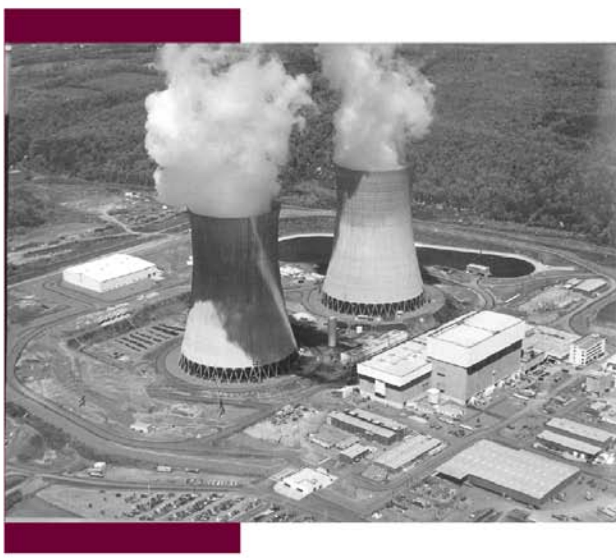
Plant Support Engineering: Methodologies for Monitoring and Adjustment of Reactor Power Measurement Drift



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Plant Support Engineering: Methodologies for Monitoring and Adjustment of Reactor Power Measurement Drift

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Final Report, September 2007

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REPORT SUMMARY

This report documents work undertaken by EPRI and Electricité de France (EDF) to identify and evaluate methodologies for monitoring measurement drift and error in an effort to support more accurate estimation of reactor thermal power (RTP) at nuclear power plants. Several methodologies are considered, with a primary area of focus being the accurate measurement of feedwater flow—a critical parameter for estimating RTP.

Background

In recent years, a series of events involving overestimation and underestimation of thermal power has affected nuclear plants in the United States and France. In the United States, during the period 1990–96 many units experienced venturi fouling problems that led to overestimation of thermal power, with associated generation losses. During 2000–03, the opposite phenomenon occurred—underestimation of thermal power led to a series of 14 overpower incidents that were documented by the Institute of Nuclear Power Operations (INPO) as "leading to a reduction of the safety margins." In France, during the period 2002–07 six units encountered fouling of their feedwater flowmeters that led to underestimation of thermal power; in each case the operators reduced power and informed the French Safety Authority. These nuclear power industry experiences in the United States and France have highlighted the need for methodologies to monitor RTP measurement drift and error. The practices currently in place for such monitoring vary from plant to plant.

Objective

- To assemble information on the practices currently used by thermal performance engineers at nuclear plants to detect and monitor drift or error in RTP measurements

Approach

EPRI and EDF conducted a joint project in four phases:

- Phase 1: A Plant Performance Enhancement Program (P^2EP) survey of units affected by feedwater flow measurement drift/error (February–April 2006)
- Phase 2: A first analysis of the survey results (June 2006)
- Phase 3: On-site visits to three U.S. nuclear plants to perform detailed analysis of representative monitoring methods (August 2006)
- Phase 4: Preparation of this technical report compiling and analyzing information gathered in Phases 1–3

Results

Four methods in general use for monitoring RTP measurement drift/error are presented in the report, along with a discussion of their advantages and limitations. (It should be noted that methods other than these four have been locally developed and implemented, but they are beyond the scope of this report.)

Two of the methods provide a relative or differential analysis:

- A trend analysis method (based on key power parameter trend analysis)
- EDF's ΔP/P method (based on high-pressure turbine first-stage pressure monitoring)

The other two methods provide an "absolute" estimate of RTP error/drift:

- The River Bend calorimetric verification method (documented in an INPO publication and performed by many U.S. plants)
- The data reconciliation method (performed by EDF and other European nuclear plants)

As part of the discussion of the methods, a classification system is proposed that organizes the methods in terms of their complexity of implementation and relevance of diagnosis.

EPRI Perspective

The estimation of RTP and the closely related subject of feedwater flow measurement are areas of considerable interest to EPRI and its members. This report describes several methods that plants are currently using to monitor and respond to measurement error and drift in order to support more reliable determination of RTP.

Keywords

Thermal power
Monitoring
Feedwater flow measurement
Venturi
UFM
Orifice plate

ACRONYMS AND ABBREVIATIONS

ΔP	differential pressure (also abbreviated DP)
$\Delta P/P$	EDF's thermal power monitoring method
BWR	boiling water reactor
DP	differential pressure (also abbreviated ΔP)
DR	data reconciliation
EDF	Electricité de France
EPRI	Electric Power Research Institute
FMF	feedwater mass flow
HP	high-pressure
INPO	Institute of Nuclear Power Operations
NRC	United States Nuclear Regulatory Commission
P^2EP	Plant Performance Enhancement Program
PSE	Plant Support Engineering
PWR	pressurized water reactor
RB	River Bend
RTP	reactor thermal power
SG	steam generator
TPE	thermal performance engineer
UFM	ultrasonic flow measurement or ultrasonic flowmeter

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INTRODUCTION

1.1 The Role of Feedwater Flow Measurement in the Computation of Reactor Thermal Power

Reactor thermal power (RTP) is directly proportional to feedwater flow (feedwater mass flow) for pressurized water reactors (PWRs) and boiling water reactors (BWRs), as defined by the following equation:

$$\text{Reactor Thermal Power} = \text{FMF} \times (h_s - h_{fw}) + (\text{heat gain/loss}) \qquad \textbf{Eq. 1-1}$$

where:

FMF	=	feedwater mass flow
h_s	=	steam enthalpy, dependent on temperature, pressure, and moisture
h_{fw}	=	feed enthalpy, dependent on temperature and pressure
heat gain/loss	=	from reactor-attached piping and pumps

Because of the key role of feedwater mass flow in this equation, it is not surprising that uncertainty computations for PWRs show that feedwater flow accounts for at least 80% of overall uncertainty in RTP estimation.

Figure 1-1 illustrates aspects of thermal power measurement in a PWR.

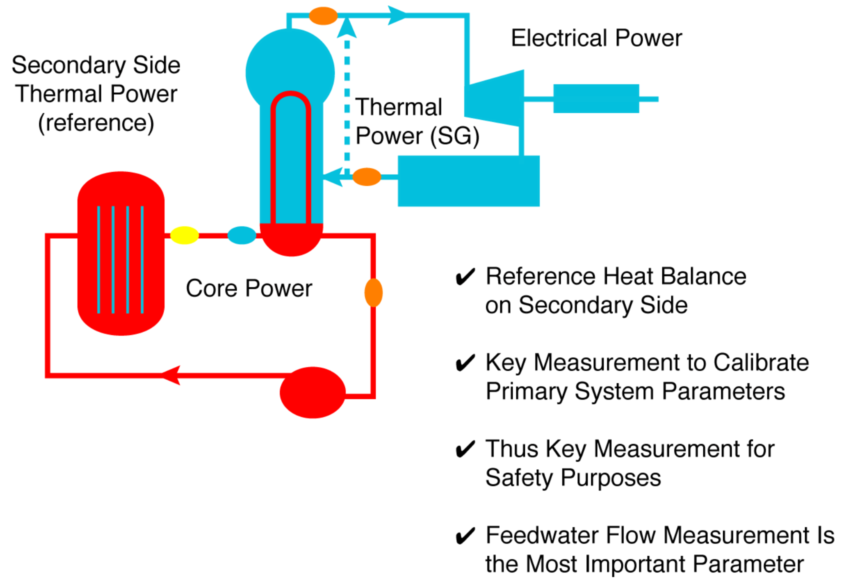


Figure 1-1
Thermal Power Measurement in a PWR

1.2 Reactor Thermal Power Measurement: Performance and Safety Issues

1.2.1 Overestimation of Power: A Performance Issue

Any overestimation of RTP (including overestimation resulting from a feedwater flow measurement error) can lead to reduced generator output. This can result in a significant financial penalty to operating units. For example, a 1% overestimation of reactor power for a 1200-MWe unit will result in a reduction of 12 MWe. At $35 per MWh, this amounts to an annual financial penalty of nearly $3.5 million (assuming a 95% unit capacity factor).

1.2.2 Underestimation of Power: A Safety Issue

RTP measurement is used as a reference measurement to calibrate other power control systems, such as:

- Neutron power range channels
- Reactor coolant system ΔT power channels
- Reactor coolant system protection channels

Thus, any underestimation of RTP impacts plant safety, because actual power will be higher than indicated by measurement systems.

1.3 Reactor Thermal Power Measurement Drift and Error: Some Recent History

1.3.1 Experience in the United States

By design, U.S. nuclear power plants were equipped with venturis for feedwater flow measurement and for Appendix K thermal power estimation (10CFR50 Appendix K [1]). During the period 1990–96, many U.S. units experienced venturi fouling problems that led to losses of generation as a result of overestimation of thermal power. These losses were typically 2%, that is, 20 MWe per unit. Chemistry investigations were undertaken to assess the cause of the problem, which turned out to be magnetite fouling on venturi surfaces.

Subsequently, there was a U.S. fleetwide effort to secure small power uprates under Appendix K, as documented in EPRI report 1000607 [2]. The basis for this effort was the hope that more accurate measurement instrumentation—specifically ultrasonic flow measurement (UFM) devices—would allow a smaller uncertainty with regard to RTP. The UFM feedwater flow measurement was meant to replace the venturi measurement in the RTP computation.

Then, in 2000–03, the opposite phenomenon happened: cases of underestimation of thermal power. The Institute of Nuclear Power Operations (INPO) documented 14 overpower incidents among U.S. plants "leading to a reduction of the safety margins." Among these was a case of one plant operating at 102.7% of allowed nominal power for a period of 15 months. U.S. thermal performance engineers (TPEs) detected the drift with varying success by using available plant process data.

In a 2004 document (SER 3-04 [3]), INPO assessed the sources of errors, which included both technical errors and human errors, on both the vendor side and the operator side. INPO's conclusions included the following:

- Factors included "overreliance on vendor expertise, lack of a questioning attitude by station personnel, and inadequate verification testing."
- "Independent methods of correlating reactor power with other power-dependent plant parameters were not rigorously performed."
- "Several opportunities were missed to identify and resolve the issue of operation at excess power levels over the three-year period."

These events were due in large part to insufficient mastery of new technologies (ultrasonic flowmeters) by both vendors and/or operators, on units that were pursuing small power uprates based on reduction of uncertainty of feedwater flow measurement, following the recommendations in [2]. In some instances, operators ultimately had to rely on the ISO/ASME standardized method of radioactive tracer testing [4] to prove and quantify measurement error by ultrasonic flow measurement.

1.3.2 Experience in France

By design, all French nuclear power plants were equipped with both orifice plates and venturis for feedwater flow measurement (see Figure 1-2).

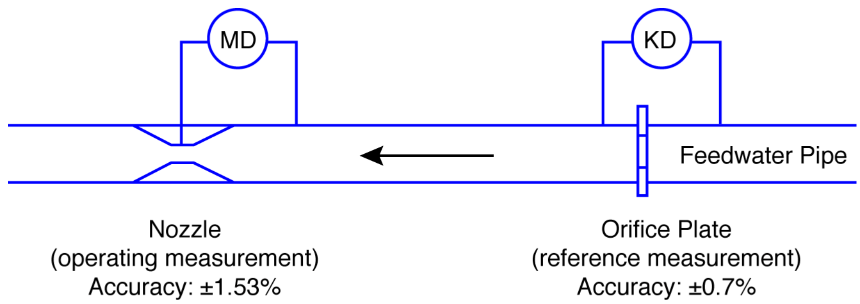


Figure 1-2
Feedwater Flow Instrumentation Used on EDF PWRs

The measurement taken with the orifice plate is used as the reference feedwater flow to calculate RTP measurement (with 0.45% uncertainty), whereas the venturi measurement is used for control purposes. Orifice plates are the most accurate ISO-standardized flow measurement device (as documented in EPRI report 1003040 [5]) and had been error-free until recently. However, in 2002–07, magnetite deposits on the sharp edge of the orifice plate led to underestimation of the measured differential pressure, which in turn led to underestimation of feedwater flow. Newly manufactured and installed orifice plates can be affected by a typical bias up to -1% (from plant restarting until end of cycle). Venturis are also affected but in the converse way—magnetite deposits on the venturi surface in the nozzle lead to an increase of the measured differential pressure, thus leading to overestimation of feedwater flow. Experience shows that venturis can be biased up to +2.5%.

During the 2002–07 period just mentioned, seven EDF units encountered fouling of their feedwater flowmeters. Since the reference for feedwater flow measurement is the orifice plate, the fouling of which leads to underestimation of flow, the measured thermal power was underestimated (thus potentially leading to reduction of safety margins). As soon as the drift was identified by the local operator, each unit reduced power and informed the French Nuclear Safety Authority. The Nuclear Safety Authority, acting conservatively, then imposed a power downrate of up to 3.6% of nominal power until appropriate corrective action was taken and demonstrated.

The French Nuclear Safety Authority required that in 2007 EDF estimate a threshold of detection of drift of reactor power measurement (for potential fleetwide implementation) and investigate the impact on the safety analysis.

1.3.3 The U.S. and French Plant Experiences: Mutual Concerns and Commonalities

The recent history in the two countries makes it clear that the problem of RTP measurement error can arise with any feedwater measurement technology. The incidents involved both ultrasonic flowmeters and differential flowmeters, and the measurement errors led to both overestimation and underestimation of reactor power. At present, there is no guarantee for any operator that feedwater flow measurement will never again drift—either slowly or suddenly.

A number of common observations can be made regarding the U.S. and French events:

- Significant effort was required from TPEs to identify error/drift (both the source—feedwater flow measurement—and the amount of error/drift involved).
- Detection of error/drift occurred quite late. By the time it was detected, the discrepancies were too large to discard as nonsignificant or noncoherent in relation to expected uncertainties.
- The efficiency of error/drift detection was dependent on the operator's experience.
- Prior to corrective action, accurate estimation of the error/drift was essential.

Taken as a whole, the events show the need for adequate verification testing that is as efficient as possible. This testing should be of significant help to all operators, regardless of their depth of experience.

As of yet, there is no single method that is guaranteed (or approved by regulators) to ensure full confidence in reliable monitoring and early detection of drift and error in RTP measurement. Currently, the successful performance of drift detection depends to a large extent on the applied knowledge of the individual plant. It was in large part to document this collective experience that the joint effort leading to this report was undertaken by EPRI and EDF.

2
TECHNOLOGY FOR MEASUREMENT OF FEEDWATER FLOW

The technology in common use for measuring feedwater flow in nuclear plants can be divided into two categories: methods based on measurement of differential pressure created by an inserted device (orifice plate, venturi, or nozzle) and methods based on measurement of high-frequency sound waves (ultrasonic technology). This section provides a brief overview of both technologies along with a short discussion of errors associated with each and some known corrective measures. More detailed information is available in the EPRI *Nuclear Feedwater Flow Measurement Application Guide,* TR-112118 [6].

2.1 Differential Pressure Measurement

Measurement methods involving differential pressure are all based on the principle of inserting a primary device into fluid flowing under pressure in a pipe, creating a differential pressure (Δp) between the upstream length and the throat of the device (downstream). The commonly used devices are orifice plates, nozzles, and venturis. (See Figures 2-1, 2-2, and 2-3, all reproduced from the *Nuclear Feedwater Flow Measurement Application Guide* [6].)

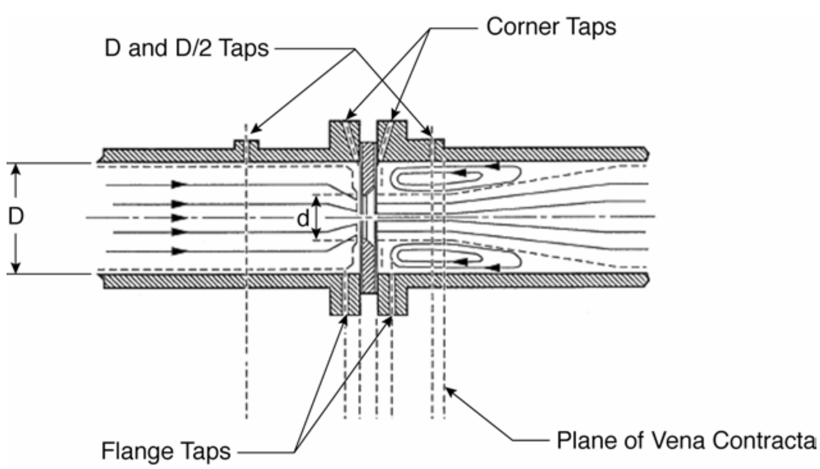


Figure 2-1
An Orifice Plate

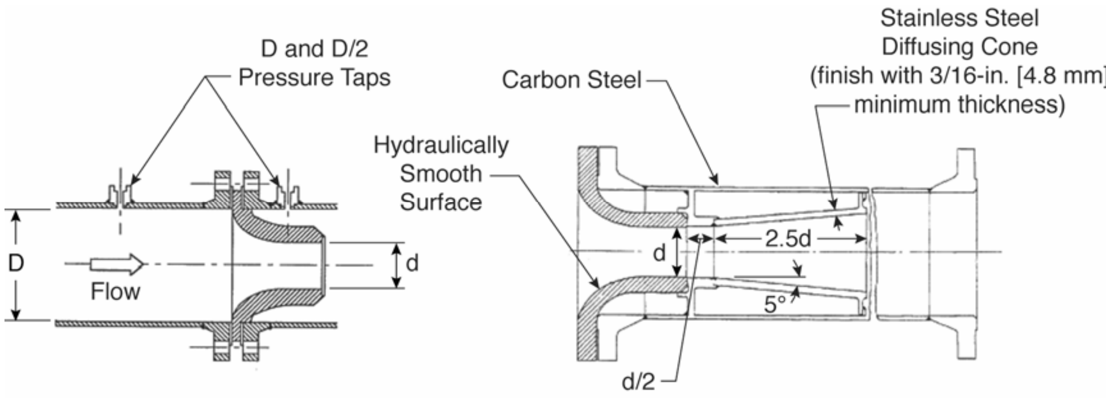


Figure 2-2
Nozzles

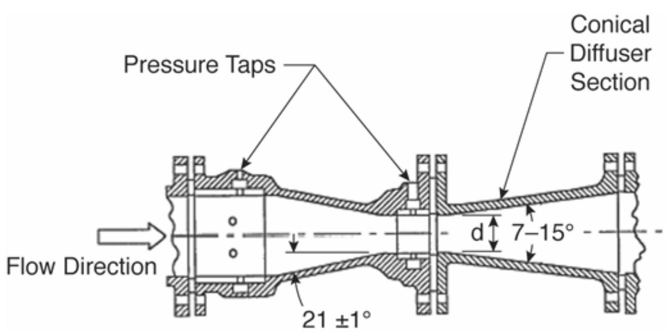


Figure 2-3
A Venturi

Underlying all differential pressure measurement methodology is the Bernoulli principle, according to which differential pressure is proportional to the square of the velocity of a flowing fluid. The following equation can be used to calculate the mass flow of the fluid:

$$q_m = \frac{\pi}{4} \mathrm{CEd}^2 \varepsilon \sqrt{2(\Delta \mathrm{p})\rho}$$ **Eq. 2-1**

where:

q_m	=	mass flow
C	=	discharge coefficient
E	=	$1/\sqrt{(1-\beta^4)}$ = velocity of approach factor
d	=	diameter of orifice
ε	=	expansion factor (= 1 for incompressible fluids)
Δp	=	differential pressure
ρ	=	fluid density
β	=	d/D = beta ratio

This measurement method is described in the international standard ISO 5167 [4] and the EPRI *Nuclear Feedwater Flow Measurement Application Guide* [6]. The values of C and uncertainties regarding C vary depending on the type of primary device (orifice plate, venturi, or nozzle) and on the installation conditions.

The use of orifice plates for feedwater flow measurement in EDF's PWRs is further documented in EPRI report 1003040 [5].

2.2 Ultrasonic Flow Measurement

Two types of industrial flowmeter are pertinent to this discussion. They are based on different techniques (known as *multichordal* and *cross-correlation*) and are approved by the U.S. NRC for small power uprates under Appendix K [2].

Figure 2-4, from the EPRI *Nuclear Feedwater Flow Measurement Application Guide* [6], depicts a device (from Caldon) used in conjunction with the multichordal technique. The instrument is a spool piece allowing measurement of velocity across four chords, with a weighting computation. It has the advantage of tolerating the loss of some ultrasonic transducers without fully losing the measurement. One drawback of this device is that it is not nonintrusive (strap-on).

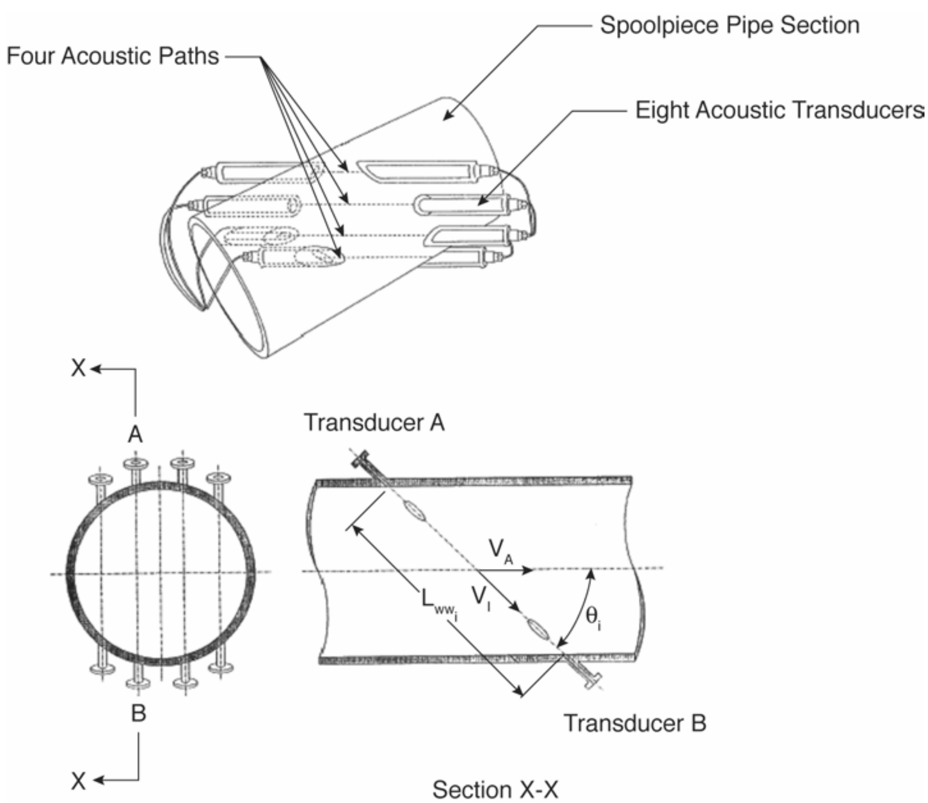


Figure 2-4
Multichordal UFM

Figure 2-5, also from the EPRI *Nuclear Feedwater Flow Measurement Application Guide* [6], depicts a device (from Westinghouse/AMAG) that is used in conjunction with the cross-correlation technique. It is a strap-on, but it may suffer a loss of measurement if an ultrasonic transducer fails. It does not provide a multichordal weighting computation, and it may be more sensitive to flow velocity profile.

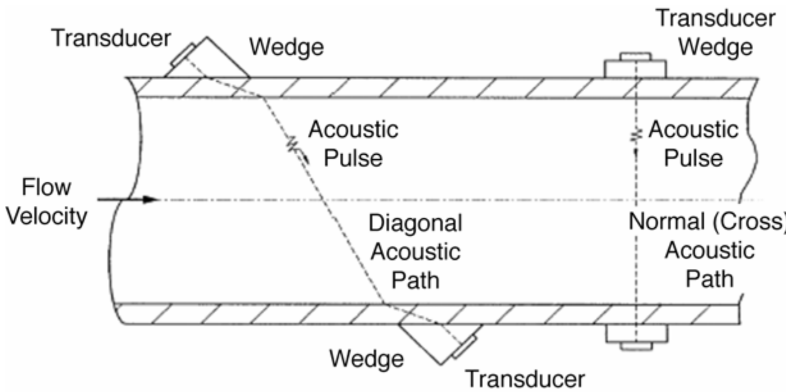


Figure 2-5
Cross-Correlation UFM

2.3 Principal Errors Associated with Flow Metering Technologies

2.3.1 Errors Related to Differential Pressure Flow Measurement

As documented in the EPRI *Nuclear Feedwater Flow Measurement Application Guide* [6], the main errors related to differential pressure flow measurement can be grouped into the following categories:

- Density errors
- Errors in differential pressure measurement
- Errors due to the plant computer
- Errors due to impulse line condition
- Errors due to thermal expansion
- Errors in the discharge coefficient
- Errors due to changes in the internal conditions: erosion, corrosion, or fouling affecting the surface condition of a primary device

The application guide points out that deposition of corrosion products in front of the throat, in the throat section, and in the recovery cone of the throat tap flowmeter can increase the pressure drop across the meter, resulting in an erroneously high flow indication. U.S. plants have experienced such problems with venturis (during the 1990–96 period mentioned in Section 1).

Recent EDF experience (also mentioned in Section 1) has confirmed not only the venturi fouling problem but also the fouling of orifice plates. EPRI report 1003040 [5] documented EDF's experience with orifice plates up to 2001, but no magnetite fouling event had been experienced up to that point. The recent experience with magnetite fouling events on seven units in 2003–07 could now be included as an addition to EPRI report 1003040.

2.3.2 Errors Related to Ultrasonic Flow Measurement

Technical errors potentially affecting ultrasonic flow measurement include the following:

- Dimensional errors
- Density errors
- Timing errors
- Profile factor errors (experimental uncertainty, piping configuration, pipe roughness, Reynolds number extrapolation, and so on)
- Miscellaneous errors including sensitivity to transducer equipment

As mentioned in Section 1, in 2004 INPO assessed ultrasonic flow measurement errors (both technical errors and human errors) in conjunction with a series of events involving U.S. plants and issued SER 3-04 [3], which analyzes the errors and draws some conclusions.

2.4 Corrective Measures

The EPRI *Nuclear Feedwater Flow Measurement Application Guide* [6] addresses preventive actions for minimizing fouling phenomena that can lead to flow measurement errors. Two key points are the following:

- One approach to reducing fouling is periodic cleaning of the flow element, such as through hydrolyzing, mechanical cleaning, or chemical rinses.
- Water treatment programs have also been designed to reduce fouling. These programs include the addition of morpholine in PWRs and hydrogen and zinc in BWRs. The removal of copper-bearing alloys from the cycle has also been found to reduce fouling at some generating stations, although not at others.

In conjunction with measures aimed at prevention of fouling, it is necessary to implement some sort of monitoring to confirm that fouling is not occurring, and when fouling does occur it is important to be able to gauge its impact on RTP measurement error/drift.

Regarding errors associated with ultrasonic flow measurement technology, investigation is still ongoing with the involvement of the U.S. NRC, and corrective measures will be documented. TPEs have been sharing their experience as part of this effort.

3
THE CURRENT PROJECT

3.1 Project Goals

U.S. and French nuclear plant operators have been faced with the need to detect and estimate error/drift in feedwater flow measurement (and thus error/drift in RTP) as early and as reliably as possible. In response, different operators have locally developed various methods for their plants, with varying degrees of success. Each operator had to use other process measurements, independently of actual feedwater flow measurement, to compute a reactor power estimate. The 2004 INPO SER on ultrasonic flow measurement events [3] recommends that "evaluations of complex technical issues with conflicting indications should include the application of diverse testing and analysis methodologies to confirm the extent and nature of the condition."

EPRI and EDF jointly undertook the project that is the subject of this report because the two organizations share a strong common interest in identifying the most reliable means of monitoring and adjusting reactor power measurement drift. Doing so entails pursuing the following goals:

- To support the earliest possible detection of reactor thermal power measurement drift, with a guaranteed level of uncertainty (for example, 95% confidence), that is, with a defined threshold of drift detection
- To enable the identification of measurements that cause RTP measurement drift
- To support the estimation of the amount of error/drift with a given uncertainty (for example, 95% confidence)
- To enable the computation of a substitution power estimate, replacing measurement values with a guaranteed degree of uncertainty
- To propose a guideline of prioritized corrective actions
- To build a fully documented generic demonstration for approval by regulators, in order for plants to be authorized to use a substitute power estimate in lieu of measured power

Specific objectives of this technical report are:

- To assemble a picture of current practices in use by TPEs (U.S., EDF) in response to suspected error/drift in RTP measurement
- To outline future steps: assessing best practices and proposing guidelines for their use

3.2 Project Phases

3.2.1 Phase 1: The Plant Performance Enhancement Program (P²EP) Survey of Units Affected by Feedwater Flow Measurement Drift/Error

With a timeframe of February–April 2006, this phase was aimed at investigating the current practices being used at EDF and at U.S. and other nuclear plants to measure and calculate the true reactor power. Designated as P²EP 2006-01 and titled "Experience Sharing of Reactor Power Drift Monitoring Methods," the survey was written by EDF R&D and subsequently validated and sent by EPRI/PSE/P²EP to P²EP coordinators (TPEs). The survey asked respondents to describe problems that caused feedwater flow drift/error at their plants and to describe local methods developed and used to detect and estimate drift.

The survey and the compiled responses are presented in Appendix A of this report.

3.2.2 Phase 2: Initial Analysis of the Survey Results

This phase was performed in July 2006. Specific goals of the analysis were as follows:

- To assess the relevance of the methods
- To classify the potential performance of the methods
- To identify the most representative practices

Sections 5 and 6 of this report present the analysis results and additional commentary.

3.2.3 Phase 3: On-Site Visits to Three U.S. Nuclear Plants to Perform Detailed Analysis of Representative Monitoring Methods

This phase was conducted jointly by EPRI and EDF in August 2006.

3.2.4 Phase 4: Preparation of This Technical Report Compiling and Analyzing Information Gathered in Phases 1–3

This report presents information collected in Phases 1–3. Additionally, Section 7 of the report proposes further joint EPRI-EDF work to take place in 2007–08 with the objective of developing methodologies for improved reactor power drift monitoring and correction.

4
INFORMATION SOURCES: AN OVERVIEW

This section provides an overview of the main sources of information used to build a picture of practices in use by TPEs (in the United States and at EDF) in response to suspected error/drift in RTP measurement at their plants. These sources are:

- The P²EP 2006-01 survey results
- The site visits to three U.S. plants during August 2006 (organized by EPRI/PSE/P²EP with EDF participation)
- Correspondence with the River Bend plant

In addition to these three main information sources, EDF provided information regarding its own practices for monitoring feedwater flow drift.

4.1 P²EP 2006-01 Survey Results

As mentioned in Section 3, the P²EP 2006-01 survey "Experience Sharing of Reactor Power Drift Monitoring Methods" (reproduced in Appendix A) was sent out by EPRI/PSE/P²EP to P²EP coordinators (TPEs) in February 2006. During the development of this survey, a site visit was made to the Byron nuclear power plant, and the survey reflects the input from staff there.

The survey asked questions about feedwater flow/RTP measurement drift/error and whether the survey participants had a drift/error detection method at their plants.

The survey was answered by staff at 19 plants:

- 17 U.S. nuclear power plants
- 1 Japanese nuclear power plant
- 1 British nuclear power plant

4.2 Site Visits

On the basis of responses to the P²EP 2006-01 survey, three plants were identified as being particularly representative of U.S. practices for monitoring RTP measurement drift/error:

- The Sequoyah plant (TVA, 2 PWR units)
- The Limerick plant (Exelon, 2 BWR units)
- The Three Mile Island plant (Exelon, 2 PWR units)

In August 2006, an on-site mission was organized in collaboration with EPRI/PSE/P²EP and EDF. The goal of this mission was to review in detail the methods and practices for monitoring RTP measurement drift/error in these three plants.

4.3 Correspondence with the River Bend Plant

Personnel at the River Bend nuclear power plant were a primary source of information concerning the River Bend calorimetric verification method. Details about the method were obtained through direct communication with staff at the plant.

5

P²EP 2006-01 SURVEY RESULTS AND ANALYSIS

5.1 Survey Participants

The P²EP 2006-01 survey "Experience Sharing of Reactor Power Drift Monitoring Methods" was answered by 19 plants (EPRI-member utilities) from the United States (17 plants), the United Kingdom (British Energy) and Japan (TEPCO). Not all of these plants reported having experienced RTP measurement drift.

5.2 Reported Problems

Of the 19 plants that answered the survey, 14 have experienced reactor power measurement drift, which indicates that this problem is a common concern for nuclear plants. Reported causes of drift were as follows:

- Feedwater flow venturi fouling: 3 plants
- Feedwater flow venturi erosion: 1 plant
- Steam generator flow nozzle fouling: 1 plant
- Feedwater flow venturi transmitter drift: 1 plant
- Feedwater flow transmitter power supply offset: 1 plant
- Feedwater ultrasonic flowmeter error: 1 plant.
- Steam generator blowdown flow instrumentation failure: 1 plant
- Feedwater temperature sensor error: 1 plant
- Temperature element failure in the blowdown system: 1 plant

As the above list shows, a number of different types of problems can lead to reactor power measurement error/drift, even if problems related to feedwater flow drift/error are the most frequent cause.

5.3 Plant Implementation of Reactor Power Drift Monitoring Methods

The following information was collected regarding plant decisions to implement a reactor power drift monitoring method:

- 10 out of 14 plants have implemented a method while experiencing suspected reactor power measurement drift.
- 2 out of 5 plants have implemented a method while not experiencing suspected reactor power measurement drift.

It is not surprising that most of the plants (70%) that experienced reactor power measurement drift/error have decided to implement a monitoring method. The fact that two of the plants without any suspected reactor power measurement drift have decided to implement a monitoring method confirms that nuclear plants are aware that this type of problem can appear in any nuclear power plant regardless of the measurement technologies involved.

5.4 Types of Monitoring Methods

The survey results indicated that there are two types of monitoring methods implemented at the plants:

- A trend analysis method, employed by 9 plants.
- The use of parameters as thermal power indicators (including the River Bend calorimetric verification method), employed by 5 plants. These plants combine this methodology with trend analysis.

5.5 Development and Use of the Methods

Concerning the development of monitoring methods, plants responded as follows:

- When asked whether they have locally developed a method for monitoring drift, 8 out of 9 plants responding answered yes.
- When asked whether they have had their method reviewed by their TPE, 3 out of 4 plants responding answered yes.
- When asked whether they have had their method reviewed by the U.S. NRC, 2 out of 5 plants responding answered yes.

In response to other questions:

- 8 out of 10 plants responding have detected feedwater flow measurement drift (also confirmed after investigation).
- Even though 8 out of 9 units responding said that they are satisfied with the method they use, 10 out of 10 plants responding said that they are interested in the EPRI-EDF collaborative project on this subject.

6 FOUR METHODS FOR MONITORING REACTOR POWER MEASUREMENT DRIFT

Based on the P²EP 2006-01 survey and on additional input from EDF, four methods have been identified for discussion in this section of the report:

- A trend analysis method (used by nine plants that responded to the survey)
- The River Bend calorimetric verification method (used by five plants that responded to the survey)
- EDF's ΔP/P method
- The data reconciliation method (used by EDF and also by other European nuclear plants)

It should be noted that there are other methods that have been locally developed. (For example, Exelon's Byron generating station has implemented a method based on the monitoring of five independent indicators and their average, with a threshold of 0.20%.) Thus, the above list of methods cannot be regarded as exhaustive.

6.1 Trend Analysis

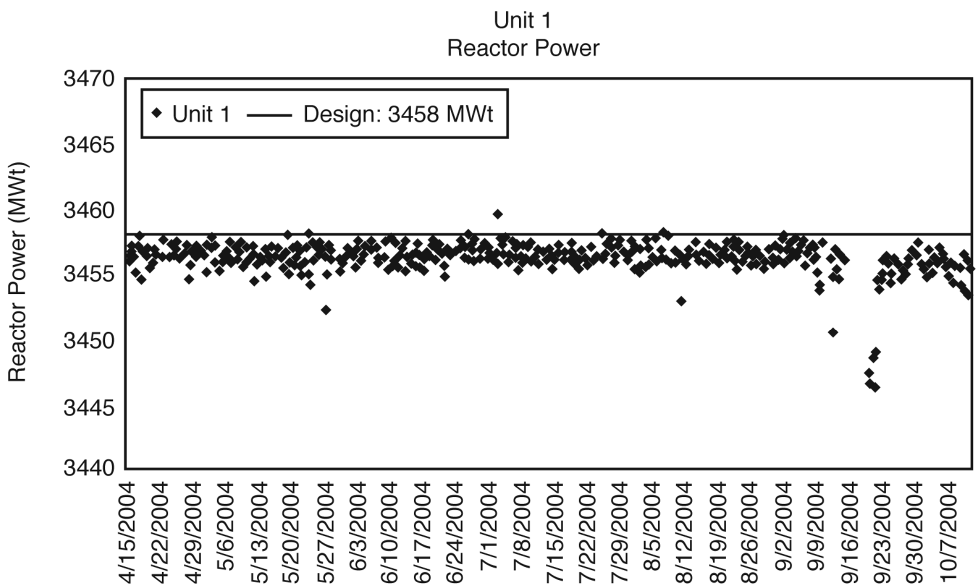
Nine plants use trend analysis to monitor reactor power measurement error/drift. This method is applied by monitoring a ratio of parameters or key parameters that have a direct relation to reactor power. Because the reactor power measurement is supposed to be constant during the cycle, a common trend evolution of the ratios or the key parameters being monitored is considered a reliable indication of reactor power measurement drift.

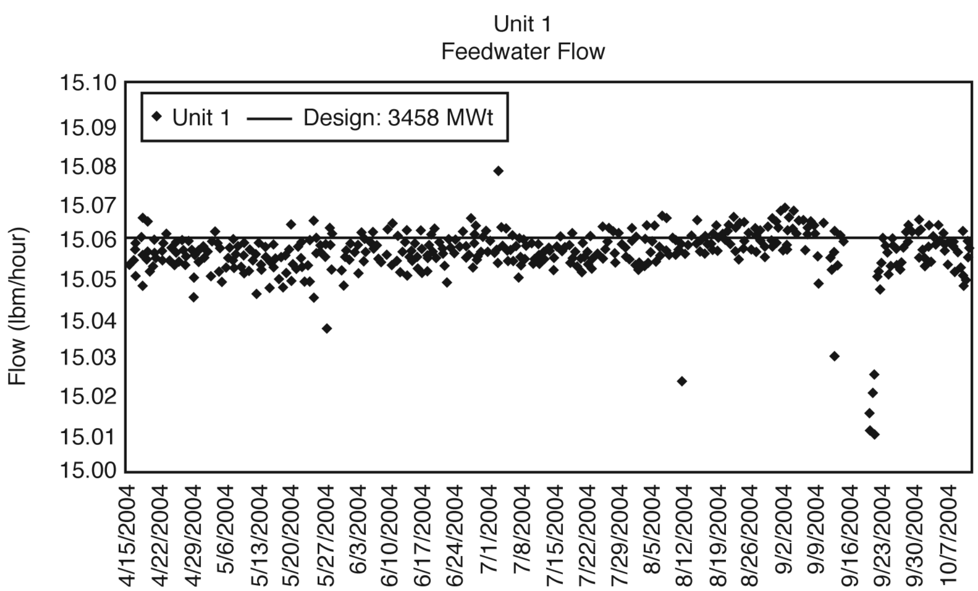
The parameters that are frequently used for trend analysis are:

- Feedwater flow (venturi, UFM, orifice plates, and other technologies)
- Main steam flow
- HP turbine first-stage pressure
- Primary ΔT
- Feedwater temperature
- Gross electric power
- Steam generator blowdown flow

Generally, the method is carried out by comparing the trended indication to a predetermined threshold. The analysis requires considerable expertise and is usually performed by the local TPE.

Figures 6-1 and 6-2 provide an example of data used in trend analysis. In Figure 6-1, the power and feedwater flow data appear to be constant. However, trend analysis of the HP turbine inlet pressure data shown in Figure 6-2 points to a suspected case of thermal power drift.





1 lbm/hour = 0.000126 kg/second

Figure 6-1
Trend Analysis Data: Power and Feedwater Flow

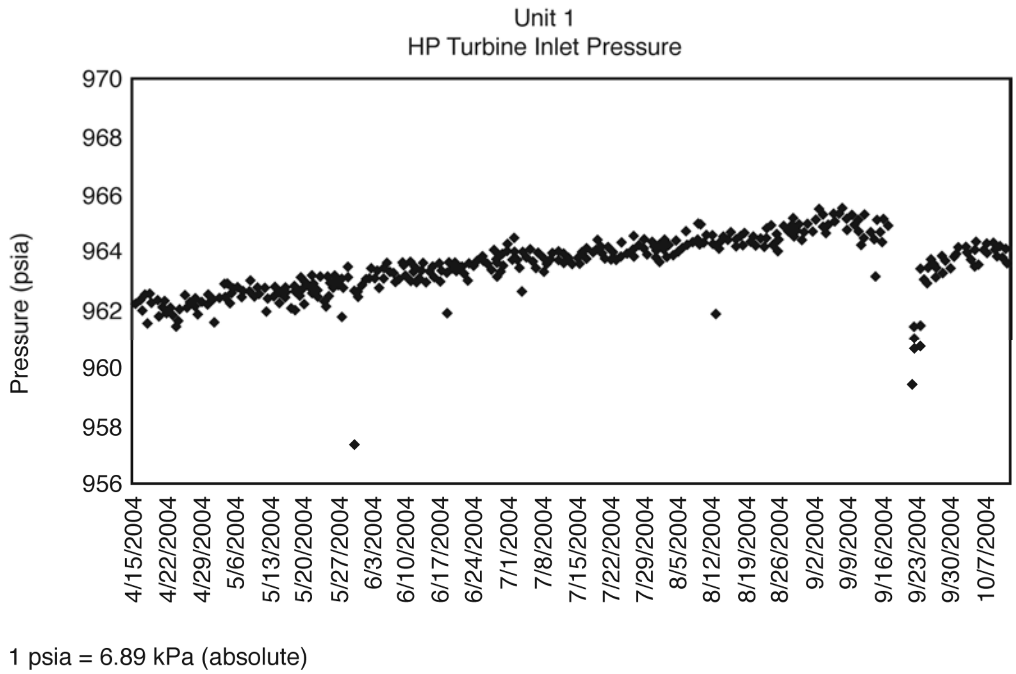


Figure 6-2
Trend Analysis Data: HP Turbine Inlet Pressure

6.2 The River Bend Method Calorimetric Verification Method

As a complement to the trend analysis, five plants that responded to the survey use more sophisticated methods that are based on the same principle as the River Bend calorimetric verification method, often referred to simply as the *River Bend method.* The principles and implementation of this method are described in the 2004 INPO document "River Bend Station Best Estimate Core Thermal Power," INPO NX-1057 [7].

Some key aspects of the method are as follows:

- There are 16 measurements that are used as indicators of reactor power measurement on the secondary system. These measurements include HP turbine first-stage pressure, steam generator flow, moisture separator reheater pressures, feedwater flows (from venturis not corrected by UFMs), and feedwater temperature. Because the feedwater flow measurement (regardless of the feedwater flow technology) may in fact be the main cause of reactor power measurement drift, this set of 16 key measurements supports another means of verification.
- A verification test is performed when the plant is perfectly stable at full load. Then the average of the 16 key measurements is calculated over 2 hours, with an acquisition update every 2 minutes.
- A characteristic reference value of these 16 measurements at full load exists that has been determined when the unit was running without any suspicion of reactor measurement drift.

- For each of the 16 measurements, a proportional relation is applied to calculate the reactor power during the test in comparison with the reference power associated with the reference value of the measurement. (For temperatures, since they are not 0°F at 0% power, the proportional relation is replaced by a linear relation calculated using historic data.) Based on the 16 key measurements, 16 separate calculations of reactor power are made.
- The measurement uncertainties for the 16 key measurements are used to calculate 1/variance (1/uncertainty^2) for each measurement. These terms are then divided by the sum of the 1/variance on all 16 measurements. These values are called *confidence factors* because they correspond to the confidence in the measurement according to its uncertainty. (The lower the uncertainty, the greater the confidence factor.)
- An estimate of the reactor power designated as *RB Best Estimate Core Thermal Power* (or simply *Best Estimate Core Thermal Power*) is made. It is derived by adding the products obtained by multiplying each of the 16 separate calculations of reactor power by its pertinent confidence factor.
- An uncertainty calculation for the Best Estimate Core Thermal Power is carried out based on the uncertainties of the 16 original measurements.
- For each of the 16 measurements, a low limit and a high limit are defined to ensure that the measurement used is correct. If a measurement falls outside this range, it is not used in the calculation of the reactor power (and maintenance of the pertinent instrumentation is scheduled).
- To monitor drift, a comparison between reactor power measurement and the Best Estimate Core Thermal Power (taking into account their respective uncertainties) is performed periodically (typically, with a time frame of days or weeks).

This method requires qualified experienced personnel to perform the review and the analysis.

6.3 EDF's ΔP/P Method

EDF has a monitoring method that it uses to detect reactor power measurement drift during the operating cycle. It has been applying this method since 2005 at its affected plants. This method is based on the monitoring of a single relevant parameter—turbine first-stage pressure—during the operating cycle.

Figure 6-3 illustrates EDF's ΔP/P method.

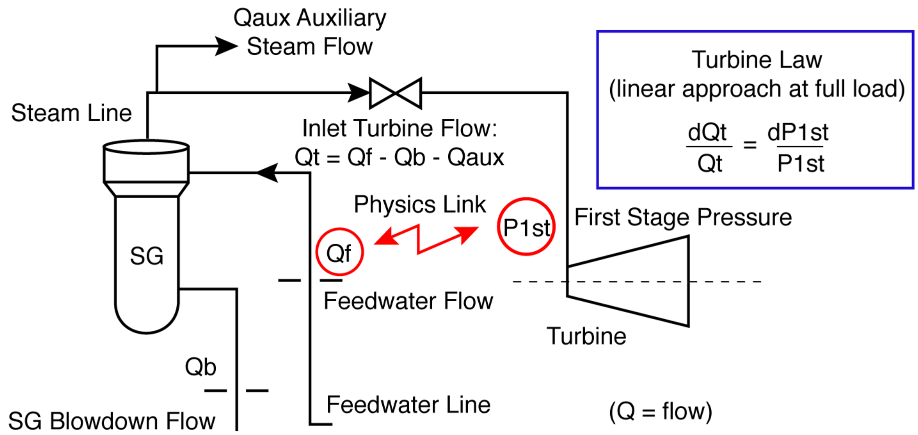


Figure 6-3
EDF's ΔP/P Method for Power Drift Monitoring

Some specific points about the method are as follows:

- The inlet turbine steam flow Qt is directly linked to the total feedwater flow Qf. The relationship dQt = dQf applies because the steam generator blowdown flow Qb and the auxiliary steam flow Qaux are constant at full-load operating point.
- Because the turbine first-stage pressure P1st is not influenced by fouling, the pressure sensor can detect a very small deviation due to feedwater flow drift. The monitoring method is based on the deviation of the quantity $E = \frac{dQt}{Qt} - \frac{dQf}{Qf}$ between the beginning of the cycle and any full-load operating point.
- A threshold is defined that takes into account a level of drift that is considered acceptable with regard to the safety requirement and the accuracy of the method.

Figure 6-4 shows data from an actual example of drift monitoring with this method, for a plant with no suspicion of drift. The red line in the figure represents the warning threshold.

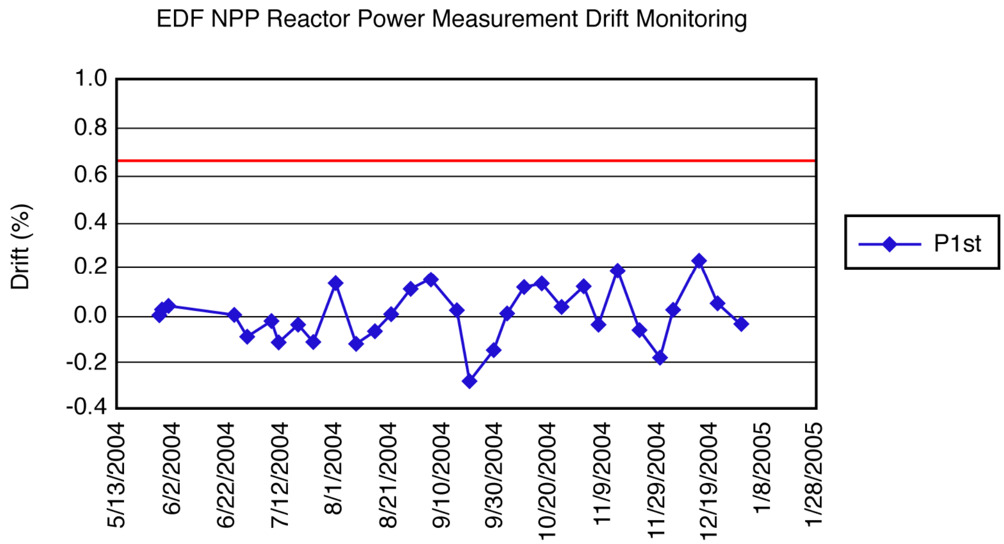


Figure 6-4
Example Application of EDF's ΔP/P Method: A Diagnosis of No Power Drift

Figure 6-5 shows data from another example of drift monitoring with this method, in this case for a plant with suspected drift. Again, the red line represents the warning threshold.

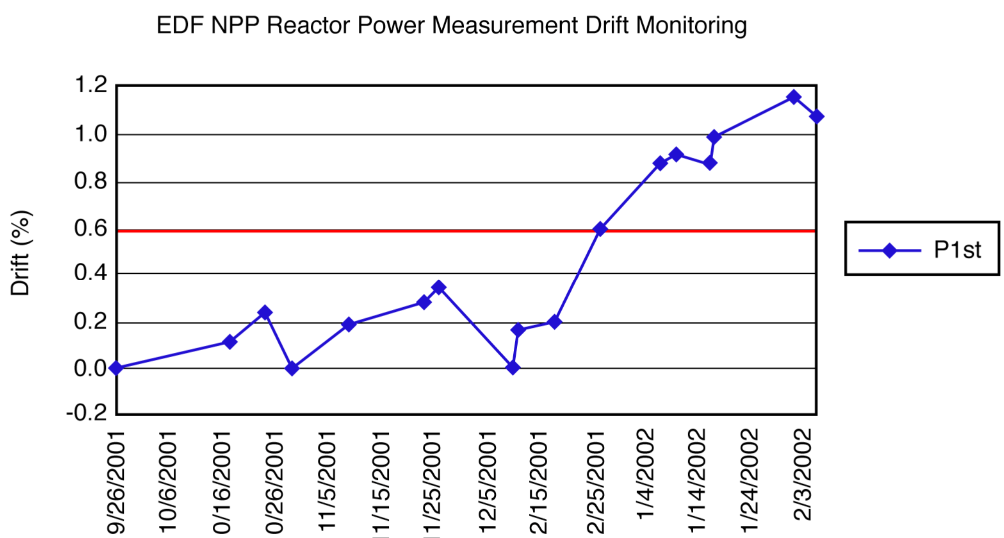


Figure 6-5
Example Application of EDF's ΔP/P Method: A Diagnosis of Power Drift

6.4 The Data Reconciliation Method

The data reconciliation method is another method used at EDF and also at other European plants. A key feature of this method is that it takes advantage of information redundancies coming from all the measurements related to a given process. When the process involved is the secondary circuit of a nuclear power plant, the information redundancies are of two types:

- Direct measurement redundancy: There are directly redundant measurements (sensors) that measure the same physical value.
- Redundancy resulting from physical relationships between measurements: There are the existing physical relationships between measurements—in particular, heat and mass balance, efficiencies, and Stodola coefficients. These relationships result in the generation of more information than is strictly necessary to estimate the thermodynamic state of the fluid at each point of the process.

These information redundancies give rise to a set of equations that are used in process modeling. The system is generally overdetermined (that is, there are more equations than unknowns). Due to errors affecting the measurements, there is no exact solution using the “raw” measurements of the process. A way of dealing with this is provided by the data reconciliation method, which uses a mathematical approach to yield reconciled measurements that are statistically “better” (that is, more credible). The information redundancies of the process and the measurement uncertainties enable this.

A basic principle of the data reconciliation method is to correct each measurement as minimally as possible, trying to keep within the uncertainties of each measurement. With the assumption that the errors affecting measurements can be described by Gaussian laws (independently or with known correlations), based on known standard deviations, the search for the solution with the maximum of probability consists of an optimization (minimization) under constraints (resulting from the information redundancies) of the following equation:

$$\sum_{i=1}^{n} \text{penalty}(i) = \sum_{i=1}^{n} \left(\frac{y_i^* - y_i}{\sigma_i} \right)^2 \qquad \textbf{Eq. 6-1}$$

where:

y_i = measurement value

y_i^* = reconciled value (system unknown)

σ_I = measurement uncertainty

The data reconciliation method provides the following results:

- **Reconciled values** that strictly respect constraints coming from information redundancies
- Indicators that point out **suspect measurements**—ones that are identified because they are incongruous with the other measurements of the process

- A **sensibility analysis** that points out measurements used by the method to calculate the reconciled values
- **Reconciled uncertainties** that are lower than the initial measurement uncertainties

The German standardization body VDI (Verein Deutscher Ingenieure, the Association of German Engineers) has published the guideline VDI 2048, “Uncertainties of Measurement During Acceptance Tests on Energy-Conversion and Power Plants” [8]. This guideline, published in October 2000, presents the mathematical aspects of the data reconciliation method in detail.

At EDF nuclear power plants, data reconciliation with regard to RTP takes advantage of the following information redundancies:

- The direct measurement redundancy between the process control instrumentation and the additional test instrumentation for the steam generators
- Flow rate redundancies (such as between feedwater flows, feedwater pump flows, and low-pressure reheater flows)
- Redundancies due to HP turbine modeling (using efficiencies and Stodola coefficients)

As applied by EDF, the method has a sufficient degree of information redundancy to monitor reference RTP drift. Information used to calculate the reconciled reference RTP comes from many different measurements or parameters. This means that results from the data reconciliation method are not dependent on the quality of any single measurement, which may be significantly in error. The method provides reconciled data as results of increased quality (with respect to confidence, uncertainty, and so on). This results in better confidence in a plant’s ability to detect and correct a reference RTP drift.

For EDF nuclear power plants, in a case of feedwater flow drift, the reconciled RTP will be calculated without taking into account the feedwater flow (a suspect measurement). Rather, the calculation is based on many information redundancies. This information will not be coherent in comparison with the feedwater flow measurements.

The difference between the reference RTP (based on feedwater flow measurements) and the reconciled RTP (which does not take feedwater flow into account) is a relevant warning criterion for monitoring reference RTP drift. The reconciled RTP is approximately twice as accurate as the measured RTP.

6.5 Advantages and Limitations of the Four Methods

6.5.1 The Trend Analysis Method

The main advantages of the trend analysis method are:

- The method can be easily implemented on site.
- Differential drift assessment based on this method is relevant.

Some limitations of this method are:

- The method is a differential method (that is, it does not provide a substitution estimate).
- A plant needs to define its own threshold to “unambiguously” detect a drift.
- The method requires considerable expertise.
- The drift assessment is not very accurate; thus, a large uncertainty value for the correction factor has to be taken into account.

6.5.2 The River Bend Calorimetric Verification Method

The main advantages of the River Bend calorimetric verification method are:

- The method can be easily implemented on site.
- The method provides an absolute assessment of reactor power measurement drift.
- The drift suspicion is based on a threshold that takes measurement uncertainties into account.

Some limitations of this method are:

- The quantity and the quality (in terms of representativeness) of the parameters chosen have a direct impact on the Best Estimate Core Thermal Power.
- The confidence factor giving the weight of each parameter on the Best Estimate Core Thermal Power is calculated on the basis of measurement uncertainties, and because the uncertainties taken into account are “theoretical” ones instead of being issued from a detailed analysis of the components of the measurement chains, this can impact the results of the calculation.
- It is necessary to have a good “reference” (that is, an unbiased value) for the nominal set point, without any drift problems, in order to build relevant initial data. (This is referred to as the *baseline data* in this method.)

6.5.3 EDF's ΔP/P Method

The main advantages of EDF's ΔP/P method are:

- The method can be easily implemented on site.
- The method can be used at any plant because it is a differential approach (independent of turbine design).
- EDF's experience shows that the method is relevant to the detection of drift problems.

The main limitations of this method are:

- To enable an accurate diagnosis, it is necessary to have a reliable reference set point at the beginning of each cycle. On French nuclear power plants, the orifice plates are checked and the first-stage pressure sensors are calibrated during each outage (thus allowing high confidence in the reference set point).
- The method is efficient as a way to rapidly detect an emerging drift, but not accurate enough to allow quantification of the exact drift value. (For this reason, investigations are underway at EDF to quantify the drift bias, with the maximum possible accuracy, by use of the data reconciliation method.)

This method is currently being assessed by the French Safety Authority.

6.5.4 Data Reconciliation

The main advantages of the data reconciliation method are:

- Data reconciliation calculations are based on a German standardized guideline (VDI 2048, "Uncertainties of Measurement During Acceptance Tests on Energy-Conversion and Power Plants" [8]). Data reconciliation results depend only on plant modeling and measurement uncertainties.
- The reconciled reactor thermal power, without taking feedwater flow measurements into account, is a very accurate indicator (0.3% uncertainty for EDF's nuclear power plants and fellow European plants) to provide a relevant (because it is "absolute") drift assessment.
- Results from this method are not dependent on the quality of any single measurement, which may be significantly in error, and the method provides reconciled data of higher quality than the initial measurement data.
- There is very good feedback on data reconciliation, based on international experience. The method is used by many nuclear power plants in the world (particularly in Germany and Switzerland) to monitor reactor thermal power measurement drift, and it has been accepted by the safety authorities in these countries.

The main limitations of this method are:

- Many data are necessary to develop the plant modeling and to calculate measurement uncertainties.
- The fewer the existing instrumentation redundancies, the less relevant the data reconciliation will be.
- A good knowledge of data reconciliation is necessary to analyze the results.

6.6 A Proposed Classification Scheme

Based on the preceding discussion, the four methods can be classified in a way that takes into account the implementation complexity and the relevance of the diagnosis obtained. Figure 6-6 is a diagram showing this proposed classification.

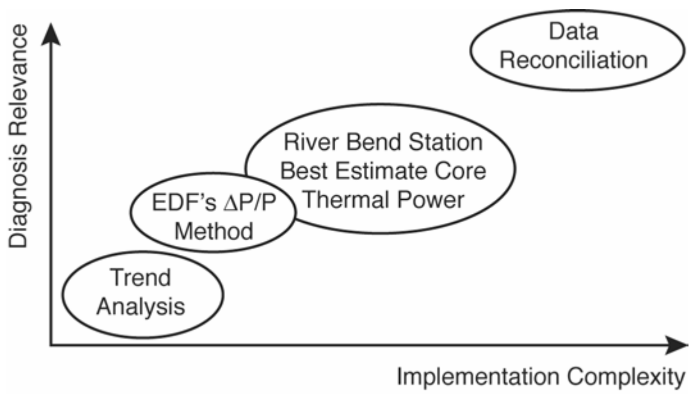


Figure 6-6
Proposed Classification Scheme for Four RTP Drift Monitoring Methods

7
A PROPOSAL FOR RELATED RESEARCH

A proposal for a joint EPRI-EDF project to be conducted in 2008 was presented at the EPRI/PSE/ P²EP annual meeting held June 28–29, 2007, in Annapolis, Maryland. Because the work that was the subject of the present report focused on the more theoretical aspects of the monitoring methods, the goal for the proposed "next-step" project would be to intercompare the methods using actual plant data. This would allow TPEs to have exposure to feedback regarding each method, for eventual comparison with their own practices.

The proposed project includes the following tasks:

- A comparison of the River Bend method and the data reconciliation method at a French nuclear power plant experiencing feedwater flow measurement drift
- A comparison of the River Bend method and EDF's ΔP/P method at a U.S. nuclear power plant
- Synthesis of previous results and the preparation of a guideline

A more detailed definition of the project is to be developed during late 2007.

8
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A
THE PLANT PERFORMANCE ENHANCEMENT PROGRAM (P²EP) 2006-01 SURVEY

This appendix reproduces the EPRI Plant Performance Enhancement Program (P²EP) survey, Experience Sharing of Reactor Power Drift Monitoring Methods, and the survey responses.

A.1 The Survey: Experience Sharing of Reactor Power Drift Monitoring Methods

A.1.1 Introduction

Feedwater Flow (FWF) measurement is a critical parameter for Reactor Thermal Power (RxTP) estimation. Numerous reported events in the USA and in France show that this measurement can be affected by various types of errors.

Experience feedback shows that no single technology is perfect: INPO's SER 3-04 for instance shows that causes for error range from technical errors to human errors, both on vendor and operator sides. Some of EDF's units were affected by fouling of their orifice plates and venturis.

EPRI and EDF have a common interest in identifying the methods allowing monitoring and adjustment of reactor power measurement drifts.

Goal of present survey:

This survey is meant to build the picture of present and actual practices by Thermal Performance Engineers-TPEs (USA, EDF) when confronted with suspicions of error/drift of feedwater flow measurement.

The end-goal will be an EPRI-EDF collaboration to propose a 2007 project to assess the best possible practices and recommend guidelines for use.

Requestor Name:	Jean-Melaine Favennec
Requestor Utility:	EDF
Requestor Email:	jean-melaine.favennec@edf.fr
Requestor Address:	Paris, France

A.1.2 Survey Questions

Question	1. Has your unit experienced FWF and/or Rx TP measurement errors/drifts? If so can you list nature and amount of errors/drifts?
Question	2. Have you implemented a drift/error detection method to check FWF measurement (or more globally on Thermal Power measurement)?
Question	3. Describe basic principle of method (e.g. ratio of FWF and feed pump flow measurements, etc)? Specify assumptions: such as parameter correlations, thermodynamic first principle (heat flux equations…), unit operation set point.
Question	4. Identify process measurements used in your method (list all).
Question	5. Describe nature of monitoring diagnosis:
Question	6. Is your diagnosis fully-detailed? Or does it require additional expertise?
Question	7. In the event of a confirmed error/drift detection, which corrective actions are taken?
Question	8. A) Was the monitoring method locally developed? B) Was it reviewed by fellow Utility TPEs? By TPEs from other Utilities? C) Was it reviewed by NRC? By independent experts?
Question	9. Since the method was installed, has it actually detected FWF measurement errors/drifts?
Question	10. If so, did the investigations confirm the diagnosis with your method?
Question	11. Are you satisfied with the method in use?
Question	12. In the next phase of context/goals of present EPRI/EDF effort, would you be willing to be interviewed for more detailed information?
Question	Additional Comments:

A.2 Compiled Responses to the Survey

Question	1. Has your unit experienced FWF and/or Rx TP measurement errors/drifts? If so can you list nature and amount of errors/drifts?
Respondent	**Answer**
Exelon - Limerick	Yes, In 2004 Limerick experience a 0.4% drift above core thermal power limits due to a feedwater flow transmitter out-of-calibration.
STPNOC - STP	No
FPLE - Seabrook	Yes, Seabrook uses a steam flow calorimetric. The steam flow elements are nozzle plates that are installed in the steam generator main steam outlet nozzles. The steam flow measurement is normalized using a 2 path leading edge flow meter (UFM). Venturi flow, steam flow, and UFM flow are checked against each other periodically. The steam flow nozzles foul slightly over our 18 month operating cycle such that gross generation sags a little. Typically we renormalize once or twice during the operating cycle and recover about 1.7 MWe (total over the cycle).
Nebraska Public Power District - Cooper Nuclear Station	No, We calibrate the dP transmitters for our feedwater nozzles every refuel outage. These nozzles are inaccessible for inspection, though, so we don't know if they are fouled. We last checked the nozzles' accuracy in 1995 with strap-on Caldon LEFM's, and the results were within the instruments' uncertainty band.
AEP - DC Cook	No

Question	1. Has your unit experienced FWF and/or Rx TP measurement errors/drifts? If so can you list nature and amount of errors/drifts?
Respondent	**Answer**
Exelon - Byron	Yes, There have been drifts and errors of different types over the years. A few will be listed. 1. FW venturi flow transmitter drift. We have 2 differential pressure flow transmitter on each main FW venturi. Trending the difference between these 2 measurements identified the drift at about 0.3 % 2. FW flow power supply card offset and drift. Found at 0.5% utilizing the same trending as in #1. 3. Final FW temperature error (2.5 F). Final FW temperature is determined from thermocouples. Had an event that affected the reference RTD in the process computer room. Issue found by trending the difference between a separate set of instruments (RTDs located at a different location). 4. S/G blowdown flow instrumentation failure. Instrument failed to zero without operator knowledge, 0.15% error. Found by trending secondary process parameters.
Exelon - Dresden	No
Entergy Operations, Inc. - Arkansas Nuclear One	Yes, FWF venturi fouling has resulted in the past to as much as 2% flow measurement error. RX flow measurement error due to a leaking valve on DP transmitter resulting in 0.5% error.
Entergy - Waterford-3	Yes, discovered that MS flow was higher than indicated after installing Caldon LEFM check plus FWF meter. Prior to that we were using MS flow based calorimetric using MS venturi. Over a period of ~5 years the indicated flow had drifted down ~1.8%. Suspected cause is venturi erosion but this was never confirmed due to difficulty associated with performing such an inspection.
Progress Energy - Harris Nuclear Plant	Yes, HNP recently had a Temperature Element in the blowdown system fail which caused an overly conservative estimate of reactor power. This resulted in a loss of approximately 3.5 MWe.
TVA - Sequoyah	Yes, FWF is measured using Caldon LEFM. Our plant has seen shifts in measured flow following maintenance of the LEFM (transducer remounting or replacement).

Question	1. Has your unit experienced FWF and/or Rx TP measurement errors/drifts? If so can you list nature and amount of errors/drifts?
Respondent	**Answer**
NMC - Point Beach	Yes, In the 1980's we experienced drifts in FWF indication of up to about 2% due to venturi fouling.
TVA - Watts Bar Nuclear	Yes, WBN uses a single Caldon LEFM on the MFW header U/S of our four individual SG FW venturis. We calculate thermal power with both the LEFM and with the venturis; however, the venturi power measurement is for information only. The venturis are used for SG level control. Our LEFM TP measurement typically will move after any significant plant transient. However, the magnitude of the change is always within the LEFM power uncertainty of 0.6%.
Tokyo Electric Power Company - Head Office	Yes
First energy - Perry/Davis Besse/Beaver Valley	Yes, Davis Besse - PWR. Venturi Fouling that has increased and decreased in magnitude through the cycle. Perry - BWR. No issues with the venturi. Beaver Valley 1 and 2. PWR. Operating with the ultrasound instrument providing input to calorimetric. Notice Venturi will change in flow rate while the ultrasonic is stable.
AmerGen Energy Company, LLC - Oyster Creek Station	Yes
British Energy - Heysham 1 Power Station	No
Constellation - Nine Mile Point	Yes
EDF	On EDF nuclear fleet, five PWR units (three 1300MWe units and two 900MWe units) have experienced FWF/Rx TP drifts since 2002. These drifts are due to orifice plate fouling caused by magnetite deposit.

Question	2. Have you implemented a drift/error detection method to check FWF measurement (or more globally on Thermal Power measurement)?
Respondent	**Answer**
Exelon - Limerick	Yes, Secondary BOP parameters and ratios are monitored daily & weekly, and purchases software from ILD Power that calculates a statistical best estimate of reactor power based on BOP parameters.
STPNOC - STP	Yes
FPLE - Seabrook	Yes, As mentioned above we compare/trend venturi flow, steam flow, and UFM flow. In addition, we have a very precise set of curves for gross generation verses condenser pressure. We also have accurate correction factors for other things that can cause changes in gross generation such as steam generator blowdown flow rate. We can usually detect changes from our gross generation baseline of less than 0.5 MWe.
Nebraska Public Power District - Cooper Nuclear Station	No
AEP - DC Cook	No, There is no formal method used to detect FWF drift/error, however the thermal performance engineer informally checks performance monitoring data for trends that check for an Rx calorimetric overpower (ex. Rx Power versus calculated missing megawatt changes, first stage pressure changes, and/or main turbine control valve position changes).
Exelon - Byron	Yes
Exelon - Dresden	Yes, Monitor independent plant parameters in relation to core thermal power.
Entergy Operations, Inc. - Arkansas Nuclear One	Yes, For Unit 1 there is a procedure that initializes the Primary to Secondary heat balance at the beginning of the cycle, then the secondary is correct to the primary as needed. Also, key parameters of both the primary and secondary heat balance are monitored for change.
Entergy - Waterford-3	Yes, We compare FW venturi flow, MS venturi flow and LEFM flow based calorimetrics and look for divergence. These calorimetrics are calculated using the same basic parameters except for the flows.

Question	2. Have you implemented a drift/error detection method to check FWF measurement (or more globally on Thermal Power measurement)?
Respondent	**Answer**
Progress Energy - Harris Nuclear Plant	Yes
TVA - Sequoyah	Yes, Comparison of FWF by LEFM to venturi based flows. Thermal power is checked against independent power indicators such as impulse pressure, feedwater pump flow or RxDT.
NMC - Point Beach	Yes
TVA - Watts Bar Nuclear	Yes
Tokyo Electric Power Company - Head Office	No
First energy - Perry/Davis Besse/Beaver Valley	No, Investigating a software product that is sold by ILD Power. Uses feedwater temperature, HP turbine 1st stage pressure, LP inlet pressure and feedwater flow to arrive at a statistical best estimate of reactor power.
AmerGen Energy Company, LLC - Oyster Creek Station	Yes
British Energy - Heysham 1 Power Station	No
Constellation - Nine Mile Point	Yes
EDF	Two types of method are used by operators to monitor Thermal Power calculation. The first method implemented on site monitors independent plant parameters in relation to core thermal power. The second method checks inlet and first bleed HP turbine pressure and total feedwater flow evolutions according to physical laws.

Question	3. Describe basic principle of method (e.g. ratio of FWF and feed pump flow measurements, etc)? Specify assumptions: such as parameter correlations, thermodynamic first principle (heat flux equations…), unit operation set point.
Respondent	**Answer**
Exelon – Limerick	Parameters and ratios are trended over time (2 weeks, 8 weeks, 6 months).
STPNOC - STP	We compare power dependent plant parameters with known norms to detect drift. We also use the Energitools calorimetric calculator.
FPLE - Seabrook	We primarily use empirical data and data averaging techniques in addition to the flow measurement trends mentioned above.
Exelon - Byron	Several different checks are performed each day by operations and the TPE. The operating department performs a daily check of all calorimetric inputs and verified they are with a small band. This small band is determine and controlled by the plant operations department with a review performed by the TPE. The TPE performs various checks (all performed with a simple spreadsheet tool linked to live data through a data historian - PI). The first set of checks is against redundant indications [track the difference between the two FW flow indications on each venturi, compare different indications of final FW temperature, review MWe accounting]. The second check is an aggregate parameter calculation or second tier parameter monitoring. A set of parameters (feedwater flow to steam flow ratio, main turbine impulse pressure, final FW temperature, main FW Pp flow, RCS loop delta Ts, and MWe accounting) are compared to a base set of data. For each parameter the difference between the current value and the base data set valve is calculated and transformed to a percentage of rated thermal power. These 6 percentages are then summed and trended to within 0.07% of base line. The goal of this second tier monitoring is to find issues that affect all instrumentation of the same type, for example, venturi fouling, S/G moisture carryover, reference RTD issues, etc.
Exelon - Dresden	Ratio of plant parameters (i.e. main steam flow) to core thermal power and trended over time.

Question	3. Describe basic principle of method (e.g. ratio of FWF and feed pump flow measurements, etc)? Specify assumptions: such as parameter correlations, thermodynamic first principle (heat flux equations...), unit operation set point.
Respondent	**Answer**
Entergy Operations, Inc. - Arkansas Nuclear One	A ratio of secondary to primary heat balance power.
Entergy - Waterford-3	We know that the maximum difference between the LEFM calorimetric and other calorimetrics should be less than 0.4%.
Progress Energy - Harris Nuclear Plant	Diverse indicators including feed pump flow, steam flow, primary calorimetric energy balance and governor valve position are used to determine if feedwater flow measurements are drifting. This process is not formalized in any guideline or procedure and mostly depends on the TPE's knowledge of system interactions for success.
TVA - Sequoyah	Ratio of FW flow to LEFM flow. Ratio of feedwater pump flow to LEFM flow. RxDT in %. Impulse pressure in %.
NMC - Point Beach	In the 1980's we installed an LEFM ultrasonic flow meter to use to periodically correct the venturi indication. We also started monitoring a FWF correction factor (LEFM flow/venturi flow) and other plant parameters to detect drift. Several years ago we switched over to using an upgraded LEFM for FWF input into the reactor power calculation instead of using the venturi's.
TVA - Watts Bar Nuclear	Ratio of LEFM flow to venturi flow. LEFM always indicates a higher flow (conservative). We also use other power indicators.
AmerGen Energy Company, LLC - Oyster Creek Station	Ratios of feedwater flow to various plant parameters

Question	3. Describe basic principle of method (e.g. ratio of FWF and feed pump flow measurements, etc)? Specify assumptions: such as parameter correlations, thermodynamic first principle (heat flux equations...), unit operation set point.
Respondent	**Answer**
EDF	The first method monitors independent plant parameters in relation to core thermal power for trends. The selected parameters to be monitored are: Difference between feedwater orifice plates and venturis (each SG) Difference between total feedwater flow and total feed pump flow Evolution of inlet HP turbine pressure Evolution of plant efficiency Evolution of primary circuit loop Delta T The second method checks thermodynamic laws (based on HP turbine Stodola equation) that some measurements have to respect. When plant reaches first full load, measurements of feedwater flow, inlet and first bleed HP turbine are considered as reference. During cycle, operator monitors that the evolution of total feedwater flow between present point and reference point is similar to the evolution of inlet HP turbine and first bleed HP turbine according to measurements uncertainties. This monitoring is only realized provided that the installation is at a similar operation set point as the reference. It is performed at least once a month.

Question	4. Identify process measurements used in your method (list all).
Respondent	**Answer**
Exelon - Limerick	Total Feedwater Flow Loop Feedwater Flow Final Feedwater Temperature Loop Feedwater Temperature Core Thermal Power Gross Electrical Output Main Steam Flow HP Turbine Inlet Pressure Condenser Pressure Condensate Flow Turbine Control Valve Position Heater Drain Flow RWCU Flow CRD Flow Reactor Recirc Pump Power
STPNOC - STP	First stage pressure, HP exhaust pressure, ratios of first stage pressure to feedwater and steam flow, UFM correction factors, SGFPT steam flow, LP turbine inlet pressure, final feedwater temperature.
FPLE - Seabrook	Main Steam Flow Steam Generator Blowdown Flow Main Steam/Auxiliary Steam Reducer Position Reactive Power Load Feedwater Flow (Venturi) Feedwater Flow (UFM) Gross Electric Power Condenser Pressure Feedwater Temperature (Feedwater RTDs) Feedwater Temperature (UFM)
Exelon - Byron	FW venturi Flow S/G blowdown flow final FW temperature main steam flow main steam pressure main FW pump flow main turbine impulse pressure RCS loop Delta Ts MWe accounting (includes all calorimetric inputs, Cw inlet temperature, and generator output)

Question	4. Identify process measurements used in your method (list all).
Respondent	**Answer**
Exelon - Dresden	Main steam flow, condensate flow, HP turbine first stage pressure, HP turbine exhaust pressure, feedwater heater shell pressures.
Entergy Operations, Inc. - Arkansas Nuclear One	RX flow, Thot, Tcold, RCS pressure for primary heat balance FWF, SG pressure, FW pressure, Main Steam Temp, and FW Temp for secondary heat balance.
Entergy - Waterford-3	See above
Progress Energy - Harris Nuclear Plant	Feedwater flow, Feed pump suction flow, governor valve position, RCS delta T.
TVA - Sequoyah	See above. Also, on specific occasions, we have tried to use dependent power indicators to access thermal power based on the River Bend calorimetric verification method.
NMC - Point Beach	Besides the FWF correction factor, there was no formal list of what measurements were used. Basically any and all measurements were considered in backing up if there was drift in the FWF indication. The major parameters used besides the FWF correction factor were the different steam flow indications, turbine first stage pressure, and turbine extraction pressures.
TVA - Watts Bar Nuclear	See above.
EDF	See above.

Question	5. Describe nature of monitoring diagnosis:
Respondent	**Answer**
Exelon – Limerick	Parameters are trended with or without thresholds. Thresholds are developed based on data from tracer tests performed after turbine retrofits.
STPNOC - STP	The diagnosis compares the trended indication to a predetermined threshold. (Provide threshold value below) We don't have a threshold value. If we find a trend that indicates any drift we investigate.
FPLE - Seabrook	The diagnosis compares the trended indication to a predetermined threshold. (Provide threshold value below) The empirical data that we use would be too complicated to include in this survey.
Exelon - Byron	The diagnosis compares the trended indication to a predetermined threshold. (Provide threshold value below) For the individual parameter trending, the threshold differs from parameter to parameter. For FW flow - 0.3%, final FW temperature - 0.3 F, For the aggregate parameter review - 0.07%. The above thresholds were determined from past events and parameter trendability/stability.
Exelon - Dresden	The diagnosis compares the trended indication to a predetermined threshold. (Provide threshold value below) Threshold of about 1%
Entergy Operations, Inc. - Arkansas Nuclear One	The diagnosis compares the trended indication to a predetermined threshold. (Provide threshold value below)
Entergy - Waterford-3	The diagnosis compares the trended indication to a predetermined threshold. (Provide threshold value below) see above
TVA - Sequoyah	See below for a description of how our monitoring diagnosis works. If all independent power indicators shift together, it is an indication of actual (real) power shift.

Question	5. Describe nature of monitoring diagnosis:
Respondent	**Answer**
NMC - Point Beach	See below for a description of how our monitoring diagnosis works. An "off-line" FWF correction factor was monitored and if a drift was also backed up by other indications, a new FWF correction factor was determined by a formal procedure and entered into the plant computer calculation of the venturi FWF. There was no formal threshold. Now the LEFM is used as a direct input to the reactor power calculation.
TVA - Watts Bar Nuclear	The diagnosis estimates an uncertainty value. Returns ratio and values.
First energy - Perry/Davis Besse/Beaver Valley	The diagnosis estimates an uncertainty value.
AmerGen Energy Company, LLC - Oyster Creek Station	See below for a description of how our monitoring diagnosis works.
EDF	The second method indicates if total feedwater flow is coherent with inlet and first bleed HP turbine according to measurements uncertainties. If not, trend analysis of independent parameters described in first method is to be performed to confirm the diagnosis.

Question	6. Is your diagnosis fully-detailed? Or does it require additional expertise?
Respondent	**Answer**
Exelon – Limerick	Not fully detailed, requires some engineering judgment.
STPNOC - STP	It requires additional expertise
FPLE - Seabrook	No - it is not fully detailed. It requires additional expertise.
Exelon - Byron	It is full automated, but as always, qualified experienced personnel should perform the review and analysis.
Exelon - Dresden	Fully detailed
Entergy Operations, Inc. - Arkansas Nuclear One	Additional expertise.
Progress Energy - Harris Nuclear Plant	Additional expertise required. There are no set points or pre-established action limits.
TVA - Sequoyah	It is not fully detailed.
NMC - Point Beach	It was not fully detailed. It relied on engineering judgment.
TVA - Watts Bar Nuclear	Detailed.
EDF	The second method uses a threshold according to measurement uncertainties. If the threshold is not respected additional expertise is required to analyze trends from first method.

Question	7. In the event of a confirmed error/drift detection, which corrective actions are taken?
Respondent	**Answer**
Exelon – Limerick	Initiate an issue report, additional investigation and troubleshooting.
STPNOC - STP	The unit would be down powered and the UFM taken out of service.
FPLE - Seabrook	Determine the cause. Renormalize the steam flow measurement if necessary. Correct (repair) a drifting instrument. Remove a redundant drifting instrument from the calorimetric. Renormalize feedwater temperature instrument(s) if necessary.
Exelon - Byron	1. Generate site issue report. 2. Contact Shift manager 3. If non-conservative error, recommend power reduction based upon detected error and magnitude. If conservative error, do not recommend power reduction and do not recommend power increase/calorimetric offset to minimize MWe loss. 4. Consult with reactor engineering. 5. Notify station management. 6. Provide input to maintenance for trouble shooting.
Exelon - Dresden	Troubleshooting, additional investigation.
Entergy Operations, Inc. - Arkansas Nuclear One	Correction factors are adjusted to bring the secondary back in line with the primary heat balance.
Entergy - Waterford-3	Troubleshoot to determine potential cause. Since inception it has detected drift of a MS flow transmitter. The LEFM auto calibrates the MS and FW flows so that if the LEFM fails we can operate on MS or FW venturi calorimetric for several days. In this case, we were operating normally on the LEFM calorimetric but the drift in the MS flow transmitter was noted.

Question	7. In the event of a confirmed error/drift detection, which corrective actions are taken?
Respondent	**Answer**
Progress Energy - Harris Nuclear Plant	NCR initiated, if the drift was nonconservative power would be reduced, work orders are completed on an expedited basis. Note that HNP has not experienced venturi fouling. Most errors are due to instrument circuit failures and can be repaired on-line.
TVA - Sequoyah	An event where a shift in power is outside our uncertainty calculation has not occurred. In general, maintenance has been scheduled on the LEFM (transducer replacement) when a shift is detected. Normally a degradation of the LEFM signal is also present.
NMC - Point Beach	In the past when we used and updated a FWF correction factor, a formal procedure was used for updating the FWF correction factor used by the plant computer in calculating the venturi FWF. The procedure verified that the LEFM was operating correctly and plant conditions were stable during the period (about 1/2 hr) that a new correction factor was determined.
TVA - Watts Bar Nuclear	Troubleshooting.
First energy - Perry/Davis Besse/Beaver Valley	Not implemented at this time
EDF	In case of drift detection, operators have to assess thermal power drift and correct thermal power measurement. This corrected thermal power is therefore used to adjust operation set point. The plant is operated with an additional safety margin to ensure the respect of maximum power.

Question	8. A) Was the monitoring method locally developed? B) Was it reviewed by fellow Utility TPEs? By TPEs from other Utilities? C) Was it reviewed by NRC? By independent experts?
Respondent	**Answer**
Exelon – Limerick	Locally developed. Reviewed by fellow utility TPEs. No
STPNOC - STP	It was locally developed. It was not reviewed by fellow utilities but it follows the guidelines of the Crossflow Ultrasonic Flow Meter User Guidelines. It was not reviewed by the NRC or independent experts.
FPLE - Seabrook	Our monitoring was developed locally. The calorimetric process including the renormalization of calorimetric inputs (e.g., steam flow and feedwater temperature) has been reviewed by the NRC. The UFM uncertainty calculation developed by the UFM vendor, independently reviewed by a 3rd party organization, and independently reviewed by utility design engineering personnel.
Exelon - Byron	Locally developed.
Exelon - Dresden	Locally developed
Entergy Operations, Inc. - Arkansas Nuclear One	A) No B) Yes C) Yes, by independent experts
Entergy - Waterford-3	Locally
Progress Energy - Harris Nuclear Plant	A) Yes B) Yes C) No, No
TVA - Sequoyah	A) Locally. B) Fellow Utility TPEs. C) Not formally reviewed by NRC. Working with an EPRI contact on some of these issues, Brandon Rasmussen.
NMC - Point Beach	I believe it was developed locally. I do not believe it was reviewed by any others.

Question	8. A) Was the monitoring method locally developed? B) Was it reviewed by fellow Utility TPEs? By TPEs from other Utilities? C) Was it reviewed by NRC? By independent experts?
Respondent	**Answer**
TVA - Watts Bar Nuclear	Reviewed by corporate staff.
EDF	Both methods have been developed by engineering support and then sent to plants. These methods have been reviewed by EDF Research & Development Department and are being reviewed by Safety Authorities.

Question	9. Since the method was installed, has it actually detected FWF measurement errors/drifts?
Respondent	**Answer**
Exelon – Limerick	None have been detected.
STPNOC - STP	None have been detected
FPLE - Seabrook	Yes. As mentioned above we correct for drift once or twice per cycle.
Exelon - Byron	Yes. See #2 above.
Exelon - Dresden	Yes
Entergy Operations, Inc. - Arkansas Nuclear One	Yes
Entergy - Waterford-3	Yes, see 7 above.
Progress Energy - Harris Nuclear Plant	No
TVA - Sequoyah	Yes
NMC - Point Beach	Yes it did.
First energy - Perry/Davis Besse/Beaver Valley	Yes - by reviewing historical PI data
EDF	Both methods are in operation on site. They have detected thermal power drifts on units having problems with orifice plates fouling.

Question	10. If so, did the investigations confirm the diagnosis with your method?
Respondent	**Answer**
Exelon – Limerick	N/A
STPNOC - STP	NA
FPLE - Seabrook	Yes
Exelon - Byron	Yes
Exelon - Dresden	Yes
Entergy Operations, Inc. - Arkansas Nuclear One	Yes
Entergy - Waterford-3	Yes the MS flow transmitter had drifted and as found output was out of spec during cal check.
Progress Energy - Harris Nuclear Plant	N/A
TVA - Sequoyah	Yes
NMC - Point Beach	Yes, plant parameters usually returned to normal after new FWF correction factors were entered.
EDF	During the outage orifice plates are dismounted. When the methods had detected drifts, expertises have shown that orifice plates have fouled due to magnetite deposit. This confirms diagnosis provided by methods.

Question	11. Are you satisfied with the method in use?
Respondent	**Answer**
Exelon – Limerick	Yes
STPNOC - STP	Yes
FPLE - Seabrook	Yes, but we will be installing an 8 path cordal transit time ultra-sonic flow meter during our next outage for 1.6 to 1.7% feedwater flow measurement uncertainty recapture (MUR). The system was recently tested an Alden Labs in Holden Mass. with great results. This will change our feedwater flow measurement and calorimetric calculation significantly.
Exelon - Byron	Yes, very satisfied.
Exelon - Dresden	Yes
Entergy Operations, Inc. - Arkansas Nuclear One	Yes
Entergy - Waterford-3	Yes, however we are considering using Energitools software calorimetric calculator feature as another method of confirming the accuracy of reactor power indication.
Progress Energy - Harris Nuclear Plant	For the most part, considering that venturi fouling has not historically been a significant issue at HNP.
TVA - Sequoyah	No. We are continuing to look at additional methods for monitoring thermal power.
NMC - Point Beach	That method was ok but is not as good as having an LEFM directly input into the reactor power calculation.
EDF	Yes

Question	12. In the next phase of context/goals of present EPRI/EDF effort, would you be willing to be interviewed for more detailed information?
Respondent	**Answer**
Exelon – Limerick	Yes
STPNOC - STP	Yes
FPLE - Seabrook	Yes
Exelon - Byron	Yes
Exelon - Dresden	Yes
Entergy Operations, Inc. - Arkansas Nuclear One	Yes
Entergy - Waterford-3	Yes
Progress Energy - Harris Nuclear Plant	I am no longer the official TPE, but my successor may be willing to assist with future efforts.
TVA - Sequoyah	Yes. I am very interested in any EPRI/EDF effort in this area.
NMC - Point Beach	Yes
First energy - Perry/Davis Besse/Beaver Valley	Yes
EDF	Yes of course.

Question	Additional Comments:
Respondent	**Answer**
FPLE - Seabrook	Generally we don't experience large changes in gross generation. This past cycle our gross generation has varied from 1267 MWe to 1271 MWe based on raw uncorrected data. After correcting for ocean temperature effects (condenser pressure) and all the other factors mentioned above we only see a variation of about 0.5 MWe.
Progress Energy - Harris Nuclear Plant	Harris Nuclear Plant, 3 Loop Westinghouse PWR

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