1a

NOTE: The document following this note is a modification of the final version of Warren C. Lyon's Memorandum to File contained in ADAMS under ML062280403. This document resulted from Warren's in-depth review to identify proprietary information in ML062280403. It differs from ML062280403 in the following ways:

1. ***ML062280403 used brackets [ ] to preliminarily identify proprietary information. This document reflects a review to more accurately and completely identify proprietary material. The original brackets have not been retained if they were incorrect and new brackets have been added as appropriate.***

2. ***This proprietary review identified that ML062280403 had an incorrect Reference 6. This error has been corrected and the change is indicated using strikeout and the bold / italic print used in this NOTE.***

3. ***Numerous versions of this document were generated during its development as the NRC staff was reviewing use of the CROSSFLOW ultrasonic flow meter for determination of feedwater flow rate in nuclear power plants. Early versions were prepared by Lyon with no review or comments from other members of the NRC staff. Further, in some cases, version sections were discussed during meetings with Westinghouse/AMAG as the sections were being developed and Westinghouse provided written comments as illustrated by Reference 6. The final ML062280403 version has management concurrence following independent review. All changes during version development were made by Lyon. Lyon's changes to the document during independent review after initial completion of ML062280403 and during concurrence were limited to wording to more clearly articulate Lyon's discussion or to change the focus from Lyon's conclusions to NRC staff conclusions. No changes were made during development of Lyon's Memorandum that affected Lyon's conclusions. Therefore, the final version provided below is considered to be an accurate representation of Lyon's work and the NRC has concluded that no information is lost by not providing copies of previous versions or draft version sections.***

4. ***The "***PROPRIETARY INFORMATION IS CONTAINED WITHIN [ ] BRACKETS***" heading and footer has been changed from the "***PROPRIETARY***" heading used in ML062280403.***

5. ***The attachment to Lyon's Memorandum contained the following statement:***

   THE NRC STAFF'S PRELIMINARY ASSESSMENT OF PROPRIETARY INFORMATION IS IDENTIFIED BY [ ]. PROPRIETARY FIGURES ARE IDENTIFIED BY ENCLOSING THE TITLE WITH THE [ ] BRACKETS. THIS ATTACHMENT MUST BE TREATED AS PROPRIETARY IN ITS ENTIRETY SINCE W/AMAG HAS NOT REVIEWED THE ATTACHMENT FOR PROPRIETARY IDENTIFICATION ACCURACY.

This statement has been rewritten as follows to correctly reflect the proprietary designations:

~~PROPRIETARY FIGURES ARE IDENTIFIED BY ENCLOSING THE FIGURE TITLE WITH [ ] BRACKETS~~.

N-2a.

6. ***Strikeout is used to delete material that is no longer applicable where its retention could be misleading.***

7. ***No other deletions, corrections, or changes have been made.***

MEMORANDUM TO: File

THROUGH: Gregory V. Cranston, Chief
Reactor Systems Branch
Division of Safety Systems

Jared S. Wermiel, Deputy Director
Division of Safety Systems

William H. Ruland, Director
Division of Safety Systems

FROM: Warren C. Lyon, Senior Reactor Engineer
Reactor Systems Branch
Division of Safety Systems

SUBJECT: ASSESSMENT OF THE WESTINGHOUSE / ADVANCE MEASUREMENT AND ANALYSIS GROUP (W/AMAG) CROSSFLOW ULTRASONIC FLOWMETER (UFM)

REFERENCE: Case, Michael J., "Final Safety Evaluation for Suspension of U.S. Nuclear Regulatory Commission (NRC) Acceptance for Referencing of Westinghouse Electric Company (Westinghouse) Topical Report (TR) CENPD-397-P, Revision-01-P, 'Improved Flow Measurement Accuracy Using CROSSFLOW Ultrasonic Flow Measurement Technology' (TAC No. MD3857)," NRC Letter from Director, Division of Policy and Rulemaking, Office of Nuclear Reactor Regulation, to Mr. James A. Gresham, Manager, Regulatory Compliance and Plant Licensing, Westinghouse Electric Company, September 26, 2007.

The Attachment was prepared to document the review that is summarized in the NRC staff's reference safety evaluation. Although the reference safety evaluation was discussed with W/AMAG and W/AMAG comments were considered in preparing the final safety evaluation, this process was not accomplished for the Attachment. ~~Further, the Attachment is proprietary in its entirety since we generated the proprietary identifications and they have not been confirmed by Westinghouse.~~ This Memorandum is nonproprietary when separated from the Attachment.

T. Collins, W. Lyon, and J. Wermiel for W. Ruland concurred on a previous version of the Attachment (ML072700499) on September 27, 2007. S. Turk returned it with comments on October 24, 2007. These comments and several clarifications have been addressed in the Attachment. No changes affected the NRC staff conclusions nor have any updates been provided in regard to activities conducted after the reference safety evaluation was issued.

Distribution: JGrobe GCranston JThompson
Accession Number: ***ML062280403***

OFFICE	DSS	SPWB	DSS/D	OGC
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DATE	09/27/07	09/29/07	09/27/07	10/24/07

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Attachment

Assessment of the Westinghouse / Advance Measurement and Analysis Group (W/AMAG) CROSSFLOW Ultrasonic Flowmeter (UFM)

PROPRIETARY FIGURES ARE IDENTIFIED BY ENCLOSING THE FIGURE TITLE WITH [ ] BRACKETS.

EXECUTIVE SUMMARY

CROSSFLOW, a UFM marketed by W/AMAG, is typically claimed to measure feedwater flow rate in nuclear power plants within an uncertainty of approximately ±0.5 percent. Consequently, it is (1) used to compensate for fouling in venturis[1] that could lead to operation at less than licensed thermal power and (2) used in conjunction with license amendments to operate at higher power levels consistent with the July 31, 2000, change in 10 CFR Part 50 Appendix K to take advantage of more precise flow rate measurement. The former application is referred to as "power recovery" and the latter as a measurement uncertainty recapture power uprate or simply "power uprate." (b)(4) US nuclear power plants have installed CROSSFLOWs for power recovery by applying 10 CFR 50.59 which does not require prior NRC staff review. CROSSFLOWs are used in (b)(4) US nuclear power plants for power uprates. The power uprates require a license amendment under 10 CFR 50.90 and 50.92 since an increase in licensed thermal power is achieved.

CROSSFLOW application and the NRC staff approval are addressed in topical report CENPD-397-P-A (ML052070504). Based on the information reviewed at the time, the NRC staff concluded that CROSSFLOW could achieve the accuracy stated in the topical report and the report was approved by the NRC staff on March 20, 2000. CENPD-397-P-A provides the regulatory basis for implementation under both 10 CFR 50.59 and 10 CFR 50.90.

The key consideration in the NRC staff's evaluation was the ability of CROSSFLOW to achieve a flow measurement uncertainty of ±0.5 percent or better at the 95 percent confidence interval for fully developed flow. The NRC staff's evaluation noted that actual uncertainties would be determined on a plant specific basis by using guidelines and equations provided in the topical report. The NRC staff concluded that the desired level of measurement uncertainty is achievable only when the plant specific operating conditions and flow uncertainty parameters strictly follow the guidelines in the topical report.

Operating experience at plants using CROSSFLOW for feedwater flow measurements has led to identification of significant issues regarding the ability of plants to achieve the desired measurement uncertainty using the theory, guidelines, and methods described in the topical report. For example, CROSSFLOW was placed in use at Braidwood Units 1 and 2 in June

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[1]The term "venturi" is used in this report as a general term for determination of flow rate due to a differential pressure across a change in flow area. Flow nozzles are used in some nuclear power plants to determine flow rates. There are important differences between flow nozzles and venturis, such as the fouling characteristics, that are not addressed in this report or in the information provided to the NRC staff by W/AMAG. These differences may be important when addressing individual plant applications.

1999, and at Byron Units 1 and 2 in May 2000. On August 28, 2003, Byron Units 1 and 2 were reported to have been overpowered by as much as 1.64 and 0.42 percent, respectively. On August 31, 2003, Braidwood Unit 2 was reported to be overpowered by 0.39 percent. The overpowers were attributed to noise that contaminated CROSSFLOW's indicated flow rate. On March 30, 2004, the values for Braidwood Units 1 and 2 were revised to 1.07 and 1.21 percent, respectively, and on March 31, 2004, the Byron overpowers were revised to 2.62 and 1.88 percent. The later revisions were attributed to unrecognized flow profile inconsistencies. The overall effect was operation for several years in excess of licensed thermal power.[2]

The Byron and Braidwood experience led to an increase in NRC staff and W/AMAG involvement in reviewing the use of CROSSFLOW in nuclear power plant feedwater lines. Part of the NRC staff involvement included formation of an NRC staff task group to assess the Byron and Braidwood experience. The task group concluded that:

- CROSSFLOW is sensitive to the plant configuration.
- CROSSFLOW has not provided the intended accuracy at some facilities and accuracy questions have arisen at others.
- 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.
- CROSSFLOW users must address the concerns that are specific to CROSSFLOW in order to provide the required assurance of compliance.

The NRC staff followed up on the task group findings by reassessing the continued use of CENPD-397-P-A in licensing applications. This reassessment took into account the original CENPD-397-P-A information as well as the theoretical basis for CROSSFLOW, the experimental data supporting the claimed uncertainty, the installation and calibration requirements included in the implementation guidelines, supporting analysis, and other additional information that has come to light as part of operating experience reviews. For example, Ft. Calhoun requested a 1.67 percent power uprate on July 18, 2003. This was revised to 1.6 percent on August 28, 2003, approved on January 16, 2004, revised to extend implementation time due to difficulty in achieving the claimed CROSSFLOW uncertainty on February 6, 2004, amended to return licensed thermal power to the original 1500 MWt on May 4, 2004, as difficulties continued, and resubmitted as a 1.5 percent uprate on March 31, 2005. Although Ft. Calhoun was never determined to have operated in excess of its licensed thermal power, this history reflects the continuing identification of problems as the licensee attempted to install and operate CROSSFLOW while applying additional scrutiny as the generic examination of CROSSFLOW led to identification of previously unidentified issues.

Calvert Cliffs Unit 1 and Unit 2 started using CROSSFLOW for power recovery in July 2003. On January 31, 2005, the licensee requested a power uprate. The licensee encountered difficulties when it pursued CROSSFLOW operation for the uprate and also found that it had

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[2]Some of the installation and operation practices that were in place will no longer be used for new installations. However, no inconsistency was recognized at the time between the practices that will no longer be used and the methodology approved by NRC.

operated at a maximum thermal power of 100.4 and 100.74 percent of licensed power in Units 1 and 2, respectively, from July 2003, until CROSSFLOW systems were removed from service in September 2005.

The original Calvert Cliffs CROSSFLOWs were installed at locations where the laboratory calibrations were not completely applicable, a condition addressed in CENPD-397-P-A. Consequently, an additional CROSSFLOW was installed in one feedwater line where the calibration was believed correct and this CROSSFLOW was to be used to calibrate the other four CROSSFLOWs in the four feedwater lines as described in CENPD-397-P-A. However, the CROSSFLOW calibration was found to be incorrect because of an upstream perturbation of the flow profile. Root causes were stated by the licensee to include:

- Failure to consider data within CENPD-397-P-A indicating that the piping/component configuration could produce flow distortions farther downstream than analyzed.
- Weak oversight by W/AMAG.
- Inadequate design input contained in CENPD-397-P-A.
- Inadequate design review addressing placement of the upstream CROSSFLOW.

Testing also showed that the concept of using one CROSSFLOW to calibrate the other four was incorrect because each CROSSFLOW had a different calibration coefficient. The plan now appears to be to calibrate all CROSSFLOW meters at Calvert Cliffs from tracer measurements performed on each feedwater loop, completely eliminating the laboratory testing approach that has been used for all other CROSSFLOW installations. Furthermore, W/AMAG has stated that using (b)(4)
(b)(4)

W/AMAG introduced the term "stable flow" in September 2005 as the flow condition that exists when the CROSSFLOW meter readings are independent of axial and angular orientation of the CROSSFLOW meter about the pipe. This was claimed to meet the intent of using "fully developed flow" in CENPD-397-P-A but W/AMAG pointed out that it does not refer to developed flow in the classical sense where the flow profile is fully developed. The NRC staff did its original review on the basis of "fully developed flow," not "stable flow." The terms do not have the same meaning. Furthermore, W/AMAG did not achieve orientation independence when concluding that stable flow exists due to inconsistent and inappropriate use of statistical bounds, insufficient data, and claimed test laboratory uncertainties. For example, W/AMAG stated that the applicable test was that the same flow indication exists for different angular and axial locations within the uncertainty of the measured time delay, which is usually on the order of (b)(4) percent. This is an incorrect use of uncertainty, which means that one expects to be outside of the bound only 5 percent of the time. Further, data scatter is expected to be less than uncertainty when comparing changes due to a small location change, The correct approach is to obtain sufficient data to reasonably determine that the mean value has been acceptably bracketed.

The NRC staff has concluded that the CENPD-397-P-A topical report does not provide a sufficient theoretical or experimental basis to generically disposition the issues that have been manifested in the staff's reviews. The key concerns are summarized below:

- CROSSFLOW calibrations are not traceable to certified standards. The original calibration of CROSSFLOW is based on tests conducted at the Alden Research Laboratory (ARL). The flow rates and flow rate uncertainty determined at ARL are traceable to the National Institute of Standards and Technology (NIST) standards. However, the calibration of CROSSFLOW is highly dependent upon a specific flow profile. The relation between a certified standard and the flow profile obtained during testing has not been addressed, nor has there been an assessment of the contribution of flow profile variations on the uncertainty of the device. As such, there is no standards continuity when using the test calibration for a CROSSFLOW installation in a plant. Similar concerns apply to in-situ calibration where the original calibration may include traceable elements but traceability may be lost during post-calibration operation.

- The statistical acceptance tests for comparisons and for data convergence are unacceptable. A typical rationale provided by W/AMAG is that if a data set is being evaluated for convergence and the data appear to be converging, then when one or two data values are found that are within the uncertainty bound, one cannot expect better and no further data need be obtained. NRC staff examination of some of the data established that trends were still evident when W/AMAG concluded no further data were needed. Another rationale is that two data values, such as two flow rates obtained from different sources, are in agreement if the uncertainty bounds overlap. Statistically, this concludes that the data agree when the probability of agreement is a small fraction of a percent. The correct comparison is with respect to mean values since the expectation is that most data will be grouped about the mean value.

- The flow rate error provided by an uncalibrated CROSSFLOW is about (b)(4) percent. This error must be corrected by one or more calibrations and calibration precision is important due to the large correction. Yet:

  - Calibration is sensitive to changes in flow profile.

  - CROSSFLOW cannot independently recognize a change in flow profile.

  - Laboratory test flow profiles and uncertainty due to noise in laboratory testing have not been satisfactorily established.

  - One test for a satisfactory calibration and installation is claimed to involve a fully developed flow profile or at least a flow profile that is consistent with stable CROSSFLOW operation, but flow profile is affected by a change in pipe roughness while fully developed flow continues to exist. This item has not been acceptably addressed.

  - The uncertainty associated with transfer of laboratory test calibrations to plant installation has not been acceptably determined. The existing W/AMAG assumption that the test uncertainty is (b)(4) (b)(4) has not been demonstrated to be correct and is unacceptable.

  - The uncertainty associated with changes during plant operation has not been acceptably determined.

- CROSSFLOW noise contamination uncertainty in installations has not been acceptably addressed. The extensive data processing appears to have reduced noise contamination concerns but a residual contribution to overall CROSSFLOW uncertainty remains that must be quantified.

- Chemical tracer in-situ calibrations have not been demonstrated to provide sufficient sensitivity to support the claimed uncertainties. The ARL test data assessed by the NRC staff exhibit a test sensitivity of (b)(5) percent when translated to flow rate. This is insufficient for calibration of CROSSFLOW with a claimed uncertainty in the vicinity of 0.5 percent. Furthermore, use of ARL data to establish a recalibration of tracer results does not appear to consider uncertainty of the ARL data and the recalibration introduces a non-conservative factor into the CROSSFLOW calibration.

- Venturi in-situ calibrations have unresolved issues that potentially affect the claimed uncertainties. These include concerns regarding test pipe diameters, venturi differential pressure determination, and venturi fouling.

- In-situ calibrations have not been demonstrated to acceptably address issues associated with CROSSFLOW calibration change due to changes in flow profile following calibration.

Consequently, it has not been demonstrated that a CROSSFLOW installed in accordance with the topical report guidelines can adequately differentiate between an actual flow rate change and biases introduced as a result of flow profile changes. This is important because precise calibration of the CROSSFLOW instrument is required due to the large correction needed and the small uncertainty to be achieved.

- Secondary calibrations using laboratory tests have been used to determine correction factors associated with stable flow and with flow profile as affected by elbows or other non-standard installations. The calibration data provided to the NRC staff have not been adequate to support the claimed uncertainties. For example, convergence to an acceptable secondary calibration coefficient has been assessed by increasing CROSSFLOW distance from the perturbation to the flow profile and rotating CROSSFLOW circumferentially until a location is found where it is judged that CROSSFLOW movement does not cause a significant change in CROSSFLOW indication. No statistical basis has been provided and the rational used to determine "no significant change" appears to be based on an inadequate number of data points, an unacceptably large data scatter, and a failure to acceptably demonstrate convergence with respect to position. Furthermore, in some cases tracer testing and analyses have shown that the approach is incorrect.

- In-plant determination of acceptable CROSSFLOW locations has not been demonstrated. An acceptable location is determined, in part, by moving CROSSFLOW axially and circumferentially until a location is found where it is deemed that movement does not indicate a flow rate change. The NRC staff has not been provided data to support this conclusion, data and uncertainties associated with this process have not been adequately addressed in the information provided to the NRC staff, this process does not address other NRC staff concerns such as an increase in uncertainty due to the change from a laboratory calibration to in-plant operation, and the NRC staff is concerned that the above-identified approach to convergence has been used. Furthermore, the NRC staff is aware that the test has failed in at least one recent case (Calvert Cliffs).

- CROSSFLOW calibration is affected by changes that routinely occur in a nuclear power plant. Changes that can invalidate the calibration include:
    - Thermal power level and hence feedwater flow rate
    - Valve position and valve wear or replacement
    - Feedwater heater configuration
    - Feedwater pump operation, wear, and replacement
    - Feedwater pipe fouling, defouling, and other changes that affect pipe roughness
    - Noise

- Although information has been provided to support a claim that CROSSFLOW accuracy and uncertainty have been demonstrated "under fully developed/stable flow conditions" little information was provided specifically addressing the presence of non-stable flow at CROSSFLOW locations in existing, previously-approved installations. Further, some of the laboratory calibration processes used in existing applications are now recognized as incorrect and are not to be used for new applications. The impact of issues identified in this report on existing applications has not been satisfactorily assessed.

- The NRC staff recognizes that approximately (b)(4) database monitoring parameters are assessed by online monitoring and system diagnostic alarms and, if an alarm is received, then other plant parameters may be assessed to determine CROSSFLOW validity. It also appears that the calibration coefficient can typically vary (b)(4) percent before an alarm in initiated and alarm setpoints can be adjusted based on licensee judgement regarding the cause of venturi calibration changes. The NRC staff review has not established that calibration coefficient variation is consistent with the claimed uncertainty.

- Part of the process for checking CROSSFLOW involves comparisons to other plant parameters that can be used to track thermal power. These parameters generally have larger uncertainties than claimed for CROSSFLOW. This makes it difficult to assess CROSSFLOW performance. W/AMAG has not provided a statistically valid application of other parameters to substantiate that CROSSFLOW is operating as claimed and to provide early detection of CROSSFLOW problems.

- Some licensees have claimed that CROSSFLOW has operated well and has met expectations and some comparisons with in-plant instrumentation and other test data have been provided to substantiate these claims. The results have been mixed and data were not provided for many applications. The NRC staff has not confirmed that this information acceptably establishes that the claimed uncertainties are achieved.

- Existing CROSSFLOW installations were put in place without addressing many of the recently identified issues. The NRC staff was informed that this was addressed by a re-validation activity that was to confirm that existing CROSSFLOW systems are installed consistent with the design and licensing bases consistent with [the assumptions used for the uncertainty calculations at the time of CROSSFLOW commissioning]. However, existing CROSSFLOW installations have not been established as being consistent with the latest information applicable to CROSSFLOW installation and operation, nor has the existing information been established as adequate to reasonably assure the claimed uncertainty is achieved.

W/AMAG has attempted to correct for some of the weaknesses by the following measures:

- W/AMAG has stated that, in general, (b)(4) (b)(4) and CROSSFLOW should be used on-line in conjunction with plant instrumentation.

- CROSSFLOW operation is recommended to be restricted to plant conditions where the calibration is perceived to be valid.

- CROSSFLOW data are subjected to complex processing in an attempt to identify operation where claimed uncertainty bounds are exceeded.

- Where flow cannot be shown to be stable, (b)(4) (b)(4)

- W/AMAG provided the "CROSSFLOW Ultrasonic Flow Meter User Guidelines" in June 2005. This provided generic guidance for CROSSFLOW users although it did not address all known issues. An update is planned.

- W/AMAG plans to revise the topical report so that (b)(4) (b)(4)

CROSSFLOW's inability to directly assess the flow profile and flow profile changes, the need for a substantial calibration factor that is strongly influenced by changes in flow characteristics, and failure to achieve traceability to recognized standards are major weaknesses that are the direct cause of many of the other identified issues.

Most of the above information was not appreciated when the NRC staff initiated its investigation of the Byron / Braidwood overpower condition and, at that time, W/AMAG and the licensees initially maintained CROSSFLOW was operating correctly and was consistent with the claimed precision. However, as the NRC staff continued its investigation, W/AMAG increased its own followup and, as summarized above, discovered an increasing number of problems, some of which invalidated previously provided information. As a result of this experience, the NRC staff has concluded that CENPD-397-P-A contains errors and does not address many issues associated with changes in W/AMAG descriptions, installation, commissioning, and monitoring, and issues remain that must be satisfactorily addressed before there is reasonable assurance that the uncertainties associated with CROSSFLOW measurement of feedwater flow rate have been acceptably determined.

Consequently, the NRC staff has concluded that (1) the existing previously approved CENPD-397-P-A topical report is an inadequate basis for using CROSSFLOW to determine feedwater flow rate and (2) a basis has not been established for such use that acceptably addresses the issues discussed in this NRC staff assessment.

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LIST OF FIGURES

ACRONYMS AND DEFINITIONS

A	Cross-sectional flow area
AMAG	Advance Measurement and Analysis Group
ARL	Alden Research Laboratory
ASME	American Society of Mechanical Engineers
BVR	Baseline validation report
BWR	Boiling water reactor
C_0	Velocity profile correction factor, VPCF
CE	Combustion Engineering
CENP	Combustion Engineering Nuclear Power LLC
CFD	Computational Fluid Dynamics
CTF	PWR Owners Group CROSSFLOW Task Force
ECCS	Emergency core cooling system
EDF	Electricite de France or Everest Laboratory
f	Friction factor
FPCF	Flow profile correction factor for nonstandard installation
L	Transducer axial separation distance
LAR	License amendment request
LER	Licensee event report
L/D	Length to diameter ratio
MUR	measurement uncertainty recapture power uprate
MWe	Megawatts electric
NIST	National Institute of Standards and Technology
NRC	Usually Nuclear Regulatory Commission but may be National Research Council - Canada Hydraulic Centre (refers to hydraulic laboratory test facility in Ottawa, Canada)
PR	Power recovery
PSU	Pennsylvania State University (generally used instead of PSU-ARL)
PSU-ARL	Pennsylvania State University's Applied Research laboratory
PWR	Pressurized water reactor
PWROG	Pressurized water reactors owners group
r	radius perpendicular to the longitudinal axis of a pipe
RAI	Request for additional information
Re	Reynolds number
RSSI	receiver signal strength indication
SE	Safety Evaluation
SRSS	Square root sum of the squares
(b)(4) [redacted]	
TS	Technical Specification
UFM	Ultrasonic flow meter
V_a	Average velocity of fluid in a pipe
V_m	CROSSFLOW-indicated or measured velocity
VPCF	Velocity profile correction factor
W	Mass flow rate
<u>W</u>	Westinghouse Electric Company LLC
<u>W</u>/AMAG	The term used by the vendor responsible for CROSSFLOW marketing, installation, and training when referring to itself. The NRC uses the same term.
WOG	Westinghouse Owners Users Group

z	axial distance
ρ	Fluid density
σ	Standard deviation. 2σ = uncertainty as used herein (~95 percent of data is expected to be between ± 2σ)
τ	Time for an eddy to pass between two sets of transducers
θ	angular location with respect to a reference radius vector in a plane perpendicular to the longitudinal axis of a pipe

1 INTRODUCTION AND SUMMARY

1.1 Introduction

CROSSFLOW, a UFM marketed by W/AMAG, is typically claimed to measure feedwater flow rate in nuclear power plants within an uncertainty of ±0.5 percent. Consequently, it is used to compensate for fouling in venturis that can lead to operation at less than licensed thermal power and it is used in conjunction with license amendments to operate at higher power levels consistent with the July 31, 2000, change in 10 CFR Part 50 Appendix K to take advantage of more precise flow rate measurement. The former application is referred to as power recovery (PR) and the latter as a measurement uncertainty recovery (MUR) power uprate or "power uprate."

CROSSFLOW operational problems became a focus of NRC's resident inspectors at the Byron and Braidwood nuclear power plants and of NRC's Region III personnel in 2002 due to inconsistencies between CROSSFLOW and all other indications that provided insight into thermal power level at the Byron and Braidwood nuclear power plants. Investigation by the NRC staff identified that the licensee's management and W/AMAG were inappropriately concluding that CROSSFLOW was correct and something was wrong with opposing conclusions being drawn in regard to all other indications. This NRC staff involvement was followed by a significantly enhanced W/AMAG involvement and establishment of an NRC Task Group that determined that the power plants were operating in excess of the licensed thermal power and that there were unresolved issues associated with CROSSFLOW use in nuclear power plants (Reference 1). Subsequent work by W/AMAG and some licensees using CROSSFLOW led to significantly improved understanding of CROSSFLOW operation when installed in nuclear power plants. This increased focus also identified inadequacies and previously unidentified issues that led to assignment of the NRC staff to completely re-examine the hydraulic aspects of UFM operation. This re-examination of the CROSSFLOW UFM is the subject of this report.

The following definitions are used in this report:

- Fully developed flow - The steady state flow condition that exists when at a sufficient axial distance from any perturbation to the flow profile so that there is no variation of velocity with angular or axial position and therefore velocity is only a function of radial position. This may require an axial distance of more than100 to 200 pipe diameters downstream of anything that can perturb the flow profile. Furthermore, different pipe surface roughness and different flow rates will result in different flow profiles with fully developed flow existing in all cases.

- Stable flow - W/AMAG introduced the term "stable flow" in Reference 2. Stable flow or fully developed flow (as used in CENPD-397-P-A, Rev. 1) (Reference 3) is stated to be a condition where the CROSSFLOW meter readings are independent of axial and angular orientation of the CROSSFLOW meter about the pipe. The change with respect to Reference 3 was that fully developed flow no longer referred to developed flow in the classical sense where the flow profile is fully developed.

  In practice, W/AMAG appears to view the test for independence as met when movement does not cause an indicated flow rate change to exceed perceived test condition uncertainty. The NRC staff does not accept this independence test because uncertainty defines a bound where 95 percent of the data are expected to be within the bound and the comparison should be made on the basis of sufficient data to establish an acceptably small bound about the mean value. Furthermore, W/AMAG repeatedly stated that the laboratory test data uncertainty used for calibration, and hence the CROSSFLOW calibration uncertainty, is 0.25 percent. This contrasts with the NRC staff's experience with tests in the same facility where a 0.088 percent uncertainty was obtained and test laboratory personnel estimated an uncertainty of 0.12 percent for the CROSSFLOW tests (Reference 5). In response to the 0.12 percent estimate, W/AMAG stated one should add (b)(4) (b)(4) (Reference 6). W/AMAG also stated that the applicable test was that (b)(4) (b)(4) (b)(4) These values are inconsistent with the CENPD-397-P-A topical report (Reference 3), which stated that the basis for the calibration factor uncertainty was the weight tank uncertainty of 0.25 percent.

The NRC staff uses the term "stable flow" as the flow condition that exists when the CROSSFLOW meter readings are independent of axial and angular orientation of the CROSSFLOW meter about the pipe.

- Non-fully developed flow - This term is used by W/AMAG to describe a location where movement of CROSSFLOW would result in a change in flow rate indicated by CROSSFLOW when there was no actual change in flow rate.

- Standard installation - W/AMAG considers an installation to be "standard" if flow at the CROSSFLOW location is stable, there is no dependency as a function of power greater than (b)(4) and there is no indication of swirl[3] or correlated noise at the measurement location (Reference 7). The Alden Research Laboratory (ARL) calibration (b)(4) (Reference 8). This term was not used in the Reference 3 topical report.

- Non-standard installation - A CROSSFLOW installation in which the flow profile is not in a fully developed/stable flow condition and the calibration must be determined for the specific configuration. Calibration is performed by an in-situ calibration or by extrapolation of a calibration in a test facility where the piping system was modeled.

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[3]Swirl is the existence of a component to the fluid velocity vector that is circumferential or perpendicular to the longitudinal axis of the pipe. With respect to venturis, the ASME established the upper limit for a precision installation as two percent. The NRC staff has not examined the effect of this limit on accuracy. This must be evaluated if venturis are to be used with an uncertainty that is less than the original 2 percent required by the original 10 CFR Part 50 Appendix K. An upper limit for CROSSFLOW has not been established.

1.2 Background

1.2.1 CROSSFLOW Installations

Reference 9 identified the following (b)(4) power recovery CROSSFLOW installations:[

(b)(4)

]and it identified the following (b)(4) power uprate CROSSFLOW installations:[

(b)(4)

]

In general, additional information is necessary for the NRC staff to assess these installations with respect to the claimed uncertainties. This is discussed further in the remainder of this report.

1.2.2 Experience at Byron and Braidwood

Each of the Byron and Braidwood facilities have two units with each unit having a W four loop pressurized water reactor (PWR). CROSSFLOW systems were installed in each of the four feedwater pipes in each of the units with movement of some CROSSFLOW system components between units so that continuous flow rate information was not provided all of the time for all units. CROSSFLOW systems were reviewed, installed, and tested at Braidwood in June, 1999, and at Byron in May, 2000, for power recovery purposes. Installation was in accordance with AMAG procedures for CROSSFLOW operation in existence at the time of installation. Discrepancies were immediately evident between CROSSFLOW and other plant instrumentation, and multiple evaluations were conducted from 1999 through 2003. During this time, the Byron units were operated with the assumption that CROSSFLOW was correct and the Braidwood units also used CROSSFLOW indication of the flow rate for operation.

CROSSFLOWs were installed on feedwater headers in accord with the most recent installation criteria in 2003 and the feedwater header data were compared with data from the previously used CROSSFLOWs on individual feedwater lines. The licensees and W/AMAG initially concluded that there was a good correlation between Braidwood CROSSFLOWs but that the comparison criteria were not met at Byron Unit 1. W/AMAG subsequently found signal noise contamination in some feedwater line CROSSFLOWs and preliminarily concluded that the identified discrepancies were due to noise contamination. On August 28, 2003, Byron Units 1 and 2 were reported to have been overpowered by as much as 1.64 and 0.42 percent, respectively (Reference 10). On August 31, 2003, Braidwood Unit 2 was reported to have been overpowered by as much as 0.8 percent (Reference 11). On March 30, 2004, Braidwood's overpower condition was revised to 1.07 and 1.21 percent for Units 1 and 2, respectively

(Reference 12). On March 31, 2004, Byron's overpower was revised to 2.62 and 1.88 percent, respectively (Reference 13). (Based principally on Reference 14 with overpower values from licensee event reports (LERs) as referenced.)

Permanent CROSSFLOW systems were installed in the common feedwater headers at Byron and Braidwood in 2004. W/AMAG assessed these installations and found them to be free of noise contamination but discrepancies remained between the header and individual feedwater line flow rates determined by CROSSFLOW. A decision was then made to perform an independent validation test using a radioactive tracer. During final stage heater isolation to support installation of tracer test taps, an unanticipated shift in CROSSFLOW calibration factor was observed. (Based principally on Reference 14.)

Tracer testing was conducted at Byron Units 1 and 2 in 2004 with feedwater flow simultaneously measured by venturis, CROSSFLOWs, and a radioactive tracer. Comparisons with the test information and other plant indications led to the conclusion that CROSSFLOWs on both Byron units were under-metering feedwater flow rate and an overpower condition would occur when the units were operated with CROSSFLOW used as the basis of determining thermal power. Subsequent hydraulic testing led to the conclusion that the velocity profile was not developed sufficiently to provide an accurate CROSSFLOW correction factor due to the upstream feedwater configuration. (Based principally on Reference 14.) CROSSFLOW is no longer used at Byron and Braidwood.

W/AMAG summarized the Byron experience in Reference 6 by stating that "noise contamination of the CROSSFLOW signal and the lack of fully developed/stable flow were the prime reasons for the discrepancies at Byron. The lessons learned were incorporated into both the W/AMAG procedures and the new PWR Owners Group CROSSFLOW Task Force (CTF) User Guidelines (Reference 15)."

1.2.3 Experience at Calvert Cliffs

The Calvert Cliffs units were operated for some time with CROSSFLOW in use for power recovery when the licensee requested a power uprate (Reference 16). The licensee encountered difficulties when it pursued CROSSFLOW operation consistent with its planned power uprate and also found an overpower condition. Some of the difficulties have not been resolved.

Each of the Calvert Cliffs units contains a Combustion Engineering (CE) PWR. Unit 1's feedwater loops are designated as loops 11 and 12 and Unit 2's are designated as loops 21 and 22. Each loop includes a control valve, a pipe run with several elbows, a Mitsubishi type flow straightener approximately 11 pipe diameters upstream of a CROSSFLOW, and a downstream feedwater flow venturi. These CROSSFLOWs are in non-standard locations and the ARL calibration was modified to correct for the location effects. W/AMAG stated (b)(4)

(b)(4)

(b)(4) consistent with the requirements of Reference 3 for a fully developed flow condition. (Quote from Reference 6.) Consequently, an additional CROSSFLOW was installed in loop 12 upstream of the flow straightener to calibrate the four permanent CROSSFLOWs.

Reference 17 summarized results from tracer testing performed on August 18 - 19, 2005. On the basis of this testing, Constellation Energy reported Calvert Cliffs Unit 1 operation was at a maximum thermal power of 100.4 percent of licensed power and Unit 2 was at 100.74 percent due to reliance on CROSSFLOW systems. The condition existed from July 22, 2003 (Unit 1) and July 8, 2003 (Unit 2). Therefore, CROSSFLOWs were removed from service on September 12, 2005. Root causes were stated to include:

- Failure to consider data within Reference 3 indicating that the piping/component configuration could produce flow distortions farther downstream than analyzed.
- Weak oversight by W/AMAG.
- Inadequate design input contained in Reference 3.
- Inadequate design review addressing placement of the upstream CROSSFLOW.

The licensee also concluded that "the maximum analyzed steady state reactor core power levels, of 102 percent of rated thermal power or 2754 MWth, were not exceeded during operation with the non-conservative correction factors installed." This conclusion is incorrect since the uncertainty must be applied to the actual power level and not the licensed power level. However, the NRC staff did not recommend pursuing this issue because of the ongoing generic assessment, the perceived small likelihood of having exceeded 102 percent of licensed thermal power, and the margin of safety associated with accident analyses that are affected by changes in thermal power.

Reference 18 provided data from followup testing conducted as part of the commissioning process for a measurement uncertainty recapture (MUR) power uprate where it was decided to confirm the performance of the CROSSFLOW meters using a non-radioactive chemical tracer test. (Some of the Reference 18 tests were observed by the NRC staff on January 25, 2006.) Tracer testing is discussed further in section 3.4.5.

Reference 6 summarized the Calvert Cliffs experience by stating that (b)(4) [redacted] Reference 6 also states that (b)(4) [redacted]

In January 2005, the Calvert Cliffs licensee submitted a licence amendment request (LAR) to increase licensed thermal power. The NRC staff has not responded to the Reference 16 LAR and has stated that it would not do so until the generic CROSSFLOW review was completed.

1.2.4 Experience at Ft. Calhoun

The Ft. Calhoun licensee submitted a LAR for a 1.67 percent power uprate based on a thermal power uncertainty of 0.33 percent on July 18, 2003 (Reference 19). This was revised to a 1.6 percent power uprate on August 28, 2003. The NRC staff approved this request on January 16, 2004 but the licensee encountered difficulties in achieving the claimed CROSSFLOW uncertainty and requested a change in implementation time from 30 days to 120 days on February 6, 2004. The NRC staff approved this request on February 13, 2004. A later LAR resulted in the licensed thermal power being returned to 1500 MWt on May 4, 2004. The power uprate request was resubmitted for a 1.5 percent uprate on March 31, 2005 (Reference 20).

Reference 6 stated that (b)(4) [redacted]

(b)(4) [redacted]

(b)(4) [redacted] ***(Much of this information is provided in Reference 20.)***

The licensee also conducted tests to calibrate its venturis at ARL. These tests are described in section 3.4.4.

The NRC staff has not provided a formal response to the Reference 20 LAR and has stated that it would not do so until the generic CROSSFLOW review was completed.

1.2.5 NRC Staff Response to Operational Experience (Reference 21)

The NRC staff formed a task group in response to the Byron and Braidwood experience to address the following questions:

1. Are UFMs 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?

With respect to the CROSSFLOW UFM, the task group considered CROSSFLOW design, development, testing, application, implementation, maintenance, and W/AMAG followup. The task group determined that generic issues existed and it expanded its investigation to assess temporary installations, power recovery, and power uprates. It used a broad range of sources of information that included extensive data obtained from interaction with NRC Region III, and it conducted independent evaluations of flow profile behavior that could affect CROSSFLOW calibration. In part, the task group concluded that:

- CROSSFLOW is sensitive to the plant configuration, a condition that results in some licensee's limiting its use to the configuration existing at the time of installation.

- CROSSFLOW has not provided the intended accuracy for feedwater flow measurement at some facilities and accuracy questions have arisen in some other plant installations. Some of the questions involve basic CROSSFLOW design.

- CROSSFLOW 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 task group's computational fluid dynamics analyses indicate that a fully developed flow profile can be attained at a distance between 20 and 30 diameters downstream of a uniform velocity inlet but fully developed flow is not obtained even at 100 diameters downstream of an elbow. It will be challenging for any device to properly characterize the flow with one measurement at locations downstream of an elbow if it is not properly calibrated for the given configuration.

The task group concluded "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 (CROSSFLOW) users must address the concerns that are specific to the AMAG UFM in order to provide the required assurance of compliance."

1.3 Conclusions

1.3.1 Traceability to Certified Standards

CROSSFLOW calibrations are not traceable to certified standards. The original calibration of CROSSFLOW is based on tests conducted at ARL. The flow rates and flow rate uncertainty determined at ARL are traceable to the National Institute of Standards and Technology (NIST) standards. However, the calibration of CROSSFLOW is highly dependent upon a specific flow profile. The relation between a certified standard and the flow profile obtained during testing has not been addressed, nor has there been an assessment of the contribution of flow profile variations on the uncertainty of the device. As such, there is no standards continuity when using the test calibration for a CROSSFLOW installation in a plant. Similar concerns apply to in-situ calibration where the original calibration may include traceable elements but traceability may be lost during post-calibration operation.

1.3.2 Statistical Acceptance Tests

The statistical acceptance tests for comparisons and for data convergence are unacceptable. A typical rationale provided by W/AMAG is that if a data set is being evaluated for convergence and the data appear to be converging, then when one or two data values are found that are within the uncertainty bound, one cannot expect better and no further data need be obtained. The NRC staff found that the uncertainty bounds used for the comparisons were approximately a factor of two too large. Further, NRC staff examination of some of the data established that trends were still evident when W/AMAG concluded no further data needed to be obtained. Another rationale is that two data values, such as two flow rates obtained from different sources, are in agreement if the uncertainty bounds overlap. Statistically, this concludes that the data agree when the probability of agreement is a small fraction of a percent. The correct comparison is with respect to mean values since the expectation is that most data will be grouped about the mean value.

1.3.3 Underlying Theory

The NRC staff believes that any attempt to establish the reliability of CROSSFLOW must overcome the basic CROSSFLOW restriction that the flow profile is only sampled along one path between each transmitter and its corresponding receiver. The NRC staff believes that assessment along multiple paths is necessary for a UFM to recognize a flow profile change that may affect calibration.

1.3.4 Calibration Sensitivity

The flow rate error of an uncalibrated CROSSFLOW is about (b)(4) percent. This error must be corrected by one or more calibrations and calibration precision is particularly important due to the large (b)(4) percent correction. As discussed below, CROSSFLOW calibration is sensitive to changes in flow profile and, as identified above, error recognition and correction is complicated by CROSSFLOW's inability to independently recognize a change in flow profile that affects the calibration coefficient.

1.3.5 Basic Laboratory Calibration

The basic CROSSFLOW calibration was accomplished at ARL under what was assumed to be fully developed flow conditions. An observer would typically conclude that fully developed flow existed at the CROSSFLOW location because sufficient separation existed between CROSSFLOW and upstream pipe configuration changes. However, examination of the facility shows that flow at the entrance to the test sections is highly asymmetrical and a high degree of swirl is likely. CROSSFLOW is sensitive to flow profile changes, particularly those associated with swirl.[4] Consequently, the NRC staff believes that fully developed flow must be proven to exist at the CROSSFLOW location in any test facility when that condition is basic to CROSSFLOW's application. W/AMAG has not provided that proof.

Determination of the basic CROSSFLOW calibration coefficient (the velocity profile correction factor or VPCF, C_0) is based upon limited ARL data. However, If the test conditions actually provide a fully developed flow profile, then the determined C_0 appears reasonable for those test conditions. Setting aside the question of adequate simulation of the installation configuration, the NRC staff notes that the ARL data require a factor of five extrapolation of the Reynolds number (Re) to be applicable to nuclear power plant conditions, and evaluation of uncertainty at the Re associated with nuclear power plant operation is not adequately supported.

(b)(4)

(b)(4) the effect of residual noise, if any, on uncertainty or bias was not adequately addressed.

1.3.6 Secondary Laboratory Calibrations

Calibration of CROSSFLOWs located downstream of flow perturbations such as elbows has been accomplished and an additional correction factor has been applied. Typically, W/AMAG assumed flow at the entrance to elbows is fully developed, but this has not been substantiated and, if it is not the case, the calibration may be affected. Where such calibrations are to be used, the effect must be assessed.

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[4]Reference 15 stated that (b)(4)
(b)(4)
With respect to CROSSFLOW, the effect of swirl cannot be predicted to the precision necessary to provide a correction, and the claim that CROSSFLOW measurement will be (b)(4) than actual has not been substantiated.

The calibration data provided to the NRC staff have not been adequate to support the claimed uncertainties. For example, convergence to an acceptable secondary calibration coefficient has been assessed by increasing CROSSFLOW distance from the perturbation to the flow profile and rotating CROSSFLOW circumferentially until a location is found where it is judged that CROSSFLOW movement does not cause a significant change in CROSSFLOW indication. No statistical basis has been provided and the rationale used to determine "no significant change" appears to be based on an inadequate number of data points, an unacceptably large data scatter, and a failure to acceptably demonstrate convergence with respect to position. Furthermore, in some cases tracer testing and analyses have shown that the approach is incorrect. Reference 6 recently addressed part of this concern by stating that, (b)(4) [redacted]

(b)(4) [redacted]

1.3.7 Application of Laboratory Calibration to Plant Operation

In general, W/AMAG's claimed CROSSFLOW accuracy might be acceptable if (a) CROSSFLOW was operated under controlled conditions that were fully encompassed by the test conditions used for CROSSFLOW calibration, and (b) traceability to recognized standards was established. However, the test conditions have not been fully established and it is unlikely that the test conditions will exist in a nuclear power plant. This is important because a change in flow condition may affect the flow profile, CROSSFLOW's calibration is sensitive to changes in flow profile, and CROSSFLOW does not directly recognize a change in flow profile. Furthermore, traceability has not been established.

W/AMAG addresses part of this situation by applying a "stable flow" criterion. Reference 6 states that stable flow exists when the flow profile is independent of orientation and axial location, a definition that is identical to the definition of fully developed flow but, in practice, is inconsistent because of the way "independence" is determined. In practice, a stable flow location is determined by comparing to criteria to establish that sufficient distance exists from upstream perturbations and confirming the adequacy of the location by moving CROSSFLOW axially and circumferentially to assess whether movement causes an insignificant change in CROSSFLOW indication. One issue is determination of what constitutes an insignificant change since the distance effect criterion appears to be that the change is within the claimed uncertainty criterion and the number of data points is insufficient to establish lack of variation. Another issue is presented by the assumption that fully developed flow existed in the test facility when the basic CROSSFLOW calibration was performed.

Where test facility results are used in a nuclear power plant application, a clear basis and value(s) of the uncertainty / bias associated with transferring CROSSFLOW calibration test results to in-plant operation must be established. The existing approach is to state that no allowance is necessary and, for most cases, the test-determined calibration factors may be used directly because this is consistent with venturi applications. As discussed in section 3.4.3.1, this is unacceptable. There must be a well-founded basis for applying test results, including determining uncertainties and/or bias, to in-plant operation where the flow profile may be different from that existing in the tests used for determining calibration factors. A basic problem is CROSSFLOW's inability to directly recognize a change in flow profile when moving from the test facility to the plant installation. This, in turn, raises the question of "Is the

CROSSFLOW-indicated velocity identical to what would have been indicated in the test facility if operated at the plant conditions?" The response must be "yes" for the existing approach to be valid.

A successful CROSSFLOW application requires that CROSSFLOW be operated within a region where the calibration and application flow profiles are sufficiently identical that the calibrations continue to apply. W/AMAG has not established that CROSSFLOW will meet this criterion when transferring from test conditions to plant conditions. (Changes during operation are addressed in section 1.3.9.)

1.3.8 In-Situ Calibrations

In some cases, in-situ calibrations eliminate the issues associated with transfer of laboratory calibrations to plant applications. However, in-situ calibrations have not been demonstrated to acceptably address issues associated with CROSSFLOW calibration change due to changes in flow profile following calibration. There are questions regarding in-situ calibrations that must be addressed before an initial calibration uncertainty can be acceptably established. For example, chemical tracer in-situ calibrations have not been demonstrated to provide sufficient sensitivity to support the claimed uncertainties. The test data assessed by the NRC staff exhibit a test sensitivity of (b)(4) when translated to flow rate. This is insufficient for calibration of CROSSFLOW with a claimed uncertainty in the vicinity of 0.5 percent. Furthermore, use of ARL data to establish a recalibration of tracer results does not appear to consider uncertainty of the ARL data, and the recalibration introduces a non-conservative factor into the CROSSFLOW calibration.

Venturi in-situ calibrations have unresolved issues that potentially affect the claimed uncertainties. These include concerns regarding test pipe diameters, venturi differential pressure determination, and venturi fouling.

1.3.9 Operational Assessment

CROSSFLOW calibration is affected by changes that routinely occur in a nuclear power plant. Changes that can invalidate the calibration include:

- Thermal power level and hence feedwater flow rate
- Valve position and valve wear or replacement
- Feedwater heater configuration
- Feedwater pump operation, wear, and replacement
- Feedwater pipe fouling, defouling, and other changes that affect pipe roughness
- Noise

W/AMAG recognizes these calibration challenges and has taken steps to address them. One such step is to restrict operation to conditions where operating conditions are believed to be sufficiently consistent with test conditions that the flow profiles and hence calibrations remain unchanged. Thus, for example, power level is typically limited to (b)(4) percent or greater and valve configuration changes that are recognized to potentially change the flow profile are not permitted when CROSSFLOW is being used to determine flow rate.

Reference 22 stated that CROSSFLOW systems include comprehensive diagnostics and self-checking to alert the user of off normal conditions. The NRC staff recognizes that approximately (b)(4) database monitoring parameters are assessed by online monitoring and system diagnostic alarms and, if an alarm is received, then other plant parameters may be assessed to determine CROSSFLOW validity. It also appears that the calibration coefficient can typically vary by (b)(4) percent before an alarm is initiated, and alarm setpoints can be adjusted based on licensee judgement regarding the cause of venturi calibration changes. However, the NRC staff has not seen an acceptable demonstration to establish that the calibration coefficient variation is consistent with the claimed uncertainty

Part of the process for checking CROSSFLOW involves comparisons to other plant parameters that can be used to track thermal power. These parameters generally have larger uncertainties than claimed for CROSSFLOW. This makes it difficult to assess CROSSFLOW performance. W/AMAG has not provided a statistically valid application of other parameters to substantiate that CROSSFLOW is operating as claimed and to provide early detection of CROSSFLOW problems.

W/AMAG has significantly improved checking for noise contamination since 2000 and extensive data processing appears to have reduced noise contamination concerns. However, W/AMAG has not acceptably addressed the effect of residual CROSSFLOW noise contamination on uncertainty.

The ability to remain within conditions where the flow profile is sufficiently close to the profile that existed during calibration to reasonably ensure meeting the claimed uncertainty is an unresolved issue.

1.3.10 Operating Experience

Operating experience ranges from overpower conditions to claims of excellent performance and stable operation. Some of the stable operation claims were not verified when the NRC staff closely examined the data. No instances were found where the claimed uncertainty was acceptably verified. Further, data were not provided for many applications.

The NRC staff concludes that W/AMAG has not substantiated that this information acceptably establishes that the claimed uncertainties are achieved.

1.3.11 Other Operational Considerations

Existing CROSSFLOW installations were put in place without addressing many of the recently identified issues. The NRC staff was informed that this was addressed by a re-validation activity that was to confirm (b)(4) (b)(4) (b)(4) (Reference 15). However, existing CROSSFLOW installations have not been established as being consistent with the latest information applicable to CROSSFLOW installation and operation, nor has the existing information been established as adequate to reasonably assure the claimed uncertainty is achieved

W/AMAG has stated that for all Appendix K applications, the specific issues found occurred during the commissioning process and not during operation. Although the statement appears to be correct in regard to the W/AMAG work, it is incorrect from the NRC staff's viewpoint because numerous issues have been identified in all aspects of CROSSFLOW use. The plant-specific issues have been found during followup regarding recent license amendment requests (LARs) where more intensive resources have been applied. Whether application of similar intensive resources would result in discovery of unrecognized issues in previously approved applications is a concern.

Although information has been provided to support a claim that CROSSFLOW accuracy and uncertainty have been demonstrated under fully developed/stable flow conditions (Reference 23), no information was provided specifically addressing the presence of non-stable flow at CROSSFLOW locations in existing, previously-approved installations.

Some of the laboratory calibration processes used in existing applications are now recognized by W/AMAG as incorrect and are not to be used for new applications. The impact on existing applications has not been satisfactorily assessed.

1.3.12 User Guidelines

W/AMAG provided Revision 0 of the "CROSSFLOW Ultrasonic Flow Meter User Guidelines" in June, 2005. This improved generic guidance for CROSSFLOW users but did not address all known issues. The NRC staff observes that information obtained since the Guidelines were written has rendered that document obsolete and W/AMAG is rewriting the Guidelines.

1.3.13 Topical Report

The NRC staff has concluded, from information that became available following its initial review of the topical report, that its understanding of the basis of Reference 3 at the time of its review was incorrect. As a consequence, the NRC staff's previous review described in Reference 24 is no longer valid. Therefore, the NRC staff concludes that Reference 3 is no longer acceptable as a basis for use of CROSSFLOW for either power uprates or power recovery.

The NRC staff notes that W/AMAG plans to revise the topical report so (b)(4) (b)(4) (b)(4) (Reference 6) This topic is discussed in section 3.3.7.

1.3.14 Future Requests for CROSSFLOW Use

CROSSFLOW calibration processes and CROSSFLOW use need improvement. Although W/AMAG have provided substantial improvement since early 2005 with such guidance as the User Guidelines (Reference 15) and the potential use of in-situ calibrations for non-standard installations, further improvement is necessary.

Physical aspects of the installation must be improved. An acceptable installation process must be followed and corresponding commitments to follow this process must be in place.

Further changes are planned, including (from Reference 6) (b)(4) (b)(4) (b)(4)

Since these planned improvements have not been finalized or fully described to the NRC staff, they are not been directly addressed in this report and the degree to which they address the NRC staff's concerns has not been determined.

Any request for future application of CROSSFLOW to determine feedwater flow rate should, at a minimum, address all of the issues identified in this evaluation. Failure to do so may result in rejection of the LAR. To minimize NRC staff, vendor, and licensee resource requirements, the NRC staff recommends that a revised topical report that contains suitable references to other new or revised reports be used as the basis for future applications. This should include coverage of aspects specific to power recovery since some of the data usage may differ from that used for operation under a power uprate condition.

1.3.15 Conclusion Summary

CROSSFLOW's inability to directly assess the flow profile and flow profile changes, the need for a substantial calibration factor that is strongly influenced by changes in flow characteristics, and failure to achieve traceability to recognized standards are major weaknesses that are the direct cause of many of the other identified issues.

Most of the above information was not appreciated when the NRC staff initiated its investigation of the Byron / Braidwood overpower condition, and W/AMAG and the licensees initially maintained CROSSFLOW was operating correctly and was consistent with the claimed precision. However, as the NRC staff continued its investigation, W/AMAG increased its own followup and, as summarized above, discovered an increasing number of problems, some of which invalidated previously provided information. As a result of this experience, the NRC staff has concluded that CENPD-397-P-A contains errors and does not address many issues associated with changes in W/AMAG description changes, pre-installation testing, installation, commissioning, and monitoring, and issues remain that must be satisfactorily addressed before there is reasonable assurance that the uncertainties associated with CROSSFLOW measurement of feedwater flow have been appropriately determined.

Consequently, the NRC staff has concluded that (1) the existing previously approved CENPD-397-P-A topical report is an inadequate basis for using CROSSFLOW to determine feedwater flow rate and (2) a basis has not been established for such use that acceptably addresses the issues discussed in this NRC staff assessment.

2 INSTRUMENTATION AND REGULATORY CONSIDERATIONS

2.1 Instrumentation Calibration

Traceability is a process whereby a measurement is related to a standard. The standard must be acceptable to all parties with an interest in the measurement and is usually a standard maintained by a national laboratory such as NIST. Each step between the measurement and the standard must be clearly defined and can contain no unverified assumptions, and the steps must provide an unbroken path between the measurement and the standard. Furthermore, since there will be an uncertainty associated with each step, the total uncertainty of the measurement must reflect the aggregate uncertainties of each step in the process.

There are several considerations applicable to CROSSFLOW uncertainty that are associated with hydraulic behavior. These include:

- Pre-delivery: When an experimentally determined calibration coefficient is to be applied to a plant application, the coefficient must be measured over a sufficient range of conditions that the calibration is applicable to the conditions of use when installed in the plant. Furthermore, the test facility flow methodology must use certified standards that are traceable to NIST or a similar keeper of standards. The uncertainties should be bounded by analysis of test results. W/AMAG has not established the traceability to standards with respect to extrapolation of Reynolds Number from the test facility to the plant application. Furthermore, the test data that meet certified traceability to standards used for obtaining the calibration coefficient are limited[5] and the test conditions have not been proven to provide fully developed flow when determining the calibration coefficient.

- Commissioning: A complete comparison of test and in-plant results must be accomplished to validate accuracy. Comparisons should also be made with other plant parameters as a check and to provide insights relative to plant operation. W/AMAG has not established traceability to standards for this step nor has it shown that the CROSSFLOW calibration coefficient remains valid since there is no proof that the flow profiles in the test facility and the plant installation are sufficiently close to satisfy the uncertainty claims.

- Operation: CROSSFLOW characteristics are monitored and annunciated if changes occur that are considered to be greater than ascribable to normal condition changes. An additional check is recommended using comparison of CROSSFLOW predictions with other plant parameters consistent with good operating procedures applicable to any instrumentation. However, W/AMAG has not established that the monitoring process is consistent with the claimed operational uncertainty, it has not established that the cause of the change can be determined consistent with the claimed operational uncertainty, and licensees have not established that they will follow the monitoring process as part of the licensing basis.

2.2 Compensatory Confirmation for Calibration Weaknesses

In Reference 22, W/AMAG pointed out that References 3 and 24 recognize the use of in-situ calibration where the ARL C_0 is not directly applicable. The NRC staff agrees, but notes there are qualifications regarding such applications that were not addressed in the references. For example, W/AMAG has not established that future operation will be under conditions that are sufficiently close to those existing at the time of calibration for the claimed uncertainties to remain valid. Another example is that a change in swirl can affect the flow rate indicated by both CROSSFLOW and the venturi, a condition W/AMAG has not identified to the NRC staff and a condition that potentially complicates validation of CROSSFLOW when comparing to other plant parameters or correcting for venturi fouling.

W/AMAG has not addressed the interaction between corroborating information that has a relatively high uncertainty, sometimes of several percent, and the typical CROSSFLOW claim of achieving a 0.5 percent thermal power uncertainty. It would be informative, for example, to

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[5]ARL determinations of feedwater flow rate provide a clear example of traceability to recognized standards. This traceability has not been established in regard to the ARL flow profile. Many of the feedwater flow rate plant comparisons using in-plant instrumentation and CROSSFLOW do not satisfy the traceability requirement.

compare the statistical uncertainty associated with multiple "other plant indications" as part of the application. It would also be informative to consider the difference between assessment for the purpose of establishing thermal power and for trending a change between CROSSFLOW and the other indications. In response to this observation, Reference 6 stated the W/AMAG/CTF members (b)(4)

(b)(4)

Such assessments may not meet the certification process of relating the measurement to a standard that was described above. Achieving that relationship would require at least one of the instruments involved in the certification to have traceable credentials. Finally, although one may establish an acceptable certification with respect to the conditions existing at the time of the certification, one must also be able to establish that conditions existing at other times are sufficiently close to the certification conditions that the certification remains valid.

2.3 Licensing Basis for Application of Crossflow to Thermal Power Determination

All 10 CFR 50.90 LARs for use of CROSSFLOW and the applicable W/AMAG generic communications either incorporate topical report CENPD-397-P Revision 01 (Reference 3) by reference or use it as part of the justification for the application.

The Reference 24 approval stated that:

(1) AMAG (CROSSFLOW) 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 AMAG to pursue plant operation at a higher power level, within the limitations of the license.

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

(4) The increased AMAG accuracy 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.

Experience obtained since publication of References 3 and 24 has shown that CROSSFLOW 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. Any change in velocity profile between the test and the initial plant installation will potentially affect the calibration. Furthermore, any change in plant operating conditions, such as changing feedwater valve positions or swaping feedwater pumps, has the potential to change velocity profile or generate noise that affects the CROSSFLOW flowrate indication.

These effects have been found to be more prevalent and to propagate for significantly greater distances downstream of the perturbation than were believed to be the case when the NRC staff performed its Reference 24 review.

At the time of its review of Reference 3, the NRC staff believed that the theoretical basis for CROSSFLOW was well founded in the fully developed flow condition and that deviations from this condition were similarly well founded. Furthermore, W/AMAG has changed aspects of its approach such as referring to a specific location of eddies preferentially sensed by CROSSFLOW in the pipe radius as representative of the CROSSFLOW output and via the introduction of the "stable flow" concept that is claimed to be identical to "fully developed flow" insofar as CROSSFLOW output is concerned[6]. The NRC staff has established that the theoretical basis of the NRC staff's understanding when it prepared Reference 24 is no longer correct via such work as Reference 25 (see section 3.1.2), and the NRC staff has concluded that the actual basis for CROSSFLOW applications in determination of thermal power in nuclear power plants is essentially empirical.[7]

The guidelines addressed in Reference 3 were broad, not consistently followed, and operating experience obtained since the NRC staff approved CROSSFLOW has shown that the Reference 3 guidelines were not sufficient to reasonably ensure acceptable operation. New guidelines (Reference 15) have been published that provide significant improvement but these are not sufficient to meet CROSSFLOW usage requirements. A revision is being prepared.

The licensee and the W/AMAG submittals that have been provided since publication of References 3 and 24 have concentrated on power uprate applications under 10 CFR 50.90 that require NRC approval. With the exception of the user guidelines (Reference 15), there has been little mention of power recovery that has been addressed by application of 10 CFR 50.59. The NRC staff, as identified in item 4, above, intended that the same rigor be applied to power recovery applications as was needed for power uprates. This was not the case at the Byron / Braidwood installations (References 21 and 26) and the NRC staff has not been provided with docketed information to substantiate that it is the case for all other power recovery applications. At present, such confirmation would require individual inspections at each potentially affected licensee's site, a resource-intensive process for both the NRC and individual licensees. Addressing the situation by a generic process that was approved by the NRC and could be referenced by the licensees would be a better approach. However, both the 50.59 and the 50.90 processes require an acceptable CROSSFLOW basis that addresses the issues identified in this report.

In Reference 24, the NRC staff stated:

> Should our criteria or regulations change so that our conclusions as to the acceptability of the report are invalidated, ABB-CE and/or the applicants referencing the topical report will be expected to revise and resubmit their respective documentation, or submit justification for the continued applicability of the topical report without revision of their respective documentation.

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[6]The term "stable flow" does not appear in References 3 or 24.

[7]This should not be interpreted to mean that an empirical basis is unacceptable.

The NRC staff has concluded that the NRC staff's understanding of Reference 3 at the time of its review was incorrect. Furthermore, Reference 3 is obsolete and, as discussed in section 3.3.7, is to be rewritten. As a consequence, the Reference 24 review is no longer valid. Reference 3 is no longer an acceptable basis for use of CROSSFLOW for either power uprates or power recovery.

Reference 22 stated that "the PWROG (pressurized water reactors owners group) participants have confirmed that their installations satisfy the recommendations made in TB-04-4." In Reference 6, W/AMAG stated the (b)(4)

(b)(4)

(b)(4) As previously identified, such confirmations have not been provided on the docket to the NRC and, if they were, the present understanding would be insufficient to address the issues identified herein.

2.4 Issue Resolution

As is discussed later in this report, the NRC staff has concluded that:

- The tests that W/AMAG has reported for determination of stable flow are inadequate,
- Establishment of stable flow during installation does not ensure that stable flow will continue during operation, and
- The criteria used by W/AMAG to determine a standard configuration where laboratory calibration data are considered to be directly applicable are inadequate.

Reference 9 summarized the domestic CROSSFLOW installation status as of October, 2004, and included related findings from the CROSSFLOW Baseline Validation Reports (BVRs). Some of that information is provided in the following table where numbers in the last column refer to NRC staff observations that are provided following the table:

(b)(4)

(b)(4)

(b)(4)

Note Number	Apparent Deficiency Based On Limited Information Provided In Table
General	Many of the NRC staff observations are the result of an inadequate quantitative basis for the W/AMAG conclusions or an unacceptable statistical test. An example of the former is inadequate data to clearly establish convergence of CROSSFLOW indication as a function of axial position downstream of an elbow to establish the distance where the elbow no longer affects CROSSFLOW indication. An example of the latter is the assumption that obtaining one or two data points that are within the 95 percent uncertainty bound is sufficient to establish agreement or convergence, an assumption that fails to consider that the most likely condition for agreement or convergence is represented by multiple values in the immediate vicinity of the mean value. The NRC staff notes that (b)(4) (b)(4) (Reference 15). This excludes new information and new procedures that are identified in many of the following notes that may invalidate the calibrations. This is discussed further immediately following this table.

Note Number	Apparent Deficiency Based On Limited Information Provided In Table
1	The L/D correlations that address CROSSFLOW response to distance downstream of elbows is not acceptable. Closely related to this topic is the Reference 6 comment that (b)(4) [redacted]
2	Use of a calibration method in one loop is generally not acceptable for calibration in another loop. Reference 6 stated that (b)(4) [redacted]
3	The assumption that test data or extrapolated test data may be used without change in an application has not been established to be acceptable. Closely related to this topic is the Reference 6 comment that (b)(4) [redacted]
4	The assumption that an indication of change by CROSSFLOW is due to a flow rate change requires an in-depth comparison to plant data that is based on an acceptable methodology. Reference 6 stated that (b)(4) [redacted]
5	An acceptable uncertainty must include consideration of all contributors. These must typically include the uncertainty associated with transfer from a test facility to an application (if used), the uncertainty associated with in-site calibration (if performed), and uncertainty where a change in CROSSFLOW indication occurs due to the need to verify behavior by use of other plant parameters.
6	The NIST report was not provided and consistency between (b)(4) [redacted] and NIST was not established.
7	Recommended testing was not addressed.
8	Quantitative justification for "close agreement" was not provided.
9	Components that potentially disturb the flow profile must be acceptably addressed.
10	The effect of feedwater heater changes was not addressed.

Reference 9 also stated that (b)(4) [redacted] Reference 6 stated that (b)(4) [redacted] Based on the Reference 6 discussion, the NRC staff anticipates that these improvements will address (b)(4) [redacted] The NRC staff also notes that Reference 9 states, in regard to non-standard installations, that a CROSSFLOW can be

"calibrated using a second CROSSFLOW meter that meets the requirements of a standard installation on either the same loop or on a second loop with a similar piping geometry. (b)(4)
(b)(4)

3 CROSSFLOW ASSESSMENT

3.1 Crossflow Technology

3.1.1 Operation Summary

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

$$W = \rho A V_a \quad (1)$$

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

and it is assumed that the fluid is at a uniform temperature since ρ is treated as a constant over the cross-sectional area of the pipe.

The objective of a UFM is to provide V_a.

The one thing many UFM designs have in common is that they use one or more transducers to generate and receive an acoustic wave. The way the wave interacts with the fluid and the method used to process the results of the interaction may be completely different with no relationship between various UFM designs.

A schematic illustration of a CROSSFLOW installation is illustrated in Figure 1 where 1 and 2 are transmitters that send a vertical acoustic wave downward to the receivers. The transmission wave with a frequency of about (b)(4) is perturbed by turbulence in the flow that affects propagation speed and the receiver reads a random phase-modulated version of the transmitted signal. When receiver 2 recognizes a phase-modulated signal from transmitter 2 as similar to the one previously received by receiver 1, the differential time is the time it took for the eddies that caused the perturbation to travel the distance between the two sets of transducers. Thus, CROSSFLOW provides a differential time signal that is the time for an eddy to pass between two sets of transducers, τ, that are a known axial distance, L, apart. The CROSSFLOW-indicated or measured velocity, V_m, then follows from:

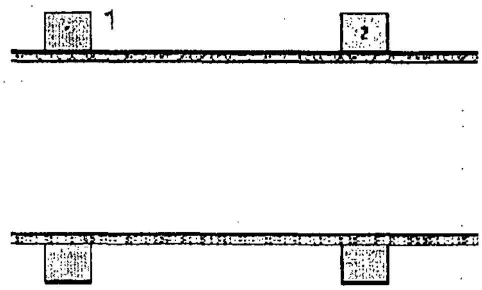

Figure 1. CROSSFLOW Schematic

$$V_m = L / \tau \quad (2)$$

If CROSSFLOW were "perfect" and directly indicated the actual average velocity, v_a, there would not be an issue concerning hydraulic behavior and CROSSFLOW indication. But CROSSFLOW, in common with other UFM designs, is subject to errors that are potentially significant in light of the small uncertainties claimed for feedwater flowrate determination in nuclear power plants.

There is no available theoretical correlation of V_m that will guarantee an acceptably accurate 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 CROSSFLOW. V_a follows from:

$$V_a = W / (\rho A) \quad (3)$$

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

$$V_a = C_0 \; V_m \quad \text{or} \quad C_0 = V_a / V_m \quad (4)$$

where: C_0 = Velocity profile correction factor (VPCF)

Test data typically result in a C_0 of about (b)(4) for CROSSFLOW and hence C_0 has a significant effect on the flow rate provided by CROSSFLOW. Therefore, to realize the claimed uncertainty, C_0 must be accurately determined and, equally important, the effect of any changes that affect the calibration must be accurately accommodated

Prior to 2005, W/AMAG described CROSSFLOW as tuned to preferentially select an eddy size and hence a velocity that corresponded to a specified radial location (b)(4) between the surface and the centerline of the pipe. This is stated in Reference 3 in the response to the NRC staff's request for additional information (RAI)-3 that states "it can be observed that (b)(4)
(b)(4)
(b)(4) There is no valid theoretical or experimental basis for this statement. More recent descriptions omit the radial location reference and correctly describe the uncorrected CROSSFLOW indicated velocity as representative of eddy velocity. For example, Reference 28 states that "CROSSFLOW measures the weighted average velocity of the turbulent pattern (eddies) in the pipe; not the velocity profile." This is a valid statement with respect to CROSSFLOW since CROSSFLOW does not measure the velocity profile nor does it measure any particular velocity. Either description leads to the same initial approach to CROSSFLOW calibration where W/AMAG has assumed appropriate test conditions existed for determination of C_0. The NRC staff notes that W/AMAG clarified the eddy location topic in Reference 6 by pointing out that (b)(4)
(b)(4)

There has been significant questioning and discussion regarding whether CROSSFLOW can directly provide information that identifies if a change in flow profile has occurred that affects C_0 for fully developed flow (or a standard installation), or the additional calibration factors that must be applied for nonstandard installations if using a laboratory calibration. The NRC staff, and W/AMAG via a contract to Pennsylvania State University's Applied Research laboratory (PSU-ARL), have independently developed theoretical assessments in References 25 and 29, respectively, to gain insight into this topic. These assessments are covered in sections 3.1.2 and 3.1.4.

3.1.2 NRC Staff Theoretical Analysis

In Reference 25, Orechwa addressed the fundamental question of whether CROSSFLOW would capture sufficient information to support the claimed accuracy and precision. He approached this by focusing on the way CROSSFLOW output is related to the velocity profile. The first step was to rewrite the basic flow rate Equation 1 as follows:

$$\mathbf{W}_{fw} = C * A_p * \tilde{n}_{fw} * \mathbf{v}_B \qquad (5)$$

where: A_p = flow area of the pipe
$\tilde{n}_{fw}$ = density of the water
$\mathbf{v}_B$ = estimated mean value of the bulk fluid velocity
C = calibration coefficient that corrects $\mathbf{v}_B$ to an average mean value

The fluid velocity as a function of position and time can be represented by Figure 2 and by Equation 6:

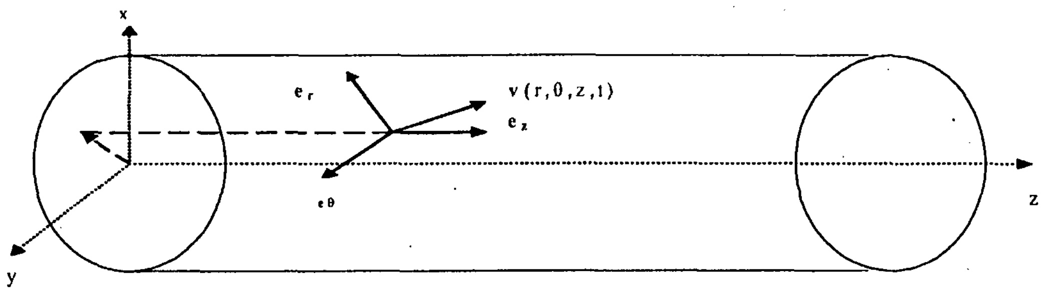

Figure 2. Velocity Representation

$$\mathbf{v}(r, \grave{e}, z, t) = v_r(r, \grave{e}, z, t)\mathbf{e}_r + v_{\grave{e}}(r, \grave{e}, z, t)\mathbf{e}_{\grave{e}} + v_z(r, \grave{e}, z, t)\mathbf{e}_z \qquad (6)$$

where $\mathbf{e}_r$, $\mathbf{e}_{\grave{e}}$ and $\mathbf{e}_z$ are the usual orthonormal basis vectors of the cylindrical coordinate system. Now, $\mathbf{v}_B$ can be obtained by evaluating the expression:

$$\frac{1}{\pi(R^2)} \int v(r,\theta,z,t) \cdot \mathbf{e}_z \, dA$$

where R is the pipe radius and A is the cross-sectional area. This leads to:

$$\mathbf{V}_B(z,t) = \frac{1}{\pi R^2} \int_0^R \int_0^{2\pi} \mathrm{V}_z(r,\theta,z,t)\, r\, dr\, d\theta \qquad (7)$$

where only the axial component of the fluid velocity field contributes to the computation of $\mathbf{v}_B$.

Figure 3 is a schematic representation of the essential elements of CROSSFLOW:

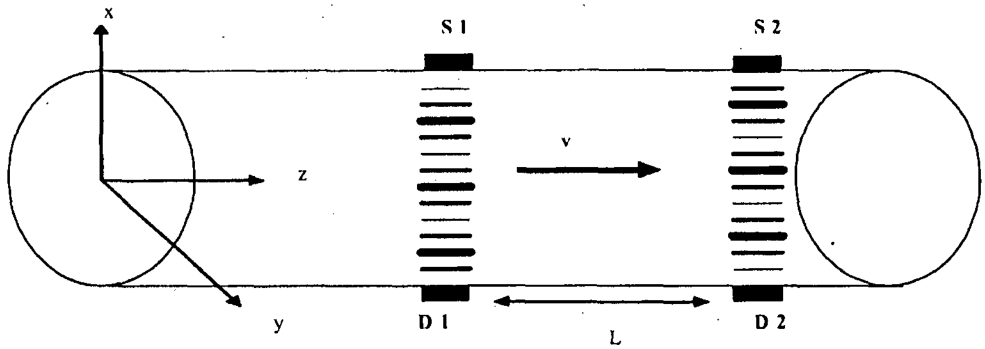

Figure 3. CROSSFLOW Essential Elements

The Crossflow algorithm is predicated on the ability to associate a "signature" with the fluid passing the detector at a given point in time. If the signature is sufficiently unique and stable to be "recognized" at another downstream detector, the axial fluid velocity in the pipe can be estimated by dividing the distance L between the two detectors by the difference in the time τ at which the signature is detected at each detector. That is:

$$\mathbf{v}_B = L / \tau \qquad (8)$$

Now assume a monochromatic sound wave is generated by the transducer S1 that is illustrated in Figure 3. This generates a plane wave in the diametric direction of the pipe, i.e. $\mathbf{k} = -k\,\mathbf{e}_r$ where $k = 2\pi/\lambda$. In general, this plane wave can be written as:

$\varphi_T(\mathbf{r}, t) = A \exp$ (b)(4) (9)

where c_s is the velocity of sound in the fluid. If the fluid is stationary, the detector D1 response is also given by Equation 9. If the fluid is moving with a velocity $\mathbf{v}$, the detector response is given by (Reference 30):

$\varphi_D(\mathbf{r}, t) = A \exp$ (b)(4) (10)

Thus, due to the moving fluid, the frequency shift in the detected plane wave is governed by the inner product of the direction of the plane wave and the velocity of the fluid.

For ideal non-rotational flow (laminar flow), only the axial component of the fluid velocity exists ($\mathbf{v} = \mathbf{v}_z\mathbf{e}_z$) and the detected plane wave is the same as the source plane wave ($\mathbf{k}\cdot\mathbf{v} = k\mathbf{v}_z\,\mathbf{e}_r\cdot\mathbf{e}_z = 0$). Consequently, CROSSFLOW will not indicate a flow rate. Stated differently - no turbulence, no signal; a conclusion that is immediately obvious because, to generate a signal, CROSSFLOW senses velocity changes with components parallel to the radial direction along the sonic beam that are associated with eddies that result from turbulence.

Feedwater flow is characterized as turbulent flow that is both rotational flow and a spatially complex distribution of vorticity **ω(r,t)** which advects itself in a chaotic manner in accordance with (Reference 31):

$$\frac{D\omega}{Dt} = (\omega \cdot \nabla)\mathbf{v} + \upsilon \nabla^2 \omega \tag{11}$$

The velocity field **v(r**,t**)** is related at any instant to the vorticity **ω(r,t)** through the Biot-Savart law:

$$\mathbf{v}(\mathbf{r},t) = \frac{1}{4\pi} \int \frac{\omega(\mathbf{r}',t) \times (\mathbf{r}-\mathbf{r}')}{|\mathbf{r}-\mathbf{r}'|^3} d\mathbf{r}' \tag{12}$$

Now consider **ω(r,t)** as a random vector from a probability density function g(**ω(r,t)**)[8] where g(**ω(r,t)**) completely characterizes the state of turbulent flow. Then, as a function of **r**, **ω(r,t)** is a time-dependent random field. It follows from Equation 12 that the measured quantity that completely characterizes the random field **v(r**,t**)** is also a random field characterized by some probability density function f(**v(r**,t**)**). Thus, the fluid velocity in turbulent flow is a random vector field with three non-zero random components v_r(r, θ, z, t), v_θ(r, θ, z, t), and v_z(r, θ, z, t). And the existence of the non-zero radial component v_r(r, θ, z, t) means that the phase shift in the expression that is Equation 10 is non-zero. In other words, CROSSFLOW will provide a signal. The phase shift at the detector D can be expressed in its most general form as:

$$\xi(\theta,\ z, t) = 2 \int^{t} dt' \int_{0}^{R} dr\ v_r(r, \theta, z, t') \tag{13}$$

The function ξ(θ,z,t) is the signature seen by CROSSFLOW. Since v_r(r, θ, z, t) is a random function, the integral and consequently the phase shift are also random functions. Now, conceptually, CROSSFLOW computes $\mathbf{v}_B$ in Equation 8 by measuring the time τ between the observations of the same signature given by Equation 13 at the two positions on the pipe.

Now several observations may be made:

- The fundamental equation for the mean velocity, Equation 7, is a function of only the axial component of velocity, v_z(r, θ, z, t). Conversely, the basis of CROSSFLOW's determination of mean velocity in Equation 8, ξ(θ,z,t) from Equation 13, is only a function of the radial random component of velocity, v_r(r, θ, z, t).

- The relation of ξ(θ,z,t) to v_r(r, θ, z, t) is not unique. As shown in Equation 13, CROSSFLOW sees only an integral of the velocity field component and does not see its distribution. Yet it is the distribution that characterizes the velocity field and not its integral. In effect, Equation 13 represents the classic inverse problem (Reference 32) that can only be addressed with a-priori knowledge about the integrand in Equation 13.

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[8]g(**ω(r,t)**) is a probability density function with respect to the random variable **ω** and a function with respect to the variables **r** and t.

- The CROSSFLOW signature cannot take into account azimuthal or axial velocity components should they exist. Such components will likely exist unless a fully developed flow condition exists.

- Even with fully developed flow, $v_r(r, \theta, z, t)$ will be a function of Reynolds number and pipe roughness, variables that CROSSFLOW does not address.

Reference 25 continues with further discussion of interactions between turbulence, mean flow rate, the velocity distribution, and Reynolds considerations, and identifies a mathematical formulation of why a fully developed flow condition is necessary for CROSSFLOW determination of flow rate. However, the above discussion is sufficient to identify the concerns with respect to this NRC staff's evaluation.

The above discussion is limited to a single transmitter transmission frequency. Section 3.1.4 introduces the thought of using (b)(4) (b)(4) Even if this can be sufficiently developed to be viable with respect to the uncertainties that are desired, the NRC staff notes this would only provide a velocity distribution along one path through the flow stream. Multiple paths would be necessary to obtain the velocity distribution through the plane perpendicular to the pipe axis, and the complete velocity distribution is necessary to determine flow rate from the velocity distribution.

3.1.3 Discussion of W/AMAG Response to NRC Staff Analysis

In response to Orechwa's paper, Reference 22 stated that "Westinghouse/AMAG do not fully concur with NRC on performance in non-fully developed flow conditions. (b)(4) (b)(4) (b)(4) W/AMAG continued by identifying "the need for calibration in prototypic flow field conditions." Calibrations identified are laboratory testing, comparison with a CROSSFLOW meter in a "standard" installation, tracer testing, or use of a calibrated venturi..

The NRC staff notes that, on page 1, Orechwa stated the he wished to address "the fundamental question (of) ... whether the necessary information in the velocity field is captured by the instrument so that the flow ... is predicted with the accuracy and precision claimed." On page 2, he stated that "the central issue that we wish to explore is whether the information captured through a Crossflow measurement is sufficient for the prediction of the bulk velocity of the fluid with reasonable assurance that the uncertainty claimed is valid." He concluded that CROSSFLOW, for other than fully developed flow, does not provide sufficient information to identify a change in the velocity profile that affects the calibration coefficient. W/AMAG appears to agree with this conclusion, but adds that the issue can be addressed via suitable calibrations.

For the W/AMAG qualification to be valid, W/AMAG must establish that the initial calibration is sufficient to support the claimed uncertainty and that the conditions that existed during the calibration do not change sufficiently to affect the qualification. The issues therefore are establishing that the claimed CROSSFLOW uncertainties are valid and that CROSSFLOW is only relied upon when conditions are sufficiently close to the calibration conditions for the calibration to remain valid. In conclusion, the W/AMAG response is for non-fully developed flow conditions where Orechwa concluded the theoretical basis is insufficient. This is the situation in most, if not all, nuclear power plant feedwater installations.

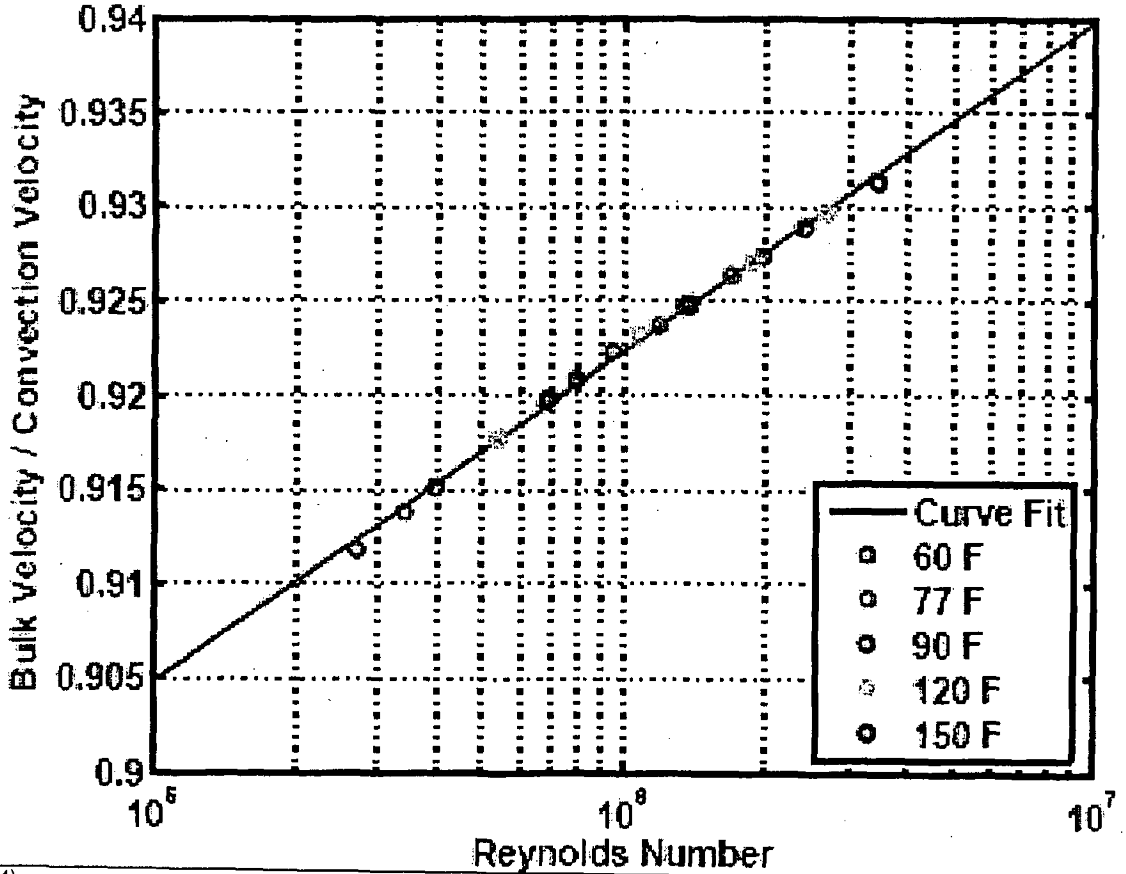
3.1.4 W/AMAG/Pennsylvania State University Theoretical Analysis

PSU assumed (b)(4) of the turbulence on the basis that the former is often a reasonable approximation in complex flows and computationally intensive simulations would otherwise be necessary, and the latter is claimed to be a reasonable approximation given the roughly one diameter transducer axial spacing. (b)(4) may be reasonable in the absence of swirl and other perturbations, such as in fully developed flow that is not close to the wall, but may have significant limitations in nuclear power plant applications. (b)(4) is reasonable in fully developed flow without swirl but, again, these conditions are unlikely in a nuclear power plant. Orechwa made essentially the same assumptions but with one distinction - the Orechwa model was for the purpose of obtaining insights and was not an attempt to portray behavior.

In its initial modeling effort, PSU used a simplified CFD simulation that would not capture large scale non-symmetric flow disturbances like swirl to predict the characteristics of a 12 inch diameter pipe with smooth walls for comparison to model calculations that covered Re up to (b)(4)

(b)(4) Results are illustrated in Figure 4 where bulk velocity is the slug flow value at the entrance and convection velocity is the prediction of the value that would be provided by

[9]The PSU model would not address large scale non-symmetric flow behavior but the use of a more complete CFD simulation would provide a wider range of comparisons.



(b)(4) [redacted]
CROSSFLOW.

The PSU curve fit to the data was reported as:

(b)(4) [redacted]

where:

- U_o = bulk (slug flow) velocity
- U_c = calculated CROSSFLOW-indicated velocity

and the velocity ratio is the equivalent of the CROSSFLOW calibration coefficient. The authors "cautioned that the curve fit may only be valid over the Reynolds number range of (b)(4) [redacted] (b)(4) [redacted] Values were not provided and the NRC staff therefore could not numerically evaluate the curve fit. However, the NRC staff notes that the input values exhibit a decrease in slope with increasing Re that is not reflected in the straight line curve fit.

For comparison purposes, the NRC staff compared the above equation predictions with the following equation that W/AMAG developed from ARL smooth pipe data for what was assumed to be fully developed flow as discussed in section 3.4.2.1:

(b)(4)

(b)(4)

where C_0 is the CROSSFLOW calibration coefficient. The result is illustrated in Figure 5.

The difference at the lowest Re is (b)(4) percent and this decreases to (b)(4) percent at Re = (b)(4) behavior that may lead to the lines crossing at higher Re. (Note this is beyond the PSU limit of (b)(4) With reference to the observation regarding curvature with increasing Re in Figure 4, the correspondence may be closer than illustrated.

(b)(4)

PSU provided the comparison to data reproduced in Figure 6. The data are confusing. For example, the Alden (ARL) data are below the model curve, but in the NRC staff's comparison, it was above the curve.

This is illustrated in Figure 7. The top curve is a curve fit to the ARL data the NRC staff has referenced in numerous locations in this report that is used by W/AMAG for CROSSFLOW calibration; the middle curve is the PSU theoretical curve; and the bottom curve, reproduced approximately from Figure 6, is stated by PSU to be ARL smooth pipe data. The NRC staff understands that the top curve is for plastic pipe that is essentially smooth pipe. The difference is unexplained at this time. (Further attention is given to the effect of pipe roughness in section 3.4.2.1.)

(b)(4)

Reference 6 also presented curves showing the predicted behavior with (b)(4)

(b)(4)

On page 45 of Reference 6, W/AMAG states that (b)(4)

(b)(4)

(b)(4) These conclusions are incorrect. The NRC staff notes that the PSU-ARL work is preliminary and not fully substantiated, the theoretical developments assume (b)(4) in developing the mathematical representations that are used to provide insight, it is incorrect to presume that fully developed flow and stable flow are the same, Orechwa did not conclude that CROSSFLOW was capable of identifying a change in flow or of quantifying the magnitude of that change, and it is incorrect to state that flow profile is only a function of the Reynolds number. The last point is illustrated by considering a condition in which Reynolds number is constant and flow rate is constant, but there is a change in the pipe wall condition so that the friction factor changes. This change can affect the flow profile and hence have an influence on the CROSSFLOW transit time calculation. Furthermore, Reference 7 states that (b)(4)

(b)(4)

Reference 7 also raises the possibility of (b)(4)

(b)(4)

(b)(4) The NRC staff does not recall previous identification of this concept and, to the NRC staff's knowledge, it is not incorporated into CROSSFLOW's data processing algorithm. Furthermore, no information has been provided regarding uncertainties associated with the measurements and the probability distribution function is not known. The NRC staff regards this approach to obtain more information as conjecture until such time as additional information is provided. Furthermore, even if the determination could be satisfactorily developed, Reference 7 goes on to state that (b)(4)

(b)(4)

The NRC staff concludes that the modeling work is interesting and predicts certain general behavior for fully developed flow, but it is not sufficiently developed to predict within the uncertainties claimed for CROSSFLOW nor is it applicable to non-fully developed flow - the conditions that are generally of concern for nuclear power plant applications.[10]

Where feedwater enters a common header upstream of the UFM, there is a possibility that temperature will not be uniform at the UFM location. In some cases with off-normal feedwater heater operation, a temperature difference of as much as 30°F or 40°F may occur. Non-uniform temperature is not addressed by the theory.

Finally, (b)(4) the single path information provided by CROSSFLOW and the theory, by itself, will provide little insight regarding changes in the flow profile from the flow profile that existed in the experiment and such changes, if they occur in the application, may invalidate the calibration.

3.2 Fully Developed Flow Versus Stable Flow Versus Non-Fully Developed Flow

Reference 3 described CROSSFLOW as tested and applied with "fully developed flow," but did not identify the term. The NRC staff observes that there is no generally accepted theory or model that will provide the velocity profile during turbulent flow with sufficient precision to meet the uncertainty claims associated with CROSSFLOW. Thus, it is unlikely one can confidently use a theoretical model to correlate flow rate to any particular measured velocity. The best that can be expected is a combination of measurements of axial velocity as a function of radial and angular position in a plane perpendicular to the pipe axis in combination with an empirical approach to establish an axial velocity plane that can be integrated over the plane to obtain flow rate. From this viewpoint, a fully developed flow condition would be established when at a sufficient axial distance from any perturbation to the flow profile so that there was no variation with respect to axial distance or angular position within the plane. This is the definition the NRC staff has consistently applied to "fully developed flow."

Experimentally and by CFD analyses, when swirl is present, fully developed flow may not be achieved in less than an axial distance of more than about 100 to 200 pipe diameters

[10]Neither PSU nor W/AMAG claimed the theory was sufficiently developed to achieve predictions within the uncertainties claimed for CROSSFLOW.

downstream of anything that can perturb the flow profile.[11] The NRC staff notes that the long pipe length requirement was not identified in References 3 and 24 and all of the information provided at that time did not involve identification of the potential need for these long pipe lengths.

W/AMAG introduced the term "stable flow" in Reference 2 with the statement that:

> Stable flow or 'fully developed flow' (as used in CENPD-397-P-A, Rev. 1) refers to a condition where the CROSSFLOW meter readings are independent of axial and angular orientation of the CROSSFLOW meter about the pipe. It does not refer to developed flow in the classical sense, (i.e., where the flow profile is fully developed).

W/AMAG further stated:

> There has been no change in the condition needed by CROSSFLOW to achieve its flow measurement function as defined in CENPD-397-P-A, Rev.1. There has only been a semantic change made in an attempt to clarify a recognized point of confusion.

The introduction of "stable flow" is inconsistent with the NRC staff's understanding of the term "fully developed flow" when it performed the Reference 3 topical report assessment. For example, in Reference 24, the NRC staff reported that "the VPCF (velocity profile correction factor) curve developed in the topical report assumes that the velocity profile is fully developed, and the curve compared favorably to experimental data from the tests using smooth pipe[12].... This limiting condition provides confidence that the velocity measured by the UFM will be equal to or greater than the actual flow velocity."

The difference is important since fully developed flow may not be achieved in a nuclear power plant and the definition difference, as applied, has important operational and theoretical impacts. This is illustrated by considering that CROSSFLOW provides a differential time that is a measure of the axial component of eddy velocities located along a diametral path with essentially an unknown weighting as a function of eddy size provided it does not register an eddy that has moved radially or tangentially between the two axial transducer locations. Flow rate is obtained by correlating experimentally determined flow rate to the CROSSFLOW indication. Thus, if CROSSFLOW is located in a region where the flow profile differs from the calibration test profile, there is a potential that the CROSSFLOW calibration will not be valid since it is not evident that CROSSFLOW can recognize that the flow profile has changed from the valid calibration condition.

The NRC staff will continue to use the term "fully developed flow" as having the meaning used by the staff in the above discussion. In contrast, the NRC staff will accept the W/AMAG definition of stable flow as a characteristic applicable to CROSSFLOW for purposes of the

[11] These distances are identified in many references. See, for example, Reference 1.

[12] The assumption that the use of smooth pipe results in a velocity equal to or greater than the actual flow velocity, a conservative condition, has not been established, as discussed in section 3.4.2.1.

review and the reader should recognize that the definitions may result in different flow profile conditions.

Non-fully developed flow is used by W/AMAG to describe a location where movement of CROSSFLOW would result in a change in time difference, and hence flow rate, indicated by CROSSFLOW when there was no actual change in flow rate.

3.3 General Considerations

3.3.1 Support Activities

When the Byron / Braidwood difficulties were first being recognized, W/AMAG support activities were limited in comparison to what is provided today. There has been a significant change. The owners groups have reorganized and are more active, as evidenced by publication of user guidelines and interactions with the NRC staff, and W/AMAG has provided enhanced in-depth support to assist in addressing installation and operation problems. As mentioned in the next section, the users guidelines were an excellent step in approaching application of CROSSFLOW to determine feedwater flow rate although much work remains. In addition, the analysis of flow profile downstream of the flow control valve at Calvert Cliffs, as discussed in section 3.4.3.4, provided a clear understanding of what was occurring and led to potentially significant changes in guidance for CROSSFLOW installation and operation.

3.3.2 User Guidelines

The guidelines addressed in Reference 3 were broad and not consistently followed. Operating experience obtained since the staff approved CROSSFLOW has shown that the Reference 3 guidelines were not sufficient to ensure acceptable operation and supplemental guidance and improved vendor/user interactions have been provided by W/AMAG to correct some of the weaknesses. One step in improving guidance was development of the User Guidelines (Reference 15). These were described in Reference 2 as covering the following areas:

- Theory and Overview of the CROSSFLOW Technology
- Use and Application
- Operation Management
- Operating Experience

The reference continued by stating that the User Guidelines (b)(4) [redacted] (b)(4) [redacted] (b)(4) [redacted] The NRC staff notes that the Guidelines provided new information, and the NRC staff considers the Guidelines as an excellent improvement over past guidance to reliably assess, install, and use CROSSFLOW in the feedwater systems of nuclear power plants, although the Guidelines did not acceptably address all issues identified at the time he Guidelines were written. Many aspects of the Guidelines have been identified during discussion elsewhere in this report and will not be repeated here. This is particularly true of Appendix D to the Guidelines. However, one aspect was particularly important in attempting to compensate for a basic CROSSFLOW weakness, as summarized in the remainder of this section.

In the Byron overpower situation, many plant parameters were inconsistent with the thermal power that resulted from use of CROSSFLOW to determine feedwater flow rate. Most licensee personnel, W/AMAG personnel, and NRC staff members accepted the CROSSFLOW determination on the basis of the perceived accuracy, and the licensee continued to operate in an overpower condition until it was proven that CROSSFLOW was incorrect. Reference 15 directly addressed this situation by stating that (b)(4) [redacted]

(b)(4) [redacted]

(b)(4) [redacted] The following list contains typical points measured in nuclear power plants that are directly related to or are indicators of feedwater flow rate:

- Steam generator or reactor feedwater flow (venturis)
- Feedwater pump suction flows
- Feedwater pump discharge pressure
- Final feedwater temperature
- Reactor steam dome pressure (BWRs)
- Condensate pumps discharge flow
- Heater drain pumps discharge flow
- Steam flow
- Turbine first stage pressure
- Low pressure turbine inlet pressure
- Generator MWe output
- Turbine throttle (control) valve position
- Additional CROSSFLOWs
- Turbine vendor heat balance
- Feedwater pump driver amps or steam flow rate

Reference 15 continued with recommendations to improve the precision of some of the above items, and provided examples of values and uncertainties as a function of steam flow rate.

Had these items been objectively considered initially, the NRC staff believes that the Byron overpower condition would have been identified immediately.

With the possible exception of ASME flow sections, the distribution functions and uncertainty associated with the listed items are not as well known as is claimed for CROSSFLOW, but individual item uncertainty is clearly larger than claimed for CROSSFLOW. Information from the listed parameters could be statistically combined insofar as is practical to reduce the overall uncertainty for assessing CROSSFLOW, but the NRC staff has not been provided with that assessment. Furthermore, the parameters and CROSSFLOW should be trended to maximize information use and to provide an early indication if a parameter is becoming inconsistent with other parameters. Processes of this type must be accomplished as an input to any acceptable process that is used to establish CROSSFLOW uncertainty when installed in a nuclear power plant feedwater pipe.

Significant additional information and understanding have been obtained since the guidelines were published. W/AMAG and the AMAG Westinghouse Users Group (WOG) (b)(4) [redacted]

(b)(4) [redacted]

3.3.3 Noise Contamination

The eddy transit time measured by CROSSFLOW can be contaminated by noise originated by such behavior as pipe vibration and interaction with pipe supports. Typically, the signal was to be checked for noise as part of the installation process and corrections were to be made if noise was found so that it would not be a factor during operation. This was briefly identified in Reference 3 with the statements that "this type of noise rarely occurs" and "proper filtering can be used to eliminate undesirable frequency." The NRC staff did not audit W/AMAG's and the user's treatment of noise and this subject was not mentioned in the NRC's Reference 24.

In investigating the Byron / Braidwood overpower condition, the NRC staff found that some users were not aware of this potential condition. Furthermore, operational experience has shown that the noise handling process was inadequate, noise contamination has contributed to plant operation above the licensed thermal power level, and noise has complicated both laboratory testing of CROSSFLOW and its installation and operation. These difficulties were not recognized by the vendor in the first few years of CROSSFLOW use. For example, (b)(4)

(b)(4)

(Reference 33). The rejected results were later reported to have been contaminated by noise. Furthermore, when CROSSFLOW was installed at Byron, a cursory noise evaluation was conducted in which noise was not recognized. If all Byron and Braidwood installation configurations had been checked, the NRC staff believes it is likely that noise would have been discovered as a problem that had to be addressed.

Reference 26 reported on application (b)(4)

(b)(4)

There is general agreement between the (b)(4) correction methodologies but clearly, there is an uncertainty associated with correction for noise that must be considered in assessing overall CROSSFLOW performance.

Reference 2 identified (b)(4)

(b)(4) Since then, the inadequacy has been addressed by W/AMAG supplemental guidance and improved vendor - user interactions and further improvements are planned. For example, Reference 6 stated that (b)(4) (b)(4) The NRC staff anticipates that this will improve noise handling processes and further reduce the likelihood that unrecognized noise will significantly contaminate CROSSFLOW output data. On this basis, and in recognition of the past work accomplished by W/AMAG, the NRC staff believes that issues due to noise have been effectively reduced by supplemental guidance and improved vendor - user interactions. Consequently, noise contamination is no longer of significant concern to the NRC staff provided CROSSFLOW is installed and operated in accord with W/AMAG guidance that addresses the issues identified in this report and provided an acceptable uncertainty is used to cover noise contamination that may remain after correction.

3.3.4 Bracket Installation and Transducer Replacement Considerations

(b)(4)

W/AMAG, in Reference 6, stated that (b)(4) (b)(4)

Reference 34 provided data for (b)(4) (b)(4) where the transducers were removed, the brackets were moved, and the transducers were replaced. Reference 4 provided additional information regarding the tests, identified that there were (b)(4) (b)(4) Reference 6 reported that a review of the (b)(4) (b)(4) The NRC staff independently confirmed that these values are consistent with the data. Reference 4 continued with the conclusion that (b)(4) (b)(4) (b)(4) Reference 6 later stated that, (b)(4) (b)(4)

As discussed in section 3.4.1, the NRC staff expects most data to be well within the 2σ limit, a limit that realistically includes most outliers but is not the expectation. In fact, 68 percent of the results are expected to be within a 1σ limit. Stated differently, if the SRSS for a 1σ limit is 0.25, then (b)(4) is within that limit and perhaps not too far removed from the mean. This implies that uncertainty associated with the effect of moving brackets and reinstalling transducers may be small and data uncertainty may be a more significant contributor. Nonetheless, an uncertainty must be included given the small overall uncertainty claimed for CROSSFLOW.

In its June 2, 2006 Reference 6, W/AMAG stated that (b)(4) [redacted] The NRC staff's position is that data must be provided to substantiate the success (b)(4) [redacted]

3.3.5 Use of Flow Straighteners

Flow straighteners that consist of roughly 25 holes of various sizes drilled in a thick plate are often used to reduce the effects of upstream perturbations on flow instruments such as venturis. They work by increasing the velocity within the holes and generating approximately parallel downstream flow paths that are typically assumed to recombine within about 5 to 10 L/Ds downstream with a significant reduction in swirl. This may be beneficial with CROSSFLOW assemblies provided the assembly was calibrated with a flow straightener in the same location since it is doubtful the vortices sensed by CROSSFLOW will have reached an equilibrium condition for some distance. For example, Reference 18 stated that flow profile downstream from the Mitsubishi style flow straighteners was not stabilized at the CROSSFLOW locations. The separation distance is a little greater than 10 L/Ds. If a sufficient separation distance exists, then such installations may meet the criteria for stable flow.

Further evaluation of flow phenomena and interaction of flow with CROSSFLOW appears to substantiate this conclusion for ARL and other test conditions for those tests where noise contamination was absent, a Reynolds number extrapolation is not required, and when test conditions are consistent with a fully developed flow condition; however, as discussed in section 3.4, this has not been proven. This conclusion does not apply to installations in a nuclear power plant because, in part, W/AMAG assumes the test condition uncertainty applies to the plant if fully developed or stable flow conditions exist in the plant.

3.3.6 Use of Computational Fluid Dynamics

Computational Fluid Dynamics (CFD) provides a picture of flow behavior within piping but must be applied with care since, at its present state of development, it is as much art as science. For example, mesh size and boundary modeling can have a significant effect on results and cannot be relied upon to predict flow profile as a function of axial position in a pipe.

Reference 3 discussed use of CFD to assess applications where layouts were inconsistent with previous installations or there was a potential for anomalous conditions that could impact flow measurement, testing, or in-situ calibration. Reference 22 stated that (b)(4) [redacted] Further, Reference 15 stated that CFD could be used to evaluate flow disruptions such as due to thermo-wells, welds, and thermal streaming from feedwater heaters. Yet, only three cases of CFD have been identified to the NRC staff and two of those, for Ft. Calhoun and Calvert Cliffs, were conducted following installation when problems occurred. These were the most recent installations and they were subjected to more in-depth examination by the NRC staff than was used when examining previous installations. In addition, the Ft. Calhoun and Calvert Cliffs installations appear to have been subjected to the most in-depth evaluation by W/AMAG using the latest accumulated information. Information to adequately establish that CFD analyses were unnecessary in other applications has not been provided. This implies that serious consideration of CFD for nuclear applications was only recently accomplished.

W/AMAG has concluded that CFD is (b)(4) (b)(4) (Reference 2) The NRC staff agrees. The NRC staff notes that the value of CFD has been demonstrated several times when addressing UFM issues. For example, the staff used it to illustrate the distance a flow disturbance can propagate downstream of a disturbance in Reference 1, and CFD's value in assessing the CROSSFLOW inaccuracy found at Calvert Cliffs was clearly illustrated in Reference 18.

3.3.7 Topical Report Revision

Reference 35 described plans to revise Reference 3 (b)(4)

(b)(4)

3.4 Calibration

3.4.1 Overview

W/AMAG has provided methods for assessing corrections for such configurations as upstream single elbows, multiple elbows, and other hardware effects. These assessments are based upon limited data, and careful examination of the flow profile effects and the result on CROSSFLOW flow rate indication show they do not adequately support the W/AMAG conclusions regarding CROSSFLOW location and uncertainty.

One of the problems is the W/AMAG use of uncertainty to support adequate agreement or convergence. Typically, if the convergence of data is within the uncertainty, then W/AMAG has sometimes assumed the data have converged and no further data need to be obtained. Similarly, if two sets of data are compared and the uncertainties of each set overlap, then W/AMAG concludes the data agree. To examine this approach, consider the Figure 8 illustration of a normal distribution that is reproduced from Wikipedia (July 15, 2006):

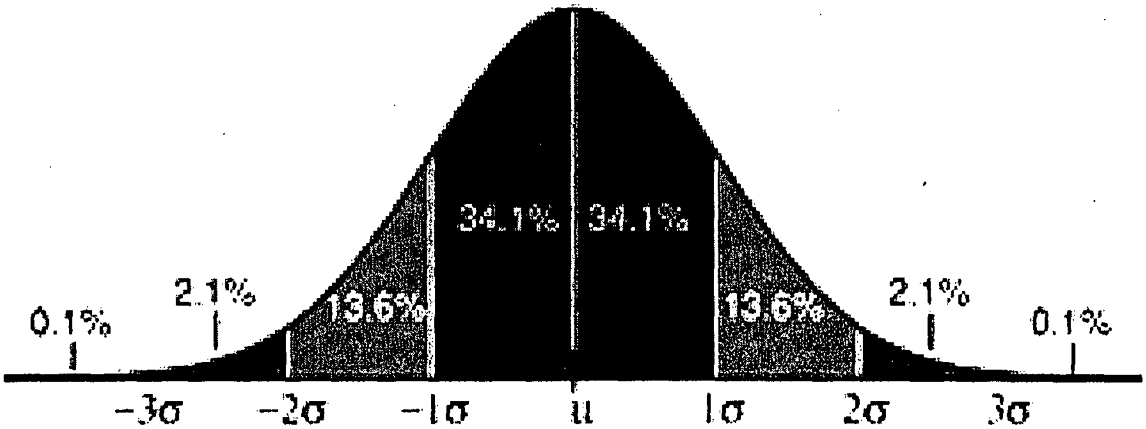


Figure 8. Normal Distribution

where μ is the mean value and σ is the standard deviation. One expects that 68.2 percent of the time, a data point will fall within 1σ of the mean and 95.4 percent of the time, it will fall within 2σ of the mean. (Uncertainty, as used by the organizations of interest here, is represented by the 95 percent bound which is approximately the same as 2σ.) To conclude that data have converged on the basis of one or a few samples being within the 2σ limit because the data scatter means one cannot do better is illogical. It fails to recognize that the expected value is the mean value, that the mean of a large number of samples will approach the true mean value, and, if the samples exhibit a trend, then sampling must be continued until convergence toward a mean is reasonably assured. W/AMAG and licensees appear to meet these principles when determining mean CROSSFLOW-indicated flow rate in power plants, but do not meet them when making decisions regarding test data applicable to such effects as determination of distance necessary downstream of an elbow so that the elbow no longer affects CROSSFLOW.

A similar misapplication of statistics has been used when deciding whether CROSSFLOW results are acceptable. Consider information provided by two independent variables where there is an overlap of the data as illustrated in Figure 9:

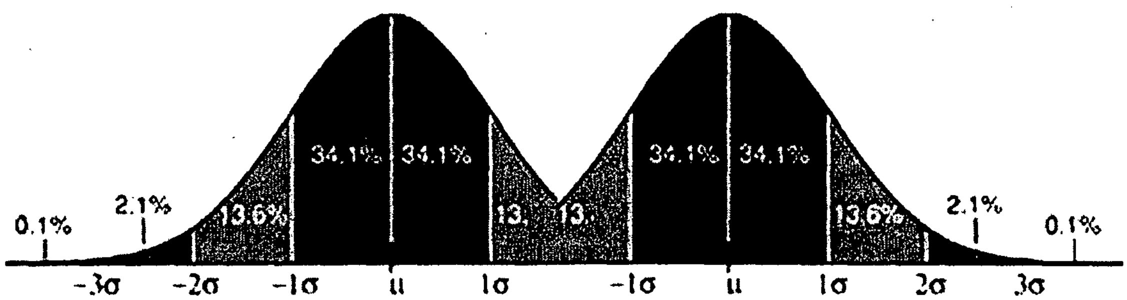


Figure 9. Overlapping Distributions

The area to the right of the mean is 0.5. The area to the right to the point of overlap in the left variable is 0.341 + 0.130 = 0.471, and the overlapped area is 0.5 - 0.471 = 0.029. Data selected at random for the left variable will overlap data for the right variable 2.9 percent of the time and the same is true for overlap of the left variable by data from the right. Stated differently, the probability that a datum from the left will overlap the right distribution at the same time as a datum from the right overlaps the left distribution is 0.029 X 0.029 = 0.00084, an unlikely occurrence. Yet this is the rationale that was applied to Byron when CROSSFLOW indicated one flow rate and other parameters indicated a different flow rate when the licensee concluded that the data were in agreement when the uncertainty bounds overlapped.[13]

3.4.2 Laboratory Testing

Tests at high Reynolds numbers are discussed in section 3.4.6.

3.4.2.1 Fully Developed Flow

Reference 24 states that Reference 3 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 CROSSFLOW test data obtained at ARL in 1996 with (b)(4) [redacted] (b)(4) [redacted] Many other W/AMAG references have provided the data, including the 1996 Reference 33 and the March 17, 2006, Reference 36, illustrating that W/AMAG has consistently based C_0 on the same ARL data.

The NRC staff has assessed the data by initially considering the ARL test facility and its operation consistent with traceability to accepted reference standards. The facility is illustrated in the Figure 10 sketch of the ARL test facility used for CROSSFLOW testing. Flow

[13]The indicated probability is only an example to indicate the process. The quantitative value should not be taken as applying to Byron or any other case.

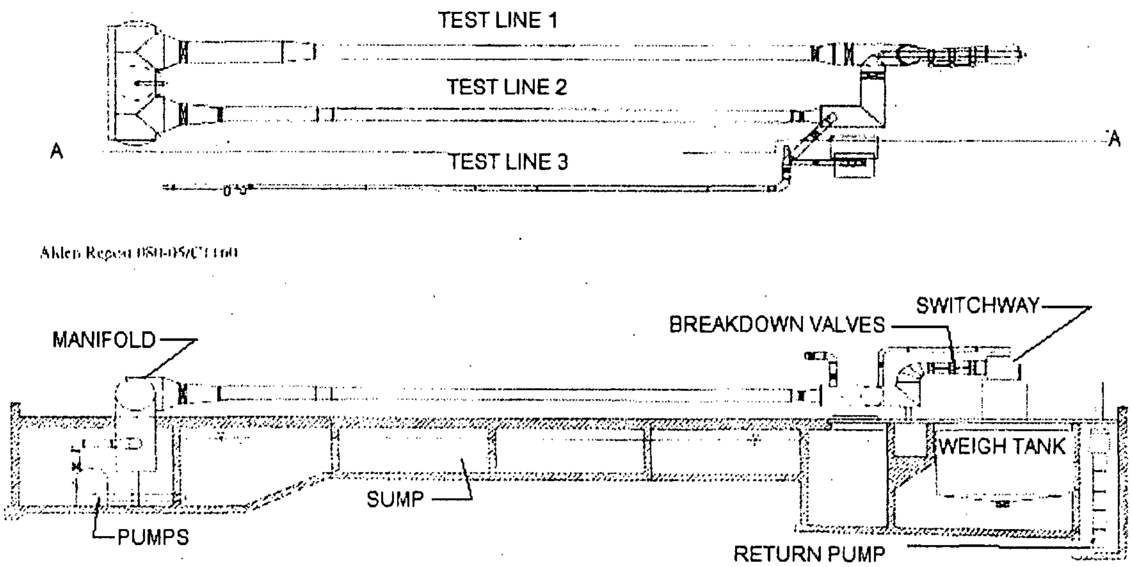


Figure 10. ARL Test Facility

in the test sections starts with a pair of pumps in the lower left, passes through the test sections, through the breakdown (throttle) valves, through the switchway (diverter), and either into the weighing tank or into the sump. The outlet from the breakdown valves is at atmospheric pressure and activities in the switchway have no influence on flow rate. The switchway consists of a manifold where water drops vertically onto a knife edge diverter plate that sends flow to the weighing tank or to the sump. During steady state operation, the knife edge is out of the flow stream. During switching, the knife edge accelerates to a constant rate prior to entering the flow stream and decelerates after leaving the flow stream as illustrated in Figure 11. This restricts diverter interaction with the flowstream during diverter movement to times when diverter movement is constant. Hence, by recording time in the center of the diverter movement for both initiation and termination of weighing tank fill, error due to switching is minimized.

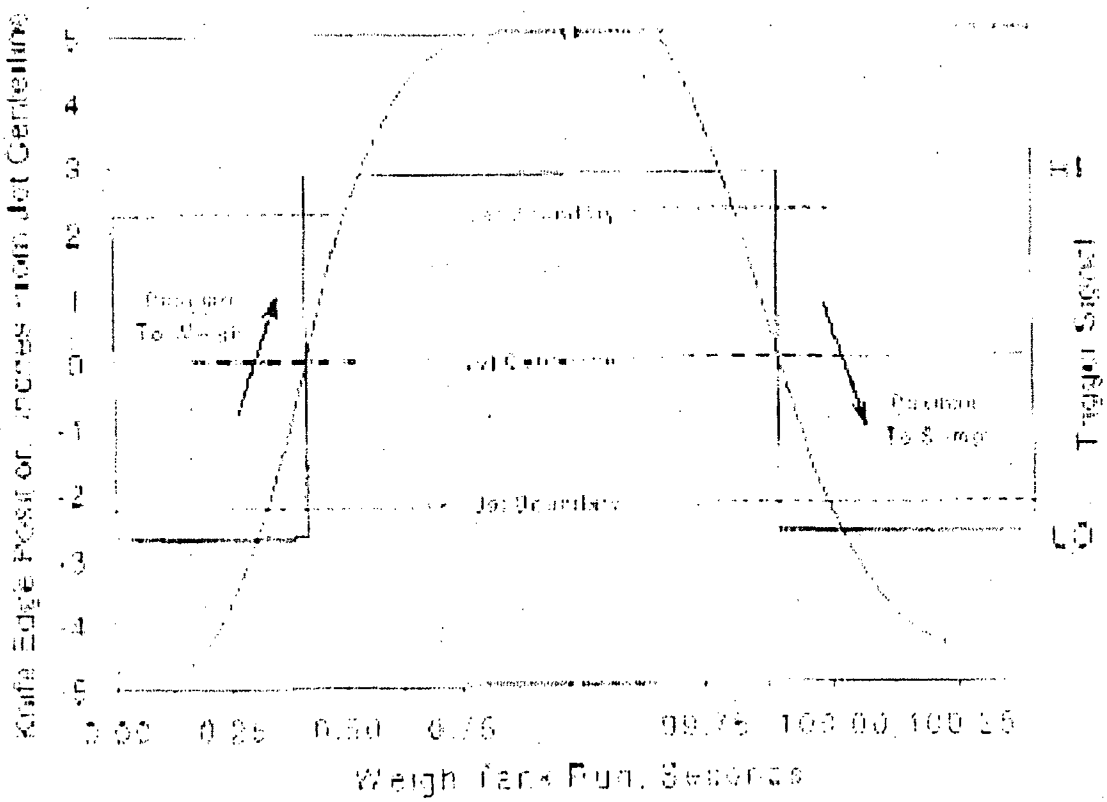


Figure 11. ARL Diverter

Jim Nystrom, Senior Vice President of ARL, provided an analysis of the facility in support of the tests described in Reference 5, in which he stated that the standard deviation due to the diverter was 0.0100 percent (Reference 37). This is a small contribution to the overall standard deviation of 0.044 percent (uncertainty of 0.088 percent or two standard deviations) that applied to the tests being conducted at that time. The other contributors to uncertainty are controlled by NIST-certified standards (mass, time, and temperature), transfer standards, and determination of such variables as water density and buoyancy due to air.

In examining the ARL facility, note that flow from the pumps into the manifold and from the manifold into the two test sections occurs over a short path with abrupt turns. This introduces the possibility of noise, poorly developed flow profiles, and swirl in the test sections; all items of concern with UFMs that are generally of lesser concern when testing other devices. It has no effect on the weigh tank results and on the ARL test flow rate uncertainty.

Overall, although there is no proof that fully developed flow exists in the ARL tests, the combination of flow straighteners, pipe lengths, and the comparison of CROSSFLOW coefficients obtained from ARL and from (b)(4) lead to a conclusion that the ARL data may be reasonably representative of close to fully developed flow and likely meet the criteria for stable flow insofar as CROSSFLOW behavior is concerned. However, in light of the small claimed uncertainties, the NRC staff is concerned that an unquantified uncertainty due to a small deviation from fully developed / stable flow may exist. Information regarding the ARL tests provided to the NRC staff has not addressed this potential situation, and this has not been included in the W/AMAG uncertainty assessments.

W/AMAG has repeatedly stated that the uncertainty of the ARL data, and hence of the CROSSFLOW calibration, was 0.25 percent, significantly greater that the 0.088 percent stated above. An NRC staff member discussed this with Dr. Nystrom on January 18, 2006. Dr. Nystrom said the 0.25 percent value is a generic value that is provided if a test-specific uncertainty is not requested. He estimated that the test-specific uncertainty associated with the 1996 ARL CROSSFLOW tests was less than about 0.12 percent. This difference is significant since W/AMAG cites the 0.25 percent value repeatedly to support conclusions regarding test results and that one cannot do better than 0.25 percent when comparing the CROSSFLOW correlations to other data. Furthermore, as discussed above, use of uncertainty in this manner is incorrect. Uncertainty, as used for CROSSFLOW application and assuming the ARL uncertainty applies, means that one expects to find results within the uncertainty band of 2σ = 0.12 percent 95 percent of the time and within 0.06 percent (1σ) 68 percent of the time. Stated differently, one should expect results close to the mean most of the time. Any other uncertainty assumption regarding the ARL data is unacceptable. The same conclusion applies to any other applications with respect to the uncertainty values that apply to other applications.

When the NRC staff provided this assessment to W/AMAG, W/AMAG confirmed the (b)(4)

(b)(4)

(b)(4) This inclusion of additional uncertainty contributors is in direct conflict with Reference 3, which stated that the ARL data provided the bases for assigning the ARL weight tank uncertainty of 0.25 percent to the correction factor.

The NRC staff does not believe the uncertainty discussion in Reference 6 is correct. (b)(4) CROSSFLOW flow rates were obtained from the ARL tests with about (b)(4) CROSSFLOW data points per flow rate. The configurations were as follows (Reference 33):[

(b)(4)

]

The (b)(4) test is clearly independent of the (b)(4) tests with respect to L/D and flow area. However, the (b)(4) tests were likely conducted with the same pipe and the area would not be expected to vary from test to test. The (b)(4) tests may have been conducted without moving the transducer brackets and, if this was the case, transducer spacing would be expected to be constant. Furthermore, if a bracket was used that provided a fixed axial transducer spacing, then transducer spacing would not be independent in any of the (b)(4) tests. Consequently, the SRSS method would not be applicable since data independence is necessary to use the method. Finally, the NRC staff does not believe the flow area uncertainty is the same for (b)(4)

Reference 33 provided the Figure 12 sketch of the (b)(4)

(b)(4)

W/AMAG has discussed the use of plastic pipe for its calibrations and has stated that this is a conservatism (see, for example, References 3, 6, and 38). This is an important consideration since introduction of conservatism would tend to reduce the potential impact of concerns regarding presence of non-fully developed flow in the ARL tests. Comparison of plastic and steel pipe is covered later in this report section.

Flow straighteners were discussed in section 3.3.5. Other aspects of these tests are discussed in the remainder of this subsection.

(b)(4) test results were reported, of which (b)(4) were reported in Reference 33 to have been rejected by applying Chauvenet's criteria as being unlikely to have come from a true Gaussian population. The rejected results were later reported to have been contaminated by noise (Reference 33).

Each test result is an average of about (b)(4) CROSSFLOW readings (Reference 3). The following (b)(4) acceptable test results were reported in several references, including References 3 and 6:[

(b)(4)

CROSSFLOW was calibrated using the acceptable test results to calculate C_0 by rewriting (b)(4) as follows:

(b)(4) (14)

where (b)(4) (15)
(16)

Re	= Reynolds Number = $D\ V_a\ \rho\ /\ \mu$
D	= pipe diameter
ρ	= density
μ	= viscosity

and the coefficients, (b)(4)
(b)(4))

In effect, this is an empirical curve fit to the CROSSFLOW / ARL data based upon the equation (b)(4) to correlate fully developed flow test results.

Reference 39 stated that, "because of the use of limited ARL data set (b)(4) the associated prediction uncertainty is not the true representation of the confidence interval estimates for the regression analysis." Reference 39 went on to state that "using the mean predicted value confidence interval prediction formula the associated uncertainty is (b)(4) for Reynolds Numbers close to plant conditions (Re=30 Million). The calculated value is higher than the ARL accuracy of ±0.25%, however, as it was mentioned previously, the major contribution to this confidence interval limits calculation is the limited number of ARL calibration data points. The small sample size resulted in Student's t values for 95% confidence interval of *Student's* (b)(4) Increasing the calibration data sample size will significantly reduce the associated predicted confidence interval."

Although Equation 17 is (b)(4)
(b)(4)

(b)(4) (18)

or:

(b)(4) (19)

where (b)(4)

(b)(4) (20)

W/AMAG uses Equation 20 to extrapolate from test results obtained for Re (b)(4) to feedwater applications where Re is of the order of $30X10^6$.

W/AMAG conducted a number of tests at low Re that further clarify the behavior. In response to an RAI, it recalculated Equation 17 using all data to obtain (Reference 39):

(b)(4) (21)

For comparison, Equation 17 is:

(b)(4) (17)

(b)(4)

Reference 39 further stated "that the associated uncertainty due to the mean value prediction is less than the uncertainty (±0.25%) associated with the 1996 ARL data." It further provided Figure 13 which predicts that the mean percent error at the Reynolds Numbers of interest in the plants is about (b)(4) percent. This indicates that error in the Reynolds number extrapolation could be significant and a verifiable uncertainty factor must be used.

With respect to operations, if indicated average velocity is higher than actual, then the indicated flow rate is higher than actual and the thermal power level determined from that flow rate will be higher than actual. This is a conservative result since the plant will be operated to keep the indicated thermal power level no higher than the licensed power level, and actual power level will be less than the licensed power level. The same rationale applies to the FPCF, C_0. If a C_0 is used that is greater than actual, then the predicted average velocity and flow rate will be greater than actual. This is the rationale that W/AMAG has followed with respect to the correlations for a straight pipe where W/AMAG claimed that a conservatism was introduced in the ARL test data used for its calibration by testing with plastic pipe, including References 3 and 38. The NRC staff, in Reference 24, considered this when reaching its conclusions by stating "the low pipe wall friction of smooth pipe, relative to the friction expected in a typical feedwater pipe of a nuclear power plant, provides a limiting condition that maximizes the velocity measured by the Crossflow UFM. This limiting condition provides confidence that the velocity measured by the UFM will be equal to or greater than the actual flow velocity." Reference 38 addressed this in detail and provided calculated behavior illustrating that the FPCF, C_0, decreased with increasing roughness over all Re of interest. Hence, basing a calibration on smooth pipe was believed to provide a C_0 that was greater than would occur in the plant. Consequently, it was believed that a CROSSFLOW calibrated in this manner would provide a conservative result.

Reference 36, among others, provided data for the following conditions:

(b)(4)

The NRC staff fitted each data set to Equation 14, the same equation used by W/AMAG to

(b)(4)

obtain C_0, and then calculated the behavior as a function of Re to obtain information suitable for direct comparisons.[14] These results, as well as the Reference 38 results for three friction factors (f), are provided in Figure 14. The three friction factor curves illustrate the W/AMAG claim that C_0 decreases with increasing f. The ARL plastic pipe results show a slightly greater C_0 than the f = 0 curve (not the expected result but not unusual for experimental data) and the plastic pipe C_0 is significantly larger than the f=0.0015 and f=0.01 curves. Thus, according to these curves, since the application pipe is expected to have a rougher surface with a higher f, using the smooth pipe for calibration will likely result in an over-prediction of flow rate, which is the claimed conservative result. (b)(4) (b)(4) which is the opposite result from the result

[14] The points are calculated valves, not data.

claimed by W/AMAG, and a result that leads to a conclusion that using C_0 based on smooth pipe is actually non-conservative.

(b)(4)

The Figure 14 curves represent a significant Re extrapolation from the data. The data were in the range from Re = (b)(4) The same comparison without extrapolating data is provided in Figure 15.[15] The NRC staff observes that the ARL plastic pipe curve in Figure 15 is below every other curve except the (b)(4). On the basis of only the Figure 15 (b)(4) (b)(4) data, the W/AMAG conclusion is correct. On the basis of the other Figure 15 information, the W/AMAG conclusion is not substantiated. Overall, the NRC staff believes that the W/AMAG conclusion that using plastic pipe is conservative has not been substantiated.

Reference 6 (b)(4) (b)(4) in Figure 16: (b)(4)

[15]The points provided in Figure 15 are calculated values, not data.

(b)(4)

The top line represents a smooth pipe (f = 0). It is essentially identical with the f = 0 and the ARL plastic pipe behavior provided in the above NRC staff results, thus indicating consistency between results from the two sources.

On page 63 of Reference 6, W/AMAG notes that the comparisons show (b)(4)

(b)(4)

(b)(4) On the following page, W/AMAG states that the conservatism has been (b)(4)

(b)(4)

Reference 40 provided information on flow profile for 18 nuclear power plant feedwater lines. It concluded that velocity profile changes occurred at all of the plants over time, that swirl was present in the lines and varied over time, and "the respective roles of swirl and wall roughness in distorting velocity profiles are interrelated and cannot be separated." Furthermore, swirl will tend to flatten a flow profile, moving the profile in the direction that would be expected when smoothing a pipe wall, and a reduction in pipe wall roughness will increase the propagation of swirl down a pipe.

The NRC staff concludes that the W/AMAG assumption of a conservative C_0 due to testing with plastic pipe is not adequately supported by the data and experience in nuclear power plants.

3.4.2.2 Stable Flow and Standard Configurations

Tests were conducted to assess CROSSFLOW indication following an elbow and to determine the distance necessary before CROSSFLOW would no longer be affected by the elbow. As discussed below, W/AMAG concluded there is no need for correction for presence of a 90 degree elbow if located (b)(4) L/Ds or more downstream of the elbow and there is no additional uncertainty associated with such an installation.

Reference 3 stated that experimental data were obtained from the (b)(4)

(b)(4)

Reference 3 also stated that the ARL data provided the bases for assigning the ARL weight tank uncertainty of 0.25 percent to the correction factor. Reference 6 expanded the description by stating that the ARL data provided a set of formal measurements, where the calibrating instrumentation could be traced to NIST standards and no additional uncertainty was assigned to this correction since it is always used in conjunction with the C_0 curve, which has an uncertainty of 0.25%.

Reference 6 stated that (b)(4)

(b)(4)

The section 2.4 information indicates that some licensees may be using the equation where CROSSFLOW is located less than (b)(4) L/D downstream of an elbow. Furthermore, the NRC staff believes there is an additional uncertainty associated with use where L/D > (b)(4) since the data do not adequately substantiate that CROSSFLOW indication is independent of position for that condition. This is illustrated by References 4 and 8 which provide the following Figure 17 for a test configuration that compares a nonstandard application to a standard 90 degree elbow application:

(b)(4)

This appears to show that there is limited change in Delta for L/D greater than about (b)(4) although CROSSFLOW continues to show a clear variation with rotation about the pipe. However, the effect of rotation at L/D = (b)(4) may be an indication that the flow profile is continuing to change with L/D in an unanticipated manner. Furthermore, for the data where CROSSFLOW is in the plane of the elbow, the NRC staff calculates 2σ = (b)(4) (b)(4), which is a substantial change. In Reference 6 (b)(4) (b)(4)

This W/AMAG statement is inconsistent with the most recent information from W/AMAG (Reference 6) which states that (b)(4) (b)(4) (b)(4) This neglects the uncertainty associated with convergence as a function of L/D.

Reference 8 provided Figure 18, which shows FPCF behavior downstream of a tight out-of-plane two elbow configuration:

(b)(4)

This shows that the changes in the flow profile are affecting the CROSSFLOW indication for at least (b)(4) L/Ds downstream of the last elbow. There are only three data points where the CROSSFLOW indication does not appear to change with increasing L/D, not enough to establish that flow profile does not change further downstream of about (b)(4) The NRC staff notes this is consistent with the Reference 8 conclusion that uncertainty is greater for non-standard configurations; but the NRC staff also notes that this cannot be used to conclude that stable flow is achieved for distances greater than about (b)(4) In response, Reference 6 stated that (b)(4)

(b)(4)

In regard to other configurations, Reference 3 stated that, (b)(4)

(b)(4)

(b)(4) Reference 6 modified this approach by stating (page 71) that "(b)(4)

(b)(4)

(b)(4) The NRC staff

has received little record of this followup. CFD was not recognized to be necessary for Calvert Cliffs before an overpower condition was recognized and only three examples have been provided.

Reference 3 concludes the correction factor discussion by stating that (b)(4) [redacted]

(b)(4) [redacted]

W/AMAG continued by stating that fully developed/stable flow calibrations are applicable when the CROSSFLOW readings are independent of meter orientation about the pipe and with axial location along the pipe and that typical flow accuracy will be ±0.5 percent or better. The NRC staff understands that the calibration CROSSFLOW that was installed at Calvert Cliffs met the requirements of the W/AMAG axial and angular location criteria but the CROSSFLOW-indicated flow rate was found to have an unacceptably high bias by tracer testing. Post-test CFD calculations illustrated that swirl had been introduced a substantial distance upstream of an elbow. This is discussed further in section 3.4.3.4.

3.4.2.3 Non-Standard Configurations

Reference 8 describes a nonstandard CROSSFLOW installation as one in which "the flow profile is not a fully developed/stable flow condition. (b)(4) [redacted] Equation 21 is then cited. This is consistent with the Reference 3 description with the exception that Reference 3 did not mention stable flow. For non-standard conditions, Reference 8 describes an in-situ calibration in which a CROSSFLOW is installed (a) in a standard location and is then used to calibrate a second CROSSFLOW that is located where the flow is not stable or (b) in a test facility that models the piping system and a calibration coefficient is determined that is then extrapolated for use in the plant installation conditions.

In Reference 3, W/AMAG also addressed applications where fully developed flow does not exist and where a calibration CROSSFLOW is not available. The necessary corrections were developed by considering the following equation:

(b)(4)

3.4.3 Application of Test Facility Calibration Information

3.4.3.1 Transfer from Test to Application

Reference 40 reported that the flow profiles in 18 feedwater pipes were generally flatter than those corresponding to fully developed flow, generally due to swirl that distributed flow toward the pipe wall. It added that external meters that are calibrated for fully developed flow will read non-conservatively under these conditions and that swirl varies over time.

The test UFM uncertainty is applied by W/AMAG without change to the plant installation consistent with what is typically assumed for venturis with the assumption, in many cases, that the test configuration is sufficiently close to the application that no further consideration is necessary with respect to the transfer. W/AMAG has also stated that the venturis are then operated at much higher Reynolds numbers with no additional compensation for a higher uncertainty (Reference 3) as justification for the same approach with CROSSFLOW. And, in Reference 6, W/AMAG stated that, under fully developed/stable flow conditions, there is no additional uncertainty introduced when the meter is used under field conditions. W/AMAG further states that this has been confirmed by comparing CROSSFLOW measurements with independent measurements of the same flow using high precision plant instrumentation.

These assumptions are unjustified, because:

- Venturi uncertainty in nuclear power plants has never been justified in licensing applications as comparable to the claimed CROSSFLOW uncertainty. To date, the NRC staff has not granted a license amendment for a thermal power uncertainty that was less than two percent when venturis were the sole source for determination of feedwater flow rate. Furthermore, the NRC staff would require an acceptable uncertainty analysis that covered the transfer from test to plant application.

- There are many years of experience with venturis and they have been found to be less sensitive to swirl than appears to be the case for CROSSFLOW. Furthermore, importantly, the effect of swirl is to increase venturi discharge coefficient and to under-register flow rate - i.e. - the actual flow rate is less than indicated, a conservative result since actual thermal power will be less than calculated from the registered flow rate. These observations are not necessarily correct for CROSSFLOW since, as noted in Reference 6 (b)(4) [redacted][16]

- Venturi installations in nuclear power plant feedwater lines, in combination with flow straighteners and sufficient L/D from an upstream perturbation, are relatively insensitive to perturbations that would potentially affect a CROSSFLOW device at the same location.

- There are numerous cases where the perceived fully developed flow test results have been assumed applicable to CROSSFLOW under what were believed to be stable flow conditions but post-LAR submittal experience has shown the assumption to be wrong.

- The uncertainty associated with physical relocation of brackets and transducers is neglected when no allowance is made for change induced in moving from test conditions to a plant application.

- The correction introduced by the calibration coefficient for a venturi is smaller than the correction required for CROSSFLOW. This implies less sensitivity to coefficient determination.

- There is a viable theoretical description applicable to venturis that does not exist for CROSSFLOW.

- As discussed in section 3.4.4, below, there is extensive ASME guidance for using venturis whereas there is little comparable information available for CROSSFLOW.

Reference 6 stated that for fully developed/stable flow, (b)(4) [redacted] (b)(4) [redacted] (b)(4) [redacted] This message is repeated several times. This is incorrect and does not accurately portray CROSSFLOW response. For a constant Reynolds Number, changes in pipe roughness can affect the flow profile and hence potentially perturb a CROSSFLOW calibration. Furthermore, W/AMAG has not established that there is no uncertainty associated with a factor of five extrapolation in Reynolds Number. Comparisons of CROSSFLOW indication with other plant instrumentation are addressed in several other sections of this report.

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[16]Reference 6 also stated that in general, (b)(4) [redacted] (b)(4) [redacted]

3.4.3.2 CROSSFLOW Installation

Reference 2 summarized the installation procedures that are used to establish the initial system performance baseline as follows:

(b)(4)

-
-
-
-

The reference then introduced the User Guidelines that were developed to help ensure CROSSFLOW is consistently operated as designed and licensed. The User Guidelines are addressed in section 3.3.2, above.

The NRC staff notes that in-depth post-installation evaluation of the two most recent power uprate requests identified problems and raises a concern that similar in-depth evaluation of other installations may also find previously unrecognized problems.

3.4.3.3 Standard Installation

Reference 8 describes a standard application as existing when the flow profile is a fully developed/stable flow condition. For this condition, W/AMAG states that the Topical Report (Reference 3) C_0 value will be used. The C_0 was obtained from ARL tests.

The test results were obtained for Re < (b)(4) but the feedwater applications involve Re ≈ $30X10^6$. This requires a substantial extrapolation of a correlation based on only (b)(4) data points. W/AMAG addressed this by plotting a number of other experimental points over the full range of Re using Equation 11 (References 3, 34, and 41). Reference 3, in response to NRC RAIs 1 and 18, stated that the equation for the friction factor, (b)(4)
(b)(4)
(b)(4) Thus, W/AMAG is relying, in part, on the friction factor representation obtained by (b)(4) for fully developed flow for its Re extrapolation. The NRC staff notes that no uncertainty information has been provided for (b)(4) work.

W/AMAG provided other information to justify the Re extrapolation as well. Figure 19 from Reference 3 compares the (b)(4)
(b)(4)

(b)(4)

With respect to Figure 19, during a meeting with W/AMAG on October 6, 2005, the NRC staff was told that the difference at Re = (b)(4) was within the uncertainty of the ARL data and therefore one could not expect a better correlation to be obtained. This neglected the influence of the extrapolation, allowed no uncertainty in the (b)(4) correlation, did not consider a change due to transfer from the ARL conditions to plant conditions, and, as discussed above, is a misapplication of uncertainty. The NRC staff independently calculated the values at the upper limit of the Re curves and found a difference of (b)(4) percent. This is outside the limit the NRC staff would expect if the basic ARL uncertainty is assumed applicable over the full range of Re (a questionable assumption) and there is no uncertainty associated with (b)(4) equation. The NRC staff concludes this comparison is of little value with respect to establishing the validity of the Re extrapolation with respect to the uncertainty limits of interest here.

W/AMAG recently verified the approach for using calibration information by stating that the C_0 curve presented in CENPD-397-P-A, Rev. 1 is used for installations satisfying the criteria for a 'standard' installation (i.e., a fully developed/stable flow profile) (Reference 22). It provided data in Reference 28 to illustrate the effect of CROSSFLOW positioning by showing two orientations as a function of L/D downstream (b)(4)

(b)(4)

(b)(4) Adequate data would include multiple orientations coupled with sufficient axial locations to clearly establish that there was no effect with increasing L/D.

W/AMAG stated on page 31 of Reference 6 that "the (b)(4) (b)(4) [redacted]" However, comparison rationale based on uncertainty is inappropriate since most of the data will be much closer to the mean than the tails of an expected data distribution and comparisons should be based on expected deviations from the means. Also, if the flow profile between the two locations is changing that much, the immediate questions are "what is the change between following locations and how many following locations must be included before a satisfactory convergence is obtained?" Page 33 provides a partial W/AMAG perspective on this issue when it states that "as an aside, the CFD analysis would never have been used as a final determination of flow stability. Flow stability can only be determined by actually installing two meters on the same pipe with several pipe diameters between them. If the CFD analysis indicates that there is no swirl and the flow measurements taken from the two meters are statistically equivalent, only then can the flow be declared to be stable." The NRC staff's position is that, whereas CFD analysis can provide valuable insight, there may be swirl that is not predicted by CFD and basing results on two meter positions is not sufficient to establish statistical equivalency.

3.4.3.4 Non-Standard Installation

Flow accuracy for nonstandard installations was stated to be a function of the piping configuration and the uncertainty would be higher than for the standard case. Cases discussed included downstream of a single elbow and downstream of out-of-plane elbows.

Reference 22 stated that (b)(4) (b)(4) (b)(4) [redacted] It also stated that (b)(4) (b)(4) [redacted] and a tracer test can be used to calibrate a CROSSFLOW meter subject to identified considerations.

Reference 3 describes an approach if fully developed flow does not exist at the desired AMAG installation location and there is a location where fully developed flow does exist. This approach 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, as is recognized in Reference 3, 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.

The W/AMAG process of using a calibration CROSSFLOW in one loop to calibrate CROSSFLOWs in other loops is not adequately supported since this can introduce errors that have not been adequately addressed in uncertainty determinations. This is illustrated by the results of a CROSSFLOW UFM that was installed in loop 12 at Calvert Cliffs where stable flow

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(b)(4) [redacted]

was believed to exist. Length to diameter ratio to a horizontal elbow downstream of a vertical elbow that translated downward flow to horizontal flow was 6.0 and the CROSSFLOW UFM was located at an L/D = 13.2 downstream of the horizontal elbow as illustrated in Figure 20 (from Reference 18):

(b)(4)

However, W/AMAG overlooked a control valve upstream of the vertical elbow that introduced swirl. The swirl propagated into the CROSSFLOW and invalidated its indicated flow rate. In assessing the behavior, W/AMAG obtained the Figures 21 and 22 CFD analysis results for the velocity profile with and without the control valve perturbation (Reference 18):

(b)(4)

(b)(4)

[redacted]

The lines represent calculated axial velocity as a function of position along diametral paths located at 0, 45, 90, and 135 degrees from horizontal. When compared to Figure 22, Figure 21 clearly illustrates the flow distortion caused by the feedwater control valve. Interestingly, Figure 22 indicates that the flow profile is not fully developed since, if it were, all lines would be identical. Furthermore, the lines are not symmetrical. Yet this location was believed to meet the requirements for a stable flow location. The potential implication is that the correction coefficient obtained in the laboratory may not be applicable since the flow profile may differ from the laboratory calibration profile. This is one of the NRC staff's concerns regarding CROSSFLOW installation and post-installation operation.

As discussed in section 1.2.3, there is a CROSSFLOW installed in each of the four feedwater loops at Calvert Cliffs and these were originally used for power recovery since there was a history of venturi fouling. However, these were non-standard installations. The plan was to use a CROSSFLOW meter installed in the loop 12 feedwater line at an upstream location believed to be a standard location so that the ARL calibration would apply, and to use this CROSSFLOW in place of the originally installed loop 12 CROSSFLOW. This upstream CROSSFLOW was also to be used to provide a correction factor for the loop 11, 21, and 22 CROSSFLOWs since it was "demonstrated through cold laboratory tests that the Loop 12 downstream meter calibration could be also used for the remaining three meters on Loops 11, 21 and 22" (Reference 18). The correctness of this "demonstration" can be assessed by examining the correction factors obtained from the chemical tracer testing described in section 3.4.5 that are summarized in the following table:

(b)(4)

(b)(4) shows that a significant calibration difference exists for the permanent CROSSFLOW devices that were intended to be recalibrated by the CROSSFLOW device located in LOOP 12.[18] This raises a serious question regarding the W/AMAG approach to using a calibration CROSSFLOW device, or any other device, to calibrate CROSSFLOW devices installed in other loops which was an approach the NRC staff believed acceptable at the time it accepted Reference 3. It further raises serious questions regarding the W/AMAG assumption that a CROSSFLOW device calibrated at a test facility can be installed without further calibration in a nuclear power plant where stable flow is expected to exist.

In its reply to the above concerns, (Reference 6, page 34), W/AMAG stated that the significant differences between each of the loops are due to the different upstream piping configurations. It further stated that the cold laboratory model tests that were used to determine that the meters would read the same only considered the differences in the piping configuration just upstream of the flow straighteners, and did not include the effects of the control valves and the differences in the rest of the upstream piping between the straighteners and the control valves. W/AMAG further stated that, If this additional detail had been included in the model, it would have most likely shown that a single calibration based on the Loop 12 meters would not have been applicable for the three remaining loops. According to W/AMAG, the more rigorous installation and commissioning process rectifies this situation. The NRC staff notes this additional detail would have required modeling over a greater L/D than has typically been considered necessary by W/AMAG.

Page 15 of Reference 6 contains the statement that, (b)(4)

(b)(4)

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[18] The permanent LOOP 12 CROSSFLOW device is not shown because only 2 hours of CROSSFLOW data were obtained in each part of the calibration and the licensee stated this was not sufficient to obtain acceptable statistics. The LOOP 12 UPSTREAM column is the CROSSFLOW UFM described above that was intended to be the calibration UFM and most of the (b)(4) percent error has been ascribed to swirl caused by the flow control valve.

(b)(4)

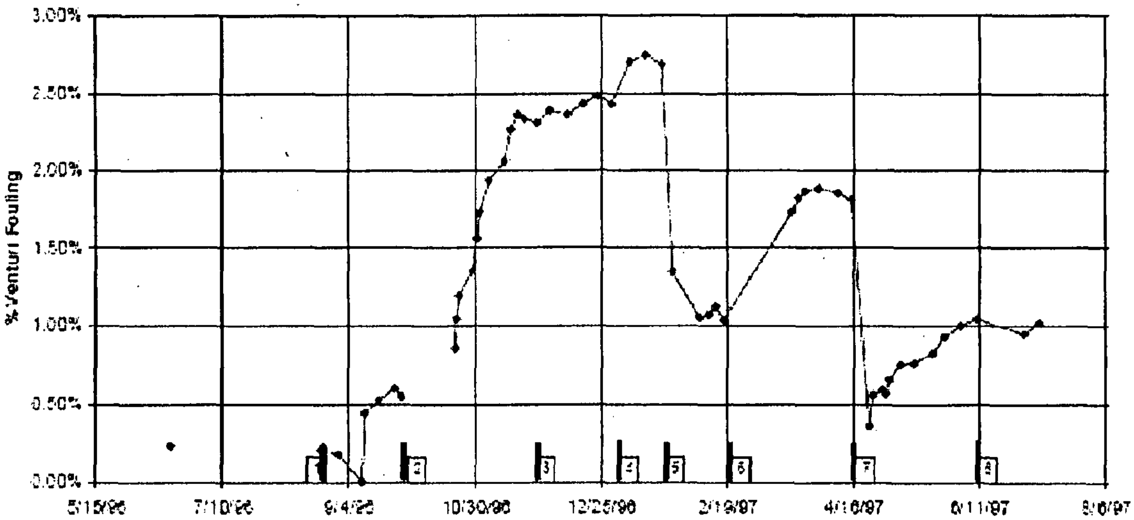
However, this appears to be inconsistent with other statements in Reference 6 regarding non-stable flow installations. On page 1 of Reference 6, W/AMAG stated that, (b)(4) (b)(4) (b)(4) A similar statement is provided on page 14 and page 16 stated that for installations where the flow is not fully developed/stable, both the NRC and W/AMAG agree that (b)(4) is not acceptable due to the increase in uncertainty.

In regard to using one meter in a fully developed/stable location to calibrate multiple meters, page 17 states that (b)(4) (b)(4) (b)(4) However, data were not provided to support the view that the increased uncertainty was sufficient to compensate for the potential error in using a meter in one loop to calibrate a meter in other loops.

3.4.4 Use of Venturi data for CROSSFLOW Calibration

In Reference 22, W/AMAG stated that a venturi may be used to calibrate a CROSSFLOW meter based on recent calibration of the venturi, no history of fouling upon unit start-up, the venturi is installed in accordance with ASME standards, and the differential pressure (ΔP) instrumentation is calibrated before the CROSSFLOW commissioning and is verified afterwards. The NRC staff agrees in principle but notes that in-situ calibrations should be conducted as soon after venturi installation as practical. Using a fouled venturi would result in CROSSFLOW predicting a flow rate greater than actual, a conservatism. Lack of fouling can be assessed by comparison with all available plant parameters, including the CROSSFLOW indication, although this may not provide sufficient accuracy to make a precise determination. Further, the in-situ calibration is only "good" at the time of and during the flow conditions existing during the calibration. Extrapolation of the calibration to other operating times and conditions must be acceptably addressed.

The importance of a clean venturi and of accomplishing a CROSSFLOW calibration on the basis of a venturi as soon as practical after venturi calibration is illustrated in Figure 23. This shows the bias introduced by venturi fouling at Watts Bar during the first cycle of operation.



Notes:

1. Plant starts steady state operation.
2. Mid Cyle Outage on 10/1/96 .
3. Downpower to 50% on 11/25/96.
4. Turbine inlet valve testing on 12/30/96.
5. Plant tripped on 1/22/97 and then tripped again on 1/27/97.
6. Plant tripped on 3/3/97 and in outage for several weeks. During this outage the venturis were exposed to air.
7. Plant tripped on 4/20/97.
8. Plant runback to approximately 50% power on 6/17/97.

Figure 23. Venturi Fouling During Operation (from Reference 42)

However, it is not sufficient to assume a venturi is unfouled just because it was recently calibrated. This is illustrated in Figure 24 which shows an example of venturi fouling at Millstone 3 in August 1998 before it could be returned to power following an outage. (The blue scattered data points are representative of the venturi fouling behavior that initiates at about 400°F. The lighter- colored pink points without significant scatter are feedwater temperature measurements and are an indication of power level.) Since the fouling occurred between about 400°F and full power at 437°F, it would be difficult to recognize this condition from evaluation of changes in other plant parameters. The NRC staff believes that this type of behavior must be reasonably established as not occurring in order to justify use of venturis for CROSSFLOW calibration.

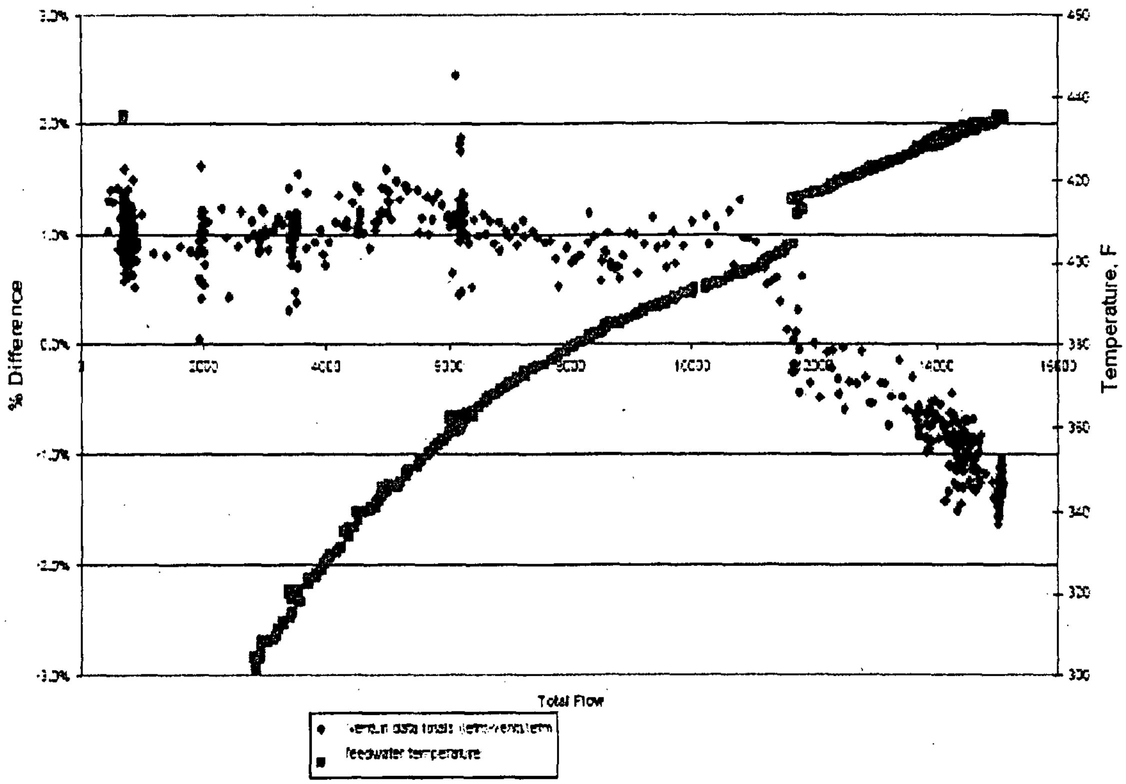


Figure 24. Venturi Fouling During Startup (from Reference 42)

Reference 18 discussed plans to use venturi response to obtain a correction factor for the power dependency exhibited by CROSSFLOW. The reference first stated "knowing that the venturi is going to respond in a linear manner and that the CROSSFLOW is in a region where the flow profiles are prone to change, it must be concluded that the accuracy of the (CROSSFLOW) meter can be affected under these conditions." Consequently, it was planned to quantify the CROSSFLOW and venturi responses and compare them during a downpower event, thus obtaining a CROSSFLOW correction factor that could be used to correct for the effect of power on CROSSFLOW output. The discussion also identified the need for including an additional uncertainty term. The NRC staff notes that there is an unstated assumption in the statement that a venturi will respond in a linear manner. This may not be true if swirl is involved and, as will be seen below, although the venturi calibration coefficient is a weak function of Re, nonetheless, the effect of this assumption on results should be determined.

Reference 43 provided ARL venturi calibration information for two 16 inch diameter Ft. Calhoun feedwater venturis. The test configuration, shown Figure 25, included a 14'10" section

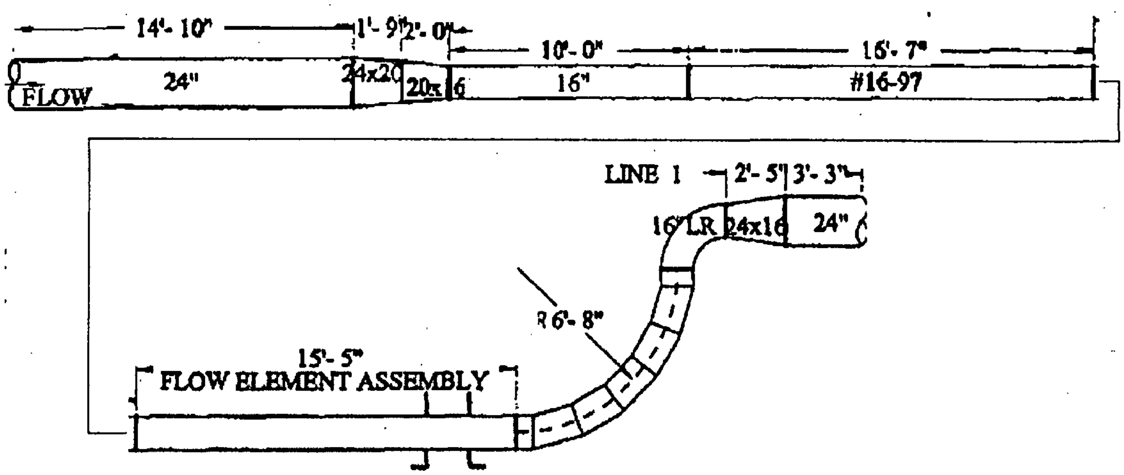


Figure 25. Venturi Test Section

of 24" diameter pipe, a reduction to 16" diameter pipe over 3'9", 26'7" of 16" diameter pipe, a 15'5" flow element assembly, a 90° 6'8" radius curve, and other downstream piping. The venturi was located about 10' from the inlet end of the flow element assembly so that the separation distance from the reducers to the venturi was about 32 L/Ds. However, this is not the complete picture. Feedwater nozzle assembly serial number 158458FE1101/1395 is stated to have a pipe diameter of 13.9250 inches and a throat diameter of 7.9710 inches. Serial 158459FE1102/1398 dimensions are 13.9380 and 7.9700 inches, respectively. The inside diameter of schedule 100 16" pipe is 13.938 inches. If schedule 100 pipe was used in the test, the pipe radius for the first-listed nozzle would change by 0.006 inches at the entrance to the flow element assembly, neglecting dimension changes associated with tolerance from published values. The NRC staff judges this would not cause a substantial perturbation to the venturi indication since the dimension change was about 9 L/Ds from the venturi. If, however, something like schedule 40 pipe was used, the published diameter would be 15 inches and a substantial sharp edge change in diameter would occur upstream of the venturi. The actual test pipe diameter should be provided for a complete assessment of the test conditions.

There was no mention of flow profile effects in the Reference 43 submittal. Ordinarily, a 32 L/D separation would be judged sufficient to mitigate flow profile concerns for a venturi. However, that is not sufficient to mitigate swirl if it existed at the entrance to the test section and, as a generality, swirl is known to cause a venturi to indicate high because it increases velocity across the pressure taps. This is a potential concern when attempting to achieve small uncertainties and should be addressed.

The ARL facility provides a weight of water accumulated over a known time. Calculation of flow rate is straightforward and includes corrections for such factors as the weight of air displaced by the accumulated water, a factor that affects the third to fourth significant figure when converting weight to volume.

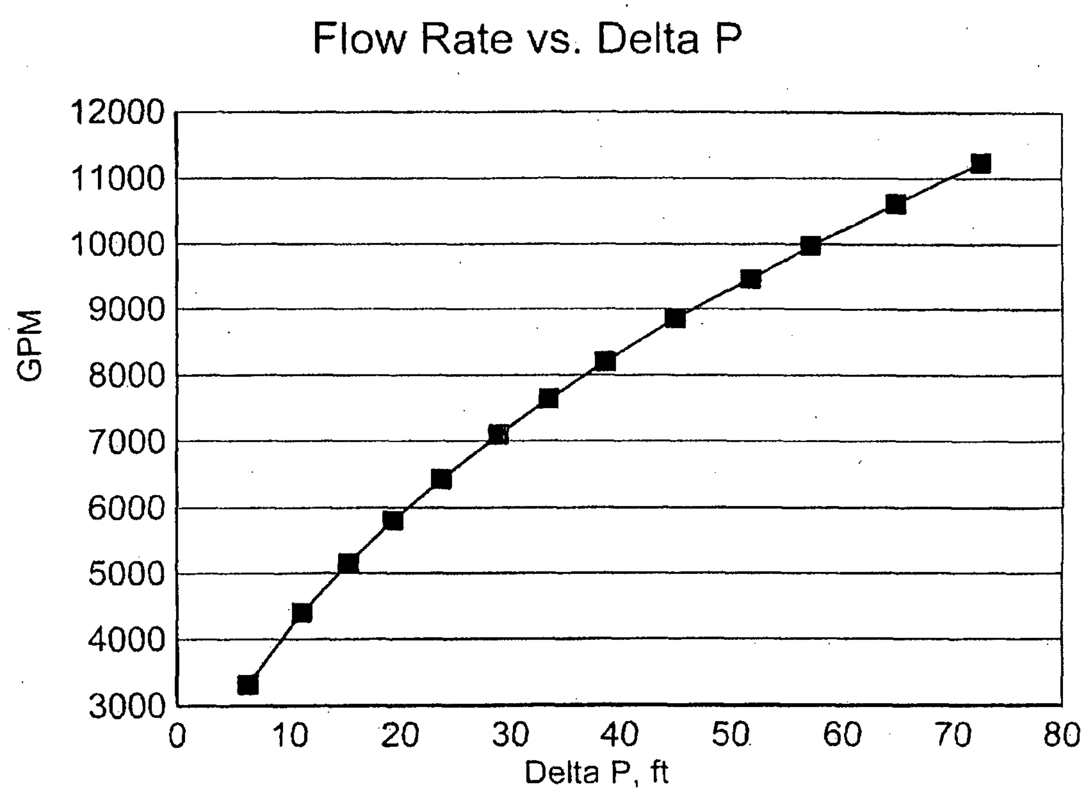


Figure 26. Flow Rate vs. Delta P

Each venturi had two sets of pressure taps, and a total of four sets of calibration data were obtained for a range of flow rates. In Figure 26, the NRC staff plotted one set of flow rates as a function of measured differential pressure where the data points are connected by straight lines.[19] At this scale, the data exhibit no observable scatter and the correlation appears to be excellent.

The venturi discharge coefficient is given by:

$$C = q_a / q_t$$

where:

q_a	= *actual flow rate obtained from test data*
q_t	= theoretical flow rate

and q_t is obtained from:

$$q_t = F_a K_m (\Delta h)^{0.5}$$

[19]Venturi serial number 158458FE1101/1395 data and associated calculations will be used to illustrate behavior.

where:

F_a	= thermal expansion factor
K_m	= meter factor = $a_t \{2 g_l / (1 - \beta^4)\}^{0.5}$
Δh	= differential head at line temperature
a_t	= throat area
g_l	= local gravitational constant, 32.1625 at ARL
β	= ratio of throat to pipe diameter

Reference 43 provided plots of C as a function of Reynolds number, Re, for each of the four data sets. One of the plots is provided in Figure 27:

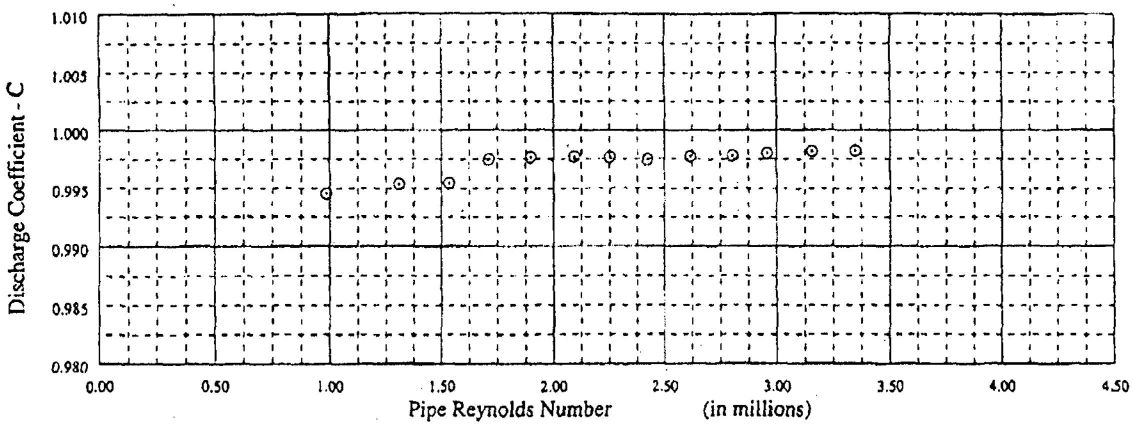


Figure 27. Variation of Venturi C with Re

The reason for the first three C's at lower Re being lower than the other data points was not addressed. The NRC staff notes that this scatter was less pronounced in the data for the other venturi.

The maximum Re is lower than will be encountered during use in the plant. To extrapolate from test conditions to the larger Reynolds number, Reference 43 stated that the following ASME MFC-3M 1988 Equation 32 was used:

$$C = 0.9975 - 0.00653 \, (10^6 \beta / Re)^{0.5}$$

The deviation of the measured C from the calculated C, ΔC, was calculated for each test Re and the average deviation, ΔC_{ave}, was used to calculate the C for any Re by the following equation:

$$C = 0.9975 - 0.00653 \, (10^6 \beta / Re)^{0.5} + \Delta C_{ave}$$

This equation is predicated on the unstated assumption that ΔC_{ave} is not a function of Re.

Figure 28 illustrates the extrapolation:

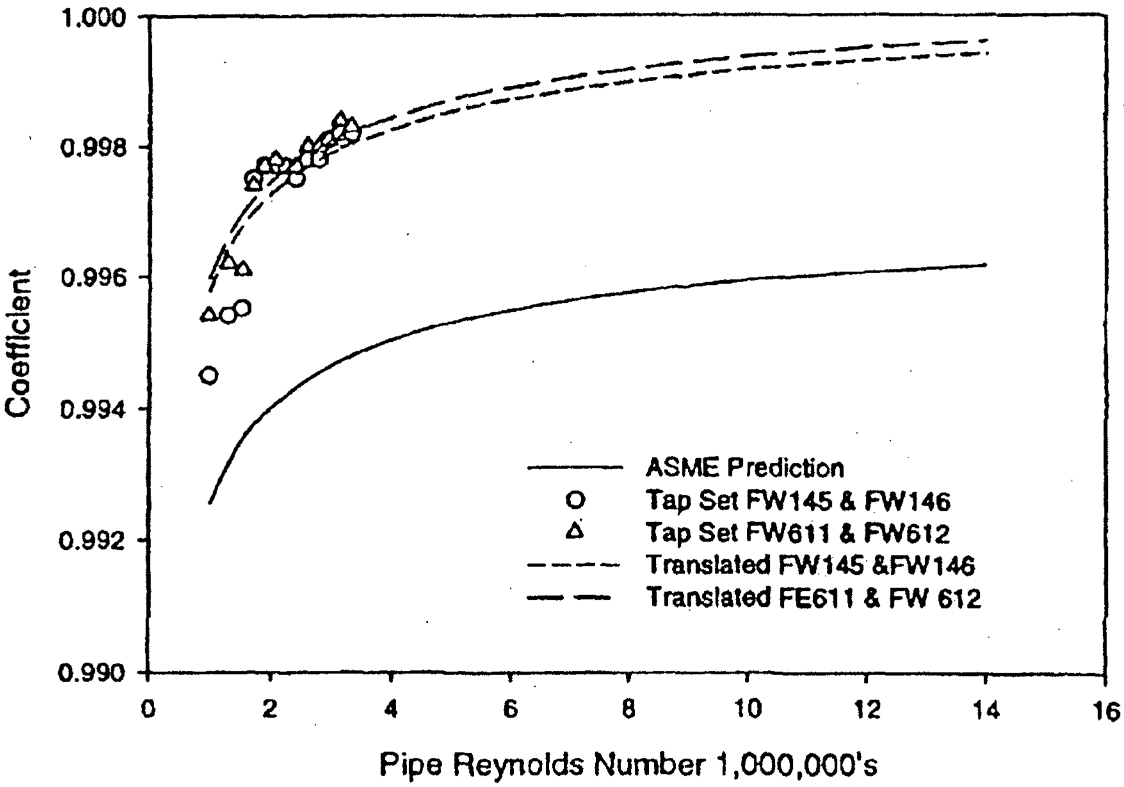


Figure 28. Re Extrapolation of Calibration Coefficient

where the two data sets are for the same venturi.

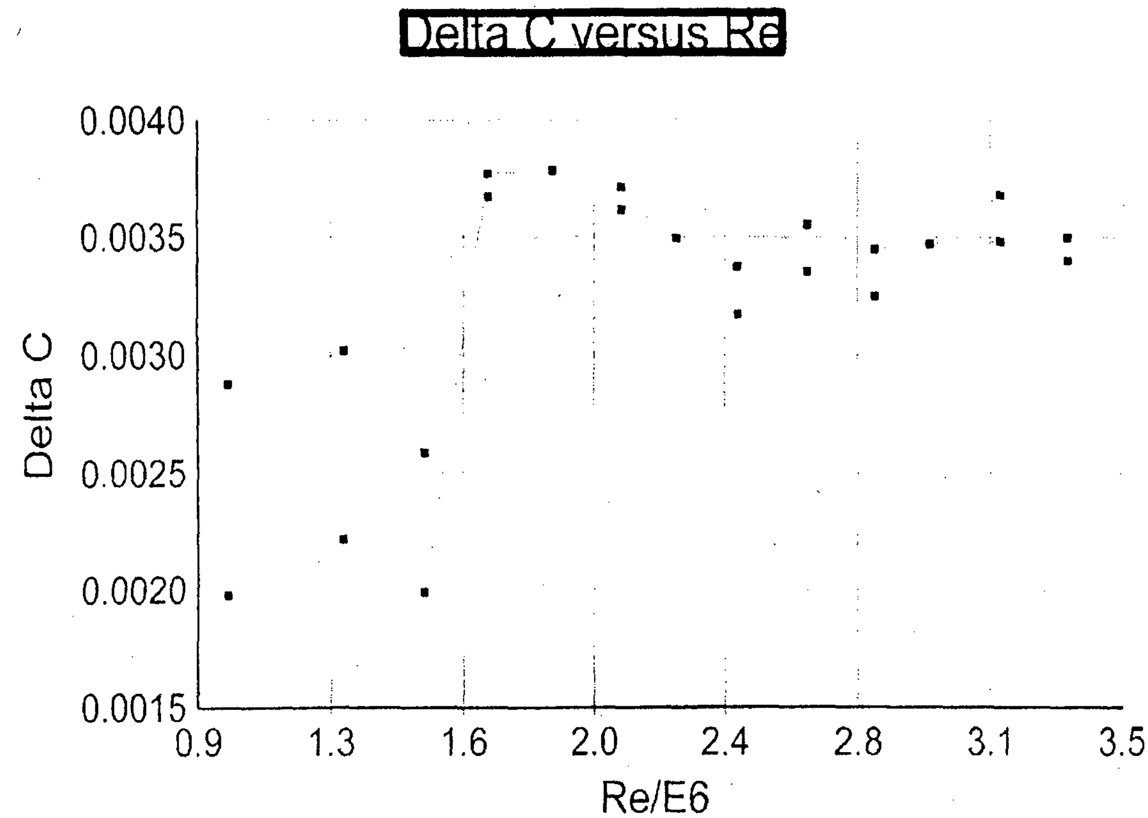


Figure 29. Comparison of PSU Theory and ASME Prediction

To better understand this behavior, the NRC staff generated Figure 29, which shows the difference between the coefficient calculated from data / theory and the ASME prediction. This shows the effect of the first three data points while the remainder of the data illustrate a higher average difference of about 0.0035. The increased scatter for the lower Re values may be in part due to the increased sensitivity of C with Re for smaller values of Re. The scatter appears to become smaller for Re greater than about $2X10^6$. Reference 43 stated the average difference was 0.0032 and 0.0034 for the two data sets, a calculation based on all of the data. The latter values would be used for the Re extrapolation. The difference between the data and the ASME equation is about 0.33 percent. The actual extrapolation from the maximum test Re to a typical value for use in the plant, assuming the ASME equation behavior is representative, is a correction of about 0.14 percent. Reference 43 calculated the uncertainty associated with C to be 0.133 percent and stated that "the flow measurement uncertainty is better than 0.15%." The NRC staff has the following observations:

1. The effect of swirl on the test results has not been addressed. This should be included.

2. An uncertainty should be applied to the Re extrapolation.

3. The differential pressure measurement capability that was used at ARL and the plant capability may have different characteristics. This should be addressed when using the venturis for in-situ calibrations.

4. Differences in flow profile and temperature uniformity between the test and the plant installation should be addressed.

3.4.5 Use of Tracer Tests for CROSSFLOW Calibration

Reference 18 provided the following discussion of tracer testing:

> The tracer test measures the flow in a pipe based on the principle of conservation of mass, which states that the concentration of the tracer times its rate of injection must be equal to the concentration in the feedwater line times the feedwater flow rate. The only term in this equation that is not known is the feedwater flow rate. In practice, the conservation of mass equation is usually rearranged so that the feedwater flow rate is set equal to the injection rate of the tracer times the dilution ratio, where the dilution ratio is defined as the ratio of the concentration of the tracer being injected into the pipe divided by the concentration of the feedwater samples.
>
> When performing a chemical tracer measurement[20], injection and sampling points must first be selected that prevent the loss of tracer, while assuring complete mixing. The loss of tracer is minimized by avoiding flow branches prior to achieving complete mixing, plus (avoiding) large surface area such as feedwater heaters, where the large surface increases the chance of tracer plating out on the surface. It should be noted that if tracer is lost, the flow measurement is biased high, so from an overpower perspective the lost (sic) of tracer is conservative. Complete mixing can be assured when the injection and sample points are at least 250 pipe diameters apart (Reference 44).

The Reference 44 tests were with smaller pipe, lower Reynolds Numbers, and different injection methods than apply to a nuclear power plant. Furthermore, the tests established that mixing distance increases with increasing Reynolds Number. Consequently, the NRC staff does not agree that mixing is assured at 250 pipe diameters but does agree that it takes a considerable distance to accomplish the equivalent of complete mixing. The NRC staff believes that sampling locations must be varied and sufficient data must be obtained to establish that increasing distance from the injection to the sampling locations has essentially no effect on results. Furthermore, there will be an uncertainty associated with incomplete mixing.

The following table summarizes the tracer test conditions for the Calvert Cliffs plant:

Item	Discussion and Licensee Conclusions / NRC Staff Comments
Injection location	Just upstream of main feedwater control valves and downstream of feedwater heaters.

[20]The same principles apply to using a radioactive tracer.

Item	Discussion and Licensee Conclusions / NRC Staff Comments
Bypass lines	Licensee: A feedwater control valve 8 inch diameter line connects to the 16 inch diameter main feedwater line several pipe diameters downstream of the main control valve. The equivalent mixing distance through the valve is > 2000 diameters so that the mixing upstream of the line connection will have diluted the injected tracer and the error due to tracer accumulation in the 8 inch line will be minimized.
	NRC staff: Mixing in the control valve will dilute the tracer concentration before flow reaches the 8 inch line connection so that any tracer loss initiates from a more dilute mixture. However, the NRC staff does not accept the > 2000 diameters statement without proof, and mixing may not be complete at the connection. Tracer loss should diminish over time as water in the 8 inch line comes into equilibrium with respect to tracer accumulation and, assuming sample concentration determination is sufficiently sensitive, the overall effect of tracer loss can be ascertained by examining concentration as a function of time in the samples taken from the downstream sampling location.
Feedwater heaters	All connections are downstream of the feedwater heaters and tracer accumulation in heaters is not a concern.
	NRC staff: Agreed.
Mixing	Mixing in a feedwater control valve and a flow straightener between the injection and sampling location more than meets the tracer mixing requirements.
	NRC staff: The NRC staff notes there are several elbows in the feedwater line and the feedwater line length is significant although not long enough to ensure mixing by itself. These attributes will contribute additional mixing. The NRC staff also notes one test was performed with a sampling location closer to the injection location to assess completeness of mixing. This test information has not been provided. Sufficient information should be provided to quantitatively establish mixing completeness.
Injection Cart	(b)(5)

Item	Discussion and Licensee Conclusions / NRC Staff Comments
	NRC staff: The setup provides reasonable assurance that (b)(4) (b)(4) (b)(4) so holdup will not have a significant effect on the tracer test. Any effect on deposition on the hose surface (plus all other surfaces) can be assessed by sample behavior, again assuming sufficient concentration determination sensitivity.
Sampling Cart	(b)(4)
	NRC staff: Sample volumes are unimportant and, with respect to the samples, tracer concentration is the only quantity necessary to determine flow rate. Influence of the connecting hose from the feedwater line is similar to that discussed above for the injection cart.
Pre-test	(b)(4)
	NRC staff: The NRC staff observed the balance, weights, and the tracer injection cart that contained the injection equipment and discussed the process at Calvert Cliffs on January 25, 2006 while the cart was connected to a feedwater system. The NRC staff concludes that the injection and sampling equipment and pre-injection process are consistent with the requirements for a precision measurement system provided the (b)(4) (b)(4) is acceptably determined.
Injection	(b)(4)

Item	Discussion and Licensee Conclusions / NRC Staff Comments
Post-test calibration	(b)(4) [redacted]

Numerous additional steps are taken to control the tracer and samples and there is additional proprietary discussion that describes post-test sample processing and analysis. This information is not described herein but was considered by the NRC staff during its evaluation.

Contributions to uncertainty are stated to be from the (b)(4) [redacted] the regression curve obtained from processing the data, sample variation, and a (b)(4) [redacted] percent high bias in tracer flow in a correction factor obtained from testing at ARL. Given the apparent precision of the observed test setup and treatment of test concentrations, the NRC staff does not immediately understand the basis and reasons for a correction factor.

The ARL tests, described in Reference 45, were conducted to determine the correction factor for the ChemTrac testing process by determining flow rate using the ARL test facility described in section 3.4.2.1. The test process appears consistent with the process used at Calvert Cliffs.

(b)(4) [redacted]

The NRC staff elected to examine flow rates determined by (b)(4)

(b)(4)

(b)(4) This introduces a possibility of bias that was not addressed by Reference 45. Furthermore, with the indicated behavior, it is difficult to conclude that the indicated straight line fit to the data that represents a trend line is meaningful. However, the indicated trend line, if correct, would be consistent with early loss of chemical due to adsorption on pipe walls that decreased as time increased and the walls became more saturated with chemical. (b)(4)

(b)(4)

Overall, because of the chemical analysis sensitivity identified in the previous paragraph, without clarification, the NRC staff is not convinced that the ARL tests provide the sensitivity necessary to support the desired uncertainty results, and there is question regarding application of the ARL correction factor identified above. Furthermore, if the Calvert Cliffs data exhibit similar characteristics, the same conclusion will apply.

The correction factor will reduce flowrate deduced from the ChemTrac tests. This will cause a reduced indicated flow rate in CROSSFLOW when it is calibrated to ChemTrac results. Consequently, the effect is to increase plant feedwater flow rate and plant thermal power above the value that would be applicable without the correction, a potential non-conservative effect that needs to be addressed when considering uncertainties of the size under consideration here.

The NRC staff's brief consideration of analysis of the ARL test data did not identify how ARL weight tank test uncertainty was treated. If this uncertainty was not considered, then the ARL flow rate determined from the weight tank results would have been treated as absolutely correct with no uncertainty. The NRC staff observed tests described in Reference 5 where the uncertainty was ± 0.088 percent and ARL estimated the ARL uncertainty associated with initial calibration of CROSSFLOW was about ± 0.12 percent. This aspect of the test data analyses should be clarified or the reported treatment should be identified to the NRC staff.

At Calvert Cliffs, tracer test samples are obtained for between three and four minutes but several hours are required to obtain statistically acceptable CROSSFLOW results. Thus, one cannot directly obtain a CROSSFLOW calibration because there may be variations in flow rate during the process. This is addressed by essentially calibrating the venturis using the tracer test results and, with the assumption that the venturis do not change during the process, using the venturis to calibrate CROSSFLOW. This was described in Reference 22 which provided the velocity profile correction factor for non-standard piping as[:

(b)(4)

[redacted]

]The uncertainty associated with this correlation is taken as the traditional square root of the sum of the squares of the terms in the equations.

The acceptability of the above equations will be a function of the determination of the uncertainty terms, and is addressed at the end of this section.

Each of the four feedwater loops was tested and loop 21 was tested two additional times to assess repeatability. The sampling location for one of these repeatability tests was moved closer to the injection location to assess completeness of mixing. The test results were summarized in section 3.4.3.4, above. However, no information was provided regarding the individual loop 21 tests and the effect of moving the injection location. This information is necessary for the NRC staff to complete its assessment.

Reference 22 stated that (b)(4) (b)(4) and Reference 18 stated "when performed properly, flow measurements with accuracies between 0.2% and 0.4% with a 95% confidence interval can be achieved. However, the actual accuracy of each feedwater flow measurement is determined based on the specific uncertainty of the injection rate and the chemical analysis." The Calvert Cliffs uncertainty analyses and uncertainty results have not been provided to the staff.

The NRC staff determined that:

- Tracer testing as described above for Calvert Cliffs is capable of providing a feedwater flow rate that is acceptable for determination of thermal power level at the time the tracer test is conducted. The calibration uncertainty has not been established.

- The combination of tracer testing and use of installed venturis, as identified in section 3.4.3.4 and discussed above, is acceptable for CROSSFLOW calibration at the time the tests are conducted. The calibration uncertainty has not been established.

- The test results only apply when the flow profile and temperature uniformity are identical to those existing at the time of the test. Extrapolation to the potential of a different flow profile that may exist during long term operation and at different power levels has not been demonstrated.

- Application of a calibration determined through tracer testing must address the issues applicable to use of venturi data as identified in section 3.4.4.

- These determinations are predicated upon provision of acceptable uncertainty analyses and test sensitivities that also address any bias and provision of information consistent with the information needs identified above for the Calvert Cliffs submittals and the ARL test results report.

Tracer testing is not limited to chemicals. Radioactive material is also used, as identified in Reference 26 for assessment of CROSSFLOW in Byron. Many of the same considerations apply but decay behavior of the radioactive tracer must also be considered.

3.4.6 High Reynolds Number Comparisons

References 3, 34, and 41 provided curves showing comparisons with in-plant tests "where it is known that the venturi and plant instrumentation have recently been calibrated and will provide an accurate measurement of the flow." In response to an NRC staff request, W/AMAG provided the following data for large Reynolds Numbers (References 36 and 39):

(b)(4)

(b)(4)

The "C Measured" is the correction coefficient necessary to obtain agreement between the CROSSFLOW indication and the reference instrument, and the percent error is based on the difference assuming "C Measured" is correct. The NRC staff understands the reference instruments for the power plants were recently calibrated venturis. (b)(4) (b)(4) show good agreement, illustrating that the CROSSFLOW calibration and Reynolds Number extrapolation methodologies are reasonable for these examples, although there is no uncertainty information to allow a full assessment.[21] (b)(4) is disappointing. The NRC staff has not commented on the (b)(4) test since it is relatively old and may not be representative of more recent installation practice.

Reference 39 also provided comparisons to plant data and concluded that

> "the results comparison are within the VPCF ARL laboratory accuracy of ±0.25%. The associated prediction error is based on a fixed confidence interval band defined by the value of ±0.25% resulting from the ARL data. Since the differences between the measured and calculated values of VPCF are less than the stated ARL accuracy of ±0.25%, it is assumed that any VPCF obtained using Equation 1 (this report's Equation 8) will also have a 95% confidence interval of ±0.25%. This approach to uncertainty based on the ARL laboratory data and laboratory uncertainty is consistent with industry practice for other flow instrumentation (e.g., venturi, orifice plate, flow nozzle). Venturis are calibrated at a hydraulic laboratory under low temperature and Re Number conditions and are assigned an uncertainty equal to the uncertainty of the calibrating instrument (typically a weigh tank). The calculation of the confidence interval for the slope of the linear regression follows the statistical rules for calculating the associated uncertainty for predicted (extrapolated) VPCF at higher Reynolds Numbers."

The NRC staff notes that assigning a plant uncertainty as equal to test facility uncertainty may not include provision for differences between differential pressure determination where the test facility may have more precise instrumentation. Furthermore, as previously addressed in several locations in this report, the NRC staff does not accept the rationale for transferring information from the test facilities to a plant without complete justification.

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[21] Reference 41 states that the (b)(4) data were obtained in one day. Hence, the CROSSFLOW uncertainty may be higher than would normally be the case for an in-plant test.

The (b)(4) test data show significant scatter; further, Reference 23 stated that (b)(4) (b)(4) The NRC staff is not convinced this is correct when all data are considered For example, the (b)(4) (b)(4)

(b)(4)

(b)(4) The NRC staff's plot of the data is shown in Figure 31. (b)(4) (b)(4)

The W Owners Group, in an enclosure to Reference 46, provided the following comparison of CROSSFLOW and what was stated to be an ASME flow section at Kewaunee:
[

(b)(4) [redacted]

Detailed ASME flow element uncertainty information was not provided.

Reference 23 provided the following chemical tracer test comparisons for (b)(4) [redacted]

(b)(4) [redacted]

Reference 23 also provided the following information:

(b)(4) [redacted]

[22]This is incorrectly listed as (b)(4) [redacted] in the reference.

(b)(4) [redacted]

Although the high Re data were obtained under different circumstances, and the reference CROSSFLOW calibration was not identified, the NRC staff elected to examine the totality of the data. The NRC staff calculated the mean value of the percent differences to be

(b)(4) [redacted]

This information illustrates that, for the data sources considered, there are no gross CROSSFLOW errors associated with the plant installation and extrapolation to high Reynolds numbers, although the scatter indicates that careful examination of individual applications is necessary if uncertainties in the vicinity of 0.5 percent are to be supported. Further, the data do not address whether flow rate determined by the venturis is better or poorer than the flow rate determined by CROSSFLOW.

3.5 Installation

Installation considerations addressed in this review are limited to those that potentially affect the hydraulic characteristics sensed by the transducers. Such steps as installation of wiring and data processing equipment, electronics performance assessment, hardware and software diagnostics checks, receiver signal strength indicator diagnostics, and calibration of the signal conditioning unit with a calibrated NIST-traceable flow simulator are generally outside the scope of this report.

A number of references have covered installation and installation guidance. Typical are the descriptions in Reference 15 and photographs provided in Reference 47. In addition to previously conducted activities in support of the Reference 3 review, the NRC staff has discussed this topic with several licensee representatives and recently examined the Calvert Cliffs installation which included several walkdowns of the feedwater piping outside containment in both units.

Generic installation guidance begins with an evaluation of plant piping configurations, pipe material, pipe size and schedule, and a walk-down of feedwater piping. The intent is to identify suitable installation locations and potential flow profile perturbations due to welds, instrumentation penetrating into the pipes, elbows, valves, and feedwater heaters. Findings are used to provide recommendations for additional work such as scale model tests, CFD calculations, and tracer tests. Historically, the NRC staff observed that few scale model tests were determined to be necessary and, with the exception of recent activities, no CFD calculations or tracer tests were identified.

Actual installation includes such steps as careful preparation of the external surface of the feedwater pipes, an in-depth determination of pipe diameter and wall thickness, attachment of the CROSSFLOW bracket, and in-depth determination of transducer separation distance. Typically, a number of installation locations and transducer orientations are evaluated to assess CROSSFLOW time delay variation while controls are in place to provide a constant feedwater flow rate. Also typically, for recent installations, CROSSFLOW certification is specific to plant configurations that are considered to be consistent with the evaluated configurations. However, the NRC staff is concerned that the acceptance tests associated with time delay variation may be too coarse to be consistent with the claimed uncertainty, and that evaluated configurations may not encompass actual configurations when CROSSFLOW remains in operation.

In practice, installation adjustments are continued into the CROSSFLOW commissioning phase when noise and sensitivity to plant configuration changes are assessed. In this regard, Reference 15 stated that (b)(4)

(b)(4)

The NRC staff notes that in-depth review associated with the two most recent LARs for Calvert Cliffs and Ft. Calhoun identified numerous previously unrecognized issues associated with changes in operating configurations.

3.6 Operation

3.6.1 Operation and CROSSFLOW Performance Checking

Once installed, CROSSFLOW appears to provide consistent flow rate indication as long as the flow profile does not change. Hence, CROSSFLOW must be operated under conditions where the flow profile is essentially unchanged from the profile used for calibration or a transit time (and hence indicated flow rate) error may be introduced. To address this requirement, W/AMAG has developed an assessment methodology that is composed of CROSSFLOW self-assessment and comparison to other plant parameters.

Reference 2 summarized self assessment by stating that continuous monitoring of system performance ensures acceptable flow results are maintained and unacceptable flow results are recognized by system alarms. The assessment process that leads to system alarms is summarized and assessed in the remainder of this subsection.

The process consists typically of setting (b)(4) database monitoring parameters for on-line monitoring and system diagnostic alarms. The parameters are then divided into (b)(4) categories based on level of importance as illustrated in the following table that was reproduced from Reference 6:

(b)(4)

(b)(4)

Following installation and initial checkout, (b)(4)

(b)(4)

[23]This is not the equation generally used for determining standard deviation or uncertainty when sampling a variable that consists of one variable divided by another.

[24]For example, in discussing ARL test result uncertainty, W/AMAG stated that total uncertainty was due to (b)(4)

(b)(4)

(b)(4)

(b)(4)

(b)(4) The identified issue at this juncture is that potential bias has not been acceptably addressed. Essentially, (b)(4) is assumed to be correct on the basis that whatever method of calibration was used continues to apply.

Reference 6 listed the parameters, the setup values, the category, and provided remarks for a two loop installation. Several parameters that are of interest to this discussion include:

(b)(4)

(b)(4)

(b)(4) Other characteristics are also checked and an alarm is generated if specified criteria are not met as summarized in the following table:

(b)(4)

---

[25] These buffer sizes differ from the above table.

(b)(4) [redacted]

Reference is made in the first table to an uncertainty obtained from the "Quality Assured Calculation," (QA Calc). The NRC staff has not reviewed this calculation and cannot attest to its validity. This process is critical to understanding part of the issue regarding whether CROSSFLOW operation will be maintained within the claimed uncertainty bound or whether an expanded uncertainty is required to obtain reasonable assurance of acceptable operation.

Reference 18 stated that, in industry's experience, most problems such (b)(4) [redacted] Furthermore, the licensee can change the range limits. This appears to be a substantial allowable variation when contrasted to a claimed uncertainty of about 0.5 percent

If any of the limits or uncertainties are exceeded, then W/AMAG has stated that CROSSFLOW (b)(4) [redacted] (Reference 6).[26]

If all tests are successful and venturi characteristics are determined to have changed, then the information is used for venturi correction.

An example of changing limits to compensate for venturi changes to avoid false out-of-limit alarms was provided in Reference 48 and is reproduced in Figure 32.

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[26]The NRC staff notes that the use of "should" and "suggested" implies an option or that exceptions are permitted. A more appropriate term is "required."

(b)(4)

[redacted]

Until approximately July 26, C_f is approximately constant. Then C_f begins to decrease, a characteristic of venturi fouling. At approximately August 18, the licensee started changing upper and lower limits that, if retained, would result in continuous alarms. In order to accept the validity of these changes, the specific rationale applied to the limit changes should be provided. And, as discussed in several places in this report, the rationale must include sufficient other plant parameter information to reasonably assure that venturi fouling is the sole cause of the observed behavior or, if not the case, that other contributors have been evaluated. Furthermore, the uncertainty associated with the changes must be factored into the overall claimed uncertainty.

Reference 48 also provided a three year history, which is reproduced in Figure 33

(b)(4)

[redacted]

where the top data are F_u, the middle data are F_v, and the bottom data are C_f.

Prior to the region where no data are provided that is probably an outage, the variation in calibration coefficient is about (b)(4) percent. Following the outage, little variation is observed. Data are within a band of about (b)(4) percent on each side of the mean for each point in time. This tends to support a rationale that CROSSFLOW operation can be stable in the long term although there is a slight slope in some regions of the data that may be of significance when compared to the claimed uncertainties..

Another issue identified by the NRC staff stems from C_f being based on two means of flow measurement, CROSSFLOW and a venturi, that are claimed to be independent. A basic question is "Was the change due to a change in CROSSFLOW, in the venturi, or both?" A second question relates to dependency. Both flow measurement devices are affected by swirl, changes in flow profile, and non-uniform temperature (affecting density, for example, that is assumed to correspond to measured temperature that may not be the correct bulk temperature), and, in this sense, they may not be independent.

In some plant designs, a flow control valve is located upstream of the CROSSFLOW and a licensee has claimed there are few realignment events that could affect the meter because the flow control valves will dominate the flow process so that any change in upstream flow profile would be masked by control valve turbulence (Reference 18). However, data have not been provided to substantiate this claim. The NRC staff also notes that changes in upstream feedwater heaters would introduce nonuniform feedwater temperature upstream of the flow control valve and mixing would help achieve a uniform temperature. Such mixing is also beneficial when doing a chemical tracer test. However, quantitative information has not been provided to show this.

The data handling process will likely recognize sudden changes such as a flow profile change due to an upstream configuration change that affects CROSSFLOW but has a different impact on the corresponding venturi. However, data from other sources may be needed to determine whether the cause was something like venturi defouling or an upstream change that could, for example, be caused by a change in the upstream flow path. Sudden CROSSFLOW malfunctions should also be recognized. It may be more difficult to separate slow changes that influence the flow profile from real flow rate changes and, again, data from additional sources may be needed. Finally, the CROSSFLOW self-assessment process will provide only limited information regarding the relationship between the original test facility flow rate calibrations and actual flow rate in the installation.

The assessment process addresses changes that may occur during operation but, as identified in section 3.5, it does not address the potential change in uncertainty when moving from test to operating conditions. Furthermore, the "trigger point" for action due to an indicated change introduces an uncertainty that does not appear to have been included in the overall uncertainty assessment.

The data handling process used for the CROSSFLOW self assessment is complex, but it does not appear adequate to achieve the objective of reasonably assuring operation within the stated uncertainty. Consequently, the process to control parameters that potentially affect flow profile must be clearly stated and licensees must commit to follow the process. Furthermore, the use of additional means to assess operation is necessary and needs to be improved.

Reference 15 discussed a re-validation activity that was to confirm (b)(4) (b)(4) (b)(4) The NRC staff believes that this approach is unacceptable. Many of the issues were not recognized at the time of commissioning.

3.6.2 Operational Examples

The NRC staff elected to examine characteristics associated with the U.S. plants identified in section 3.4.6 that exhibited the best calibrations. The following were selected where the installation information is reproduced from the section 2.4 tabulation:

[

(b)(4)

]

This illustrates that, on average, the deviation of the mean from the typical claimed 0.5 percent uncertainty is a positive bias of (b)(4) percent. The overall conclusion is that there is good agreement between CROSSFLOW and venturi or flow nozzle indications for the plants selected on the basis of best agreement between CROSSFLOW and other installed flowmeters for the plant conditions that existed when the data were obtained. However, the NRC staff notes this does not justify a conclusion that CROSSFLOW is more accurate than the venturis or flow nozzles, that all applications are consistent with the selected results, or that a similar agreement will result if plant conditions change.

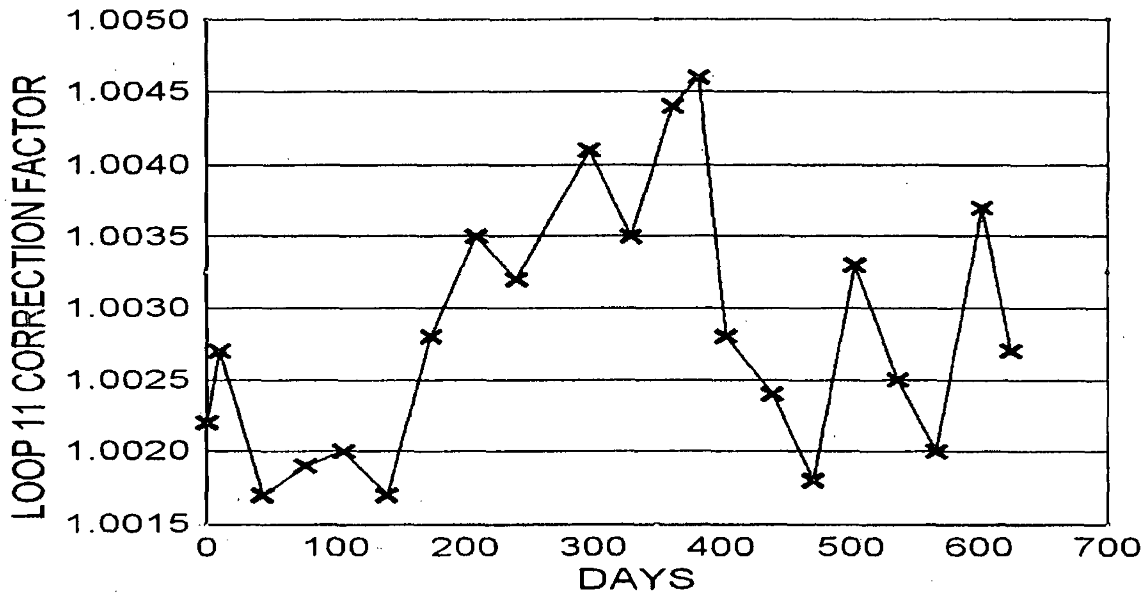

Figure 34. Calvert Cliffs Loop 11 Long Term Behavior

Reference 18 tabulated data for Calvert Cliffs loop 11 where CROSSFLOW is located downstream of a Mitsubishi flow straightener and a venturi is located immediately downstream of CROSSFLOW. The period covered is the time CROSSFLOW was put in service on July 21, 2003 to April 7, 2005 when "the feedwater venturi was first observed to foul." The table was titled "Stability of Venturi Correction Factor Over Time" and the reference stated that these data "demonstrated that the meter "located downstream of the Mitsubishi style flow" straightener is "repeatable." The NRC staff plot of these data is provided in Figure 34. The NRC staff observed that there appeared to be a trend that initiated at day 43 and continued past day 382. The NRC staff then plotted the data for this time span as shown in Figure 35. The correction factor data are scattered over a span of 0.32 percent and the fitted straight line in Figure 35 clearly shows a steady change in correction factor over the illustrated time. This does not support the Reference 18 conclusion that CROSSFLOW "is capable of maintaining a precise

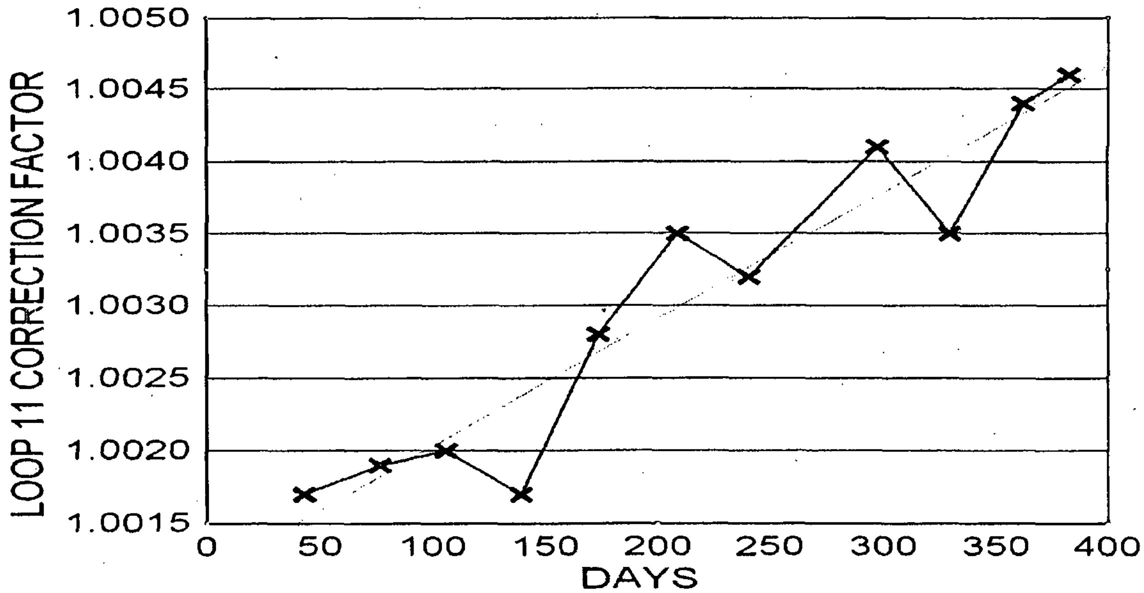

Figure 35. Calvert Cliffs Loop 11 Trend

calibration." Reference 18 presented similar data for loops 21 and 22 that are illustrated in

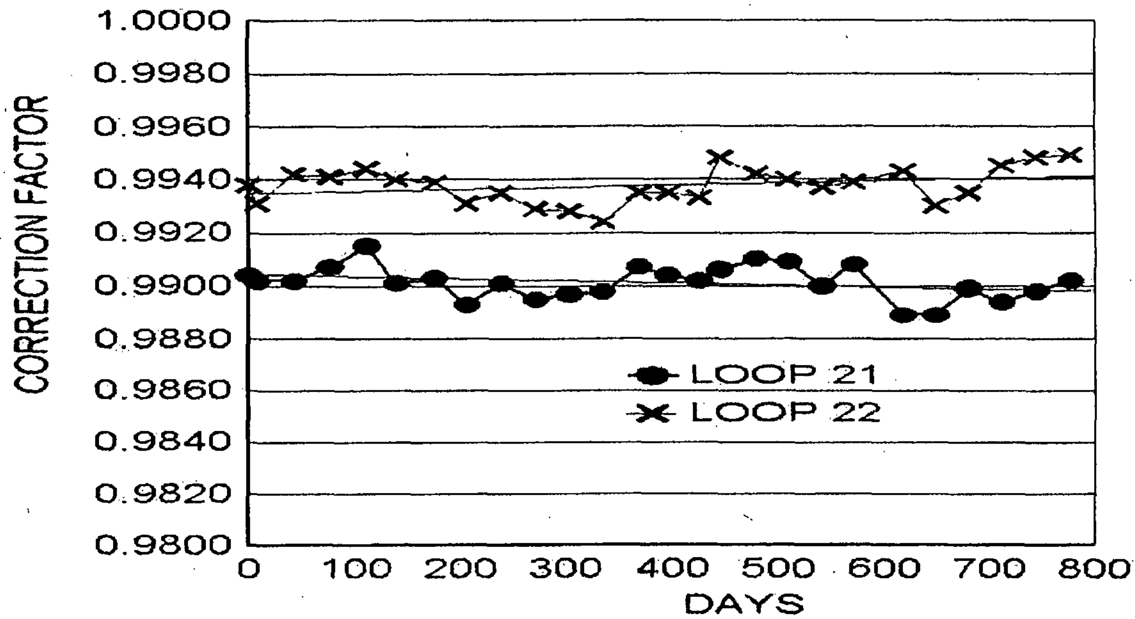

Figure 36. Calvert Cliffs Loops 21 and 22 Long Term Behavior

Figure 36. Over close to 800 days, loop 21 shows a slight upward trend of 0.05 percent and loop 22 has a slight downward trend of 0.06 percent. These data tend to support the Reference 18 conclusion that CROSSFLOW "is capable of maintaining a precise calibration," although

there is some variation with time - a variation that is roughly 10 percent of a typically claimed uncertainty of 0.5 percent .

Swirl has been reported as varying by as much as 10 percent over time in locations that comply with ASME criteria for venturi installations and this could cause a venturi error of as much as two percent. (Reference 40) This would cause affected venturis to overpredict flow rate, which is a conservative error, but an error that could be incorrectly attributed to fouling. If the venturi were the only flow rate indicator that was affected, then a correction using CROSSFLOW should make no difference in the overall correction scheme. However, swirl also affects CROSSFLOW indication and, as identified in References 6 and 40, may cause CROSSFLOW to indicate low, an effect that CROSSFLOW cannot directly identify. This introduces the possibility that the venturi will be over-corrected and an overpower condition will be initiated.

3.6.3 Use of Recent Knowledge for Previously Installed CROSSFLOWs

In late 2004, Reference 49 reported that "inadequate installation practices led to the use (of) erroneous feedwater flow determinations by Ultrasonic Flow Measurement (UFM) systems at some operating plants and, when used, caused the plants to exceed licensed power. Similar problems have been found at other plants preparing to operate their systems." "Utility members of the Westinghouse Owners Group (WOG) using CROSSFLOW systems have formed a Task Force (CTF) whose purpose is to support and participate in the issue resolution activities and, going forward, to benefit from effective communication of relevant operating experience. These utilities, along with support from Westinghouse Electric Co., LLC (Westinghouse), its technology partner and the CROSSFLOW system vendor, the Advanced Measurement and Analysis Group, Inc. (AMAG), have undertaken a comprehensive program to understand and resolve the installation practices that led to the determination of incorrect feedwater flow measurements."

A re-validation activity was identified that (b)(4) [redacted] (b)(4) [redacted] (b)(4) [redacted] Future work was described as including (b)(4) [redacted] (b)(4) [redacted]

This effort led to publication of the User Guidelines described in section 3.3.2 and to a number of improvements that are identified throughout section 3. However, as addressed in section 3.6.4, these and planned improvements have not reached the level where the NRC staff can accept the claimed CROSSFLOW uncertainties.

4 CONCLUSIONS

Information obtained since approval of topical report CENPD-397-P-A has resulted in the NRC staff identifying errors in the topical report and the conclusion that the topical report fails to address many issues. Issues are associated with W/AMAG description changes, pre-installation testing, installation, commissioning, and monitoring. CROSSFLOW's inability to directly assess the flow profile and flow profile changes, the need for a substantial calibration factor that is strongly influenced by changes in flow characteristics, and failure to achieve traceability to recognized standards are major weaknesses that are the direct cause of many of the other identified issues. Such issues must be satisfactorily addressed before there is reasonable assurance that the uncertainties associated with CROSSFLOW measurement of feedwater flow have been appropriately determined. Consequently, the NRC staff has concluded that (1) the existing previously approved CENPD-397-P-A topical report is an inadequate basis for using CROSSFLOW to determine feedwater flow rate and (2) a basis has not been established for such use that acceptably addresses the issues discussed in this NRC staff assessment.

5 REFERENCES

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2 "Crossflow Ultrasonic Flow Measurement System, Cross Flow Status Update," W/AMAG slides from meeting with NRC, September 12, 2005.

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

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6 ~~Gresham, James A., "Applied Research Laboratory / Pennsylvania State University Investigations Concerning the CROSSFLOW (Proprietary)", Letter to NRC from Manager, Regulatory Compliance and Plant Licensing, Westinghouse Electric Company, LTR-NRC-06-36, June 1, 2006.~~

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10 Kuczynski, Stephen E., "Licensee Event Report (LER) 454-2003-003-00, 'Licensed Maximum Power Level Exceeded Due to Inaccuracies in Feedwater Ultrasonic Flow Measurements Caused by Signal Noise Contamination,'" Letter to NRC from Site Vice President, Byron Nuclear Generating Station, September 29, 2003.

11 Braidwood Unit 2, Licensee Event Report 40123, August 31, 2003.

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13 Kuczynski, Stephen E., "Supplement One to Licensee Event Report (LER) 454-2003-003-00, 'Licensed Maximum Power Level Exceeded Due to Inaccuracies in Feedwater Ultrasonic Flow Measurements Caused by Signal Noise Contamination,'" Letter to NRC from Site Vice President, Byron Nuclear Generating Station, March 31, 2004.

14 Kouba, Bill, "Byron/Braidwood Thermal Power Measurement," Slides from NRC Meeting with Licensees Using Ultrasonic Flow Measurement Devices, Exelon Nuclear, September 17, 2004. (Proprietary) (Received during NRC Meeting with W/AMAG on October 5, 2005) (See Reference 50.)

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