDING THE WESTINGHOUSE/AMAG CROSSFLOW ULTRASONIC FLOW METER

Allegation Task Group Leader:

Jared S. Wermiel

Allegation Task Group Members:

Clifford K. Doutt

Warren C. Lyon

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June 7, 2004

ENCLOSURE 1

SUMMARY AND RECOMMENDATIONS

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

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

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

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

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

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

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

This evaluation report addresses the W/AMAG evaluation. The Caldon UFM evaluation is provided separately.

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

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

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

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

The following W/AMAG UFMs were considered by the Task Group:

Designation	Typical Uncertainty, Percent	Task Group Comments
Crossflow	≤0.5	External strap-on. Reports one velocity that W/AMAG claims is averaged across a large portion of the cross-sectional area.
Crossflow X-Beam	≤0.5 [( )]	External strap-on. Reports [ ] velocities that W/AMAG claims are averaged across a large portion of the cross-sectional area.

The Task Group accomplished a broad, preliminary assessment of the Crossflow UFM but the Task Group's plant-specific review concentrated on the Byron and Braidwood plants where problems had been recognized. Operation at most of the other W/AMAG Crossflow installations was not investigated. The Task Group's conclusions from this evaluation are as follows[2]:

Item	W/AMAG
Owners group	Historically not a productive forum for addressing issues. No web site found. Improvements were initiated in early 2004. Shifted to W Owners Group in April, 2004.

[2]The Task Group review was completed in early April, 2004. The Task Group is aware that W/AMAG has accomplished additional work since completion of the review. That work is not addressed herein.

Item	W/AMAG
Operational knowledge and response to problems	Historically poor in the applications reviewed by the Task Group. The record of installations provided to the Task Group was inconsistent. AMAG has ability to directly connect to plant UFM to obtain data. Bi-weekly teleconferences with users initiated in February, 2004. W sent comprehensive survey to users on March 5, 2004. 10 responses received by March 26. Remainder requested by April 16, 2004.
Problem type experienced during operation	The most significant problems that were identified occurred at the Byron and Braidwood stations due to unrecognized plant-specific flow characteristics. Problems also were found at Fort Calhoun. A few hardware and operator problems were also identified.
Installation approach	Limited full scale testing. General reliance on generic scale testing of plant configurations unless W/AMAG determined plant-specific scale model testing was needed. Installation documentation and processes poor with respect to the plants reviewed by the Task Group.

Based on recent overpower events, W has initiated a high priority action plan to address operating experience, the velocity profile correction factor and signal contamination, installation criteria, a root cause investigation, and integrated assessment of data and information. Many of the subtasks are scheduled for near term completion, although completion dates for others have not been established. (A preliminary action plan dated March 25, 2004 was provided to the Task Group on March 26, 2004.) The plan should result in improvements in use of the W/AMAG UFM. The Task Group has observed improvement in problem analyses and followup, but believes it will be at least several months before a successful resolution is achieved.

The W/AMAG UFMs capture a unique turbulent eddy current pattern at the UFM's upstream and downstream transducer stations. This information is translated into volumetric flow rate by using test information obtained prior to installation in a plant. Any deviation in the velocity distribution as a function of position in a plane perpendicular to direction of flow between the test and the plant can potentially affect this translation. The Crossflow UFMs typically have built-in error checks to "look" for changes against the test standards that may invalidate the calibration. The Task Group's assessment of the effectiveness of these error checks and the historical ability of the Crossflow UFMs continuing to provide a correct flow rate is summarized in the following table:

Designation	Sonic Paths	UFM Response to Flow Profile Change That May Cause Flow Error*	
		Automatic Recognition	Continues to Provide Correct Flow Rate
Crossflow	1	Fair	Probably Not
Crossflow X-Beam	[ ]	Fair to Good	Not Evaluated
*These conclusions are based on information from installations evaluated by the Task Group where difficulties had been identified. The Crossflow X-beam design was not installed in the evaluated installations.			

The Crossflow UFM has been found to be sensitive to plant configurations. Consequently, some licensees do not use it for configurations that are recognized to differ from the configuration that existed when the UFM was installed and the Task Group understands that some licensees cross-check with a number of other plant parameters of greater uncertainty than the Crossflow UFM to help assess correct operation.

Plant-specific operating experience at Byron, Braidwood, and Fort Calhoun indicates that the Crossflow UFM has not provided the intended accuracy for feedwater flow measurement at these facilities. Further, accuracy questions have arisen in some other plant installations that use Crossflow UFMs 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 additional events may have occurred where the staff does not have information. The Task Group does not have specific information on licensee efforts to correct many of these past problems. Further, unlike many instruments that can be relied upon for the full range of measurement and plant conditions, UFMs are unique in that they must be installed and used within carefully defined bounds if the claimed uncertainties are to be obtained. The Task Group believes that staff action is needed to ensure that the UFMs are providing the necessary accuracy and that licensees are, therefore, in compliance with their licenses. The anticipated improvements resulting from the W action plan should provide increased confidence in future as well as in existing AMAG applications. However, the Task Group notes that W/AMAG can only recommend improvements for existing applications.

The Task Group believes that all licensees using UFMs must provide information to demonstrate that the devices are providing the claimed accuracy in order to ensure compliance with the licensed power level and AMAG users must address concerns that are specific to the AMAG UFM in order to provide the required assurance of compliance.

With regard to the above questions that the Task Group was formed to address, the Task Group concludes that the Crossflow UFM may be capable of providing the claimed accuracy when operated by well trained operators in conjunction with a carefully controlled plant configuration that is consistent with the laboratory calibrated configuration including velocity profile. The pre-installation analysis and testing to support Crossflow operation appears to have been weak and experience indicates that problems arise in the implementation of the device that must be addressed. The problems include, but are not limited to, changes in plant configuration such as feedwater valve manipulations, changes in operating feedwater pumps, changes in feedwater temperature, or other flow disturbances that unacceptably impact licensed operation when UFMs are used for power uprates as reviewed by the staff or for power recovery under 10 CFR 50.59.

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. Further, increased thermal power operation based on these practices should not continue unless acceptably justified to the staff.

The Task Group anticipates that W will provide the staff with action plan results that may lead to a supplement to the approved topical report for the AMAG instrument and a supplement to the staff's safety evaluation. However, the need for assurance that licensees are meeting their licensed power level should not wait for the results. Consequently, the Task Group recommends that the staff take the following action:

> Issue a generic communication (bulletin) to all licensees who rely upon information obtained from AMAG UFMs which requires that information be provided to demonstrate that the device is providing the intended accuracy consistent with the plant license. Specific questions on system/piping configuration, instrument implementation, calibration configurations (laboratory to field), and maintenance should be addressed. If the necessary information cannot be provided within a reasonable time, the licensees must describe the actions they will take until the required demonstration of compliance can be provided. For plants crediting the AMAG UFM in a power uprate, if the necessary information cannot be provided within a reasonable time, this will necessitate reliance on the feedwater flow venturis and operation at the pre-uprate licensed thermal power level. However, in such cases, the Task Group does not believe it is necessary to change technical specifications or plant instrument settings to be consistent with the reduced thermal power because there appears to be sufficient margin to alleviate a safety concern when the change is limited to a thermal power reduction.

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APPENDICES

ABBREVIATIONS

AMAG	Advanced Measurement and Analysis Group Inc. (Manufacturer of the Crossflow UFM)
C_f	venturi correction factor
CFD	computational fluid dynamics
CR	Condition Report
INPO	Institute of Nuclear Power Operations
LOCA	loss-of-coolant accident
M	feedwater flow rate
MAROG	Mid-Atlantic Regional Operating Group (Exelon)
MUR	measurement uncertainty recapture (the10 CFR 50 Appendix K uprate)
MWe	megawatts electric
MWth	megawatts thermal
NRC	Nuclear Regulatory Commission
NRR	NRC Office of Nuclear Reactor Regulation
NSAL	Nuclear Safety Advisory Letter
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
TB	Technical Bulletin
UFM	ultrasonic flow meter
W	Westinghouse Electric Company LLC (The vendor responsible for the AMAG UFM)

1 INTRODUCTION

There has been an increasing trend in the number of events that involve UFM applications for determining feedwater flow in recent years. The problems have affected safety analysis margins and, in mid-2003, were found to result in exceeding the licensing basis analysis limits on thermal power level in some plants. In particular, the staff became aware of problems involving the W/AMAG Crossflow UFM in approximately 2001 and the staff's concern has increased as the implications became more serious. Staff involvement increased in late 2002 and early 2003 with recognition of issues at the Byron station. The Task Group believes that Byron 1 was operating at more than 2 percent over its licensed thermal power level for several years prior to August, 2003. These and related concerns led to investigations by Exelon (a root cause and an evaluation of management), by W/AMAG, by the Omaha Public Power District, and by the Institute of Nuclear Power Operations (INPO, March, 2004). The W/AMAG involvement increased in 2003 and there was a large increase in resource commitment in February following the implementation of a tracer test at Byron 1 and identification of configuration sensitivity issues at Byron, Braidwood, and Fort Calhoun. An additional increase in resource commitment followed initial contact with the Task Group.

The Task Group reviewed relevant documentation including topical reports, safety evaluations, requests for additional information, inspection reports, licensee event reports, information notices, 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 W/AMAG staff and management.

The Task Group review investigated the capability of the Crossflow UFM to perform within its stated accuracy and uncertainty claims as specified in the approved topical report CENPD-397-P-A. The Task Group's charter was to determine whether questions regarding the accuracy claims for the Crossflow UFM were valid and what, if any, action should be taken with regard to the use of the device. The initial Task Group review indicated that recommendations generic to UFM feedwater flow measurement applications were necessary and, therefore, the Task Group expanded its investigation to provide a broader, more inclusive assessment of potential problems. The Task Group review consequently covered UFMs provided by W/AMAG and Caldon in one-time only, power recovery, and power uprate applications.

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

2 BACKGROUND

2.1 Thermal Power Measurement

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

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

where: Q_{core} = core thermal power
Q_{SG} = calorimetrically-determined steam generator (SG) thermal output

Q_P	=	reactor coolant pump (RCP) heat addition rate
Q_L	=	RCS net heat loss rate including contributions for letdown, makeup, RCP cooling, RCP seal injection, insulation and support heat losses, control rod drive heat loss, and the pressurizer.

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

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

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

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

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

2.2 One-Time Measurements

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

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

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

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

2.3 Power Recovery

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

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

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

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

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

where:

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

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

2.4 Appendix K Power Uprates

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

2.5 Velocity Profile and Relation to Flow Rate

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

A next step in translating laboratory results is to assume fully developed flow is realized in both

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

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

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

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

The Task Group performed preliminary analyses using Computational Fluid Dynamics (CFD) to provide insight into the effect of upstream perturbances on the velocity profile. Figure 1, from the analyses described in Appendix C, 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. If two offset elbows had been assumed instead of one, the profile distortion would be greater.

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

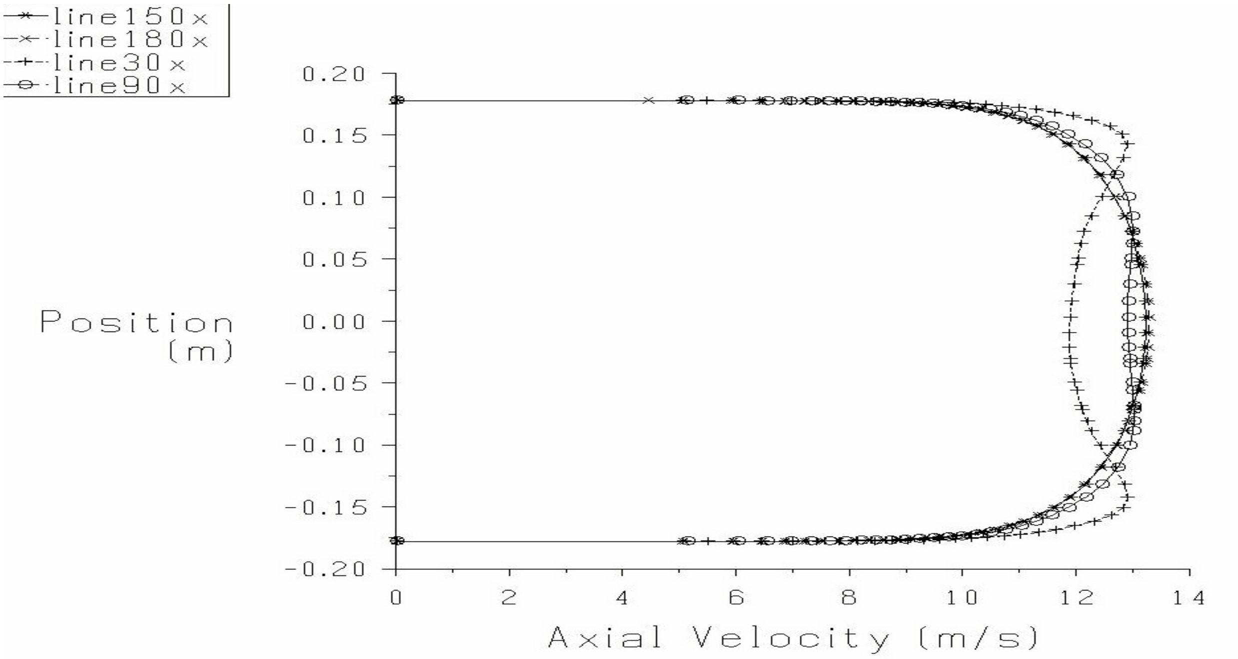

Figure 1. Velocity Profile from Above

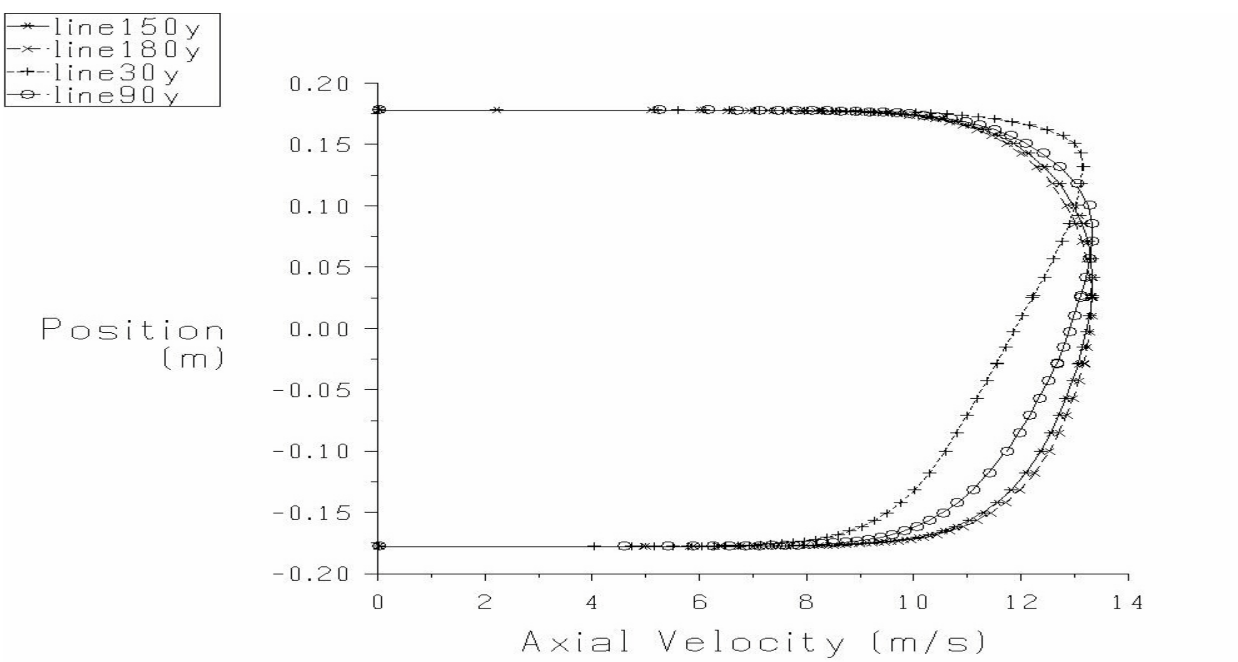

Figure 2. Velocity Profile from the Side

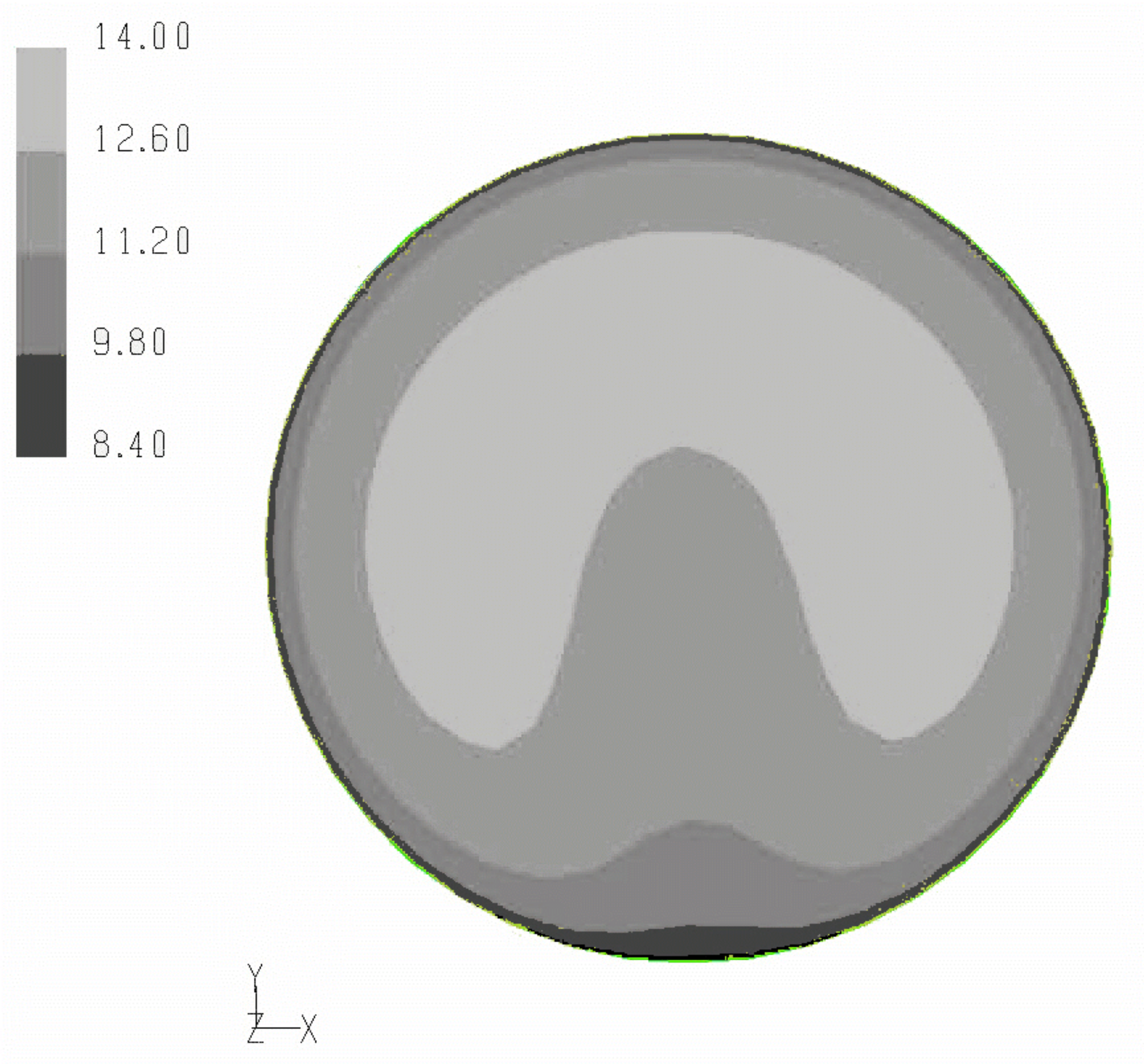

Figure 3. Illustration of Velocity Profile 60 Pipe Diameters Downstream of Elbow

UFMs are often installed at less than 20 diameters downstream from flow perturbations such as elbows. Clearly, UFMs are often installed where the flow profiles are not fully developed and the translation between the measured velocities and the flow rate requires correction for the profile. This correction is obtained via calibration testing in a laboratory using a representation of the plant configuration.

A few full scale tests of the Crossflow UFM have been performed, but most testing has been with three inch pipe diameter scale models in a test facility. There are no tests for some plant installations where similar configurations were tested in the laboratory. W/AMAG states this is an acceptable approach because the UFM is non-intrusive to the flow stream and an in-situ calibration is used when no plant-specific testing was accomplished. The Task Group does not understand how this approach addresses potentially unique changes to the flow profile, such as due to repositioning a valve or pumping into a header from a different pump, nor does it understand how in-situ testing will ensure an accurate as-installed initial volumetric flow rate that is consistent with the stated uncertainty budget.[7]

2.6 Industry Experience

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

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

In its limited consideration of the operational history, the Task Group found that W/AMAG does not have Crossflow information readily available through an Internet site or by other means. During the past several months, W/AMAG provided several lists of nuclear power plant installations, each of which differed from the previously supplied list. The Task Group estimates that Crossflow UFMs have been installed in about [ ] United States nuclear power plants. Post-installation behavior documents do not appear to exist. Limited information appears to support an operational requirement that Crossflow cannot be used under widely varying conditions. Rather, the data are only applicable to one or perhaps a few valve and pump conditions. And even here, as exhibited by the Byron, Braidwood, and Fort Calhoun experience, unknown impacts have resulted in erroneous data from Crossflow UFMs.

The limited Crossflow UFM operational information obtained by the Task Group was summarized above. The background of experience obtained by the Task Group, principally in

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[7] W/AMAG have stated that their UFM reports velocity averaged across a large portion of the cross-sectional area. If this is correct, then the UFM should be relatively insensitive to flow profile changes. The Task Group does not understand this W/AMAG claim since the UFM has been observed to provide incorrect flow rates in some applications and there is general recognition that the UFM may provide incorrect volumetric flow rates when the configuration differs from the one that existed when the UFM was installed. The Task Group also does not understand how the built-in diagnostics are assured to recognize flow profile or other changes that may cause erroneous UFM results or how operation within the bound of "out-of-limit" conditions provided by the diagnostics does not affect the claimed UFM uncertainty by introducing a bias.

Byron and Braidwood, is summarized in Appendix B. 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 Crossflow UFM operational history in most nuclear power plants where Crossflow UFMs have been installed.

3 EVALUATION OF THE W/AMAG Crossflow ULTRASONIC FLOW METER

3.1 Theory and Operation

A cross correlation flow meter of the type supplied by W/AMAG operates on the principle that flow induced eddies can be "tagged" by an ultrasonic signal and, based on the transit time of the eddies over a defined distance, the flow rate of the fluid can be determined. Unlike time-of-flight UFMs, a cross correlation UFM does not determine velocity by the influence of flow rate on the ultrasonic signal (fluid speed of sound and dimensional properties of the transducer path). The W/AMAG cross correlation UFM consists of two sets of transmit and receive transducers offset by a defined length. Both sets of transducers transmit ultrasonic signals diametrically and perpendicular to the pipe surface. [

] Once the time delay is determined, the velocity of the eddy is established by the distance between the transducers and the measured time delay. The volumetric flow rate is then the product of the average fluid velocity (as determined by average turbulent eddy velocity), pipe cross sectional area, and a velocity profile correction factor (meter factor). Mass flow is obtained by the product of the volumetric flow and density of the fluid. The form of the equation for the velocity profile correction factor is developed from hydraulic theory and through laboratory testing and is a critical influence on cross correlation flow meter uncertainty.

3.2 System Description[8]

The Crossflow UFM consists of four ultrasonic transducers (two transmitters and two receivers) mounted in a support frame which is externally attached to the pipe in which the flow is to be measured.[9] The ultrasonic transducers are connected to a signal conditioning unit and a data processing computer. There are two transducer designs in use: one with an aluminum box-type support frame and the other with a carbon steel saddle-type frame. The box-type frame is field

[8]Taken from the staff SER approving topical report CENPD-397-P.

[9]A more recent design, the Crossflow X-Beam, [ ] transducers. The [ ]

assembled and is no longer available. The saddle-type support frame is used for new installations. The frame provides accurate alignment of the transducers to each other and the pipe. The signal conditioning unit consists of the transmitter circuit, receiver circuit, digital bus, and the test signal modulator circuit. The output of the transmitter circuit drives the ultrasonic transducers and receivers. The receiver circuit demodulates and further processes the eddy information. The digital bus provides control to the signal conditioning unit. The test signal modulator circuit is used to test the signal conditioning unit reference delay time. The data processing computer performs digital signal processing on the demodulated ultrasonic signals and, in conjunction with the supplied application software, calculates the delay time for the fluid. The fluid time delay is then used in conjunction with the known transducer distance and velocity profile correction factors to provide the average flow velocity. Mass feedwater flow can then be calculated using the measured cross sectional area of the pipe and the measured density.

3.3 System Uncertainties and Sensitivities

3.3.1 Overview

The uncertainties for the AMAG Crossflow UFM were classified as follows by the Task Group:

- Hydraulic uncertainty - This includes calibration laboratory and velocity profile correction factors including those attributable to the plant specific installation.

- Geometric uncertainties - These include pipe dimension uncertainties including area and transducer mounting uncertainties, upstream to downstream transducer spacing, and applicable mounting frame uncertainty.

- Time measurement uncertainty - This addresses the accuracy of the time delay measurement.

- Sampling - The Crossflow system is sample based and requires up to many hours of data gathering to attain a stated uncertainty.

- Computational error - This is related to Crossflow signal processing.

According to the vendor, the error analysis for the Crossflow UFM is based on the methodology outlined by ISA S67.04.02, “Methodologies for the Determination of Setpoints for Nuclear Safety-Related Instrumentation - Recommended Practice,” and are stated to be consistent with Regulatory Guide (RG) 1.105, “Setpoints for Nuclear Safety Related Instrumentation used in Nuclear Power Plants.” RG 1.105 endorsed ISA 67.04.01, “Setpoints for Safety-Related Instrumentation.” The standard, the recommended practice, and the RG were 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 of the sum of the squares (SRSS) method to combine random uncertainties and the algebraic combination of non-random terms. This is consistent with the Task Group’s understanding for safety related setpoint development. W/AMAG stated that all uncertainty terms have been determined to be random and independent. The total error for the Crossflow UFM is represented by the percent error (uncertainty) of each variable and its associated sensitivity coefficient and these are combined per the guidance of ISA 67.04.01. Variation in results would be expected between

ISA 67.04 and ANSI ASME PTC 19.1, "Measurement Uncertainty," based on the assumptions and methodologies used to determine the uncertainty of a UFM measurement. However, either methodology was found to be acceptable by the staff for power uprates using UFMs subject to the conditions stated in the staff topical report SERs

The following subsections of Section 3.3 address the uncertainty associated with selected contributors to AMAG uncertainty.

3.3.2 Inside pipe diameter

Since the Crossflow UFM measures fluid velocity to determine volumetric flow, the area of the flow element must be determined and found to remain constant (no corrosion or material deposition occurs). The Crossflow instrument uses the feedwater pipe as the flow element. As a result, feedwater pipe dimensions and in particular the inside diameter of the feedwater pipe must be determined. The diameter measurement is needed to determine the pipe area and, in conjunction with average fluid velocity, allows for determination of volumetric flow rate. Measurements are made of the pipe diameter at locations corresponding to the upstream transducer, a middle location relative to the transducers, and the downstream transducer. To make the measurement, feedwater pipe wall thickness is measured with ultrasonic thickness gauges calibrated near the feedwater pipe operating temperature using a calibration block adjusted for pipe surface temperature. This minimizes uncertainty required for operating temperature correction. Uncertainties related to different temperature/pressure conditions during measurement as compared to operating conditions are applied as required. The Task Group notes that there appears to be no uncertainty allowance for dimensional changes in service (erosion or corrosion) although this allowance may have a small impact on flow uncertainty. In addition, manufacturing tolerances do not appear to be considered with the field measurements. The field measurement of pipe diameter depends on accurate pipe measurements and, unlike the laboratory calibration for profile correction factor, these dimensions are not calibrated out for plant operation. The Task Group notes that Topical Report CENPD-397-P-A Section 8.1.1.2 states that deposition does not usually change flow area to a measurable degree and that pipe wall thickness is not routinely monitored or trended. The topical report contains a recommendation that licensees evaluate this potential on a plant specific basis.

3.3.3 Transducer spacing

Transducer spacing is critical to the velocity measurement in that it defines the path length for the eddies and, with the measured time delay, enables the velocity of the eddy to be determined. W/AMAG has stated that the as-built transducer spacing is measured prior to shipment to the field for installation. Topical report CENPD-387-P-A Section 8.3.1 states that, once the transducer is installed, transducer spacing is measured by taking multiple measurements (five transmitter and five receiver) of transducer station to station spacing. Corrections are then made for transducer spacing thermal growth at feedwater temperature. Changes in spacing are monitored and compensated for during Crossflow operation as a function of feedwater temperature. The measurement of the transducer spacing includes uncertainty with respect to the support bracket tolerances, measurement equipment, and transducer tolerances. In addition, transducer alignment and installation uncertainties are included here.

3.3.4 Velocity profile correction factor

When installed in a plant, the velocity profile correction factor that must be applied to correct for changes from a fully developed velocity profile is a function of several factors. These include corrections for upstream disturbances that differ from the test conditions and corrections for differences in Reynolds number between laboratory data and plant operating conditions[10]. In considering the uncertainties associated with these corrections, the Task Group formulated the following observations:

- The tests are conducted with a smooth pipe which the vendor considered applicable with respect to feedwater pipe installations and conservative when defining the profile correction factor. Although conservative, no random or systematic uncertainty is taken for the variations in pipe roughness that may be experienced in the field.

- Many of the early tests were run at facilities with relatively large flow uncertainties. To address this, W/AMAG ran additional tests at Alden Labs to confirm previous observations and to establish an uncertainty estimate for the profile correction factor. Profile correction factors were developed for both straight pipe and an elbow (including various distances from the elbow). W/AMAG concluded that the calibration facility uncertainty of 0.25 percent was adequate to bound the velocity profile correction factor for these configurations. Additional tests were referenced by W/AMAG including laboratory tests and in plant testing at higher Reynolds numbers. These data compared favorably with the calibration velocity profile correction curve developed at Alden Labs. The Task Group notes that these data (or the associated uncertainty) are not used in the development of the velocity profile calibration curve and, therefore, the 0.25% uncertainty of the velocity profile correction factor may not be representative at all Reynolds numbers.

- For thermal power measurements, it is customary to include installation effects based on the plant specific installation. It isn't clear that all flow profile correction factor uncertainties are calibrated out by laboratory testing. For piping configurations that are based on straight pipe or an elbow, the profile correction factor uncertainty is based on the calibration facility stated uncertainty. This correction factor (C_o) is based on Reynolds number input and calibration laboratory testing. Additional correction factors C_p and ΔC are used for pipe configuration and distances from flow disturbances as required. In addition, as presented in Appendix C, there may be uncertainty due to random changes in velocity profile or due to feedwater piping configuration or operation. It appears that additional uncertainty for these effects is not included in the uncertainty estimate for the profile correction factor and may be understated depending on plant installation and piping configuration. The Task Group does note that Alden test results provided by W/AMAG show that Crossflow sensitivity to flow disturbances downstream of an elbow is minimal if the meter is located 15 or more diameters downstream of a short radius elbow. Additional calibration laboratory testing of alternate piping

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[10] W/AMAG provided the Task Group with test data that indicated the UFM was accurate at Reynolds numbers greater than $26X10^6$. However, the Task Group does not have uncertainty information applicable to the tests and it notes that the test flow rate was apparently determined by venturi.

configurations with related sensitivities to upstream disturbances were not provided to the Task Group.

- Installations of the Crossflow UFM sometimes employ in-situ calibration techniques that can use various combinations of Crossflow UFMs as the calibration standard for the permanently installed Crossflow unit(s). Uncertainty in the velocity profile and installation uncertainties at the selected calibration standard pipe location that are different from that encountered during laboratory testing may also affect the calibration of the permanently installed Crossflow UFM. Westinghouse testing and experimental data provides guidance in the installation of the Crossflow UFM but recent plant experience and the fact that not all pipe installations are tested or tested under the same laboratory uncertainty suggests there is a possibility that profile correction factor and installation uncertainties are understated. Full or scale model testing of a plant installation may provide further insight and result in improved profile factor uncertainty. The sensitivity of the Crossflow meter to profile disturbances or modeling parameters (plant installation matches known laboratory test conditions exactly) are not included in the profile correction factor function developed for Crossflow UFMs.

- The laboratory test runs presented to the staff were limited in number (as were the pipe diameters tested) for the Alden tests, which may have an impact on the noted uncertainty for a sample rate based UFM such as Crossflow. In addition, noise contamination during testing corrupted some of the tests requiring data points to be removed. However, the Task Group notes that the uncorrupted test results at Alden compared favorably with the calculated values using the Crossflow UFM developed correlations.

Based on the above, it is possible the uncertainty allowance for the baseline profile correction factor can be underestimated in a plant specific installation.

3.3.5 Feedwater density

Feedwater density is used in the determination of feedwater mass flow rate. The Crossflow UFM, based on the data available to the Task Group, does not provide a feedwater temperature measurement. Therefore, feedwater temperature measurement was not evaluated by the Task Group with respect to performance of the Crossflow UFM directly. However, temperature does affect the transducer spacing/orientation/coupling, piping measurements, and the velocity profile correction factor as discussed above. Temperature uncertainty with respect to feedwater mass flow rate is included in the feedwater mass flow rate uncertainty budget. The feedwater mass flow rate uncertainty does not consider the feedwater temperature sensitivity of each component of feedwater flow, but was evaluated for individual uncertainties for each parameter with regard to temperature and SRSS applied.

3.3.6 Time delay uncertainty

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] The collection of time delay data points is controlled by the sample size and the average of the cross correlation data. Once the data requirements are reached, the average time delay is calculated. The average time delay is then used with the known transducer spacing to calculate a flow velocity. The calculation of the time delay includes acceptance criteria for both the cross correlation data and the resulting cross correlation curves.

The uncertainty in the cross correlation data resides in the fact that a Crossflow UFM requires a large number of demodulated signal samples to perform this calculation at a stated uncertainty. Adequate uncertainty is obtained by defining the required standard deviation, number of data points, sample period (stable operation), and the average time delay. These values are obtained through installation and testing.

The uncertainty for the time delay also includes uncertainties related to Crossflow UFM related environmental factors and acceptance test specification criteria, including time delay calibration tolerances. The sensitivity of the time delay measurement is also checked by assigning different data point samples to the time delay calculation. There does not appear to be an assigned uncertainty that accounts for any data filtration or algorithm errors. W/AMAG stated that the impact on instrument uncertainty has been evaluated through plant and laboratory comparison tests but this information was not reviewed by the Task Group.

3.4 Laboratory Calibration

Calibration of the Crossflow UFM is basically the same as any other UFM - one determines a profile correction factor at a calibration facility. However, because of the clamp-on nature of the Crossflow UFM, as indicated above, there is a dependence on field derived measurements for dimensional data and instrumentation.

The laboratory calibration of the Crossflow UFM was intended to confirm the profile factor correction factor correlation and provide information on the impact of flow disturbance on the profile correction factor (elbow). In addition, the test provides an uncertainty for the profile correction factor. The calibrations performed were to quantify the uncertainty in the profile correction factor and such tests were not done on a specific plant configuration. Tests were done to quantify the effects on profile factors downstream of an elbow and to validate guidance criteria and establish a flow profile correction factor for instrument locations downstream of flow profile disturbances (elbow). Full scale or model scale tests are not generally run for plant specific applications.

Part of the problem with UFM flowmeter calibration for feedwater service is that the calibration cannot usually be run at the Reynolds numbers that the UFM will encounter in service. When the Reynolds number cannot be met in testing, it becomes necessary to develop a methodology to project the profile correction factor developed in the laboratory to the expected Reynolds numbers for plant feedwater service. For the Crossflow UFM system, the profile correction factor is derived from a theoretical equation that provides a basis for calculating the profile correction factor based on Reynolds number. The calibration test results were incorporated into the equation to develop the profile correction factor for straight pipe. W/AMAG then assigned a profile factor uncertainty of 0.25% (the calibration lab uncertainty is considered bounding based on calibration results). W/AMAG also provided additional data to compare to the velocity profile correction curve developed from the calibration facility data and the theoretical equation. Calibration laboratory data was also used to develop guidance on the location of the Crossflow UFM for installations downstream of an elbow applicable to the straight pipe velocity correction factor.

To utilize the velocity profile correction factor in a plant installation, the topical reports reference guidelines for the location of the Crossflow UFM. For locations that do not conform to the laboratory test conditions, W/AMAG uses one of two methods to locate the Crossflow. First, CFD may be used and, based on these results, a preliminary meter location selected. If the CFD shows that the velocity profile correction factor for the Crossflow UFM would be adversely affected, a scale model of the piping installation would be built to calibrate the Crossflow UFM. As an alternative, W/AMAG may also perform what they call an in-situ calibration. In situations where a satisfactory flow profile location cannot determined at the desired permanent meter location, an additional number of Crossflow UFMs may be installed temporarily as a transfer standard(s). The transfer standard(s) is (are) located so that, according to W/AMAG guidelines, it (they) will provide flow conditions that are compatible with the laboratory calibration configuration. Using the transfer standard(s), the profile correction factor is developed for the plant specific installation. The resulting in-situ profile correction factor is applied to the permanently installed meter with the intention of calibrating out the velocity profile error. This methodology requires that the location of the Crossflow UFM(s) used as the transfer standard is (are) such that the laboratory calibration criteria/assumptions with respect to velocity profile correction factor remain valid for the selected plant specific transfer standard location(s). Recent plant experience suggests that flow measurement errors may have occurred using this methodology and may have resulted in errors in the Crossflow baseline calibration.

In addition, the calibration of a field installed Crossflow UFM also depends on the calculations and the resulting pipe dimension, mounting bracket installation, and transducer installation uncertainties which are not calibrated out in a field installation. The criteria for the number of data points, average time delay, and the time delay standard deviation must also be determined through commissioning tests.

Based on the above, the Task Group is concerned that the velocity profile correction factor and flow profile installation guidelines may not accurately transfer to a field installation and the velocity profile correction factor may vary from that obtained through laboratory calibration. There is concern that the calibration laboratory uncertainty may not bound the velocity profile correction factor once installed in the field. Appendix C CFD data, recent plant events, and the additional data provided by W/AMAG to validate the profile correction factor contribute to this concern.

The Appendix C CFD data show variability in the velocity profiles such that there is some question in the bounding nature of the Crossflow UFM velocity profile correction. Second, based on plant experience, there is concern that even when the Crossflow UFM is located consistent with testing and procedural guidelines, the uncertainty budget of the Crossflow UFM installation may be compromised due to the potential for flow profile changes not recognized by the installation, maintenance, procedures, or the sensitivity of Crossflow to upstream flow disturbances not previously considered or recognizable by the Crossflow UFM.

There is also concern that, although the calibration test data are incorporated into the profile correction factor, additional data points (with varying uncertainty - but some data reflective of calibration labs) are used only to make comparisons to the developed velocity profile correction factor with the intent of justifying its uncertainty. It is possible that the data represent variability in the velocity profile correction factor on Crossflow performance, but it is not recognized by the present equation. Crossflow system vulnerabilities, such as noise contamination that may not be recognized during commissioning or operation based on assumed plant configuration or operation, are additional concerns. The Task Group is concerned that the stated uncertainty budget for the Crossflow UFM may not be attained in the field.

3.5 Installation, Implementation, and Operation

A review of Crossflow UFM documentation shows a reasonably comprehensive set of procedures for the installation, setup, and operation of a Crossflow UFM. The scope of the procedures covers functional, design, operational, surveillance, test, and final commissioning requirements. Procedures reviewed by the Task Group included the system users manual, calibration procedures, plant specific calculations (including commissioning data), configuration requirements, and uncertainty assessment.

Customer training is offered by the vendor. W supports a Crossflow UFM Users Group but, based on the Task Group's review and information obtained from W, the Crossflow UFM Users Group has not historically been used extensively for feedback of design or operational experience. The Task Group did note that efforts are being made by W/AMAG to improve data collection in these areas.

Once installed, the Crossflow UFM requires that certain assumptions and configuration settings be input and control of these settings be established by the plant to meet the stated uncertainty for the Crossflow UFM during system operation. Configuration and system setup data are supposed to be maintained and implemented per provided procedure.

The Crossflow UFM incorporates various on-line diagnostic and verification methods that are used during system commissioning and normal plant operation. The diagnostic capabilities of a Crossflow UFM, as stated by W/AMAG and described in topical reports and presentations made by W/AMAG, are presented below as related to stated uncertainties:

- Data point rejections are noted on the operator screen. Should the number of rejected data points become higher than normal it is recommended that an operator not rely on the Crossflow and the operator should reference maintenance procedures to trouble shoot the problem. Data are rejected based on three criteria related to the cross correlation of the data.

- A time delay test is performed to ensure operation of the signal conditioning units. This test confirms that the test time delay and measured time delay are within acceptable design tolerances. In addition, an internal manually initiated time delay test is available during normal operation and is performed through scheduled surveillance.

- Initial system tests are performed to determine the frequency range of the measurement and additional tests are performed to find those frequencies that improve ultrasonic transmission through the water and minimize pipe wall transmission, path reflections, and crosstalk.

- Tests are run to confirm the presence of correlated noise in the cross correlation and the need for filtering, if any.

- Although not part of the Crossflow UFM plant instrumentation, uncertainties that input to the Crossflow are controlled through established plant calibration frequencies.

- Additional diagnostics are available to identify changes in the venturi calibration factor (either by rate or preset limits).

W stated that velocity profile changes are detectable by the Crossflow UFM and would be manifested by an increase or decrease in flow velocity and an increase in the standard deviation (due to swirl). The Crossflow UFM effectiveness in identifying changes in flow profile due to other flow disturbances was not discussed specifically in available documentation. Information provided by W also states that a failure or degraded transducer signal would be identified either by a reduction in data (rejected data points), a possible increase in the time delay standard deviation, or a failure of the Crossflow UFM itself. Plant operating experience reviewed by the Task Group does not provide a clear picture of whether the Crossflow UFM can consistently detect profile changes during plant operation within the uncertainty assumed in the topical reports.[11] The task group notes that the parameters monitored by the Crossflow are key contributors to the Crossflow UFM uncertainty budget. A concern of the Task Group is that the diagnostic capability of the Crossflow UFM may be adequate to detect variances from an initial baseline calibration assumption, but based on installation practices and results available to the Task Group, may not provide reliable feedback that the intended calibration uncertainty transfer from laboratory to field installation has been met.

Overall, operational experience is mixed. Some licensees appear satisfied with Crossflow performance, but only use it under certain configurational conditions. Others have had poor experience and, in the case of Byron, Braidwood, and Fort Calhoun, unexplained behavior has led to difficulties. In general, the Task Group has seen only limited data, and additional information is necessary to formulate a complete picture.

4 CONCLUSIONS AND FINDINGS

The perceived accuracy of UFMs has been credited for a reduction in the uncertainty associated with determining thermal power level. This, in turn, has allowed licensees to operate

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[11] As previously identified, the Task Group conclusions are based on a small sample of operational experience where problems had occurred. W/AMAG claims that the Crossflow UFM will detect out-of-allowable performance, but the Task Group did not study the data to substantiate this claim.

at increased thermal power while believing that there was reasonable assurance that licensed thermal power would not be exceeded. Currently, the UFMs used for this purpose are manufactured by W/AMAG and Caldon. However, the Byron and Braidwood nuclear power plants were found to be operating in excess of their licensed thermal power when the Crossflow UFMs were used. This led to questions regarding the Crossflow UFM technology at other facilities.

The impact of various piping arrangements on the correction factor for the Crossflow UFM was developed using experimental data obtained on limited pipe configurations. The resultant installation guidance does not compensate for the inherent sensitivities of the device to all installations and operating modes. It is not clear if in-situ testing of the Crossflow UFM accounts for all plant effects including insitu testing uncertainties. In-situ testing is done in place of system modeling (including scale model testing at a calibration facility or CFD analyses) for most installations. The associated uncertainty may not represent an accurate baseline uncertainty or the resulting uncertainty seen in some plant installations. W/AMAG has recognized that current issues with some plant-specific configurations have occurred and is investigating these problems as described in Nuclear Safety Advisory Letter NSAL-03-12 and Technical Bulletin TB-04-4.

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

The following table provides a summary of characteristics of the Crossflow UFMs that are commonly used in power recovery and power uprate applications:

Item	AMAG Crossflow
Number of velocity locations sampled	[ ] recently became available in the Crossflow X-beam UFM.
Timing	Milliseconds.
Method	Tag-type meter using timed flow for an eddy over a known length.
Diagnostics	The Task Group did not develop sufficient understanding of built-in diagnostics to provide a summary assessment. However, it does have reservations regarding sufficiency. It further notes that the vendor recommends comparison to other plant parameters such as venturi, secondary side characteristics, and RCS characteristics, and the vendor apparently does not recommend Crossflow operation when the plant configuration is not identical to the commissioned configuration.

Item	AMAG Crossflow
Experimental testing	Testing includes [ ] test series with some tests rejected when evaluated later, selected scaled tests (3 inch diameter) at [ ] with a calibrated venturi to obtain flow rate, and several full scale [ ]. Generally, site model tests are not conducted if past experience is believed to apply.
Users group	Historically not an effective forum for addressing issues. User interchange is being improved to increase participation and understanding of operating experience.
Historical record	Partial users involvement. W/AMAG taking action to improve.
Reasonable assurance UFM is operating as expected	No. Some installations have resulted in extended overpower operation and the reasons are not yet understood. The Task Group believes that Crossflow use must be restricted to certain plant configurations and/or operating conditions, but the Task Group has not seen reasonable assurance this will be accomplished.
Effectiveness in addressing flow profile changes	[ ] The Task Group believes this has limited effectiveness and it has almost no value for flow profile changes in other planes.
Effect of built-in error detection	The Task Group has reservations with respect to built-in error evaluation, but has not been able to evaluate these.
Control room information	Plant computer. Alarms may be on a monitor in some plants.
Adequate operator response to diagnostic indications	Inadequate response identified in some plants.
Sensitivity to plant configuration changes	Yes - apparently in most or all plants.
Temperature	Sensitive to non-uniform distribution (density calculation).
Configuration	Strap-on
Vendor Involvement	Limited - non-existent for extended times in some cases. W/AMAG is improving. This is also a function of the licensee.
Historical improvement to address problems	Poor - feedback processes have been inadequate to non-existent. W/AMAG is improving. Design improvements concerning transducer design and mounting were noted.
Uncertainty	$\leq$0.5. Crossflow X-Beam is [ ] The Task Group does not believe the claimed values are adequately substantiated for plant installations.

Item	AMAG Crossflow
Meter orientation impacts uncertainty	Yes. Meter results may vary due to flow disturbance. Required orientation if laboratory calibration used (elbow)

The Task Group believes the Crossflow UFM can be overly sensitive to plant configuration changes and subject to error when these occur in conjunction with the existing calibration, installation, and operational guidance. The Crossflow X-Beam should be an improvement with regard to limiting some uncertainties and may be better able to recognize and accommodate changes in the velocity profile.

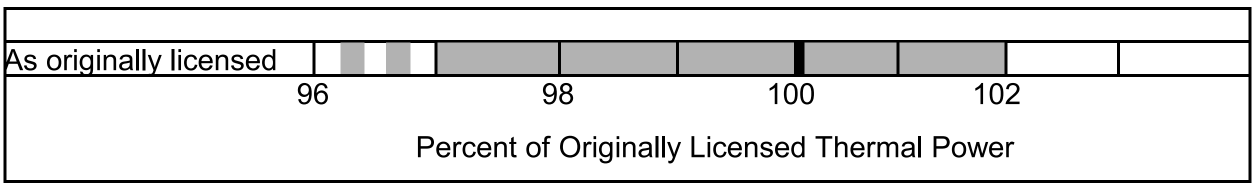
The Task Group's recommendations for further staff action were provided in the SUMMARY AND RECOMMENDATIONS section, above, and will not be repeated here.

APPENDIX A

THE EFFECT OF UFM 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.[12] 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.[13] Such calibrations are based on the presumption that the UFMs provide a more accurate feedwater flow measurement than the venturis and that the venturi characteristics will not change to indicate a lower flow rate. Such changes could occur due to venturi defouling. The staff does not traditionally evaluate this use of UFMs. As discussed in Section 2.2, above, the Task Group finds this to be an unacceptable use of UFMs unless complete justification is accomplished.

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

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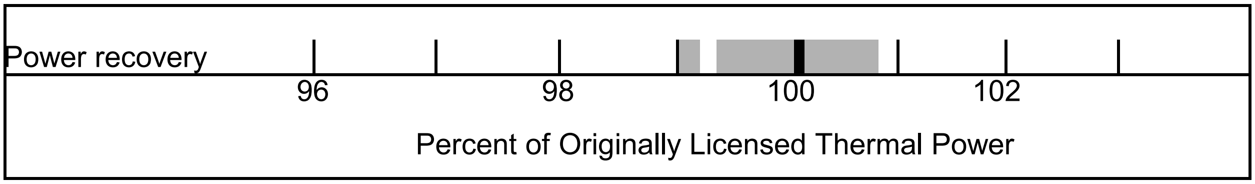
[12]The UFMs are removed following venturi calibration.

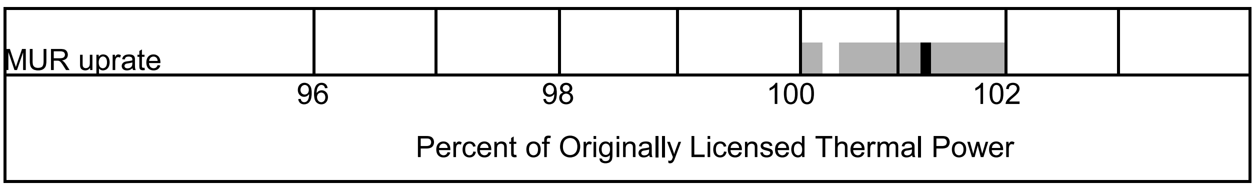
[13]This correction is still in effect. Since the plant is being operated below 98.7 percent thermal power, the licensee does not consider this to be a current concern. However, a combination of weather and condenser conditions could result in exceeding 98.7 percent thermal power in May, 2004. The licensee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

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



This UFM application is accomplished using the 10 CFR 50.59 process and does not require NRC review or approval since there is no licensing basis change (licensed power level stays the same).[14]

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



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

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

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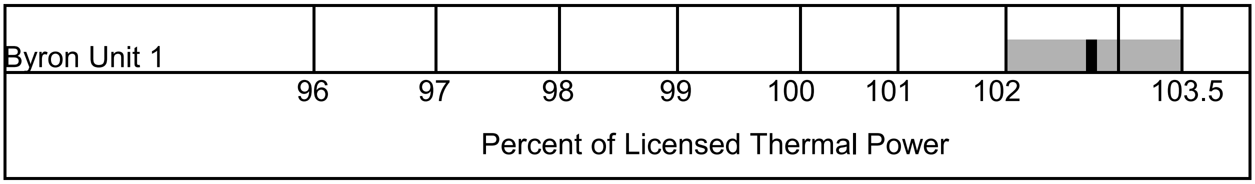
[14] The two percent allowance for uncertainty between 100 percent and 102 percent thermal power remains in place. The cause of thermal power less than the original 98 percent due to venturi fouling or other long-term instrumentation bias accumulation is essentially eliminated if this process works as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



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

Appendix A References

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

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

APPENDIX B

EXPERIENCE LEADING TO IDENTIFICATION OF AMAG PROBLEMS

The following is a partial chronological tabulation of information related to potential AMAG inaccuracies that is known to the Task Group:

	Observation	Comments
Pre-1999	The four units at Byron and Braidwood are operating within ± 2 MWe using feedwater venturis.	Byron 1 and Braidwood 1, and Byron 2 and Braidwood 2, are as close to identical as one is likely to encounter.
4/1999	Crossflow is installed in each of four feedwater lines at each Braidwood unit and each hardware installation is verified to be correct.	
5/1999	Crossflow is installed in each of four feedwater lines at each Byron unit and each hardware installation is verified to be correct.	
6/1999	Byron implementation is delayed due to C_f inconsistencies between plants that would result in the Byron units producing ~ 12 MWe more than the Braidwood units.	The result was not expected. The cause has not been determined as of the time of preparing this Task Group report.
6/1999	Braidwood implementation. Output is increased by ~ 11 MWe.	Braidwood output appeared at the time to be consistent with licensee expectations. It was later found that both Braidwood units appeared to be operating in excess of licensed thermal power
5/2000	Byron implementation. Byron 1 is now producing ~15 MWe more than produced by Braidwood 1.	Some Byron and Braidwood personnel believe there is an unidentified problem.
½002	Byron Condition Report (CR) 91771 is initiated to document unexplained, unexpected plant differences.	
1/22/2002	The Byron Resident Inspector raises questions regarding CR 91771.	
-	A Crossflow bracket is installed on the feedwater common header at Byron Unit 1.	This installation allowed a check between header flow and total feedwater line flows using Crossflow.
3/2002	Feedwater header versus sum of feedwater line tests indicates flow agreement is at the high end of the allowable statistical limit. The licensee concludes that operation is acceptable since it is within the statistical limit.	Other available parameters are all consistently near limits that correspond to overpower and unexplained issues continue to exist. This condition continues until late August, 2003.
10/2002	CR 91771 provided to Resident Inspector	
11/2002	CR 91771 completed. The apparent cause of the observed behavior is found to be indeterminate.	
-	Region III discusses support from NRR for Byron / Braidwood	
12/2002	Resident Inspector requests Region III assistance regarding Byron / Braidwood	
~12/16/2002	NRR technical reviewers receive Region III documentation	
1/22/2003	NRC letter to Exelon expresses concern with potential to be operating above licensed thermal power.	
1/24/2003	NRC / Exelon meeting on thermal power issue.	
<8/28/2003	Crossflow is installed on the feedwater header at Byron 1.	
8/2003	Comparison of the feedwater header and total of feedwater line flowrates using Crossflow at Byron 1disagrees by 1.572%. This is outside the acceptance criterion of 0.70%. Byron 1 and 2 return C_f to 1.0 and reduce power. Overpower potentially existed since May 2000.	This result convinced the licensee that something was wrong with the feedwater flow determination.
-	C_fs indicate worst case power correction of 2.62% for Unit 1 and 1.88% for Unit 2.	
8/28/2003	Byron 1 and 2 exceeded licensed maximum power level by 1.64% and 0.42%, respectively.	

	Observation	Comments
<9/29/2003	Byron header installation is believed to be accurate since there is no noise contamination.	Noise contamination is implied to be the problem. This is later shown to only be one contributor. The others were undetermined at the time of report preparation.
11/2003	Crossflow is installed at Fort Calhoun as part of equipment to be used for a 1.6% MUR uprate. (The other contributor pertained to determination of thermal conditions.)	
½004	Crossflow use is not implemented at Fort Calhoun because Crossflow incorrectly indicates flow rate changes depending upon which feedwater pump configuration is active.	The reasons for this behavior are not known and W/AMAG is working with the licensee in attempting to resolve the problem.
2/12/2004	"Changes in Crossflow performance when feedwater system configuration or alignments are changed is not unexpected based on operating history." "Westinghouse/AMAG have not yet determined the cause of the ... recent unexplained configuration change sensitivity observations...."	Information Regarding Recent Crossflow Ultrasonic Flow Measurement System Performance Observations," Westinghouse Electric Company Technical Bulletin, TB-04-4, February 12, 2004.
	"Westinghouse/AMAG recommends that the performance of the Crossflow system be re-evaluated whenever a modification is made to the feedwater system that has the potential to affect the flow characteristics and/or a power uprate is implemented.	The concern is that AMAG appears to be sensitive to such perturbations as valve position, pump operation, and power. The Task Group is concerned that a key flow meter appears to exhibit such sensitivities and, further, how it is established that AMAG is correct for the configuration that exists when installed.
	"As long as the value of C_f remains steady and within the plant specific upper or lower maximum operational limits reasonable assurance exists that the Crossflow system is performing properly."	
	"The Crossflow system is designed to achieve flow measurement uncertainty of 0.5% or better ... when installed in accordance with ... (CENPD-397-P-A, Rev. 1) and there is confirmation of the absence of signal interference.	
	"Westinghouse/AMAG considers that reasonable assurance that the Crossflow system is operating as designed can be obtained by making use of other corroborating plant performance parameters or plant specific operating history." Seven examples of corroborating information are listed as "for example, but not limited to."	These are checks for consistency. However, the uncertainty of the corroborating parameters is significantly greater than the claimed AMAG uncertainty.
3/1/2004	"Braidwood is conservatively reporting an overpower condition on Unit 1 due to the implementation of an ultrasonic flow measurement system ... (of) a maximum of 1.07% ... between June 1999 and September 2003.... Currently Braidwood Unit 1 and Unit 2 are controlling power level based only on the venturi feedwater flow indication."	"24-Hour Condition of License Report Involving Potential Violation of Maximum Power Level," Braidwood Unit 1, LER Event Number 40559, March 1, 2004

APPENDIX C

THEORETICAL INVESTIGATIONS

C-1. Computational Fluid Dynamics (CFD) Investigation

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

Preliminary Computational Fluid Dynamics (CFD) analyses were performed using the FLUENT[15] code to investigate the effect of upstream perturbances on the velocity profile. A steady state isothermal model was used in each simulation. The Renormalization Group Theory RNG k-epsilon model was chosen to model turbulence in the core flow, while the standard wall function was used to bridge the core flow to the laminar sublayer near the wall. A Neumann boundary condition with zero normal gradient was applied at the pipe exit. The first nodal layer near the pipe wall was carefully placed for the proper use of the RNG-k-epsilon model using the standard wall functions. Boundary layer meshing was used near the wall to achieve mesh orthogonality to reduce numerical error due to the additional tensor geometrical coefficients in the conservation equations.

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

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

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

The results from the first configuration simulation showed that the fully developed profile can be attained at a distance between 20 and 30 diameters downstream of a uniform velocity inlet and the velocity profile changes only radially and uniformly in the tangential direction.[16] 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

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

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

most if not all installations in nuclear power plant feedwater lines.