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EVALUATION OF THE WESTINGHOUSE CROSSFLOW ULTRASONIC FLOW METER

1 SUMMARY AND CONCLUSIONS

2 INTRODUCTION

2.1 Operational and NRC Review Background

The Crossflow ultrasonic flow meter (UFM) was originally developed by the Advance Measurement and Analysis Group (AMAG) and marketed to licensees of nuclear power plants in conjunction with Combustion Engineering (CE) Nuclear Power LLC (CENP). The Westinghouse Electric Company LLC (W) later purchased CE and the UFM is now marketed by W/AMAG. The principal application of the Crossflow UFM in nuclear power plants is to improve feedwater flow rate measurement accuracy, a measurement that accounts for most of the uncertainty associated with determination of reactor thermal power. The UFM is generally used in one or two ways:

(1) To recalibrate feedwater venturis to compensate for fouling, thereby recovering lost generating capacity while staying within the plant's licensed operating power level, and

(2) To reduce the power level margin used in the plant emergency core cooling system (ECCS) evaluation by amending the licensed thermal power level to allow operation at higher power levels while not changing the ECCS licensing basis.

10 CFR 50.59 allows Item 1 to be accomplished without prior NRC approval. Item 2 requires a licensee amendment by 50.90 since there is a change in the licensed power level. Item 1 applications have been used since the mid-1990's in United States plants. Item 2 was addressed in a submittal to the NRC in 1999 and was approved in 2000 (See References A and B). The approval stated that:

(1) The Crossflow UFM is designed and tested to achieve the flow measurement uncertainty of 0.5 percent or better, with a 95 percent confidence interval, when the plant-specific operating conditions and flow uncertainty parameters strictly follow the guidelines in topical report CENPD-397-P Revision 01.

(2) The report is generically suitable for reference by utilities employing the Crossflow UFM to pursue plant operation at a higher power level, within the limitations of the license.

(3) Licensees may use the increased accuracy of the UFM to support a reduction in the power level margin used in the plant ECCS evaluation and may seek a license amendment to operate the power plant at higher power levels on this basis.

(4) The increased accuracy of the UFM will allow a licensee to have an in-plant capability to periodically recalibrate the feedwater venturi for the effect of fouling, thereby allowing recovery of lost generating capacity while staying within the plant's licensed operating power level.

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The Crossflow UFM[1] measures the time an eddy takes to pass between two locations in a feedwater pipe. An average MEAN??eddy velocity is then calculated from approximately [redacted] A velocity profile correction factor (VPCF) is then applied to the average eddy velocity to obtain the average velocity that is representative of actual flow rate. The VPCF is obtained experimentally by conducting AMAG tests where the vendor believes fully developed or stable flow exists[2]. If there are any differences in the velocity profile used to obtain the VPCF between the tests and during plant operation, then additional correction factors must be applied to obtain the correct flow rate. This was addressed by Item 1, above, by the statement that the plant-specific operating conditions and flow uncertainty parameters had to strictly follow the guidelines provided by Reference A. Operating experience obtained since the staff approved the AMAG has shown that the Reference A guidelines were not sufficient to ensure acceptable operation and supplemental guidance and improved vendor/user interactions have been provided by W/AMAG to correct the weaknesses.

The eddy transit time measured by the AMAG can be contaminated by noise originated by such behavior as pipe vibration and interaction with pipe supports. Typically, the signal was checked for noise as part of the installation process and corrections were made if noise was found so that it would not be a factor during operation. This was [redacted] the statements that "this type of noise rarely occurs" and "proper filtering can be used to [redacted] The staff did not audit W/AMAG's and the user's treatment of noise and this subject was not mentioned in the staff's Reference B. Further, in the last few years the staff has recognized that many users were not aware of this potential condition. Operational experience showed that the noise handling process was inadequate and noise contamination has led to plant operation above the licensed thermal power level. This inadequacy has also been addressed by the W/AMAG supplemental guidance and improved vendor - user interactions.

2 INSIGHTS AND IMPROVEMENTS RESULTING FROM OPERATING EXPERIENCE

2.1 Byron / Braidwood (References C, ??)

AMAGs were installed and tested at Braidwood in June, 1999, and in Byron in May, 2000 for power recovery application. Installation was in accordance with the AMAG procedures that existed at that time. When AMAG was used to recalibrate the venturis, the thermal performance engineers immediately determined that numerous other indicators for thermal power indicated an overpower condition. Multiple unsuccessful evaluations were conducted from 1999 through 2003 to determine the differences between AMAG indication and all other

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[1]We will refer to the Crossflow UFM as the AMAG to be concise.

[2]Fully developed flow is the condition that is achieved in a long, straight pipe where there is no change in velocity profile with respect to axial location in the pipe. Stable flow is defined as corresponding to axial locations where AMAG indication is only affected by change in flow rate. If symmetric or non-symmetric flow rotation with respect to the pipe axis, referred to as swirl, has been introduced into the pipe by upstream pipe configurations, this can affect the velocity profile and potentially the AMAG indication for more than a hundred pipe diameters downstream of the configuration.

indications while, for most of the time, the plants continued to be operated with the presumption that AMAG was correct. Header comparison testing in 2003 led to discovery of noise contamination. Tracer testing in Byron Units 1 and 2 in 2004 and subsequent hydraulic testing identified that the velocity profile at the AMAG locations differed from the previously presumed developed profile and the VPCF was therefore incorrect.

3 ASSESSMENT OF CORRECTION FACTORS AND APPLICABLE GUIDELINES

3.1 Overview

As discussed in Section 2, above, experience obtained since publication of References A and B has shown that AMAG is more sensitive to changes in velocity profile than originally anticipated. Further, velocity profile has been found to change in a number of unanticipated ways when installed in nuclear power plants. This sensitivity requires a complete understanding of the tests used for original calibration since, if the test facility velocity profile is not as presumed, then the calibration may be incorrect. The same understanding is necessary for installation in the feedwater lines of a power plant. Any change in velocity profile between the test and the initial plant installation will potentially affect the calibration. Further, any change in plant operating conditions, such as changing feedwater valve positions or swaping feedwater pumps, has the potential to affect velocity profile at the AMAG location. These effects have been found to be more prevalent and to propagate for significantly greater distances downstream of the perturbation than originally thought. The W/AMAG improvements to address these phenomena have been vital for reasonably ensuring that the claimed uncertainties are achieved in practice. These improvements must be incorporated into the installation process and into the guidelines used by each licensee in order to comply with the NRC's Reference B approval. Further, consistent with the reasoning provided by Reference A for application of AMAG, they must be used for both power recovery and power uprates to reasonably ensure compliance with the licensed thermal power level.

3.1 Determination of the Velocity Profile Correction Factor

The mass flow rate in a pipe, W, is defined by:

$$W = \rho A V_a$$

where:
- ρ = fluid density
- A = cross-sectional flow area
- V_a = average velocity of fluid in the pipe

AMAG measures the time for eddies to pass between two sets of transducers, τ, that are a known axial distance, L, apart. Hence, the AMAG-indicated velocity, V_m, is determined by:

$$V_m = L / \tau$$

There is no available theoretical correlation of V_m that will provide V_a and the relationship must be determined experimentally. This is accomplished by determining W in either a full size or scaled test facility while simultaneously measuring V_m by AMAG. V_a follows from:

$$V_a = W / (\rho A)$$

and, since V_m was obtained from the same test, V_a and V_m can be correlated by:

$$V_a = C_0 \; V_m \quad \text{or} \quad C_0 = V_a / V_m$$

where: C_0 = velocity profile correction factor, VPCF

These equations were provided in Reference A and in more recent references.

Prior to 2005, W/AMAG described AMAG as tuned to preferentially select an eddy size and hence a velocity that corresponded to a specified radial location in the flow stream. The philosophy appeared to be to tune AMAG so that V_m was close to V_a for fully developed flow to minimize the change induced by C_0, (C_0 closer to 1). More recent descriptions omit the radial location reference and describe the uncorrected AMAG indicated velocity as representative of eddy velocity. Either description leads to the same initial approach to AMAG calibration where fully developed flow is assumed in testing to obtain C_0. Thus, an initial step in assessing the AMAG calibration process is to address the experimental flow profile.

Reference B states that Reference A includes a C_0 versus Reynolds Number (Re) curve that is based on the assumptions of fully developed turbulent flow in a straight pipe with a small pipe wall friction factor. This curve was obtained by applying AMAG test data obtained at Alden Labs in 1996 with (b)(4) pipe. Upstream length to diameter (L/D) ratios of (b)(4)

(b)(4)

(Reference D) (b)(4)

Each test result is an average of about 30 to 40 AMAG readings (Reference A). The following four acceptable test results were reported:

Pipe Size (in)	L/D	Indicated AMAG Flow Rate (gpm)	Corrected AMAG Flow Rate (gpm)	Alden Weigh Tank Flow Rate, (gpm)	C_0	Reynolds Number X 10^{-6}	Corrected AMAG to Alden Difference (percent)
(b)(4)			17,652.1	17,645.6	(b)(4)	6.9630	+0.04
			489.6	489.8		0.7865	-0.04
			1,424.8	1426.0		2.2611	-0.08

Pipe Size (in)	L/D	Indicated AMAG Flow Rate (gpm)	Corrected AMAG Flow Rate (gpm)	Alden Weigh Tank Flow Rate, (gpm)	C_0	Reynolds Number X 10^{-6}	Corrected AMAG to Alden Difference (percent)
(b)(4)			490.2	489.8	(b)(4)	0.7865	+0.08
Proprietary and non-proprietary information is from References D and E, respectively. *Older values from Reference A.							

where AMAG was calibrated using the acceptable test results to calculate C_0 by the process discussed in Section 3.2, below.

3.2 The Effect of Reynolds Number

W/AMAG correlated the Section 3.1 C_0 by rewriting (b)(4)

(b)(4)

(b)(4)

(b)(4) References A, E, and F.

?? W/AMAG - WE NEED A BETTER ANALYSIS OF ALL OF THESE DATA (INCLUDING STANDARD DEVIATION) AND THE FIT. WE ALSO WANT A CURVE OF C_0 AS A FUNCTION OF Re FOR ALL DATA WITH STANDARD DEVIATION INFORMATION.

3.3 Application Where Fully Developed Flow Does Not Exist

Reference A describes an approach if fully developed flow does not exist at the desired AMAG installation location and there is another location where fully developed flow does exist either upstream or downstream of the desired location. This is to install a second meter at the fully developed flow location and use it to calibrate the permanent meter. This is claimed to eliminate the need for model tests since the permanent meter is calibrated at full power under operating conditions. However, there is an increase in uncertainty associated with this application since the uncertainty associated with the "calibration" UFM must be considered in determining the uncertainty of the meter that is to be calibrated. Further, the Reference A description only directly encompasses meters installed in the same pipe. Applications have used the calibration UFM to calibrate permanent UFMs in other pipes under the unstated and sometimes unjustified assumption that the permanent UFM velocity indications were identical if flow rates were identical. Complete justification and uncertainty analyses must be developed for such applications where calibrated and calibrating UFMs are installed in different pipes.

Reference B states that formulae and guidelines are provided in Reference A for determining the additional correction factors that are to be applied to C_0 where fully developed flow does not exist. This was developed by considering the following equation:

(b)(4)

(b)(4)

(b)(4)

3.4 Other Uncertainty Considerations

Contribution of such items as pipe diameter and transducer spacing were addressed in the Reference B review and are not repeated here. Items not previously assessed include the

[3]Reference A incorrectly stated "where the flow is not fully developed or downstream of a 90° elbow."

following:

- Path length due to such variations as path angle

Reference A states that errors due to the ultrasonic path length and path angle and the associated uncertainties are eliminated by the perpendicular orientation of the UFM transducers.

NEED: ORIENTATION EFFECT
PIPE ROUGHNESS
REPLACEMENT OF TRANSDUCERS
OLD VS NEW BRACKET
DISCUSSION OF MANY OF UNCERTAINTY ANIMALS REVIEWED BEFORE

Reference A discussed two types of brackets for attaching transducers to feedwater pipes. The older bracket is no longer in use and, based upon information in Reference ??, the new design eliminates the identified problems associated with the older design.

4 ASSESSMENT OF NOISE CONTAMINATION AND APPLICABLE GUIDELINES

5 REFERENCES

A "Improved Flow Measurement Accuracy Using Crossflow Ultrasonic Flow Measurement Technology," ABB Combustion Engineering, CENPD-397-P-A, ML052070504, May 31, 2000. (Proprietary)

B Richards, Stuart A., "Acceptance for Referencing of CENPD-397-P, Revision-01-P, 'Improved Flow Measurement Accuracy Using Crossflow Ultrasonic Flow Measurement Technology' (TAC No. MA6452)," Letter to ABB Combustion Engineering from NRC, ML003694197, March 20, 2000.

C Kouba, Bill, "Byron/Braidwood Thermal Power Measurement," Slides from NRC Meeting with Licensees Using Ultrasonic Flow Measurement Devices, Exelon Nuclear, September 17, 2004. (Proprietary)

D "Crossflow 1996 Alden Lab Test Data," Slides from NRC Meeting with W/AMAG, October 6, 2005. (Proprietary)

E "Alden Research Laboratory," Slides from NRC Meeting with ABB Combustion Engineering, February 25, 1999.

F "Crossflow System/Theory & Application," Slides from NRC Meeting with W/AMAG, October 3, 2005. (Proprietary)

G "Crossflow Standard and Nonstandard Installation," Slides from NRC Meeting with W/AMAG, October 6, 2005. (Proprietary)