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Use of Data Validation and Reconciliation Methods for Measurement Uncertainty Recapture

Topical Report

2020 TECHNICAL REPORT

Use of Data Validation and Reconciliation Methods for Measurement Uncertainty Recapture
Topical Report

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ABSTRACT

Core Thermal Power (CTP) determination in the nuclear power industry has typically relied on the accurate measurement of various inputs to the power calculation, in particular feedwater flow. These input measurements are often single element measurements and therefore a failure of the instrumentation will result in an error of the power calculation. Data Validation and Reconciliation (DVR) offers the nuclear power industry plants a method of improving the reliability of CTP calculations by reducing single point measurement vulnerabilities. DVR methodology uses analytical thermodynamic principles and measurement uncertainty analyses that allows for the incorporation of additional plant instrumentation. The material contained within this report is the development of a Topical Report for implementation of Data Validation and Reconciliation (DVR) as a means to reduce the uncertainty of determinations of nuclear power plant CTP and evaluate the DVR for use in a measurement uncertainty recapture (MUR) uprate.

In the two decades since the MUR uprates have been implemented, there have been numerous recorded down powers by power plants as a result of instrument failure; most commonly on the part of the ultrasonic flow meter or as a result of fouling of the differential pressure flow meter. Operating Experience also exists in which plants have operated higher than their core thermal power license limit as a result of the erroneous plant feedwater flow metering.

The approach used in the development of this Topical Report is intended to establish the technical basis for DVR for MUR uprates and perform related evaluations to substantiate the uncertainty claims of the DVR process. Evaluating the DVR process for performing MUR includes performing failure modes and effects analyses (FMEA) to identify all areas of possible errors in the results and objective justification for self-identification of process failure.

Portions of this report have been derived from the EPRI report, *Guidance for Implementing a Data Validation and Reconciliation Program at Nuclear Power Plants*, EPRI 3002013197.

Keywords

Core thermal power
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Data validation
Performance monitoring
Measurement uncertainty recapture
Thermal performance

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EXECUTIVE SUMMARY

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PRIMARY AUDIENCE: Commercial nuclear reactor licensees considering using Data Validation and Reconciliation (DVR) to determine reactor power

SECONDARY AUDIENCE: Nuclear Regulatory Agencies, operators of coal-fired and combined cycle fossil plants considering using DVR for other purposes.

KEY RESEARCH QUESTION

Core Thermal Power (CTP) determination in the nuclear power industry has typically relied on the accurate measurement of various inputs to the power calculation, in particular feedwater flow. These input measurements are often single element measurements and therefore a failure of the instrumentation will result in an error of the power calculation. Use of DVR technology offers the nuclear power industry plant a method of improving the reliability of CTP calculations by reducing single point measurement vulnerabilities, thus resulting in a more robust approach The objective of this report is to establish the technical basis for DVR and perform related evaluations to substantiate the uncertainty claims of the DVR process. The material contained within this report is the development of a Topical Report for implementation of DVR as a means to reduce the uncertainty of determinations of nuclear power plant Core Thermal Power and evaluate the DVR for use in a measurement uncertainty recapture (MUR) uprate.

RESEARCH OVERVIEW

Use of DVR software as an alternate CTP measure or indicator has been investigated. This report provides a detailed mathematical explanation of the DVR process. These issues include flow element fouling, erosion, flow anomalies, ultrasonic flow meter hardware and software. This report provides examples of benchmarking that consists of showing actual applications of DVR as compared to other plant flow metering and core thermal power calculation methods. DVR has been used to correct the CTP calculation at plants in Europe and Brazil. DVR is currently being implemented at more than 20 nuclear plants in the U.S.

KEY FINDINGS

- A comparative analysis of the CTP uncertainty calculated using DVR methods to the ASME PTC 19.1 Taylor Series Method (TSM) and Monte Carlo Methods (MCM) was performed. The analysis shows uncertainties calculated by the DVR method provide lower uncertainties for the results.
- The effects of potential bias errors with the plant measurements or other DVR input data on the DVR results were examined. The DVR algorithm uses a Gaussian correction fitting method for calculation of the CTP uncertainty results, the method is appropriate, and will properly bound the CTP uncertainty results regardless of the input error distribution form provided the input error is bounded.
- The reliability of the DVR calculations in actual use for 11 nuclear operating units has been examined. Based upon this sample a DVR reliability of greater than 99% can be routinely expected.
- For the case where DVR CTP uncertainty is used as part of a MUR (measurement uncertainty recapture uprate), or with licensed uncertainty margin of less than two percent, it has been demonstrated that the DVR process can provide the necessary uncertainty to allow its implementation for MUR.

WHY THIS MATTERS

There have been numerous failures experienced in the nuclear industry due to the reliance on only a few instruments to determine core thermal power. The DVR process provides an opportunity to include significantly more instruments to the evaluation of core thermal power, thus resulting in a more robust approach. DVR can also be useful for detecting problems with other instrumentation related to the CTP, or any other instruments that are included in the DVR calculations.

HOW TO APPLY RESULTS

Implementation of DVR at a nuclear operating unit will require the Licensee to evaluate the safety classification of DVR CTP implementation per their license basis. Their design change process will provide this classification with justification as part of their license amendment request, if required. Implementation of DVR at a plant site for use as a measure of CTP will require proper administrative and design controls using the Licensee's design change process, software quality assurance plans, and other programs and procedures as required

LEARNING AND ENGAGEMENT OPPORTUNITIES

- *Improving Heat Rate Calculations* (EPRI 3002018588) explores the use of DVR for heat rate monitoring with a focus on the reduction of heat rate uncertainties that DVR may permit.
- *Guidance for Implementing a Data Validation and Reconciliation Program at Nuclear Power Plants* (EPRI 3002013197) provides research and guidance for a plant to evaluate and implement DVR Methods contained in the German standard, VDI-2048, to monitor core thermal power.
- The American Society of Mechanical Engineers (ASME) is currently looking into using DVR for testing and for heat rate calculations in conformance with the Affordable Clean Energy (ACE) rule.

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ACRONYMS

AANN	auto-associative neural networks
AME	assumed measurement uncertainties
AOT	allowed outage time
APRM	average power range monitoring
APU	acoustic processing unit
AQ	augmented requirements
ASME	American Society of Mechanical Engineers
ATP	site acceptance test plan
BME	bounding modeling error
BTP	Branch Technical Position
BWR	boiling water reactor
CAP	corrective action program
CD	compact disc
CDA	critical digital assets
CF	correction factor
COTS	commercial-off-the-shelf
CRD	control rod drive
CTP	core thermal power
DDPS	digital data processing system
DRE	data reduction equation
DVR	data validation and reconciliation
ENBIPRO	ENergie-BIllanz-PROgram
EPRI	Electric Power Research Institute
EPU	extended power uprate
FAT	functional acceptance test

FDS	functional design specification
FMEA	failure modes and effects analyses
FPT	feedwater pump turbine
FSAR	Final Safety Analysis Report
FW	feedwater
FWFCF	feedwater flow correction factor
GDC	general design criteria
GNPP	Gundremmingen Nuclear Power Plant
GUI	graphical user interface
GUM	guide to the expression of uncertainty in measurement
HPT	high pressure turbine
I&C	instrumentation and control
ICA	independent component analysis
ISO	International Organization for Standardization
KKL	Kernkraftwerk Leibstadt
LAR	license amendment request
LCL	lower confidence limit
LCO	limiting condition for operation
LEFM	leading edge flow meter
LER	license event report
LPT	low pressure turbine
LWR	light water reactor
MCM	Monte Carlo Method
MMS	method of manufactured solutions
MSET	multivariate state estimation technique
MSR	moisture separator reheater
MTE	measuring and test equipment
MUR	measurement uncertainty recapture
MWe	megawatts electric
MWth	megawatts thermal
NLPLS	non-linear partial least squares

NPP	nuclear power plant
NRC	Nuclear Regulatory Commission
NRHX	non-regenerative heat exchanger
OE	operating event
OE	operating experience
OS	operating system
P&ID	Piping and Instrument Diagram
PC	personal computer
PFD	process flow diagrams
PRA	probable risk assessment
PTS	performance test code
PWR	pressurized water reactor
QA	quality assurance
RCP	reactor coolant pump
RCU	reconciled uncertainty
RHX	regenerative heat exchanger
RPS	reactor protection systems
RTO	reactor thermal output
RWCU	reactor water clean up
SAT	site acceptance test
SCMP	software configuration management plan
SDD	software design description
SG	steam generator
SJAE	steam jet air ejector
SPDS	safety parameter display system
SQA	software quality assurance
SQAP	software quality assurance plan
SRS	software requirements specification
SRV	safety/relief valve
SVVP	software verification and validation plan
TR	topical report

TRM	technical requirements manual
TS	technical specifications
TSM	Taylor Series method
UFM	ultrasonic flow measurement
UFSAR	Updated Final Safety Analysis Report
UME	unknown measurement errors
UPC	unmodeled performance changes
UPCLR	unplanned capability loss factor
V&V	verification and validation
VDI	Verein Deutscher Ingenieure

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1 INTRODUCTION

This Topical Report was developed for implementation of Data Validation and Reconciliation (DVR) methodology as a means to reduce the uncertainty of determinations of nuclear plant Core Thermal Power (CTP). This document establishes the technical basis for DVR methodology and performs related evaluations to substantiate the uncertainty claims of the DVR process. Evaluating the DVR process for performing Measurement Uncertainty Recapture (MUR) power uprates will include performing failure modes and effects analyses (FMEA) to identify all areas of possible errors in the results and objective justification for self-identification of process failure. The DVR for MUR was developed using the topical report for MUR with an Ultrasonic Flow Meter (UFM) as a guide [80].

1.1 Background

Core Thermal Power determination in the nuclear power industry has typically relied on the accurate measurement of various inputs to the power calculation, in particular, feedwater flow. These input measurements are often single element measurements and therefore, a failure of the instrumentation will result in an error of the power calculation.

In the two decades since the MUR uprates have been implemented, there have been numerous down powers by the plants due to an instrument failure, usually on the part of the ultrasonic flow meter or venturi/nozzle fouling. There have also been instances where plants have operated higher than their core thermal power license limit due to issues with the plant feedwater flow metering. In many cases, these conditions are due to a failure of a single instrument.

The increasing number of incidents involving ultrasonic flow meters prompted INPO to commission Topical Report TR4-34, "Review of Feedwater System Ultrasonic Flowmeter Problems" [37], which was published in March 2004.

Related to core thermal power performance operating experience, an extensive search was conducted of licensing and utility databases to extract information related to issues and concerns. The results of this study are given in Section 5.0, Benchmarking and Operating Experience (OE), of this document.

1.1.1 Use of Numerical Methods to Identify Core Thermal Power Issues

A large amount of research into the use of software utilizing a variety of pattern recognition and other numerical methods to identify possible measurement errors with the CTP has been conducted over the past 30 years. As personal computer hardware and software technology have advanced the practicality of using advanced numerical methods, algorithms in a typical plant environment have increased.

Numerical methods technologies and algorithms that have been investigated or proposed for CTP error detection use include:

- Multivariate State Estimation Technique (MSET)

  MSET has been used by the Department of Energy as a signal validation method at the Florida Power Corporation Crystal River 3 nuclear plant. MSET uses state estimation models, "trained" using sampling of plant data and a Fault detection model that performs statistical tests [38, 39].

- Auto-Associative Neural Networks (AANN)

  AANNs have been used for image recognition in computer and robotic vision systems. Use of neural network technology for detection of errors with nuclear plant feedwater flow instrumentation, and the CTP, have been investigated by the University of Tennessee Department of Nuclear Engineering. AANNs are "trained" using samples of plant data [40, 41, 42].

- Non-Linear Partial Least Squares (NLPLS)

  NLPLS has been developed as an improvement over traditional regression analysis where strong non-linear relationships may exist between different data sets in the process under review. NLPLS has been primarily used in the chemometrics and chemical process industries [40, 43].

- Independent Component Analysis (ICA)

  ICA has been used for facial and pattern recognition. ICA is a computational method for separating a multivariate signal into additive subcomponents [44].

- Gaussian Correction and Closed Mathematical Derivation Method

  The German VDI-2048 engineering standard [1] was developed as an industry code for balance of plant turbine acceptance testing. The code introduces the concept of using Gaussian corrections and mass-energy balance calculations of the plant components and cycle as a means to correct errors with the test instruments and assess the quality of the test measurements and results. Commercial software products are available that implement the VDI-2048 methods. The terms "process data validation" and "data validation and reconciliation" are typically used by the commercial products to describe use of the VDI-2048 methods or similar, equivalent methods. Henceforth, in this document this technology will be referred to as DVR.

1.2 Purpose and Objectives

The purpose and objectives of this Topical Report are to demonstrate that DVR methodology is an effective technology for the calculation of plant CTP and the detection of plant measurement errors with CTP related or other plant instrumentation.

This Topical Report will provide case studies and numerical evidence that:

- The Gaussian correction method used in DVR will properly bound the DVR calculated CTP value and uncertainty, even for bias drift errors or other non-Gaussian error distribution shapes on plant measurements used as inputs for DVR.

- The DVR solution method limitations and failure modes are clearly identified, and effective mitigation strategies are devised.
- The DVR solution provides accurate results when compared to other solution methods and actual test results data.
- The DVR method complies with, and is compatible with, existing accepted engineering codes and standards from the American Society of Mechanical Engineers (ASME), Verein Deutscher Ingenieure (VDI), and International Organization for Standardization (ISO) pertaining to the methods used in and the results from DVR.

In addition, this Topical Report will identify:

- Licensing Requirements
- Plant and Licensee Implementation Requirements

1.3 Industry Experience with DVR Applications

DVR software has been used by the nuclear power industry in the U.S. and Europe to assess turbine cycle thermal performance, balance of plant feedwater flow metering and accuracy of the plant CTP.

Detailed benchmarking studies of DVR applications in the nuclear industry have been performed and are given in Section 5.0, "Benchmarking and Operating Experience (OE)", of this document. Details are provided as to how various nuclear plants have been or are successfully utilizing DVR in studies or actual applications. In addition, information regarding previous EPRI studies related to DVR for fossil and combined cycle plant DVR applications is provided.

1.4 Beneficial Features of DVR Technology

The CTP at most nuclear plants is calculated via a heat balance calculation that utilizes measurements of steam generator (PWRs) or reactor feedwater flowrates (BWRs). The feedwater flowrate is the main error contributor to the CTP calculation. Many plants use feedwater flow metering that consists of venturis, nozzles, or UFMs. Each of these single point methods may be prone to specific error conditions.

Use of DVR technology provides a method of improving the reliability of CTP calculations by reducing the dependence on single point measurement vulnerabilities. DVR can also reduce the uncertainty of CTP calculations as the method is based upon a statistical reconciliation of other CTP related plant instrumentation. In addition, the DVR CTP calculation can be more robust as it uses a number of plant measurements (typically 80 to >200) and is less vulnerable to single point instrument errors.

The DVR technology is unique in that it couples thermodynamic first principles-based engineering and physics calculations, system, cycle mass and energy calculations with statistical methods. Use of a statistical approach to monitor a nuclear power plant's safety functions have been commonly used in the PRA (Probable Risk Assessment) process and is also a factor with the 10 CFR 50.69 process.

DVR can be used to detect potential metering problems with existing plant feedwater flow metering (UFMs, venturis, nozzles, etc.) [19]. DVR may also be used to supplement plant feedwater flow metering (to improve the statistical accuracy of the flow measurement by combining the values from DVR and the plant metering). DVR can be useful for detecting problems with other instrumentation related to the CTP, or any other instruments that are included in the DVR model.

DVR is an enabling technology for the calculation of the plant CTP using plant instrumentation and for finding measurement errors with the plant instrumentation.

1.5 Licensing and Basis Requirements

The feedwater flow rate measurement devices (venturis, nozzles, ultrasonic flow meters and associated instrumentation) used at BWRs and PWRs for the determination of licensed reactor core power are typically supplied and installed to high quality, commercial standards.

Feedwater flow measurements systems are typically classified as non-safety related components and systems. The plant's Updated Final or Final Safety Analysis Report (FSAR) contains the safety classification of the feedwater flow measurement system.

Feedwater flow measurements systems may be classified as important measurements that are used during and following an accident.

The safety classification for DVR technology will depend on the application.

Section 2.0, "Licensing and Basis Requirements", provides details on licensing requirements for implementation of DVR when DVR is used for CTP power recovery or MUR efforts.

1.6 Overview and General Description of DVR Methodology

The DVR solution method given in VDI-2048 is derived from work by Streit and others [3, 4]. In simple terms the solution method uses Gaussian fitting of the measurements from the plant constraining the DVR estimates of the measurements with results from mass-energy, or thermal performance calculations of the plant components and cycle. Streit and the VDI-2048 refer to the mass-energy balance and thermal performance calculations as "Auxiliary Conditions" calculations. Figure 1-1 provides a simple overview of the DVR solution process.

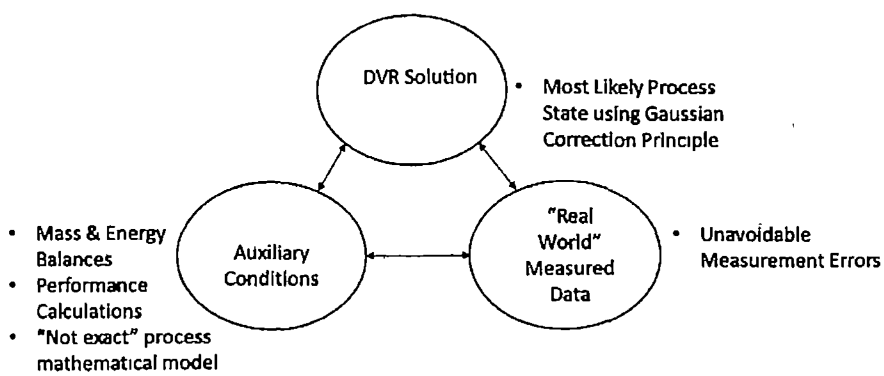

Figure 1-1
Simple overview of the DVR solution process

Streit's "Algorithm for Practical Use", given below as Equation 1-1, provides a fundamental form of the DVR solution method.

$$\overline{\boldsymbol{X}} = \boldsymbol{X} - \boldsymbol{R_X} * \boldsymbol{F} * (\boldsymbol{F^T} * \boldsymbol{R_X} * \boldsymbol{F})^{-1} * \boldsymbol{f(x)} \qquad \textbf{Eq. 1-1}$$

Where,

X is the vector of the measured values

$\overline{X}$ is the vector of the consistent estimated values

R_X is the matrix of covariances of the measured variables

$F = \left[\frac{\partial f}{\partial x}\right]$ is the functional matrix of the auxiliary conditions

$f(x)$ is the vector of contradictions

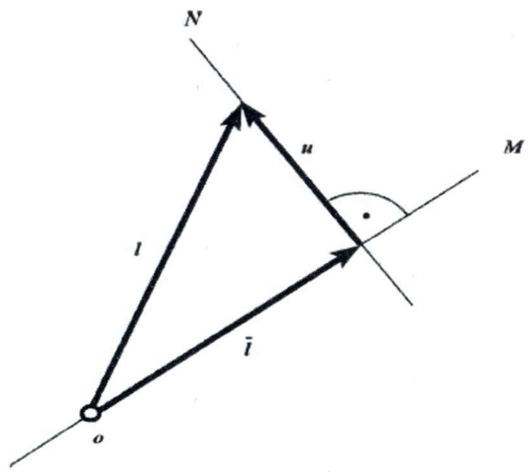

Figure 1-2
Vector representation – correction task for distributed independent random variables

Where,

u represents the vector of contradictions between the random variable ***l*** and the variable calculated with the auxiliary conditions $\bar{\boldsymbol{l}}$

M is the subspace of solutions of the auxiliary conditions

N is the subspace of the contradictions

$\bar{\boldsymbol{l}}$ is the position of the corrected state point

o is the unknown true state point

l is the position vector of the measured state point

DVR evaluates the system state of the vector space of the measured values with empirical estimates of random errors applied to the measurements, subject to constraints from the auxiliary condition calculations.

Details of the algorithms and methodologies used in the DVR solution are given in Section 3.0, "Methodology".

1.6.1 Simple Overview of the DVR Solution Method

As the details of the DVR solution are complex, and utilize numerous matrix operations, a simplified geometric overview of the solution method is provided. This graphical overview approximates what is achieved with the actual DVR algorithm.

Figure 1-3 represents the data point cloud of the initial results from DVR for the reconciled values obtained from the auxiliary conditions calculations and the values of the plant measurements along with the empirical probability uncertainty of each variable.

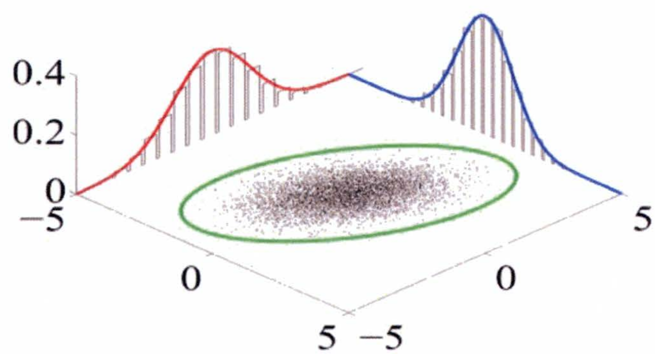

Figure 1-3
Representation of joint probability distribution for reconciled and measured values
(Source: Wikipedia, user IkamusumeFan)

Figure 1-4 shows the Euclidean space of the solution of DVR result for a measurement value. The "football" shape represents the possible solution space of a reconciled measurement and the original plant measured value.

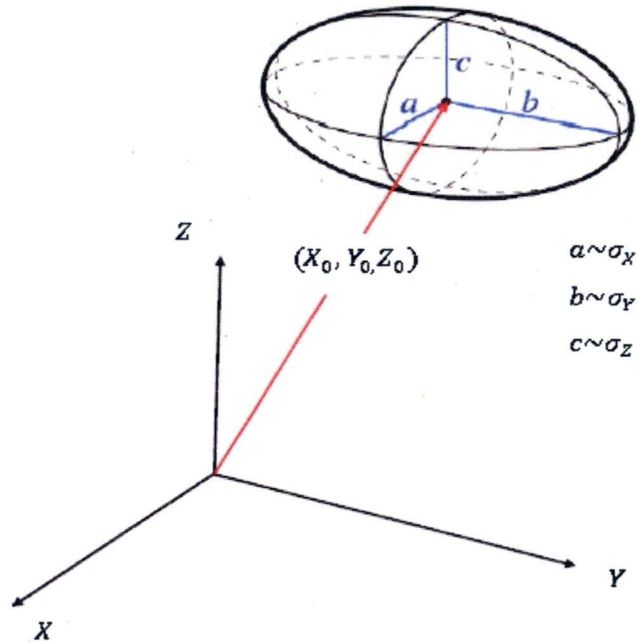

Figure 1-4
3D example of measurements X, Y, Z as a vector of mean values X_0, Y_0, Z_0 95% confidence interval is a, b, and c
(Source: Geometric Formulation of the DVR Method and the Effect of Various Factors on Reconciled Values and Uncertainties, Yuri Gurevich, Nuclear Plant Performance Program Combined (HXPUG, P2EP, SWAP) Users Group Meetings–January 2020)

Figure 1-5 and Figure 1-6 illustrate what the DVR solution objective function seeks to achieve. The "bands" of ellipses represent the range of empirical uncertainties for the values.

The DVR solution seeks to find the minimal value of the error, represented by the distance between the auxiliary conditions reconciled values and the plant measured values. The solution lies at the minimal, or closest, value of the auxiliary conditions reconciled value to the plant measured value, which lies within a plane of the football shape (the grey "slice" in Figure 1-5).

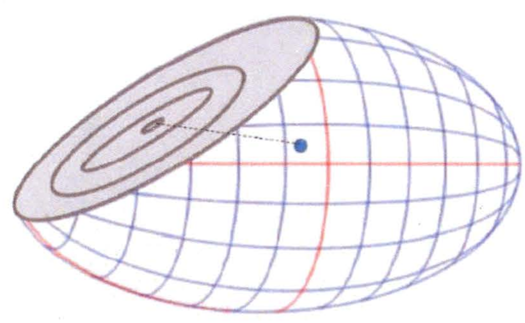

Figure 1-5
Shortest distance to plane represents highest probability reconciled value

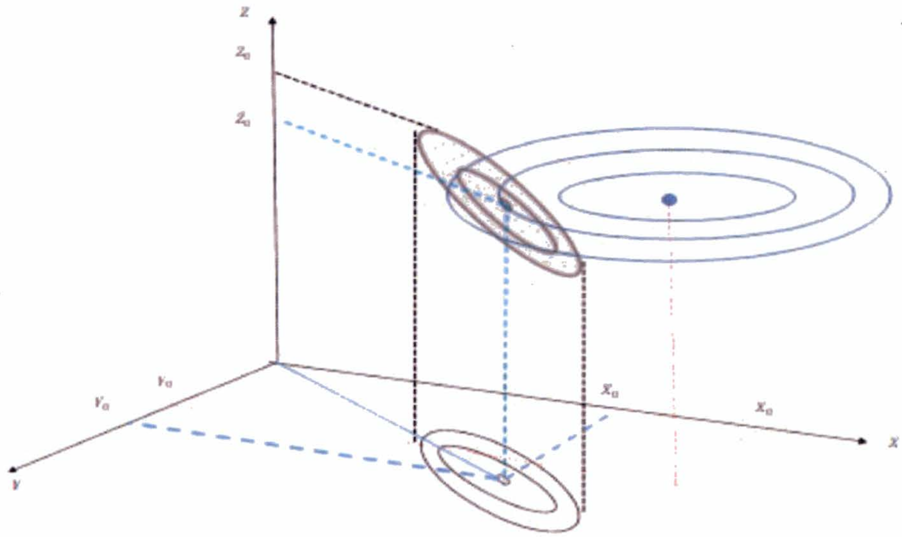

Figure 1-6
Defines reconciled values of standard deviations and uncertainties

Figure 1-7 represents the final solution for the reconciled values. The DVR solution method seeks not only to minimize the error from each individual plant measurement value from the auxiliary conditions value, but to minimize the total error for all the values.

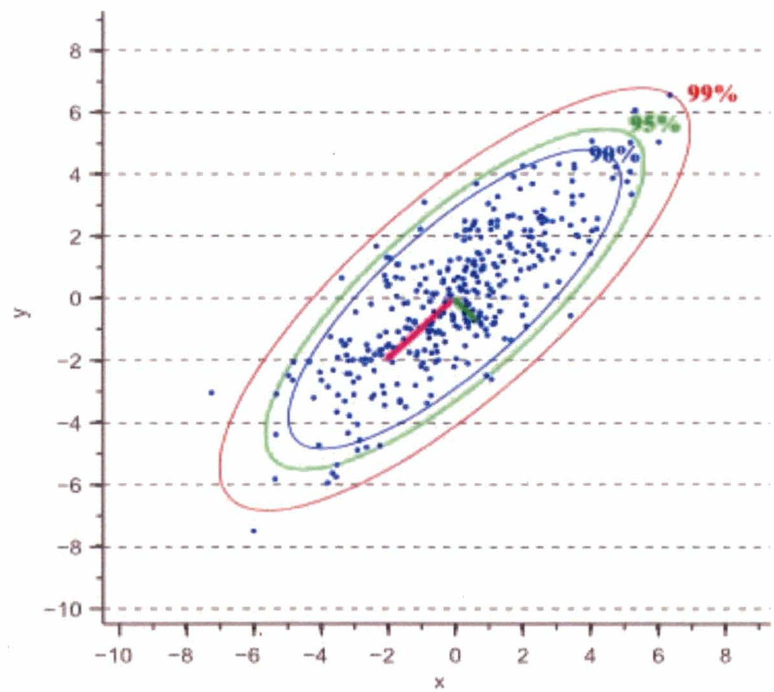

Figure 1-7
Projections of probability distribution of final DVR results

1.7 Comparisons of DVR Methods to ASME and International Codes and Standards

Presently, VDI-2048 is the only engineering code that has accepted the methods used by DVR. Originally, the code was developed for calculating the uncertainties of turbine acceptance test measurements and results. Later, application for use as an alternative means for CTP calculations was developed and has been implemented at several international nuclear plants (see Section 5.0, "Benchmarking and Operating Experience (OE)", for details).

Internationally, the development of rules and methods used for the determination of measurement uncertainties largely originates with the "Guide to the Expression of Uncertainty in Measurement", or "GUM". The GUM has been issued as an ISO standard [7].

In the United States, ASME PTC Codes PTC 6, "Steam Turbines" [6], and 19.1, "Test Uncertainties" [5] provide guidance on the conduct of steam turbine testing and uncertainty evaluation of the test measurements and output results.

Section 3.0, "Methodology", of this document provides comparisons of these codes to the methods used in DVR.

Section 3.0, "Methodology", also provides analytical and sensitivity studies of bias propagation errors for DVR results as compared to the Taylor Series and Monte Carlo methods as used in ASME 19.1.

1.8 Verification and Validation of DVR Software

Section 4.0, "Verification and Validation of DVR Software" presents the results of case studies used to demonstrate the DVR software has been properly developed to comply with VDI-2048, and to demonstrate the DVR calculations compare favorably to vendor heat balance diagram calculations and a vendor turbine retrofit acceptance test data. A brief overview of the case studies are provided in Sections 1.8.1 through 1.8.4.

1.8.1 Simplified Verification Test Case

The purpose of this test case is to verify the DVR to the results the method demonstrated in VDI 2048, Part 1, Appendix A [1], and a 3rd party DVR software calculation that uses a different calculation scheme.

1.8.2 Comprehensive Verification Test Case

The results of DVR software for this test case are compared to the results from the retrofit example in VDI 2048, Part 2, Section 7 [2].

1.8.3 Validation Using Heat Balance Diagram

DVR model calculations are compared to a vendor heat balance calculation diagram.

1.8.4 Validation Using Turbine Retrofit Test

The DVR software was used to calculate data from a recent nuclear plant turbine retrofit. The DVR results are compared to the vendor data.

1.9 Application of DVR Methodology

Section 6.0, "Application of DVR Based on Power Plant Data", provides details on how to configure a DVR model for a typical nuclear plant. This section includes information related to:

- Process of validating the model to design data
- Tuning of the model to reduce turbine design data uncertainties
- Tuning the empirical measurement uncertainties used in the model
- Testing of the model and acceptance criteria in relation to the VDI-2048 standards
- Implementation of a feedwater flow correction factor
- Evaluation of Potential Errors and Overall Accuracy of the DVR Plant Model and Application
- CTP error contributors and overall uncertainty calculation

Section 7.0, "Demonstration Application", provides detail on the design change process requirements needed to implement a DVR model when used for CTP power recovery or MUR efforts. This section includes:

- Administrative Controls for Implementing DVR Results to the CTP
- Design Control and Documentation Requirements
- Software V&V Requirements
- DVR software functional and site acceptance testing requirements

1.10 DVR Failure Modes

Section 8.0, "DVR Failure Modes Evaluation", provides and addresses:

- A DVR Calculation Failure Affinity Diagram that provides all failure modes
- A DVR Calculation Cause and Effect Diagram that provides the consequences of each failure
- Invalid or Bad Plant Measured Data
- Model and Algorithm Limitations
- Effects of model assumptions on the DVR results
- Case studies of worst-case error effects of plant measured data on the DVR results
- Examples of propagation of bias errors into the DVR Calculated CTP Uncertainty
- Evaluation of the Overall CTP Uncertainty for a DVR Model
- Mitigation Methods and Alternate Indicators to ensure the DVR CTP uncertainty is not exceeded

1.11 Off Normal Conditions, Reliability, and Limitations of DR Methodology

DVR performance, reliability, and limitations of use are given in Sections 9.0 through 12.0 of this document.

Section 9.0, "Off Normal", describes the plant state and conditions for which the DVR results are valid or invalid.

Section 10.0, "DVR Reliability", provides metrics for the reliability of DVR for at 11 operating units, three of which are Pressurized Water Reactors (PWRs) and eight that are Boiling Water Reactors (BWRs).

Section 11.0, "Limiting Condition for Operation", provides information on the degree to which DVR may impact Limiting Condition for Operation (LCO). LCOs are documented in a licensee's Technical Specifications (TS) document.

Section 12.0, "Limitations", provides information when the feedwater flow correction factor calculated with DVR is valid, and not valid.

2
LICENSING AND BASIS REQUIREMENTS

The feedwater flow rate measurement devices (venturis, nozzles, ultrasonic flow meters and associated instrumentation) used at BWRs and PWRs for the determination of licensed reactor core power are typically supplied and installed to high quality, commercial standards.

Feedwater flow measurements systems are typically classified as non-safety related components and systems. The plant's Updated Final or Final Safety Analysis Report (FSAR) contains the safety classification of the feedwater flow measurement system.

Feedwater flow measurements systems are typically classified in a licensee FSAR as important measurements that are used during and following an accident.

Results from the DVR calculations of plant measured data may be used to implement a recalibration of the licensed core power feedwater flow rate measurement devices or "Power Recovery". In this application, the DVR method's accuracy or uncertainty must be sufficient to ensure the site's licensed reactor core power uncertainty, typically 2%, is maintained.

In 2000, the Nuclear Regulatory Commission (NRC) amended 10 CFR 50, Appendix K, to provide licensees the option of maintaining a 2% power margin or applying a reduced margin based on the improved measurement uncertainties resulting from incorporation of more accurate feedwater flow measurement instrumentation [46].

A limited number of Appendix K uprates (Measurement Uncertainty Recapture-MUR) have been performed in the U.S. using higher accuracy ultrasonic feedwater flow metering systems. The process required an NRC approved license amendment as the safety margins for the plant are affected. One potential application of the DVR process is to use the calculation results to facilitate a MUR.

2.1 Safety Classification

The safety classification for DVR technology will depend on the application. For some plants the calculation of reactor Core Thermal Power (CTP) may not be safety related as prescribed in the Updated Safety Analysis Report (most likely in Chapter 7 or related to Feedwater systems), however, the CTP may be used to calibrate the reactor neutron monitoring instrumentation which feeds safety related Reactor Protection Systems (RPS). Also, in some plant situations measurement of CTP is used for maintaining adequate safety margins in the chapter 14 or 15 Accident Safety Analyses. Therefore, regarding this topical, the DVR technology software and any required additional instrument changes which would be entirely plant dependent and should be evaluated on a case by case plant application scenario. For purposes of this topical, the safety classification is not prescribed as it would depend upon the application for the DVR software. Requirements for the safety classification should be identified, evaluated, described and documented in a plants individual license amendment request for a DVR application.

Licensees would need to evaluate the safety classification per their license basis and requirements through their design change process and provide this classification with justification as part of their license amendment request.

2.2 Discussion of the Application of 10CFR Part 50, Appendix B to the Design and Implementation of the DVR Model

As noted in NUREG-0800 Branch Technical Position (BTP) 7-14 [48], Revision 5, the regulatory basis for Software reviews of digital computer based instrumentation and control systems regarding potential application of 10 CFR Part 50 Appendix B is recommended to be evaluated in context with the individual plant DVR application through the license amendment request. A plant DVR application may need to evaluate if 10 CFR Part 50, Appendix B Criterion are applicable and document such in the license amendment request. Examples of Criterion that might be applicable for a plant implementation are Design Control, Instructions, Procedure/Drawings, Document Control, Control of Purchase Material, Equipment/Services and Test Control. Each licensee needs to ensure that they have evaluated and documented their specific DVR implementation and application regarding the relevance of 10 CFR Part 50 Appendix B Criterion. It is recommended that the DVR software model and its platforms be part of the evaluation as well regarding the full licensee implementation. If a Criterion is applicable a detailed explanation of how it will be met should be documented in the licensee's amendment request. For those licensees that have determined that Criterion are applicable, the sections below provide some further discussion for consideration as part of their license amendment request process.

2.2.1 Criterion III, Design Control

DVR Software

Related to design control that is pertinent to the DVR software design control measures, if it is determined to be applicable, it should be established for the software to provide verifying or checking adequacy of design, such as by the performance of design reviews of the software or by the use of alternate or simplified calculational methods or by the performance of suitable testing program. In regard to the DVR software this verification can be conducted through plant specific models and checking of such models. The software and implementation of such should then be placed under design control measures such that procedures are established for control of design interfaces. Design control measures can include a process for review, approval, release, distribution and revision of DVR software.

DVR Implementation

Regarding design control for facilities that have MUR, those plants would have already been analyzed to the recaptured power level. Implementation of DVR should not impact those previously analyzed conditions, i.e., it will not increase or adjust the power levels over the previously analyzed MUR safety analyses. The facility uncertainty analyses as credited in the licensee's safety analyses will not be altered or impacted as a result of DVR implementation. For those facilities that have MUR the existing component credits and uncertainties shall remain the same, and the methodology for crediting those is not altered either through DVR implementation. For example, a plant that has already been approved to credit a LEFM Check Plus™ as part of their MUR will still remain unaffected by DVR implementation. That is, all of the safety analyses previously performed (including the uncertainty analyses) to support MUR through credit of the Leading Edge Flow Meter (LEFM) Check Plus™ will be considered still bounding after implementation of the DVR. The power levels will never exceed what the facility was licensed for through the MUR process. All existing trip setpoints will be considered functional and operational after DVR implementation and therefore will perform as designed.

Implementation of DVR will also not affect the components and/or the equipment analyses such as plant trips or setpoints as it is not interfaced with plant components credited for those systems. DVR implementation to the facility shall be via plant procedures (i.e., operator manual correction factor input). Therefore, the existing trip setpoints and equipment credited for trips will not be affected via DVR interface (for both non-MUR and MUR facilities). Any change in power will still be subjected to the existing plant trip functions and is not anticipated to be affected by DVR.

For those licensees that have already implemented MUR the licensee would take credit for the existing safety analysis, components and systems evaluations and it would not be expected that revisions to those analyses would be necessary to facility DVR changes (i.e., power recovery). The licensee must still perform an evaluation that the existing safety, components, and systems analyses are applicable with the proposed DVR changes (i.e., not impacted negatively or bounded). It is required that the licensee evaluate and document the DVR implementation via a 10 CFR 50.59 process to ensure that facility changes can be made without requiring a License Amendment Request (LAR). Any 10 CFR 50.59 evaluation that identifies that the change cannot be processed with existing plant procedures would require a LAR. Since each DVR application can be unique a 10 CFR 50.59 Screening is necessary, and a full evaluation may be required prior to implementation. Also depending upon the DVR design application, i.e., if additional equipment or components need to be installed to facilitate the changes these would also fall under necessary 10 CFR 50.59 review for design control. There may be some instances that would require a LAR, and each facility will need to review such under their processes and procedures prior to implementation.

2.2.2 Criterion V, Instructions, Procedures, and Drawings

If Criterion V has been determined to be applicable related to DVR technology, documented instructions should be prescribed for implementation of the software/integration with plant equipment through plant specific instructions, and procedures. Plant specific drawings should be created to prescribe interfaces with plant systems and components. These plant specific drawings can be used to illustrate the integration of the DVR technology with the plant computer and any other interfacing systems. Procedures related to the installation/implementation, testing of DVR software might include appropriate quantitative and qualitative acceptance criteria for determining satisfactorily accomplished measures. If maintenance is required for ongoing operations of the DVR technology maintenance specific procedures should be prescribed for plant specific applications as necessary.

2.2.3 Criterion VI, Document Control

If Criterion VI has been determined to be applicable related to DVR technology and implementation thereof, measures should be established to control the issuance of documents, such as instructions, procedures, and drawings, including changes thereto, which prescribe all activities affecting quality. The proposed DVR technology may then fall within the individual licensee document control processes relevant to changes, reviews for adequacy and approval for initial release and subsequent changes by authorized personnel. Plant specific changes to DVR technology documents should be controlled by the same organization that performs the original review and approvals unless so designated to another responsible organization.

2.2.4 Criterion VII, Control of Purchased Material, Equipment, and Services

If Criterion VII has been determined to be applicable, DVR technology/software should be controlled and procured through an individual plant procurement program. Each individual plant utilizing the DVR technology should use pre-established licensee procurement controls and processes related to designation for its specific classification for procurement of the DVR software. If a Licensee needs to replace existing equipment that process shall be controlled by the plant prescribed license requirements.

2.2.5 Criterion XI, Test Control

If Criterion XI has been determined to be applicable, prior to implementation of DVR technology a test program should be established to assure that all testing required to demonstrate that systems and components will perform satisfactorily in service is identified and performed in accordance with written test procedures which incorporate the requirements and acceptance limits contained in applicable design documents. The types of tests should be identified as part of each licensee's implementation process. Depending upon the licensee's individual application, a factory acceptance test may need to be performed on the DVR software prior to installation. Operational tests may need to be performed as part of the process of integrating the DVR technology with the existing plant systems. Test procedures developed for DVR technology should include provisions for assuring that all prerequisites for a given test have been met, that adequate testing instrumentation is used and available, and that the test is performed under suitable environmental conditions. If a FAT and operational test are required, they should be documented and reviewed to assure that test requirements have been satisfied.

2.3 Applicable Codes and Standards

This section identifies some potential applicable codes and standards. The latest version issued on the date of this document is applicable unless so noted. The individual Licensee must perform an applicable codes and standards evaluation as part of their LAR submittal. A codes and standards applicable assessment should be part of the LAR including conformation to such. Also, a Licensee should evaluate their commitments to code versions if applicable or not as part of their design change process. Only a sampling of some potential codes and standards is provided in the sections below. Each Licensee should conduct an exhaustive search, justification and review for all appropriate codes and standards that would apply to their DVR application. The following terms are used in this section:

- **Plant Licensing Documentation** – This refers to plant level documentation that is specific to a group of plants or a single plant, such as a License Amendment Request or a Final Safety Analysis Report.

- **Software Components** – This refers to the various software components proposed to be used for the DVR Model. The potential software components shall be commercial grade standard business software.
- **Equipment** – This refers to the components that may be required to be installed for implementation of the DVR Technology. For purposes of this topical the equipment supporting the DVR software will be installed on one personal computer (PC). The PC will function as the DVR and SQL Database Client/Server. The PC itself hosting the DVR Software and SQL Database Client/Server shall be classified as non-safety related.

2.3.1 Potential Applicable Regulatory Guides, Regulatory Information, Branch Technical Position, NRC Inspection Reports and Interim Staff Guidance

1. RG 1.97, Rev. 3 Instrumentation for Light Water-Cooled Nuclear Power Plants to Assess Plant Conditions During and Following an Accident [50]
   a. Implementation of the DVR methodology and interface should not impact any process and display signals from accident monitoring instrumentation. Therefore, normally this regulatory guide would not be applicable with this software/technology implementation. However, a licensee should evaluate that there is not any accident monitoring that could be impacted as part of the design change process to implement the interface as described in plant licensing documentation. From NRC Regulatory Guide 1.97, Revision 3 the feedwater flow rate measurement for BWRs and PWRs has been classified a Type D, Category 3. Type D variables are "(1) to determine if the plant is responding to the safety measures in operation and (2) to inform the operator of the necessity for unplanned actions to mitigate the consequences of an accident." "Category 3 is intended to provide requirements that will ensure that high-quality off-the-shelf instrumentation is obtained and applies to backup and diagnostic instrumentation. It is also used where the state of the art will not support requirements for higher qualified instrumentation."
   b. Results from the DVR calculations of plant measured data may be used to implement a recalibration of the licensed core power feedwater flow rate measurement devices, provided the DVR method's accuracy or uncertainty is sufficient to ensure the site's licensed reactor core power uncertainty is maintained. These "recalibrations" may be implemented as correction factors on the base feedwater flow calibration factor or the feedwater flow rate itself.
   c. For a typical Licensee, the licensed reactor core power uncertainty used for safety analyses is ±2%. The ±2% value should be confirmed by reviewing the Licensee's Final Safety Analysis and other documents related to licensing of the reactor core power. The feedwater flow measurement system and components, used for the licensed calorimetric, must deliver an accuracy that ensures the safety analysis value of ±2% is met. As such, these components are subject to measuring and test equipment (M&TE) requirements to ensure the calibrations of the instruments that comprise the system stay within their stated or design accuracies, in order to maintain the ±2% safety analysis value. The M&TE section addresses this requirement.

d. For those licensees that have already implemented MUR the licensee would take credit for the existing safety analysis, components and systems evaluations and it would not be expected that revisions to those analyses would be necessary to facility DVR changes (i.e., power recovery). The licensee would credit the same existing instruments for trip functions. The licensee should still perform an evaluation that the existing safety, components, and systems analyses are applicable with the proposed DVR changes (i.e., not impacted negatively or bounded). It is required that the licensee evaluate and document the DVR implementation via a 10 CFR 50.59 process to ensure that facility changes can be made without requiring a LAR. Any 10 CFR 50.59 evaluation that identifies that the change cannot be processed with existing plant procedures would require a LAR.

2. RG 1.152 Criteria for Programmable Digital Computers in Safety Systems of Nuclear Power Plants [51].

   a. This guidance relates to methods to be used for specifying, designing, verifying, validating and maintaining software for plant installed equipment credited for safety systems. The DVR software and DVR technology classification may be non-safety related with augmented requirements or non-safety related and as such the methods to meet the intent have been specified within this topical related to design, verification, and validations. Related to specifications the software is recommended to be part of a licensee SQA program and the applicable life cycle of the software, and methods for controlling software security threats if any should be evaluated and documented.

3. RG 1.173 Developing Software Life Cycle Processes for Digital Computer Software Used in Safety Systems of Nuclear Power Plants [52].

   a. The DVR software and DVR technology may be classified as non-safety related with augmented requirements (AQ) or as non-safety related depending on the application. As such, guidance from this document will be important relevant to specifying a software life cycle process. A software life cycle process for the digital platform to be used or described in this Topical may need to be developed by each Licensee. The software life cycle should be specified within the design change process for implementation of this Topical relevant to I&C system descriptions and design processes.

4. RG 1.181 USAR Updates "Content of the Updated Final Safety Analysis Report in Accordance with 10 CFR 50.71(e)" [53].

   a. Each licensee will need to evaluate how their implementation of DVR technology will affect their existing UFSAR through the design change process. Each licensee will need to review applicable sections for example such as Section 7 and 15. Any potential revision of the UFSAR could be conducted through the normal licensing 6 month update process as long as a change is not required through the 10 CFR 50.90/92 process.

5. NRC Inspection Report 35750 QA M&TE [54].

   a. The Licensee's DVR accuracy will be documented in the Licensee's DVR Functional Design Specification. Depending upon the Licensee application a review may be necessary relevant to this NRC inspection report.

   b. As the typical Licensee's licensed reactor core power uncertainty is ±2% and the DVR method's accuracy or uncertainty is much less than ±1%, a recalibration of the feedwater flow rate measurement system using the DVR results should allow the NRC Inspection Procedure 35750 criteria to be easily met. Depending upon the Licensee application, continuous monitoring of the DVR derived feedwater flow correction factor may need to be performed to ensure the Licensee's licensed reactor core power uncertainty of ±2% is maintained.

6. RIS 2002-03 MUR Guidance on the Content of Measurement Uncertainty Recapture Power Uprate Applications [55].
   a. This document is applicable to Licensee Measurement Uncertainty Recapture license amendments and not directly applicable to this Topical Report. However, it is mentioned as being indirectly applicable if a licensee would choose to apply DVR technology as part of Measurement Uncertainty Recapture license amendment. This document would in that case serve as additional guidance for a license amendment.
7. BTP 7-14 Revision 5 Guidance on Software Reviews for Digital Computer-Based Instrumentation and Control Systems [48].
   a. A review of BTP 7-14 in relationship to DVR methodology has identified that portions of A.3.1 "Definition of Software Planning Characteristics", A.3.2 "Definitions of Functional and Process Characteristics" and B.3.3 "Acceptance Criteria for Design Outputs" may be applicable to DVR software depending upon the ultimate implementation of the technology at a Licensee's facility.
8. Digital I&C ISG-06, Digital Instrumentation and Controls, Interim Staff Guidance [56]
   a. This document provides guidance for NRC staff related to review of license submittals related to digital instrumentation and controls. This document highlights the various guidance documents that staff uses when performing reviews of license submittals and would be relevant when a Licensee makes a license amendment that invokes this topical. Each Licensee may need to review this guidance document to determine its relevance to the plant application.

2.3.2 Potential Industry Codes[1]

1. ASME PTC 19.1 1998 or (2018) Test Uncertainty [5].
   a. (ASME) 19.1 [5] Depending upon the Licensee application this code may need to be addressed for a plant implementation. This methodology includes systematic, random errors, and parameter uncertainties.
   b. VDI-2048 [1, 2] describes the theoretical and practical calculation methods to assure the quality of measurements and evaluate their results for energy conversion and power plants. Measurement uncertainties are taken into account by representing material and system variables as measured variables. The true value of the measured variable is

[1] A licensee should as part of the license amendment request conduct a codes and standards evaluation as part of the DVR application to document their applicable codes relevant to their design and license basis.

superimposed by the sum of random and independent influences, along with the sum of the unknown systematic deviations. By application of the central limit theorem, a sum of independent random variable converts into a normal distribution. These variables are combined in a measured variable vector to form an n-dimensional random variable.

c. A key element of this process is to estimate the covariances of the measured variables to enable their stochastic dependencies to be considered. Derived variables from first principals are equated with the measured variables and combined in the vector of the measured variables. The combined uncertainty of the measured values is expressed in an empirical covariance matrix.

d. As stated above, the application of the central limit theorem applies due to the treatment of all the variables as random. This results in the application of the statistical certainty of 95% and given at 95% confidence interval.

2. ASME PTC 19.5 1972 (2004) Flow Measurement [57].

   a. This standard is applicable only from the aspect of how flow measurement devices that are already installed at a Licensee's facility could be used in conjunction with the DVR technology. This standard provides general information related to various types of flow measurement devices that may be found installed. It is being listed as a good engineering practice.

3. ASME PTC 6 1985 (2004) Performance Test Code on Steam Turbines [6].

   a. This standard is applicable as a discussion point with the integration of plant thermal performance models that will be part of the processes for checks, verification and validation functions of the DVR technology. It is being listed as a good engineering practice.

4. ANS 10.4 1987, Guidelines for the Verification and Validation of Scientific and Engineering Computer Programs for the Nuclear Industry [58].

   a. The computer program/software used to develop the technology/methodology and monitoring is described in the design process section of this Topical report.

5. ANSI N18.7 1976 Administrative Controls and Quality Assurance/Nuclear [59].

   a. Quality assurance procedures by the DVR software supplier will include certification that the software conforms to the VDI-2048 calculations. The DVR software supplier will provide software release letter documentation that describes Quality Standards and Practices, and the testing methods used in the software development. This will help ensure the software functions properly with the software environment and computer hardware selected for the plant. Documentation will be provided for all uncertainties and plausible assumptions developed during the DVR model development and implementation phases. These assumptions will be used to develop an overall bounding uncertainty value for the reactor power estimate. The details of the documentation will be such that the plant can replicate the calculations as needed and provide sufficient detail to satisfy any independent reviews by other interested parties or regulatory bodies.

b. Licensees should review sections 5.2.7.2, 5.2.13.2, 5.2.15, 5.2.19 and 5.3 of ANSI N18.7, 1976 for applicability to their sites related to potential implementation of DVR methodology.

6. ANSI/ANS N58.14 Safety And Pressure Integrity Classification Criteria For Light Water Reactors [60].

   a. This standard specifies criteria for the safety classification of items (SSCs and parts, including consumables) in a LWR nuclear power plant as safety-related (Q), non-safety-related with augmented requirements (A), or non-safety-related (N). In addition, pressure integrity classification criteria are provided for the assignment of Classes 1, 2, 3, 4, or 5 to pressure-retaining items. With respect to DVR technology a Licensee will need to conduct their own safety classification and document such as part of their design basis process.

7. IEEE 7-4.3.2.1 2003 Criteria for Programmable Digital Computer Systems in Safety Systems of Nuclear Power Generating Stations [61].

   a. Key elements of this standard related to DVR technology are software quality, life cycle processes, Independent verification and validation, and communication links.

8. IEEE 1059 Software V&V Guide [62].

   a. Guidance in preparing Software Verification and Validation Plans (SVVPs).

9. IEEE 1012-2004 "IEEE Standard for Software Verification and Validation," as endorsed by Regulatory Guide 1.168 Revision 1, "Verification, Validation, Reviews, And Audits For Digital Computer Software Used In Safety Systems Of Nuclear Power Plants" [9].

   a. Guidance relevant for verification and validation is provided in this standard. The Verification and Validation process for DVR software includes the various processes, reporting, administration, documentation and planning as noted in this standard.

10. ISO 9001 International Organization for Standardization Quality Management Systems [63].

    a. The DVR software was designed and developed to ISO 9001 requirements and is certified as such.

2.3.3 Potential Code of Federal Regulations (CFRs)[2]

1. 10 CFR 50 Appendix A GDC 1 Quality Standards and Records [64].

   a. Each licensee should evaluate their safety classification for DVR and identify if GDC 1 is applicable or not.

[2] As long as a plant is not linking any of the DVR calculations to a plant's Safety Parameter Display System (SPDS) or using the methodology for maintaining safety limits 10 CFR 50.34 and 50.36 would not apply. If a plant is linking the DVR calculations/methodology to the above aforementioned SPDS or using to maintain safety limits then those sections of CFR would apply and each Licensee would have to evaluate impacts from this type of application.

2. 10 CFR 50 Appendix A GDC 19 Control Room [64].
   a. The non-safety related software and monitoring provides information to a licensee network. How the licensee interfaces the site network with the plant PC should be evaluated related to Control Room interfaces. The proposed DVR software will reside on a stand-alone PC, but might be interfaced to Corporate Engineering applications and databases. It is recommended that each licensee evaluate its explicit installation related to the Control Room (if applicable) as part of their design change process.
3. 10 CFR 50 Appendix B, Criterion III, V through VII and XI
   a. Sections 2.2.1 through 2.2.5 explicitly discuss implications of this topical relevant to the CFR noted.
4. 10 CFR 50 Appendix K MUR [46].
   a. In 2000, the Nuclear Regulatory Commission (NRC) amended 10 CFR 50, Appendix K, to provide licensees the option of maintaining a 2% power margin or applying a reduced margin based on the improved measurement uncertainties resulting from incorporation of more accurate feedwater flow measurement instrumentation.
   b. A limited number of Appendix K uprates (MURs) have been performed in the U.S. using higher accuracy ultrasonic feedwater flow metering systems. The process requires an NRC approved license amendment as the safety margins for the plant are affected.
   c. One potential application of the DVR process is to use the calculation results to facilitate a MUR. This is possible because the reconciled results from a DVR calculation often have improved uncertainty levels when compared to measured plant data. The reconciled results can be used as the basis for corrections to plant measurements such as feedwater flow that are based upon ultrasonic flow measurement (UFM) methods.
   d. If a Licensee desires to implement an MUR utilizing DVR, the site would need to make a license amendment to support a safety margin reduction to less than 2%. As the safety margins are reduced with the MUR, as opposed to the DVR power recovery application where the ±2% safety analysis values are maintained, additional engineering analyses or justifications for using DVR may be required by the NRC for license amendment approval.
5. 10 CFR 50.36 (1) (2) (i), (3) (4) Technical Specifications Limiting Conditions for operations, Surveillance Requirement, Design Features. Some of the sections from 50.36 that may need to be review/evaluated by a Licensee as part of their LAR process [65].
   a. Regarding (1) DVR software it most likely will not be used as a digital safety or non-safety system to maintain safety or control limits. Therefore, this section may not be applicable, but a Licensee would need to review and justify their particular application.
   b. Regarding (2)(i) "When a limiting condition for operation of a nuclear reactor is not met, the licensee shall shut down the reactor or follow any remedial action permitted by the technical specifications until the condition can be met." The DVR software implementation could be considered as a remedial action basis for equipment required for safe operation that may be in a limiting condition for operation. If there is equipment that is in technical specifications that is required for power measurement and necessary for

safe operations, the DVR system could be relied upon to satisfy as a remedial action until said component condition can be met (i.e., design or surveillance). A Licensee would need to evaluate this impact if any and provide justification for such.

c. Regarding (3) Surveillance requirements, if a Technical Specification requirement related to surveillance could not be met that is important to power measurement uncertainty, the DVR system might potentially satisfy as a remedial action the surveillance requirements relating to test, calibration, or inspection to assure that the necessary quality of systems and components is maintained.

d. Regarding (4) Design Features, if a Technical Specification requirement related to design features is not met that is important to power measurement uncertainty, the DVR system could potentially satisfy as a remedial action until as such time the design feature is restored. Such features could include pipe wall thinning beyond vendor criterion for ultrasonic feedwater flow monitoring as an example.

6. 10 CFR 50.55a (a)(1) Quality Standards for Systems Important to Safety [66].

   a. The DVR software was developed to ISO9001 standards, not to a 10 CFR Appendix B QA program.

7. 10 CFR 73.54 (a) (1) (i) Protection of digital computer and communication systems and networks [67].

   a. The applicable section of this CFR that potentially could apply is related to "important to safety". A licensee would need to evaluate the effects of DVR implementation related to the requirements as specified in this CFR if any have been classified as important to safety.

2.3.4 Potential NUREGs

1. 0800 SRP Chapters 7-14 and 18 (I&C, QA) [48].

   a. This NUREG is only considered applicable if a licensee must credit the non-safety related functions for monitoring safety related plant instrumentation and/or controlling safety related plant components. A licensee should evaluate individual plant applications related to DVR technology as interfaced to their plant systems. The Licensee should document applicability of this NUREG in their LAR process as appropriate.

2. NUREG/CR-6101 Software Reliability and Safety in Nuclear Reactor Protection Systems [68].

   a. The DVR technology/software most likely will not directly link to the plant Reactor Protection Systems. As such, from that aspect the NUREG is not applicable. However, the NUREG does highlight recommendations for software that are important for consideration for software development in use at a commercial nuclear facility. Section 4 addresses recommendations for planning, requirements, design, implementation, validation, integration, and installation that could be part of the DVR technology approach. The NUREG is only used as potential reference material for this Topical in light of its recommendations for software reliability.

3. NUREG/CR-6421 A Proposed Acceptance Process for Commercial-Off-The-Shelf (COTS) Software in Reactor Applications [69].
    a. This NUREG is considered applicable since the software has been designed for commercial applications as well. A Licensee depending upon their application may want to review this NUREG for applicability.

2.3.5 Other Documents

The EPRI documents below are only provided as potential references for information.

- TR-102323 EM Interference Testing [70]
- TR-102348 Licensing Digital Upgrades [71]

2.4 Software Quality Assurance and Verification and Validation (V&V Process)

The Software Quality Assurance Plan (SQAP) describes the requirements and methodology to be followed to ensure the processes in developing the DVR models, using and maintaining the DVR software for the enhancing plant operations for the licensee. The SQAP will rely on each licensee's SQAP processes and procedures. Depending upon the requirements for the overall implementation of DVR will dictate what software integrity levels may be necessary to meet the Licensees SQAP. Each Licensee should evaluate their application in accordance with their SQA classification process and document that evaluation. Each utilities SQAP process maybe slightly different as such a detailed generic application for requirements is not possible in this document. Some elements that may need to be part of a Licensees SQA for DVR software are audit reports, software documentation, software development, configuration management, change control, problem reporting, software/system testing, and validation testing. Each Licensees SQAP process as required should be detailed in the LAR related to the DVR application if appropriate and required.

2.5 DVR Model Software Security

Individual plant applications of the DVR model may need to have a software security assessment performed with respect to the requirements for the DVR software installation. Since each plant application could be different a generic single method of application regarding software security and DVR models/software is not possible.

DVR software depending upon the plant implementation may be planned to be installed on a server located at the site or at a utility corporate headquarters.

The DVR installation contains various commercial software products. While these software products are developed to high commercial standards, they potentially may contain software security vulnerabilities similar to other commercial software products. Individual plant utilities will need to evaluate the DVR installation software components through their prescribed engineering change process to determine any special software security requirements needed for the DVR installation.

Details of the DVR installation software components are provided in the Site Acceptance Test (SAT) documentation. In general, these components include:

1. Microsoft Windows
2. Microsoft SQL Server
3. Microsoft Excel
4. DVR
5. Plant Data Historian Clients – OSI PI, eDNA OPC, etc. This server can be installed at the plant facility or corporate headquarters. Each utility should evaluate this server under their software security program.

An overview diagram of one type of DVR installation is given in Figure 2-1. Figure 2-1 shows the DVR setup used for one type of installation. All of the DVR software components and other supporting software will be installed on one personal computer (PC). The PC will function as the DVR and SQL Database Client/Server.

Content Deleted-EPRI Proprietary Information

2.6 Operator Controls

Depending upon each Licensees DVR application if Operator Controls are necessary the following discussion would then be applicable. The Control Room's determination of the correct result produced by software will be a multistage verification. The first portion of this will be functional and in-service testing of the software. Verification of the software in controlled environments is paramount prior to implementation of the software to provide operations with confidence with the values provided. Once the software is in service, the procedures and human verification will provide confidence that the program is working. Under normal conditions the Shift Technical Advisor would verify the software is functioning correctly and the provided value is within an acceptable range. The number provided would be peer checked when transferred to the procedure. This value would be provided to the Shift's Senior Reactor Operator for second verification and approval prior to being transferred to the plant's computer. This value would then be entered by a Licensed Operator and the effects of this change would be verified by observing the plant response. This sequence is consistent with other critical values used to calibrate or change control room parameters. It would provide a consistent method of control and ensure plant response is as expected. Additional details are discussed below that a utility should utilize as part of Operator Controls process.

- Validation steps of the model itself are included in each iteration of correction factor update review. These checks are done via the software, but the software is documented and tested via the software Verification and Validation (V&V) as part of the design process and in accordance with the utility software quality assurance program.
- Hard-coded plant specific bounds in the plant process computer for the correction factor are recommended, with analyses to verify that entry of acceptable values on their own cannot trip/adversely impact the unit (i.e., all correction factor changes must be between these pre-analyzed bounds, entries outside of this are rejected by the plant computer) The analyses will be included in the initiating engineering change process, with the bounding values only modifiable via a configuration change.
- Use of secondary thermal cycle parameters to verify the station is operating as expected.
- Requiring manual entry of the correction factor (if necessary) into the plant process computer, which is only available to Operators within the main control room
- The DVR software does not have a direct tie-in to the running unit. Failure or gross errors in the model cannot impact the running unit.
- The specific site specific validation steps are to be developed for each site, but should include input and buy-in / signature and traceability from the site thermal performance group (the model owner), along with onsite reactor engineering, system engineering (as needed), and shift manager approvals before it gets to plant process computer entry.
- Operational procedure and/or onsite engineering input also will include pre-correction factor update computations to verify the expected system response (primarily to core thermal power, but can include alternate indications) prior to entry. Training and Simulator scenarios, showing the expected responses would provide the operators with the level of competence needed in using this software to ensure the values provided are correct.

3 METHODOLOGY

The data validation and reconciliation (DVR) calculation methodology employs a combination of statistical procedures and first principle analyses to provide a qualified representation of the plant system.

The DVR algorithm is primarily based upon the work of Streit [3] and others [4, Section 8.5], to establish a computerized form of a general-purpose estimation method for power plant acceptance test calculations. The method can also be applied to the plant Core Thermal Power (CTP) calculation.

Various commercial software products are used in the industry to calculate the DVR algorithm. This document will describe the methodology and mathematical basis for one software platform and compare it to VDI 2048 [1].

Generic Description of the Methodology

The DVR calculation requires measurements (with associated uncertainties) and a system of auxiliary conditions. The auxiliary conditions include mass and energy balances and other performance calculations for components comprising the plant system model.

The auxiliary conditions create additional redundant variables based on actual measurements and derived from physical properties which helps with the elimination of systematic errors with the measurements. The auxiliary conditions are fundamental equations such as mass and energy balance, pressure equalities, thermodynamic properties and isentropic efficiencies of turbines and pumps.

Unknown systematic errors often or likely exist in the measured data. These systematic errors may arise due to the characteristics of the sensor design, calibration, location or installation of the measuring instrument.

The accuracy (uncertainty) values for the measurement and auxiliary (unmeasured) variables for input to the DVR algorithm are provided as an input to the overall calculation. These accuracy estimates may include approximations of the systematic and random errors of the measurement based upon the user's knowledge of the measurement variables, or plausible assumptions using engineering judgement.

An empirical covariance matrix is developed in the DVR algorithm that relates the errors of the measurement uncertainties and the auxiliary conditions.

DVR uses the empirical covariance matrix and a Gaussian correction principle to remove the inconsistencies, or contradictions between the measurements and the auxiliary conditions.

As a measure of the amount of correction applied to the measurements, an objective function is used to assess the statistical quality of the outcome. Individual variables are also statistically assessed by comparing the magnitude of correction applied to the specified uncertainty of the measurement.

By application of the central limit theorem a sum of independent random variables, and variables containing unknown systematic errors, will convolve to form a normal distribution as the number of variables increases. As a result of the central limit theorem, any systematic errors not eliminated, may be passed into the final solution. Therefore, additional assessments of a large set of DVR runs is typically performed to identify potential biases with the results. This is particularly true for low redundancy variables such as the unmeasured turbine efficiencies.

By law of propagation of uncertainty [7], more commonly referred to as the general law of the error of propagation, the results may be affected by unknown systematic errors. The systematic errors can be assessed by analyzing the results to identify possible sources of the error. At this point the system model of the auxiliary conditions may be refined to better model potential sources of systematic errors, or the user estimates of a measurement uncertainty may be modified. The DVR calculation can be repeated to observe if the overall Chi-square distribution of the variables improves. This process may be repeated until the end user is satisfied the system model and measurement uncertainties reflect the plant state for the data under review.

The final results are corrected measurements that fulfill the auxiliary conditions. These reconciled values have the highest possible likelihood to represent the true values and have a lower uncertainty (reconciled uncertainty) than the input measurement uncertainties. These results satisfy the heat balance equations and auxiliary conditions established in the plant model.

3.1 DVR Algorithm Overview

Based upon formulations from Streit [3], and [4], DVR evaluates the system state of the vector space of the measured values with empirical estimates of random errors applied to the measurements, subject to constraints from the auxiliary condition calculations. The DVR algorithm methods from Streit [3] are derived from his earlier works from 1975.

See below for a list of important symbols and notations used in Section 3.1. These symbols and some additional symbols may be discussed and defined in the body of this section when appropriate.

Important symbols and notations

σ	Standard deviation
σ^2	Variance
$D(X_i)$	Standard deviation of X_i.
$D^2(X_i)$	Variance of X_i
v_{X_i}	Confidence interval (or uncertainty)
n	Number of measured values
x	n dimensional position vector of measured values

X	n dimensional vector of the normally distributed random variables (i.e., measured values)
R_X	Empirical covariance matrix, dimensions n x n
$V(X_i,X_j)$	Covariance of measured variables X_i and X_j
$\bar{X}$	n dimensional vector of the normally distributed estimated values (also referred to as corrected measurements or reconciled values)
v	n dimensional vector of improvements
r	Number of auxiliary conditions
f(x)	Contradictions
f(x+v) or f($\bar{X}$)	Auxiliary conditions
F or $\left[\frac{\partial f}{\partial x}\right]$	Functional matrix (or Jacobian matrix), dimensions r x n
Q	Statistical quality
$\chi^2_{r,95\%}$	Chi-squared value for r degrees of freedom and 95% confidence

3.1.1 Variance of a Single Measured Random Variable

The variance of a random variable X_i is standard deviation of the variable squared:

$$\sigma^2 = D^2(X_i) \qquad \text{Eq. 3-1}$$

The confidence interval, v_{X_i} of random variable X_i for a 95% confidence interval is:

$$v_{X_i} = 1.96 * \sigma_{X_i} \qquad \text{Eq. 3-2}$$

The confidence intervals of the measured variables are typically expressed as an *accuracy* value. The accuracy values for the measured variables are developed based upon on empirical observations, or conservative assumptions of the performance of the measurement system in the field.

For measurements, it is common practice to specify an uncertainty with a statistical confidence of p = 95% as a 95% confidence interval $x_i \pm v_{xi}$. The widths of the 95% confidence intervals are mostly defined and assumed on the basis of empirical values; taking the measurement device used, the measurement method, etc. into consideration [1].

3.1.2 All Measured Variables Combined as a Multi-Dimensional Random Variable

The various measurements collected during an acceptance test, or system state calculation using DVR, may contain random errors that are interdependent in nature.

The measurements and variances can be combined as a multi-dimensional vector to allow analysis of the overall random error for each measured variable.

Let $g(x) = g(x_1 \ldots x_n)$ be a function of the n measured values that represent a n dimensional vector. $x_1 \ldots x_n$ represents the random measured variables such as mass flow, temperatures, pressures, electrical output, etc., that comprise the test data.

x represents the position vector of measured state point in Figure 3-1, below.

$$x = \begin{bmatrix} x_1 \\ \vdots \\ x_n \end{bmatrix} \quad \textbf{Eq. 3-3}$$

This vector is a single value of the n dimensional normally distributed random variable:

$$X = \begin{bmatrix} X_1 \\ \vdots \\ X_n \end{bmatrix} \quad \textbf{Eq. 3-4}$$

The vector μ as shown in Figure 3-1 is the position vector of the unknown true state point of the plant undergoing evaluation.

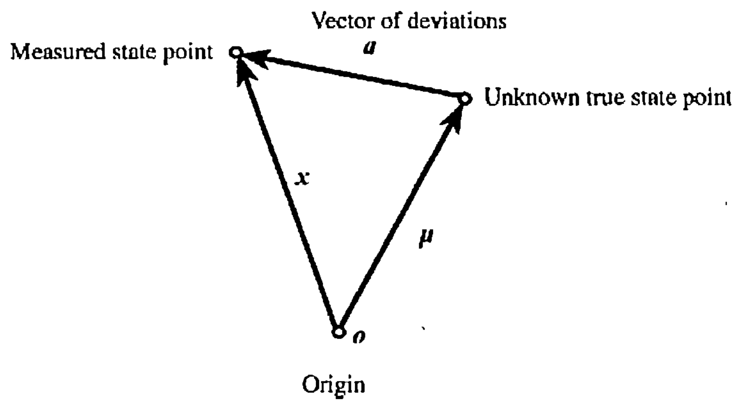

Figure 3-1
Depiction of measured and true state point (source: [1])

Linearization is possible if the partial derivatives of the function g(x) are practically constant within the confidence intervals of the measured variables when they are adequately measured.

The variance of G is the result variable:

$$D^2(G) = \left[\frac{\partial g}{\partial x}\right]^T * R_X * \left[\frac{\partial g}{\partial x}\right] \quad \textbf{Eq. 3-5}$$

This is the general form of the law of error propagation for a single result variable.

$$v_G = 1.96 * D(G) \quad \textbf{Eq. 3-6}$$

The confidence interval of the single result variable.

The matrix of the covariances of the *n* dimensional random variable is given with,

$$R_{X=} \begin{bmatrix} D^2(X_1) & \cdots & V(X_1, X_n) \\ \vdots & \ddots & \vdots \\ V(X_n, X_1) & \cdots & D^2(X_n) \end{bmatrix} \quad \textbf{Eq. 3-7}$$

Where V are the covariances of the measured variables, X_1 in respect to the other measured variables, X_n and D^2 are the respective variances of the X_n variables.

R_X represents the *empirical covariance* matrix of the measured variables X.

3.1.3 Generalized Form of the Least Squares Method and the Gaussian Correction Principle

To obtain the estimated values of the random variable, $\overline{X}$, the algorithm adds a vector of improvements v to the measured values X:

$$\overline{X} = X + v \qquad \text{Eq. 3-8}$$

The vector of improvements v is determined such that the quadratic form is a minimum:

$$Q = v^T * R_X^{-1} * v \rightarrow Min \qquad \text{Eq. 3-9}$$

Equation 3-9 is a generalized form of the least squares method and the Gaussian correction principle. In this case the least squares method is used to minimize the sum of squared errors while accounting for the variances and covariances of the measured values. The inverse of the empirical covariance matrix, R_X^{-1} (referred to as the weighting matrix in Appendix A.1) is used to account for the quality of the measured values. Measured values with smaller uncertainties (the more trustworthy measurements) are improved to a lesser extent than those with larger uncertainties, which are not as trustworthy and would be more freely adjusted [4, Section. 8.5.5].

3.1.4 Introduction of Auxiliary Conditions

A commonly used method to assess the accuracy of the measured variables is to use a mathematical model to calculate equivalent estimates. These models or calculations typically contain mass and energy balances, or other performance calculations developed to determine the system state. However, typical estimates from mathematical models have only been used for comparative measures.

DVR introduces the concept of using estimates obtained from the mathematical models, or auxiliary conditions calculations, to form additional functional redundancies which may be used to further evaluate the actual measured data.

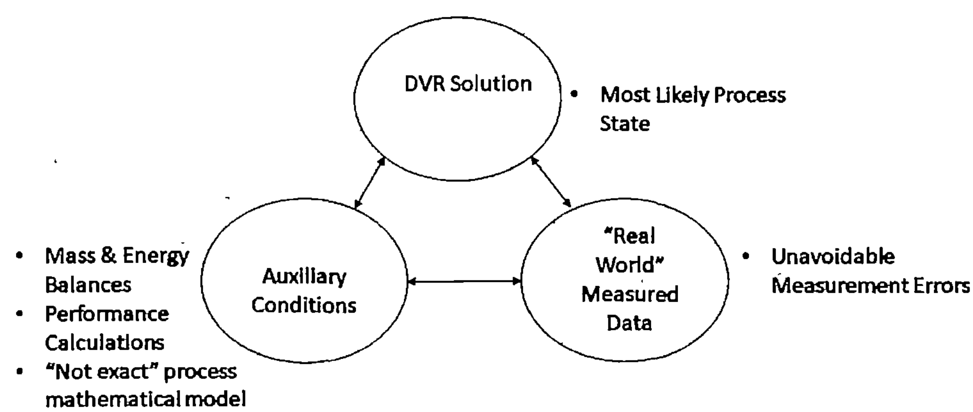

Figure 3-2
Overview of DVR process

Ideally, the auxiliary conditions of the system state would provide measured estimates that are nearly perfect as they are based upon first principles and other engineering calculations. However, the mathematical models will almost always be imperfect as they typically represent simple models of the plant state. Therefore, the uncertainties of the auxiliary conditions calculations must be considered when evaluating the final results. While it is noted the auxiliary conditions will never perfectly model the system state, Appendix A.1.5 shows that the uncertainties of the measured values will always be reduced with DVR. This holds true even if the auxiliary conditions are imperfect.

Figure 3-2 depicts the problem of statistically resolving the measured data with the auxiliary condition. Use of the auxiliary conditions estimates allows for statistical evaluation of the measurements within the vector space that the final solution must lie.

The basic idea is to set up the measured values along with their variances together with the *r* auxiliary conditions which must be met by the true values. As depicted in Figure 3-1, the true values are an unknown state point. Since the true values represent a state with zero errors, they fulfill the auxiliary conditions with no contradictions.

Let,

$$\mathbf{f}(\mathbf{x}) = \begin{bmatrix} \mathbf{f}_1(\mathbf{x}) \\ \vdots \\ \mathbf{f}_r(\mathbf{x}) \end{bmatrix} \qquad \textbf{Eq. 3-10}$$

The measured values will not fulfill the *r* auxiliary conditions, and contradictions will yield as a result of the unavoidable stochastic (random and systematic) errors. Since the true values fulfill the *r* auxiliary conditions, it is obvious this must also apply to $\bar{X}$.

$$\mathbf{f}(\mathbf{x} + \boldsymbol{v}) = \mathbf{0} \qquad \textbf{Eq. 3-11}$$

Provided the partial derivatives of f(x) are practically constant (higher order partial derivatives $\partial^2 f/\partial x^2$, $\partial^3 f/\partial x^3$, etc., can be considered negligible), and the improvements *v* are small enough, linearization of Equation 3-11 by use of the Taylor series yields,

$$\boldsymbol{f(x+v) = f(\bar{X}) = f(x) + \frac{1}{1!}\left[\frac{\partial f}{\partial x}\right]^T * (\bar{X} - x) = f(x) + \left[\frac{\partial f}{\partial x}\right]^T * v = 0} \qquad \textbf{Eq. 3-12}$$

Provided the functional matrix $\left[\frac{\partial f}{\partial x}\right]$ is regular concerning the columns (i.e., not linearly dependent). Equation 3-12 is a set of *r* linear equations for *n* unknowns *v*. The solutions of the *r* auxiliary conditions of Equation 3-12 are located on a (*n-r*) dimensional subspace, M, as shown in Figure 3-3. That is why the corrected state point (i.e., estimated value) and auxiliary conditions lie directly on the subspace M as shown in Figure 3-3.

As mentioned before, the improvements will lead from inconsistent measured values *x* to consistent estimated values, $\bar{X}$. Therefore, the vector of improvements *v* calculated by the least squares method must be one of the solutions of Equation 3-12. This is obtained by introducing Equation 3-12 with Lagrange multipliers, *k*, into Equation 3-9:

$$\boldsymbol{Q = (v^T * R_X{}^{-1} * v) - 2 * \left(f(x) + \left[\frac{\partial f}{\partial x}\right]^T * v\right) * k \rightarrow Min} \qquad \textbf{Eq. 3-13}$$

The first term of the right-hand side of Equation 3-13 is the generalized form of the least squares method (Equation 3-9). The second term of the right-hand side is the auxiliary conditions of the estimated values, $f(\bar{X})$, multiplied by the Lagrange multipliers (and a cofactor of 2). This is a multi-dimensional minimization problem with *n* variables and *r* constraints. The purpose here is to minimize the sum of squared errors while constraining the ultimate result (estimated values,

$\bar{X}$) to adhere to engineering principles and the laws of physics. The constraints, or auxiliary conditions, could be mass flow rate balances, conservation of energy equations, or other empirically based engineering equations (i.e., valve discharge equations).

3.1.5 Algorithm for Practical Use

From Streit [3, Section 3.5], the *Algorithm for Practical Use* for the state estimation method is developed. The calculation of the vector of the consistent estimated values $\bar{X}$ from the vector of measured values X according to Equation 3-8 is:

$$\overline{\boldsymbol{X}} = \boldsymbol{X} - \boldsymbol{R_X} * \boldsymbol{F} * (\boldsymbol{F^T} * \boldsymbol{R_X} * \boldsymbol{F})^{-1} * \boldsymbol{f}(\boldsymbol{x}) \qquad \textbf{Eq. 3-14}$$

Where:

R_X is the matrix of covariances of the measured variables

$F = \left[\frac{\partial f}{\partial X}\right]$ is the functional matrix (or Jacobian matrix) of the auxiliary conditions. The auxiliary conditions are the mass and energy balances and other performance calculations specified in the system model.

$f(x)$ is the vector of contradictions.

DVR evaluates the vector space of the measured values with covariances applied, to values calculated from the auxiliary conditions. Referring to Figure 3-3, the subspace N represents the differences with the equivalent measured variable value from the system state calculated using the auxiliary conditions and the actual measured variable value. These differences, or contradictions, contain the random errors of the measured variable and may also contain unknown systematic errors that have not been incorporated or simulated with the system model of the auxiliary conditions.

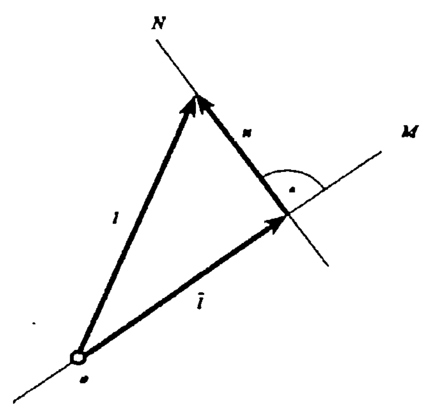

Figure 3-3
Depiction of correction task in space of distributed independent random variables (source: [1])

Where:

u represents the vector of contradictions between the random variable l and the variable calculated with the auxiliary conditions $\bar{l}$.

M is the subspace of solutions of the auxiliary conditions.

N is the subspace of the contradictions.

$\bar{l}$ is the position of the corrected state point.

o is the unknown true state point.

l is the position vector of the measured state point.

3.1.6 Assessment of the Quality of the Measured Value Estimates and Detection of Severe Errors

From Figure 3-3, the square of the vector of contradictions in the l space u^2 is a single value of the random variable u^2 distributed as χ^2.

The statistical quality, Q, of the measured values are given as:

$$Q = u^2 \leq \chi^2_{r,95\%}$$ **Eq. 3-15**

Where:

χ^2 is the Chi-square distribution

r is number of auxiliary conditions.

u^2 is the square of the vector of the contradictions

It is noted here that for DVR applications, the number of degrees of freedom is equivalent to the number of auxiliary conditions. Or alternatively stated, there are r number of independent ways the system is free to vary. For DVR applications at a nuclear power plant the number of auxiliary conditions would be in the order of magnitude of the hundreds (approximately 100–200 for nuclear power plants).

If Equation 3-15 is not fulfilled, the acquired data are to be refused as the contradictions are too severe. This may occur when the actual errors of the measured values are greater than their confidence intervals (the user specified accuracy value). Thus, in addition to a global assessment of the data, selective indications of severe errors with the measurements are also provided.

The global assessment of the acquired data in terms of Equation 3-15 is:

$$Q = u^2 = f^T(X) * (F^T * R_X * F)^{-1} * f(x)$$ **Eq. 3-16**

The covariance matrix of the consistent estimated values $\bar{X}$:

$$R_{\bar{X}} = R_X - R_X * F * (F^T * R_X * F)^{-1} * F^T * R_X$$ **Eq. 3-17**

3.2 Statistical Basis for Uncertainty

The DVR process applies commonly accepted, standard statistical methods to account for errors in the measurement data.

Codes and standards to address measurement uncertainty calculation and the effects on test results have been issued by the ASME and the ISO. Their application to the DVR process is discussed in the following sections.

3.2.1 Measurement and Test Results Uncertainties

The development of rules and methods used for the determination of measurement uncertainties largely originates with the "*Guide to the Expression of Uncertainty in Measurement*" [7]. Also commonly referred to as the "*GUM*", the standard developed recommendations to address the expression of uncertainty in measurement in conjunction with the national standards laboratories. The GUM has been issued as an ISO standard [7].

ASME PTC 19.1-2005, "*Test Uncertainty*" [5], has been developed to be the reference for the ASME Performance Test Codes and Standards, for measurement and test uncertainty analyses. ASME PTC 19.1 has been developed compliant with the methods recommended by the ISO GUM, but differs with the classifications of error terms.

Whereas the ISO GUM largely deals with measurement errors, ASME PTC 19.1, Appendix C [5] addresses methods to assess the effects of measurement errors on the calculated results.

3.2.2 Systematic and Random Errors

ASME 19.1 [5] classifies measurement uncertainty errors as systematic or random. Systematic errors tend to be bias type errors that are fixed for the duration of the measurement process. Errors classified as random typically exhibit scatter in repeated observations.

The ISO GUM [7] categorizes measurement uncertainty errors as types "A" and "B". Type "A" measurement uncertainty errors have data with which to calculate standard deviations. Therefore, ISO GUM Type "A" errors typically—but not always—correspond with the ASME definition of "random".

The ISO GUM [7] states that type "B" measurement uncertainty errors will be evaluated "by means other than the statistical analysis of series of observations". These types of errors would typically be classified as systematic by the ASME definition.

3.2.3 Sample Size and Outlier Discussion

To ensure the random error of the measurement is characterized properly, a sufficient number of measurement readings, or sample size, must be obtained.

In general [22, Table 2.3], a sample size of greater than 20 measurements will yield an uncertainty with the 95% confidence interval of about ±0.65. In simple terms this means with a sample of size 20 measurements, the 95% confidence interval upper limit of approximately two standard deviations yields 94.35% to 95.65% confidence interval. Therefore, in practice, the required sample size of plant measurements to establish a 95% confidence interval with the standard deviation of the measurements is relatively small (>20).

Typically, the input data for a single DVR run consists of a number of plant measurements obtained from 80 to 200 instruments. The sample period is usually for a one (1) hour set of data that is typically composed of more than 60 samples of each variable. The data are averaged for input to the DVR calculation. The data is usually obtained from a plant data historian that uses a data compression scheme. As 60 or more samples are obtained for each hourly averaged data used for analysis, random errors due to the sample size are extremely small.

Since the data analyzed represents an hourly average, the ability to analyze a sample set of data for outliers is limited. However, when the DVR model is set up, a large number of sample periods are analyzed to ensure the number of data runs containing spurious data that could affect the accuracy of the DVR results is relatively small (<5% of all cases).

3.2.4 The Central Limit Theorem

The central limit theorem states that if measurement is not dominated by a single error source but instead is affected by multiple, independent error sources (random errors), then the resulting distribution for measurement will be approximately Gaussian, or normal [7, 22].

A normal distribution will often be appropriate for a variable even if some of the error sources are systematic in nature, and have distributions that are non-Gaussian (uniform, triangular, etc.). The central limit theorem allows that when the random and systematic errors of a measurement are combined, the resulting distribution of the measurement is also Gaussian, or normal [22].

In practical use of the DVR algorithm, it is impracticable to determine the distribution shapes of the errors from the measurements of the plant instrumentation used as inputs. In actuality, the measurements could be non-Gaussian in form due to unknown systematic errors. While the DVR algorithm considers the input error distributions as Gaussian in form, this is not a concern as the error, input as an instrument accuracy, bounds the error uncertainty of the measurement. The uncertainties, or accuracies, for the DVR outputs of the DVR algorithm are calculated based upon the inputs of many measurements of varying error distribution forms.

The convolved DVR results are assumed to be Gaussian in form, using the Central Limit theorem as the bases. However, the true distribution of the DVR results could in theory be slightly skewed or non-symmetric in form. Regardless, when interpreting DVR results, the actual distribution shape is primarily of academic interest, and of little concern in actual practice. Additional details on the effects of the propagation of measurement errors on the DVR results is given in the following sections.

3.2.5 Propagation of Measurement Uncertainties and Errors

The ISO GUM [7] describes the "*law of propagation of uncertainty*", which considers the propagation of systematic and random uncertainty effects when estimating the measurement uncertainty. More commonly referred to as the *general law of the error of propagation*, the test results are affected by the errors with the measurements and input variables used to calculate the test results. The propagation of the errors is conducted by analyzing how the uncertainties of the test result equations outputs vary as a function of the inputs.

The overall combined uncertainty of a measurement may be determined by the Monte Carlo (MCM) or Taylor Series (TSM) methods [22, Section 1-3.4]. The ISO GUM [7] describes application of the TSM method, and ASME PTC 19.1, Appendix B [5] adapts the ISO Uncertainty method (which is the TSM). ISO GUM [8] describes application of the MCM.

From [22], Section 2-3.3 and 2-3.4, the *expanded* uncertainty of a measured variable is the root mean square of the combination of the random and systematic terms, with a stated confidence interval. Provided the sample size is large enough, the measurements are mostly discrete and not convolved, the TSM results are approximately equivalent to MCM. The distributions of the results will be Gaussian due to the central limit theorem.

Figure 3-4 illustrates how non-normal distribution systematic error terms will convolve with random terms *to* form a Gaussian distribution for the measurement.

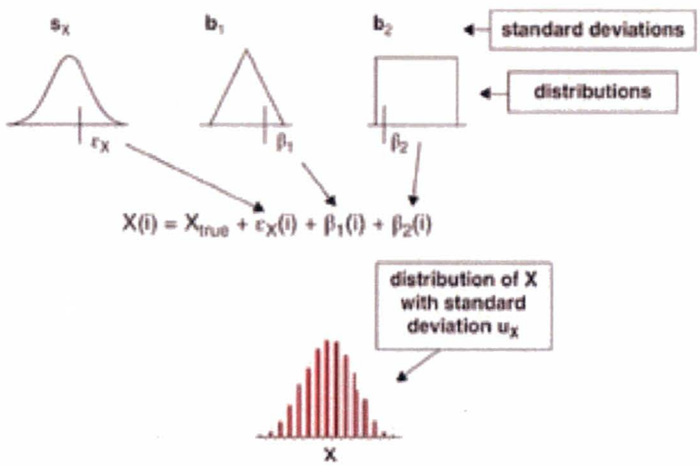

Figure 3-4
Gaussian distribution of a measurement containing systematic error (Source: [22])

There are two ways to address the convolved systematic error. The first is to increase the uncertainty of the measured value such that the Gaussian distribution encompasses the true value. The second method is to evaluate the systematic error when assessing the test results to determine appropriate test data corrections to be applied to raw, sampled data.

Systematic errors with the measured data may cause the test results to be consistently low or high as compared to expectations, when assessing many test results. Systematic errors often may be more easily detected by analyzing the test result data than investigating the error contributors of the measurement.

Once the systematic errors are detected, and the source(s) of the error are determined, corrections can be applied, and the test results can be recalculated. It may also be possible to reduce the uncertainty of the measurement related to the random errors to improve the Gaussian distribution of the measurement. Figure 3-5 illustrates correction of systematic error using DVR.

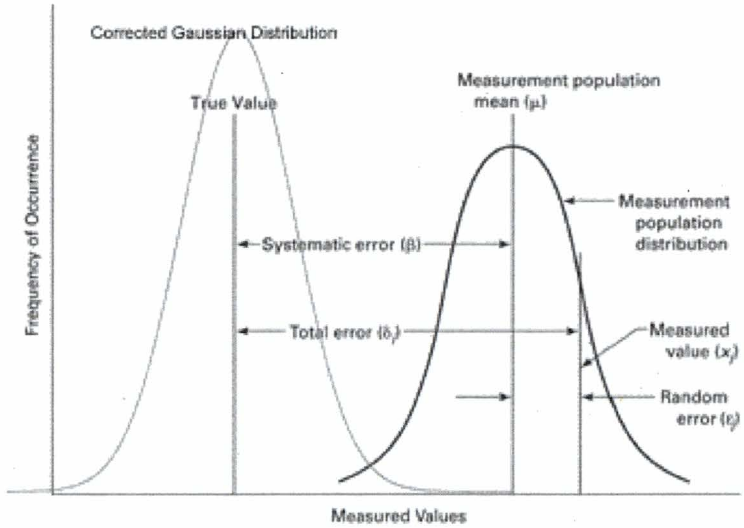

Figure 3-5
DVR corrected Gaussian distribution of a measurement

Provided the error terms used for the TSM are estimated conservatively, the resulting distribution will bound the results which would be obtained using the MCM. Systematic errors can then be identified and analyzed by reviewing the test results.

3.2.6 Effects of Measurement Uncertainties on the Test Results

ASME 19.1 [5], Appendix C provides a method of propagating measurement uncertainties into the test results using Taylor Series. This method may be used for determining the accuracy of test results when conducting an ASME Performance Test Code test.

The approach relates the deviation in a test results value with measurement deviations by means of a 1st order Taylor series expansion in the neighborhood of the measured data point expanded uncertainty.

The method presents an expression of the variance of the test results in terms of the variances and covariances of the measurements. The method assumes the random and systematic terms are independent and combine using the root mean square method. This is a combined uncertainty; the approximate expanded uncertainty for a 95% confidence interval is two (2) times this value. The factor of 2 assumes a sufficiently large sample size for the 95% confidence level (i.e., t-distribution value ≈ 2).

With DVR, an estimate value, and the expanded uncertainty for each estimate value, are calculated for each measured and unmeasured variable. The unmeasured values are typically the mass-energy balances, stage turbine efficiencies, core thermal power, or other *auxiliary conditions* as previously described in Section 3.1.

Referring to Equation 3-12, the partial derivatives of the auxiliary conditions developed by DVR algorithm will be approximately equivalent to those derived using the ASME 19.1, Appendix C method [6]. Therefore, the test results uncertainties calculated using the DVR algorithm will be approximately the same as those using the ASME PTC 19.1 Appendix C method [5].

When a DVR model is constructed, auxiliary conditions are created using component models to provide the system state and the desired test result output variables. For example, a system model of a turbine cycle could be developed to perform turbine acceptance testing using the plant instrumentation. The model can then be set up to calculate outputs needed for the acceptance testing, such as the low-pressure turbine efficiencies. The DVR calculations allow for the determination of how the accuracy of any plant test measurement used for the testing affects the test output results.

ASME PTC 19.1 Appendix C [5] also describes the propagation of systematic in addition to the random terms but notes the error terms will combine into a normal, Gaussian distribution.

The DVR error propagation calculations use empirically derived estimates of the total errors of the measurement accuracies (uncertainties) that do not differentiate the systematic and random error terms. Therefore, systematic measurement errors have the potential to create biases with the DVR output results. The end user can account for the systematic errors by examining the output results to determine if there are errors with the assumptions for the used instrument accuracy values, or the auxiliary conditions (system models) are inaccurate. It may be necessary to validate the field accuracy performance for some of the measurements or refine assumptions with the system models (auxiliary conditions) to better approximate the field measurements. Provided the DVR inputs for the input measurement accuracies sufficiently bound the overall systematic and random, or total error, the output results uncertainties will also be bounded.

For further discussion and example problems of the ASME PTC 19.1 error propagation methods, see Section 3.5.

3.3 Comparison to International Codes for the Error Propagation Methods

The methodology and requirements of turbine acceptance testing in the United States are primarily given in ASME PTC 6 [6] and 19.1 [5]. ASME PTC 6 describes the test requirements, including instrumentation, and how to perform the mass and energy balance calculations used for the thermal performance calculations. ASME 19.1 [5] provides details on the calculation of instrument and test uncertainties that may be applied to the ASME PTC 6 [6] test results.

In Europe, information related to turbine and power plant acceptance testing is given in the DIN 1943 [21] and the VDI-2048 [1, 2, 20] codes.

VDI-2048 [1, 2, 20], established in 2000, is largely based upon the Elimination Algorithm According to Streit (1975) [4, pg. 735].

VDI-2048 [1, 2, 20] promotes the concept of using an empirical covariance matrix, auxiliary conditions, and Gaussian compensation to correct errors with the test instruments and assess the quality of the test measurements and results. The code combines the measurement and test results uncertainty evaluation in one method as the uncertainty evaluations are conducted simultaneously with the test results calculations.

3.4 Simple Example of the DVR Process

The measurement values are improved by means of a correction calculation which applies conditions based on mass flow balances and energy balances. In the case of a splitter with two outputs, a relationship between the measured variables exists which will never precisely fulfill the physical law of conservation of mass; the actual measurements will not add up.

DVR relies on the principle of redundant measurements of which there are two types: functional and hardware. Functional redundancy results from applying the physical properties and first principle relationships between various measurements. Figure 3-6 shows the functional redundancy when three flows are measured and there is a functional relationship between the three flow measurements. There is one auxiliary condition ($m_1 - m_2 - m_3 = 0$) and zero unknowns, which results in one redundancy. Figure 3-7 is an example of hardware redundancy which is simply multiple measurements of the same parameter.

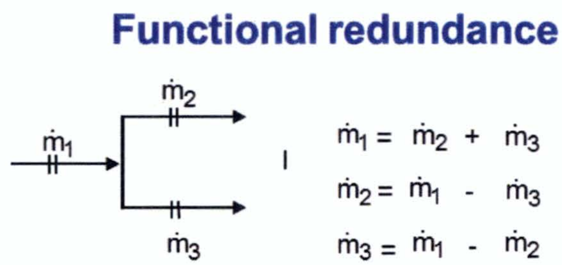

Figure 3-6
Functional measurement redundancy

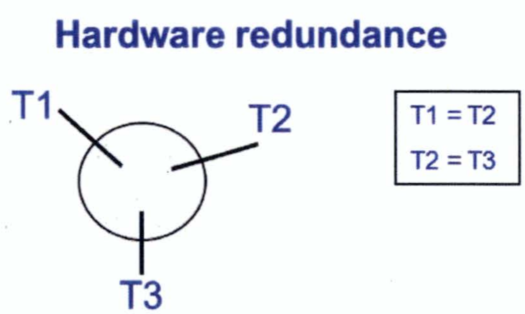

Figure 3-7
Hardware measurement redundancy

In Figure 3-6 the measured values of $\dot{m}_2$ and $\dot{m}_3$ will rarely add up exactly to the measured value of $\dot{m}_1$. Inevitably, there will be contradictory measured values. Therefore, in order for the calculation to be balanced, corrections must be applied to all the variables. A correction calculation is performed which takes into account all of the covariance analysis and produces a correction and an estimated value for each variable. The corrected values have the lowest possible uncertainty.

3.4.1 Example of DVR Calculation

Based on Figure 3-6, a simple example is provided of the mathematical process of the data reconciliation calculation. In order to relate the entire steam cycle parameters, the calculation is obviously much more complex. This example is adapted from Langenstein and Jansky [35] and is provided to describe the basic principles.

Initial corrections (v) are made to the measured values x to obtain the reconciled values $\bar{x}$ by Equation 3-18.

$$\bar{x} = x + v \qquad \textbf{Eq. 3-18}$$

Where:

$\bar{x}$ is the corrected value

x is the measured value

v is the correction value

The corrections v are determined to minimize the quadratic form as shown in Eq 3-19.

$$\epsilon_0 = v^T S_x^{-1} v \rightarrow \boldsymbol{Minimum} \qquad \textbf{Eq. 3-19}$$

Where:

S_x^{-1} is the inverse empirical covariance matrix of random variables x

ϵ_0 is the sum of squared errors

v is the vector of corrections

v^T is the transposed vector of corrections

The empirical covariance matrix S_x contains on its diagonal the estimated uncertainties of the measured values, x. This is the general form of the Gaussian correction principle.

Applying this process to our simple example, assume the mass flow rates in Figure 3-6 are measured as:

$$\dot{m}_1 = 500.00 \pm 25.00$$
$$\dot{m}_2 = 245.00 \pm 12.25$$
$$\dot{m}_3 = 250.00 \pm 12.50$$

3.4.2 Determination of Reconciled Values

The first step in the data reconciliation process is to define a set of characteristic equations, or auxiliary conditions, of the system, *f(x)*. For this example, only one characteristic equation is required based on the relationship between the three measured flows. Applying conservation of mass to Figure 3-6 the sum of all flows entering or leaving the system must equal zero, as shown in Equation 3-20.

$$f(\bar{x}) = \dot{m}_1 - \dot{m}_2 - \dot{m}_3 = 0 \qquad \textbf{Eq. 3-20}$$

To reconcile the measured mass flow rates to this condition, a correction v must be applied to each measured value according to Equation 3-18. This is shown in Equation 3-21.

$$f(\bar{x}) = f(x + v) = 0 \qquad \text{Eq. 3-21}$$

Linearizing Equation 3-21 results in Equation 3-22. The assumption is that the corrections v are independent of the measurements x. This is required to solve Equation 3-28 and Equation 3-29 for v.

$$f(\bar{x}) = f(x) + \frac{\partial f}{\partial x} v = 0 \qquad \text{Eq. 3-22}$$

The function *f(x)* is the sum of all measured flows entering or leaving the system is calculated in Equation 3-23.

$$f(x) = \dot{m}_1 - \dot{m}_2 - \dot{m}_3 = 5 \qquad \text{Eq. 3-23}$$

The functional matrix (or Jacobian matrix) of *f(x)*, $\frac{\partial f}{\partial x}$, is calculated by taking the partial derivative of *f(x)* with respect to each independent measurement. This results in Equation 3-24, Equation 3-25, and Equation 3-26. The individual partial derivatives are combined into a matrix that summarizes the entire system as $\frac{\partial f}{\partial x}$ in Equation 3-27.

$$\frac{\partial f}{\partial \dot{m}_1} = 1 \qquad \text{Eq. 3-24}$$

$$\frac{\partial f}{\partial \dot{m}_2} = -1 \qquad \text{Eq. 3-25}$$

$$\frac{\partial f}{\partial m_3} = -1 \qquad \text{Eq. 3-26}$$

$$\frac{\partial f}{\partial x} = \begin{bmatrix} \frac{\partial f}{\partial \dot{m}_1} & \frac{\partial f}{\partial \dot{m}_2} & \frac{\partial f}{\partial \dot{m}_3} \end{bmatrix} = \begin{bmatrix} 1 & -1 & -1 \end{bmatrix} \qquad \text{Eq. 3-27}$$

The corrective vector v is found by substituting Equation 3-22 into Equation 3-19 using the Lagrange multiplier λ.

$$\epsilon_0 = v^T \cdot S_x^{-1} \cdot v - 2\lambda \cdot f(\bar{x}) = v^T \cdot S_x^{-1} \cdot v - 2\lambda \cdot \left(f(x) + \frac{\partial f}{\partial x} v\right) \Rightarrow Minimum \qquad \text{Eq. 3-28}$$

Equation 3-28 is at a minimum when its derivative with respect to v is equal to zero as shown in Equation 3-29.

$$\frac{\partial \epsilon_0}{\partial v} = 2\left(S_x^{-1} \cdot v - \left(\frac{\partial f}{\partial x}\right)^T \cdot \lambda\right) = 0 \qquad \text{Eq. 3-29}$$

Solving Equation 3-29 for v results in Equation 3-30.

$$v = S_x \cdot \left(\frac{\partial f}{\partial x}\right)^T \cdot \lambda \qquad \text{Eq. 3-30}$$

A system of equations can be created using Equation 3-30 and Equation 3-22 to solve for the Lagrange multiplier in terms of the known functions $f(x)$, $\frac{\partial f}{\partial x}$, and S_x. Substituting the result into Equation 3-30 results in the equation for the corrective vector v as shown in Equation 3-31.

$$v = -\left(\frac{\partial f}{\partial x} \cdot S_x\right)^T \cdot \left(\frac{\partial f}{\partial x} \cdot S_x \cdot \left(\frac{\partial f}{\partial x}\right)^T\right)^{-1} \cdot f(x) \qquad \text{Eq. 3-31}$$

The covariance matrix S_x is calculated using the standard deviations of each measurement assuming a 95% confidence interval. The definitions of the covariance matrix S_x and each measurement standard deviation are given in Equation 3-32.

$$S_x = \begin{bmatrix} s_{x1}^2 & s_{x1,2} & s_{x1,3} \\ s_{x2,1} & s_{x2}^2 & s_{x2,3} \\ s_{x3,1} & s_{x3,2} & s_{x3}^2 \end{bmatrix}, where: s_{xi}^2 = \left(\frac{v_{xi}}{1.96}\right)^2 \qquad \text{Eq. 3-32}$$

Note: v_{xi} used in Equation 3-32 are the measurement uncertainties assuming a 95% confidence interval (see Equation 3-6). 1.96 is based on 95% of the area under the normal distribution being within 1.96 standard deviations of the mean. 1.96 is the approximate value of the 97.5 percentile point of the normal distribution.

Substituting the measured variance of $\dot{m}_1$, $\dot{m}_2$ and $\dot{m}_3$ into Equation 3-32 results in Equation 3-33. Each measurement is assumed to be independent of each other measurement. This means the covariance of each measurement with respect to each other measurement is zero, i.e., $v_{x1,2} = 0$.

$$S_x = \begin{bmatrix} \left(\frac{25.00}{1.96}\right)^2 & 0 & 0 \\ 0 & \left(\frac{12.25}{1.96}\right)^2 & 0 \\ 0 & 0 & \left(\frac{12.50}{1.96}\right)^2 \end{bmatrix} = \begin{bmatrix} 162.69 & 0 & 0 \\ 0 & 39.06 & 0 \\ 0 & 0 & 40.67 \end{bmatrix} \qquad \text{Eq. 3-33}$$

Substituting Equation 3-33 and Equation 3-27 into Equation 3-31 results in the corrective vector v as shown in Equation 3-34.

$$v = -\left([1 \quad -1 \quad -1] \cdot \begin{bmatrix} 162.69 & 0 & 0 \\ 0 & 39.06 & 0 \\ 0 & 0 & 40.67 \end{bmatrix}\right)^T \cdot \left([1 \quad -1 \quad -1] \cdot \begin{bmatrix} 162.69 & 0 & 0 \\ 0 & 39.06 & 0 \\ 0 & 0 & 40.67 \end{bmatrix} \cdot ([1 \quad -1 \quad -1])^T\right)^{-1} \cdot 5 = \begin{bmatrix} -3.36 \\ 0.81 \\ 0.84 \end{bmatrix} \qquad \text{Eq. 3-34}$$

Applying this to the vector of measured values x results according to Equation 3-18 results in the reconciled values as shown in Equation 3-35.

$$\begin{bmatrix} m_1 \\ m_2 \\ m_3 \end{bmatrix} = \begin{bmatrix} 500.00 \\ 245.00 \\ 250.00 \end{bmatrix} + \begin{bmatrix} -3.36 \\ 0.81 \\ 0.84 \end{bmatrix} = \begin{bmatrix} 496.64 \\ 245.81 \\ 250.84 \end{bmatrix} \qquad \text{Eq. 3-35}$$

The reconciled values $\dot{m}_1 = 496.64$, $\dot{m}_2 = 245.81$, and $\dot{m}_3 = 250.84$ are determined based on the statistical process defined in VDI-2048. This information can then be used to further determine the uncertainty of the reconciled values. This is the summary of the overall mathematical process described in Section 3.1.

3.4.3 Uncertainty Determination

The reconciled uncertainties are found by calculating the covariance matrix of corrections, defined in Equation 3-36.

$$S_v = \frac{\partial v}{\partial x} \cdot S_x \cdot \left(\frac{\partial v}{\partial x}\right)^T \qquad \text{Eq. 3-36}$$

Solving for $\frac{\partial v}{\partial x}$ by linearization of Equation 3-31 and substituting the result into Equation 3-36 results in Equation 3-37.

$$S_v = \left(\frac{\partial f}{\partial x} \cdot S_x\right)^T \cdot \left(\frac{\partial f}{\partial x} \cdot S_x \cdot \left(\frac{\partial f}{\partial x}\right)^T\right)^{-1} \cdot \left(\frac{\partial f}{\partial x} \cdot S_x\right) = \begin{bmatrix} 109.49 & -26.24 & -27.3 \\ -26.2 & 6.28 & 6.54 \\ -27.33 & 6.55 & 6.83 \end{bmatrix} \qquad \text{Eq. 3-37}$$

Applying this correction to the original covariance matrix in Equation 3-33 yields the corrected covariance matrix as shown in Equation 3-38.

$$S_{\bar{x}} = S_x - S_v = \begin{bmatrix} 162.69 & 0 & 0 \\ 0 & 39.06 & 0 \\ 0 & 0 & 40.67 \end{bmatrix} - \begin{bmatrix} 109.49 & -26.24 & -27.3 \\ -26.2 & 6.28 & 6.54 \\ -27.33 & 6.55 & 6.83 \end{bmatrix} =$$
$$\begin{bmatrix} 53.2 & 26.24 & 27.3 \\ 26.2 & 32.78 & -6.54 \\ 27.3 & -6.55 & 33.84 \end{bmatrix} \qquad \text{Eq. 3-38}$$

Assuming a 95% confidence interval, the measurement uncertainties can be found using the equation $s_{xi}^2 = \left(\frac{v_{xi}}{1.96}\right)^2$ from Equation 3-32. Solving for the variance v_{xi} results in Equation 3-39.

$$v_{xi} = 1.96 * \sqrt{s_{xi}^2} \qquad \text{Eq. 3-39}$$

Applying Equation 3-39 to the diagonal elements (variances) of Equation 3-39 results in the reconciled measurement uncertainties as shown in Equation 3-40.

$$\begin{bmatrix} v_1 \\ v_2 \\ v_3 \end{bmatrix} = \begin{bmatrix} 1.96 * \sqrt{53.2} \\ 1.96 * \sqrt{32.78} \\ 1.96 * \sqrt{33.84} \end{bmatrix} = \begin{bmatrix} 14.3 \\ 11.2 \\ 11.4 \end{bmatrix} \qquad \text{Eq. 3-40}$$

The final reconciled results with uncertainties are summarized below.

$$m_1 = 496.64 \pm 14.3$$
$$m_2 = 245.81 \pm 11.2$$
$$m_3 = 250.84 \pm 11.4$$

Comparing the final reconciled results to the initial measured values and uncertainties in Section 3.4.1, demonstrates that the mass balance auxiliary condition is satisfied and the uncertainties have been reduced. For a comparison of these example problem results to ASME PTC 19.1 TSM and MCM, see Sections 3.5.4 and 3.5.5.

3.4.4 Quality Control of the DVR Process

The reconciliation quality is a key performance indicator (KPI) about the quality of the reconciliation process. The quality is defined as the ratio of the Objective Function and chi squared (χ^2).

$$Quality = \frac{Objective\ Function}{\chi^2} \qquad \text{Eq. 3-41}$$

The Objective Function is defined in Equation 3-44 and Chi-Squared is a statistical value for model redundancies. The value of the quality must be smaller than 1 in order to fulfill the first VDI-2048 criterion [1]. If this criterion is not fulfilled, the following errors can be responsible:

- The idealized model is not correct.
- The uncertainties are set as too small.
- There are suspect measurements.

Note: The Quality defined in Equation 3-41 and used in the software that implements DVR differs from the statistical quality, Q, derived by Streit [4] and used in Equation 3-15. The statistical quality, Q, as used in Equation 3-15 is equivalent to the square form of errors, ϵ_0 as defined in Equation 3-19.

3.4.5 Individual Parameter Quality Measurement

Quality control is provided to detect serious errors to evaluate if the measured or estimated values are incorrect and not suitable for reliable results. This measure is defined as a Single Penalty in VDI-2048 [1], equation 141. The single penalty is a key performance indicator (KPI) for each measurement. The definition in terms of associated variance is:

$$\left| \frac{v_i}{\sqrt{max\left(s_{v,ii}, \frac{s_{x,ii}}{10}\right)}} \right| \leq 1.96 \qquad \text{Eq. 3-42}$$

Where:

v_i is the measurement correction (reconciled value – measured value)

$s_{v,ii}$ is the variance of correction applied to measurement

$s_{x,ii}$ is the variance of measured value

For application in software that implements DVR, the VDI 2048 [1] Single Penalty equation is rewritten into an equivalent form. Both sides of Equation 3-42 are squared and the variance terms are converted to uncertainty values (Equation 89 of VDI 2048 [1], variance = uncertainty^2/1.96^2).

$$Single\ Penalty = \frac{(reconciled\ value - measured\ value)^2}{max\left(correction\ uncertainty^2, \frac{measurement\ uncertainty^2}{10}\right)} * (1.96^2) \leq 3.84 \qquad \text{Eq. 3-43}$$

Where correction uncertainty^2 = reconciled uncertainty^2- measurement uncertainty^2 (Equations 89 and 132 in VDI 2048 [1]).

If any value exceeds the limits imposed by Equation 3-43 it is considered suspect and can be removed from the calculation. If a suspected value occurs either the measurement is itself erroneous or the uncertainty assigned to this measurement is too small. By this methodology any errors introduced by a faulty instrument can be detected and removed. The removal of the instrument will reduce the number of redundancies and thus increase the overall uncertainty, however a quantifiable basis for removing the instrument is achieved and the overall result is improved. This methodology permits one to identify instruments for replacement, repair, or recalibration, which may reduce the error and improve the overall result.

3.4.6 Overall Process Quality Measurement

One of the advantages of using the DVR process is the incorporation of an objective method to determine the quality of the overall process and thus the confidence that can be placed in the results. This quality determination is defined in VDI-2048 [1].

An objective function is used to determine the overall quality of the system of variables. This function is defined as:

$$\text{Objective Function} = \sum \left\{ \frac{\textit{measured value} - \textit{reconciled value}}{\textit{standard deviation}} \right\}^2 \rightarrow \textit{minimum} \qquad \text{Eq. 3-44}$$

The objective function must be less than the chi-squared test value to have assurance that the measured values are within their specified confidence ranges. Generally, the quality criterion would not be satisfied when in a certain number of measured values deviate from their true values by an amount exceeding the specified confidence region (based on VDI-2048-criterion no. 1, equation 128) [1].

$$\text{Quality} = \frac{\textit{Objective Function}}{95\%\ \textit{quantile of Chi}^2} < 1 \qquad \text{Eq. 3-45}$$

3.4.7 Summary of Quality Control

In summary the process and quality control functions based on VDI-2048 [1] are as follows:

- Reconciliation of the data by closing all the mass and energy balances with the Gaussian correction principle (Equation 3-44).
- Application of VDI-2048 criteria No. 1, quality control for the whole process (Equation 3-45).
- Application of VDI-2048 criteria No. 2, quality control for each measured data point (Equation 3-43).

3.5 Alternative Bias Error Propagation Methods

The purpose of this section is to further investigate alternative methods used to calculate the propagation of bias errors in measurements. Of main interest in this section is the methods described in ASME Performance Test Code (PTC) 19.1 [5]. In addition to investigating these alternative bias error propagation methods, this section provides example calculations to compare their results to the VDI 2048 DVR method.

3.5.1 ASME PTC 19.1 Uncertainties

ASME PTC 19.1 [5] primarily deals with the uncertainties in test measurements and the propagations of these uncertainties into the uncertainty of test results. This standard classifies errors in two discrete categories, random errors and systematic errors. This differs from how ISO GUM [7] and VDI 2048 [1] treat and analyze errors and their associated uncertainties. ISO GUM categorizes uncertainties as type "A" or type "B" and VDI 2048 does not treat the uncertainty differently based on the type of error source.

Aptly, ASME PTC 19.1 [5] uses methods to calculate separate uncertainties due to random and systematic errors. These random standard and systematic standard uncertainties are combined to calculate the combined standard uncertainty and becomes the square root sum of the squares.

$$u_{\bar{X}} = \sqrt{(b_{\bar{X}})^2 + (s_{\bar{X}})^2} \qquad \textbf{Eq. 3-46}$$

Where b_X and s_X are the systematic standard uncertainty and random standard uncertainty, respectively.

The combined standard uncertainty is used to calculate the expanded uncertainty, which is analogous to the confidence interval, v_{X_i}, which is discussed in Section 3.1.

$$U_{\bar{X}} = 2u_{\bar{X}} \qquad \textbf{Eq. 3-47}$$

Where u_X is the combined standard uncertainty and the coefficient 2 is an approximate value from the t-distribution for 95% confidence. As discussed in Section 3.2.5, a t-distribution value of 2 is valid for virtually all cases where DVR will be utilized (cases where there are numerous measurements and auxiliary conditions and the sample size is 30 or greater).

This expanded uncertainty is used to determine a confidence interval, $\bar{X} \pm U_{\bar{X}}$, around which the true value of a measurement is expected to be contained.

The objective of ASME PTC 19.1 to reach a specified confidence interval is similar to the DVR methodology. However, the methods to reach this objective differ.

3.5.2 ASME PTC 19.1 Error Propagation Methods

ASME PTC 19.1 [5] utilizes two distinct methods for determining the propagation of uncertainties. These two methods are the Taylor Series Method (TSM) and the Monte Carlo Method (MCM). The TSM requires the determination of sensitivity coefficients—analogous to partial derivatives used VDI 2048—and standard uncertainties for each source of error (systematic or random). Of these two methods, the TSM is more similar to the methods of VDI 2048 because VDI 2048 essentially uses a Taylor series expansion when using the partial derivatives in their equation for the auxiliary conditions of the estimated measurements (see Section 3.1.4).

The MCM requires estimation of the probability distributions and standard uncertainties for each error source. One major difference between the MCM and TSM is that the MCM doesn't calculate separate standard uncertainties for the systematic and random errors. Rather, the MCM determines a confidence interval based on the standard deviation of its results. For example, if 1000 simulations are run, the bounds of the 95% confidence interval would be equivalent to the

25th and 975th values (the middle 95%). One advantage of this MCM is that is a simple exercise to modify the desired confidence interval by simple changing the bounds of the results of the simulation (i.e., a 99% confidence interval would be the 10th and 990th values for 1000 simulations).

An example of each of these methods in practice is shown in Section 3.5.4 and 3.5.5. For simplicity the sample example problem shown in the Methodology section of this report was used. This also has the benefit of showing a comparative analysis of VDI 2048, ASME PTC 19.1 TSM, and ASME PTC 19.1 MCM.

3.5.3 Bias Error Propagation

In the utilizing the methods prescribed in ASME PTC 19.1 [5], the systematic errors are those that could resemble errors due to bias or drift. An example of this potential bias could be multiple redundant measuring devices that were calibrated to same standards or at the same calibration metrology facility. The resulting measurements would be biased towards these calibration error sources (due to imperfect standards, ambient conditions or altitude at facility) and result in a deviation from the unknown true value by some unknown amount.

In the DVR applications, numerous measurements are used to contribute to the result of a measured variable (i.e., Core Thermal Power (CTP)). However, of these numerous measurements, only a single, or select few measurements, could cause bias error propagation. One potential approach to account for bias error propagation into a result is to utilize a coverage factor, K [22, Appendix B]. The coverage factor is essentially a coefficient the combined standard uncertainty is multiplied by to obtain the expanded uncertainty (or confidence interval).

$$\boldsymbol{U_r = K u_c} \quad \text{Eq. 3-48}$$

Where U_r and u_c are expanded uncertainty of a result and the combined standard uncertainty, respectively.

VDI 2048 [1] methodology essentially utilizes a coverage factor of 1.96 (assumes perfectly Gaussian error distribution) and ASME PTC 19.1 recommends a t-distribution value of 2 for almost all engineering applications. Other approaches (i.e., Abernethy approach [22, Appendix B]) attempts to use the Welch-Satterthwaite formula to calculate effective degrees of freedom based on the sensitivity coefficients (i.e., first order partial derivatives) and the random and systemic uncertainty associated with each measurement. The effective degrees of freedom can then be used to determine an appropriate t-distribution values.

However, as degrees of freedom increases, the t-distribution approaches a value of approximately 2. This renders use of the Welch-Satterthwaite formula unnecessary for most engineering applications, except for those applications where only a small amount of information is available. Another weakness of the Welch-Satterthwaite formula is that is does not account for the correlated systematic uncertainties (covariances).

Observing the t-distribution table, for a 95% confidence, it can be seen that for degrees of freedom greater than 9 the values are within about 13% of the large sample t-distribution value of 2. ISO GUM, Appendix E, Table E-1 [7], shows that for 9 degrees of freedom, that the standard deviation of the random uncertainties are within 24% of the standard deviation of the mean (or measured value). This concludes that the uncertainties inherit in estimating the random uncertainties (or statically based uncertainties) is much greater than any small differences in the t-distribution values used. Even if the Welch-Satterthwaite formula is used to account for bias errors, it is not expected to have any significant effect on the calculated confidence interval. Due to the central limit theorem, for applications of greater than 9 degrees of freedom, any significant bias error contribution due to the number of observations (degrees of freedom) are expected to be overwhelmed by the random errors and any uncertainties in estimating these random errors (the uncertainties of the uncertainties). Therefore, for DVR—where there is a sufficiently large number of auxiliary conditions—it is recommended the central limit theorem be applied yielding a Gaussian error distribution.

3.5.4 TSM Example Problem

In this section, the simple mass flow balance problem that was used in Section 3.4.1 of the report will be analyzed using the TSM.

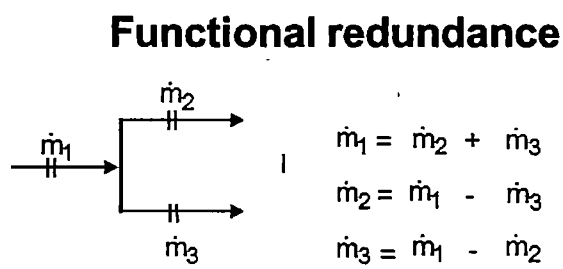

Figure 3-8
Example problem showing functional redundance

To help compare the results, it will be assumed the measurements and assumed accuracies of the measure are the same as those used in the DVR example problem.

$$\dot{m}_1 = 500.00 \pm 25.00$$
$$\dot{m}_2 = 245.00 \pm 12.25$$
$$\dot{m}_3 = 250.00 \pm 12.50$$

3.5.4.1 Determination of Systematic and Random Standard Uncertainties

The accuracies listed for m_1, m_2 and m_3 are essentially the expanded uncertainties (assuming 95% confidence interval) for the measured values. Additionally to use the TSM, the random and systematic error sources must be known or estimated using engineering judgement. The DVR example problem does not provide that specific information. Therefore, for the purpose of demonstrating the TSM, it will be assumed half the error contribution is from random sources and half the error contribution is from systematic (bias error) sources. Applying the combined standard uncertainty and expanded uncertainty equation from ASME PTC 19.1 to m_1 yields:

$$\boldsymbol{U_{m_1} = 2u_{m_1} = 2\sqrt{(b_{m_1})^2 + (s_{m_1})^2}} \qquad \text{Eq. 3-49}$$

Where:

U_{m_1} is the expanded uncertainty,

u_{m_1} is the combined standard uncertainty,

b_{m_1} is the systematic standard uncertainty, and

s_{m_1} is the random standard uncertainty

For m_1, substituting the expanding uncertainty from the problem assumptions above result in:

$$\left(\frac{25.00}{2}\right)^2 = \left(b_{m_1}\right)^2 + \left(s_{m_1}\right)^2 \qquad \textbf{Eq. 3-50}$$

As previously mentioned, for this example problem it will be assumed that half the error contribution is from random sources and half the error contribution is from systematic (bias error) sources. Using basic trigonometry by setting b_{m_1} on the y-axis, s_{m_1} on the x-axis, and half the expanded uncertainty as the hypotenuse, the systematic and random standard uncertainties can be determined.

$$\boldsymbol{b_{m_1}} = \left(\frac{25.00}{2}\right) * \mathbf{sin}(\boldsymbol{\varphi}) \qquad \textbf{Eq. 3-51}$$

$$\boldsymbol{s_{m_1}} = \left(\frac{25.00}{2}\right) * \mathbf{cos}(\boldsymbol{\varphi}) \qquad \textbf{Eq. 3-52}$$

Where the angle φ is an arbitrary value to force the systematic and random standard uncertainties to equal each other. For this example problem φ = π/2 (or 45°).

$$\boldsymbol{b_{m_1}} = \left(\frac{25.00}{2}\right) * \mathbf{sin}\left(\frac{\pi}{2}\right) = \left(\frac{25.00}{2}\right) * \frac{\sqrt{2}}{2} = \mathbf{8.839} \qquad \textbf{Eq. 3-53}$$

$$\boldsymbol{s_{m_1}} = \left(\frac{25.00}{2}\right) * \mathbf{cos}\left(\frac{\pi}{2}\right) = \left(\frac{25.00}{2}\right) * \frac{\sqrt{2}}{2} = \mathbf{8.839} \qquad \textbf{Eq. 3-54}$$

The systematic and random standard uncertainties for m_1 have been determined. Using the above process to determine the systematic and random standard uncertainties for m_2 and m_3 yields:

$$\boldsymbol{b_{m_2}} = \left(\frac{12.25}{2}\right) * \frac{\sqrt{2}}{2} = \mathbf{4.331} \qquad \textbf{Eq. 3-55}$$

$$\boldsymbol{s_{m_2}} = \left(\frac{12.25}{2}\right) * \frac{\sqrt{2}}{2} = \mathbf{4.331} \qquad \textbf{Eq. 3-56}$$

$$\boldsymbol{b_{m_3}} = \left(\frac{12.50}{2}\right) * \frac{\sqrt{2}}{2} = \mathbf{4.419} \qquad \textbf{Eq. 3-57}$$

$$\boldsymbol{s_{m_3}} = \left(\frac{12.50}{2}\right) * \frac{\sqrt{2}}{2} = \mathbf{4.419} \qquad \textbf{Eq. 3-58}$$

3.5.4.2 Determination of Sensitivity Coefficients and Mass Balance Check

The next step in the process is to calculate the sensitivity coefficients for each mass flow. These sensitivity coefficients are equivalent to the first order partial derivatives that are used in the Jacobian matrix (or functional matrix) in the DVR method.

$$z = \dot{m}_1 - \dot{m}_2 - \dot{m}_3 \quad \text{Eq. 3-59}$$

$$\theta_{m_1} = \frac{\partial z}{\partial m_1} = 1 \quad \text{Eq. 3-60}$$

$$\theta_{m_2} = \frac{\partial z}{\partial m_2} = -1 \quad \text{Eq. 3-61}$$

$$\theta_{m_3} = \frac{\partial z}{\partial m_3} = -1 \quad \text{Eq. 3-62}$$

It is reasonable to assume the random errors associated with each measurement have a normal distribution, are symmetric, and have a mean of zero. Therefore any mass imbalances in the system of measurements would most likely be the result of bias errors present. For the mass balance check to be satisfied, the absolute value of z must equal to or less than the systematic uncertainty in z:

$$|z| \leq 2b_z \quad \text{Eq. 3-63}$$

Using the TSM error propagation approach for systematic (bias) errors in the system mass flow balance can be expressed by:

$$b_z{}^2 = \sum_{i=1}^{3}\left(\theta_{m_i} b_{m_i}\right)^2 + \sum_{i}^{2}\sum_{k=i+1}^{3}\theta_{m_i}\theta_{m_k}b_{m_i m_k} \quad \text{Eq. 3-64}$$

$$b_z = \left[\left(\theta_{m_1}b_{m_1}\right)^2 + \left(\theta_{m_2}b_{m_2}\right)^2 + \left(\theta_{m_3}b_{m_3}\right)^2 + 2\theta_{m_1}\theta_{m_2}b_{m_1}b_{m_2} + 2\theta_{m_1}\theta_{m_3}b_{m_1}b_{m_3} + 2\theta_{m_2}\theta_{m_3}b_{m_2}b_{m_3}\right]^{1/2} \quad \text{Eq. 3-65}$$

The terms $b_{m_1}b_{m_2}$, $b_{m_1}b_{m_3}$ and $b_{m_2}b_{m_3}$ are the covariances of the systematic errors. Per Section 3.4.2, each measurement is assumed to be independent of each other measurement. Therefore the covariances are zero.

$$b_z = \left[\left(\theta_{m_1}b_{m_1}\right)^2 + \left(\theta_{m_2}b_{m_2}\right)^2 + \left(\theta_{m_3}b_{m_3}\right)^2\right]^{1/2} \quad \text{Eq. 3-66}$$

Substituting the sensitivity coefficients and computing b_z:

$$b_z = \left[\left(b_{m_1}\right)^2 + \left(b_{m_2}\right)^2 + \left(b_{m_3}\right)^2\right]^{1/2} \quad \text{Eq. 3-67}$$

$$b_z = [(8.839)^2 + (4.331)^2 + (4.419)^2]^{1/2} = 10.79 \quad \text{Eq. 3-68}$$

$$|z| \leq 2b_z = 21.58 \quad \text{Eq. 3-69}$$

$$|z|_{measured} = (500.00 - 245.00 - 250.00) = 5.00 \leq 21.58 \quad \text{Eq. 3-70}$$

3.5.4.3 Determination of Confidence Intervals

Therefore the condition of conservation of mass is validated. The next step is to calculate the confidence intervals using the expanded uncertainties.

$$U_{m_1} = 2\sqrt{(b_{m_1})^2 + (s_{m_1})^2} = 2\sqrt{(8.839)^2 + (8.839)^2} = 25.00 \quad \text{Eq. 3-71}$$

$$U_{m_2} = 2\sqrt{(b_{m_2})^2 + (s_{m_2})^2} = 2\sqrt{(4.331)^2 + (4.331)^2} = 12.25 \quad \text{Eq. 3-72}$$

$$U_{m_1} = 2\sqrt{(b_{m_3})^2 + (s_{m_3})^2} = 2\sqrt{(4.419)^2 + (4.419)^2} = 12.50 \quad \text{Eq. 3-73}$$

$$\overline{\dot{m}_2} \pm U_{m_2} = 500.00 \pm 25.00$$

$$\overline{\dot{m}_2} \pm U_{m_2} = 245.00 \pm 12.25$$

$$\overline{\dot{m}_3} \pm U_{m_3} = 250.00 \pm 12.50$$

3.5.5 MCM Example Problem

In this section, the simple mass flow balance problem that was used in Sections 3.4.1 and 3.5.4 will be computed using the MCM. To help compare the results, it will be assumed the measurements and assumed accuracies of the measurements are the same as those used in the previous example problems.

$$\dot{m}_1 = 500.00 \pm 25.00$$
$$\dot{m}_2 = 245.00 \pm 12.25$$
$$\dot{m}_3 = 250.00 \pm 12.50$$

3.5.5.1 MCM Approach

The accuracies listed for m_1, m_2 and m_3 are essentially the expanded uncertainties (assuming 95% confidence interval) for the measured values. To use the MCM, the random and systematic error sources must be known or estimated using engineering judgement. For the purpose of demonstrating the MCM, it will be assumed half the error contribution is from random sources and half the error contribution is from systematic (bias error) sources. Additionally, the distribution of these error sources must be known or estimated. It is appropriate to assume that the random error sources have a Gaussian distribution. For the systematic error sources it will be assumed there are finite lower and upper bounds and it is equally likely to be between these lower and upper bounds. This would mean it would be appropriate to assume the systematic errors have a rectangular distribution.

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Figure 3-9
MCM flowchart (Source: ASME PTC 19.1 [5]) -"Reprinted from ASME PTC 19.1-2018, by permission of The American Society of Mechanical Engineers. All rights reserved". No further copies can be made without written permission from ASME. Permission is for this edition only.

The process used in the example problem will follow the MCM procedure described in ASME PTC 19.1 [5]. See Figure 3-9 (reprinted from ASME PTC 19.1 [5]) for a flowchart of the process. The only step that will be skipped is the "Calculate the result from the DRE" step. This will be skipped because in the simple mass flow balance problem used, each measurement is assumed to be independent of each other, and the there is no result formula (i.e., valve discharge formula) each measurement feeds into or a Data Reduction Equation (DRE) used.

3.5.5.2 MCM Inputs

The measured value of each mass flow is used as an estimate of the "true" value for initiation of the MCM method. The random standard uncertainty and systematic standard uncertainty for each mass flow will be assumed to be the standard deviations of each error source. The number of simulations, M, will be a value large enough so that the standard deviation of the MCM result, s_{MCM}, converges to within 1% to 5%. This is usually a good approximation of the combined standard uncertainty. For this example problem, a value M will be chosen such that that s_{MCM} converges to <5%. Due to the relatively low cost of computational power, for actual engineering applications improved results will occur if one chooses an M value such that s_{MCM} convergences to <1%. These various inputs to the MCM are shown in Table 3-1.

Table 3-1
MCM example problem inputs

	m1	m2	m3
m "true"	500.00	245.00	250.00
b	8.839	4.331	4.419
s	8.839	4.331	4.419
M	500		
b distribution	Rectangular		
s distribution	Gaussian		

3.5.5.3 MCM Implementation

The MCM for this example problem was implemented in *Microsoft Excel 2013*. The *RAND()* function was used to acquire a pseudo-random number on the unit interval from 0 to 1, which will be denoted as *U(0,1)*. Each simulation for each mass flow, three *U(0,1)* values were generated. Two were used to generate the random error source Gaussian distribution. The random error Gaussian distribution was generated in *Excel* using the Box-Muller transform. The Box-Muller transform takes two *U(0,1)* values and generates a random Gaussian distribution with a mean of zero and unit variance ($\sigma^2 = 1$). The third *U(0,1)* value is used to generate the rectangular distribution for the systematic errors. Since the rectangular distribution has finite lower (LL) and upper bounds (UL), this error source will be uniformly distributed across the range LL to UL, where the mean of the systematic error distribution is (UL-LL)/2 and the systematic standard uncertainty (treated as standard deviation in MCM) is (UL+LL)/(2√(3)).

For each simulation, an estimate of the result is computed by simple summation of the "true" value, random error, and systematic error. After the appropriate convergence is reached, the average of all the simulated estimated results for a specific mass flow is the MCM mean.

$$\boldsymbol{MCM\ mean = \frac{1}{M}\sum_{i=1}^{M}(m_{true} + \varepsilon_i + \beta_i)} \qquad \textbf{Eq. 3-74}$$

Where ε_i and β_i are random error and systematic error for each simulation, respectively.

3.5.5.4 MCM Results

The results of the MCM analysis for the simple mass flow balance problem are shown below in Table 3-2. As expected, these results closely resemble the TSM results. Figure 3-10 and Figure 3-11 show the distribution of the random errors and systematic errors for m_1, respectively. Figure 3-12 shows the MCM result for m_1. The standard deviation of the distribution shown on Figure 3-12, s_{MCM}, is the approximation of the combined standard uncertainty for m_1, u_{m_1}.The same process applies to the MCM results for m_2 and m_3. Since m_2 and m_3 both have Gaussian random error distributions and rectangular systematic error distributions, their distribution plots have as similar form as those shown in Figure 3-10 through Figure 3-12.

Table 3-2
MCM results

Measurand	MCM mean	S_{MCM}	U_m
m_1	499.92	12.163	24.33
m_2	245.74	6.189	12.38
m_3	250.31	6.353	12.71

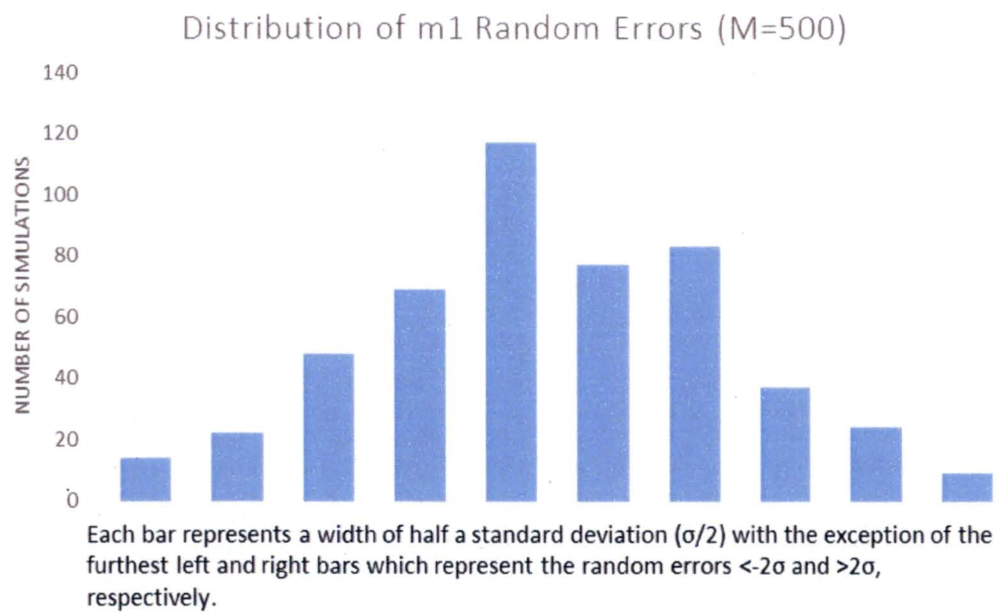

Figure 3-10
Distribution of random errors for m_1

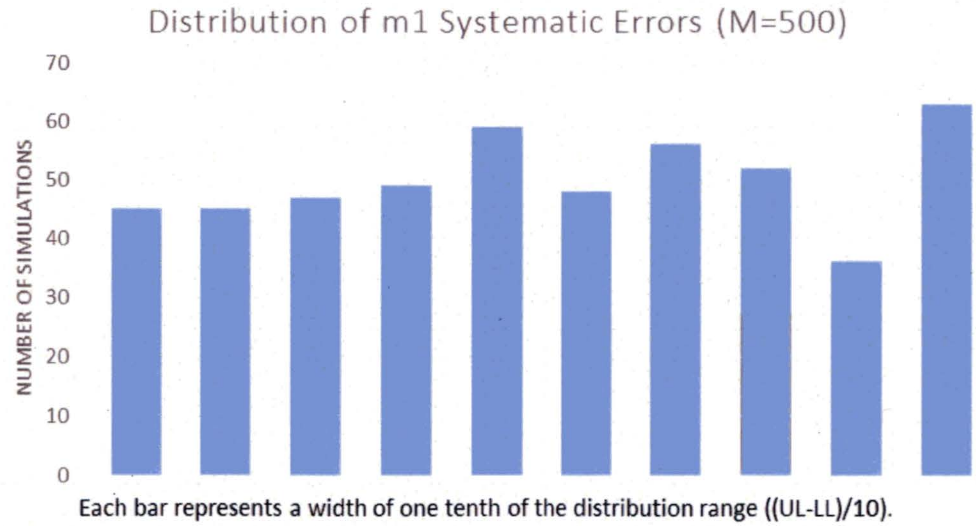

Figure 3-11
Distribution of systematic errors for m_1

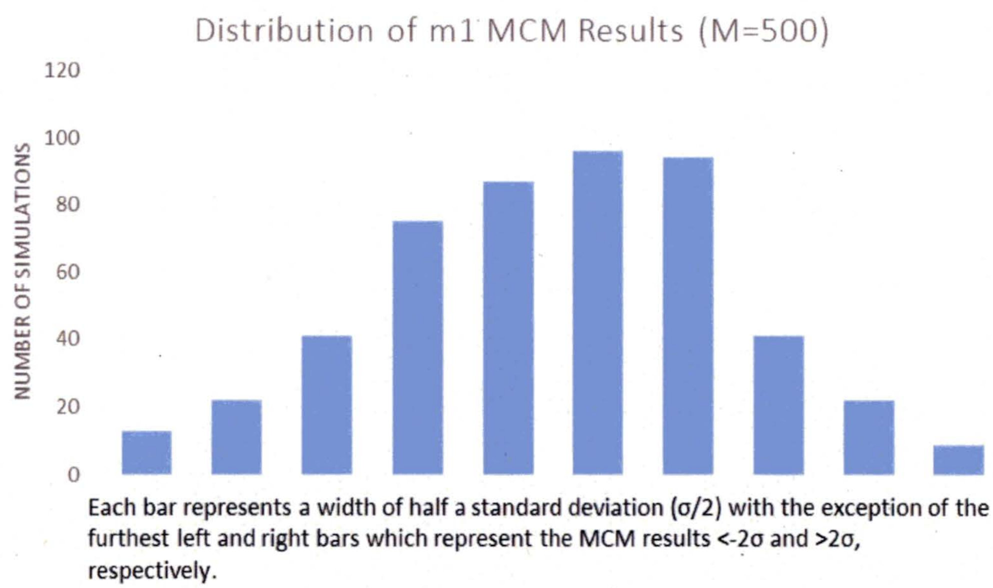

Figure 3-12
Distribution of MCM results for m_1

3.5.6 Comparison of TSM, MCM, and VDI 2048 Example Problem Results

A comparison of the results of the TSM, MCM and VDI 2048 for the example problem is shown in Table 3-3.

Table 3-3
95% confidence intervals for various error propagation methods

	Measured			TSM			MCM			VDI 2048		
m_1	500.00	±	25.00	500.00	±	25.00	499.92	±	24.33	496.64	±	14.3
m_2	245.00	±	12.25	245.00	±	12.25	245.74	±	12.38	245.81	±	11.2
m_3	250.00	±	12.50	250.00	±	12.50	250.31	±	12.71	250.84	±	11.4

As can be seen in Table 3-3, each error propagation method results in different confidence intervals. The TSM initially appears to provide no value, but the assumptions inherit in the example problem must be taken into account. For the example problem it was assumed each measurement was independent of each other (covariances equal zero). Additionally, each mass flow measurement was determined by a single measurement, the mass flows were not the result of a DRE that had inputs from various other measurements (this may not be true for actual engineering applications, but it is for this simple example problem). Therefore, the TSM did not improve, change, or correct the result.

The MCM results also more closely match the TSM or measured values as opposed to the VDI 2048 results. The differences between the TSM and MCM results can be attributed to the inherit randomness in the MCM approach and the number of simulations run. For this example problem 500 simulations were run which resulted in a convergence of the combined standard uncertainty to <5%. As more simulations are run, it is expected the MCM results will approach the TSM results, for this example problem[3].

The VDI 2048 results differ from the TSM and MCM results. From a mathematical perspective, this is primarily due to solving the constrained optimization problem using the Lagrange multiplier method (see Equation 3-13). This is the purpose of Equation 3-13, which is to minimize the square of the errors while constraining the ultimate result to the auxiliary conditions (i.e., mass flow balance). This improves the result by using the vector of improvements. The TSM and MCM provide no means to improve the result using an optimization problem and vector of improvements. This shouldn't be construed as a weakness or oversight in the TSM and MCM, but more merely not within its intended scope.

The calculated uncertainties using the VDI 2048 approach are all smaller than the uncertainties using the TSM and MCM. Again, from a mathematical perspective, this is due to the weighting matrix (inverse of the covariance matrix) used in the implementation of uncertainty reduction in DVR (Refer to Appendix A.1.5 for a more descriptive explanation and a mathematical proof that DVR always reduces the uncertainties).

[3] The expectation that MCM results approach the TSM results as M increases is valid for this example problem, but may not be valid for other applications. This is due to the TSM using sensitivity coefficient (first order partial derivatives), whereas the MCM uses the actual result formulas (or DREs) – not just first order linear approximations that TSM uses. Therefore, when comparing MCM and TSM results, the MCM results are preferred [22].

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3.6.3 Recommendations and Takeaways from Sensitivity Study

This sensitivity study makes no prescriptive recommendations that DVR methodology or DVR implementation (software) should change. However, there are implementation features that are applied to improve the overall output of the DVR model.

- For important measurements (have an effect on CTP or other import plant parameters) where a “rule-of-thumb” uncertainty was used in the input, consider performing a detailed uncertainty analysis. This could involve looking at instruments measured values over time and estimating the random error contribution and standard random uncertainty from available data. Or looking into the calibration of the associated instrument to see if there are any bias errors that could be present. This can be used at the front of DVR implementation, by modifying the accuracy (or uncertainty) inputs.
- Perform sensitivity studies on a DVR model by introducing bias errors into results and seeing how they propagate through the model and into results.
- Setting limits on the single penalty values can be used as a method to ensure the bias error does not cause the CTP to exceed its rated uncertainty.
- Lowering the DVR input accuracy (making the value larger) for certain measurement to allow for a way to compensate for the bias error in the DVR calculations. This could be used directly in the DVR calculations if the bias is known to exist. Otherwise, this method could be used to establish bounding CTP uncertainty calculations when it is believed or known that contributing measurements may drift between calibration intervals. This potential bias or drift can be detected by observation of the trending of Penalty values > 3.84.

3.7 Detailed Examples of the DVR Process

See Section 4, Verification and Validation of DVR Software, for more detailed examples of the DVR process.

4 VERIFICATION AND VALIDATION OF DVR SOFTWARE

4.1 Introduction

4.1.1 Background

DVR has been used by the nuclear power industry in the U.S. and Europe to assess turbine cycle thermal performance, balance of plant feedwater flow metering and accuracy of the plant calorimetric, or measure of the plant's licensed reactor power.

DVR technology involves the use of complex models and mathematics to derive the reconciled and validated data from numerous plant measurements. Modeling the turbine cycle and calculating plant calorimetrics of a nuclear power plant requires a significant number of equations to be solved. These equations, or auxiliary conditions, are the first order thermodynamic energy and mass balance equations. The numerous plant measurements and their uncertainties are inputs to the model. Due to the sheer complexity and mathematics involved, solving the system state using the DVR methodology requires the use of software. The Verification & Validation (V&V) of one of the commercially available DVR software will be discussed in this section.

V&V is a process to determine whether the development of a product for a given activity conform to the requirements of that activity and whether the software satisfies its intended use and user needs. This determination may include analysis, evaluation, review, inspection, assessment, and testing of software products and processes [9].

V&V of a DVR method is intended to ensure the correctness and suitability of the method. The overall V&V processes consist of two separate but interrelated processes. These are the verification process and the validation process. Verification is the process to determine that the software correctly represents the developer's conceptual description. It is used to decide whether the software was "built" correctly. Validation is the process to determine that the software is a suitable representation of the real world and is capable of reproducing phenomena of interest. The validation process seeks to determine if a certain product (and its methods) is appropriate. It is used to decide whether the software was "built" right.

4.1.2 Objectives

The purpose of this section is to provide an abridged demonstration of the V&V for a commercially available DVR software. The amount of technical rigor and documentation presented in this section is commensurate with the objective to demonstrate the verification of the DVR software. More specifically, the solution verification will be investigated. Of special interest is comparing the results of the DVR software to other data validation methods. The validation of the software will involve comparison of the results of DVR data to data that is a representation of the actual plant (i.e., heat balance/thermal kit or calibration data).

The verification process has two primary components: code verification and solution verification [11]. The code verification focusses on the verification of the numerical algorithms. This process involves documenting all the mathematical model equations and numerical models. Additionally, code verification typically implements support for Method of Manufactured Solutions (MMS) and constructs and regularly runs a suite of order-of-convergence tests using the MMS approach [11].

It is not the purpose of this section to perform verification activities on the code of the software (i.e., code verification). This specific verification activity is primarily the responsibility of the organization that develops the software. Knowledge of the inner workings and proprietary source code for any DVR software would typically not be revealed or available to the end user. Therefore, these activities will not be discussed further. The particular software used by a licensee should provide assurance of code verification by means of demonstrating compliance with a quality standard (i.e., ISO 9001 [63], IEEE Standard 1012 [9], etc.).

Additionally, this section is not intended to be a substitute for a nuclear operating unit's specific V&V procedures. Use of any DVR software at a nuclear operating unit would still be subject to the applicable design change procedures (if applicable) and use of software procedures.

4.1.3 Approach

Since the V&V presented in this section is an abridged V&V for demonstration, it will not strictly follow any V&V process, such as IEEE Std. 1012, IEEE Standard for Software Verification and Validation [9], or Regulatory Guide 1.168, Verification, Validation, Reviews, and Audits for Digital Computer Software Used in Safety Systems of Nuclear Power Plants [10]. The approach used in this section will focus on the solution verification and validation of the DVR results.

4.2 Simplified Verification Test Case

The first test case shown in this section covers a simplified thermal circuit of steam turbine plant. This simplified verification test case provides a comparison of the DVR results from a commercially DVR software to other published results. However, due to the simplified nature of this test case, it is not indicative of the complete DVR calculations at a nuclear power plant.

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4.4 Validation Using Heat Balance Diagram

4.4.1 Introduction

Validation is the process to determine that the software is a suitable representation of the real world and is capable of reproducing phenomena of interest. It is used to decide whether the software was "built" right. Validation is more than demonstrating that the algorithms used in the software are mathematically correct and free of errors.

Part of the model development process involves comparing the DVR model against a set of ideal data, typically from a vendor heat balance calculation and data gleaned from the vendor thermal kit. The purpose of this comparison is to verify that the DVR model auxiliary conditions calculations set up in the DVR model emulate the vendor calculation methods used for the reference heat balance diagram and thermal kit data for the plant's turbine cycle.

To check that the DVR model properly emulates the vendor calculations, a set of measured data is derived from a reference heat balance diagram and the DVR calculation is performed. Ideally, as the vendor data is "perfect" and contains no measurement errors, the DVR model calculations will exactly match the vendor heat balance data.

However, at times, differences may occur with the DVR model and vendor calculations due to the use of different steam table formulations, calculation numerical methods (convergence criteria and numerical precision), or other model or vendor assumptions. In these situations, engineering judgement is required and the base heat balance diagram data may need to be adjusted. For example, a vendor base heat balance may use older IFC67 [72] steam tables whereas the DVR model software uses IFC97 [73]. In this case, the DVR model calculated turbine efficiency values can be slightly different than the vendor data due to slight enthalpy value differences between IFC67 and IFC97.

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balance auxiliary conditions, the results are identical, with the exception of one variable. One mass flow variable using the Z-algorithm method had and absolute difference of 0.0005 kg/s and a percent difference of 0.1%, all other variables were identical and had a percent difference of 0.0%.

These results show that when comparing the calculated reconciled values and uncertainties from DVR software to other published results using alternative numerical methods, the DVR model produces comparable outputs. DVR models are not expected to be contingent on a single, specific numerical method to provide reasonable results. Therefore, the DVR model is robust in regard to different numerical methods.

10.8 Implementable Corrective Routines

There are fix-up or corrective routines that can be implemented in the DVR models or handled administratively to improve the reliability and robustness of DVR models.

Often, DVR software will have features which allow application of corrective filtering to the measured values that provide input to the DVR CTP calculation. These filters can be configured to allow the DVR calculation to proceed in case of a large measured value change from the default or typical measured values. For example, the actual plant and the DVR model may have a configuration of four condensate pumps for the condensate system. However, the plant may only use three of the four pumps at a time, and they may swap around which ones are running. For the DVR model, this creates a problem as the measured flow rates for the pump that is turned off may read close to zero, and the algorithm may fail for the input value. To manage this problem a cutoff filter is used in the DVR model to remove the pump from the calculation when it is off. The cutoff filter allows the DVR calculation to continue. In most cases the cutoff filters have little or no effect on the CTP uncertainty. However, potential effect on the DVR CTP calculation and uncertainty is assessed when performing reliability testing.

Additional filtering can also include setting lower, middle, and upper bounds for a specific measurement, and replacement options for the value of that measurement. Additionally, filters can be defined over a specific range. For example, if an instrument is known to perform more accurately over a specific range, the model can set a higher accuracy value for that range and assign a lower accuracy value outside the range. Filters can be particularly useful for measurements that are not significant contributors to the CTP; measurements that may fail or change values excessively from time to time. Filters on these measurements allow the DVR calculation to proceed. Thus, use of filters have the effect of making the DVR model more reliable. However, whenever filters are used, their potential impact on the calculated DVR CTP must be evaluated.

DVR fix-up methods are generally developed during the model development and back-testing. Back-testing is performed with the Functional Acceptance Testing (FAT) of the model. See Section 6 for additional details regarding model development, and Section 7 for details regarding the FAT. If upon implementation of the DVR model at the plant/site, conditions are encountered not observed during the FAT that cause the model to fail, corrective actions may need to be developed including the use of additional filters or other corrective methods for the model.
In this scenario, any changes to the model would be subject to the facilities software quality assurance program (SQAP) and any required configuration controls (i.e., modification process).

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5 BENCHMARKING AND OPERATING EXPERIENCE (OE)

5.1 Introduction

The purpose of this section is twofold to address 1) Data Validation and Reconciliation (DVR) benchmarks from the U.S. (studies) and other countries (actual applications), 2) Operating Experience (OE) issues related to core thermal power (CTP). Related to core thermal power operating experience, an extensive search was conducted of licensing and utility databases to extract information related to issues and concerns. A brief summary of each individual plant OE is provided in Section 5.2 to illustrate the different issues which have arisen with nuclear plant operations throughout the years related to core thermal power. The list is not all encompassing as it mostly focuses on plant core thermal power OE of the U.S. fleet. A summary of the OE for the nuclear fleet is discussed at the end of Section 5.2. The summary section identifies that there either have been or are recurring concerns related to core thermal power. This OE section provides information that can be used by utilities to potentially justify consideration of DVR applications to offset potential future concerns related to these type of OE issues. This OE section captures CTP issues that may be useful when considering use of DVR applications.

Section 5.3 contains benchmarking of DVR applications in the nuclear industry. The current DVR actual applications in the nuclear fleet for thermal power monitoring is largely based upon international experience. There have been U.S. plants that have used DVR as a corroborating method for CTP and they are discussed in Section 5.3. Studies have also been conducted for plants in the U.S. that have applied DVR techniques. Section 5.3 provides details as to how various nuclear plants have been or are successfully utilizing DVR (in studies or actual applications). Section 5.3 also provides information regarding two BWRs in the U.S. that are planning to implement DVR to monitor plant parameters and provide information to improve the quality of the core thermal power (CTP) measurement. Section 5.4 summarizes EPRI studies that have been conducted related to DVR for a fossil fueled and combined cycle plant applications.

5.2 Operating Experience (OE)

5.2.1 BWR 1

Venturi fouling (and de-fouling) became particularly evident after a refueling outage in 2000 when zinc injection was initiated. An Extended Power Uprate (EPU) was implemented in 2002 the following cycle, after which the unit was generator limited and allowed to operate up to approximately 97% MWth (megawatts thermal) power (indicated). Post-EPU operation data showed that the indicated power was approximately 1% higher than expected at the fixed generator output and operating conditions (i.e., back-pressure). This was confirmed in 2002 via temporary ultrasonic instruments to be due to feedwater venturi fouling.

A 10 CFR 50.59 analysis in 2002 allowed BWR 1 to implement a 1% correction factor to correct the indicated venturi measurements. The feedwater venturi started de-fouling (cleaning) itself after hydrogen injection was initiated in July 2002. By the summer of 2003, BWR 1 recognized the flow values were moving in a non-conservative direction and the 1% correction factor was removed in early 2004. The extent of venturi fouling has varied since 2004 and increased significantly during the summer of 2011.

Unit capability was changed to 97% reactor power limited after and outage in December 2009. The current capability loss is estimated to be approximately 50 MWth, or approximately16 MWe (megawatts electric) [15]. BWR 1 is currently implementing DVR to support power recovery efforts related to the venture fouling.

5.2.2 PWRs 1 and 2

In 1999, a fleet utility implemented installation of Crossflow ultrasonic flow meters at four different plants. The first plant it was installed at was a BWR station (BWR 2).

When the installation at BWR 2 was put into operation, the measured feedwater flow was very close to the previous tracer test results, the previous temporary demonstration installation of a strap-on Leading Edge Flow Meter (LEFM), and the predictions of a very tightly tuned PEPSE® software model. The original feedwater pump discharge nozzles had a history of overly conservative flow measurement due to the nozzle construction and installation. The next plant was a PWR station (PWR 1) and the Crossflow meter showed both units could get about 10 MWe more. When it was put into operation at another PWR (PWR 2), the indicated flow showed each unit could get another 20 MWe.

Note that PWRs 1 and 2 are identical plants. There is no significant difference between them. The PEPSE® models at both plants were predicting no shortfall of power due to overly conservative feedwater flow measurement. An investigation spanning over a 5-year period finally found that there was an ultrasonic wave generated by the feedwater regulating valves that influenced the Crossflow meter readings. Both plants had operated for a significant period using a non-conservative flow rate to calculate reactor power. The end result was that the Crossflow meters were removed from all three plants and they all operated on uncorrected nozzle/venturi flows until the LEFM meters were installed. Due to the problems discovered at PWRs 1 and 2, Crossflow was never installed at the remaining originally noted BWR above.

5.2.3 PWR 3

A PWR 3, unit average power level was calculated to have been 100.1% power for greater than 8 hours Content Deleted-EPRI Proprietary Information This power level resulted from an instrumentation failure on the LEFM which was utilized by the DDPS (Digital Data Processing System) Plant Computer Calorimetric power level indication. A failure in the DP1 transducer path on the 'A' Loop of the LEFM instrument resulted in a decreasing feedwater (FW) flow output value. This resulted in a non-conservative feedwater flow rate being used in the reactor power calculation and the plant operated for more than 8 hours at 100.1% licensed power. Operations reduced power immediately upon discovery. The LEFM was repaired and put back in service.

5.2.4 PWR 4

In the summer of 2003, a PWR 4 station process computer indicated a "Power Limit Warning" alarm. The LEFM power indication showed an increase from 2337 MWth to a peak of 2346.73 MWth. Redundant power indications did not show an actual power increase, however, Operations conservatively adjusted power down approximately 5 MW net while an LEFM investigation was performed.

Investigations into the incident indicated that the Acoustic Processing Unit (APU) had failed. The card was replaced and the faulty unit was sent to the vendor for study. Analysis indicated that the card was functioning properly, but there was an error on one line of the code that operated it. A software patch was implemented to correct the error, which was determined to be the cause of the non-conservative flow reading.

5.2.5 PWR 5

On July [redacted] 2001, the commissioning test for the newly installed LEFM revealed that PWR 5 had been running at approximately 101.5% power using the venturis. Further investigation showed that the LEFM was operating properly and no root cause could be found on why the venturis were reading high. Power was reduced by 2% to stay within the safety analysis margins and the venturis were recalibrated to agree with the LEFM, which was accepted as the feedwater flow reading. The operators were able to go up 0.5% in reactor power after this was done.

Another incident in September 2002 happened when the LEFM indicated again that reactor power was too high. The delta-T values and impulse pressure values indicated that the plant was not at full power. No dilutions had been performed for approximately 30 hrs. Also, the difference between the MWth values using the LEFM vs. the flow venturis was greater than the historical value of 37 MWth. The difference was approximately 65 MWth. An investigation by the LEFM vendor revealed that a recent software upgrade had errors in it that caused the failure.

Another LEFM failure was experienced on the Unit 2 LEFM on the summer of 2013. The Unit 2 Control Room received an annunciator alarm for LEFM Trouble. The LEFM was found to be ‘Failed’ and was declared Non-Functional. Consequences: The LEFM was not restored to Functional status prior to the next required daily calorimetric heat balance measurement per Surveillance Requirement 3.3.1.2, and steady-state Thermal Power had to be reduced to less than or equal to 98.6% per LRM 3.3.8 until the LEFM was restored to functional status. Investigation by Engineering identified that the ‘A’ Bus power supply was not working. The Fix-it-Now (FIN) team replaced the failed +5/+12/-12 VDC power supply eleven days after the failure was experienced.

The root cause was determined to be a defective circuit (LEFM ‘A’ Bus +5/+12/-12 VDC power supply failure) in the Unit 2 LEFM. The Unit 1 LEFM was different in that it had redundant power supplies and was not vulnerable to this failure.

5.2.6 PWR 6

In August 2002, PWR 6 received Feedwater Ultrasonic Flow Measurement System (UFM) related alarms. The indicated UFM flow dropped to zero on both steam generators. Operations commenced lowering turbine load and reactor power to maintain secondary calorimetric power to less than 100%. Power indication was reduced to 99.8% via feedwater venturi indication.

Operations attempted to locally reset the LEFM which would not reset. A turbine building air washer pump on the local air handler was out of service and the local air temperature was measured at approximately 110 degrees F. The UFM ambient cabinet temperature was 124 degrees F and 129 degrees F at the power supply. The design specification for the LEFM is 100 degrees F maximum.

Representatives from the vendor replaced two computer boards, and adjusted the coarse gains and peak detect signals. The vendor verified that the LEFM was performing within its ± 1.0% uncertainty value. Also, temporary AC cooling was provided to the LEFM cabinet. Four days after receipt of the UFM alarms, the LEFM was placed back into service and reactor power was returned to normal. The unit down power resulted in an estimated generation loss of approximately 2600 MWhr, which contributed an approximate 0.26% Unplanned Capability Loss Factor (UPCLF) for the month of August.

This failure was related to the high ambient temperature in the area the LEFM cabinet was installed in. Temporary air conditioning was put in place at all three units.

5.2.7 BWR 4

The presence of a "Low Virtual Memory" alarm on the LEFM panel screen could be a precursor to the system going offline. Rebooting the system may be a compensatory action which prevents the system from stopping. Content Deleted-EPRI Proprietary Informatio BWR 4 upgraded the LEFM Check Plus™ Content Deleted-EPRI Pro a "Low Virtual Memory" alarm was generated on the front panel screen causing the LEFM Check Plus™ System to be lost.

The vendor was contacted and advised BWR 4 personnel to acknowledge the alarm and allow the system to continue to operate. The vendor initiated an internal deficiency document and started to review the operating system and software for potential problems. Approximately two weeks later, the system unexpectedly went off-line for approximately three minutes. When the system returned itself to service all parameters appeared to be normal. The LEFM vendor was notified of this occurrence and another deficiency document was generated and research efforts were increased. At that time, it was not certain if the problem resided within the software or the mainframe of the LEFM.

Later, the vendor was able to duplicate the problem as two more plants reported the same problem and was able to make changes to prevent it from re-occurring.

5.2.8 BWR 5

In late December Content Delet, with Unit 2 at 100% power and producing greater than expected electrical output, operability of the LEFM system could not be confirmed and thus, per Technical Requirements Manual (TRM) 3.20, reactor power was lowered from 3514 MWth to 3458 MWth. Based on the review of several heat cycle parameters, the magnitude of the change was determined to be approximately 0.15 percent, which was within the uncertainty of the LEFM system.

However, because the change could not be explained, it was conservatively decided to lower power to 3458 MWth (the pre-uprate power level) and declare the LEFM system inoperable. The cause was determined to be low-impedance grounds have affected the accuracy of the LEFM feedwater flow measurement. While the leak repairs performed fixed the majority of the external leaks, the continuing problems are also most likely due to the effects of moisture intrusion/leaks. It is believed that the moisture is from leaks of the type recently experienced by PWR 4 (inside the transducer housing).

A later load drop in February Content Deleted to repair the leaks was extended by 12 hours when repairs to the leaks caused several transducers to fail. Additional OE (OPEX) regarding BWR 5 was noted from Content Deleted 2020 and is described next. The engineering group determined that underlying assumptions in the vendor analysis for the current U2 Core Thermal Power Uncertainty Analysis were not accounted for when considering the impact of a Leading Edge Flow Meter (LEFM) in maintenance mode coming out of a refueling outage. The vendor had communicated to the site the effects that large downpower events (load drops and refuel outages) can have on the LEFM process data that feeds into an assumption that determines the accuracy of an LEFM in Maintenance Mode.

Specifically, when in Maintenance Mode, the Uncertainty Analysis assumes that the Plane Balance Variability of an LEFM is capped at 0.35% and is calculated using LEFM process data from when the LEFM was last reading in Normal Mode. As a result, the uncertainty assumed with one meter in Maintenance Mode is dependent on if a successful self-check between its two planes had been performed in Normal Mode. Further required evaluations were necessary to identify power operations with the condition noted above. BWR 5 identified that Unit 2 never operated greater than 4014.34 MWth as an average for any shift. These values were backed up by the official operator logs signed off by the Operators every shift.

5.2.9 BWR 6

In May Content Delete, it was discovered that the Caldon model 8300 strap-on LEFM in use at the station was giving a non-conservative feedwater flow that caused the plant to operate at 102.7% power for over 15 months. According to the manufacturer, the analyses of the LEFM data, as well as data from the feedwater flow venturis and the feedwater RTDs, have established that there were three contributing causes of the LEFM's errors:

1. There were non-conservative assumptions made regarding calibration of the instrument.
2. Changes that occurred when feedwater flow was significantly increased due to a 5 percent power uprate produced non-conservative feedwater flow indication error.
3. A measurement error during installation resulted in non-conservative error in the indicated flow reading. Therefore, when the external LEFM 8300 data was used to correct feed flow for CTP calculations, the LEFM 8300 was not providing data within its specified accuracy.

The LEFM was removed at a later outage and a new program to calculate a best estimate for reactor power was developed.

Another LEFM incident at this station occurred in June Content Delet. The Main Control Room Thermal Heat Balance Computer, ONE, indicated LEFM failure. After reviewing the condition, it was determined that 'A' CPU was locked up on the DOS boot screen. I&C Maintenance and System Engineering contacted the vendor who recommended restarting the CPU.

Based on this information, the 'A' CPU was rebooted and the LEFM returned to service. While at the LEFM cabinet, it was observed that its air conditioning unit was not running. Due to the fact that no temperature measurements could be taken to determine if the AC unit should be running, a work request was generated to investigate the functionality of the AC unit. The completion of a work request found the AC unit functional and the thermostat set at the correct temperature, 82 degrees F. The condition has been corrected and not observed since the CPU was restarted.

5.2.10 PWR 7

Reactor thermal output was observed shifting from the LEFM measurement system to the feedwater venturi. Operators responded conservatively by reducing power by approximately 2% to account for potential uncertainties with the feedwater venturis. The cause for the equipment shift was due to a faulty hard drive card that was replaced.

In November Content Delet operators observed the reactor thermal output (RTO) shifting from the LEFM system over to the feedwater venturis. Operators conservatively reduced Unit 2 load (by approximately 2% power) to account for potential uncertainties of the feedwater venturis. Unit 1 LEFM was functioning correctly during this time. The flow measurement system is designed to measure feedwater flow much more accurately than the feedwater venturis, and is preferred over the venturis. Troubleshooting commenced and identified the cause of the equipment shifting was due to a faulty hard drive card. The card was replaced via a work order and post-maintenance testing was successfully performed.

5.2.11 BWR 7

Content Deleted-EPRI Proprietary Information BWR 7 Unit 1 LEFM system entered MAINTENANCE mode due to a hydraulic asymmetry alarm. In accordance with the TRM, the CTP calorimetric was swapped to the original venturi system resulting in a reduction in plant power of approximately 6 MWth due to differences between the two system's measured flows.

Investigation of the alarm condition at the LEFM panel showed the 'B' LEFM spool in MAINTENANCE mode due to a "Hydraulic Asymmetry" alarm with all other indications as expected. Both planes of the 'B' LEFM spool continued to calculate and output mass flow and the other two spools remained in NORMAL mode.

When this issue occurred, the Unit was near end of cycle with the 6th stage feedwater heaters out of service. Planar balance, the parameter measured for the hydraulic asymmetry alarm, compares the current difference between each measurement plane's velocities to those set during system commissioning. Since the spool flow output from the system is an average of the two planes, this parameter is used to adjust flow indication when only one plane is available. Note that the parameter has an adjustable "wind-up" time described in LEFM documentation.

There were no corrective actions as the cause was determined to be changes in the flow profile based upon the taking the #6 FW Heaters out of service.

5.2.12 BWR 8

In June 2002 a detailed analysis of an event in May 2002 determined that the ultrasonic flow detection equipment used to detect feedwater flow was malfunctioning because of calcium silicate insulation lodged between the clamp and pipe. The malfunction of the cross-correlation instrumentation correction factor resulted in the reactor exceeding its licensed power level by an average of 0.25% for eight hours.

Immediate corrective actions included removing the cross-correlation instrument from service and reducing power below the 1.4% uprate value. Additional corrective actions included the installation of new cross-correlation transducers and validation of the existing cross-correlation performance. The mounting configuration was also changed.

5.2.13 BWR 9

Content Deleted-EPRI Proprietary Inf BWR 9 brought the plant down to inspect the flow conditioner in the feedwater line A and found foreign material lodged in front of the flow conditioner. The plant restarted after this short outage and the hydraulic metrics returned to their original "as commissioned" values. An anomalous response of the LEFM was observed at BWR 9 station during the startup following the plant outage Content Deleted-EPRI Proprietary Informatio.

While increasing power, the operator observed that the electrical output was greater than expected for the thermal power indicated by the plant monitoring instruments. The operator interrupted the power ascension until the cause of the anomalous power conversion efficiency could be determined.

The root cause was determined to be debris caught in the flow conditioner in feedwater line A. Tubular flow conditioners form jets which affect the velocity profile at distances of at least 8 diameters downstream. The debris removed from the flow apparently affected the pattern of these jets, thereby altering the axial velocity profile seen by the Loop A LEFM. The altered profile apparently introduced bias in the Loop A LEFM calibration.

While this was not a failure of the LEFM itself, it highlights the ease with which any change in hydraulic parameters can change the flow profile the LEFM depends upon for calculation of flow rate. This also affected the flow measurement by the installed nozzles. Of particular note with this example is the failure of the UFM to self-identify the problem as it was the observation of higher than expected electrical generation which prompted the investigation [79].

5.2.14 PWR 8

PWR 8 determined that a potentially larger uncertainty existed in the feedwater flow measurement system than that assumed during initial system analysis and calibration. The feedwater flow measurement system installed in 2003 improved the accuracy of feedwater flow measurement allowing the power calorimetric uncertainty to be reduced from 2.0% to 0.6%. System data was collected and analyzed to provide a better understanding of the actual system performance and to confirm system measurement uncertainty. Based on this data, the vendor Content Deleted-EPRI Proprietary Information) could not support the originally assumed calorimetric error. If a larger than analyzed system measurement uncertainty is determined to have existed, the Technical Specification rated thermal power level could have been exceeded. However, they assessed that there was reasonable assurance that PWR 8 had not exceeded its rated thermal power limit.

Short term corrective action was taken to conservatively limit calculated steady-state reactor power to no more than 99.69% (1766.5 MWth). The limit remained in effect pending completion of the long-term corrective action.

Long-term corrective action was to perform a full system recalibration during the next refueling outage.

5.2.15 PWR 9

License Event Report (LER) was submitted in 2015, due to an overpower event that occurred in PWR 9. It was discovered that the ultrasonic flow Feedwater correction factors had been trending in a non-conservative direction since installation resulting in an overpower of approximately 1.8% (max) for the period of 2.5 years. Pipe wall thickness measurements were then taken in the Unit 1 Feedwater piping in the vicinity of the Ultrasonic Flow Measurement System (UFM), and it was determined that pipe wall thicknesses were less than the original values resulting in increased flow diameters. The overpower condition in Unit 1 resulted in reactor trip instrumentation being inoperable longer than allowed by Technical Specifications (TS), thus reportable under 50.73(a)(2)(i)(B) Condition prohibited by TS. The Root Cause for this event is that the PWR 9 License Amendment Request implementation process did not require a formal, documented review of plant specific requirements and recommendations from vendor supplied documents that are used as a basis for a license amendment. The corrective action to prevent recurrence of this event was to develop or revise a Licensing procedure accordingly to require a formalized, documented review.

5.2.16 PWR 10

When PWR 10 returned to 100% power after the Fall 2017 outage it was observed that plant generation was lower than expected by approximately 4–5 MWe. PWR 10 performed preliminary analysis to identify the cause of the shortfall in plant generation. The two most significant parameters that changed were plant generation and first stage pressure. The actual cause of the lost generation could not be determined by conventional data analysis due to the relatively small changes in plant parameters pre to post outage coupled with variables that could have possibly been introduced by maintenance performed during the Fall 2017 outage. As such, an evaluation of the plant was performed using DVR. The DVR evaluation identified the probable cause to be an error in feedwater flow measurement resulting in a conservative calculation of CTP. The DVR evaluation used several turbine cycle instruments for input. The DVR model flags instruments that are found to deviate significantly from the reconciled value for that parameter. In one case, hot re-heat temperature to a combined intercept valve was flagged by the DVR model, which claimed the instrument was reading approximately 2.3 degF (-16.5 degC) low. Maintenance I&C personnel then checked the instrument in May 2019 using calibrated test equipment and found the computer point indication reading 3-4 degF (-16.1–15.56 degC) lower than expected, supporting the information provided by DVR. The data information from the calibration was verified in July 2019.

5.2.17 Utility Fleet Development

Fleet Development of DVR models is currently in progress for several U.S. utilities. For a large fleet, the development of plant DVR models for the purpose of thermal performance is nearing completion. The next stage of DVR utilization at the utility is to implement additional enhancements to the models to allow utilization as a power recovery tool. The plant CTP calculations will be enhanced through the use of reconciled DVR models to result in a more accurate indicated CTP. A resulting correction factor will then be applied to the plant feedwater flow. BWR 1 is currently proceeding with the design change process to implement the DVR model as a tool for power recovery. As discussed in Section 5.2.1 BWR 1, venturi fouling results in impacts to plant generation.

Through this process additional considerations should be noted, such as the inclusion of common plant off normal operating conditions and plant downpower conditions. Examples of scenarios where the DVR model could be utilized are turbine control valve testing, rod adjustments, leaking SRV (Safety/Relief Valve), Shape Annealing Factor testing, Primary Resin Beds put into service, Turbine runback, Rotating Feedwater pumps, loss of heater drain components, condensate issues, loss of feedwater heating, or the removal of feedwater heaters at the end of cycle conditions. The off normal and downpower conditions at BWR 1 are currently being assessed with past plant data to assess how the DVR model responds to those types of changes. It should be noted that the DVR models are tuned generically to full power operating conditions and limitations to what power levels the DVR model is credible for should be considered. When operating outside of set bounding parameters the plant will need to return to a pre-established correction factor.

Through the use of the fleet DVR models for thermal performance monitoring some common data issues were seen throughout the fleet. Care should be given to review flagged tags in the models to identify plant instrumentation issues and apply uncertainties accordingly. The model runs should ensure that DVR model quality and CTP uncertainty remain within established parameters. To meet VDI Criteria the DVR model Quality shall be less than 1.0. Plant tags that contribute greater than 0.5% to the model's total CTP uncertainty are reviewed during the model development and if any are flagged by the model the feedwater flow correction factor is not valid. The vendors and utilities must work closely together during the model development phase.

5.2.18 Core Thermal Power Operating Experience Summary

A conclusion of this operating experience is that there has been and continues to be a problem in the industry with generation losses due to instrumentation failures in flow measurement equipment, especially the ultrasonic flow meters.

The usual mode of generation losses is from powering down to the original ±2% uncertainty pre Measurement Uncertainty Recapture (MUR) reactor power to ensure the reactivity control margins are maintained until the problematic instrumentation is repaired/replaced. LEFM transducer problems seem to have tapered off, but card failures within the LEFM, deviations from normal operating modes, and bugs in updated software can still catch operating plants off guard.

It also makes the point that a lack of design basis understanding for single point vulnerabilities from power supplies, unit cards to temperature environments, etc., exists within the industry. It also appears that with aging, temperature and environmental conditions, the current systems will continue to be a single point vulnerability if the LEFM cards are not in a preventive maintenance program.

The increasing number of incidents involving ultrasonic flow meters prompted INPO to commission a Topical Report TR4-34, "Review of Feedwater System Ultrasonic Flowmeter Problems", which was published in March 2004 [37]. The report concluded that:

1. There is an increased trend over the past four years in the number of events involving ultrasonic flow meters used to calculate reactor power. This trend is a concern because many of the events resulted in reduced margins to safety. This indicates that users of this technology need to carefully monitor instrument output and closely oversee the installation of new systems.
   - Reactor power indication was directly affected in 10 of the 14 reported events over this period. Reactor power limits (100 percent) were exceeded during seven events with one station operating slightly in excess of its 102 percent analyzed limit for approximately 15 months. For example, a hypothetical 1000 MWe nuclear plant operating on a 1.7% MUR would have to de-rate 17 MWe to go back to the original 2% uncertainty. In a 24-hour period, this would be 408 MW-hrs, costing the plant about $18,400 at $45 MW-hr. If the de-rate lasted several days, this would amount to a serious revenue loss to the utility.
   - Both flow meter types experienced problems during the analyzed period. Four events involved the use of the cross-correlation flow meter during which reactor power limits were exceeded. One of these stations operated above 100 percent reactor power for more than three years. Transit time flow meters LEFMs were involved in the remaining ten events. Three of these events reported operation above 100 percent reactor power.
   - Nine of the 14 reported events involved human error. Seven of the nine involved some type of error, oversight or lack of knowledge on the part of the vendor.
2. Based on these events, there may also be an over-reliance on vendor expertise. More detailed review and questioning by station personnel pertaining to the basis for software programming and post modification testing, as well as acceptance of post installation test results, could have prevented some of these adverse events.

5.3 Benchmarking Specific DVR Operating Experience

DVR software has been used by the nuclear power industry in the U.S. and Europe since 1999 [76] to assess turbine cycle thermal performance, balance of plant feedwater flow metering and accuracy of the plant calorimetric, or measure of the plant's licensed reactor power. DVR technology has been used by Kernkraftwerk at a plant for power recovery from feed nozzle fouling. The DVR technology used at a Kernkraftwerk plant allows compliance with VDI-2048 [1].

At another Kernkraftwerk plant in Germany, the DVR technology has been used to correct the venturi feedwater flow metering for measurement errors [74]. The method has been approved by the local regulators. The MUR process has also been initiated at the Kernkraftwerk plants noted above with approval of TÜV Süd (independent certifying body) and the Bavarian Environmental Ministry (Regulator).

At a nuclear power plant in Switzerland, DVR technologies have been used since 2004 and have replaced use of radioactive sodium tracer testing as a means of feedwater flow metering calibration [75].

Two PWRs in Brazil utilize DVR to form an integrated approach for the following:

- Automatic and online access to the heat & mass balances of the primary and secondary cycles.
- Reliable and most accurate parameters for the reactor thermal power computation.
- A tool for tracking "lost" Megawatts and plant inefficiencies, improving thermal power management and detecting instrumentation failures.
- DVR is directly used as one of the inputs for adjustment of the electrical power setpoint. Operations uses the DVR model's calculation of reactor power to drive the plant.
- It is also used as a reference to calibrate the External Neutron Flux Power Detector.
- The DVR program was presented to the Brazilian Nuclear Authority before implementing the reactor power correction who approved it with no caveats.

DVR technologies have also been used to assess the balance of plant thermal performance, perform turbine acceptance testing, and detect errors with plant instrumentation in Switzerland, Sweden, and Germany.

In the United States, DVR technology has been used at several sites with Operating Event issues (see examples earlier in this section) due to suspected errors with the ultrasonic feedwater flow metering used with the plant licensed calorimetric. The plant calorimetric is a measure of reactor power and is also known as the CTP calculation.

Power plants that have used DVR to resolve issues with the plant licensed calorimetric include PWR 8, PWR 9 units, and PWR 11 units. It should be noted, however, that in the U.S., DVR as a method to assess the accuracy of the plant feedwater metering and calorimetric has largely been a corroborating method.

In the U.S., DVR software has also been used to assess the balance of plant thermal performance, perform turbine acceptance testing, and detect errors with plant instrumentation at the PWR 8, PWR 9 units, PWR 11 units, and PWR 12. DVR studies have been recently conducted additionally for PWR 6 and PWR 10 related to utilization of DVR. The PWR 6 and PWR 10 benchmark studies will be discussed next. Following this discussion U.S. applications regarding DVR that are in process will be discussed.

PWR 6

DVR models were developed for all three units at PWR 6 during January to March 2017 with the intention of determining the reason for the difference in gross generation in Unit 2. The models were developed to be identical so that any deviations between the units could be easily identified. Determination of absolute values by a model tuning process which involves calibration and or repair of suspected plant instrumentation was beyond the scope of the study. The models were developed only to the extent necessary for efficient unit comparison, but were not tuned for use in plant operation or decision making. This evaluation did not consider the effects of Cooling Tower Efficiency which was discussed in a previous assessment report.

During the review of the reconciled results from the finished models, several parameters were identified as contributing to the higher electrical generation in Unit 2 including CTP, Condenser Efficiency, and Turbine efficiencies. Review of the extent of reconciliation applied by the model to the CTP values for each unit, shows that Unit 1 and Unit 3 were indicating much more closely to their actual power conditions, while the Unit 2 Core Power received a larger magnitude of correction from the DVR model. Of particular interest in the DVR evaluation was the turbine performance. It was noted that the turbine efficiencies were highest in Unit 2 on all High Pressure and Low Pressure Turbine (LPT) groups, with the exception of the last stage in LPT B. The improved turbine efficiency in Unit 2 was estimated to increase the electrical generation by approximately 2–4 MWe when compared to the other units. By collecting all independent variables and combining the generation effects, an evaluation of the sum of their influences on Gross Generation was performed. This process reduced the delta between Unit 2 and Unit 1 from 4.5 MWe to 2.7 MWe, and reduced the delta between Unit 2 and Unit 3 from 7.5 MWe to 2.0 MWe in the DVR model. The remaining adjustments could be found in various locations in the plant including component degradation or unidentified cycle isolation loses. Lists of suspect measurements in this DVR model were also provided to be used as a starting point for analysis of other plant areas. Some of the suspect measurements common to the units identified were; condenser pressure, feedwater pump turbine steam flow, main steam temperature, moisture separator temperature, HP turbine exhaust pressure, heater drain pump power.

The reconciled values produced by the study conducted for PWR 6 explained why the Unit 2 Gross Generation was consistently higher than that of the other units. Some of the key parameters in the DVR evaluation were CTP, Condenser performance, and Turbine performance. More detailed model tuning was identified that could provide a better understanding of absolute core thermal power. Future DVR modeling was recommended that would require the evaluation of various plant parameter measurements and possible calibration/repair of some of the instruments identified in the study as questionable. Because the data reconciliation process has identified the largest difference between the plant calculated CTP and DVR reconciled CTP on Unit 2, it was identified that the elevated flow rates in Unit 2 would be a good starting point for further evaluation. Table 5-1 below shows a summary comparison of the PWR 6 units DVR model assessment by description of overall impact related to power generation for the reported time evaluated.

Table 5-1
Summary of cycle effects

Description		Unit 1	Unit 2	Unit 3
Gross Generation	**MWe**	**1407.7**	**1412.2**	**1404.7**
Core Thermal Power	MWe	1.0	0.0	4.1
Steam Generator Blowdown	MWe	0.0	0.0	-0.1
Condenser Pressure	MWe	1.2	0.0	0.8
Auxiliary Steam Flow	MWe	-1.4	0.0	-1.4
Feedwater Heater #7 TTD	MWe	0.2	0.0	-0.5
Feedwater Heater #6 TTD	MWe	-0.1	0.0	0.2
Feed Pump Suction Temp	MWe	-0.1	0.0	-0.2
Miscellaneous (Cycle Isolation)	MWe	0.5	0.0	1.0
Turbine Efficiencies	MWe	5.9	0.0	5.8
Adjusted Gross Generation	**MWe**	**1414.9**	**1412.2**	**1414.2**

PWR 10

A December 2018 report [16] documented an evaluation of the PWR 10 thermal performance which indicated two areas of possible reduced generation: feedwater flow measurement error or degraded turbine efficiency. A DVR model was developed for the PWR 10 with the intention of determining the reason for reduced MWe output following the fall 2017 outage. The model was developed using the plant thermal kit and tuned to pre-outage data. The model conditions were kept unchanged with the introduction of post outage data so that any deviations in the post outage condition could be more easily identified. The model was developed only to the extent necessary for efficient pre/post outage comparison and was not tuned for online monitoring or use in plant operation.

During the review of the reconciled results from the finished model, a lower than measured feedwater flow was identified as the main contributor to the lower electrical generation in the post outage condition. This indicates that the most likely cause of the change from pre to post outage plant generation is due to a change in the feedwater flow measurement accuracy. Based on the model results differential flow was approximately 0.36% over the time periods evaluated which would result in an average reduced generation of approximately 4.8 MWe. Part of this loss is due to the error in the flow measurement as well as the effect on the actual flow due to the consequences of lower first stage pressure effect on Final Feed temperature. The overall effect is an error in CTP as shown in Table 5-2, below.

Table 5-2
PWR 10 core thermal power evaluation

Date	REU1118 (Measured)	DVR (Reconciled)	Percent Difference	Overall Generation Effect
	MWth	MWth		MWe
1/18/2018	3563.53	3549.33	-0.40%	-5.2
2/14/2018	3562.96	3550.29	-0.36%	-4.7
4/11/2018	3562.59	3549.46	-0.37%	-4.8

In addition to the overall analysis to determine the cause of the generation loss the model identified various plant instruments that may need attention. A list of those instruments was established in the DVR study. A total of 148 process measurements were included in the PWR 10 DVR model.

The DVR model successfully ran all the pre-outage data sets that it was given. There were no major flagged tags or issues identified in the pre-outage data sets and the quality of the DVR solutions easily met the statistical criteria of being acceptable. With the post-outage data sets the model was able to run successfully and the quality of the DVR solutions still met the statistical criteria. The DVR process took these post outage data sets and had to determine what the most likely solution was that could fit the lower power output with the rest of the plant data and the model. Despite having a relatively small assumed uncertainty of ±1%, there was a consistent correction applied to the measured SG feedwater flows. Thus, the conclusion of the DVR evaluation was that a lower flow was the most likely cause of the lower power output.

The reconciled values of the feedwater flow indicate a larger correction was applied to all of the post outage data. The reconciled post outage total FW flows were approximately 0.24% lower than the values measured by the plant instruments. This would imply that the conditions around the feedwater flow nozzles could have changed following the fall 2017 outage. The overall effect of this error was potentially that a lower actual CTP than the indicated CTP.

Recommendations from the DVR study indicated that PWR 10 could remove the flow nozzle and recalibrate it at a suitable calibration facility. Other recommendations of the DVR study indicated that flow nozzle inspection and cleaning could be performed, provision of correction factors for steam flow discharge could be generated via DVR. Additionally, correction factors for feedwater flow nozzle could be determined using DVR, and finally a list of instruments that were identified as suspect could be calibrated and/or repaired. An example of the list of instruments included Feedwater heater shell pressure measurements, circulating water supply temperature, and steam generator feedwater pump suction flow for the days of measurements included [16].

It should be noted that this model did not undergo a full data driven tuning process to evaluate the efficiency of the last LP turbine stage. This is typically done for a DVR model that will run online and continuously reconcile data. However, the effort involved with this type of tuning was beyond the scope of the study and instead a simpler approach based on the thermal kit and PEPSE® model was used. The end result is that the DVR model was less accurate when the condenser pressures deviate too far from the thermal kit conditions (as is the case in the summer months).

U.S. DVR Applications Currently in Process

BWR 7 and BWR 5 units are in the process as of fall 2019 of installing DVR software to monitor plant parameters and provide information to improve the quality of the CTP measurement. Functional Acceptance Test (FAT) guidance was developed by the vendor for each unit to implement the DVR software. The Functional Design Specifications (FDS) for each unit was also performed in the fall of 2019 and is briefly discussed below along with the initial FAT for each unit evaluated.

The results of the Functional Acceptance Test on the DVR model indicate that the uncertainty of the reconciled CTP for the BWR 5 U2 DVR model did not exceed 0.40% for successful model runs with Quality<1.00. Going forward, the CTP uncertainty stated in the FDS will continue to have some fluctuation based on input data but is not expected to regularly exceed a value of 0.40%.

The results of the FAT on the DVR model indicate that the uncertainty of the reconciled CTP for the BWR 7 U1 DVR model did not exceed 0.43% for successful model runs with Quality<1.00. Going forward the CTP uncertainty stated in the FDS will continue to have some fluctuation based on input data but is not expected to regularly exceed a value of 0.43%.

Detailed models for both BWR 7 and BWR 5 have been developed and are formalized for implementation related to monitoring plant parameters. The graphs below show a comparison of DVR technology to current applications for each unit. The first graph, Figure 5-1, for BWR 7 compares a traditional feedwater flow based high accuracy heat balance CTP calculation with the value calculated by the BWR 7 U1 DVR model.

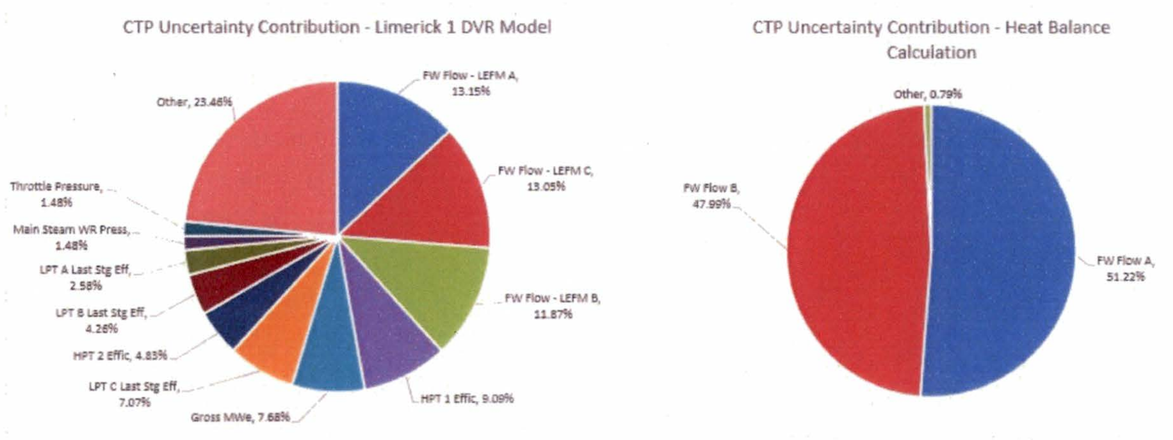

Figure 5-1
BWR 7 DVR CTP uncertainty contributions

The second graph, Figure 5-2, for BWR 5 unit 2 compares a traditional feedwater flow based high accuracy heat balance CTP calculation with the value calculated by the BWR 5 unit 2 DVR model.

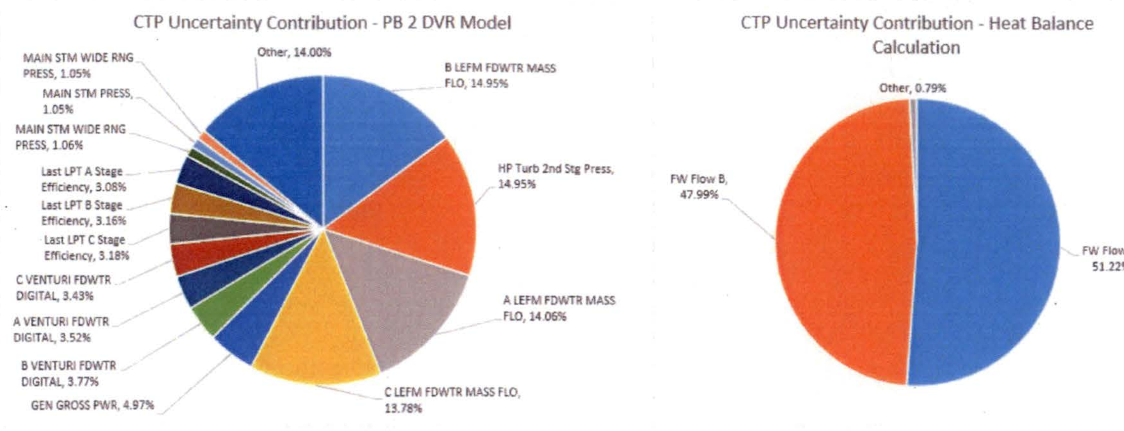

Figure 5-2
BWR 5 Unit 2 DVR CTP uncertainty contributions

5.3.1 Plants Currently Using DVR

Several plants worldwide are currently using DVR to monitor plant performance.

Brazil

PWR 13

PWR 13 is a Siemens 4 loop PWR operating at 3765 MWth. It is used to keep energy and mass balance under control and increase accuracy and reliability of the plant process data, with the objective of improving thermal power management and detecting instrumentation failures. Operations uses the DVR model's calculation of reactor power to drive the plant. It is also used as a reference to calibrate the External Neutron Flux Power Detector. The results are presented in the DVR Report and is analyzed by the Performance Engineers in the plant. A summary is presented in a management daily meeting. Other analysis is made along the fuel cycle. The daily follow-up helps the staff to keep up to date with the plant health and take actions to plan, correct or improve processes.

Before implementation, the plan was presented to the Brazilian regulator (CNEN), who approved it with no caveats.

Czech Republic

PWR 14

PWR 14 is a PWR VVER 440 design (4 units). DVR is used at PWR 14 for measurement validation, for thermal cycle optimization, for evaluation of unmeasured quantities, and provides parameters for the calculation of reactor thermal power. It is also used as an equipment diagnostic tool. It is not used directly as a power correction factor or a correction factor applied to feedwater flow and temperature. DVR is used at PWR 14 as a comparison to standard methods. The performance engineers and main control room staff use the information regarding potential "lost MW". When applying DVR to the station it was noted that some missing sensors (measured values) had to be substituted with fixed values (constants). Also, approximate relationships between quantities had to be used (e.g. related to the condenser, equality of heat flows to cooling water lines). No regulatory issues were identified when implementing DVR at PWR 14 upon review of the regulator. The benefits realized by PWR 14 was the capability to increase electrical output from 1-2 MW per 1000 MW twin units.

PWR 15

The PWR 15 plants are a PWR VVER 1000 type of design (2 units). DVR is implemented at this facility to perform turbine island measurements and validation. It is also used for turbine island equipment diagnostics. The DVR process is not used to adjust CTP by a power correction factor or a correction factor applied to feedwater flow or temperature. The performance engineers use DVR as a diagnostic tool at the station. The regulator was responsible for the plant modification review prior to implementation.

Belgium

PWR 16

PWR 16 is a PWR 1054 MW plant in Belgium that uses DVR methodology. PWR 16 uses DVR as a validation of raw measurements for primary, secondary and tertiary cycle systems. DVR is used at PWR 16 for improving knowledge about the thermal balance based on reconciling values (clear and reliable views of the complete heat cycle). DVR is also used to look for malfunctions. DVR is not used as the official means to adjust CTP. It is used for maintenance on sensors or if needed by the performance department. The DVR validation is run every 15 minutes. A daily check is performed to look for deviation behaviors. PWR 16 also looks at biggest penalty components as a follow-up. No issues have been identified with use of DVR at PWR 16. As mentioned, DVR is used for performance monitoring only and as such was not subject to regulating authorities in Belgium.

Spain

BWR 9

As previously noted in Section 5.2 anomalies had been noted in feedwater flow measurements. In order to understand those anomalies and look at thermal performance DVR technology was applied. The DVR application took operational data from 2012 and showed good consistency between LEFM measurements and other operational data. It was identified that the DVR system could be used for BWR 9 as an online monitoring tool for their entire process, and for CTP. The DVR application for BWR 9 showed that it could detect erroneous measurements, inner leakages, and changes in component behavior (e.g. potentially condenser fouling). Assessments were conducted on the impact of loss of LEFM and it was noted that in the case of BWR 9 they would not necessarily need to reduce power in the case of a Level 2 alarm. The BWR 9 assessment indicated that they would not need to go to a complete non LEFM power level, and that they could be 2.15% above the non LEFM power level. Therefore, a higher CTP level could be justified if there was a loss of LEFM with application of DVR (reconciled uncertainty was +/-0.75%).

Switzerland

BWR 10

Content Deleted-EPRI Proprietary Inform utilized DVR for various applications related to performance testing and plant monitoring. BWR 10 used DVR in at least three applications: 1) performance testing for LP Turbine retrofit acceptance testing, 2) performance testing cooling tower optimization, and 3) plant monitoring. BWR 10 successfully used DVR applications for the design of new LP turbines based on validated heat cycle information. BWR 10 was able to perform acceptance testing of the new LP turbine with plant instrumentation and DVR. They were able to realize about 40 MWe more with the new turbine at the design point. This application was conducted in collaboration with their turbine vendor in order to optimize and derive a solution for turbine replacement.

BWR 10 also utilized DVR for cooling tower internals vendor verification. BWR 10 applied DVR before cooling tower refurbishments were conducted. Between the BWR 10 reconciled plant data they were able to work with comparing vendor data. The vendor was able to confirm the accuracy of the BWR 10 supplied reconciled data. As a result, the acceptance test of the refurbishments was based upon plant instrumentation supported by data reconciliation. The end result of the cooling tower modification completed in 2012 was that there was a thermal performance improvement of 12-15 MWe.

Lastly, BWR 10 has utilized DVR for plant monitoring. It was noted that feedwater flow measurements drifted as a result of online noble chemistry injection (platinum and hydrogen injection). In 2011 the operators noted a mismatch of feedwater flow and main steam flow. DVR showed the mismatch between the measured value and reconciled value of thermal reactor power and feedwater flow. After analysis of the available data after noticing the mismatch BWR 10 was able to provide correction of feedwater flow with correction factors. They were able to display calculated reactor power and to illustrate main steam flow measurements as being confirmed to be correct by DVR and plant characteristics. The mismatches were noted two more times after platinum injections in Cycle 28, and each time feedwater flow drift was detected and corrected with DVR. The difference between the main steam flow minus CRD flow and feedwater flow was used to monitor the drift of the feedwater flow measurements. BWR 10 was able to verify steam flow measurement quality and compute feedwater corrections with DVR. Due to plant monitoring with DVR they were able to fine tune and change the injection point to a different location for noble chemistry during the 2011 refueling outage. It was noted in 2013 BWR 10 was potentially to use DVR for a condenser retrofit, but this has not been verified at this point in time.

Germany

BWR 11

DVR was first applied at BWR 11 in 2004 at Unit B. The first application considered an evaluation of LP preheater modifications. Once that was completed in 2005 and 2006 at BWR 11 verification of deviations in feedwater flow measurements was performed and resulted in recalibration of flow measurements. An online DVR system was installed in February 2007 at BWR 11. Data was collected over a couple years and the first implementation of feedwater flow correction factors occurred in December 2009. Some lessons learned that BWR 11 applied was electromagnetic compatibility guidelines had to be followed if the reconciliation server was installed in the same room as the plant process computer. This concerned the used of hardware components in that only well-known server types could be used to fulfill their electromagnetic compatibility guidelines. The also identified that data extracted from systems such as process computers must be non-reactive, and that automatic write back of values from the DVR system to the process computer were not permitted.

Additionally, other lessons learned and major findings from BWR 11 application of DVR were that upper and lower limits had to be defined in order to intercept incorrect correction factor inputs. As such it was defined which correction factors would only be valid, and if they fell within a defined limit range. At BWR 11, the input of correction factors had to be performed in the presence of regulators. After the implementation, the thermal balance calculation had to be checked. Uniquely for BWR 11 at the time implementation of new correction factors required a new amendment notice, and that the correction factors had to be checked by the authorities twice per year in a site inspection regarding reactor core and plant dynamics. In that context the plant operators presented the DVR data from the online system, which included trends of the feedwater mass flow and recalculation of the correction factors since the last site inspection.

For BWR 11 the impact of feedwater mass flow correction on thermal core power, calibration of neutron flux measurements and limit values regarding thermal core power and neutron flux were verified and clarified with DVR application. Any change to the DVR software version required a reconciliation against the new model/DVR software release. BWR 11 required an evaluation of the influences if any of a model and/or release change against reconciliation results. For BWR 11, the plant application results in 14 new measurements integrated into the plant process computer. Some examples are correction factors for venturi measurements, correction factors for orifice plates measurements, feedwater mass flow for venturies correction factors, and feedwater mass flow for orifice plates with correction factors. BWR 11 importantly noted that the newly corrected values (feedwater mass flows) are not used as input values then for the reconciliation calculation.

BWR 11 noted that for calculation of correction factors in their application that only data that fulfilled the following requirements was used:

- Stationary process operations were necessary (i.e., no change of feedwater or condensate pumps, no changes in condensate or reactor water cleanup systems). As such, no swapping of pumps was included for data used related to correction factors.
- Reconciled thermal core power had to be above a set value (>99.4%).
- All DVR criteria established had to be fulfilled (e.g. zero suspected tags).

With utilization of DVR at BWR 11 it was noted that regarding the stability of correction factors that they would be verified every 6 months by the regulators. So all data from the respective 6 months would be analyzed. If there was a small deviation noted, i.e., smaller than +/- 0.15% (based on the full feedwater mass flow) that correction factors would not need to be adjusted. BWR 11 then further evaluated the use of DVR for future MUR applications (1.5% uprate of plant). Content Deleted-EPRI Proprietary Information

5.4 Non-Nuclear Plant Applications

Two EPRI Studies were conducted to evaluate utilization of the DVR process at other types of power plant applications. The first EPRI study was conducted in October 2017 and was for a Fossil Fueled Plant application [17]. The second EPRI study was conducted in November 2018 and was for a Combined Cycle Plant application [18].

The Fossil fueled plant application conclusions will be discussed first. It should be noted that this EPRI study was over 80 pages long and only the conclusions are presented in this topical report. The combined cycle EPRI report was over 65 pages long and only the conclusions are presented in this topical report. For the full details of the EPRI studies such as DVR model development, results, and recommendations the detailed reports would need to be reviewed.

Fossil Fueled Plant Application

The DVR process produced a reconciled data set that represented a best estimate of the true process state and individual process parameters for a fossil fuel plant (i.e., model). It was noted that the reconciled data could be used as realistic feedback to plant controls to optimize unit operation, efficiency and dispatch. In addition, the availability and use of reconciled data based upon the study could enable improvements in plant capability, availability and maintenance that should yield substantial costs savings with regards to improved operation, maintenance and unit dispatch.

The improved accuracy and consistency of a reconciled data set was demonstrated using a sample set of data from the above noted fossil power plant. Reconciliation of the data used in the net heat rate calculation resulted in a change in indicated heat rate of +167 Btu/kWhr (+1.7%). Much of this was due to reconciled values of feedwater flow, throttle pressure and hot reheat steam temperatures. Reconciliation of feedwater train data also showed significant improvements in the consistency and realism of calculated values for feedwater heater performance.

It was noted that the process of building and tuning the model could aid in the identification of plant parameters that are not measuring correctly by producing a list of suspect tags. When suspect tags in the model have to be disabled or given higher uncertainties. The study identified that not repairing the measurements can degrade the overall quality of the results. Disabling a suspect tag decreases a model's ability to reconcile and also increases uncertainty in the reconciled output. Increasing the uncertainty of a suspect tag (without disabling it) it was noted could increase uncertainty in the reconciled output.

This study identified several instruments that should be addressed to improve the overall quality of the model. During the model tuning process for this report 24 suspect tags were disabled and numerous uncertainty increases were assigned to other tags. While the adjustments allowed the model to meet the VDI 2048 criteria for an acceptable solution, they increased the uncertainty of some reconciled outputs.

The EPRI report noted ideally any suspect tags identified by a DVR model would be repaired by plant staff and then restored in the model with updated data. This would ensure the best possible reconciliation solution. The EPRI study illustrated the value of using the data reconciliation process to improve a plants ability to identify measurements that may be incorrect as well as provide a more accurate assessment of plant heat rate.

Combined Cycle Plant Application

Same as was noted in the Fossil fueled plant application, the DVR process produced a reconciled data set that represented a best estimate of the true process state and individual process parameters. This reconciled data for a combined cycle plant can be used as realistic feedback to plant controls to optimize unit operation, efficiency and dispatch, and to plant engineers to better monitor and evaluate plant performance. In addition, the EPRI study noted that the availability and use of reconciled data can enable improvements in plant capability, availability and maintenance that should yield substantial costs savings with regards to improved operation, maintenance and unit dispatch.

The improved accuracy and consistency of a reconciled data set was demonstrated using a sample set of data from Content Deleted-EPRI Proprietary Information combined cycle power plant. Reconciliation of the data used in the net unit heat rate calculation resulted in a change in indicated heat rate of +266 Btu/kWhr (+4.25%). Much of this was due to reconciled values of total fuel gas flow. Reconciliation of steam turbine input parameters also showed significant improvements in the accountability of steam turbine MW losses.

The EPRI report noted that the process of building and tuning the DVR model would aid in the identification of plant parameters that are not measuring correctly by producing a list of suspect tags. Just as in the fossil fuel plant applications, these instruments can then be targeted for maintenance and repair. When suspect tags in the model are not repaired, they often need to be disabled or given higher uncertainties and this can degrade the overall quality of the model results. Disabling a suspect tag decreases a model's ability to reconcile and also increases uncertainty in the reconciled outputs. Increasing the uncertainty of a suspect tag (without disabling it) can cause a weaker reconciliation and increase uncertainty in the reconciled outputs.

This EPRI study identified several instruments that should be addressed to improve data quality and the overall quality of the model. During the model tuning process for the EPRI report, 8 suspect tags were disabled and numerous uncertainty increases were assigned to other tags. While these adjustments allowed the model to meet the VDI 2048 criteria for an acceptable solution, they increased the uncertainty of some reconciled outputs.

The 2019 follow up evaluation provided a DVR model results consistent with the 2018 results presented by this EPRI report. The plant's main fuel flow meter still appeared to be in error and the applied gas density appears to be the cause. It was noted in the EPRI report that if this metering error can be confirmed and corrected the plant would have a more accurate value of unit heat rate and fuel consumption (both would increase by approximately 4%).

The issue of fuel gas density can often be a source of confusion and potential error at natural gas units. Trouble with online gas chromatographs or internal conversion factors can produce conflicting flow indications. The EPRI report demonstrated that the DVR process can aide with identifying these types of errors. By forcing all measurements to reconcile in an objective manner the most likely error sources can be identified.

Just as noted above for the fossil fuel plant applications, ideally any suspect tags identified by a DVR model would be repaired by the combined cycle plant staff and then restored in the model with updated data. This would ensure the best possible reconciliation solution.

The EPRI study demonstrated the value of using the data reconciliation process to improve a combined cycle plant's ability to identify measurements that may be incorrect as well as provide a more accurate assessment of unit capacity and plant heat rate. The value of using DVR was shown in the EPRI study as well as an understanding of the complexity of the modeling process. This complexity requires a fairly significant investment of time to develop the models and to iterate with various plant organizations.

6
APPLICATION OF DVR BASED ON POWER PLANT DATA

6.1 Overview

The process of implementing the DVR application at a typical plant consists of the following steps (see Figure 6-1):

1. Construction of a first principle based thermal-hydraulic, heat balance DVR model of the plant systems and overall plant under analysis using plant design data.
2. Testing of the DVR model with design data to verify the DVR calculations.
3. Tuning of the DVR model to account for deviations of the as-constructed plant as compared to the design bases, and to reduce systemic errors with the design data.
4. Evaluating the DVR model with plant historical data. This evaluation will be referred to henceforth as the back-testing the model.
5. Assessment, evaluation, and reconciliation of differences in the historical data sets identified by objective criteria through examination of instrument calibration records and physical examinations of the plant equipment, if necessary. The evaluation will proceed until measurement deviations have been:
    a. Accounted for with a high level of confidence.
    b. All plausible assumptions used in the analysis have been confirmed.
6. Evaluation of all errors contributing to the DVR results. Establishment of DVR model bounding uncertainties, limitations, and conditions of use.

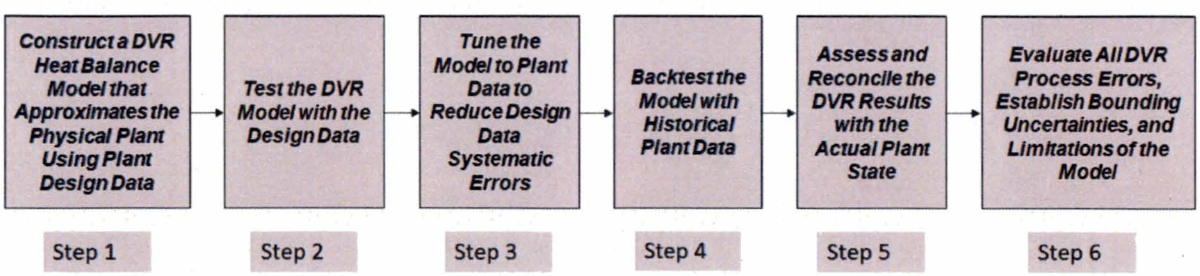

Figure 6-1
Overview of the steps comprising the DVR process

6.2 General Methodology for DVR Model Configuration and Setup

Implementation of DVR technologies at a typical U.S. nuclear plant involves reviews and assessments of:

- Plant instrumentation, calibration methods, and records.
- Plant design documents, including changes, modifications, and retrofits.
- Special tests or any tests related to balance of plant thermal performance.
- The plant thermal performance program including the cycle isolation program.
- Historical plant data.
- Plant computer, data acquisition system and data historian installation.
- Licensed plant calorimetric or Core Thermal Power (CTP) calculations including any uncertainty analyses and related Technical Specifications.

6.2.1 Plant Instrumentation Used as Inputs for the DVR Model

In most cases the typical nuclear plant has a sufficient quantity and quality of instruments to obtain good results with DVR. In general, if a plant has an on-line, computer calculated value of the CTP, the plant should have the minimum number of plant instruments needed for implementation of a DVR model and calculations. If a plant does not have an on-line CTP calculation, a review of the available instrumentation will be necessary to determine the feasibility of implementing a DVR model and calculations.

The plant instrumentation available for DVR use will need to be reviewed prior to model construction.

The typical list of instruments which may be utilized by DVR include the following:

- Primary System Parameters – Pressurized Water Reactor (PWR)
  - Cold Leg Temperature
  - Hot Leg Temperature
  - Reactor Coolant Pressure
  - Pressurizer Heaters parameters
  - Reactor Coolant Pump (RCP) parameters (including flow if available)
  - Charging and Letdown parameters
  - Calculations for Energy Credits or Losses
  - Stream Generator Differential Pressure (SG DP) measurements if available
- Primary System Parameters – Boiling Water Reactors (BWR)
  - Reactor Water Cleanup
    - Inlet temperature
    - Outlet temperature

    - Flow
    - Non-Regenerative Heat Exchanger (NRHX) inlet temperature
    - NRHX outlet temperature
    - Regenerative Heat Exchanger (RHX) inlet temperature
    - RHX outlet temperature
  - Recirculation Pump parameters (including flow if available)
  - Control Rod Drive inlet temperature
  - Control Rod Drive Flow
  - Reactor Dome Pressure
- Reactor Power Parameters (other than those already identified)
  - Final Feedwater Temperature/pressure
  - Final Feedwater Flow
  - Reactor/SG moisture fraction (steam quality)
  - Reactor/SG Outlet Temperature/pressure
  - Secondary System Parameters
  - Steam Generator (SG)
    - Dome Pressure
    - Outlet Pressure
    - Blowdown Flow
    - Blowdown Temperature
    - Blowdown Pressure
    - Feedwater Inlet Temperature
    - Feedwater Inlet Pressure
  - Main Steam
    - Temperature
    - Pressure
    - Flow
  - Auxiliary Steam Pressure, Temperature and Flow
  - Feedwater Heater
    - Inlet Temp
    - Outlet Temp
    - Shell Pressure

  - Drain Temp
  - Drain Flow (if available)
- Turbine Parameters
  - Throttle Valve Position (from turbine control system)
  - Throttle Pressure
  - First Stage Pressure (exit of first stage)
  - Turbine First Stage Bowl Pressure (no nozzle block)
  - Turbine Stage Extraction Pressures
  - HP Exhaust Pressure
  - LP Inlet Temperature
  - LP Inlet Pressure
  - Turbine Stage Extraction Temperatures
- Moisture Separator Reheater
  - Moisture Separator Drain Flow (if available)
  - Moisture Separator Shell Pressure
  - Moisture Separator Drain Temperature
  - Heating Steam Flow for each stage of reheat
  - Inter stage reheat temperature (if available)
  - Hot Reheat Temperature
  - Reheater Drain Flows (for each stage, if available)
  - Reheater Drain Temperature (for each stage)
- Condensers/Cooling Water/Cooling Tower
  - Shell Pressures
  - LP Hood Temperatures
  - Cooling (Circulating) Water inlet and outlet temperature
  - Condenser Hotwell Level
  - Condenser Hotwell temperature
  - Cooling water differential pressure
  - Cooling water flow rate (if available)
  - Air Removal system flow
  - Cooling Tower Fan Power
  - Wet bulb temperature
  - Dry bulb temperature

  - Relative Humidity
  - Wind Speed/Direction
  - Cooling Water TDS
- Misc Heat Exchangers and components
  - Demineralizer Flow
  - Air Ejector Steam Pressure
  - Air Ejector Condenser inlet and outlet temperatures.
  - External Drain Cooler inlet, outlet and drain temperatures
  - Gland Exhaust Condenser inlet, outlet temperatures
  - Deaerators
- Pumps
  - Heater Drain Pump Suction & Discharge Pressures, Temperatures and flow
  - Condensate Pump Suction & Discharge Pressures, Temperatures and flow
  - Condensate Booster Pump Suction & Discharge Pressures, Temperatures and flow
  - Reheater Drain Pump Suction & Discharge Pressures, Temperatures and flow
  - Feed Pump Suction & Discharge Pressures, Temperatures and flow
  - FW Pump Turbine steam flow, inlet pressure, inlet temperature, exhaust pressure (if available)
- Electrical
  - Pump Powers (or Amps)
  - Generation meters/transducers
  - Gross Generation (upstream of transformer)
  - Generation (downstream of transformer)
  - Auxiliary Power
  - Startup Transformer Power
  - Net Gen – After house loads
  - Generation Transducer output
  - Generator MVAR/MVA (Reactive power)

- Digital Signals – Any signals that would aid in allowing the model to identify various states (such as pumps on/off).

6.2.2 Review of the Plant Piping and Instrument (P&ID) Drawings

The plant drawings are reviewed to determine the instrumentation location and layout.

The following is a list of typical plant drawings which would be reviewed to develop and tune the model:

- P&ID's for all Primary and Secondary Steam Cycle Systems
  - Main Feed
  - Main Steam
  - Condensate (including demineralizer)
  - Extraction Steam
  - Heater Drain
  - Moisture Separator
  - Circulating Water
  - Cooling Tower
  - Sealing Steam
  - Steam Generator (PWR)
  - Reactor Coolant (PWR)
  - Reactor (BWR)
  - Reactor Water Clean Up System (BWR)
  - Steam Generator Blowdown (PWR)
- Electrical Diagrams showing Generation Metering locations
- Isometrics for selected piping and components. The selection would be based on the actual instrument location relative to other instruments or conditions that are required to be determined. For example:
  - Main Steam from Steam Generator (or Reactor) to turbine throttle to determine pressure drop
  - Condenser Hotwell to condensate temperature measurement.
  - Drain Tank piping from tank to pressure /temperature measurement
  - Piping from turbine extraction to feedwater heater
  - Piping from HP exhaust to MSR
  - Piping from MSR outlet to LP inlet

6.2.3 Selecting Plant Instrumentation for the Plant's DVR Model

The instrumentation given in the previous section are general candidates for use when developing a DVR model for a plant.

In general, the instrumentation used as inputs for the DVR model calculation are those used to calculate the vendor heat balance diagrams and the plant CTP. Typically, these include secondary or steam plant flow rates, temperatures, pressures, and electrical measurements for the steam turbine cycle.

6.2.4 Measurements Correlated to CTP

Selection of the instrumentation for use in the plant specific DVR model requires some knowledge as to how specific measurements affect the results of the DVR CTP calculation. Table 6-1 provides a summary of the relative effects of various plant measurements on the DVR CTP results accuracy (uncertainty) for a typical plant installation.

As large a number of plant measurements from the Table 6-1 that can be practically used are configured for the preliminary DVR model. Following model tuning, a portion of erroneous plant measurements which degrade the DVR CTP results may be removed to improve the overall fidelity of the model, but understanding and considering the effect on the model uncertainties that removing them has on model accuracy.

Table 6-1
Relative effects of various plant measurements on the DVR CTP accuracy

Item #	Measurement	Contribution to DVR CTP Accuracy
1	DVR Model Turbine Efficiency Values	High
2	Megawatts Generation	High
3	Other Final Feedwater Flow Measurements	Moderate to High
4	Final Feedwater Temperature	Moderate
5	Other Flows (main steam and, condensate flows)	Moderate
6	Main Steam Quality	Low
7	Main Steam Pressure	Low
8	Reheat Temperatures	Low
9	MSR moisture removal effectiveness	Low
10	Generator Efficiency	Low
11	Condenser Pressure	Low to Moderate
12	Feedwater heater temperatures and pressures	Low to Moderate
13	Turbine steam path pressures. Use of Stodola[1] functions may yield a High contribution to CTP.	Low to High
14	Other CTP measurements	None. (Only for comparative use)

[1] Stodola Functions are discussed in Section A.2.12 in Appendix A

6.2.5 Instrumentation Measurement Accuracy and Calibration Requirements

As certain plant measurements contribute more to the CTP accuracy than others, those that have a significant effect on the CTP of greater than 0.5% of the 100% CTP value, will require validation or conservative bounding of the measurement's accuracy used as input to the DVR model.

A key concept to note is that the measurement accuracies input to DVR are empirical accuracies. The DVR input measurement accuracy should encompass any plant calibration records, loop accuracies, systematic errors, localization errors, or other measurement phenomena.

As previously discussed in Section 3, any of the aforementioned measurement errors will convolve as a Gaussian distribution. The individual instrument measurement errors can be further assessed with DVR during the model tuning process for possible refinement. Refinement to the accuracy value may include accounting for systematic errors, localization errors, or other measurement phenomena that may bias the results.

When available manufacturer performance specifications for the in-situ field performance and/or plant calibration records are used, and the overall loop accuracies of the measurement through the plant computer output are calculated or estimated.

If these data are not available, conservative estimates of the in-situ field accuracies of instruments in question, based upon industry experience with similar devices, are developed.

When difficulties are encountered resolving the accuracy of an instrument that is a significant DVR CTP results contributor; additional measures will need to be taken to identify the source of the error. Cross comparisons of measurements in question in the field using instrumentation with a known, lab-traceable accuracy may be used as a means to identify measurement errors. Otherwise, conservative bounding of the accuracy estimate may be used, and/or, additional margins to account for the errors may be added to the DVR CTP accuracies when evaluating the DVR CTP overall accuracy.

6.2.6 Measurement Redundancies

Data redundancy is a core attribute of the DVR algorithm to improve the estimation of plant instrumentation measurement errors. In the situation where insufficient plant measurements are available to create sufficient redundancies, the DVR algorithm will give an error message that the DVR calculation cannot be performed. This situation is rare as typical instrumented nuclear plants will contain sufficient measurements to allow for DVR calculation. A review of the proposed instrumentation as described in Section 6.2.1 should be performed prior to DVR model construction to ensure the instrumentation at the plant will yield sufficient DVR model measurement redundancy.

In the case where several instruments measure similar local conditions, the Gaussian distributions will combine to create a more accurate measurement. This concept can be useful at the plant as several lower accuracy instruments can provide a more accurate measurement than one device that is of a high accuracy standard.

In cases where the process conditions differ, and that difference can be characterized with an auxiliary conditions calculation, redundancies can be created between the upstream and downstream measurements. The data redundancies create additional information to correct the upstream and downstream measurements to satisfy the auxiliary conditions calculations. The auxiliary conditions calculations may include mass and energy balances, pressure drops, component efficiencies, component heat transfer coefficients, or other user specified calculations.

6.2.7 Review of the Current Plant Design and Testing History

Nuclear plants typically have several design changes over the life of the unit. Design changes may include turbine retrofits, heat exchanger replacements (steam generator, condenser tubing, feedwater heaters, and moisture separator reheaters), MUR uprates, and changes to plant instrumentation, including the addition of ultrasonic feedwater flow metering.

The design changes and their impact on the current plant thermal performance will be considered and evaluated when constructing the DVR model. Reviews of any acceptance or specialized tests, including turbine tests or moisture carryover tests, may be performed to help with the determination of the actual current plant state.

6.2.8 Review of the Plant Calorimetrics (CTP)

A review of the plant calorimetrics, or CTP, will be performed. This includes:

- Review of CTP calculation software specification for the plant computer.
- Latest calibration records for the CTP input instruments.
- Uncertainty calculations for the CTP.
- Operating Procedures which address maintaining core thermal power.
- Reactor Engineering Procedures for CTP.
- Ultrasonic Flow Meter (UFM) information.
- Flow Venturi, Nozzle, or other differential pressure flow metering device. Drawings and lab calibration data.
- Isometrics for Feed System, including location of measuring equipment (including UFM if applicable) and all upstream piping back to the second highest pressure Feedwater heater.
- UFM installation package including uncertainty calculation and design information.
- Any alternate feed flow tests (Tracer Testing).

6.2.9 Review of the Plant Thermal Performance Program

A review of the plant thermal performance program will be conducted. This program review will include the following:

- Plant heat balances and vendor turbine thermal kit that reflects the current design.
- Design specifications related to thermal performance for major turbine cycle components such as feedwater heaters, moisture separators, reheaters, condensers, feed pumps, etc.
- Existing plant software-based heat balance models for possible use in the plant DVR model to derive auxiliary conditions calculations and pseudo-measurement variables.

- Plant performance calculations or trend data that characterize the empirical performance of the plant over time.
- The Cycle Isolation program and historical data. Estimates of typical and maximum observed cycle isolation leakages will be evaluated to determine the possible effects of cycle leakage on the DVR model CTP uncertainty.
- History of plant operations to determine conditions or standard plant evolutions that could potentially affect the use of DVR.
- History of component or instrument failures.

6.2.10 Plant Computer and Data Acquisition System Review

A review of the source of plant instrumentation data used for input to the DVR model will be performed. This review will include:

- Source of plant measured data – plant computer, data acquisition system, plant data historian.
- Interface requirements.
- Plant instrumentation measurement data source.
- Tag name, engineering units, and conversion factors.
- Sampling rates and frequencies for each measurement.
- Averaging, outlier rejection, compression, or other data processing made when acquiring measurement data to calculate an output value from the plant measurement data source.

The source of data for input to the DVR model will need to be determined. The data might be gathered from a plant computer system, data acquisition system, or plant data historian. As many plants have plant data historians, these can greatly simplify the plant data collection process for assessing large amounts of plant data, or historical data. These systems often employ data compression schemes to save disc space, and are particularly convenient for performing the model back-testing.

Plant computer tag names and instrument data, associated with the plant measurements, including all engineering conversion factors, will need to be obtained to allow for determination of what measured data is available for the DVR process, and how it will be used. This information is lined-up with the piping and instrumentation drawings, isometrics, circuit wiring diagrams, and other plant instrumentation records to determine the precise instrument locations and any localization corrections.

The data in aggregate needs to be checked against the data source used for input to the DVR model to ensure all loop accuracies, engineering conversions, and localization effects have been accounted for when determining the measurement's readings and field accuracy.

The sample size and time interval of the measurements used for DVR input will need to be determined. Typically, the DVR calculations are configured to run hourly using an average of plant measured data for the previous hour. In general, this yields a sufficient sample size, and standard deviations of the data tend to be small, which means the uncertainty associated with the random data scatter is small.

Regardless, the frequency of the DVR calculations and the sampling requirements to support the calculations; while minimizing random data scatter may need to be determined on a case by case basis. The DVR calculations should be performed at a sufficient frequency to allow for trend analyses of the DVR output data.

The sampling method used for DVR model input should also be evaluated for any data manipulation or processing steps including outlier detection and rejection, effects of compression settings when using data acquired from a source that uses data compression, or any other methods that could affect the value of the sample mean.

The sampling method will be evaluated to determine the overall contributing effects on the overall DVR CTP results uncertainty.

6.2.11 Use of the Turbine Vendor Thermal Kit, Heat Balances, Software Based Heat Balance Models, and Other Design Data Used for DVR Model Inputs

Figure 6-2 illustrates the use of heat balance models during the DVR process. Consider a typical physical power plant unit. The power generation process is governed by thermodynamic principles. The process can be simulated use of first principles based heat balance models. These heat balance models capture the interaction between the performance of the system components with the corresponding dependent variables such as temperature, pressures, enthalpies, etc. To carry out a detailed heat balance a large number of input variables are required; however, only a subset of these variables is measured.

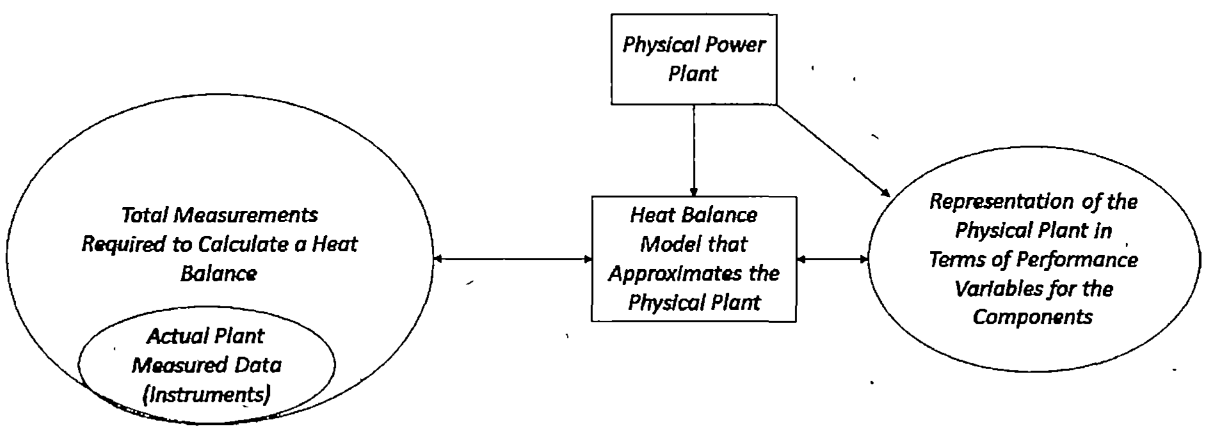

Figure 6-2
Correlation between the physical plant unit and the DVR process

Use of the heat balance models also allows us to create estimates for measurements required to perform the heat balance calculation that are not measured by the plant. These estimates will be referred to as pseudo-measurements. Though pseudo-measurements are not a direct measurement, they are true in the fact as they must adhere to the first principles calculation.

The assumption is made that there is some knowledge of the performance state of each component as provided by the vendor design data, heat balance diagrams, and turbine thermal kit. For the condenser, feedwater heaters, and heat exchangers a range of values for the heat transfer characteristics may be known from the vendor design data sheets. For the steam turbines a range of sectional efficiencies from the turbine thermal kit may be known. These additional pseudo-measurement variables provide additional data for solving the DVR model component and cycle heat balance calculations.

Streit [3] and VDI-2048 [1] refer to these additional calculations as auxiliary conditions. These auxiliary conditions are the component and mass and energy balances, or other user defined calculations that comprise the DVR model.

The auxiliary conditions must be met by true values. The plant measured values will contradict these due to errors with the plant measured data, or possible errors with some of the pseudo-measurement variables used in the auxiliary conditions. By consideration of the uncertainty intervals with both pseudo-measurement and plant measured variables the errors can be minimized to convolve to the true state of the plant.

The contradictions of plant measurements to this true state represent quantifiable measurement errors.

6.3 DVR Model Construction and Determination of Software Settings

The steps involved with developing a DVR model for plant use are:

- Extraction of data from vendor thermal kit, vendor heat balances diagrams or software heat balance model. The extracted data are used as pseudo-measurement values of the turbine efficiencies, and to develop other thermal kit correlations as auxiliary conditions calculations in the DVR model.
- Building a DVR model to match the vendor heat balance or the software heat balance model.
- Modifications of the DVR model to represent the actual physical layout of the plant and incorporate plant systems which may not show on the vendor heat balance diagrams.
- Tuning the DVR model to plant data to reduce systematic errors associated with margins in the turbine vendor calculations of low-pressure turbine efficiency.

Following the DVR model tuning process, the DVR will be back-tested using historical data. The result of this process may include refinement of the empirically derived estimates of the plant instrument measurement accuracy values. The DVR model at this point is ready for plant use for on-line monitoring of the current conditions.

6.3.1 Extraction of Data from Heat Balance Diagrams, Thermal Kit, and Use of Software Heat Balance Models

The heat balance diagrams and turbine vendor thermal kit are used to obtain the turbine efficiencies and thermal kit correlations for use in the DVR model for variables that cannot be directly measured at the plant. Thermal kit data relevant to the DVR model includes the turbine stage moisture removal effectiveness, last stage exhaust losses or last stage MW output change as a function of exhaust pressure, stage pressure vs flow correlations, and generator losses calculations.

The thermal kit data are used to provide pseudo-measurement values of the turbine efficiencies for use in the DVR model as the turbine stage efficiencies cannot be directly measured or calculated in the plant wet steam cycle. The thermal kit data are also used to develop auxiliary conditions calculations in the DVR model to correct the DVR model heat balance calculations for the effects of turbine stage moisture removal, exhaust losses, and the generator losses.

The thermal kit and/or heat balance diagrams may also contain other data such as steam line pressure drops and pump efficiencies that are used in the DVR model. This data may be modified with actual plant data or vendor design data following matching of the initial DVR model to the thermal kit reference data. Of key importance is that the pseudo-measurement values extracted for use from the thermal kit are maintained or corrected properly when they are used in the DVR model.

In place of using the thermal kit and heat balance diagrams, an energy balance software program model may be useful. If an energy balance software program model is used that has already been tuned to plant data, care will need to be taken as the possibility exists that biases could introduced into the DVR model using the pseudo-measurement values extracted from the software heat balance model.

For example, when tuning an energy balance software program model to plant data, plant instrumentation errors can propagate into the tuned model such that the calculated turbine efficiency values differ from the original thermal kit data. Therefore, the energy balance software program model will need to be carefully compared against the latest vendor thermal kit design data. Any differences will need to be evaluated as to the possible effects on the DVR model results.

In summary the extraction of the data requires the following:

1. Perform hand calculations of the design heat balance data to extract the turbine efficiencies and moisture stage removal effectiveness values.
2. Reconcile the hand calculations to the design heat balance and thermal kit data. Note the use of different steam tables which could affect the calculations. In general, the mass flows, enthalpies, and electrical generation should match within about 0.1% to the original design data to properly reconcile and account for the differences between the two calculation methods.
3. If using a software heat balance model, compare the turbine efficiencies, moisture stage removal effectiveness values, and exhaust loss calculations to those used in the design heat balance hand calculations. If the values differ by greater than 0.1% as compared to the original design data an engineering assessment of the energy balance software program model will need to be performed. If the software model data are to be used in the DVR model, justifications as to why the deviations from the original heat balance calculations are acceptable must be developed.
4. If the energy balance software program model includes components that are not shown on the vendor heat balance diagrams, or the performance of some components differs from that of the vendor heat balance diagrams, evaluate and reconcile the effects on the extracted data to be used in the DVR model.

Determine and bound the possible error effects on the DVR model calculations related to the data extraction.

6.3.2 Model Construction and Preliminary Settings

This section will document the creation of a sample model using the DVR software.

Using the DVR software, a model is developed and configured to represent the systems and components that makeup the plant cycle. Process flow diagrams (PFDs) are created to represent the cycle layout as shown on the design heat balance diagrams or the software heat balance model.

Steam table data from the design heat balance source (vendor heat balance diagrams and thermal kit or software heat balance model) such as temperatures, pressures, flow rates, and enthalpies, along with the pseudo-measurement data developed and extracted in the previous section, are entered into the PFD component models.

User configured auxiliary conditions calculations are developed in the DVR model to replicate the function of vendor calculations such as the turbine moisture stage removal effectiveness.

Measured data tags are then setup in the DVR model to allow input of plant measurement data to the DVR estimation algorithm.

A set of control data, typically the design heat balance diagram data, is developed, read, and calculated with the DVR model to compare the output results to the original data source. This step helps to confirm the extracted pseudo-measurement and auxiliary conditions calculations have been developed properly. The intent is to replicate the original source design data mass-energy balance calculations with the DVR model.

In general, the mass flows, enthalpies, and electrical generation should match within about 0.1% to the original design data. Any discrepancies will require an engineering assessment to reconcile the differences. The effects on the DVR model calculations due to uncertainties of extracted data as compared to design are then determined and bounding uncertainties are applied to the extracted data values.

The DVR model at this point has a design traceable calculation pedigree.

In summary, the steps involved with the DVR model construction and initial settings are:

1. Model abstraction. Component models are configured with the DVR software to create PFDs that represent the cycle and system heat balance calculations. The plant P&IDs and design heat balance diagrams are used to determine the layout of the configured components.
2. Mapping of tag locations in the DVR model corresponding to the heat balance design data source for pressures, temperatures, and flow rates. Optionally, tags for plant measurements from the plant computer, data acquisition system, or data historian may be created at this time, but will not be activated.
3. Initial setting of accuracies for the measurements corresponding to the heat balance design data source.

6.3.2.1 Sample Model Source Data and Configuration

Figure 6-3 gives the design heat balance diagram used to create the sample model. Table 6-2 provides a summary of the plant equipment to be modeled with the DVR software.

Using the plant P&IDs and plant systems descriptions, the DVR model PFDs are developed. Figure 6-4 through Figure 6-11 provide details of the system PFDs. Figure 6-12 provides the Main PFD which is made up of the individual system PFDs. Note the PFD figures show the configuration of plant computer tags.

With the DVR software, individual system PFDs may be executed separately from the Main PFD. Executing the Main PFD executes all the system PFDs. Having the ability to execute individual system PFDs simplifies the DVR model building process.

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Table 6-2
Plant equipment included in the sample DVR model

Plant System	Equipment description
Reactor Cooling	2 Reactor Recirculating Pumps
	1 Reactor Water Clean Up (RWCU) Pump
	2 parallel trains of RWCU Heat Exchangers – 1 regenerative, 1 non-regenerative. Logic switch will disable out-of-service heat exchangers
Reactor	1 reactor component
Turbines	3 High Pressure (HP) Turbine stages, two extraction lines
	2 Low Pressure (LP) turbine with 6 stages and 4 extractions on each
Moisture separator-reheaters	2 parallel moisture separators
	2 parallel reheaters, just downstream of moisture separators (only 1 stage of reheat)
Condenser	1 Condenser component receiving combined LP Turbine exhaust, Feedwater (FW) heater drains, Feedwater Pump Turbine (FPT) exhaust, and seal steam
	1 Condenser component with Circulating Water Inlet and Outlet streams
Condensate	1 Steam Packing Exhauster component
	1 Steam Jet Air Ejector (SJAE) component, fed by assumed main steam flow
Condensate Pumps	4 parallel condensate pumps. Logic switch will disable out-of-service pumps
	4 parallel condensate booster pumps. Logic switch will disable out-of-service pumps
LP feedwater train	2 trains with 5 LP Feedwater Heaters supplied by turbine extraction lines
	2 parallel External Drain coolers preceding the first LP Feedwater Heaters
Heater drains tank	2 Heater Drain tanks for the second LP Feedwater Heaters
Feed water pumps	2 parallel Feedwater Pumps driven by steam turbines
	2 Feed Pump Turbines driven by hot reheat steam supply
HP preheaters	2 parallel HP Feedwater heaters supplied by turbine extraction steam
Generator	1 Generator component

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6.3.2.2 Sample Model Assumptions

The Sample DVR model source of data for the pseudo-efficiency values of turbine efficiencies and other thermal kit turbine correlation data was extracted from an energy balance software program model of the plant that had been tuned to match the source heat balance diagram.

The energy balance software program model had been tuned to match the turbine vendor thermal kit data. The turbine efficiency values, listed in Table 6-3, are based on the vendor thermal kit and energy balance software program model of the plant (also based on the vendor thermal kit).

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The efficiencies in Table 6-3 have been redefined to allow use of plant measurement of pressures on the extraction lines and at the feedwater heater shells. However, the stage wheel powers are equivalent to the turbine vendor data, therefore the pseudo-measurement data of the turbine efficiencies extracted and used in the DVR model are equivalent to the turbine vendor data.

The efficiencies in Table 6-3 should remain nearly constant under normal operating conditions near full load. The efficiencies have assumed uncertainties of ±2% which should bound any potential deviations from the Thermal Kit efficiencies caused by manufacturing, installation, or margin added by the turbine vendor. See the discussion in the Model Tuning section, below, for additional details.

Table 6-4 provides a summary of the DVR modeling assumptions created when abstracting the models from the heat balance diagrams to the actual plant configuration based on the P&IDs, plant isometrics, and plant instrument locations.

Table 6-4
Model assumptions

Component	Assumption	Comment
Turbine Throttle Valve Pressure Drop	DP uses thermal kit formulation	Effect on DVR CTP value is not significant
Turbine Throttle Valve Leakage	Zero leakage flow	Effect on DVR CTP value is not significant
Turbine Stage Efficiency Values	Adjusted to match definition in software heat balance code. Wheel powers to match source heat balance.	Turbine efficiency design data is retained in the DVR model.
Turbine – LP 4th and 5th Extractions	Ratios to make system solvable	Effect on DVR CTP value is not significant
Turbine LP Moisture Stage Removal Effectiveness	Thermal kit data replicated via user calculation	Turbine efficiency design data is retained in the DVR model.
Last LP Turbine Stage Efficiency	Energy balance software program model	Turbine efficiency design data is retained in the DVR model. The value is re-tuned to plant data to remove excess margins in the vendor data
LP Turbine Exhaust Hood Pressure DP	LP Turbine Exhaust Pressure drop to improve condenser and exhaust pressure measurements	Effect on DVR CTP value is not significant
Moisture Separator-Reheaters	Moisture Separator steam outlet quality is set to 99.66% with an uncertainty of 0.34%. Pressure drops based on heat balances.	Value is modified from the base heat balance source to allow the value to be driven partially by plant measurements and yield a more realistic value than the source heat balance value.

Table 6-4 (continued)
Model assumptions

Component	Assumption	Comment
Feedwater Heaters	The shell outlet of feedwater heaters 1A/B is saturated liquid to make system solvable.	Effect on DVR CTP value is not significant.
Feedwater Heaters	No pressure drops through feedwater heater shell or tube sides.	Effect on DVR CTP value is not significant.
Condensate booster pumps, CRD pumps, reactor feed pumps and RWCU pumps	Efficiencies set to reconcile with source heat balance data.	Effect on DVR CTP value is not significant.
Feedpump turbine	Efficiencies set to reconcile with plant data.	Effect on DVR CTP value is not significant.
Circulating water	Inlet pressure is assumed to be 20 psia.	Effect on DVR CTP value is not significant.
Gland steam System	Steam jet air ejector (SJAE) is assumed to be a fixed flow rate and pressure per the source heat balance data.	Effect on DVR CTP value is not significant.
Generator Losses	Generator mechanical loss of 4.28 MW with an uncertainty of 5%. This is the loss value assumed on the Rated Heat Balance in the GE Thermal Kit.	Turbine design data is retained in the DVR model.
Main steam line pressure drop	Based on Crane calculations.	Effect on DVR CTP value is not significant.
Reheater Line Pressure Drop	A pressure drop of 2.1psi between the reheater outlets and the LP turbine CIV inlet pressure measurement was added to the model. There are four steam lines from the reheaters to the CIV valves.	Effect on DVR CTP value is not significant.

6.3.3 Model Validation to Known Cycle Heat Balance Data

For development of the sample DVR model, hand calculations were performed using the design source heat balance diagram Figure 6-3 and the vendor thermal kit. Referring to Table 6-5, it can be seen the hand calculations are in good agreement with the vendor data. Next, an energy balance software program model of the plant was used, and the result for same conditions as the source heat balance are also given in the table. Again, the data is in good agreement.

The energy balance software program model and DVR model were modified to reflect the additional model assumptions given in Table 6-4. Both models were then run and the calculations for the yielded agreement better than 0.1% for the mass-energy balances, flow rates, pressures, temperatures, and electrical output values.

Therefore, the pseudo-measurement turbine data used in the DVR model reproduces the design source heat balance and thermal kit data.

The DVR model uses IAPWS-IF97 [73] steam tables whereas the vendor heat balances and thermal kit uses ASME 1967 [72] steam table formulations. It can be observed that errors in the DVR related to different steam table usage and other numerical methods errors used with the DVR algorithm are quite small and are bounded with the <0.1% differences observed using the different calculation methods.

In summary, the errors for deriving the source heat balance data for DVR use are less than 0.1%.

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6.3.4 Tuning the Sample DVR Model to Plant Data (Model Tuning)

VDI-2048 [2], Part 2, Section 7.5.3 refers to the use of internal efficiencies, which are the estimated turbine efficiency values used in the DVR model. VDI-2048 [2], Part 2 further states "The internal efficiencies must fall within plausible limits. This knowledge can be brought into the evaluation by means of the auxiliary condition that the internal efficiency estimated, together with the uncertainty, as plausible must be equal to the measured efficiency."

Therefore, plausible assumptions on the values of the uncertainties used for the design bases turbine efficiency values must be determined for use in the DVR model to bound the overall effect on the DVR reactor power estimate MWth uncertainty.

As the source for the turbine efficiency values design data are the turbine vendor heat balance diagrams and turbine thermal kit, any errors, or biases due to margins, will propagate into the DVR estimates. Therefore, a plausible value for the accuracy of the heat balance diagrams and thermal kit data must be determined.

Based upon knowledge of how turbines are constructed and placed into service at the plant, the following assumptions are made:

1. The turbine vendor can machine the turbine components precisely, and within about 0.25% blade efficiency.
2. The vendor will account for installation errors of about 0.25% blade efficiency.
3. The vendor will add a bit of margin, say about 0.25% blade efficiency.
4. Finally, the vendor may add some more margin to help offset any acceptance test uncertainties.

Summing these up, a plausible assumption can be made that the heat balances and thermal kit design data has an uncertainty effect of about 1% overall MWe gross electrical output as the correlations to turbine efficiency are roughly directly proportional.

Therefore, assuming a 2% overall MWe gross electrical output with the design turbine efficiency values should completely bound and encompass these errors with the MWth estimate derived with DVR for the preliminary calculations. See Figure 6-13.

As the DVR process proceeds, plant measurement uncertainties will be refined with their actual calibration state and other plausible assumptions regarding the plant physical state for the test data evaluated may be developed. As this additional knowledge of the system state is developed, the turbine efficiency value uncertainties may be reduced with a goal being an overall 1% uncertainty gross output error contained in the design source data. If sufficiently accurate acceptance test data is available to analyze with DVR, it may be possible to reduce the turbine efficiency value uncertainties to less than 1%.

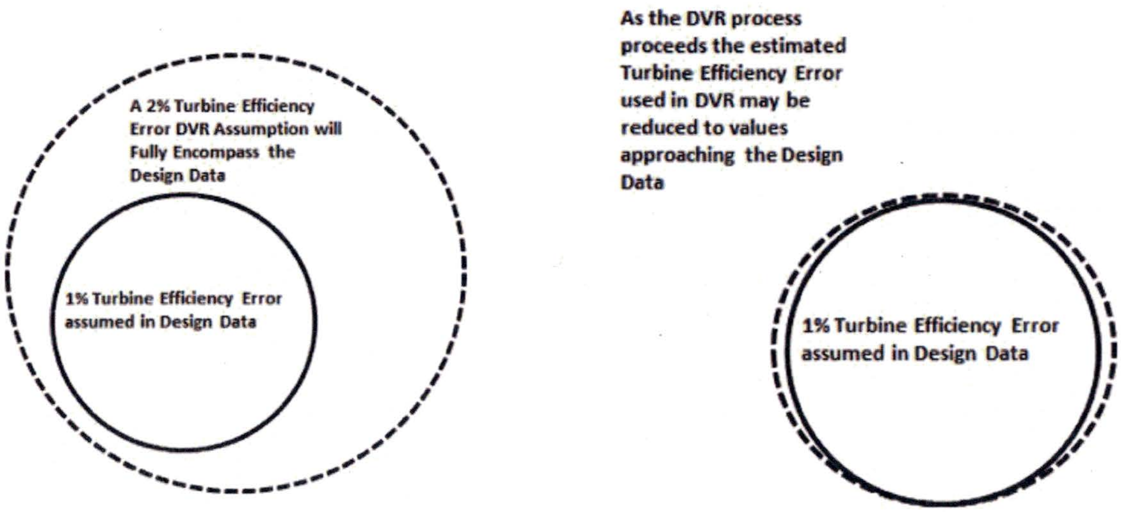

Figure 6-13
Refinement of the unmeasured turbine efficiency uncertainties

In the absence of highly accurate warranty test data, the values and shape of the last turbine stage efficiency curve may be determined using a large number of plant data to characterize the actual efficiency. Starting with a high uncertainty value of the last turbine stage efficiency of about 2% gross electric output equivalent, and reasonable values of other plant instrumentation accuracies, a large set of data is analyzed. The data are analyzed iteratively while successively reducing the last turbine stage efficiency error assumption. The objective is to derive a last turbine stage efficiency with an uncertainty that yields about 1% gross electric output equivalent.

The efficiencies will remain nearly constant under normal operating conditions for all but the last LP turbine stage (which changes with condenser pressure). The efficiency of the final LP turbine stage will fluctuate due to changes in the exhaust loss caused by natural fluctuation of the condenser pressure.

The turbine vendor often puts additional margins of the overall turbine performance in the low-pressure efficiency vs backpressure correction curve. Using the DVR model and a large set of plant data with varying condenser pressures allows for tuning of the LP turbine efficiency curve to remove vendor margins and improve the accuracy of the curve. Figure 6-14 shows the LP turbine last stage tuning process for the sample DVR model.

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The DVR tuned model performance can then be compared against the vendor data. Referring to Figure 6-15 it can be observed the actual in-plant turbine performance is within about 1% at the base pressure of 2.28 in. Hg, and within 2% of the vendor data over the turbine backpressure range. In general, this helps to confirm the plausible assumption of the vendor thermal kit uncertainty value of 2% (see Section 6.3.4 discussion). Use of the derived turbine efficiency values for the DVR model reduces the errors and bias margins in the turbine vendor data. This allows for improved DVR model performance by reducing the uncertainties related to the pseudo-measurement turbine efficiency input values.

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6.4 Empirical Tuning of Plant Tag Uncertainty Values

As previously mentioned, the measurement uncertainties for the DVR plant tag input variables are empirical uncertainties, which are synonymous with the tag accuracy values. The DVR tag input accuracies are generally based on sensor vendor specifications, and/or plant calibration data sheets. Consideration is also given to possible loop errors and installation effects.

During the model tuning process, the tag accuracies are refined based upon observations of fitting the tag value penalty values and the overall quality metric of the data with the DVR algorithm. Consideration is also given to avoid overly biasing the DVR CTP results with the accuracies of tags that contribute significantly to the DVR CTP results.

In general, the post-tuning tag accuracy values are adjusted to be conservative to encompass the observed plant values, vendor specification values, or values determined based upon typical performance for similar instrumentation.

Where discrepancies are observed with the plant measured values and the DVR results the calibration state of the measurement in question is investigated. Resolution of these variables includes re-checking the calibration state of the measurement, re-calibration of the measurement device, increasing the DVR tag input accuracy value until the error is bounded, or discarding of the measurement for use in the DVR calculation if it is not a significant contributor to the DVR CTP.

Additional refinement of the tag accuracy values may occur during back-testing; however this is typically only performed on tags that will have no effect on the model tuning.

Table 6-6 provides a summary of the development of tag accuracy values for a sample model. The tag values that contribute >0.1% DVR CTP uncertainty contribution are shown. Only those that contribute >0.5% DVR CTP uncertainty contribution are of real concern.

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6.5 Back-testing the Sample Configured DVR Model with Plant Historical Data

Following tuning of the DVR model, the model was tested with plant data that had not been used for the tuning process. Back-testing of the models helps to validate and confirm the results of the model tuning. Plant data from 5/30/2016–1/08/2018, a total of 470 time period data sample were used for back-testing. Data were not used when the plant was less than 95% licensed power or was not in a normal operating state.

The results from the testing are given in Table 6-7. The main criteria for passing the testing is that at least 95% of the runs must be successful.

The successful runs had an average Quality of 0.744 and the Core Thermal Power Uncertainty did not exceed 0.59.

Table 6-7
DVR model back-testing results

Description	# of Runs
Total # of attempted runs (5/30/16–1/08/16)	470
Failed Runs – attempted runs that failed to produce results	6
Failure of VDI Criteria 1 – completed runs with Quality > 1.00	9
Failure of VDI Criteria 2 – completed runs, met Criteria 1, but have flagged tags that affect CTP	5
Disqualified Runs – completed runs, but plant was not in normal operating alignment assumed by model	16
Total # of valid attempted runs (Total – Disqualified Runs)	454
Total # of failed runs (Failed runs+ VDI 1 failure +VDI 2 failure)	20
% Successful	95.6%
% Failure	4.4%

6.5.1 Flagged Tags

A number of flagged tags were identified during the tuning and back-testing of the model. The tags were disposed dependent on their contribution to the CTP. Tags that had little to no contribution to the CTP and were often, had their uncertainties increased or were turned “OFF”. Flagged tags that contributed to the CTP were noted.

Table 6-8 and Table 6-9 provide a summary of the tags flagged during the model testing.

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6.6 Results from Plant Monitoring with the Tuned Sample DVR Model

Following the back-testing of the DVR model, the model was deemed acceptable for use for informal plant monitoring. The DVR model was installed on the plant's servers, communications were established with the plant's OSI PI data historian, and the DVR model was setup to calculate periodically.

Table 6-10 provides a summary of the DVR results for cases where the plant power was >95% and the plant operational state was normal.

Table 6-10
Summary of DVR model results for informal monitoring

Description	Value
Total # of runs (6/10/18 - 11/14/19)	19743
Average number of flagged tags	1.5
Average Quality	0.36
Average CTP Uncertainty	<0.59%

In general, the performance of the DVR model was acceptable, and the Quality metrics were on average better than the results from the back-testing. The data are filtered to exclude DVR CTP contributors that exclude 0.5% contribution. See Figure 6-16.

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It should be noted that the plant feedwater flow meters have a history of fouling. The DVR results clearly show the plant metering is experiencing errors with the flow rate measurement, and the error varies during the monitored period. See Figure 6-17.

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Turbine first stage pressures were compared to the measured and DVR reconciled flow rates and remained within about ±1.0%. This tends to corroborate that no significant plant flow element fouling, de-fouling, or accuracy shifts occurred during this time interval. The DVR results also indicate potential bias errors with the plant flow elements readings which are higher than the DVR results by about 1%.

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6.7 DVR Model Core Thermal Power Uncertainties and Contributors

Figure 6-19 compares a traditional high accuracy heat balance CTP calculation with a value calculated by a DVR model that represents a typical plant. The figure also provides a breakdown of the typical CTP error contributors that comprise the example.

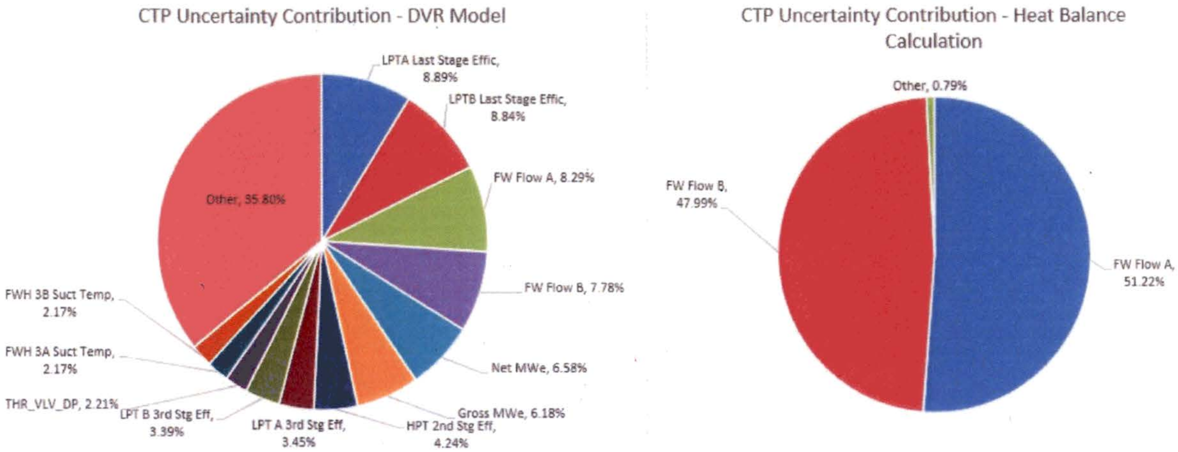

Figure 6-19
CTP error contributors

Table 6-11 provides a summary of the example DVR model CTP error contributors greater than 0.5% of the overall CTP value. While the number of CTP error contributors and accuracy contribution amounts will vary for each specific plant DVR model, the example provides data typical of that for a moderately instrumented older plant.

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A review of the DVR output for a typical run is given in Table 6-12. The model has acceptable redundancy as the value is greater than zero (0). Redundancies less than zero yield an unsolvable system of equations.

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The Gain distribution for the model in Figure 6-20 shows a large number of data points (52%) contribute to the reconciled calculations. Thus, the gain relates to the redundancy of individual measurements that contribute to the CTP. The gain value expresses the accuracy improvement and is calculated on the basis of the reconciled and the used accuracies. Higher gain values indicate higher accuracy reconciled values.

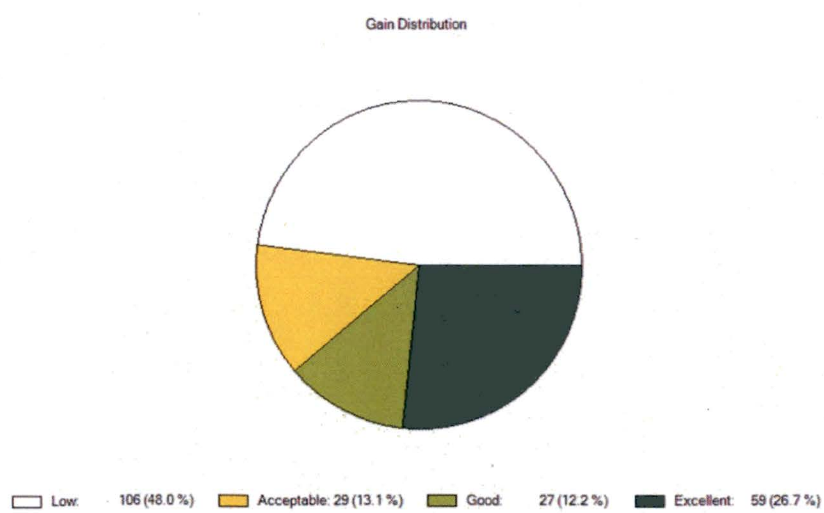

Figure 6-20
Sample model gain distribution

6.8 Evaluation of Potential Errors and Overall Accuracy of the DVR Plant Model and Application

From Table 6-10, the Sample DVR model uncertainty is <0.59% for the DVR calculated CTP. This uncertainty is calculated based upon the user specified accuracies for the DVR model inputs.

Potentially, other errors may exist for the DVR CTP uncertainty value. These include:

- Data scatter sampling error effects on the DVR results.
- Errors in the heat balance model, thermal kit, modeling errors, or incorrect plausible assumptions.
- Differences in calculation methods between the heat balance model source and the DVR model including use of different steam tables.
- Unaccounted for unknown performance changes in the plant operating cycle, or unmodeled performance changes.
- Unknown measurement errors.
- Belief that an instrument reading is correct, when it is not.
- Improper or incorrect assumed measurement uncertainties used when analyzing the data

Heat balance modeling errors may be inherent in the vendor heat balances, or data used to construct the software model. The issue of tuning the DVR turbine models was previously discussed in Section 6.3.4. Proper tuning of the DVR turbine models reduces potential errors with input turbine efficiency values used by the DVR model.

Use of different steam tables or calculation methods may be evaluated during the model validation and tuning steps (Sections 6.3.3 and 6.3.4). The possible error effects on the DVR CTP results may be bounded by specifying conservative uncertainties for input variables which are potentially affected. Otherwise, additional error margins for the DVR CTP uncertainty may be developed and applied to the final results.

Unaccounted for performance changes in the cycle, or unmodeled performance changes are another potential error source. These types of changes may include cycle isolation leakages, such as leaking valves or steam traps that have not been included, or accounted for, in the heat balance model of the plant cycle.

Sensitivity analyses have been performed for the Sample DVR model to study the effects of unmodeled turbine cycle leakage on the calculated DVR CTP results. The analyses show that approximately cycle leakages equivalent to up to 1% gross electric output will be bounded within the base tuned model uncertainty of about 0.59%. The error bounding is due to the conservative assumptions of the turbine efficiency values (2% for each stage and 5% for the last LP stage), which yields about 1% gross output uncertainty for the DVR model.

Unknown measurement errors may occur when an instrument reading is believed to be correct, and it is not. These types of errors may occur by not checking the calibration history of the plant measurements, having an improper calibration, or some other system phenomena occur that affect the accuracy of the measurement. The DVR process can often identify these errors based on redundancy with other measurements and the size of the error.

Improper or incorrect assumed measurement uncertainties used when analyzing the data during the DVR process may result in an improper fitting of the DVR results. Realistic values of plant measured data uncertainties should be used when conducting the DVR process. The uncertainties of the plant measurements should include not only the accuracies of the field devices such as pressure transmitter and thermocouples, but the entire instrument loop and measurement chain.

Measurement chain errors should be considered when developing measurement uncertainty values for the DVR model inputs. This includes the standards, or MTE (Measuring and Test Equipment), used when calibrating the field device and any potential errors caused by the field installation. Instrument loop errors may include signal conversion, data processing, and engineering unit conversion errors associated with the data acquisition system and plant process computer.

However, note that the measurement uncertainties for the DVR input variable are empirical uncertainties. These uncertainties should be based not only on analyses of the possible instrumentation measurement error components, but also on the field observations of the accuracy of the measurement. It is possible that plant instruments may measure much more accurately, and contain less error, than that estimated by analyzing the potential error components. Thus, in the case where a DVR model input uncertainty is based on field observations and fitting of the data with the DVR algorithm, the value of the measurement should be confirmed in the field with acceptable MT&E.

Once these potential errors are identified and bounding errors are developed for each category of error as described above, the total effect of the errors on the DVR process and the "actual" estimates may be objectively quantified.

The root mean square method can be used to combine the error terms for each plant measured or calculated variable, such as CTP, as follows.

1. For each measurement, use the reconciled uncertainty (RCU) calculated by the DVR process.
2. Create bounding modeling error uncertainty estimates (BME).
3. Estimate the error effect of unmodeled performance changes as an uncertainty (UPC).
4. Estimate the error effect of Unknown measurement errors (UME).
5. Estimate the error effect of incorrect assumed measurement uncertainties (AME).

Combine all the error effects using the root sum square method. Note all the error estimates should be calculated at a 95% confidence interval. Equation 6-1 below represents the overall DVR CTP uncertainty calculation.

$$\text{Total Most Likely Error of a DVR Estimate} = \sqrt{\boldsymbol{RCU}^2 + \boldsymbol{BME}^2 + \boldsymbol{UPC}^2 + \boldsymbol{UME}^2 + \boldsymbol{AME}^2} \qquad \textbf{Eq. 6-1}$$

As the error terms 2 thru 5 in Equation 6-1 are assumed, the values should be derived in order to bound the analysis within a specified uncertainty tolerance. For example, if DVR results on a measurement with an uncertainty of 0.5% at a 95% confidence are desired, the interval bounding the errors may need to be constrained, or limited, to lower values than a DVR result with an uncertainty of 1.0% at a 95% confidence interval. Smaller uncertainty requirements result in the reconciled measurement uncertainty having more weight than the assumed bounding errors on the total measurement uncertainty.

The bounding modeling error uncertainties may be obtained by analyzing the propagation of error into DVR results as the model is successively perturbed to simulate various model faults.

Unmodeled performance changes error estimates can be derived by a rigorous examination of physical plant to account for cycle isolation leakages or other physical faults within the plant. These faults may be incorporated within the model, or if sufficiently small a bounding uncertainty estimate may be derived.

Accounting for unknown measurement errors and incorrectly assumed measurement uncertainties will require a careful examination of the plant instrumentation calibration records and histories. Engineering reviews of how the instruments are installed and the overall instrument loop accuracies must be performed.

A summary of the resolution of DVR data is given in Figure 6-21. Each potential error component must be carefully analyzed to derive the final error effect on the DVR results.

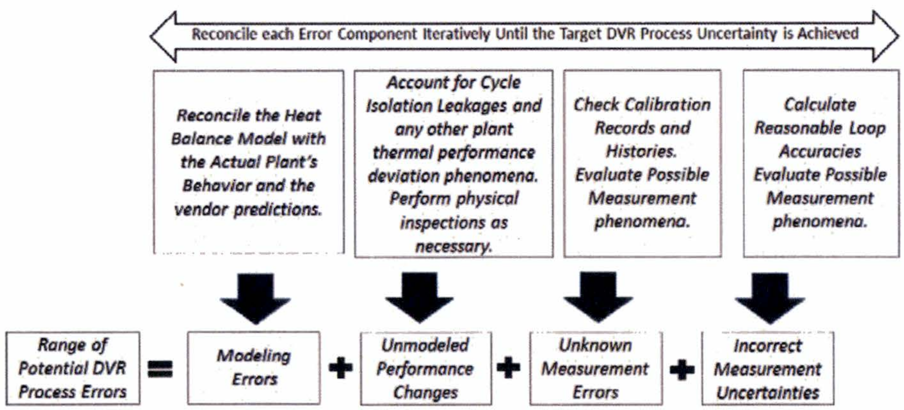

Figure 6-21
Overall DVR errors

6.9 Determine How DVR CTP can be used for Plant Operations

If the DVR CTP is used to correct the licensed plant calorimetric power, or is used to correct that power value, limitations of use must be established.

6.9.1 Establish Conditions When DVR CTP is Valid

- Power Range. As the DVR algorithm is highly linear in nature, the accuracy of the DVR results will be affected as the plant power varies. Therefore, a range of power levels should be established for when the DVR results are valid. This power range can be determined by assessing the quality and single penalty criteria (see Section 6.9.2) for data gathered during normal plant monitoring prior to implementing use of the DVR results to correct the plant CTP.
- Plant Configuration – Lineups and Evolutions. The DVR results can be significantly impacted by changes with plant lineups or evolutions that alter the normal plant operation. Plant evolutions such as turbine valve testing, condensate polisher operation, and condenser backwashing could affect the DVR results. Therefore, the DVR results should be monitored for validity during typical plant evolutions and criteria when the results should not be used must be developed.
- Critical Instrumentation. The CTP contributors that affect the DVR calculated value by greater than 0.5% (or specified value) of the value should be identified and categorized. These instruments may requirement development of improved calibration procedures including calibration methods, frequency of calibrations, and documentation. Identification of methods to reduce the overall impact of an instrument failure for a significant DVR CTP contributor may be considered (e.g. addition of a redundant instrument).
- Unmeasured Cycle Leakage. As unmeasured steam leaks or component failures may occur during a typical plant operating cycle, the impact on the DVR results must be determined. Demonstration of how these changes are captured with the DVR process quality controls should be developed. Sensitivity studies may be performed to establish margins or bounding conditions for the DVR results.

6.9.2 DVR Results Acceptance Criteria and Mitigation Techniques

When assessing DVR results, acceptance criteria for the results should be developed and used. The DVR algorithm contains a number of calculations and error checking methods to ensure the validity of the calculations.

The DVR results should be checked for:

1. The run has successfully converged.
2. VDI Quality Criteria 1 [1] for the entire process is met for the run. The Quality < 1.00.
3. VDI Criteria 2 [1] is met for each set of measured data. Single penalty values for measured data points that ≥ 3.84 are represented by flagged tags. Flagged tags must be evaluated for their possible effect on the DVR CTP results.
4. Trends of the DVR Quality value may be helpful for detecting abrupt or slow changes with the quality value which may be indicative of a plant process or instrument reading change.
5. Review the DVR CTP accuracy value to ensure the value is contained or bounded within the overall DVR CTP uncertainty (including any additional conservative error margins that may have been applied).

Mitigation techniques to recover acceptable DVR results in the event of a failure of an instrument important to the overall DVR CTP results can be developed. When the single penalty of a measured data point ≥ 3.84, the instrument is outside its input accuracy. For a measured data point that is a significant contributor to the DVR CTP results, the uncertainty or accuracy of the DVR CTP results will be affected. However, the DVR algorithm will still properly calculate the uncertainty or accuracy of the DVR CTP results.

Potentially, a single or several measured data points could fail to adversely affect the DVR CTP results and cause it to exceed an acceptable level. Therefore, it may be desirable to develop mitigation methods for these scenarios. Referring to Table 6-11, the inputs important to the DVR CTP results are given. A significant change with any of these inputs has the potential to adversely affect the DVR CTP results. For cases where these tags are flagged, the decision will need to be made to reject the DVR CTP results, or accept the results which may yield a higher, or less accurate DVR CTP results uncertainty.

Limitations and failure modes of the DVR model results and DVR technology in general are further examined in subsequent sections of this report. The information in these sections should be used to develop a set of unit specific techniques and criteria to ensure the proper use of DVR results.

6.9.3 Implementing a DVR CTP Based Correction Factor

Results from the DVR calculations may be used to implement a recalibration of the licensed core power feedwater flow rate measurement devices, provided the DVR method's accuracy or uncertainty is sufficient to ensure the site's licensed reactor core power uncertainty is maintained. These "recalibrations" may be implemented as correction factors on the base feedwater flow calibration factor or the feedwater flow rate itself.

Implementation of DVR CTP based feedwater flow meter correction factor requires:

1. Evaluation and determination of the overall DVR CTP uncertainty for the Feedwater Flow correction method.
2. Determination of plant conditions when the DVR CTP results are valid.
3. Determination of plant conditions when the DVR CTP results are not valid or may be suspect.
4. Develop simple, alternative CTP checking methods to enable quick checks of the DVR CTP results.
5. Establish bounding limits for the feedwater flow correction factor, or correction factor (FWFCF or CF).
6. Develop mitigation techniques.
7. Develop criteria when the DVR Model and CTP results are acceptable and may be used. This includes setting limits for the DVR calculation metrics for Quality and single penalty values for the tags that are significant CTP uncertainty contributors.

8. Development of Plant Procedures and Software, Design, and Administrative Controls to implement the DVR model and the Feedwater Flow correction method. Refer to Section 2 for additional details.
9. Evaluation of any impacts on the current licensing basis. Refer to Section 2 for additional details.

Plant conditions to consider when implementing a DVR CTP based feedwater flow meter correction factor requires:

1. DVR CTP results valid power range.
2. Determination of plant operating alignments and equipment in service for when the DVR CTP results are valid.
3. If the flow metering is subject to the calibration being altered due to fouling or de-fouling, conditions for when such events could occur must be identified such that any DVR based correction factor is not applied while an event is occurring. Water chemistry conditions that could affect flow element fouling should be monitored.
4. If ultrasonic feedwater flow metering (UFM) are used, DVR may be used to perform additional studies to further evaluate the in-plant performance over time. This may useful for developing better UFM maintenance practices.

There may be occasional DVR model runs or periods when these criteria are not met caused by temporary anomalies or changes in plant operation/alignment. The correction factor will still be valid as long as these are temporary isolated events and do not represent long term changes to plant operation.

6.9.3.1 Feedwater Flow Correction Factor (FWFCF) Implementation Procedure Details

The FWFCF will be updated periodically. The requirements are given below. This procedure notes use of a Calibration Validation and Calibration Check. A full Calibration Validation is typically required periodically. A suggested period is every 18 to 24 months. However, a longer or shorter interval may be necessary or appropriate based upon the actual drift performance and calibration intervals for the instruments that contribute >0.5% DVR CTP uncertainty. Additional details are given below in Section 6.9.3.3.5.

6.9.3.2 Frequency and Application of the FWFCF Calculation Results

The FWFCF will be implemented periodically based upon the observations and characterizations of the types of errors observed with the plant feedwater flow measurement system. For plants that exhibit sporadic feedwater flow measurement errors due to problems such as flow element fouling and de-fouling [19], the FWFCF may be calculated and applied more frequently than a plant where constant, bias errors with the feedwater flow measurements are observed.

1. Determine the FWFCF implementation period.
2. Execute the FWFCF procedure and apply the FWFCF.

3. Continuously monitor the FWFCF to ensure established bounding limits are not exceeded. DVR acceptance criteria for the Quality <1 and single penalty values < 3.84 for significant DVR CTP contributors for the FWFCF at minimum are applied.
4. The FWFCF is considered invalid if the established bounding limits are exceeded or DVR acceptance criteria are exceeded. An assessment by engineering is required.

6.9.3.3 FWFCF Procedure

6.9.3.3.1 Prerequisites and Acceptance Criteria

The prerequisites and acceptance criteria are given below in Sections 6.9.3.3.2 through 6.9.3.3.5.

6.9.3.3.2 DVR Model

1. Record model used for the procedure (Configuration Control).
2. Ensure software or hardware environment has not changed, or list changes.

6.9.3.3.3 Plant State

1. Plant CTP is within the DVR CTP results valid power range.
2. Normal lineups as defined in the DVR model design documentation.
3. At least 3 days minimum at or near 100% Rx power, and within the DVR CTP results valid power range.
4. Cycle isolation items – Cycle isolation items have been accounted for or will have no significant effect on the DVR CTP calculation (is bounded and less than 1% equivalent gross electrical output loss).
5. No un-accounted for thermal performance items.

6.9.3.3.4 Time Period and Sample Criteria

1. The minimum time period is 3 days' worth of data or 72 hourly samples, minimum.
2. Quality, during the period of interest, should be <0.5 (this will vary by the specific DVR model.
3. Change in Reactor Power, during sampling period <1%.
4. Correction Factor is not changing more than ½ the DVR CTP uncertainty value,
5. Some samples, up to 5% could be rejected and the results would still be acceptable. Use the Thompson-Tau method to eliminate outlying sample data. Reference 4 may be used for guidance regarding outlier sample data treatment.

6.9.3.3.5 Calibration Validations and Calibration Checks of the DVR CTP Contributors >0.5% Contribution

The FWFCF procedure will refer to the use of Calibration Validations and Calibration Checks. The differences between these two terms is explained below.

Calibration Validation

In general, a Calibration Validation has more rigor and is performed less frequently than a Calibration Check. A Calibration Validation is performed to ensure the instrumentation is within its rated calibration specifications from the vendor or tolerance value stated on a plant calibration record.

The drift performance of each instrument used as a DVR input is assessed to ensure the DVR accuracy input values will encompass the drift for the time periods between scheduled recalibration of the instruments. Historical calibration records are reviewed for a sufficient time period to characterize the drift performance of the instrument in question.

If there are insufficient records, or the drift cannot be characterized, the calibrations will need to be performed more frequently until the drift can be characterized and bounded to a value lower than the accuracy values used for the DVR input. For example, an instrument may have the calibration checked and adjusted, if needed, every 3 years. A review of the historical records shows the as-found and as-left values from each record for a 10-year period (3 records) shows drift of the instrument outside the value used for DVR input. In this situation the calibration interval frequency must be increased until the drift performance is bounded.

This process is repeated, and the calibration frequency adjusted until sufficient data is accumulated to demonstrate there is an appropriate calibration cycle for the instrument to support the DVR input value.

If there are insufficient calibration records to justify the DVR input value based on historical performance of the instrument, a calibration cross-check shall be performed. However, this is not necessary for every DVR input. For DVR inputs that have very conservative values a written engineering analysis and justification is appropriate.

For example, feedwater flow measurements typically have DVR input values that are several times the rated accuracy to avoid excess influence of the input on the DVR results. The engineering justification for this input would explain how the DVR input value bounds the accuracy of the instrument. Another example would be an instrument that has a conservative DVR input value and the instrument can be cross-checked to similar plant instruments that have calibration records. (The specific plant-unit FWFCF procedure would need to note the points cross-checked).

If there are insufficient calibration records, a cross-check cannot be performed, or the cross-check results are questionable, a calibration test will be required. A calibration test is a field or bench test of the instrument in question using M&TE (Measuring and Test Equipment). A calibration record would be created. An alternative to this is to install a calibrated test instrument in a test well or tap as close to the measurement in question as possible, or pull the instrument in question and install an M&TE test device to get a reading. The readings from the temporary test instrument are compared to the readings from the permanent installed device. The difference between these measurements shall be confirmed to be less than the DVR input values. If field measurements are performed records should be created such that drift performance can be characterized to avoid having to collect field data each time the FWFCF procedure is conducted.

The goal of the Calibration Validation is to ensure the DVR input values are reasonable, conservative, and are traceable to M&TE or engineering assumptions that can be validated.

Calibration Check

Calibration checks are simple checks of the calibration records of the instruments used as DVR inputs. For a calibration check, the record of the last and next calibration is noted.

6.9.3.3.6 Acceptance Criteria

1. The FWFCF calculated by this procedure is within 1 standard deviation of the DVR CTP uncertainty value (1/2 of the rated DVR CTP uncertainty) calculated from last execution of the procedure and within 1 standard deviation of the DVR CTP uncertainty value (1/2 of the rated DVR CTP uncertainty) from the last time the procedure was executed using Calibration Validation. This will ensure the FWFCF has not changed significantly and is within a normal repeatability range from the time when the procedure was last executed, and all DVR inputs had their calibrations validated.
2. If the FWFCF calculated by this procedure exceeds 1 standard deviation of the DVR CTP uncertainty value, the FWFCF has changed significantly from the last time the procedure was run. This means the feedwater measuring system has fouled, defouled, or may have other errors. In this situation the plant state will to be re-confirmed and a Calibration Validation performed.
3. None of the DVR CTP uncertainty contributors >0.5% contribution have single penalty >3.84.
4. Average Quality of runs < 1.0, or another set bounding limit.

6.9.3.4 Summary of Procedure Steps

A summary of the FWFCF calculation procedure follows and also given in is Figure 6-22.

1. Record DVR model used (and software environment)
2. Record Plant State.
3. Record Calibration method used for each point. This is a validation, a cross-check to a validated instrument, the engineering assumption for a point where a record is not available, the results of a field check, or the last and next calibration record dates for the instrument to show it is currently within calibration.
4. Collect the sample data. Cull the outliers per procedure methods and requirements.
5. Calculate the average FWFCF for the current period.
6. Compare the FWFCF to the value from the previous period.
7. Evaluate the results in terms of the Acceptance Criteria. If necessary, repeat the steps until the Acceptance Criteria can be met.

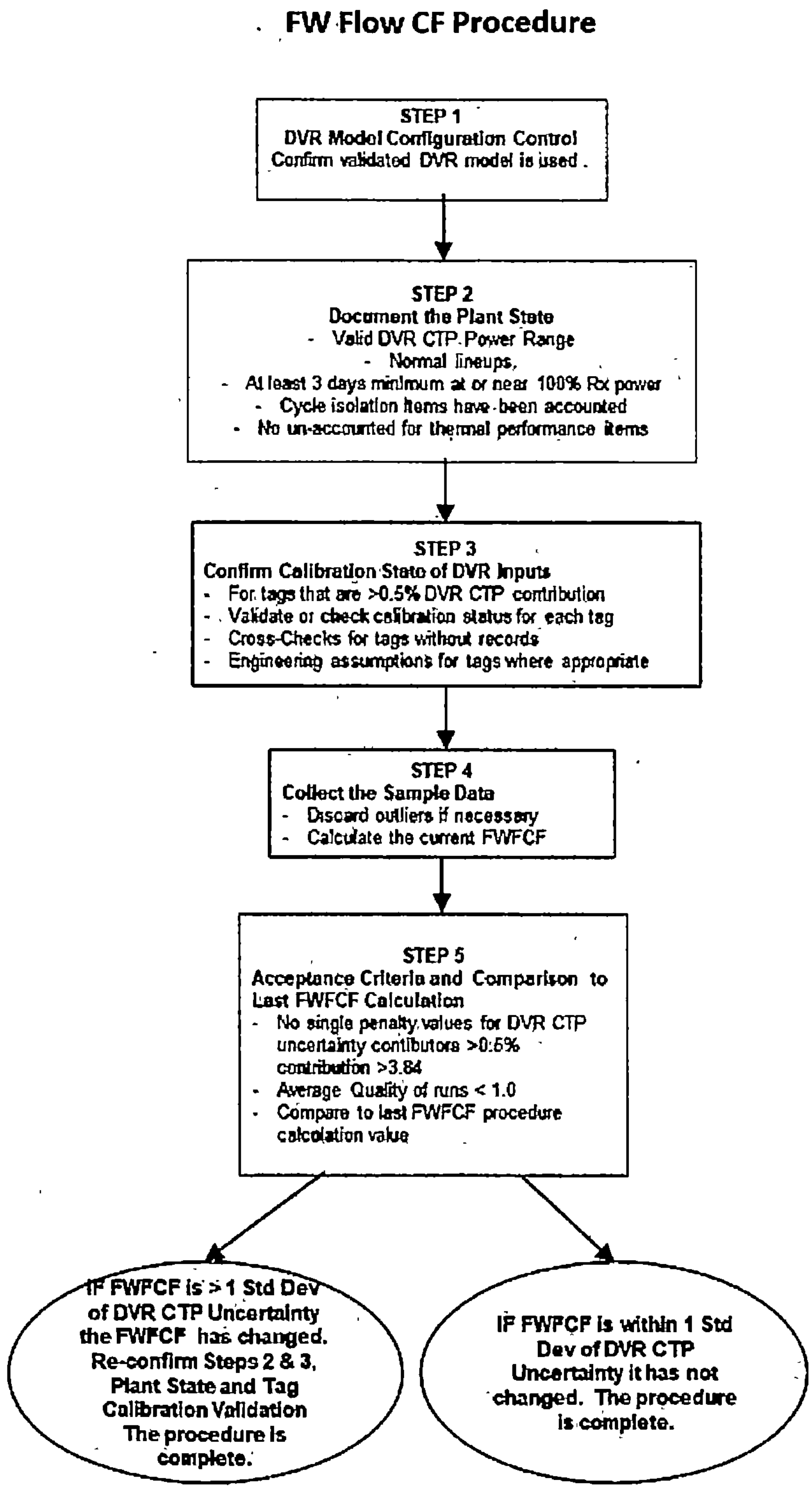

Figure 6-22
FWFCF calculation procedure summary

6.9.3.5 Additional Feedwater Flow Correction Factor (FWFCF) Implementation Details

Additional FWFCF implementation details are given as follows.

6.9.3.5.1 The FWFCF should be taken out of service when:

1. When the penalty value => 3.84.
2. When the Quality > 1.0.
3. When a DVR CTP contributor >0.5% contribution is flagged (>3.84)

The FWFCF should always be taken out of service under these conditions, however if the removal of the FWFCF could cause the CTP to be less conservative, it should be retained until the cause of the feedwater flow error can be determined. This should not usually be the case but is mentioned as the plant should fully understand when non-conservative corrections to the CTP are applied. In this situation, engineering may need to be consulted.

6.9.3.5.2 Transfer of the Calculated FWFCF to the Plant Computer

Use the calculated FWFCF and apply the sample standard deviation FWFCF to make the FWFCF more conservative.

6.9.3.5.3 Treatment of the DVR CTP Uncertainty Value

1. Normally the CTP uncertainty is not applied to the plant measured and calculated CTP value as additional margin. For plants that have licensed uncertainty margin of about 2% and are using the DVR CTP for power recovery efforts, DVR CTP uncertainties of <1% will ensure no additional CTP uncertainty is added when implementing the FWFCF on venturi or other non-UFM based feedwater flow measurement systems. In these situations, the DVR CTP uncertainty will typically be significantly more accurate than the base plant CTP flow measurement system. As the DVR CTP uncertainty is better than the base plant CTP uncertainty, the 2% licensed margin need not be altered.
2. For the case where the DVR CTP uncertainty is used as part of a MUR (margin uprate), a detailed calculation of the DVR CTP uncertainty is required. Section 8 provides additional details on this calculation.

7 DEMONSTRATION APPLICATION

7.1 Description of Administrative Controls for Implementing Results to Power Calculation

A licensee configuration control program should be in place and utilized for the initial implementation of the DVR Software Program and Model. This subsection will provide generic guidance for the licensee configuration control program. Plant specific requirements related to utility specific DVR implementation would need to be developed by the implementing utility.

A United States licensee's current Configuration Change process should be based upon the Industry Standard Design Process procedure IP-ENG-001 [23] that was developed by an industry engineering group and provides detailed guidance for developing design changes. EPRI has guidance for particular modifications provided in [77]. The initial implementation of DVR for a site could be administratively controlled as a design change due to the fact that there could be additional instruments required, and/or due to the interface with plant computer systems/networks. IP-ENG-001 is hosted on the INPO Nuclear Community site and is maintained by the Design Oversight Working Group. IP-ENG-001 includes screening criteria that allows selection of design change type depending on complexity and impact on bounding technical requirements, design basis functions and the plant-licensing basis.

The changes that do not affect these technical requirements, design basis and licensing can be designed using simpler processes. The following are the five types of design changes as implied in IP-ENG-001:

1. Document-Only Change—A change to a controlled engineering document evaluated by utility specific procedures that does not also involve or result in a hardware/configuration change.
2. Commercial Change—a change developed and implemented using codes, standards and good engineering practices typically applied during the design of structures, systems and components outside of nuclear jurisdiction. This includes use of national standards such as fire code, uniform building code, local and state standards, and other utility-defined design controls.
3. Design Equivalent Change—A change that does not result in an adverse change to those bounded technical requirements that (1) ensure performance of design basis functions or (2) ensure compliance with the plant licensing bases of either the item(s) or applicable interfaces including the applicable codes and standards to which the utility is committed.
4. Temporary Modification (Temp Mod)—a short-term alteration made to systems, structures or components that is not controlled by procedure or work order instructions and is evaluated via a temporary Commercial Change, Design Equivalent Change or Design Change.

5. Design Change—A change to those bounded technical requirements that (1) ensure performance of design basis functions or (2) ensure compliance with the plant licensing basis. Typically, this type will involve complex design changes with impact on design/licensing basis.

With the initial implementation of the DVR software/system it would be expected that the type of design changes could be similar to types 2) and 5) noted above. As such, administrative controls per a plant individual configuration change program would need to be implemented, and reference also to the terms that are put in IP-ENG-001. Once the DVR system has been implemented and if a future change is required the type of design change could fall under types 1) to 5) and would need to be evaluated for each proposed change. If the design change were for example to be only a document only change, a licensee may have a document request process program that could be utilized versus going through a more complex/detailed design changes process.

A licensee should have in place an explicit digital design guidance process for managing plant modifications that involve digital instrumentation, software/firmware and controls. If the licensee has the digital design guidance process, they should utilize this procedure or process in conjunction with the overarching configuration control process for both implementation and revisions to the DVR process. Potential types of design controls related to DVR will be explained in more detail in the design control subsection and is predicated upon portions of the generic process described in EPRI Report 3002002989 [24].

Depending upon how a utility plans to implement the DVR process may dictate whether the entire scope could be put in a utility design basis type program, such as flow accelerated corrosion, alloy 600 or similar utility programs. The reason for such would depend upon how the DVR processes are being utilized relevant to plant Core Thermal Performance monitoring and decisions made relevant to such (i.e., LCOs). Putting the DVR process into a utility-controlled design bases program ensures due diligence regarding the inputs to the model, how the data is stored/utilized/applied, and relevant to future changes that are made.

7.2 Description of Inputs to DVR Software

For the calculation of the DVR CTP, the developed and tuned DVR model is used with measured plant data. The DVR CTP calculation is composed of three fundamental elements which include:

1. The DVR model and software.
2. The model design inputs.
3. The plant measured data.

7.2.1 DVR Model and Software (As Inputs to the Final CTP Calculation)

The DVR model is constructed to represent the layout or topology of the plant. The model uses engineering calculations and steam table formulations developed by the DVR software vendor. The fundamental mathematical methods used by the DVR software vendor along with the engineering calculations and steam table formulations will have some effect on the overall DVR

CTP calculation. However, in general, these underlying calculation uncertainties tend to be quite small, and will have little effect on the DVR CTP uncertainty in plant use. See Section 8.5 for additional details on calculating the overall DVR model CTP uncertainty.

Calculation of these uncertainties may be performed using test cases by the DVR software vendor or the utility customer. The DVR software vendor may provide certification documentation or test cases which may be used to determine or bound the underling uncertainties associated with the DVR software. In Europe, DVR software is typically certified to VDI 2048 [1] standards. In the United States, no equivalent certification currently exists.

As the DVR software calculations potentially could change as new versions of the software are issued. The utility customer may need to place the DVR software and plant installation under an administrative software control process. This will ensure plant DVR CTP calculations are unaffected as new versions of the DVR software are issued and installed. The DVR software vendor may provide results from regression testing when new versions or patches of the software are issued. The utility customer may wish to conduct additional regression testing to ensure an existing DVR software and model installation is not significantly affected when DVR software is upgraded or patched.

7.2.2 DVR Model Design Inputs

Referring to Section 6.6 and Table 6-10, the overall DVR CTP accuracy or uncertainty is composed of accuracy, or error contributors, which comprise design input assumptions, along with empirically derived values of plant measured data uncertainties.

The DVR model design inputs are composed of items including:

1. Turbine stage efficiency values from the turbine vendor thermal kit or software heat balance model. These values may be tuned by the DVR model vendor for customer delivery. Plausible values of the accuracies of these inputs should be provided by the DVR model vendor.
2. Turbine stage moisture removal effectiveness. These are usually obtained from the turbine vendor thermal kit or software heat balance model. Plausible values of the accuracies of these inputs should be provided by the DVR model vendor. However, the accuracies of these variables may be contained or bounded within the turbine stage efficiency uncertainties as they primarily affect the turbine efficiency performance.
3. Moisture Separator Reheater (MSR) Effectiveness. These are usually obtained from the turbine vendor thermal kit, software heat balance model, or MSR vendor performance specifications.
4. Pump efficiencies. These are usually from pump vendor specifications.
5. Piping and valve pressure drops. These are usually obtained from the turbine vendor thermal kit, software heat balance model, or calculations based on isometric drawings.

The DVR model should use plausible values of the design inputs that can be traced back to vendor design specifications. Otherwise, plausible values should be developed, based upon good engineering practice and documented. Documentation for the sources of all the DVR model design inputs should be provided by the DVR model provider.

7.2.3 Plant Measured Data Inputs

Section 6.2.1 provides a list of plant instrumentation typically used as inputs for the DVR Model. Table 6-1 provides a general summary of the effects of various plant measurements on the DVR CTP accuracy. The DVR CTP accuracy contribution for a plant measurement varies depending on the number and type of available plant measurements, plant design and topology of the DVR model. Therefore, DVR CTP accuracy contribution values are unique for each DVR model.

Plant measured data accuracy values for input to the DVR model are developed based upon available manufacturer performance specifications, plant calibration records, or conservative estimates of the in-situ field accuracies of instruments in question, based upon industry experience with similar devices.

During the DVR model development and back-testing process (see Sections 6.3 and 6.4), the plant measured data accuracies may be refined based upon overall fitting of the DVR CTP and results.

As noted in Section 6.7, the measurement uncertainties for the DVR input variable are empirical in nature. Thus, for cases where the DVR model input measurement accuracy estimate is lower (more accurate) than available documentation, the value of the measurement should be confirmed in the field with calibrated Measuring and Test Equipment (MTE). DVR model plant measurements which are significant contributors to the DVR CTP calculation may require field verification to justify the reconciled DVR CTP calculation accuracy.

The utility customer will need to help the DVR model vendor with confirmation of the empirical plant measurement accuracy values used for DVR model inputs.

Records of the empirical plant measurement accuracy values should be maintained by the plant and should be treated as design inputs to the DVR model. Modification of the values by the vendor or plant staff may require engineering evaluations.

7.3 Description of Design Control and Documentation Requirements

Documentation of the DVR model should include details of calculation methods, design inputs, and results of model tuning and testing of the models to ensure their quality. Details on the documentation and testing requirements are given in the following sections.

7.3.1 Functional Design Specification

A Functional Design Specification (FDS) will be developed for each site as part of DVR implementation. The FDS provides the site explicit modeling process and configuration. The site specific FDS will include very detailed information regarding the model basis which would include components (reactor, turbines, moisture separators, feedwater heaters, etc.). The basis for how each component, system and verification against the design inputs and actual plant measured data will be discussed.

The FDS document and process will include at least the following sections; 1) modeling process description, 2) model configuration discussion, 3) a model basis, model output with plant data, 4) applications and basis. For example, the model process description section may include the following details:

- Overall process quality measurements
- Individual parameter quality measurements
- DVR model development and tuning
- Uncertainties

The model configuration section would include design inputs used for the site DVR model. The site DVR models would typically include a reactor, major turbine cycle equipment, reactor recirculation, and reactor water cleanup for BWRs and reactor, nuclear steam supply system, and major turbine cycle equipment for PWRs (see detailed list in subsection 6.2.1).

The Model Basis section would go into further detail regarding each component included in the model, such as detailed design information, uncertainties and model assumptions related to the reactor, throttle valves, turbines, moisture separators, feedwater heaters, steam generators, main steam pressure drops, etc.

The section addressing model output with plant data would describe in detail the process of model tuning, tuned model results, and results from model testing.

The last section would provide information regarding applications and a basis for the model. This section will be critical as it address use of the DVR CTP results to implement plant CTP correction factors.

Details on the DVR CTP uncertainties and major error contributors for the plant calculations, as described previously in Section 6.6, shall be provided in this section.

This last section will provide comparisons of the DVR model to the conventional CTP model to illustrate use of a significantly higher number of instruments than are currently used in the determination of feed flow and core thermal power. This process will help illustrate the lack of susceptibility to a single instrument failure resulting in an error to the calculation of core thermal power.

Some plants may currently experience a bias error to the feed flow measurement which causes the calculated core thermal power to be higher than the actual core thermal power. The DVR model identifies and corrects this flow bias to a value that best fits other plant instruments. Using the model's continually updated measurement corrections, the operators would still know the true reactor power due to the diverse array of alternate power measurements available.

A brief discussion of each element of the proposed DVR model FDS is discussed next.

7.3.1.1 Modeling Process Description

Only a high-level discussion will be provided for this topical as an example. The detailed FDS would include all aspects of the model process description that would be necessary for each licensee. The section of the FDS that addresses the model process would typically include the following information:

- Summary of the DVR process
- Overall Process Quality Measurements
- Individual Parameter Quality Measurements
- DVR Model development and tuning processes

This section of the FDS would include discussion of the Gaussian correction methods and equations related to the DVR process. Discussion of the DVR Objective Function (overall error minimization function), overall process quality, and individual parameter quality metrics in relation to VDI 2048 [1] acceptance criteria shall be provided, as further detailed in Sections 6.8 and 6.9. This allows for comparison of the mathematical methods used by the DVR model and software to relevant standards that provide guidance related to the DVR calculation methodology.

7.3.1.2 Model Configuration

The model configuration section of the FDS will address plant specific items such as the plant design inputs for the DVR model development. These design inputs will define plant components such as the reactor, major turbine cycle equipment, reactor coolant systems, steam generators and other relevant systems. Use of the plant specific data will be described in detail, and a list of plant equipment used in the model along with the systems will be included. This section will include figures to illustrate the overall model, reactor, turbine section, feedwater heater, and other system process flow diagrams developed using the DVR software.

7.3.1.3 Model Basis

A significant part of the FDS will be in documenting the model basis. This section of the FDS will provide explicit details about inputs, assumptions and equations that are used for the for the DVR model. These details help to define the auxiliary conditions calculations, as previously discussed in the Methodology Section 3.0, and discussed in VDI-2048 [1]. The auxiliary conditions define the mass and energy balances, and other performance calculations for components that comprise the plant system model.

This section of the FDS may include equations for valve pressure drops, turbine efficiency, and pump powers. How these equations are used in the model will be explained and justified. This section will also illustrate any curve fits used say for moisture removal, turbine efficiency and initial model results.

Included in this section of the FDS will be a subsection to discuss the model verification with an ideal data set. The ideal data set is typically obtained from a heat balance diagram from the turbine vendor thermal kit or heat balance software model. The ideal data set represents the reference, design calculations for the plant and component performance with no measurement errors.

The DVR model is run with the ideal data set as inputs and the output calculations and data are compared to the reference calculations. Differences may occur due to use of different steam table formulations, calculation numerical methods (convergence criteria and numerical precision), or model assumptions. Any differences between the DVR model results and the reference are noted and accounted for.

Typically, a < 0.1% difference with mass and energy balance differences between the DVR model and the reference data is obtained as further detailed in Section 6.3.3. Differences in this range will have an insignificant impact effect on the DVR CTP error uncertainty. If differences exceed this amount, further engineering evaluations may be necessary to reconcile the differences and their potential impact on the DVR calculations when DVR is used to calculate the plant CTP.

7.3.1.4 Tags Configuration

A "tag" is nomenclature in this Topical Report for a specific plant measurement, calculation result or assumption that is specifically identified and input into the plant model database. The tags configuration of the FDS will identify what tags are accepted from the plant computer and will list the variety of physical units for each tag. Once imported to the DVR model the units are then converted to a set of default units that will be summarized and identified in this section. Each of the tags in the DVR model will have an associated uncertainty value. These uncertainties provide the model with flexibility that the reconciliation process uses to find the best reconciled solution. All the tag uncertainties are assumed to follow a normal distribution and the default confidence level is 95% (or a standard deviation 1.96 σ). The initial site-specific measurement uncertainties are developed based on plant specific calibration data, typical industry calibration values for the types of instruments used for the explicit plant, and/or previous DVR experience. A table will be provided in this section of the FDS to provide a sample of tags and uncertainty values used for the model (see Table 7-1 below for an example). A complete listing of the tags and uncertainty values used for the model will be documented in the FDS. Any uncertainty values that deviate from the documented uncertainties should be identified and justification provided for the value used. Generally speaking, uncertainty values that are higher than documented uncertainties are expected and acceptable whereas values lower than the documented uncertainties would require justification for use. Expected uncertainties are those based on the type and model of instrument used and the plant calibration data sheets or typical vendor performance specifications. Installation effects may also need to be considered.

Table 7-1
Sample DVR model uncertainty by tag

Tag ID	Description	Units	DVR Uncertainty (±)
	GEN 1 GROSS MW OUTPUT	MW	0.50%
	FW FLOW A (FILTERED)	Mlb/h	2.00%
	FW FLOW B (FILTERED)	Mlb/h	2.00%
	STEAM DOME PRESSURE	psia	1.00%
	NARROW RNGE RX PRESSURE	psia	0.70%
	WIDE RNGE RX PRESSURE	psia	2.80%
	RTR FW INLT TEMP CH A	deg F	1.25
	RTR FW INLT TEMP CH C	deg F	1.25
	RTR FW INLT TEMP CH B	deg F	1.25
	RTR FW INLT TEMP CH D	deg F	1.25
	LP TURB 1A INLT CIV2 TMP	deg F	3.00
	LP TURB 1B INLT CIV1 TMP	deg F	3.00
	LP TURB 1A INLT CIV3 TMP	deg F	3.00
	LP TURB 1B INLT CIV4 TMP	deg F	3.00

7.3.1.4.1 Plant Computer or Historian Configuration Settings

The source of plant measured data for input to the DVR model calculations may be the plant computer or a data historian such as OSI PI or eDNA.

Details on the data source, tag unit conversion, and averaging intervals used for the data as input to the DVR model will be documented.

Where data are averaged by a measured plant data source, the method and interval of averaging are evaluated to determine the potential effects of data scatter on the DVR model calculations and results. Results of this evaluation should be included in the FDS.

7.3.1.5 Model Output with Plant Data

The model output section of the FDS will address the tuned model results and provide a brief description of the functional acceptance test (FAT). The detailed FAT is discussed in Section 7.3.3 and will not be addressed in this subsection further regarding the FDS. This section will include a brief summary of the vendor FAT as well as the actual tuned model results from the initial plant data set.

During individual plant model development plant data will be run through the model to understand the impact of modeling decisions and refinement of assumptions and inputs will occur. It is anticipated that plant model data sets will be used to illustrate good model convergence and that recent data is utilized at the time of model development. Results from the final model will be summarized in this section. An example of a tuned model result from initial plant data set is shown in Table 7-2 below, and it is anticipated that a complete list of model outputs would be documented as well as part of the FDS.

Table 7-2
Tuned model results from initial plant data set

Run QUALITY: 0.7323				
Flagged Tags: 6				
Reconciled CTP Uncertainty: 0.582%				
Tag ID	**Description**	**Units**	**Measured**	**Reconciled**
	GEN 1 GROSS MW OUTPUT	MW	1116.80	1116.32
	FW FLOW A (FILTERED)	Mlb/h	7.49372	7.40674
	FW FLOW B (FILTERED)	Mlb/h	7.25991	7.17877
	Core Thermal Power	MW	3421.55	3380.81

As seen in the table above for this example the run Quality is 0.73, which is below the 1.00 maximum specified by VDI 2048 Criteria 1. There were still 6 plant measurement tags flagged by the model. This means that VDI 2048 Criteria 2 has not yet been met. However, a review of the tags for this particular example as part of an example FDS illustrated that none of the flagged tags have an effect on thermal power, feedwater flow, or gross generation. In other words, the flagged tags did not have a significant impact on the model results. These tags were left in their flagged state for the site-specific FAT to allow for a more comprehensive review of flagged tags over an extended period of time.

The results from the example below contains a summary of the results from the FAT. The main criteria for passing the test, as outlined in the Functional Acceptance Test documentation Section 7.3.3, is at least 95% of the runs in the FAT must be successful.

The example successful FAT runs shown in Table 7-3 below had an average Quality of 0.744 and the Core Thermal Power Uncertainty did not exceed 0.59%. The example results can be documented graphically as a function of quality and number of flagged tags versus a date, and also the % uncertainty for the reconciled thermal power by date.

Table 7-3
Summary of example FAT results

Description	# of Runs
Total # of attempted runs	470
Failed Runs - attempted runs that failed to produce results	6
Failure of VDI Criteria 1 - completed runs with Quality > 1.00	9
Failure of VDI Criteria 2 - completed runs, met Criteria 1, but have flagged tags that affect CTP	5
Disqualified Runs - completed runs, but plant was not in normal operating alignment assumed by model	16
Total # of Valid attempted runs (Total - Disqualified Runs)	454
Total # of failed runs (Failed runs+ VDI 1 failure +VDI 2 failure)	20
% Successful	95.6%
% Failure	4.4%

7.3.1.5.1 Flagged Tags

In the example in Table 7-3 above a number of flagged tags were identified during the initial tuning of the model. Some additional flagged tags were identified during the Functional Acceptance Test (FAT) as noted above. A flagged tag can be eliminated by increasing the uncertainty associated with the measurement or by turning the tag OFF (which effectively removes it from the model).

7.3.1.6 Application and Bases

The application and bases subsection of the FDS will address the following items.

1. Viewing model results.
2. Effects on the DVR CTP uncertainties due to steam table differences, modeling assumptions, or any other assumptions related to the DVR model inputs or measured plant data.
3. Applications of the DVR calculation of CTP for plant use.

Viewing model results is discussed in the FDS to illustrate to the licensee how to view results from the DVR model in a separate DVR Display spreadsheet that will be developed to provide quick access and viewing of model output. The spreadsheet will be designed to retrieve data from a database where the DVR model stores results. Details of the specific functions and features of the DVR Display spreadsheet can be found in the DVR Display User Manual. As part of a typical DVR display a screen to show the correction factors along with summarized significant parameters from a model is provided.

Overall DVR CTP uncertainties will be determined to cover steam table differences with the design data reference inputs or plant CTP calorimetric calculation, modeling assumptions, or any other assumptions related to the DVR model inputs or measured plant data.

The overall DVR CTP uncertainty should be considered in relation to the plant licensed calorimetric uncertainty. This is critical when comparing the DVR results to plant calculated values or when applying the DVR CTP values as a power recovery method, or plant CTP or feedwater flow correction factor.

Applications of the DVR calculation of CTP for plant use include the application of DVR CTP values as a power recovery method and for implementation of DVR CTP based correction factors on the plant feedwater flow measurements or CTP calculations.

7.3.1.6.1 Implementation of DVR CTP Based Correction Factors

Another significant aspect of the FDS is discussion related to the implementation of the correction factor calculated with the DVR application.

The DVR based feedwater correction factor may be affected by the DVR calculation interval time and the data scatter of the averaged plant measured data used for input.

When developing an average plant feedwater correction factor based upon multiple DVR model runs and results and additional random uncertainty should be considered for each DVR run. While the DVR model will assign an uncertainty to each individual correction factor value it calculates, the random variation is not accounted for by the model and must be added separately. In accordance with the methods from ASME PTC 19.1 [5] the random uncertainty of a data set can be calculated as follows:

$$\varepsilon_{random}(\%) = \frac{S_{t(n-1,\alpha/2)}\frac{s}{\mu}}{\sqrt{n}} * 100 \qquad \text{Eq. 7-1}$$

Where:

$S_{t(n-1,\alpha/2)}$ = Student t-test value for 95% confidence level

s = Standard deviation of data set

μ = Average value of data set

n = Total number of data points

For the application of FW loop correction factors (say if assuming only two loops A and B), the total uncertainty can then be evaluated for its impact on total feedwater flow. The following equations are used in accordance with ASME PTC 19.1 [5] methodology.

$$\varepsilon_{CF\,Tot\,random} = \sqrt{(w_{CF\,A} * \varepsilon_{CF\,A\,random})^2 + (w_{CF\,B} * \varepsilon_{CF\,B\,random})^2} \qquad \text{Eq. 7-2}$$

Where:

$\varepsilon_{CF\,Tot\,random}$= Total random uncertainty of both FW correction factors

$\varepsilon_{CF\,x\,random}$ = Random uncertainty of correction factors, x = A,B

$w_{CF\,x}$ = weighting factor $(\frac{FW\,A\,Flow}{FW\,Total}, \frac{FW\,B\,Flow}{FW\,Total})$

$$\varepsilon_{Total\,CF} = \sqrt{\varepsilon^2_{CF\,Tot\,random} + \varepsilon^2_{FW\,Total}} \qquad \text{Eq. 7-3}$$

Where:

$\varepsilon_{CF\,Tot\,random}$= Total random uncertainty of both FW correction factors

$\varepsilon_{FW\,Total}$ = Uncertainty of total FW flow for correction factor averaging period (calculated by DVR model)

In addition, as part of the licensee FDS established criteria must be documented and met before the DVR results can be considered valid and the feedwater flow correction factors are implemented. Specifically, for a selected time period when a correction factor is calculated certain typical conditions must be established in the FDS, such as:

- A reactor power change can only change a set value from the average reactor power during the selected time period.
- The plant must be in a normal operating mode with all normally operating equipment in service. For example, flushing of demineralizers is considered a non-normal alignment of the DVR model. The exception to this requirement is that the model for plant operation when flushing the demineralizers has been developed to handle that particular operating mode in which case it can be used to determine the correction factor.
- The DVR model quality shall be less than 1.0 per VDI Criteria 1.
- Alternate indications of flow through the turbine cycle such as Turbine stage pressure limits must be established.
- If there are any measurements in violation of VDI Criteria 2, the tags shall be recorded and evaluated to determine the cause. If any of the flagged tags affect the CTP value, they need to be addressed before the correction factor is implemented. A table that lists tags which contribute towards the total CTP uncertainty will be established. The FDS will prescribe which tags flagged by a model that would conclude an invalid feedwater flow correction factor.
- If there is a history of feedwater flow fouling that affects measurements, the DVR model will be evaluated for correction of the fouling. Future changes in fouling would need to be monitored as to if they will increase and cause the model to be flagged. It should be noted that if increased fouling occurs that affects the model, it may need to be adjusted by increasing the uncertainty of the feedwater flow measurement and documented through a configuration change process.

7.3.1.6.2 Limitations of the Correction Factor

The plant specific FDS will identify correction factor limitations including:

- Correction factor calculated with DVR results must be calculated with a core thermal power value within ±5% of the previous calculation.
- If plant events occur that could result in a change in the nozzle fouling the correction factor may be set to 1.0 and an evaluation of the correction factor will be performed. Administrative controls for the correction factor should be governed by station procedures.

- Plant events that could result in a change in the nozzle fouling include:
  - Final feedwater temperature changes greater than 5 Deg F [-15 Deg C].
  - Significant changes in plant chemistry such as Feedwater/Condensate chemistry transients including pH, oxygen, and iron.
  - A change to the chemical treatment process such as a change to noble metal injections or dispersant injections in PWRs.
  - Significant changes to plant line ups such as removal of MSR reheat steam or taking feedwater heaters out of service.

The criteria for valid results listed in the plant specific FDS must be maintained for the continued application of the correction factor. There may be occasional model runs or periods when these criteria are not met caused by temporary anomalies or changes in plant operation/alignment. The correction factor will still be valid as long as these are temporary isolated events and do not represent long term changes to plant operation.

7.3.2 Software Controls

The purpose of this subsection is to discuss from a high-level recommended process that should be put in place by the licensee related to appropriate controls of the DVR software and required documentation prior to software installation. Control of the DVR software is necessary to ensure that the systems functions properly and provide valid results. This subsection will describe good business practices for computer processes that would be important for a licensee that is implementing the DVR software application. The DVR software application should be maintained and enhanced in coordination with the licensee IT groups. The DVR software application is considered a unique set of software routines developed using general purpose commercial software, which is used to manage, monitor, calculate, indicate, and report on or store equipment or data information. It is also considered a software application that plant personnel may use for operations, maintenance or decisions relative to station reliability, power measurement calibration, economics and/or business needs.

7.3.2.1 General Requirements

Documentation should be generated to support the life cycle expectations of the DVR software. A software configuration management plan should also be developed in accordance with the site classification levels for the DVR software. Software control measures should be identified and documented in procedural format but should not replace activities that are required by regulatory commitment, specified by other licensee programs, or directed by site management.

7.3.2.2 Software Requirement Documents

Licensee implementing documents need to be verified that they have been created for the new DVR software prior to it being placed into production. The completed implementing documents should be reviewed and approved per the site software review committee, similar group/organization, or site software review process. Final production versions of the DVR software implementing documents are recommended to be submitted to document control or configuration management for formal publishing.

The site Software Quality Assurance (SQA) plan previously discussed in Section 2 needs to be established as part of the licensee process.

The licensee SQA plan as a minimum should address the following regarding requirements and process:

- All DVR applicable software products
- Departments responsible for performing the work
- Delineation of vendor responsibilities for assigned control measures
- Required documentation
- Standards and conventions used
- Methodologies that were used to develop the software

The SQA plan to be established by the licensee as minimum should also address the following:

- Methods of performing software reviews
- Methods of error reporting and corrective actions
- Methods for identifying and tracking software change requests for new systems added
- Changes to existing systems including resubmittal of software inventory forms and function analyses

The SQA plan to be established by licensee further should address:

- Controlling the software configuration throughout the life cycle
- Methods to test software and determine accuracy
- Control of interfaces between departments working with the software
- Methods of approving/releasing dvr software for operational use
- Methods of performing maintenance on dvr software
- Methods of decommissioning the software from production use, including any retention and archival requirements for documentation, tests, and computer program code

Additionally, it is recommended that information should be detailed such as methods of migrating software to other users, methods of updating service pack releases and hot fixes, and methods of installing the software for the production environment.

7.3.2.3 Software Requirement Specifications

The licensee should also establish software function requirements and define interfaces with other software and hardware as part of the DVR implementation process. The software requirements specification (SRS) can be established in conjunction with vendor provided information for DVR software. It is recommended as a minimum that a site SRS should address the following for implementation of DVR software:

- Functions the software will perform
- Performance (time-related) issues if any
- Design constraints that restrict design options
- Attributes of the software and external interfaces with personnel and other software/hardware

7.3.2.4 Software Design Descriptions

The licensee should establish a software design description (SDD) document to identify specified requirements for the DVR software. This document can be based upon vendor provided information, but also should contain as a minimum:

- A description of the major components of the DVR software design as related to requirements
- A technical description of the software
- Allowable or prescribed ranges of the inputs and outputs for functions or modules

7.3.2.5 Acceptance Test Plan

The DVR Site Acceptance test plan (ATP) shall be implemented to ensure that it produces the correct results and operates correctly on production systems. The site ATP incorporates methods to document the following:

- Development of test cases to exercise the DVR software
- Identify DVR failures based upon the results obtained
- Proofed or corrections if any
- Evaluate adequacy for comparing software results to those obtained from established acceptable alternative methods
- Documenting test results and their acceptability
- The ATP should include tests of individual modules or subsets of the software, integration tests of the combined software, and installation tests (i.e., checkout of the software) in the production environment

Section 7.3.4 addresses the anticipated proposed DVR software site acceptance test that includes the items identified above. The proposed DVR SAT should be documented as part of the site DVR ATP.

7.3.2.6 Software Verification and Validation Plan

It is recommended that a licensee establish a site-specific Software Verification and Validation plan (SVVP) for the DVR software. This plan can utilize vendor specific information in development of site- specific processes. The purpose of the SVVP is to ensure consistency throughout software life cycle and ensures that finished DVR software satisfies specified requirements. Site verification of the DVR software installation activities is recommended to include a series of planned reviews as follows for example:

- Review the DVR software requirements specification to ensure requirements of software are complete, verifiable, consistent, and technically feasible
- Review the DVR software design description to evaluate technical considerations, assure correctness, and verify design incorporates requirements
- Review SDD to ensure completeness and acceptability of the SRS
- Verify design documentation is in configuration management processes
- Verify software user documentation is in configuration management processes
- Verify the ATP documentation for DVR
- Verify the SVVP documentation for DVR

The reviews noted above for verification can be combined if appropriate and performed in a timely manner during development process. All review findings and comments should be documented with disposition as part of the verification plan. Validation of the DVR software is also necessary and part of the implementing process. Validation activities of the DVR software as a minimum would include the following:

- Validation of the SRS
- Execution of the ATP
- Comparing DVR expected results
- Determining acceptability based on specified criteria (to be developed with DVR vendor and site)
- Document, review and approve results
- Report differences

If modifications are made to the DVR software as part of the modification process, then selective testing should be performed to ensure that the modification(s) have not caused any unintended adverse effects and to ensure the modified system(s) or system component(s) still meet site specified requirements. Independent DVR software verification and validation may be performed but is not required. However, the DVR software V&V shall be completed at the site prior to placing it into production.

7.3.2.7 Software User Documentation

The purpose for a DVR software user document is to provide instructions for proper use of the software including limitations and assumptions. Vendor information can be utilized to develop this site-specific document. The DVR software user document should include as a minimum:

- Software user instructions in operation of software and interaction of software user with the system
- Input/output specifications/formats
- System limitations
- Description of warnings/error messages
- Software user response
- Installation guides
- Load reports
- Uninstallation guides
- All DVR SQA and V&V plans, SDD, etc. shall be submitted to the licensee document control and be formally issued as software documents

7.3.2.8 User Training

DVR user training should be developed by the site software owner. It is recommended that training be given by formal means, on the job training, or job equivalent experience in all cases, and that training should be documented.

7.3.2.8.1 Software/Hardware/LAN Based Process Control/Monitoring Systems/Configuration Management Plans

A DVR site specific software configuration management plan (SCMP) should be created and documented. This site specific SCMP for DVR software ensure that the system and its components are uniquely identified and that changes to the DVR system are controlled. The following minimum elements should be included in the DVR site SCMP:

- Uniquely identify system (software, system software, and hardware) components
- Uniquely define baseline configuration (version)
- Identify and document changes if any to the baseline
- Evaluate the impact of changes on the software user and other software
- Approve DVR software changes
- Revise documentation (if necessary)
- Implement approved DVR changes
- Verify DVR software changes if necessary
- Validate DVR software changes if necessary

- Install and checkout the DVR software
- Notify software users/software owners of changes and the impact of the changes
- Conduct training on the DVR software changes if necessary
- Identify baseline after each major phase of DVR software life cycle
- Provide management of the configuration (latest approved configuration and status of approved changes) identify and make available to appropriate personnel
- Provide configuration control to include determination of impact of changes to hardware and support software
- Hardware/software may be combined under one configuration management plan

7.3.2.8.1.1 Software Database

DVR software databases that contain that contain the site-specific DVR model and plant measured and reconciled data shall be put under configuration controls to prevent inadvertent revision, corruption or deletion.

7.3.2.8.1.2 System Problem Reporting

The purpose for DVR system problem reporting is to ensure that problems are identified, evaluated and dispositioned and that errors are reported to affected personnel/departments. The site Corrective Action Report (CAP) system shall be utilized to document errors and corrective action for the DVR controlled software. It is recommended that condition reports be promptly created, and users notified of DVR software problems that affect production systems if any. A licensee condition reporting program may have additional requirements. But as a minimum it is recommended that DVR problem reporting include:

- Methods to promptly identify and document problems
- Assess each problem to determine if it is an error
- Notify licensee DVR software users of the error and its impact
- Determine the impact of the error on present and past usage of software which may require interface with the vendor
- Record retention of the error
- Documentation under the Corrective Action Program (CAP)

Potential conditions adverse to quality shall be retained using appropriate site procedures. Corrective actions if any should be documented and transmitted to the affected DVR software owners so that training can be provided to mitigate future potential errors from occurring.

7.3.2.9 Media and Access Control

The purpose for a DVR software media and access control process is to protect the media from degradation and destruction. This program also prevents the DVR software from unauthorized access and use. Media control and storage shall be in compliance with the licensee access control for portable and mobile devices. This program also ensures the following:

- Ensure backups of DVR important files
- Ensure DVR electronic media are protected against degradation
- Ensure DVR software media is clearly and uniquely identified
- Randomly test/inspect DVR backup data to ensure retrieval and accuracy
- Store DVR media in accordance with retention requirements
- Ensure DVR related archive information is retained for an appropriate period of time when software is retired from service

Access control shall prevent unauthorized access to DVR software, and when software is retired from service, prevent routine use of the software. Access control to DVR software shall include measures that ensure software users have access to software authorized for operational use. The media access and control processes should be described in the licensee's configuration management plan.

7.3.2.10 Procurement Control

The purpose for a procurement control process for DVR software is to establish requirements for acquisition of software items and services. A clear definition of the responsibility of the DVR vendor is also part of licensee procurement control.

Details regarding software procurement differ from each licensee and as such this section only addresses that a controlled procurement process be utilized for DVR software and support services.

7.3.2.11 Data Control

A controlled process should be used for changing data commensurate with the access level of the data and impact on business. The controls placed on data changes should be in accordance with a licensee product level classification. The licensee should also establish a process for changes to non-design basis data within databases of plant computer systems if they do not already have one established that would be part of the DVR data.

The licensee will also as part of DVR implementation need to ensure that data transferred or derived from DVR has been appropriately reviewed for context and intended use. The licensee will also need to evaluate transfer of DVR data across system interfaces or data communication lines to look for potential risks that should be accounted for prior to production use. Some licensee interfaces may automatically process data and therefore may need to be classified as well.

If DVR data has been found to be corrupted in any way, then the software owner or user responsible for corrupted source data should perform an impact evaluation to determine extent of condition. It is recommended that all data corruption or error notices be documented utilizing CAP.

Depending upon the nature of the problem the vendor may need to be notified of the identified error to aid in resolution and disposition. Depending upon licensee processes an error may need to be resolved immediately and coordinated with IT as part of an emergent issue process.

7.3.2.12 Placement of Production Systems into Service

Each licensee may have a different process for placing software into production. As such, each software owner needs to determine the extent to which control measure requirements are to be implemented based upon their software quality level classification. A site licensee may need to approve and issue software QA documentation for the DVR software as part of their process. The licensee should also evaluate the following whether applicable to placing DVR into production:

- Ensure appropriate control measures are specified with implementing documents for hardware/software (DVR related).
- Ensure control measures are applied to production system (operating system, computer hardware, database management system, communication/network systems) and that the DVR software installation (executable libraries, access to software).
- Once established in production, the licensee may need to also perform separate 50.59 reviews if any changes are made to the DVR production software, and may need to be evaluated on a case by case basis.
- The licensee software owner shall ensure changes to DVR software or hardware and related documentation is formally documented and controlled.
- Changes to plant equipment, including the software must comply with licensee configuration control processes and will not be discussed further in this subsection.
- The licensee DVR software owners should ensure that only authorized changes will be made to items under configuration control.
- The appropriate licensee support groups (i.e., for example IT) should ensure that software and production systems are maintained in accordance with implementing documents.

7.3.2.13 Decommissioning

The purpose for a DVR decommissioning or retirement process is such that the operation of the software will be terminated and prevented from further use with all support suspended. The licensee engineering change process will control this aspect.

Depending on how the DVR software is classified for a licensee will most likely dictate how the executable codes, source codes are backed up and/or stored. It is recommended that DVR support documentation be archived and retained as a quality record. Each licensee may also have their own decommissioning process through an information management system that needs to be completed.

7.3.3 Software Functional Acceptance Test

The purpose of the Functional Acceptance Test (FAT) for the DVR software installation is to ensure the DVR models meet the requirements set and function per the Functional Design Specification (FDS). The FAT will provide the necessary testing to ensure the DVR models are sufficiently accurate to be used for the determination of errors with plant instrumentation, specifically the feedwater flow metering and the reactor power measurement.

The FAT will also provide functional testing of the software elements that comprise the DVR software installation to ensure the key features perform as designed.

7.3.3.1 Conduct of Test and Test Records

This section provides guidance on the conduct of the test. The guidance should be used along with the vendor provided design specifications and checklists. The Test Records should include completed copies of the DVR model files, data files, and all test record documentation files. A typical test plan Checklist will be prepared for each site, and print outs or screen shots of test data results as indicated. All test model files and test data used as inputs for the DVR calculation testing should be archived and retained for possible future use. All test documentation records should be compiled and archived per site quality assurance procedures/requirements.

7.3.3.2 Assumptions

As the DVR software installation consists of a number of commercially available software programs, each individual program element will not be tested individually for that product's entire feature set. Rather, the FAT will focus on integrated testing of the DVR software installation when used in a typical manner at the plant site for evaluation of plant measured data. Key features of software installation, necessary to perform DVR data evaluations by the plant staff, will be tested.

7.3.3.3 FAT Precautions and Limitations

The software installed as part of the DVR installation may be subject to policies or requirements set forth by an individual site's or utilities' IT groups. It will be necessary to ensure the software is setup properly to comply with those requirements and will not be discussed further in this topical. Site specific IT policies regarding server setup, account administrative privileges and permissions, and port usage may affect the installation set up and process.

7.3.3.4 Hardware and Software installation (Environment)

The hardware and software required to run the DVR software will be set up and installed prior to the FAT. Compatible hardware must be used and a checklist for each site will be developed as part of the compatibility testing. The hardware compatibility requirements will be checked by reviewing the software release installation notes for each piece of software planned for use as part of the recommended DVR installation. A site-specific DVR hardware and software requirements list will be developed as part of the FAT.

7.3.3.5 Test Cases Conduct, Objectives, and Acceptance Criteria

The testing elements are broken down into DVR Model Regression Data Testing, DVR Model Testing with Historical Plant Data, and General DVR software functional testing. Each testing element will have a set of acceptance criteria based upon the objectives of the FAT and a checklist will be developed for each site as part of the process for testing and documentation. The following testing elements will be developed as part of the FAT:

1. DVR Model Regression Testing to include test purpose, conduct, objectives, and acceptance criteria.
   a. The purpose of Regression testing is to ensure the DVR models as delivered are the same as the models developed during the FDS development. The test ensures no inadvertent edits or changes have been made to the model files, and the model files provide the same numeric calculations. Regression testing may also allow testing of the models on different hardware or software requirements. Regression tests also allow testing of the models by individuals other than those that originally developed the FDS models. Regression testing may also be used to evaluate software patches or minor edits or changes to the FDS models.
   b. The test data input cases and files will need to be documented.
   c. The tests will ensure the DVR models provide the reconciled MWth uncertainty levels as stated in the FDS. This testing will also then document the reconciled MWth uncertainty level and other variables as noted.
   d. The test will involve reading selected test data inputs used in the FDS, then rerun the DVR calculation for the Regression test, and check output results to ensure they match those obtained in the FDS.
   e. The results for each test case will be reviewed, assessed, and evaluated as acceptable or not by personnel cognizant in the area of DVR and plant thermal performance calculations.
   f. Any deviation in the testing process will be documented, along with a reason for a work around or acceptance criteria adjustments. The impact on the overall test results will be documented along with any deviations.
2. DVR Model Historical Plant Data Testing to include test objectives, and acceptance criteria.
   a. The plant historical model testing will be conducted.
   b. DVR model testing will be performed by running a number of sets of plant historical data to assess the expected DVR model performance when running on-line with actual plant data from the plant data acquisition and instrumentation. The actual rest data input cases and files will also be documented.
   c. Acceptance criteria will be established for these plant historical cases in regard to penalties and measured data inputs. These criteria will consider impact of the total MWth uncertainty contribution.

d. Exceptions or outlying data may be found when running historical actual plant data cases, as the data may contain changes in normal operating modes or due to performance issues. Also, there may have been issues with plant equipment or instrumentation. For those type of cases, acceptance criteria will be based upon DVR calculations that identify suspect points, with Single Penalty and Chi-Test values used to reflect data that contains potentially erroneous data. The criteria for the test cases, with Single Penalties will be established for the measured data inputs that could be major error contributors.

e. The results for each historical test case will be reviewed, assessed, and documented for acceptance by personnel that have DVR and plant thermal performance calculation experience.

f. If a test or process cannot be performed or acceptance criteria not met, work arounds or minor adjustments may be made. The reason for the work around or acceptance criteria adjustments must be documented as part of the test process. The impact on overall test results must be explained.

3. DVR general software testing to include testing key features of the DVR software installation to ensure the features perform as described in the software user manual. This would include test conduct, objectives, and acceptance criteria.

   a. The general software testing will be conducted as specified.

   b. The software module and feature(s) tested will be identified and documented. The reason for including the test case will be documented as well.

   c. The acceptance criteria for the software features are the software feature functions as described in the software user manual.

   d. Personnel with experience in DVR feature(s) testing will review and test the software. Acceptance or any deviation in testing will be documented.

7.3.3.6 Key Features Testing

The key features testing of the DVR installation of the software functions that will typically be used by the licensee will be tested. The software components and features typically planned to be tested are as follows:

- DVR Model main software application - basic functionality and user interface: All features will be tested and verified for proper function per the DVR software provider's user manual documentation.
- DVR model software application used to schedule and read in plant measured data: The DVR model software application is used to schedule the model runs, read in plant measured data and execute the calculation process. Note that for the FAT the plant measured data source may not be the plant computer or data historian. Rather, the data files may be special text files of data extracted from the actual plant computer or data historian system. Typically, the FAT is conducted at the DVR model provider's offices and not at the plant or a utility site. The SAT (Site Acceptance Test) performs similar testing in the actual on-line DVR model hardware and software environment. Testing of the ability to schedule and read in the measured data files will be performed and verified.

- If database software is used to store results of the DVR software calculations, testing of storage of DVR results in the database will be performed and verified.
- Any add-in software provided by the DVR software vendor necessary for the site on-line installation will be tested and verified for proper function per the DVR software provider's user manual documentation.
- Any 3rd party (not provided or developed by the DVR software provider) planned for use at the actual utility site DVR software shall be tested and verified for proper function, if it is required for proper DVR software function.
- Other supporting software or applications that may be provided by the DVR software vendor such as report generation tools, displays, etc., will be tested and verified for proper function as required by the utility customer.

7.3.4 Software Site Acceptance Test

The purpose of the Site Acceptance Test (SAT) for the DVR software installation is to ensure the DVR models meet the requirements set in and function per the FDS, and function properly for a licensee when installed at their facility.

The SAT is performed following successful completion of the FAT. The FAT tests the DVR models to ensure they meet the Functional Design Specifications (FDS) with a hardware and software setup similar to the actual site installation whereas the SAT is performed on the actual site hardware and software environment.

The SAT will ensure the DVR installation performs in the licensee IT network hardware and software environment per the various DVR software component vendor installation guides and notes. The SAT will provide the necessary integrated testing to ensure the DVR models are sufficiently accurate to be used for the determination of errors with plant instrumentation, specifically the feedwater flow metering and the reactor power measurement. The SAT also performs DVR model functional testing of current, measured plant data that could not be assessed in the FDS, which uses historical plant data. This gives additional assurances that the DVR models will continue to function per the FDS with future measured plant data (see Section 3 for further details).

Sections 7.3.3.1 through 7.3.3.6 describe the FAT and all portions described in those sections will be applicable to the SAT as well. The test limitations, controls and planning as described in Sections 7.3.3.1 through 7.3.3.6 will be conducted at the site to ensure that the actual site hardware and software environments are compatible. In addition, a site installation integrated test will be performed. This is described in more detail in the section following.

7.3.4.1 Site Installed Integrated Testing

The Additional Site Installation Integrated Testing ensures the delivered DVR setup and system will continue to function properly when running on-line, or periodically with actual plant data. The test ensures the various DVR software components that interact with the site's networking and software environment are configured properly to allow normal usage of the DVR system by the plant site personnel. The test will be conducted by a prescribed site installation integrated test per checklist format. Further details are provided subject to site specifications as required.

The number of tests and the test(s) intervals are at the discretion of the DVR installation engineer.

In general, the testing elements and regime are similar to those in the FAT, see the previous sections 7.3.3.1 through 7.3.3.6. The key differences are the SAT testing is conducted with the actual on-line DVR software installation on the utility customers' hardware and software environment. Therefore, the plant measured data source is now the actual plant computer or data historian installation whereas the FAT only simulated this installation.

Integrated testing can be helpful with the identification of network security or account rights or privileges settings that may conflict with those initially configured with the DVR software components. As network user account settings are typically "pushed" down to user PCs, the potential exists that DVR software component settings may be altered which could affect the DVR set up function. Therefore, allowing the DVR setup to run for a determined time interval may help to identify any setting changes made due to the network's administrator's tools.

The acceptance criteria for the software features are the software feature functions as described in the respective user manual. To accomplish this, the Key Features Testing will be repeated. In addition, any on-line calculations or additional calculations made during the Additional Site Installation Integrated Testing should be informally reviewed to assess if the site DVR software installation calculations are reasonable and reflect the state of the plant for time period calculated. If any of the calculations are deemed to be suspect, additional follow-up actions may be required.

The acceptance criteria for any additional test data cases will be specified for all the measured data inputs. Some inputs may incur larger penalties, and this is acceptable as long as they contribute less than 0.5% of the total MWth uncertainty.

Exceptions or outlying data may be found when running the actual plant data cases as the data may contain changes in the normal operating modes or performance issues with the plant equipment or instrumentation, may occur from time to time. For those cases, the acceptance criteria will be that the DVR calculations identify suspect points and the Single Penalty and Chi-Test values will reflect the data contains potentially erroneous data.

Additional site installation integrated testing results will be reviewed by personnel cognizant in area of DVR. Determinations for causes of any unacceptable test runs from the test steps or acceptance criteria will be documented and dispositioned as acceptable or not.

7.3.5 Design Control

This subsection will not focus on a licensee's explicit design control process regarding implementation of the DVR process. Instead it will highlight design control guidance as it relates to managing implementation of plant modifications involving digital systems and inputs. A licensee is expected to evaluate their own individual DVR application and implementation regarding what explicit design controls would need to be in place. However, related to generic guidance some items can be discussed related to design controls of DVR processes. Each subsection below will address some guidance items.

Any engineering change made as a result of DVR implementation needs to be interfaced and coordinated with the licensee's configuration change control process involving digital instrumentation and control equipment and systems. Digital systems can vary in complexity based upon what may need to be part of the DVR process, i.e., installing additional parameter instrumentation, network interfaces, and monitoring requirements.

As such, since the DVR process could have variance in complexity, the functions that will be performed, consequences of failure and impact on plant operations must be assessed as part of a design change process and controlled. A digital configuration change process can be used to supplement the configuration control process to focus on key aspects of the DVR implementation. This subsection will highlight some of those considerations. The following paragraphs will describe some of those considerations that should be part of the evaluation and design control process related to DVR implementation.

7.3.5.1 Digital Configuration Change

First the proposed DVR process needs to be evaluated if it is considered a consequential digital design, that is could it have significant impact on plant reactivity, power, equipment or personnel safety, and/or operation of the plant. If the DVR process is implemented in such a way that it could have an impact on operation of the plant, then potentially this type of digital change could screen out as a "Consequential" digital configuration change, and extensive requirements would need to be met for review and implementation of such. Those requirements will be discussed from a high level, as each licensee will have their own process to follow regarding the configuration change and control of such.

If, for example, a DVR process implementation required the system to perform a "critical" function (LCO shutdown clock) then, this type of configuration change could be classified as "consequential" and would be processed accordingly. Also, since the DVR process itself may be considered by some licensees as a "first of a kind application" or a "complex technology/method" it could also be considered as meeting criteria for classifying as a "consequential" digital configuration change. An additional criterion may be that the licensee could suffer an operational impact or financial risk if the digital processes failed related to DVR. Each licensee will need to evaluate their specific DVR implementation against their digital configuration change control process.

7.3.5.2 Critical Digital Assets

Likewise, a licensee will need to evaluate if their DVR application can affect critical digital assets (CDA) such as other computers, communication systems, networks, controllers, transmitters. The DVR system will have to be reviewed to evaluate its impact to CDAs or whether it needs to be classified as a critical component. The DVR system as part of the digital configuration and design control will need to be reviewed against requirements for Cyber Security Plans under 10 CFR 73.55 [29] (that is if it has impacts on such).

If only DVR software/firmware is installed without additional changes to the plant, it still will have to fall under consideration of a digital configuration change, even if all other hardware remains unaltered. Potential changes to software/firmware in the plant system related to DVR (in the future) would also be subject to a digital configuration change program.

7.3.5.3 Failure Modes and Effects Analysis

Additional items that are considered when implementing a DVR process are a Failure Modes and Effects Analysis (FMEA), impacts on portable devices, regression testing, requirements traceability matrices, software hazards analysis, software quality assurance, functional description (described in Section 8), functional specification and verification/validation. Other sections discuss all of these components of a digital design implementation and control and will not be discussed further in this subsection. As always, if there are any impacts related to safeguards information (SGI), that information shall be controlled and documented in accordance with a licensee's procedures and plans.

7.3.5.4 Data Communication

As part of DVR process implementation, a licensee will need to evaluate and consider data communication issues. Some examples of areas that may need to be developed or confirmed relevant to design control of DVR or implementation could be architectures, use case(s), capacity, protocol(s), data management, data flow and topology, device connections and configurations. Licensees should investigate what design controls/procedures are in place related to the above data communication issues, and interface with IT personnel as well.

7.3.5.5 Plant Integration

Regarding explicit plant integration and control, detailed guidance will not be provided. However, regarding DVR and plant integration design issues the following topics should be considered as part of the configuration change or implementation process; upgrade strategies, modification boundaries, system requirements, confirmation of design inputs, physical design, interface designs, electrical independence, electrical power supply, equipment uncertainties, changes to setpoints if any, operability and maintainability, independent design verification.

Regarding DVR process digital configuration management design considerations and control, the following should be considered or identified, affected configuration items, configuration information (i.e., database inputs), current baseline (if any), interfaces, and new or modified digital configuration items.

7.3.5.6 Software Configuration Management and Licensing

Additional items that may need to be considered as part of digital design control are software configuration management plans, and licensing activities. The latter may need to include explicit licensee regulatory commitments and requirements related to DVR implementation. There also may be license constraints to the software itself that have to be identified. If a licensing submittal is required as a result of DVR implementation that is outside the scope of this subsection and would need to be addressed through licensing actions.

Related to additional digital configuration change items or control, the FAT and SAT would be part of the DVR process and discussed in detail in those sections of this topical report. If future changes are made to the DVR process, post modification testing may be necessary as part of a control process to evaluate impacts to the operating system, application software, firmware and configuration files. It is not anticipated that implementation of the DVR process would impact the licensees Probabilistic Risk Assessment or Hazard Analyses and thus, they will not be considered as part of a design change or design control aspect.

Related to digital design controls the licensee may need to perform a functional configuration audit, establish, update or release a production baseline, perform configuration status accounting. Most critically the licensee should control all electronic media related to the DVR process and its interfaces. Likewise, if necessary, develop a recovery plan, based upon operational and potential business impacts focusing on whether the DVR processes are lost or compromised.

Once the DVR process is put into service an additional consideration is the as-built configuration (i.e., to ensure software and hardware configuration changes, including tuning changes have been satisfactorily documented, and are classified and documented as a final revision. The DVR software itself should be put under licensee software QA programs. The Operating System (OS), software, firmware and configuration file revisions should be put into a document control system such as Passport. Lastly any portable media associated with the DVR software, applications and configuration files should be put into a tracking system. If tuning changes are made it is suggested that surveillance is conducted to verify updates, and then finally to ensure all procedures, drawings, schematics correctly reflect the as-built condition of the DVR process.

All applicable vendor manuals should be submitted to records management including any copies of FMEA, SHA or RTM as applicable, and any other engineering analyses for reference during future troubleshooting. If there are issues during design implementation the problems should be identified in CAP, and then ensure that all actions regarding such are open until properly managed and then confirmed closed. Any risk assessments performed related to the DVR implementation impact should be confirmed/reviewed relevant to interfacing equipment, systems and/or plant operations and for any limitation of DVR or plant operation.

8

DVR FAILURE MODES EVALUATION

8.1 Overview

When the Data Validation and Reconciliation (DVR) model is used to calculate the plant Core Thermal Power (CTP) continuously or periodically with on-line plant measured data, DVR will provide valid and accurate calculations the majority of the time. DVR calculation success typically exceeds 95% for the DVR model valid conditions. Section 10 provides reliability details for a variety of plants that are or have implemented the method. However, certain conditions may cause the DVR calculation to fail or be suspect from time to time. There are checks in the system to identify errors which could result in an error in the CTP calculated. By using the DVR system as a periodic calibration of the flow measurement devices, these errors can be identified and mitigated before the correction factor is applied to the flow measurement.

This section will describe some of the types of DVR calculation failures or causes of suspect or erroneous results. This section will also analyze the maximum amounts of errors that could occur with the DVR CTP calculation when in typical use at a plant.

Causes and effects of limitations of the DVR model for application and use at a plant as a CTP calibration standard, or a calorimetric standard, will be analytically determined. Application of the DVR CTP uncertainties for plant use will be provided.

This section will also address some mitigating strategies such as the use of alternate indicators and operations/engineering reviews. In plant use the DVR CTP would typically be implemented as a correction factor on the existing plant CTP calculations, or correction factors applied to existing feedwater flow measurements.

As mentioned, plant implementation of these DVR CTP based correction factors to the existing plant calorimetric will be manual in nature and will require operations/engineering reviews. Therefore, implementation of the correction factor means a thought through specific action must be taken first before a plant response can be experienced. The DVR application itself is not linked to the plant computer, plant calorimetric, or any other plant digital components necessary for safe shutdown or critical functions.

8.2 Failure Mechanisms of the Technology

In certain situations, the DVR CTP calculation may fail, or render suspect or inaccurate results. These situations may involve:

1. Problems with software supporting the DVR calculations.
2. Invalid or bad plant measured data.
3. DVR model used does not adequately represent the plant's current operating conditions.

4. Limitations of the DVR model or algorithm.
5. Programmatic controls for the DVR calculation process fail.

An affinity diagram of DVR failure types and causes is given in Figure 8-1. The five failure mechanisms described above comprise four categories of DVR calculation failure causes.

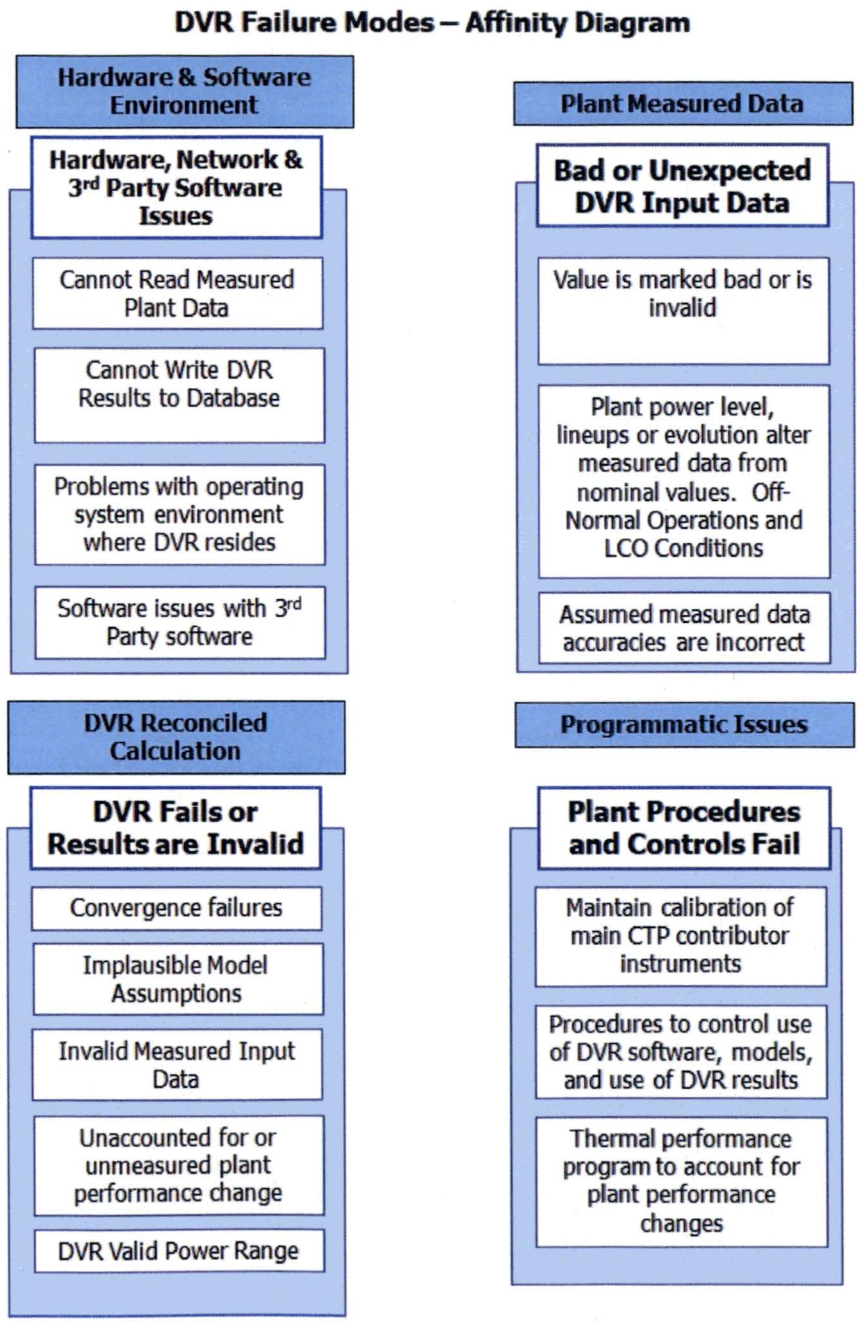

Figure 8-1
DVR calculation failure affinity diagram

8.3 Failure Modes

DVR has a variety of self-identifying features and calculations to ensure the DVR CTP results are accurate and valid. These are detailed in the Section 8.3.1.

Sources of DVR calculations failures and the effects of those failures are given in Figure 8-2.

8.3.1 DVR Self-Identification of Measurement Errors and Calculation Failures

As previously discussed in Section 6.9.2, the DVR algorithm contains a number of calculations and self-error checking metrics to ensure the validity of the calculations. The metrics and acceptance criteria include:

1. Successful convergence.
2. VDI [1] Quality Criteria 1 of Quality < 1.00.
3. VDI [1] Criteria 2 for single penalty values < 3.84 is met for each important (>0.5% DVR CTP contribution) measurement.
4. Single penalty values for measurements >1 and <3.84 are identified and should be monitored more closely. This metric indicates when a measurement value has exceeded one standard deviation but remains within the 95% confidence standard deviation of 1.96, which is related to the DVR input accuracy value. Potentially, these measurements may be experiencing slight drift error, but are still within their rated accuracy. One standard deviation of a measurement is the normal, typical error variation limit for the measurement and is often referred to as the "repeatability" of a measurement. A measurement penalty value of greater than 1, but less than 3.84 indicates the measurement has not exceeded its rated accuracy, however it contains more than normal error. A penalty value of 3.84 or greater indicates the measurement has more than 2 standard deviations of error and has exceeded its rated accuracy.

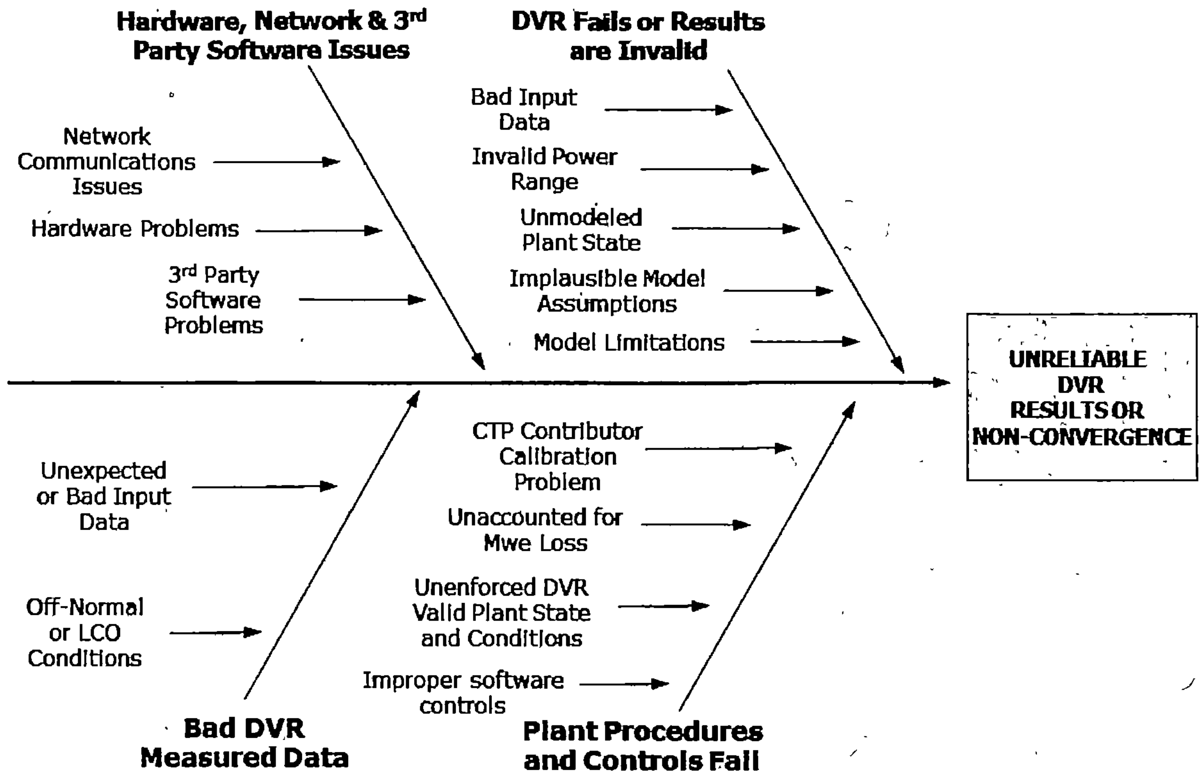

Figure 8-2
DVR calculation cause and effect diagram

8.3.2 Supporting Software Problems

Problems with software used to support the DVR calculation process may render the DVR calculation to be non-functional.

The DVR process requires plant measured data sourced from a plant computer system or data historian. Proper network communications and operation of the software used to obtain plant measured data must be maintained.

The DVR results are written to a 3rd party software database. The database software and the interface to DVR must be maintained.

Supporting software problems can be mitigated by ensuring the software and hardware installation meets the requirements and are maintained to those specified by the DVR software vendor.

8.3.3 Invalid or Bad Plant Measured Data

Measured plant data used for input to the DVR model may cause the DVR model calculations to fail when the value of a particular or group of measurements are invalid, such as a zero or null value, or far outside a normally expected range of values for the plant operating conditions, when the value is obtained.

When a measured plant data tag is an unexpected value such as a zero, a null (a blank value), a non-numeric value, or a value that greatly exceeds a reasonable upper or lower limit for the tag, the cause may be a sensor failing high or low, or the plant computer or data historian provides a faulty value to the DVR calculation.

DVR can be configured to handle routine types of measured data failures through the use of filters and other tools to help ensure reasonable values of plant measured data are used for the DVR CTP calculation. However, these filters may not be able to eliminate every type of error that can occur with the measured data values from the plant computer or data historian.

To mitigate DVR failures due to invalid or bad measured data values, the plant computer system or data historian should be configured to avoid the generation of non-numeric or faulty measured values when a sensor fails or is highly erroneous. Mitigation of the DVR failures may be further enhanced by setting up filtering methods in DVR to minimize the use of faulty values for the DVR CTP calculation.

Generally speaking, these types of DVR calculation failures tend to be spurious, infrequent, and rare. While occurrences of these types of errors can be minimized, they may not be totally eliminated. In the case of a DVR calculation failure, the DVR CTP calculations should not be used. Corrective actions should be taken to eliminate the cause of the faulty DVR input value, otherwise the DVR calculation may continue to fail.

Measured plant data tags that have reasonable or plausible values will be flagged by DVR as suspect or in error as described in Section 8.3.1 when a tag value is near or exceeds its rated accuracy value.

8.3.4 Model and Algorithm Limitations

Low redundancy inputs that are significant DVR CTP uncertainty contributors may need to be monitored more closely or require special treatment. Low redundancy inputs tend to lack strong correlation to other measured values, therefore the detection of errors (suspect or flagged status) is more difficult. While these variables may contribute significantly to the CTP uncertainty, the gains of these variables from the DVR process tend to be small. This means the accuracies of these measurements are not adjusted or altered significantly during the DVR reconciliation calculation, and the variable's output value tend to remain as input.

Redundancy for a DVR model input may be determined by conducting sensitivity analyses to analyze the correlation coefficients for the input variable and correlating variables. Low redundancy inputs characteristically have a high self-correlation factor, and low correlation factors for other variables. Low redundancy input values tend to have little to no corroborating or back-up measurements and are variables that are largely uncorrected where they are used in a DVR auxiliary conditions calculation. Therefore, the values tend to pass through the DVR algorithm with little correction. This means the reconciled and measured values will be almost the same for the variable.

Table 8-1 provides a listing of DVR model inputs that typically exhibit low redundancy. These variables may potentially affect the overall DVR CTP results and calculated uncertainty. Guidance for accounting for these variables in the overall DVR CTP uncertainty is given in the following discussion.

Table 8-1
Typical DVR model low redundancy inputs

Item	Error Effect	Comment
Main Steam Quality	May bias the DVR CTP results	Typically considered a constant in plant calorimetric calculations See discussion for additional details.
Watt-hour Metering - Gross Electrical Output MWe	May bias the DVR CTP results	May require special treatment. The DVR algorithm may not properly detect random errors. See discussion for additional details.
Turbine Efficiencies	May bias the DVR CTP results	DVR input values should bound the DVR calculation to the source data which is the thermal kit or tuned model. See discussion for additional details.
Turbine stage moisture removal effectiveness	May bias the DVR CTP results	The uncertainties for these variables are contained by the turbine efficiency values.
Unbounded Generator Losses Calculation	May bias the DVR CTP results.	If not bounded to a design calculation, a portion of the gross output may be inadvertently distributed to the variable.
Moisture separator effectiveness	May bias the DVR CTP results	If input as a constant or a limited accuracy range, the uncertainty effect on the DVR CTP should be confirmed to be <0.5%. Otherwise, additional uncertainty margin may be added external to the DVR calculation.
Use of Constants as DVR Inputs	May bias the DVR CTP results	Constants should be evaluated for their DVR CTP effect.
Pressure Drop Assumptions	May bias the DVR CTP results	Assumptions that affect the DVR CTP >0.5% CTP should be field confirmed or verified by a hydraulic calculation.
Cycle Leakage	May bias the DVR CTP results	See Section 8.3.6 for discussion of effects of cycle leakage on the DVR CTP results.

8.3.4.1 Main Steam Quality

Main steam quality cannot be actively measured and thus is always an assumed input. This variable is typically considered a constant in plant calorimetric calculations. Often, the main steam quality may be assumed to be a value of 1.0 (one), which indicates dry steam. This assumption may introduce excess conservatism in the calorimetric calculation.

For DVR input, if the value of the main steam quality is assumed to be 1.0 (one), a conservative bias effect may occur with the DVR CTP calculation. This effect on the DVR CTP calculation should be considered external to the DVR CTP calculation uncertainty when the variable is specified as a constant, or a limited error range variable.

8.3.4.2 Watt-hour Metering - Gross Electrical Output MWe

The DVR algorithm may not properly detect errors with the plant Watt-hour metering used to measure gross electrical output for cases where only one meter is used, or redundant metering is inaccurate.

In the case of a single meter, there is no redundancy and the correlation coefficients are highest with flow measurements in the model. The DVR algorithm will not always reliably identify errors with this input in this situation.

Sensitivity studies were performed to determine the effects of Watt-hour meter measurement errors on the calculated DVR CTP for a single Watt-hour meter configuration. Table 8-2 provides a summary of the sensitivity runs.

Referring to Table 8-2, it can be seen that when 0.5% metering error is imposed on the ±0.25% rated accuracy meter the DVR algorithm distributes the error between the Watt-hour meter and feedwater flow measurements. Thus, the calculated DVR CTP shifts.

For this scenario, the DVR algorithm would be expected to flag the Watt-hour meter measurement as a bad measurement with a single penalty value >3.84, but it does not due to the lack of redundancy with the Watt-hour meter measurement. Rather, the measurement is marked as suspect by the DVR algorithm.

Measurements are marked as suspect by the DVR algorithm when the single penalty value is >1 and <3.84.

Therefore, while DVR tends to indicate a problem with this measurement, it does not fully catch the error correctly.

Note the increase in the penalties for the Watt-hour meter and feedwater flow measurements which is a result of the Watt-hour meter measurement error being distributed on those variables.

Note also, the model quality value does not change significantly, limiting use of this metric as an error detection method. The DVR CTP value has shifted by 0.2133%, however the value is still contained within the DVR CTP uncertainty of 0.3564%. Thus, while the results of the DVR calculation are not completely accurate, the DVR results are still valid.

When 1.0% metering error is imposed on the ±0.25% rated accuracy meter the results are similar to above, but at a greater magnitude. In this scenario, the DVR CTP value has now shifted by 0.4260%, and the value is no longer contained within the DVR CTP uncertainty of 0.3564%. In this situation DVR properly flags the Watt-hour meter measurement error as the single penalty value of 8.9 greatly exceeds the <3.84 criterion.

Table 8-2
Single watt-hour meter - gross output error effects (for meter rated 0.25% accuracy)

MWe Error	DVR CTP % Accuracy	% DVR CTP Shift	% DVR FW Flow Shift	Quality	Watt-hour meter Penalty	Avg FW Flow Penalty
0%	0.3570	0	0	0.261	0.0505	0.4307
0.50%	0.3564	0.2133	0.1896	0.275	2.5861	0.7510
1%	0.3559	0.4260	0 3784	0.308	8 9238	1.7967

In summary, about 2x (two times) the uncertainty error on the Gross MWe value can be contained by the rated DVR CTP accuracy, whereas 4x (four times) could exceed the rated DVR CTP uncertainty. However, this data should be confirmed for a specific DVR model.

Sensitivity analyses were also conducted to study the effects of adding a redundant Watt-hour meter of lesser accuracy. Table 8-3 presents the results of the analyses. The scenarios are similar to the previous example; however, the additional Watt-hour meter has a lower accuracy of 0.5%. Errors on the Watt-hour measurements were simulated with the main assumption that Watt-hour meter 2 stays within its rated accuracy value, whereas Watt-hour meter 1 does not.

Table 8-3
Two watt-hour meters - gross output error effects: Watt-hour meter 1 DVR Accuracy 0.25%, Watt-hour meter 2 DVR Accuracy 0.5%

Watt-hour meter 1 Error	Watt-hour meter 2 Error	DVR CTP % Accuracy	% DVR CTP Shift	% DVR FW Flow Shift	Quality	Watt-hour meter 1 Penalty	Watt-hour meter 2 Penalty	Avg FW Flow Penalty
0	0	0.3537	0	0	0.26	0.0151	0.0013	0.4284
0.50%	0.25%	0.3532	0.1968	0.1749	0.275	2.3646	0.3906	0.6997
1.00%	0.25%	0.3527	0.3711	0 3294	0.331	13.0104	4.6987	1.4542

Referring to Table 8-3, it can be seen that when 0.5% metering error is imposed on the ±0.25% rated accuracy meter the DVR algorithm distributes the error on the Watt-hour meter and feedwater flow measurements. Thus, the calculated DVR CTP shifts. For the Watt-hour meter 1 measurement, the DVR algorithm marks the value as suspect.

When 1.0% metering error is imposed on the ±0.25% rated accuracy meter the results are similar to above, but at a greater magnitude. In this scenario, the DVR CTP value has now shifted by 0.3711%, and the value is no longer contained within the DVR CTP uncertainty of 0.3527%. In this situation DVR flags both Watt-hour meter measurements as the penalty values of 13.0 and 4.7 greatly exceed the <3.84 single penalty criterion.

Therefore, in summary, having an additional Watt-hour meter of lesser accuracy while improving redundancy does not significantly improve detection of the Watt-hour meter measurement error as compared to the single meter case. Adding a second or more lesser accuracy (3 meters or more total) may be required before acceptable proper DVR error detection could be achieved. These analyses are not presented here but may be conducted on a case by case basis when specific DVR models are assessed for error detection improvements.

Finally, sensitivity analyses were also conducted to study the effects of adding a redundant Watt-hour meter of equal accuracy. Table 8-4 presents the results of the analyses. The scenarios are similar to the previous example; however, the additional Watt-hour meter has an equal accuracy of ±0.25%. Errors on the Watt-hour measurements were simulated with the main assumption that Watt-hour meter 2 stays within its rated accuracy value, whereas Watt-hour meter 1 does not.

Table 8-4
Two watt-hour meters - gross output error effects: Watt-hour meter 1 DVR Accuracy 0.25%, Watt-hour meter 2 DVR Accuracy 0.25%

Watt-hour meter 1 Error	Watt-hour meter 2 Error	DVR CTP % Accuracy	% DVR CTP Shift	% DVR FW Flow Shift	Quality	Watt-hour meter 1 Penalty	Watt-hour meter 2 Penalty	Avg FW Flow Penalty
0	0	0.3484	0	0	0.26	0.0034	0.0034	0.4248
0.50%	0.125%	0.3480	0.1413	0.1255	0.289	5.3106	3.0381	0.5588
1.00%	0.125%	0.3478	0.2254	0.2002	0.434	33.0872	24.2024	0.7888

Referring to Table 8-4, it can be seen that when 0.5% metering error is imposed on the two ±0.25% rated accuracy meter the DVR algorithm distributes less error on the Watt-hour meter and feedwater flow measurements compared to the previous cases.

The calculated DVR CTP and feedwater flow rates shift as compared to the base case, but much less than the previous cases. In this situation DVR properly flags the Watt-hour meter 1 measurement error as the single penalty value of 5.3 greatly exceeds the <3.84 criterion.

For the Watt-hour meter 2 measurement, the DVR algorithm incorrectly marks the value as suspect (single penalty value is >1 and <3.84) due to redundancy and correlation to Watt-hour meter 1. While this behavior may be less than desired, the overall DVR results for this case are better than the previous cases and the Watt-hour meter 1 error is detected properly, and the DVR CTP and feedwater results shift less. Furthermore, the higher penalty on Watt-hour meter 1 (versus Watt-hour meter 2) indicates that it is a more significant error contributor.

When 1.0% metering error is imposed on the ±0.25% rated accuracy meter both Watt-hour meters 1 and 2 properly flag the measurement error with single penalty values of about 33 and 24, respectively. Again, the higher penalty on Watt-hour meter 1 indicates that it is a more significant error contributor.

Next, the use of two meters, one of higher accuracy is evaluated. Refer to Table 8-5. For these cases, 0.25% metering error is imposed on the ±0.25% rated accuracy meter while for the ±0.1% rated accuracy meter remains within its rated calibration and repeatability (within 0.05% of the measured value).

Table 8-5
Two watt-hour meters - gross output error effects Watt-hour meter 1 DVR Accuracy 0.25%, Watt-hour meter 2 DVR Accuracy 0.10%

Watt-hour meter 1 Error	Watt-hour meter 2 Error	DVR CTP % Accuracy	% DVR CTP Shift	% DVR FW Flow Shift	Quality	Watt-hour meter 1 Penalty	Watt-hour meter 2 Penalty	Avg FW Flow Penalty
+0.25%	+0.05%	0.3412	-0.03	-0.03	0.27	2.1104	1.8545	0.4336
+0.25%	-0.05%	0.3413	-0.07	-0.07	0.28	4.6787	4.5369	0.4745

From this example it can be observed that the Watt-hour meter measurements are marked as suspect (single penalty value is >1 and <3.84) for the first case where Watt-hour meter 2 has a small amount of acceptable error in the same direction. For the second case, the Watt-hour meter measurements are marked as "flagged" (single penalty > 3.84) where Watt-hour meter 2 has a small amount of acceptable error in the opposite direction. Note for both cases the CTP and feedwater flow shifts due to the measurement error are minimized and are contained within the CTP uncertainty. The takeaway from this that a smaller amount of Watt-hour measurement error may be detected by adding a redundant meter of higher accuracy while maintaining the CTP uncertainty.

The gross output MWe measurement may be further improved through the addition of net output provided the metering accuracies of the net output and auxiliary use are sufficiently accurate. Adding a net output meter can improve the calculation of the gross output by creating additional redundancies with the DVR calculation.

In conclusion, having additional Watt-hour metering, particularly of equal or better accuracy than the base meter, will improve the measurement redundancy and DVR results.

In the case of a single meter, more care may be needed with identification of metering errors as the single penalty criterion of 3.84 may only identify larger errors. In this case, detection may be aided by monitoring the DVR CTP and feedwater flow rates and establishing limits for the amount of shift allowed from the base case values.

In summary, the actual measurement drift error performance of the Watt-hour metering must be considered either in the actual runs or as margin when the overall CTP uncertainty is estimated.

The drift performance of the Watt-hour metering can be determined by checking plant calibration records. From these records, the average drift amount per calibration can be used via DVR sensitivity evaluations to develop a CTP uncertainty margin that can be then be applied to the on-line or standard DVR calculated CTP uncertainty value.

For the case where a bias error is detected during normal operation and drift margin has not been considered as a margin in the final, developed DVR CTP uncertainty; the DVR accuracy for the Watt-hour meter in question may be reduced (value increased to reflect a worse accuracy) better encompass the error. The metering accuracy would be reduced (worsened) until the single penalty values are <1.0.

Changing the metering accuracy would affect the calculated DVR CTP and feedwater flow rate values and cause the CTP uncertainty to increase. Therefore, engineering assessment and justification may be needed when adjusting the DVR accuracy input value from those developed with the tuned and documented DVR model.

8.3.4.3 Turbine Efficiencies and Turbine Stage Assumptions

Turbine stage and efficiency and accuracy assumptions were previously discussed in Section 6.3.4. As these variables have no redundant measurements, they largely remain unchanged during the DVR calculation other than the last turbine stages which are highly correlated to the exhaust (condenser) pressure. However, these are valid assumptions as in nature the turbine efficiencies of these sections remain fairly constant, particularly within a limited load range.

The electrical MWe equivalent of the turbine efficiency assumptions may be analyzed through sensitivity studies to reconcile the DVR input values to those from the thermal kit design data. In general, the turbine stages other than the last LP turbine stages will be values directly traceable to the turbine vendor thermal kit, software heat balance model, or heat balance diagram that serve as the source of the design data.

For cases where the model has been tuned to actual plant data, the last LP turbine stage efficiency values may differ from the source design data as, provided the model tuning has been performed correctly, bias errors most commonly related to vendor margins are removed.

If the model tuning has been performed incorrectly, or the source design data does not properly reflect the actual installed turbine, the DVR results could be improperly biased. These types of issues are readily apparent during the model tuning process as DVR results will typically exhibit poor quality metrics.

As previously described in Section 6.3.4, the vendor thermal kit uncertainty, typically in the order of about two percent (2%) equivalent unit gross electrical output, is reduced to less than two percent (2%) through the model tuning process. As this uncertainty is largely imposed in the DVR calculation via the last turbine stage efficiency values, following the model tuning the last stage efficiency uncertainty values are reduced from greater than 10% to about five percent (5%). Sensitivity studies are performed using the tuned model turbine efficiency values for the entire turbine, and the resulting equivalent thermal kit effect on unit gross electrical output should be less than two percent (2%).

8.3.4.4 Generator Losses

Generator losses should be calculated and applied in the DVR model per the vendor thermal kit or traceable calculation. As this calculation is tied to the turbine vendor heat balance margins previously discussed, using the vendor calculation will bound the uncertainty of this variable within the overall equivalent unit gross electrical output of less than one percent (1%) obtained from the model tuning.

If the generator losses are not bound to a vendor type calculation the resulting DVR CTP uncertainty contribution may be inaccurate. Because the variable has no redundancy and is highly correlated to the gross electrical output measurement, an excessive amount of the measured gross electrical output may be distributed onto this estimate. In this situation sensitivity studies should be performed and documented to determine the overall effect of the uncertainty on the DVR CTP results, and if necessary, the uncertainties can be applied external to the DVR calculation.

8.3.4.5 Moisture Separator Effectiveness

The values of the inputs and uncertainties for the moisture separator effectiveness for moisture separator reheater components used in the DVR model should be traceable to a vendor calculation, design document, or test data. Typically, these measurements have low redundancy. Therefore, the uncertainty effects on the DVR CTP should be evaluated to ensure they are properly bounded.

8.3.4.6 Use of Constants

In the DVR algorithm, constants are not considered as error contributors to the DVR CTP. The use of constants in a DVR model is typically minimized. Constants may be necessary at times to allow the calculations to converge. For cases where a constant is specified as a DVR input, the plausibility of this assumption should be evaluated. Otherwise, in general, an estimate of measurement uncertainty should be used for the variable instead of a constant.

When constants are specified the possible effect on the overall DVR CTP uncertainty and contribution should be calculated, documented, and applied external to the DVR calculation.

8.3.4.7 Pressure Drop Assumptions

Pressure drops for various valves and piping may have low redundancy and should be traceable to vendor or hand calculations. If necessary, field verification of the values can be performed. Typically, these inputs have a negligible effect on the overall DVR CTP uncertainty.

If specified as a constant, the impact on the DVR CTP uncertainty should be confirmed to be sufficiently small as to have no real effect on the DVR CTP calculations.

8.3.5 Unmodeled Plant State and Power Limitations

The DVR CTP results may be inaccurate during times when the plant state is different than the state assumed in the DVR model. The DVR model is typically built and tuned to represent plant equipment functioning normally, with normal line-ups and operation at the 100% rated power level.

If a plant component or piece of equipment fails, the DVR CTP results may be affected. As plant component or equipment failures typically result in lower unit electrical output, the DVR CTP results may calculate an inaccurately low plant power value.

An example of this would be a low-pressure turbine extraction line bellows rupture where the rupture causes the extraction supply steam to the affected feedwater heater to be reduced and the steam bypasses the remaining LP turbine stages passing directly to the condenser.

In this scenario, the unit gross electrical output would be lower than normal, and localized effects of altered temperatures and pressures from normal would be observed on the affected feedwater heater. In this situation, the DVR CTP calculations may be inaccurately low in value. However, the overall Quality values and single penalty values for the measurements of the temperatures and pressures around the affected feedwater heater should indicate a problem with the unit. The DVR calculations would also exhibit a change in single penalty values for the low-pressure turbine efficiencies and gross electrical output metering.

Another scenario that could occur at a plant is excessive unmeasured valve or steam trap leakage, commonly referred to as "Cycle Isolation" leakages. In cases where a leakage is large, and the DVR model does not account for the leakage, the DVR CTP results may be affected. Again, in this situation, the overall DVR CTP calculation values for Quality and the single penalty values for the low-pressure turbine efficiencies and gross electrical output metering may be affected if the losses are significant.

Accounting for unmodeled or Unaccounted-for unit electrical output losses are discussed in more detail in Section 8.3.6.

The valid power range for the DVR CTP calculations may be determined through sensitivity studies and by analyzing the results of actual plant data at other power levels.

The accuracy of the DVR CTP calculation at lower power levels may be improved by refining the uncertainties of the inputs which are major CTP contributors. For example, as the DVR CTP calculation accuracy typically has a large error component related to the turbine efficiency input values, for lower power levels the DVR turbine efficiency could be refined to better reflect the turbine vendor predictions, or further model tuning could be performed.

It should also be noted that the accuracy of the plant instrumentation may vary with the power level of the unit. Refining the DVR model input accuracies for those instruments to account for the actual field performance could improve the accuracy of the DVR CTP calculation at lower power values.

8.3.6 Unaccounted-for Electrical Output Losses (Lost MWe's)

As discussed in Section 8.3.5, unaccounted-for causes of lost unit electrical output which are not incorporated in the DVR model will affect the DVR CTP results.

The overall DVR model's output Quality and the single penalty values for the low-pressure turbine efficiencies and gross electrical output metering would be affected. If the DVR algorithm flags either or both of these variables as suspect, or flags the variables as erroneous, the DVR CTP calculation may exceed its nominal uncertainty.

In this situation unaccounted-for plant electrical output losses may be occurring. The DVR CTP results should be considered suspect or inaccurate. Resolution of this condition will require identification of the cause of the plant electrical output loss, correction of that fault condition, accounting for the loss in the DVR model, or external to the DVR calculation with additional margin considered in respect to the DVR overall CTP uncertainty. Sensitivity studies have been performed to evaluate the effects on the calculated DVR CTP of unknown and Unaccounted-for plant electrical output losses. These cases would also bound leakage of plant valves and steam traps (Cycle Isolation losses) that may normally occur during normal plant operations. The data are presented in Table 8-6, Table 8-7, Table 8-8, and Table 8-9.

These cases are extremes and represent bounding conditions for the example unit. In the actual physical plant various plant measurements other than the gross output would occur with an unknown electrical output loss. The DVR calculation will respond by adjusting measurements local or correlated to the performance issue.

Depending on the input accuracies for these tags, some of the error will be shifted to these measurements. As a result, additional tags may be flagged related to these measurements. However, the effect on the DVR CTP will be less than the bounding cases as the error is distributed across a greater number of variables. The prudent action is to investigate possible causes of unknown electrical output losses when the Gross MW tag is flagged (single penalty > 3.84) and/ or when an excessive number of tags are flagged for the DVR calculations.

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The cases above represent single Watt-hour meter cases. In the case of a single Watt-hour meter, or low redundancy with the gross electrical output measurement, it may be difficult to differentiate actual lost unit output from an unknown and unaccounted performance loss cause from possible Watt-hour meter bias drift error. However, it can be observed from the cases that unknown and unaccounted MWe losses in the range of 0.75% to 1.0% would manifest as excessive MWe single penalty values > 3.84 even for a low redundancy, moderately accurate, Watt-hour meter measurement. Improving the redundancy or accuracy of the gross electrical output measurement will further improve the detection of bias drift and unknown performance losses, and the potential effects on the calculated DVR CTP will be less than the example given above.

When DVR CTP uncertainties are developed for a specific unit and DVR model, the effects of unknown performance losses and bias drift should be evaluated. If these losses can be contained for the subject unit through repairs, maintaining the calibration state of the Watt-hour metering, or accounting for the loss in the DVR model, such as accounting for Cycle Isolation leakages in the DVR model, additional DVR CTP margin is unnecessary. However, for a plant that is less aggressive with resolving these matters, addition of DVR CTP margin may be required.

8.3.7 Programmatic Issues

The plant should place administrative policies into effect to ensure that the DVR CTP stays within its specified uncertainty. Those policies will include:

1. Maintaining the calibration and records of the major DVR CTP error contributors.
2. Having an effective thermal performance program to properly identify unaccounted-for sources of lost unit electrical output that are not accounted for in the DVR model. An effective "Cycle Isolation" program is recommended to ensure those losses do not exceed the specified uncertainty of the DVR CTP calculation.
3. Software controls to ensure the pedigree of the model remains traceable to a verified calculation. If DVR models are altered, supporting calculations should fully document the reason for the change.
4. Software and hardware controls for the DVR environment to ensure the DVR and supporting software remain functional per the DVR vendor requirements.

8.4 Propagation of Bias Errors into the DVR Calculated CTP Uncertainty

A distribution of the major error contributors of the sample DVR model used in this report was previously given in Table 6-11. Table 8-10 gives the same data but also includes the empirical measurement input accuracies for the DVR model inputs.

Bias errors related to plant measurements that contribute significantly to the CTP accuracy or uncertainty potentially could affect the DVR CTP results.

Plant measurements that should be assessed for possible bias error effects should include major CTP uncertainty contributors that could alter the base DVR CTP value and uncertainty.

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8.4.1 Propagation of Bias Errors from the Watt-hour Metering

As previously discussed in Section 8.3.4.2, the plant electrical output measurement system can have a significant effect on the DVR CTP results. Having more metering and more accurate metering will improve the DVR CTP results and reduce the overall DVR CTP uncertainty.

Drift of the plant electrical Watt-hour meters may commonly occur, and these bias error effects on the DVR CTP result are evaluated in the following examples. Table 8-11, Table 8-12, and Table 8-13 provide data on the effects of a small amount (0.25%) of drift on the plant Watt-hour metering system used for measuring the unit's gross electrical output.

Table 8-11 provides data for the effects of the 0.25% drift bias error for a single Watt-hour meter system rated at 0.25% accuracy. Table 8-12 gives similar data for single 0.25% rated accuracy Watt-hour meter augmented with a 0.1% rated accuracy meter. Table 8-13 provides data for a case where the bias drift error slightly exceeds the base accuracy rating for the 0.25% rated accuracy meter.

For the Table 8-11 case, it can be seen that a 0.25% drift error will not be fully detected using the Watt-hour meter single penalty value, and it requires 0.68% bias error before the single penalty value exceeds the > 3.84 criterion. However, note even in this case the 0.68% bias error does not cause the DVR CTP result to exceed the rated uncertainty.

Based on this case, establishing lower limits of the single penalty meter value may be required as a mitigation means to ensure the rated single meter accuracy is not exceeded.

For the Table 8-12 case, it can be seen that a 0.25% drift error is almost fully detected using the Watt-hour meter single penalty value, and it only requires an additional 0.02% error (Table 8-13) to cause the single penalty value to exceed the > 3.84 criterion. Also of interest for the Table 8-12 and Table 8-13 cases are the DVR CTP contributions are reduced from 8.82% for the single meter case to <2% for the two meter cases. This is a consequence of reducing the CTP uncertainty related to the MWe measurement.

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8.4.2 Propagation of Bias Errors from other Feedwater Flow Metering used for the CTP Calculation

Besides potential drift of the Watt-hour metering, the feedwater flow rates used in developing the DVR feedwater flow and CTP estimates may drift themselves. The feedwater flow measurements are a major CTP uncertainty contributor.

Table 8-14 provides data showing how DVR performs when one of the feedwater flow rate measurements drifts outside its rated accuracy. As can be seen from the data, the error with the DVR estimates and CTP value are contained within the base CTP uncertainty. The bias error is also properly flagged. Therefore, DVR properly catches the bias error.

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An important item to note is that as the number of redundant measurements is reduced, the bias error effect on the CTP may increase, and the shift from the base value could also increase. Therefore, the bias effects on the feedwater flow measurements should be evaluated for the specific model under review.

8.4.3 Propagation of Bias Errors from Drift of Two Major CTP Contributors of the DVR CTP Calculation

To estimate the potential worst-case results from DVR, potential drift of the measured Watt-hour metering and the feedwater flow rates are considered.

Table 8-15, Table 8-16, Table 8-17, and Table 8-18 provide data on how DVR performs when the feedwater flow rate and Watt-hour measurements drift outside their rated accuracy, both low and high. As can be seen from the data, the error with the DVR estimates and CTP value are contained within the base CTP uncertainty for all cases other than the Low-Low case (Table 8-15). However, the error is at the margins of the rated CTP uncertainty, and is properly flagged. These cases provide evidence that the DVR algorithm can properly identify multiple bias errors.

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An important item to note is that as the number of redundant measurements for the feedwater flow rate is reduced, the bias error effect on the CTP may increase, and the shift from the base value could also increase. Therefore, the bias effects on the feedwater flow measurements should be evaluated for the specific model under review.

8.5 Evaluation of the Overall CTP Uncertainty for a DVR Model

For each DVR model developed, the overall CTP uncertainty for the model should be evaluated for the Low Redundancy items in Table 8-1 and described in Section 8.3.4. An evaluation of these items for a sample DVR model are provided in Table 8-19.

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In addition to the Table 8-19 items, the following items should be considered.

1. Steam table errors. The DVR calculation use the IAPWS Industrial Formulation 1997 [25] (IFC97) steam tables. The steam table or thermodynamics uncertainty effect on the DVR CTP is estimated to be well under 0.001 units of the overall DVR CTP uncertainty value for a typical DVR model. The DVR algorithm allows for calculation of these uncertainties per the VDI-2048 methods [1,2]. When a specific DVR model is assessed for the CTP uncertainties, steam table uncertainties will be calculated and assessed. The calculation of the thermodynamics uncertainties in DVR considers the differences of the IFC97 formulations to the values given in IAWPS 1995. IAPWS AN1-03 [25] considers the steam table uncertainties in absolute terms. If the steam table uncertainties are calculated on an absolute basis for consideration as an additional error term to be applied to the DVR CTP as margin, the error would typically on average less than 0.05 units of the overall CTP uncertainty. Figure 5 of IAPWS AN1-03 [25] may be used to estimate the absolute uncertainties of specific enthalpies used for a specific DVR model.
2. Addition of margin for potential Lost MWe's items. See Section 8.3.6. Addition of uncertainty margin for this item is an option and may be used to add conservatism to the DVR uncertainty value.
3. Addition of margin for low redundancy with the Watt-hour metering. See Section 8.3.4.2. Addition of uncertainty margin for this item is an option and may be used to add conservatism to the DVR uncertainty value.
4. Document per Section 8.3.5 the valid plant state and power limitations for the DVR CTP uncertainty.
5. Evaluate the potential effects of bias errors taking into consideration the calibration data for the instruments used for the measurements. See Section 8.4. Addition of uncertainty margin for this item is an option and may be used to add conservatism to the DVR uncertainty value.

Provided the empirically derived measurement input accuracy values can be confirmed to be valid, and do not contain unknown or incorrect error assumptions, the calculated DVR CTP uncertainty will bound the value for general plant use.

For licensed CTP application, additional margins may be included to ensure conservatism. Those items should be reviewed for proper application when developing a CTP uncertainty for licensed use.

8.6 Mitigation Methods and Use of Alternate Indicators to Ensure the DVR CTP Results are Valid

The impact of potential measurement errors, including drift, on the CTP varies with each DVR model. The amount of impact varies with the number of components used in the DVR model to simulate the auxiliary conditions, the number of plant tags available for input, and the quality of the measurements of those tags.

In general, plants that have fewer measurement tags and measurements that are of poorer quality (accuracy) may require additional mitigation measures to ensure the DVR CTP uncertainty is not exceeded. Whereas, plants that are well instrumented and the measurements are of good quality may require fewer mitigation methods, and in most cases the DVR software will properly catch and identify errors with the plant measured data that may affect the accuracy of the CTP calculations.

Plant monitoring of DVR metrics can be a useful tool to identify and mitigate potential measurement errors to ensure the DVR calculated CTP remains bounded by its rated uncertainty. Monitoring of the single penalty values of the key DVR CTP uncertainty contributors can give insight as to how these plant measurements vary and drift during the operating cycle. Thus, the single penalty values of these measurements can be used to serve as an early warning, thereby allowing corrective measures to be made before the measurement exceeds its rated accuracy.

Alternate core thermal power indicators may be a useful means to detect potential measurement errors that could affect the DVR CTP calculations. Use of alternate indicators may be particularly useful for plants that have fewer or less accurate instruments.

Other mitigations measures will include operations and engineering reviews of the DVR CTP calculated feedwater flow or CTP correction factors prior to use. These mitigation strategies are discussed in Section 8.6.1.

8.6.1 Mitigation Methods

To ensure the DVR CTP calculations are accurate and remain within the rated uncertainty the following measures may be taken.

1. For DVR models that have sufficient redundancy with the Watt-hour and feedwater flow metering, the DVR CTP results should be considered suspect when any major CTP contributor single penalty > 3.84 or the Quality of the calculation >1.0. Sufficient redundancy for the Watt-hour measurements means the DVR model and unit has more than one gross electrical output meter or has a single gross electrical output supplemented with auxiliary use or net electrical output metering which would create additional redundancies with the single gross output meter. Sufficient redundancy for the feedwater flow metering means that besides the meters used primarily for the plant calorimetric, there are other redundant meters of other types (UFMs, venturis, or nozzles) at the same location as the primary meters. Redundancy with the feedwater metering can also be increased by having metering of the main steam or upstream metering at the feedwater pumps.
2. For DVR models that have insufficient redundancy with the Watt-hour and feedwater flow metering, single penalty values of major CTP contributors may need to be established based on analytical studies and be lower than the typical > 3.84 criteria to ensure conservatism. Insufficient redundancy for the Watt-hour measurements means the DVR model and unit has only a single gross electrical output meter or has a single gross electrical output supplemented with auxiliary use or net electrical output metering of poor or unknown accuracies. Insufficient redundancy for the feedwater flow metering means the meters used primarily for the plant calorimetric do not have redundant meters of other types (UFMs, venturis, or nozzles) at the same location as the primary meters. Redundancy with the feedwater metering can also be increased by having metering of the main steam or upstream

metering at the feedwater pumps. However, if these measurements are missing or of poor accuracies, the redundancy may not be improved. Additional acceptance criteria may include setting limits on the amount of single penalty change from the base amount for the measurements to change no more than 1 (which is one standard deviation) and never exceed 3.84.

3. When any major CTP contributor single penalty exceeds 3.84 or the Quality of the calculation >1.0 an instrument has drifted outside its rated accuracy value, Unaccounted-for plant performance losses are occurring, or the plant state is different than the DVR model assumptions. In these cases, instrumentation may require recalibration, or the unknown plant performance losses or plant state may require reconciliation with the operating unit.

8.6.2 Alternate CTP Indicators

For monitoring the plant licensed power when the DVR FWFCF is implemented, alternate plant indicators of power are useful. The alternate indicators are typically plant measured variables that correlate highly with plant power level changes. Though these variables are not as accurate as DVR and therefore, should not be used to determine exact values of CTP. However, they are precise enough to identify CTP level changes. Alternate indicators are based on plant measured variables, and thus are independent from the DVR calculations.

To detect a CTP level change of about 1%, plant measurements that correlate to, and approximate the CTP are used. These will be referred to as "Coarse CTP Indicators". A list of variables that are applicable to many plants is given as follows.

Coarse CTP Indicators

1. CTP power level change related to the change in turbine 1st stage pressure.
2. Average of CTP power level change to the changes for turbine 1st stage pressure.
3. HP turbine exhaust pressure, and/or LP turbine bowl pressure.
4. Final feedwater temperature vs. CTP power level change.
5. A quick check curve of gross unit electrical output and circulating water temperature.
6. Main steam flow vs. CTP power level change.
7. Other plant measurements determined to exhibit a good correlation to the CTP.

The course alternate indicators are used by plant operators or the engineering staff as a first level CTP indicator to ensure use of the DVR calculated FWFCF will not cause the CTP to exceed 101% of the rated power. This is useful when DVR is used for power recovery efforts and the plant licensed CTP uncertainty is >1%. For plants that have licensed CTP uncertainties <1%, the coarse indicators are less useful. For these cases more sophisticated means of tracking the DVR metrics will be required.

The course CTP indicators are established using a basepoint when a DVR CTP calibration validation or check is performed or can be based upon other data from heat balance models or historical data. When the basepoints are developed consideration should be given to the state of the plant in regard to cycle isolation (cycle valve leakages) and the unit performance, in general. Preferably, the basepoints are derived from a time when the cycle isolation losses are at a minimum and the unit performance is good, with little to no unknown performance loss issues.

Sample charts of the coarse CTP indicators are given below.

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Figure 8-3 and Figure 8-4 show the amount of change for the 1st stage pressure and the 3 key turbine pressures in relation to the measured and validated plant CTP. The data indicates either correlation is useful as an indicator of the plant CTP as the trends of the variables tend to follow the CTP changes. Note that Figure 8-4 data tends to show use of the 3 key pressures as a CTP indicator yields data at a finer level. Also note for both cases the normal data are contained with a 1% limit. Thus, the indicators appear to be useful as a metric to ensure the DVR FWFCF does not cause the CTP to exceed 101%.

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Figure 8-5 shows the relationship of reactor inlet feedwater temperature to the CTP for a BWR plant. A similar relationship exists for the final feedwater temperature to CTP for PWR plants. A one Deg. F change in the reactor inlet or final feedwater temperatures will yield an approximate 1% CTP change. Therefore, a value developed for a 101% CTP value is used as an upper limit indicator.

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Figure 8-6 provides data for an upper limit of the normalized (101% licensed CTP) unit gross electrical output to the circulating water inlet temperature. The upper limit curve is based upon deriving a curve for the nominal electrical output at 100% CTP and setting the upper limit 1% higher. Note the plant data 1% lower than the upper limit value is well contained within the 1% gray band, and only a few points approach the upper limit curve.

When such a curve is developed, care must be taken that the derived curve is not biased with data that contains excessive cycle isolation or unit performance losses. If the derived curve is biased too low, when repairs are made to the performance loss items, the unit electrical output may increase such that the upper limit is exceeded frequently.

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Figure 8-7 provides data for main steam flow and change in the main steam flow from a basepoint. The data clearly shows an upper limit value of 1%, which would correlate to approximately 101% CTP, is reasonable.

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Figure 8-8 provides the same data for main steam flow change in relation to the measured and validated CTP. The data clearly shows the main steam flow changes with CTP changes.

Additional Engineering DVR CTP Indicators

Detection of CTP change of less than 1% is difficult using only plant measurements. To track the performance of the FWFCF developed for use from DVR, various metrics from the DVR calculations may be monitored or trended. Use of said indicators is at the discretion of engineering.

DVR CTP Indicators

1. FWFCF calculated value and penalty value
2. DVR Quality value
3. Number of DVR Flagged Tags
4. Penalty value of the best accuracy unit electrical output Watt-hour meter
5. Penalty values of important DVR CTP contributors

Figure 8-9 through Figure 8-13 provide data for several of the indicators described above.

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Referring to Figure 8-9, it appears the fouling or feedwater flow venturi error varies a bit for the period examined. The time period of near 7/19/18 starts off with a bit of fouling, then de-fouls after an outage near 10/27/18. The fouling stays constant for a while, then starts to foul again in April 2019, and continues through the end. Note the single penalty value of the FWFCF increases as the measured feedwater values to DVR calculated results increase.

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Figure 8-10 shows the average DVR calculated FWFCF and Quality values for the same time period. The data have been filtered to remove runs with flagged tags that affect the DVR CTP uncertainty >0.5% uncertainty contribution. Note the Quality of the data is less than 1 and remains fairly constant.

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Figure 8-11 shows the raw Quality values for the same time period. For this example there are 350 sets of data, or 1.35% of the total of about 26,000, that exceed a Quality value of 1.

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Figure 8-12 shows the raw number of flagged tags (penalty >3.84) for the same time period. Datasets that have flagged tags that affect the DVR CTP uncertainty will not be used when calculating or comparing the FWFCF. The average number of tags for the entire time period is 1.4 flagged tags per dataset. The majority of the flagged tags are unrelated to the DVR CTP uncertainty.

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Figure 8-13 shows the penalty values for the unit gross electrical output Watt-hour meter. There appears to be a shift in the calibration performance of the meter from about 8/23/2019 to just before 12/1/2019. Though the calibration shift is less than 1 standard deviation (penalty value of 1), the cause of the calibration shift requires investigation and resolution to ensure the FWFCF calculations remain unaffected.

8.6.3 Summary of Use of Mitigation Methods and Alternate CTP Indicators

Use of mitigation and alternate CTP methods are summarized in the following tables.

Table 8-20
Mitigation methods and alternate indicators to ensure the DVR CTP uncertainty is not exceeded

Item	Mitigation Method and Required Actions	Comments
DVR Quality Value >1.0	Administrative procedural controls will control the use of the DVR CTP value When the DVR calculation Quality exceeds a value of 1.0, the DVR CTP results for that run will be considered invalid.	NA
Major DVR CTP Uncertainty Error Contributor (>0.5%) exceeds a single penalty value of 3.84 or a lower specified value	Administrative procedural controls will control the use of the DVR CTP value. When a major DVR CTP uncertainty error contributor single penalty exceeds a set, determined value the DVR CTP results for that run will be considered invalid.	NA
Bad DVR Measured Data	Develop DVR filters and software methods to allow the DVR calculation to proceed with minimal effect on the DVR uncertainty. Ensure the plant computer or data historian providing input data to DVR provides reasonable values of readable data.	All filtering methods will be stated in the DVR model design documentation.
Hardware, Network, & 3rd Party Software Issues.	Work with site and corporate IT to ensure software and network components are compatible with the DVR software and perform in a reliable manner	None.

Table 8-20 (continued)
Mitigation methods and alternate indicators to ensure the DVR CTP uncertainty is not exceeded

Item	Mitigation Method and Required Actions	Comments
DVR Fails or Results Invalid	Ensure bad input data is limited or does not pass into the DVR calculation as input. Ensure the model is operating within a valid power range. Ensure all model assumptions and limitations have been identified. See additional discussion in this section.	The DVR design documentation will identify the model valid operating range, model assumptions, and limitations.
Plant Procedures and Controls Fail	Proper administrative controls will be developed to control use of the DVR CTP.	Major CTP contributor calibrations will be documented. Unaccounted-for MWe losses inputs for the DVR model will be controlled per plant procedure. Plant procedures will control the DVR valid plant conditions and software controls
Low Redundancy gross electrical output measurement	Establish lower levels of single penalty values for the measurement. Or, establish allowance of the single penalty value to deviate from a base condition within a specified amount based upon bias error propagation testing.	Lower single penalty limits may cause the DVR CTP to be less useful for units that have low redundancy with the gross electrical output measurement. Or, where these meters are not sufficiently accurate. Lowering the limits of the single penalty value may cause the DVR CTP uncertainty to be deemed as invalid as excessive conservatism is imposed.
Low Redundancy feedwater flow measurement(s)	Establish lower levels of single penalty values for the measurement. Or, establish allowance of the single penalty value to deviate from a base condition within a specified amount based upon bias error propagation testing.	Lower single penalty limits may cause the DVR CTP to be less useful for units that have low redundancy with the gross electrical output measurement. Or, where these meters are not sufficiently accurate Lowering the limits of the single penalty value may cause the DVR CTP uncertainty to be deemed as invalid as excessive conservatism is imposed.

Table 8-21
Alternate core thermal power Indicators

Item	Purpose	Correlation Accuracy	Comments
Turbine First Stage Pressure or 3 Key Turbine Pressures	Establish upper limits of first stage turbine pressure or 3 key turbine pressure change	Approximately 0.5% to 1%	Depending on the accuracy of the first stage or 3 key turbine pressure measurements, the ability to detect the rated DVR CTP uncertainty may be limited when the DVR CTP Uncertainty is <0.5%
FFWT (final feedwater temperature) vs. CTP	Establish upper limits of the final feedwater temperature.	Approximately 0.5% to 1%	Depending on the accuracy of the plant measurements the ability to detect the rated DVR CTP uncertainty may be limited when the DVR CTP Uncertainty is <0.5%
Main steam flow and change in the main steam flow from a basepoint	Establish upper limits of the main steam flow.	Approximately 0.5% to 1%	Depending on the accuracy of the plant measurements the ability to detect the rated DVR CTP uncertainty may be limited when the DVR CTP Uncertainty is <0.5%
Maximum Gross Electrical Output Check	Calculates an upper limit gross MWe based on the operating conditions and margin allowed for the DVR CTP uncertainty	Approximately 0.5%	This would serve as a coarse filter to alert operations and engineering that the DVR CTP calculation may no longer be valid.

When use of the DVR CTP is implemented at a plant as a means to correct an existing plant calorimetric (power recovery), or as a means to implement a margin uprate through a license change, monitoring of key DVR metrics and/or the items given in Table 8-20 shall be required when the DVR results are used. Plant operations will monitor key DVR and alternate power indicators as provided by plant engineering. Plant engineering will establish acceptance criteria for the DVR metrics and alternate power indicators and provide plant operations with said criteria. In cases where the criteria are deemed to be exceeded by plant operations, the DVR CTP will be considered to be invalid, and plant engineering shall be consulted to resolve or reconcile the issue. Section 2.6 provides additional information regarding Operator Controls.

9
OFF NORMAL

9.1 Introduction

The DVR model is built, tuned, and tested to provide valid DVR results under normal plant operating conditions within a defined power range and plant state. When DVR is used in an unknown or untested plant state or configuration, the DVR Core Thermal Power (CTP) and feedwater flow correction factor (FWFCF) results may not be valid. Therefore, the plant conditions for when the DVR calculations may be used must be clearly identified.

Abnormal or Off-normal plant operating procedures define plant conditions that are typically temporary in nature, short in duration, and represent system or equipment line-ups or operating conditions that differ from those at the typical 100% CTP power level and state.

Each Licensee needs to address their individual plant situation, models and implementation methodology for conditions most likely to be experienced. The ultimate goal is to ensure the stability of the model's results and the reliability of the FWFCF. To accomplish this, impacting events with a reasonable probability of occurring are evaluated using historical data.

9.2 Determination of Typical, Off Normal Conditions, and DVR Untested State or Configuration

Once a model is built, historical data is evaluated to determine events impacting the model output. Those events identified are studied to determine significance to model, cause, duration, and likelihood of repetition. The testing, evaluation, and examination of historical data is typically conducted during back-testing of the model (see Section 6.5). The Functional Acceptance Test (FAT—refer to Section 7.3.3) performs the back-testing of the model. The historical data are first examined to find instances when the plant is off-line. Off-line data are not used for the back-testing calculations. The data are then examined for times when the plant is operating below 100% CTP, and when the unit's electrical output varies significantly from day to day. The data are compared to values from the vendor turbine thermal kit data, reference heat balances, software heat balance models, or other design data or algorithms used by the utility to calculate the thermal performance of the plant or equipment.

Comparisons of DVR calculated values to the design or expected values of the thermal performance criteria of the plant or equipment may include, but are not limited to items such as:

- Unit gross and net electrical output vs. CTP
- Unit gross and net electrical output vs. condenser backpressure or circulating water temperature and flow rate
- Turbine stage efficiencies

- Heat transfer coefficients or heat transfer performance of reheaters, feedwater heaters, or other of shell and tube heat exchangers used in the DVR model
- System and component mass and energy balances
- Valve and piping pressure drops
- Moisture separator effectiveness
- Condenser vacuum as a function of circulating water temperature and flow rate
- Plausible assumptions of equipment performance (see Section 6.3.2.2)

The data are assessed for reasonableness of the DVR calculations and evaluated for potential errors sources as given in Section 6.8.

The operating state of the plant and the component and system line-ups are then confirmed for each set of data to ensure that that the back-testing results can be assessed based upon a classification or categorization of data related to the plant state.

9.3 Off Normal Condition

Data obtained from periods of time from when the plant is performing an Off-Normal operating procedure are not used when performing the back-testing. Therefore, the DVR CTP or FWFCF results shall not be used when the plant is conducting an Off-Normal procedure.

Each Licensee shall identify the plant Off-Normal operating procedures and ensure the DVR CTP and FWFCF results are not used for plant operation when performing said procedures.

If an abnormal condition is included in the model and proved to be acceptable then the model can be utilized for these conditions.

9.4 Typical Conditions

Typical plant conditions include normal variations of the plant state due to environmental or seasonal changes such as the condenser cooling water variations with the calendar year, minor plant power changes, or other typical operating changes that may occur during a normal operating cycle.

The back-testing data are assessed for performance of the DVR model under typical plant conditions. Data from several operating cycles are reviewed so that effects on plant measurements due to the normal operating and seasonal variations can be characterized and accounted for. The DVR calculated Quality and single penalty values important to the DVR CTP and FWFCF uncertainty contribution are evaluated to meet the acceptance criteria of Quality <1.0 and single penalty <3.84. The stability of the FWFCF is also assessed.

When the DVR results fail to meet the uncertainty acceptance criteria, the data are examined for the plant power level and state. The causes of the calculation failures or failure to meet the uncertainty acceptance criteria for each failed set of data are then examined. The failed data sets are categorized based upon identification of the plant operating conditions, power levels, line-ups, bad measurement input value, or other condition that might cause the DVR result to fail.

Examples of plant evolutions that may occur that could potentially affect the DVR CTP and FWFCF results include, but are not limited to:

- Temporary use of a demineralizing system
- Condenser backwashing or times of circulating water flow reversal
- Turbine valve testing
- Cycling of main or booster feedwater, heater drain, condensate, or condensate booster pumps
- Final feedwater temperature reduction
- Blowdown configuration

Plants may determine or have knowledge of other evolutions which may affect the results.

Each instance of such plant evolutions must be identified when back-testing is performed to allow assessment of the DVR CTP and FWFCF results and acceptance criteria (Quality and single penalty values) when under these plant conditions. If the DVR model produces acceptable results for each of these plant conditions, the CTP and FWFCF results may be used going forward when encountering these plant states. Otherwise, the DVR model may require modifications to provide acceptable results when such a plant evolution occurs. Regardless, the DVR model must be tested under each possible plant state scenario and produce acceptable results before the model can be used in such a plant state. If the back-testing does not contain data or instances of data of a specific plant state, and the state may occur in the future, this represents an untested state or configuration. Documentation of the tested state of the DVR model are controlled under the software Verification and Validation (V&V) as part of the design process (see Sections 2.4 through 2.6).

9.5 DVR Untested State or Configuration

An untested state or configuration represents use of the DVR model with plant data for a condition that has not been tested or evaluated during the back-testing. An untested state or configuration could also refer to a design change, modification of the plant or system components, or operating change from the base DVR model.

The DVR model shall not be used for said conditions until the time the model's performance can be assessed against the established acceptance criteria under such conditions. If the DVR results are determined to be acceptable during such conditions, the DVR model may be used for calculation of the CTP and FWFCF for those conditions. Design changes on SSC's that impact the DVR model should be evaluated in the design change process.

10
DVR RELIABILITY

10.1 Introduction

DVR has been used by the nuclear power industry in the U.S. and Europe to assess turbine cycle thermal performance, balance of plant feedwater flow metering and accuracy of the plant calorimetric, or measure of the plant's reactor power.

In the United States, DVR technology has been used at several sites with Operating Event (OE) issues due to suspected errors with the feedwater flow metering within the plant licensed calorimetric (CTP) (see Section 5 for additional DVR related OE). This section captures current applications of the technology in the power industry in general and specifically in the Nuclear Power industry. The reliability of these implementations of DVR technology will be discussed in this section.

This section will demonstrate the necessary procedures to ensure the DVR applications are sufficiently accurate to be used for the determination of errors with plant instrumentation. Of special interest is the determination of uncertainties associated with feedwater flow metering and the core thermal power (CTP) measurement. The reliability of DVR will also provide assurance the software elements that comprise the DVR software perform their key features as designed.

10.2 Reliability of DVR Results

In its most basic form, reliability can be defined as the probability of success.

$$\boldsymbol{Reliability = 1 - Probability\ of\ Failure} \qquad \textbf{Eq. 10-1}$$

In most engineering applications reliability deals with the failure rate of a certain product throughout the course of its life (i.e., bathtub curve), for DVR the reliability is more akin to the probability the DVR results are successful. As defined in this section, success can be defined as DVR:

- Producing results
- Producing results that are of a suitable statistical quality
- Producing results that are correct

In this section, for the purpose of assessing DVR results, incorrect results are defined as results where the calculated MWth CTP confidence interval doesn't contain the true CTP with the specified confidence or the Feedwater Flow Correction Factor (FWFCF) is not valid for use.

Generic guidance on implementing a DVR CTP based correction factor for feedwater flow can be found in Section 6.9.3.

Providing results that are either outside the assumed uncertainty for the power calculation or results that contain an unknown bias are potential reliability failures for the DVR process. Testing the model over a significant period of time (i.e., using up to three years of plant data) provides the opportunity to assess the reliability of the model based on various plant conditions and various plant measurements. The assessment, along with the sensitivity studies described in Section 8, will provide opportunity to determine the reliability of the model.

10.3 Metrics Used to Assess DVR Results

DVR mainly uses two metrics to quantify the results, the DVR quality and single measurement penalty (single penalty). The quality is a metric used to quantify the overall results of a DVR simulation. It is expressed in Equation 3-45 and further discussed in Section 3.4.6. A quality value of less than 1.0 provides assurance the measured values are within their specified confidence ranges. Whereas a quality value of greater than 1.0 indicates it is suspected a certain number of measured values deviate from their true values by an amount exceeding the specified confidence region [1].

The single penalty metric is calculated for each measurement. It is expressed in Equation 3-43 and Section 3.4.5. It can be thought of as a quality measurement of single parameter, as opposed to the quality of the overall results. The single penalty value is a measure of the amount of the DVR improvement (difference between the reconciled and measured values), relative to the uncertainty of the improvement. A single penalty value of less than 3.84 indicates the DVR improvement is within 1.96 standard deviations (95% confidence region). Whereas a single penalty greater than 3.84 indicates the DVR improvement is outside 1.96 standard deviations. This would classify either the measured value or the estimated uncertainty of the measured value as suspect. In this document, measurements where the single penalty value is greater than 3.84 are referred to as "flagged tags".

Additionally, for DVR applications that use the FWFCF, there are two additional metrics that are used. These are the uncertainty of the FWFCF and the standard deviation of the CTP. DVR calculations will provide a confidence interval for the FWFCF with 95% confidence. This confidence interval is the uncertainty of the FWFCF (typically provided as a percentage) and is equivalent to two standard deviations. The CTP standard deviation is one half of the calculated CTP confidence interval assuming 95% confidence.

10.4 DVR Failure Criteria

Application of DVR at a nuclear power plant may utilize 80-200 measurements, and in some cases even more. For reliability of DVR applications at nuclear power plants, the model will be considered a failure if it does not produce a valid FWFCF. There is almost a direct correlation between the FWFCF and the calculated CTP, therefore it is valid to use the FWFCF as the parameter for which to be judging the reliability of the DVR model. The acceptance criteria for use of the FWFCF is described in Section 6.9.3.3.6. Of the acceptance criteria in Section 6.9.3.3.6, two will be used as prescriptive guidelines to assess the DVR results. These guidelines are described as Criteria 1 and Criteria 2:

- Criteria 1: DVR quality value < 1.0
- Criteria 2: Single penalty values < 3.84
  - Single penalty violations only invalidate the DVR results for the particular measurement that has violated this criterion.

Criteria 1 is the overall assessment of the DVR results and is based on a statistical Chi-squared test to verify there is 95% confidence in the DVR results [1]. Criteria 1 is the method used in VDI 2048 [1] for quality assessment and identification of serious errors.

Some licensees may desire to add an additional criterion to allow for closer scrutiny of the DVR results. This can be accomplished by evaluation of those measurements that have a significant contribution to the CTP uncertainty. The rationale for this is that those measurements that have an influence on CTP uncertainty should have single penalty values less than 3.84. Measurements that have single penalty values greater than 3.84 but do not contribute to the CTP uncertainty are not scrutinized as much.

The FWFCF procedure as described in Section 6.9.3 has an additional acceptance criterion. This additional acceptance criteria is to check whether any relative changes to the FWFCF (measured in percentage) since the last time the procedure was executed using Calibration Validation is within one standard deviation (measured in percentage) of the reconciled CTP value. For example, if the reconciled CTP standard deviation is 1%, as long as the FWFCF doesn't change by more than 1%, this criterion is satisfied. This acceptance criteria is part of the FWFCF procedure (Section 6.9.3.3.6, paragraph 2) and prescribes that the plant state will have to be re-confirmed and a Calibration Validation performed when the above criteria is not satisfied. The inability to satisfy this acceptance criteria indicates the feedwater measuring system has fouled, defouled, or may have other errors. Failure to satisfy the acceptance criteria for the FWFCF does not suggest that DVR results are unreliable. Conversely, it is an indication that the DVR model is working as intended and the DVR results have identified a potential issue with the plant's feedwater measuring system. The part of the FWFCF procedure acceptance criteria to check for FWFCF relative changes (Section 6.9.3.3.6, paragraph 1) is not considered a DVR failure criterion, with regards to the reliability of the DVR model.

Exceptions or outlying data may be discovered when running the historical actual plant data cases as the data may contain changes in the normal operating modes or performance issues with the plant equipment or instrumentation that may occur from time to time. For those cases, the acceptance criteria will be that the DVR calculations identify suspect points and the Single Penalty and Chi-Squared test values will reflect the data contains potentially erroneous data.

Atleast 95% of the test data cases calculated should pass DVR with Single Penalties that are < 3.84 for all the measured data inputs that are major error CTP contributors and the Quality values are <1. Single penalty values greater than 3.84 for non-major error CTP contributors would not by itself result in a Criteria 2 failure. However, if there are numerous single penalties greater than 3.84 for a case, this would be captured in the DVR quality value and may result in a Criteria 1 failure.

Additionally, there could be instances where a DVR model fails to produce a result due to an issue with the model or provided plant data. The consequence of this is that the model will not converge to a result. These issues should be eliminated during development of the DVR model and are typically rare and readily identifiable during final reliability testing of the model. However, they should still be accounted for when testing the reliability of the DVR model.

10.5 DVR Reliability Calculation

During initial implementation of DVR, the above process will be performed using actual plant data to determine the reliability of the DVR model. Based on plant operating history the length of time for performance of the reliability study may vary. It is recommended a large sample of data be used at specific time frequency. The licensee will assess the plant history and determine the length of time required for this study (see Tables 6-7 and 7-3 for an example of a sample size and time frequency for back-testing).

Three DVR failures modes have been defined:

- Criteria 1 failures
- Criteria 2 failures
- Failed runs (DVR model unable to produce results)

The reliability of the DVR model can be expressed by Equation 10-2.

$$\boldsymbol{DVR\ Reliability} = 1 - \frac{(Criteria\ 1\ failures + Criteria\ 2\ failures + failed\ runs)}{Number\ of\ runs} \qquad \textbf{Eq. 10-2}$$

The DVR reliability can be expressed in terms of fraction or percentage. When expressed as a percentage, the acceptance criteria for DVR reliability is typically 95%. This process is nearly identical to the back-testing described in Section 6.5.

$$\boldsymbol{DVR\ Reliability} > 95\%$$

In many cases, the DVR reliability is much greater than 95%. Each facility that implements DVR may request a DVR Reliability greater than 95%, but it is recommended that 95% be the minimum. An example of the DVR Reliability computation using actual plant data from a United States BWR can be seen in Table 10-1.

Table 10-1
DVR reliability calculation example

Description	Number of runs
Total attempted	604
Criteria 1 failures	0
Criteria 2 failures	3
Failed runs	0
Total failures	3
Total valid attempts (Note 1)	604
Probability of failure	0.50%
DVR Reliability	99.50%

Note:

1. There could be some instances where runs are completed but the plant was not in the normal operating alignment assumed by model (see Section 6.9.3.3.3 for details on plant state when CTP DVR results are valid). These runs should be disqualified from the total attempted runs to determine the number of valid attempts (valid attempts = total attempts—disqualified attempts).

When a DVR run fails due to a Criteria 1 or 2 failure, it should not be construed that the developed model is wrong or incorrect. It typically means DVR is able to produce results, but unable to produce results than have 95% confidence in some cases. This could be due to erroneous data from a nuclear facility's plant computer historian (i.e., PI data) or there could be something wrong with the measuring instrument itself or how it is installed. In each of these cases it is the responsibility of the organization responsible for developing or maintaining the DVR models to further investigate and determine if updates are required to improve the model (i.e., filtering measurement data as discussed in Section 10.8), or corrective actions are needed with the plant computer data historian or the plant instrumentation.

10.6 DVR Reliability Calculation Study

In this section a study will be performed on the DVR reliability calculations of DVR models for multiple commercial nuclear operating units in the United States. As shown in Section 10.5 and demonstrated in Table 10-1, quantifying the reliability of a DVR model is a rather straightforward exercise. This study will look at the DVR reliability of DVR models at 11 operating units, three of which are Pressurized Water Reactors (PWRs) and eight are Boiling Water Reactors (BWRs). The results of the DVR reliability calculation for the three PWRs and eight BWRs can be seen in Table 10-2 and Table 10-3, respectively. The distribution of the DVR reliability results can be seen in Figure 10-1.

Table 10-2
DVR reliability for PWR sample

	Number of Runs		
Description	**PWR 1**	**PWR 2**	**PWR 3**
Total attempted	429	366	792
Criteria 1 failures	1	0	0
Criteria 2 failures	0	4	1
Failed runs	3	3 (Note 1)	6
Total failures	4	4	7
Total valid attempts	426	363	792
Probability of failure	0.90%	1.10%	0.88%
DVR Reliability	99.10%	98.90%	99.12%

Note:
1. The 3 failed runs for PWR 2 happen to be the 3 runs that were disqualified. Therefore, they were not included in the Total failures value.

Table 10-3
DVR reliability for BWR sample

	Number of runs							
Description	**BWR 1**	**BWR 2**	**BWR 3**	**BWR 4**	**BWR 5**	**BWR 6**	**BWR 7**	**BWR 8**
Total attempted	604	366	664	427	605	580	1031	192
Criteria 1 failures	0	0	0	0	0	2	1	0
Criteria 2 failures	3	3	10	0	0	0	2	0
Failed runs	0	11	0	0	0	0	0	3
Total failures	3	14	10	0	0	2	3	3
Total valid attempts	604	366	664	427	604	580	1023	192
Probability of failure	0.50%	3.83%	1.51%	0.00%	0.00%	0.34%	0.29%	1.56%
DVR Reliability	99.50%	96.17%	98.49%	100.00%	100.00%	99.66%	99.71%	98.44%

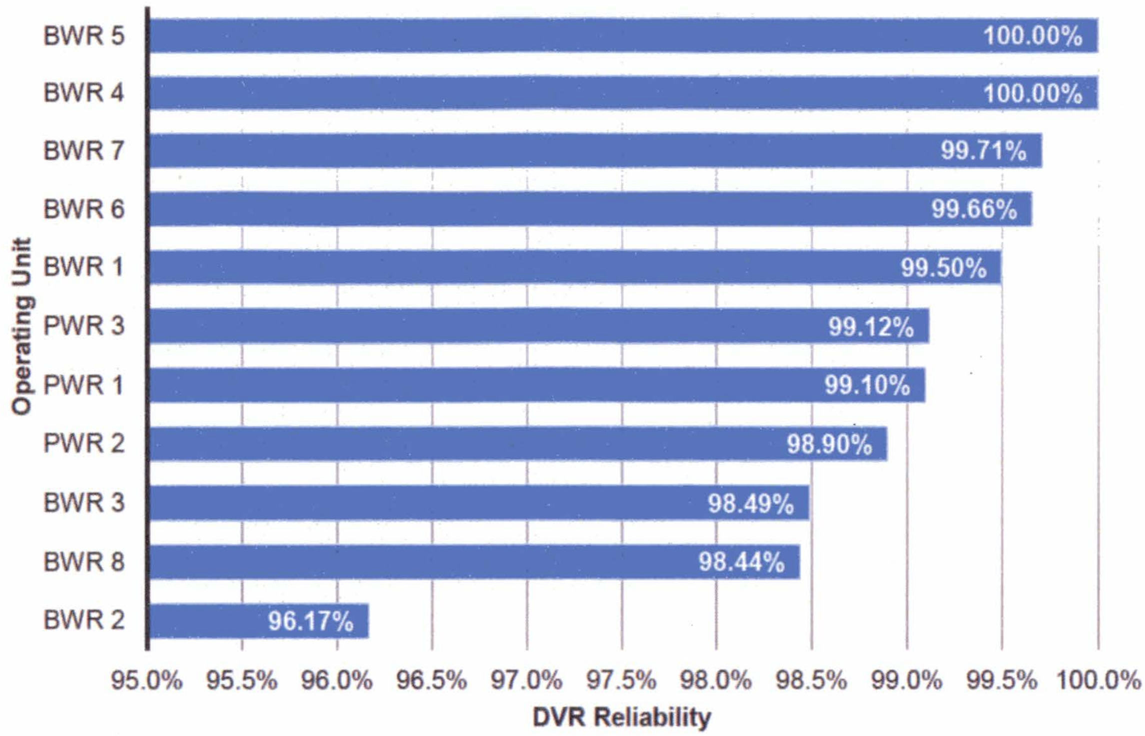

Figure 10-1
Distribution of PWR and BWR DVR reliability results

The results show that for the majority of the cases, the DVR models have a reliability greater than 98% with a mean close to 99%. Another observation is that there are only a total of four Criteria 1 failures across a total of 6,056 runs. Such few cases where quality is greater than 1.0 provides assurance the measured values are within their specified confidence regions. Although these results are only a sample of the total amount of operating units DVR potentially could be implemented at, it is still possible to quantify a confidence level for future applications. The results of the sample mean, sample variance and sample standard deviation of the DVR reliability study are shown in Table 10-4.

Table 10-4
DVR reliability statistical results

Statistic	Value
Sample Mean	99.01%
Sample Variance	1.18%
Sample Standard Deviation	1.09%

Since Table 10-4 represents a sample of plants that have had DVR models developed, the actual mean, variance and standard deviation of all nuclear operating units that may implement DVR is unknown. This is a classic example of statistical problem where information on a small sample (<30 observations) is known, but information on the total population (nuclear operating units which may implement DVR) is unknown. The method used to acquire a confidence interval is to use the Student's t distribution. For DVR reliability, it is desired to determine a lower threshold to which the true mean would lie above. This lower threshold, or Lower Confidence Limit (LCL), is calculated by Equation 10-3 [26].

$$\boldsymbol{LCL = Sample\ Mean - t_{\alpha,n-1}\frac{S_n}{\sqrt{n}}} \qquad \textbf{Eq. 10-3}$$

Where,

$t_{\alpha,n-1}$ is the Student's t value at a specified confidence and degrees of freedom (n-1)

S_n is the sample standard deviation

n is the number of samples

It should be noted that confidence, α, used to determine the Student's t value in Equation 10-3 is the one-sided, or one tailed, confidence [26]. For this DVR reliability study, two LCLs will be calculated for confidence regions of 95% and 99%.

$$\boldsymbol{LCL_{95\%} = 99.01 - 1.812\left(\frac{1.09}{\sqrt{11}}\right) = 98.41\%} \qquad \textbf{Eq. 10-4}$$

$$\boldsymbol{LCL_{99\%} = 99.01 - 2.764\left(\frac{1.09}{\sqrt{11}}\right) = 98.10\%} \qquad \textbf{Eq. 10-5}$$

As can be seen in Equations 10-4 and 10-5, it is expected the true mean of the DVR reliability to be greater than 98.41% with 95% confidence, and the true mean of the DVR reliability to be greater than 98.10% with 99% confidence. This statistical evaluation of the DVR reliability study concludes that there is a high degree of confidence that the DVR reliability will be greater than 95% (acceptance criteria per Section 10.5) if implemented at other nuclear operating units.

There are two caveats that should be taken into account when interpreting the results of this DVR reliability study. One is that there is some bias selection present in the DVR reliability values. The DVR model should not be approved if the reliability is less than 95%. If the DVR reliability was calculated to be less than 95%, the organization responsible for developing the model, should investigate the failures and correct the model before approving the model. A DVR model with less than 95% reliability should not be approved. Only sampling the "good" models would appear to instill bias and skew the results. However, it would be expected that models would be reviewed, vetted, tested and processed through some form of software quality assurance (SQA) before being implemented at a nuclear operating unit. Therefore, sampling only approved DVR models is good representation of actual DVR implementation at nuclear operating units.

The other caveat is that the three failures used in the DVR reliability calculation (Criteria 1 failures, Criteria 2 failures and failed runs) do not represent every conceivable way DVR implementation could fail. There could be issues or failures of a nuclear operating unit's plant computer system or plant historian. Faulty or no data sent to the DVR model could result in DVR quality > 1.0 and result in a Criteria 1 failure. There could be errors or failures in the transmission or processing the database data sent to the DVR model. Additionally, there could be issues with the actual computer used to implement DVR. Not accounting for these additional potential failures could skew the DVR reliability result to be greater than it may be in actual implementation. It is not the goal of this section to account for these additional failures.

Therefore, when interpreting the results of Section 10.6, it should be stressed the concern is the reliability of the DVR model or calculation, not the reliability of the overall system when implemented at a nuclear operating unit.

10.7 Robustness of DVR Calculation

In the development of models, robustness is the generic term to describe the strength of the model. A robust model is one in which it is resistant to perturbations in data and assumptions. The calculations of a DVR model comprise of numerous inputs in the form of plant measurements and estimates of the uncertainties of these measurements. Many assumptions of the physics and state of systems are used to develop the auxiliary conditions. Additionally, within the DVR industry different methodologies exist which are used.

10.7.1 Robustness Due to Diversity of Inputs

The numerous inputs as part of a DVR model add the benefit of robustness to the DVR calculation. As discussed in Section 8.4 and shown in Table 8-10, many plant instruments contribute to the CTP uncertainty using DVR, as opposed to traditional methods, which primarily used a select few feedwater flow instruments. One of the main traits of the DVR process is the use of the covariance matrix in the DVR calculation. As discussed in Section 3.1.3, the weighting matrix (inverse of the covariance matrix), is used to account for the different uncertainties of each measurement. Measurements with smaller uncertainties (higher accuracy) will be adjusted to a lesser extent than those with larger uncertainties (lower accuracy), which are not as trustworthy and would be more freely adjusted [4]. For measurements which contribute to CTP, a larger uncertainty will allow for more improvement. Thus, the measured value will have less influence on CTP. This trait demonstrates the robustness of the DVR calculation by not allowing a single measurement to significantly alter the CTP calculation.

The impact of the introduction of bias error in CTP contributing measurements is further investigated in Section 8.4. Table 8-11 through Table 8-13 show various cases where bias errors are introduced into the Watthour meter measurements for a DVR model. In the case where only a single Watthour meter was present in the model, a 0.25% Watthour error resulted in a -0.11% shift to the CTP value. However, when a second Watthour meter and redundancy was added to the model (which is typical of important CTP contributing measurements at U.S. nuclear operating units), a 0.25-0.27% Watthour error only resulted in a -0.02% shift to the CTP value. What this is demonstrating is that the diversity of inputs in the model and the introduction of redundancy results in a more robust DVR model. The DVR model will still provide reasonable results even if there are perturbations and errors present in the measurement data.

10.7.2 Robustness Due to Imperfect Assumptions

Development of a DVR model requires establishing numerous auxiliary conditions. These auxiliary conditions could be mass flow rate balances, conservation of energy equations, or other empirically based engineering equations (i.e., valve discharge equations). Most of these auxiliary conditions will be generated by the DVR modeling software and not explicitly defined by a person developing the model. For DVR applications at nuclear operating units, the number of auxiliary conditions would be in the order of magnitude of the hundreds and up to thousands in many cases.

Auxiliary conditions will never perfectly model the system state and many assumptions will be required to be made. An example of an imperfect assumptions is assuming 100% conservation of mass throughout a power cycle. Typically, the models and mass balance calculations do not account for leakage—assume every system has zero leakage—in the auxiliary conditions. This "false" assumption will impact the DVR results to some degree. Per Section 6.9.1, unmeasured cycle leakage is a significant plant condition that could impact whether the CTP calculated by DVR is valid. The impact of unaccounted electrical output losses (lost MWe) due to system leakage is further investigated in Section 8.3.6. The sensitivity study in Section 8.3.6 represent extremes and bounding conditions for the example unit. Table 8-9 shows the effect of system leakage on the MWe output and CTP when not accounted for. For leakages of 0.25% to 0.5% (percentage of MWe impact due to leakage), the MWe output penalty value is less than 3.84 and the CTP uncertainty impact was less than 0.22% MWth. For leakages of 0.75% to 1.00%, the MWe output penalty value was greater than 3.84 (Criteria 2 failure) and the CTP uncertainty impact ranged from 0.319% to 0.425% MWth.

For actual system leakages of up to 0.5%, the assumption of zero leakage still results in a reliable DVR model. For actual system leakages greater than 0.5%, the assumption of zero leakage may result in an unreliable model. The DVR model is robust in regard to imperfect assumptions up to a certain extent. A scenario that could occur at a plant is excessive unaccounted for Cycle Isolation leakages. Cycle isolation are those valves which when open either pass fluid to the condenser bypassing the turbine cycle or portions of the turbine cycle or to the atmosphere. In cases where a leakage is large, and the DVR model does not account for the leakage, the reconciled CTP value or FWFCF may be affected. Therefore, it is imperative that nuclear operating units that implement DVR verify that cycle isolation leakage is accounted for in the model.

10.7.3 Robustness Due to Different Numerical Methods

A thorough description of the DVR methodology is presented in Section 3. Over time, different numerical methods have arisen to perform data validation and reconciliation. The elimination algorithm presented by Streit [3] in 1975 was one of the first published prescriptive methods for validation of data for turbine acceptance testing. Most DVR methodologies are based on upon Streit to some extent. However, they are all not numerically identical in their methods. More precisely, the numerical methods in which auxiliary conditions and unmeasured variables are handled differs. Five methods have been considered in this study:

- Streit elimination algorithm [3]
- VDI 2048 [1]
- Commercially available DVR Software
- Algorithm According to Witkowski [4]
- Z-algorithm [4]

Different numerical methods are presented in Section 4. A simplified test case comparing the DVR software methodology (methodology presented in Appendix A.1 and A.2.) against the VDI 2048 [1] and Z-algorithm [4] methods is presented in Section 4.2. The simplified test case results (Tables 4-3) show that the when calculating the reconciled values and uncertainties using mass

11
LIMITING CONDITION FOR OPERATION (LCO)

11.1 Limiting Condition for Operation (LCO)

Most Limiting Condition for Operation (LCO) are documented in a licensee's Technical Specifications (TS) document. LCOs are located in the section of Technical Specifications that identify the lowest functional capability or performance level of equipment required for safe operation of the facility, and may apply to the performance of the plant calorimetric (CTP) at some plants. The degree to which DVR may impact LCOs is presented in the following subsections.

The LCO sections identify both limits and requirements that need to be met when exceeded. The LCO also identifies durations and actions required when the LCO is exceeded. An example of one type of LCO is; a technical specification's required operable component is out of service for longer than 72 hours. This outage duration is the limit provided in the LCO section. Therefore, in accordance with the LCO, a plant downpower is required. This type of LCO provides the duration of how long the instrument can be inoperable, and then specifies the actions required if the duration of the LCO is exceeded. A bases for these limits, relevant to each facility license, is also available. This section will discuss some potential LCOs that may need to be considered when evaluating Design Validation and Reconciliation (DVR) at a facility. This section is not intended to be an all-encompassing discussion of potential LCOs that could result from implementation of the DVR methodology.

A detailed regulatory and technical specifications (with bases) impact review would need to be conducted for each facility, as part of a process for DVR methodology implementation. Depending upon how a licensee may incorporate the utilization of the DVR process will determine the scope of both the TS changes, including drafting of new or revising existing LCOs. The scope of the License Amendment Request (LAR) will be dictated by the level of need for revisions to each licensee's existing TS.

Sensitivity studies and evaluations of plant data documented in Section 8 identify specific conditions that may impact the uncertainty or validity of the DVR calculation, and when the DVR performance may be affected such that the results exceed the expected accuracy, or the DVR calculations fail.

11.2 International DVR Applications

After a review of the international DVR applications presented in Section 5, it has been determined that LCOs for this application were not applied at the respective utilities.

11.3 Similar Applications

Analogous LAR applications using Ultrasonic Flow Measurement (UFM) for Measurement Uncertainty Recapture (MUR) were reviewed to determine the applicability to DVR. As an example, Palisades Nuclear Plant utilizes UFM to calibrate feedwater flow venturi nozzles. A similar application for DVR utilization is discussed in Section 11.5.

The use of the DVR methodology could be a similar type of application such that the DVR is used to compute a correction factor (CF) that is then entered into the plant computer by an operator using a controlled process. Further details about this application are discussed in detail in Section 11.5.

11.4 Non MUR Licensed Facilities

The remaining subsections will be divided into two categories for discussion purposes. This section will discuss facilities that have not implemented MUR and plan to submit a LAR addressing both MUR and DVR. A LAR that includes MUR and DVR implementation, may need to develop LCOs related to the applicability of power level cutoffs on RPS Instrumentation, Average Planar Heat Generation Rate, Minimum Critical Power Ratios, Feedwater and Main Turbine trips, Main Turbine bypass, and Recirculation Pump Trip Instrumentation. Potentially any LCO that incorporated a limit or applicability of thermal power levels would have to be reviewed to identify if impacted or not. Other areas that would need to be evaluated if utilizing DVR with MUR may be in the area of LCOs related to Recirculating Loops Operation Trip Setpoints. Average Power Range Monitoring (APRM) setpoints with simulated thermal power linked back to the recirculating loops may need to be evaluated for potential LCO changes. Due to MUR, some PWRs may need to look at Operable Main Steam Safety Valves (MSSVs) versus maximum allowable power range neutron flux high setpoints in percent Reactor Thermal Power (RTP) LCO changes.

If a licensee has not installed a UFM and plans to make a MUR submittal the licensee will need to review how to credit DVR as part of the implementation related to potential LCOs. The Licensee will need to evaluate the credit and effects if the correction value for feedwater flow is out of tolerance (service) and how it affects power readings. In the scenario just discussed, an LCO may need to be established that is linked to the instrument correction itself and the DVR process. This would only be applicable for those facilities that have not implemented UFMs. For those facilities that have installed UFMs and plan to incorporate DVR as part of their application, the licensee may need to implement a link to the LCO associated with to outage time of the UFM. The proposed LCO would be driven from the outage of the UFM versus only to the DVR software/monitoring.

11.5 MUR Licensed Facilities

For facilities that have already implemented MUR, the term "allowed outage time" (AOT) is specified in NRC Regulatory Issue Summary (RIS) 2002-03: Guidance on the Content of Measurement Uncertainty Recapture Power Uprate Applications [55]. The AOT that is specified in the Guidance document does not appropriately characterize the application of the DVR software and monitoring. As previously discussed in Section 7 of this topical, the DVR software and/or monitoring system will not be installed on a plant computer nor will it interface with any plant trips. As such, the terms for allowed outage time are only for those components and systems that are directly connected to a plant process computer. An LCO may not be applicable for a facility that has already implemented MUR and plans to implement DVR as a power recovery option only. A facility that has previously implemented MUR but is utilizing DVR in a monitoring only application would not need to address LCOs. Alternatively, a facility that has implemented MUR and plans to implement DVR via applying a correction factor to feedwater flow measurements in the plant computer should evaluate the implications of this application related to LCOs.

The DVR software and monitoring system will reside on a stand-alone computer platform and is not connected to the plant computer. The DVR software and monitoring system can be used as an offline calibration tool to calibrate feedwater flow measurements. The DVR software/system can be used to calibrate the venture feedwater flow indication on a periodic interval similar to the application of a UFM system implemented by Palisades [27, pages 3 to 5]. Alternatively, the DVR software/system can also be used strictly for plant thermal performance monitoring as well.

The Palisades UFM offline calibration is described as one type of implementation using the DVR software/monitoring with a required surveillance. The DVR software could be used as noted as an offline calibration tool to calibrate the venturi feedwater flow on a periodic interval or on an interval based on the amount of Feedwater Flow Correction Factor (FWFCF) change. Periodically the correction factor for feedwater flow is calculated/evaluated and the CF is input into the plant computer via a plant operations procedure. The procedure would establish how the evaluation is conducted and what specific adjustment is necessary for manual input into the plant computer. Section 6.9.3.1 through 6.9.3.3 provide detailed information for implementing a DVR correction factor. Section 6.9.3.1.1 explicitly outlines frequency and application of the FWFCF calculation results regarding the necessary guidance for FWFCF procedures. Section 6.9.3.1 identifies prerequisites, acceptance criteria, plant states, time periods for sampling, and calibration checks that need to be established for each site as part of implementing a DVR CF. This section identifies therefore limits regarding validity. Section 6.9.3.2 addresses a summary of what is necessary for establishing a FWFCF calculation procedure for implementation. Section 6.9.3.3 explicitly provides additional CF implementation details for when to be taken out of service (i.e., considered potentially invalid).

Related to actual calibrations it would be up to the licensee to evaluate whether this type of surveillance or calibration procedure would need to be part of a Technical Specification Surveillance Test and specified in that section of the TS related to intervals and any other requirements. The licensee could opt to prepare a test procedure that is similar to a Surveillance Test but not include in the TS as noted above. A licensee may need to evaluate additional inputs for the DVR interval period basis justification calculation and include power level conservatisms into the procedure. It is recommended that if an interval period for surveillance testing is established that an evaluation be conducted and documented to justify the basis for the interval period as noted per Section 6.9.3.1 details. If the application of the DVR is implemented as non-safety related a basis could be made regarding surveillance correlated to 10CFR 50.55a without actually having the DVR systems surveillance specified in technical specifications and call out that the implementation is consistent with Technical Specifications.

If a surveillance procedure for a CF interval period is established, administrative controls would then need to be in place to provide assurance that only acceptable values can be input for the manual correction, and also establish a basis related to performance of the DVR software. The implementing procedure needs to be able to identify what triggers when a FWFCF calculation and calibration needs to be performed due to changes. The procedure could instead be established based upon changes affecting the FWFCF versus a strict time period interval basis. Other examples of procedural evaluations may be necessary depending upon the application related to power transients. If the licensee is required to reduce power, procedural guidance would be put into place to remove the feedwater flow correction factors from service. Likewise, when power is restored to near 100% power the procedures would dictate recalculation of the correction factor to ensure that no plant changes have occurred due to the plant transient. Related to conditions that could affect DVR CF validity Section 8.6 provides detailed information related to mitigation methods and how to use alternate indicators for ensuring DVR CF applications.

A facility that has already been licensed to MUR should consider what types of procedures it should employ with its specific application related to potential "surveillance procedures". The licensee should evaluate the need to establish actual surveillance test procedures as part of the Technical Specifications or depending upon their application implement good practice surveillance type procedures. Should a licensee identify the need for a "surveillance procedure" the basis for the interval period of performance and what conservatisms have been identified as part of the calculation as well shall be established. The licensee can also specify in their LAR if an actual surveillance test related to the correction factor is necessary to be added to the Technical Specifications, along with the basis for this determination. This decision should be part of the overall implementation decision process related to the licensee's DVR application. This procedure would also need to identify when a correction factor is considered valid, i.e., instructions on what to do during transient power operations and upon return to near 100% power levels. Discussions about CF validity are found in topical Sections 6.9.3, 8.6 and 12.

12
LIMITATIONS

12.1 Limitations

Related to Data Validation and Reconciliation (DVR) there are situations or categories where use and reliance on the Correction Factors (CFs) generated from the software have potential limitations. This section will generically address some of the potential limitations with use of DVR regarding the CF generated and input into a plant computer for feedwater flow adjustments that can impact calorimetric calculations. The limitations will be addressed in this section with respect to categorization of CF calculations and conditions.

The categories related to potential DVR Limitations fall under two conditions. The first category is when can you calculate a CF and consider it valid. The first category will address what types of analyses would be necessary for understanding when a CF is considered valid. The second category is what conditions can invalidate a CF. The second category will focus on those types of conditions that could invalidate a CF calculation. Some of these conditions were briefly mentioned in Section 11. These categories will be discussed separately in this topical section.

12.2 Calculation of Correction Factor (CF) for Valid Conditions

The calculated correction factor is determined separately from a calorimetric calculation. Determination of the CF is accomplished by using plant data and calculates the correction factor in a separate isolated computer system and is subsequently entered as an input in the plants computer system for use. In this case the process is used as a calibration of the core thermal power or feedwater flow measurement system. In most instances, in addition to the other plant measurements, it will use the same inputs and data from plant instrumentations as the calorimetric assessment. Input parameters and instrumentation are validated prior to using the data. The validation of the inputs for DVR is a more rigorous process than is used for the secondary calorimetric. Once the data is validated the input calculated CF can be inserted in the CTP calculation to maintain the corrected power level within license limits.

Section 6.9.3 provides details regarding fundamental elements of a plant feedwater flow correction factor procedure and requirements when implementing the CF (referred to as the FWFCF in this section). Section 6.9.3 provides the CF implementation requirements, including valid conditions for the CF calculation and general use.

Section 9 provides additional criteria on the plant state and the DVR model tested configuration when implementing a CF.

Section 6.9.3.5.3 discusses treatment of the DVR CTP uncertainty value in the context of power recoveries for plants that are licensed to about 2% CTP uncertainty and plants that implement a margin uprate (MUR). Section 8.5 provides details on the evaluation and calculation of the DVR model uncertainty. When implementing a CF, the DVR uncertainty will be considered to ensure the licensed measurement uncertainty is not exceeded.

Plants that are crediting DVR along with an amendment for Measurement Uncertainty Recapture (MUR) will also need to address safety analyses implications related to the power level itself to ensure that the analyzed condition will not be exceeded even as a result of transients. The guidance for conducting those sets of analyses will not be addressed herein as they are governed by 10 CFR 50 Appendix K, and various other NRC documents (RIS).

12.3 Conditions that Invalidate Correction Factors (CF)

Generically speaking there are several types of conditions that could invalidate the existing CF. This section will generically address some of the potential known conditions that could invalidate an existing CF. Each Licensee would need to address their individual plant situation, models and implementation regarding conditions that could invalidate a CF. This subsection will address some generic conditions and the potential impact to a CF.

The CF as stated in Section 12.2 is determined (or calculated) in a separate computer system. In cases in which the periodic update to the plant cannot be made, the license time limitation for the use of the inputted correction factor will be implemented. This factor will be determined by historical data analysis.

For instrumentation credited for calculation of the correction factor, if the instrument is found to be outside of its valid range, the CF utilization will then need to be evaluated and controlled in the plants license condition requirements. Section 6.9.3.3.5 provides the instrumentation calibration requirements when calculating and implementing the CF. When the plant CF is used for plant operations the instrumentation is subject to the requirements given in Section 8.3.1—DVR Self-Identification of Measurement Errors and Calculation Failures, and Section 8.6—Mitigation Methods and Use of Alternate Indicators to Ensure the DVR CTP Results are Valid.

By far the condition that has the most impact related to the CF is fouling or defouling of the differential pressure feedwater nozzles in a power plant. For example, if a power plant has generated a valid CF for a normal operating condition at 100% power, and the feedwater nozzles defoul (i.e., the nozzle returns closer to its calibrated discharge coefficient), then this can potentially result in an invalid CF being utilized with plant power calculations. Defouling would have the impact of changing the nozzle differential pressure with respect to the flow closer to the design conditions and hence, decreasing indicated feedwater flow. Since this would, in effect, be a return to the nozzle design conditions. Therefore, the correction imposed by the CF would no longer be valid. Implementation and use of the mitigation methods and alternate indicators as described in Section 8.6 will identify times of plant operation when the CF is no longer conservative and may be invalid.

The use of independent power indications described such as nuclear and in-core instrumentation would aid the operator in identifying this condition. If defouling is suspected, then the CF will be invalidated (set to 1.0) and will need to be recalculated and evaluated. A plant will need to review past history related to fouling or defouling of instruments and determine the susceptibility to defouling and what typical plant parameters can be trended to initiate entry to procedure that would require recalculating a CF. Section 8.6.2 provides a list of alternate CTP indicators and other engineering methods for assessing changes with the DVR CTP and CF value.

If a plant has had a history of frequent defouling then it will need to investigate the nozzle discharge coefficient and potentially consider recalculating a CF on a more frequent basis. If a plant does not have a propensity for defouling then the plant would still need to evaluate the frequency at which a CF should be checked. These assessments would need to be addressed and documented as part of the DVR implementation in advance of using the DVR CF for power operation.

Conditions that could potentially cause defouling will not be addressed all inclusively as each plant may have various situations that could lead to defouling. Each plant will need to develop an assessment of potential defouling mechanisms. An example of defouling that could occur in PWRs is with chemical injection of Polyacrylic Acids (PAA) dispersants [28], Hydrazine, or other secondary side chemical additions. An EPRI technical report [19] has been previously documented that addresses "Using Data Validation Techniques to Evaluate the Impact of Chemical Addition at Nuclear Power Plants". This report in general provides an assessment of how DVR was evaluated against two types of chemical additions. The technical report had four (4) key findings, and in general it was found that DVR could be used to reliably determine feedwater flow and core thermal power when dynamic conditions were observed in the feedwater measurement equipment." Even in BWR plants there is a possibility of chemistry changes such as hydrogen injection, noble metal chemistry, or zinc injection that may affect the performance of the flow meters [19, 30, 31, 32, 33, 34]. If a plant is going to initiate a change in the condensate or feedwater chemistry, the utility must be mindful of the effect chemistry changes this could potentially have on feedwater nozzles and the resultant calculated CF. In the situation of secondary side chemistry injections, a Licensee needs to consider additional performance monitoring of the Section 8.6.2 alternate indicators. In particular, monitoring of the Section 8.6.2- Additional Engineering DVR CTP Indicators, will provide a higher level of granularity with the data such that small changes with the CF may be more easily detected.

Another example could be a plant that utilizes a CF during a coast down event. The valid power range and plant conditions for the CF are established as detailed in Section 6.5 during back-testing of the DVR model and subject to the plant state and DVR model requirements given in Section 9.2 through 9.5. As such, that Licensee will need to evaluate the bounds for when the CF will be valid during the entire power coast down. If the utility plans to use the CF outside the bounds and conditions for which the DVR model has been validated, the condition could represent a DVR untested state or configuration as described in Section 9.5. In this situation the constraints on model usage as described in Section 9.5 would apply.

Since the CF will be calculated offline, the plant should establish a frequency for reviewing the calculated CF to ensure that it remains applicable for normal or typical operating conditions. Section 9 specifies use of the DVR CTP results and the CF under various plant conditions. For normal operating conditions, this CF calculation frequency will be a function of the variation in the accuracy of the plant flow measurement system over time and can be determined by performing a study of historical plant data. Section 6.9.3.2 provides details on the frequency requirements for the calculation and application of the CF. Section 6.9.3.3.6 provides the acceptance criteria for calculation of the CF.

Transient conditions that could result in an invalid CF include large power excursions, rod changes, power system issues, Abnormal or Off-Normal Operating Procedure entries, instrument calibration issues, or balance of plant equipment being taken out of service. The list noted in the previous sentence is not all inclusive. As previously stated, the valid power range and plant conditions for the CF are established as detailed in Section 6.5 during back-testing of the DVR model and subject to the plant state and DVR model requirements given in Section 9.2 through 9.5. Outside these conditions the CF may not be valid.

Administrative procedures can be put in place to require a CF to be recalculated after a transient prior to utilizing the CF in the plant computer for full power operations. Section 6.9.3.3.4—Time Period and Sample Criteria requirements will apply to the CF calculation following a transient condition. The Palisades license amendment related to Ultrasonic Feedwater Flow measurement specified the plant would revise the plant procedures to establish limits for the CF variation due to transient conditions [27]. Similarly, with use of the DVR CF, a plant must add limits for the CF related to acceptable variation, and provide guidance in plant procedures related to the appropriate actions that should be taken if a CF is suspected to be invalid.

Related to instrument calibration issues, a facility would need to perform sensitivity analyses as part of their DVR implementation to understand which instruments have the most impact on the CF calculation. If a utility suspects that a group of instruments or instruments important to the calculation are not operating within normal parameter bands (accuracy changes), then an evaluation of the CF calculation validity is warranted. Section 6.9.3.3.5 provides details on the requirements and acceptance criteria for calibration validations and checks for instrumentation important to the DVR CTP calculation. If an instrument important to the DVR CTP calculation uncertainty exceeds the acceptance criteria or a single penalty value of >3.84, the DVR CTP and the CF are considered invalid and remedial actions are required to restore the accuracy of the instrument. The CF should be recalculated following the remedial actions.

Examples of planned power changes that could affect the CF include Rod or Rod Cluster (Control Element Assembly) Testing, Turbine Control Valve testing, Shape Annealing Factor testing, or placing a primary side resin bed in service. If back-testing of the DVR models has not been performed for these cases, the CF will be considered invalid. Section 9.2 through 9.5 provides limitations on the plant conditions for when the DVR CTP and CF is valid. There could be situational potential power changes that could affect the validity of the CF. This includes turbine runback, rotating or swapping of feedwater pumps, loss of heater drains, or other deviation from the plant normal operating conditions. For these cases the limitations of Section 9.2 through 9.5 also apply regarding validity and use of the DVR CTP and CF.

The valid power range and plant conditions for the CF are established as detailed in Section 6.5 during back-testing of the DVR model and subject to the plant state and DVR model requirements given in Section 9.2 through 9.5. If the utility wishes to use the CF outside these conditions, additional back-testing and validation of the DVR model, DVR CTP results, and the CF is required. In these situations, additional engineering evaluations, design reviews, and design changes would be required to allow use of the DVR CTP results and CF under the proposed conditions.

12.4 Limitations Summary

Use of the CF is limited to the valid power range and plant conditions for the CF and are established as detailed in Section 6.5 during back-testing of the DVR model, and subject to the plant state and DVR model requirements given in Sections 9.2 through 9.5. Outside these established/documented conditions the CF may not be valid.

If the utility wishes to use the CF outside these conditions, additional back-testing and validation of the DVR model, DVR CTP results, and the CF is required and shall be documented. In these situations additional engineering evaluations, design reviews, and design changes would be required to allow use of the DVR CTP results and CF under the proposed conditions.

13
CONCLUSION

Operating Experience from the nuclear power industry has shown numerous cases of failures or loss of accuracy with core thermal power (CTP) measurements due to issues with feedwater flow instrumentation. These issues include flow element fouling, erosion, flow anomalies, ultrasonic flow meter hardware and software. Data Validation and Reconciliation (DVR) has been used to correct the CTP calculation at plants in Europe and Brazil. DVR is currently being implemented at more than 20 nuclear plants in the U.S, including a power recovery at one U.S. facility.

The mathematics and underlying theory of the numerical methods used in DVR calculations have been explained and demonstrated (see Section 3.0, "Methodology"). DVR software derives from the development of a Gaussian compensating calculation for steam turbine acceptance tests and is compliant with the German technical standard VDI 2048. DVR software has been used at several plants in Europe to provide corrections to CTP measurements. The software has been successfully used for more than 30 years by various process industries (power generation, petrochemical, refineries, etc.) as a means to improve the quality and reliability of process data used for production.

Use of DVR software as an alternate CTP measure or indicator has been investigated. A commercially available DVR software has been validated and verified to high commercial standards using guidance from IEEE Std. 1012 (see Section 4.0, "Verification and Validation of DVR Software"). The test cases include two example cases from the VDI 2048 code, a comparison of an alternate calculation method, a comparison to turbine vendor heat balance calculations, and actual vendor test data from a recent nuclear plant turbine retrofit. The verification and validation test cases demonstrate the DVR software functions properly and the DVR calculations compare favorably to the test cases.

The propagation of data errors and uncertainties on the DVR results have been analyzed, quantified, and compared to the methods and treatments of errors as proscribed by the ISO GUM and ASME PTC 19.1 standards (see Section 3.0, "Methodology"). A comparative analysis of the CTP uncertainty calculated with the VDI 2048 method used by the DVR software to the ASME PTC 19.1 Taylor Series Method (TSM) and Monte Carlo Methods (MCM) was performed. The analysis shows uncertainties calculated by DVR method provide lower uncertainties on the results.

The effects of potential bias errors with the plant measurements or other DVR input data on the DVR results were examined (see Section 8.0, "DVR Failure Modes Evaluation"). While the DVR algorithm uses a Gaussian correction fitting method for calculation of the CTP uncertainty results, the method is appropriate, and will properly bound the CTP uncertainty results regardless of the input error distribution form, provided the input error is bounded.

The reliability of the DVR calculations in actual use for 11 nuclear operating units has been examined (see Section 10.0, "DVR Reliability"). Based upon this sample a DVR reliability of greater than 99% can be routinely expected.

Plant implementation procedure details, acceptance criteria, limitations, failure mechanisms mitigation techniques and use of alternate indicators have been developed to aid in implementation of a DVR calculated CTP at a plant, have been developed and are provided in this report (see Section 9.0, "Off Normal", Section 11.0, "Limiting Condition for Operation", and Section 12.0, "Limitations").

Implementation of DVR at a plant site will require the Licensee to evaluate the safety classification of DVR CTP implementation per their license basis. Their design change process will provide this classification with justification as part of their license amendment request, if required. Implementation of DVR at a plant site for use as a measure of CTP will require proper administrative and design controls using the Licensee's design change process, software quality assurance plans, and other programs and procedures as required (see Section 2.0, "Licensing and Basis Requirements").

For the case where DVR CTP uncertainty is used as part of a MUR (margin uprate), or with licensed uncertainty margin of a less than two percent, it has been demonstrated that the DVR process can provide the necessary uncertainty to allow its implementation for MUR.

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