ELECTRIC POWER RESEARCH INSTITUTE

Data Validation and Reconciliation (DVR) Topical Report Pre-Submittal Meeting

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Topical Report Pre-Submittal Meeting TP-EPRI-2019-005 Topical Report: Data Validation and Reconciliation Use for Determining Nuclear Power Station Reactor Power

Tentative Agenda

- 13:00 to 13:15 Introductions
- 13:15 to 13:30 Purpose and Reason for Topical Report
- 13:30 to 14:45 Data Validation and Reconciliation (DVR)
- 14:45 to 15:00 Break
- 15:00 to 15:30 DVR discussions ongoing
- 15:30 to 16:00 Current Applications
- 16:00 to 16:30 Topical Report
- 16:30 to 17:00 Wrap Up

Introductions: Industry

- EPRI
- NEI
- True North Consulting
- Exelon
- Duke
- Ameren
- Luminant
- FENOC
- Palo Verde
- Xcel Energy
- South Texas Project
- Belsim International
- Texas A&M Nuclear Engineering Department

Introductions: NRC

- Management
- PMs

Reason for DVR

- Operating Experience
- Vulnerabilities
- Statistical
- Use of DVR
- Detection of Potential Problems with Instrumentation Related to the Core Thermal Power

Operating Experience

- For about 20 years numerous down powers related to instrument failure (most notably due to UFM or venturi/nozzle fouling)
- Also plants have operated higher than CTP license limit due to FW flow metering issues
- Typically Core Thermal Power (CTP) relies on inputs such as Feedwater flow
- There are single point measurement vulnerabilities for CTP
- Numerous failures experienced in nuclear industry due to reliance on few instruments
- Not easy to detect potential metering problems in existing plant Feedwater flow metering
- Improvements to statistical accuracy of Feedwater flow alone limited

Operating Experience – Continued

- INPO Topical Report TR4-34, "Review of Feedwater System Ultrasonic Flowmeter Problems", May 2004
- Report concluded increased trend in number of events involving ultrasonic flow meters (UFMs) used for CTP
- Reactor power limits (100%) exceeded during several events
- Some of the reported events involved human error, oversight or lack of knowledge
- Over reliance on vendor expertise for UFMs related to software, testing

Vulnerabilities and Detection

- Typical applications rely on measurement of Feedwater flow for CTP
- This approach introduces a single point vulnerability
- If a failure in Feedwater flow instrumentation (ultrasonic or venturi) will result in error in CTP
- Existing technology used to support Measurement Uncertainty Recapture limited
- Even with more accurate flow meters the vulnerability still exists
- The current process can not readily detect potential metering problems with feedwater flow (UFMs, venturis, nozzles)
- Current process cannot detect problems with other instruments related to CTP

Statistical

- DVR process includes more instruments
- Uses statistical approach to monitor power plant common to PRA processes
- Uses analytical thermodynamic principles and measurement uncertainty analyses
- Incorporates additional plant instruments (typically 80 to 200 plant measurements)
- Improves reliability of CTP calculations by removing single point vulnerability
- Reconciles plant instruments with plant actual operating condition
- Improves statistical accuracy of flow measurement

Use of DVR Current Status

- Used in US and Europe to assess turbine cycle thermal performance
- Kernkraftwerk (Leibstadt plant) power recovery feed nozzle fouling
- Kernkraftwerk Gundremmingen plant corrected venturi feedwater flow
- Beznau plant used since 2004 to replace sodium tracer testing feedwater flow metering calibration
- Angra used to correct plant CTP for instrumentation errors
- Gosgen, Forsmark, Philippsburg plants used to assess plant thermal performance, detect instrument errors
- Borssele licensing for MUR
- US sites with UFM suspected errors

What is Data Validation Reconciliation

- Licensing and Basis
- Methodology

Licensing and Basis Requirements

- Safety Classification for DVR
- 10 CFR Part 50 Appendix B
- Codes and Licensing
- Software Quality Assurance, Verification and Validation
- Cyber Security
- Regulatory Compliance

Safety Classification of DVR

- DVR technology (software and any required additional instrument changes which would be entirely plant dependent) <u>should be designated as non-safety related with augmented requirements</u>

10 CFR Part 50 Appendix B

- Criterion III, Design Control
- Criterion V, Instructions, Procedures and Drawings
- Criterion VI, Document Control
- Criterion VII, Control of Purchased Material, Equipment, and Services
- Criterion XI, Test Control

Potential Applicable Codes and License Requirements

RG 1.97 Instrumentation for light Water Cooled Nuclear Power Plants to Assess Plant Conditions During and Following an Accident

RG 1.105 Setpoints for Safety Related Instrumentation

RG 1.152 Criteria for Programmable Digital Computers in Safety Systems of Nuclear Power Plants

RG 1.173 Developing Software Life Cycle Processes for Digital Computer Software Used in Safety Systems of Nuclear Power Plants

RG 1.180 EM and Radio Frequency Interference in safety Related Instrumentation and Control Systems

RG 1.181 USAR Updates “Content of the Updated Final Safety Analysis Report in Accordance with 10 CFR 50.71(e)

NRC Inspection Report 35750 QA M&TE

RIS 2002-03 MUR Guidance on the Content of Measurement Uncertainty Recapture Power Uprate Applications

BTP 7-14 Guidance on Software Reviews for Digital Computer-Based Instrumentation and Control Systems

Digital I&C ISG-06 Digital Instrumentation and Controls, Interim Staff Guidance

- Industry Codes
- ASME PTC 19.1
- ASME PTC 19.5
- ASME PTC 6
- ANS 10.4
- ANSI N18.7
- ANSI N58.14
- IEEE 7-4.3.2.1
- IEEE 1059
- IEEE 1012
- ISO 9001
- NUREGs
- 0800 SRP Chapters 7-4 and 18
- CR-6101
- CR-6421
- Other documents
- NEI 08-09
- TR-102323
- TR-102348

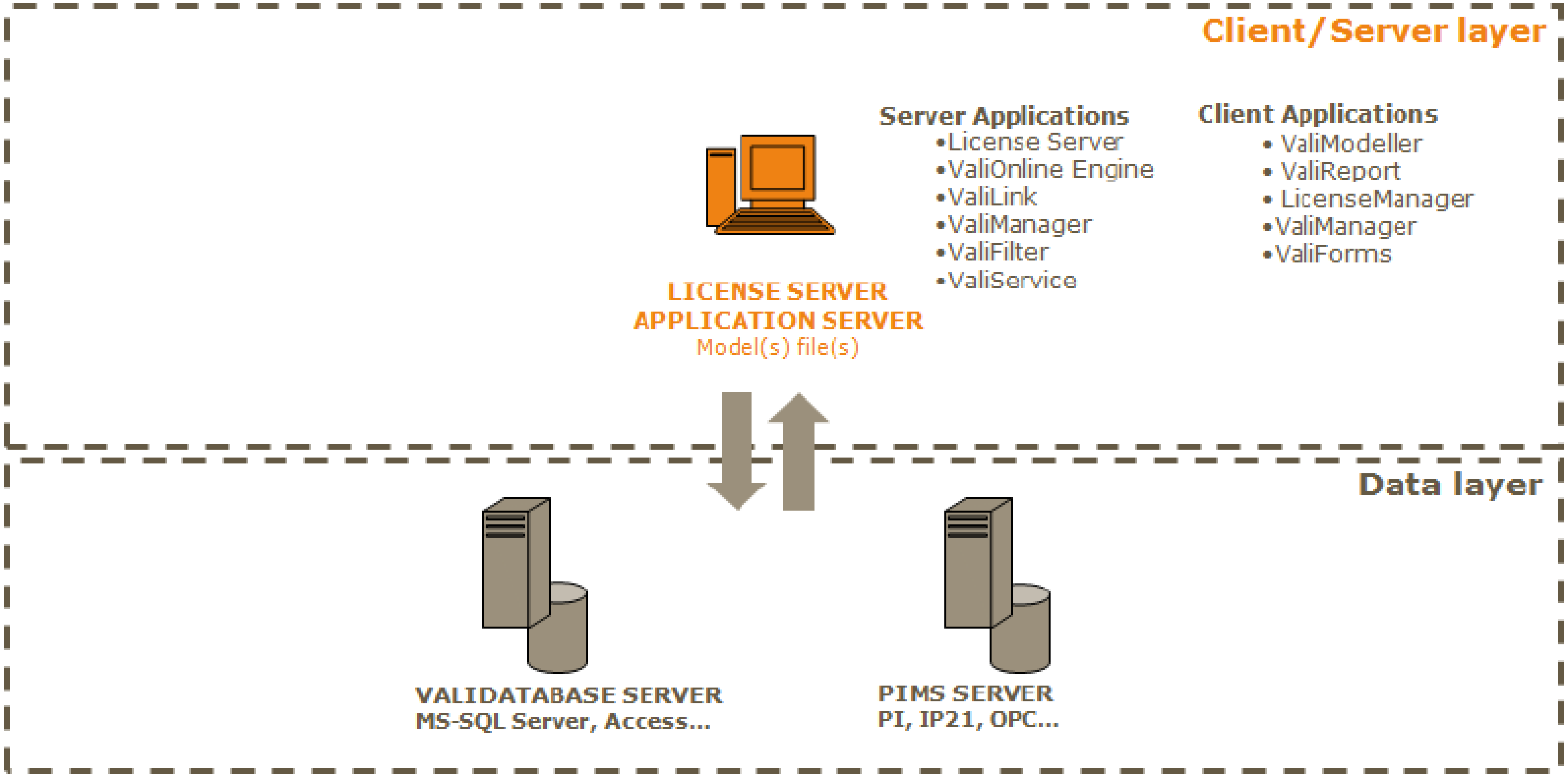
Software Quality Assurance/Verification and Validation

- The Licensee 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
- The SQAP will rely on each licensee's SQAP procedures and will comply to 10 CFR Part 50, Appendix B, and the licensee's overall QA program
- DVR Software developed for improved plant thermal performance used by each licensee shall be placed, as a minimum, into software integrity level 2 (see IEEE Std 1012-2004) ***depending upon the overall implementation***
- The software integrity level chosen dictates the required necessary tasks within the licensees SQAP for the DVR implementation

Cyber Security

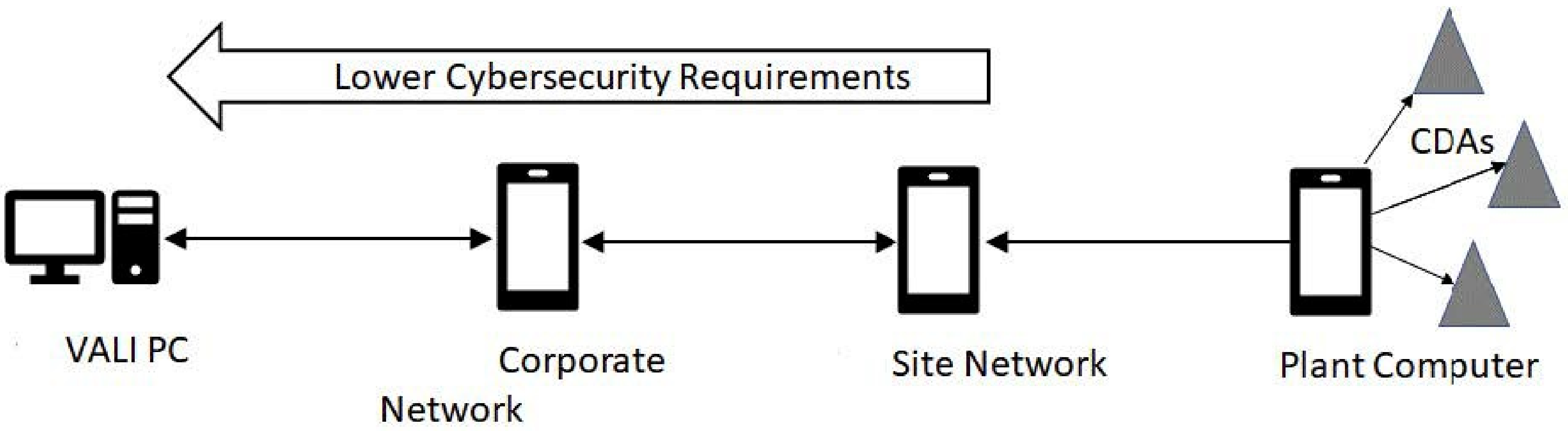
- Individual plant applications of the DVR model will need to have a cyber security assessment performed with respect to the requirements for the DVR software installation
- Since each plant application could be different a generic single method of application regarding cybersecurity and DVR models/software 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
- Individual plant utilities will need to evaluate the DVR installation software components through their prescribed engineering change process to determine any special cybersecurity requirements needed for the DVR installation

Cyber Security – Figure 1



Cyber Security – Figure 2

VALI Installation Overview



- Microsoft Windows
- Microsoft SQL Server
- Microsoft Excel
- OSI PI Client
- eDNA Client
- OPC Client
- Belsim VALI

- Corporate Engineering Applications and Databases

- Plant Measured Data Historical Databases – OSI PI, eDNA, etc.

- Instrument Tag Measured Data Points

Regulatory Compliance – Proposed Sample Table

10 CFR 50 Appendix B	Compliance discussion of DVR/VALI	Compliance	Topical Report Section
III. Design Control	Standards and procedures for design activities and verification activities will be documented. Procedures for reviewing or changing designs will also be documented.	Affirmed	2.2.1,
V. Instructions, Procedures and Drawings	All activities concerning quality of software are based on the documented procedures	Affirmed	2.2.2,

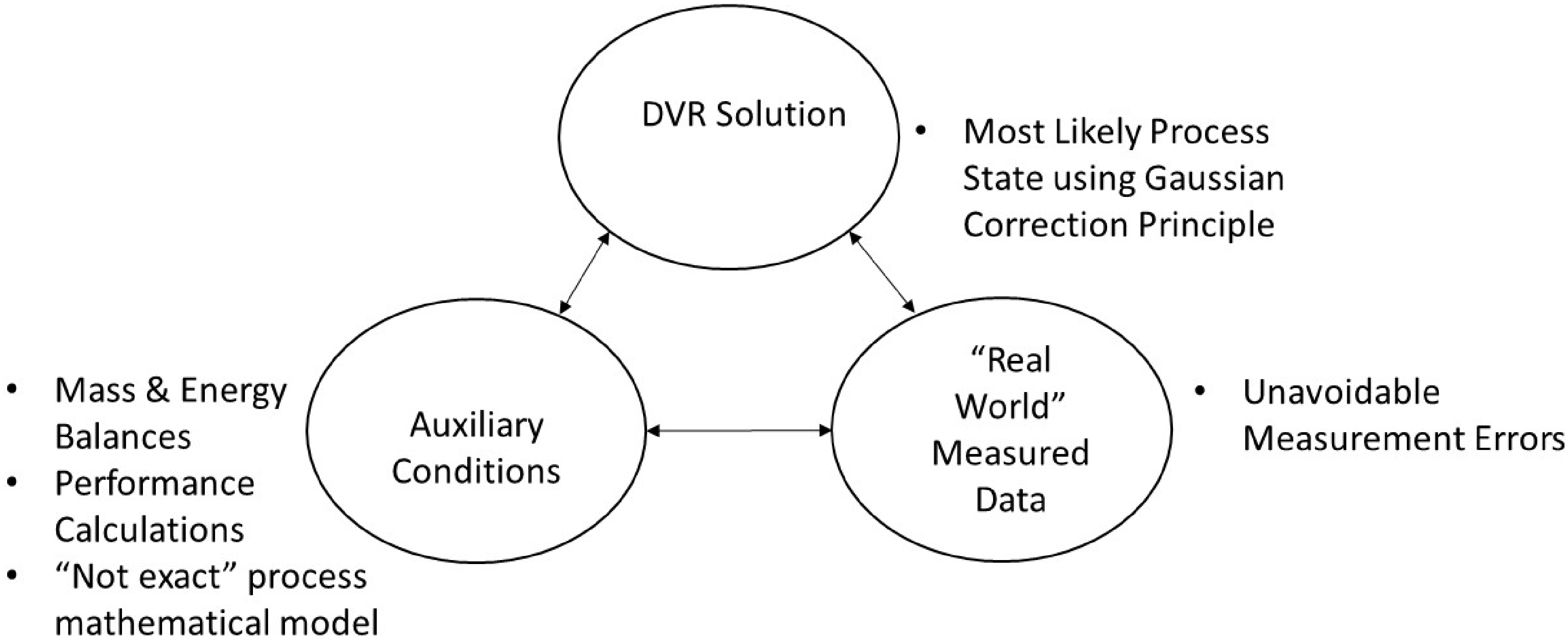
Methodology

- DVR Algorithm Overview
- Statistical Basis for Uncertainty
- Comparison to International Codes
- Theoretical Background Mathematical Basis
- Auxiliary Conditions
- Simple Example of DVR
- Comparisons

DVR Algorithm Overview

- Variance of a Single Measured Random Variable
- All Measured Variables Combined as a Multi-Dimensional Random Variable
- Introduction of Auxiliary Conditions
- Algorithm for Practical Use from Streit
- Assessment of the Quality of the Measured Value Estimates and Detection of Severe Errors

DVR Solution Overview

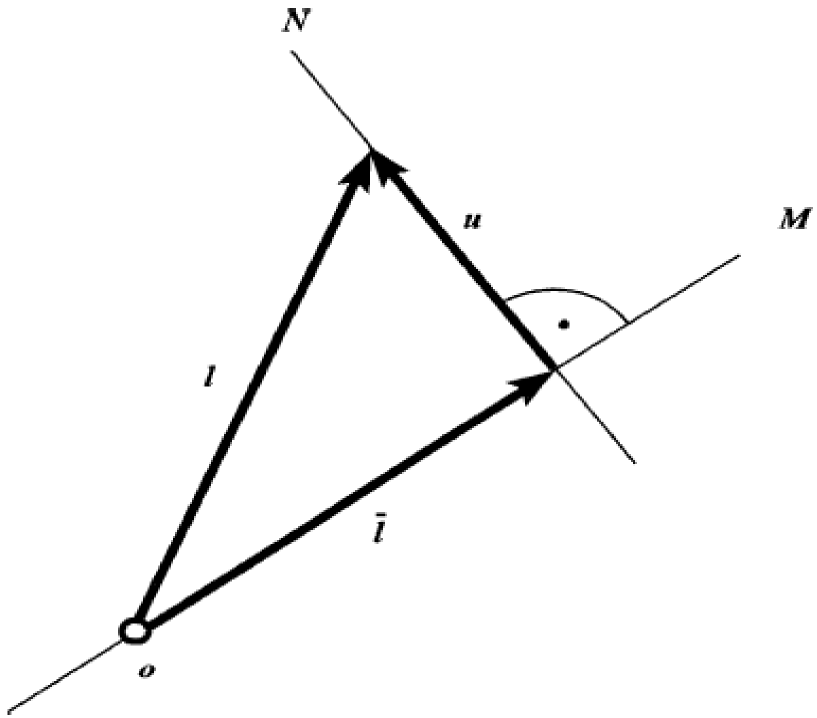


Streit's Algorithm for Practical Use

$$\overline{X} = X - R_X * F * (F^T * R_X * F)^{-1} * f(x)$$

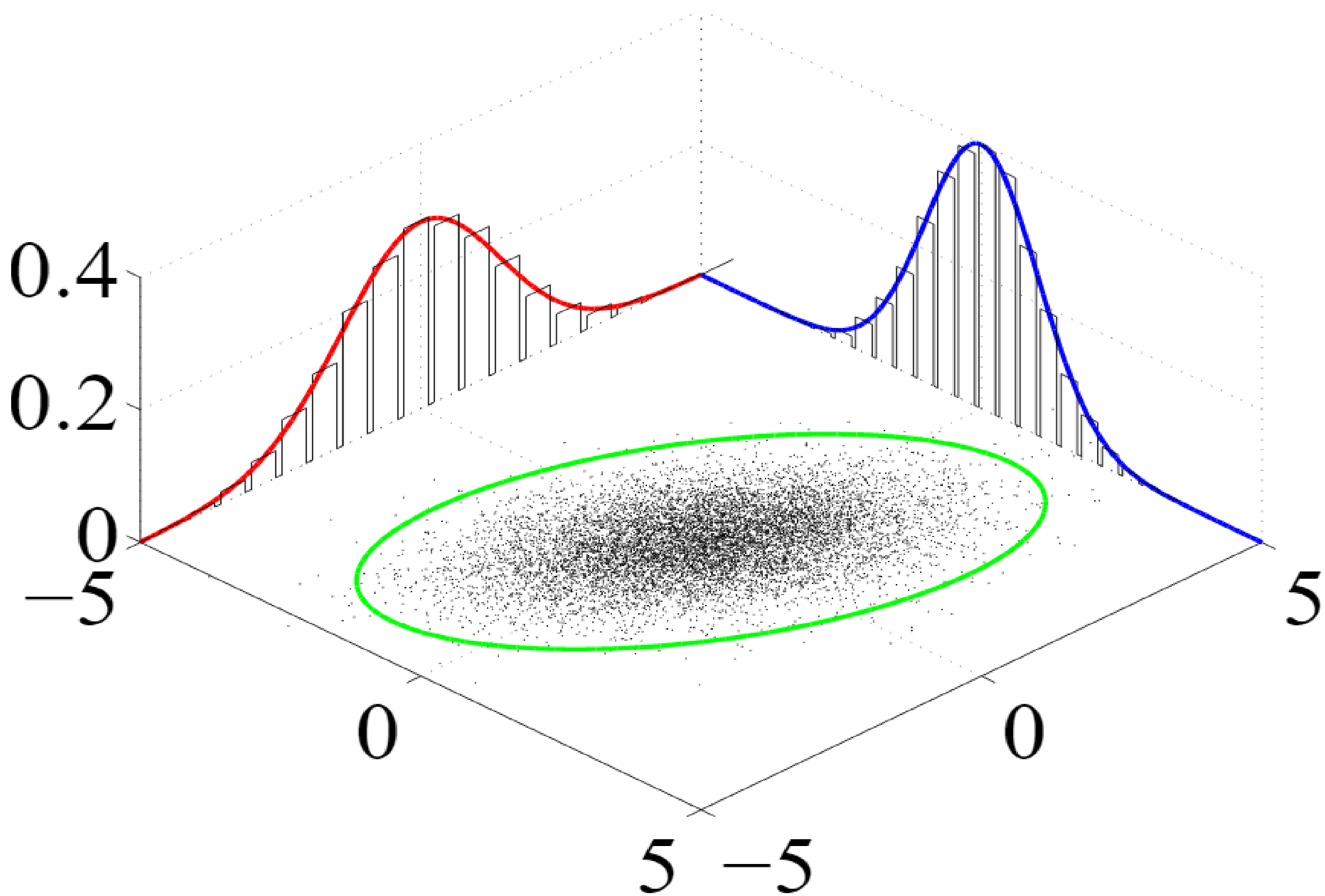
- Where:
- X is the vector of the measured values
- $\overline{X}$ is the vector of the consistent estimated values
- R_X is the matrix of covariances of the measured variables
- $F = \left[\frac{\delta f}{\delta X}\right]$ is the functional matrix of the auxiliary conditions
- $f(x)$ is the vector of contradictions

Vector Representation – Correction Task for Distributed Independent Random Variables



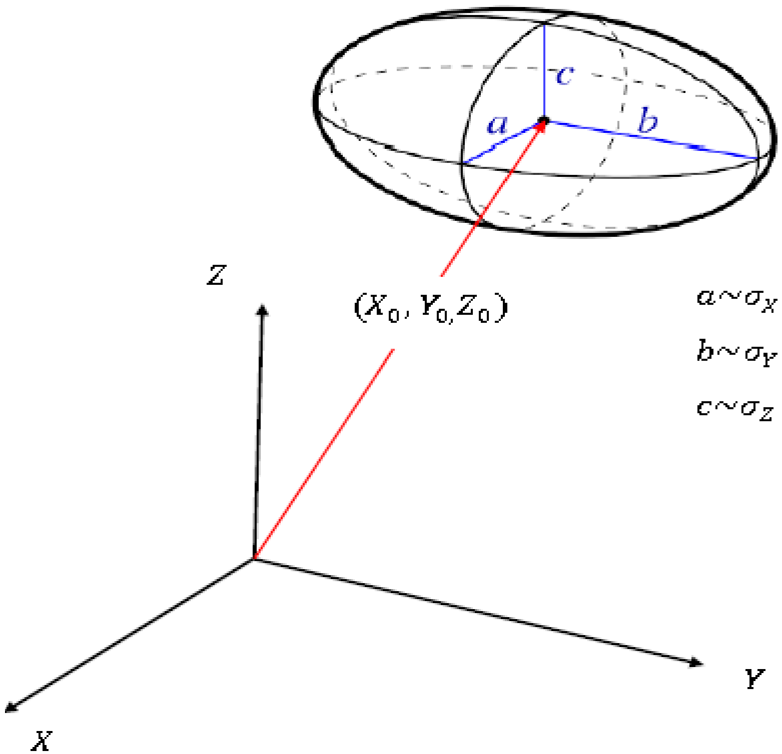
- ***u*** represents the vector of contradictions between the random variable ***l*** and the variable calculated with the auxiliary conditions $\bar{l}$
- ***M*** is the subspace of solutions of the auxiliary conditions
- ***N*** is the subspace of the contradictions
- $\bar{l}$ is the position of the corrected state point
- ***o*** is the unknown true state point
- ***l*** is the position vector of the measured state point

Graphical Representation of Joint Probability Distribution for Auxiliary Conditions and Contradictions



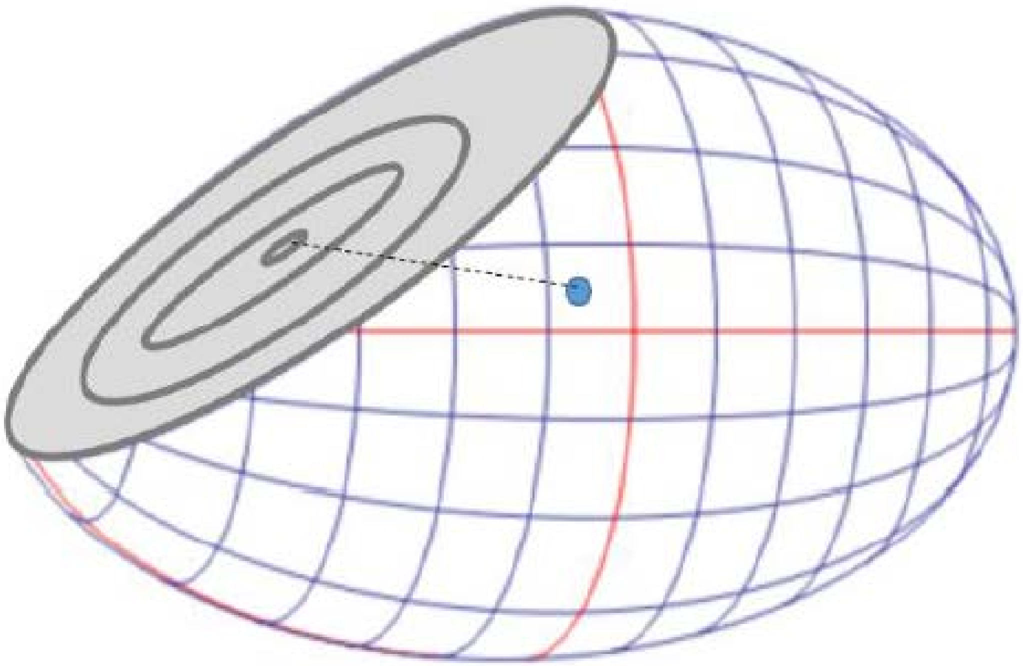
(source: Wikipedia, user IkamusumeFan)

DVR Method in Terms of Geometry – 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

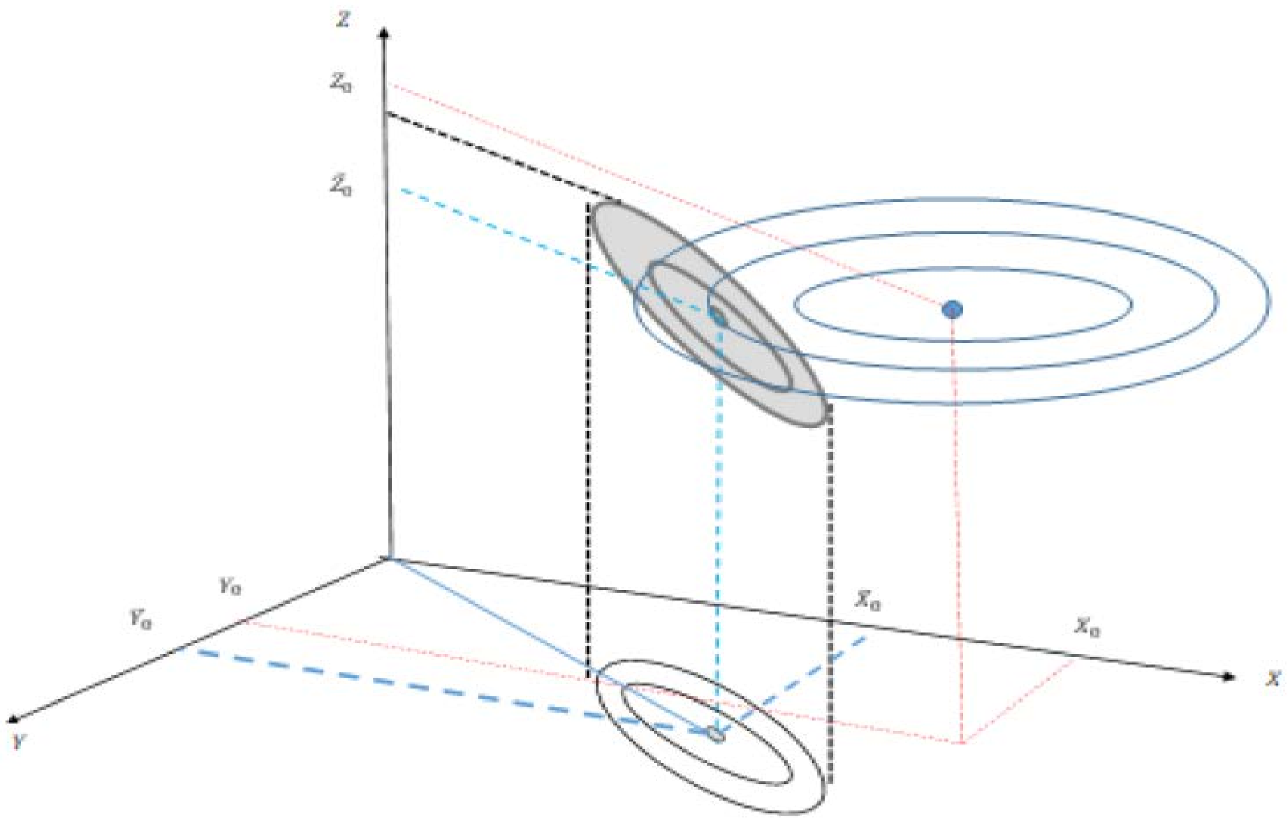
Graphical of DVR Method in Terms of Geometry – Shortest Distance to Plane Represents Highest Probability Reconciled



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

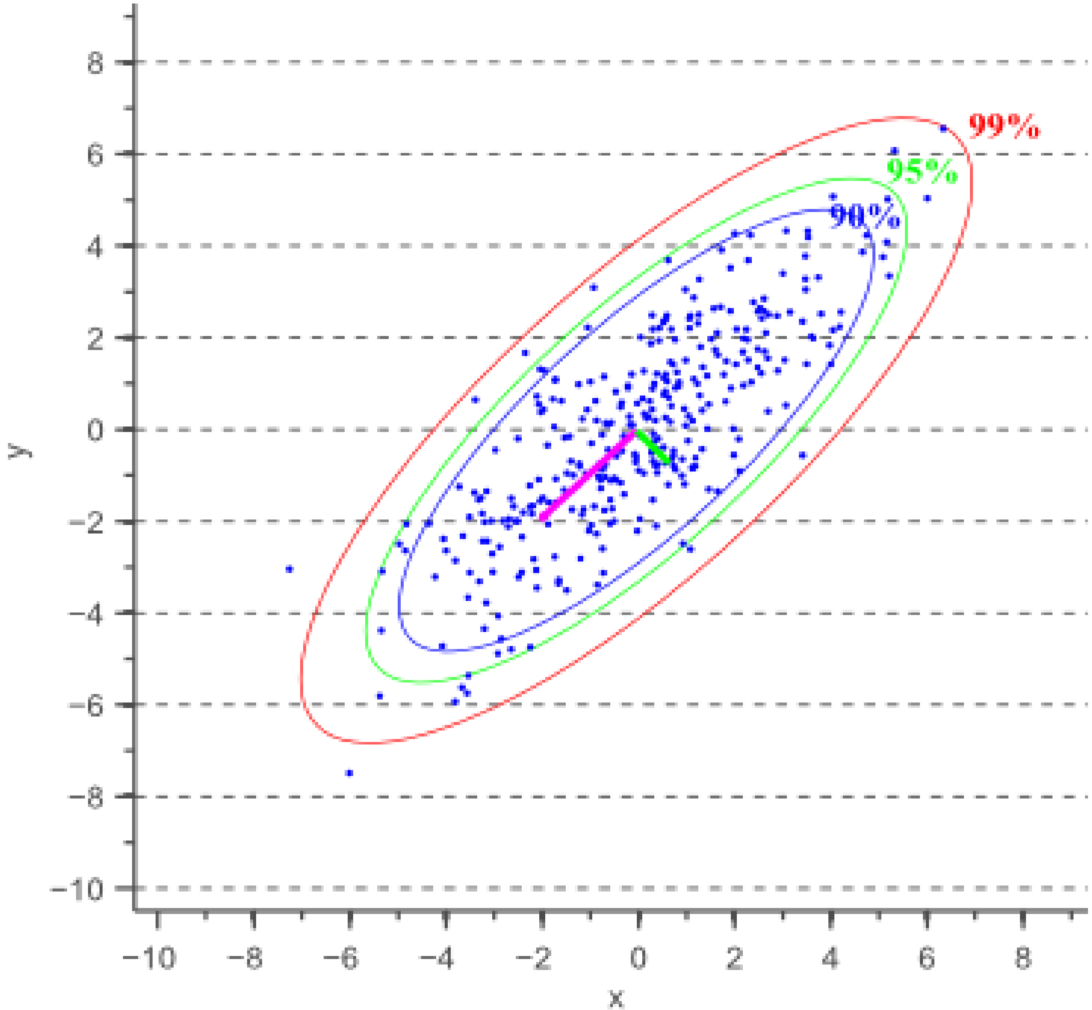
Graphical DVR Method in Terms of Geometry – Defines Reconciled Values of Standard Deviations and Uncertainties



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

Graphical DVR Method in Terms of Geometry – Projections of Probability Distribution



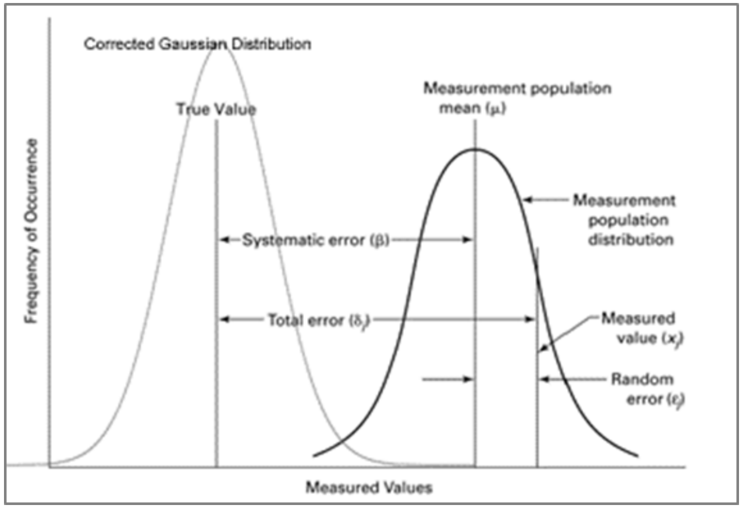
Source: Vincent Spruyt, https://www.visiondummy.com/2014/04/draw-error-ellipse-representing-covariance-matrix/

Statistical Basis for Uncertainty

- Measurement and Test Results Uncertainties
- Systematic and Random Errors
- The Central Limit Theorem
- Propagation of Measurement Uncertainties and Errors
- Effects of Measurement Uncertainties on the Test Results
- Sample Size and Outlier Discussion

Balancing Uncertainty

- How to address unknown systematic errors
  - 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.
  - 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.



Comparison to International Codes

- 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 provides details on the calculation of instrument and test uncertainties that may be applied to the ASME PTC 6 test results
  - ASME 19.1 method of propagating measurement uncertainties using Taylor series.
  - As covariance calculated using DVR measurement uncertainties are calculated using combined statistics
  - Uncertainties calculated will be approximately equivalent to ASME PTC 19.1 Appendix C
- The process described in this approach implements the VDI-2048 methods in a commercial DVR software product

Theoretical Background Mathematical Basis

- The Validation/Reconciliation Problem – Corrected Measurements, Covariances
- Bounds Handling
- Gross Error Detection
- Uncertainty Reduction
- Redundancy and Uncertainty
- Multiple Measurements on a Single Variable
- Mass Balance as Special Case of Multiple Measurements
- Specificities of VDI Mode

Auxiliary Conditions

- Equations Generated by the Software Algorithm
- Calculates mass balances, energy balance, saturation conditions and pressure drop for any process unit
- Pressure Drops Valves
- Heat Exchangers
- Liquid Vapor Separators
- Pumps
- Turbine Balances

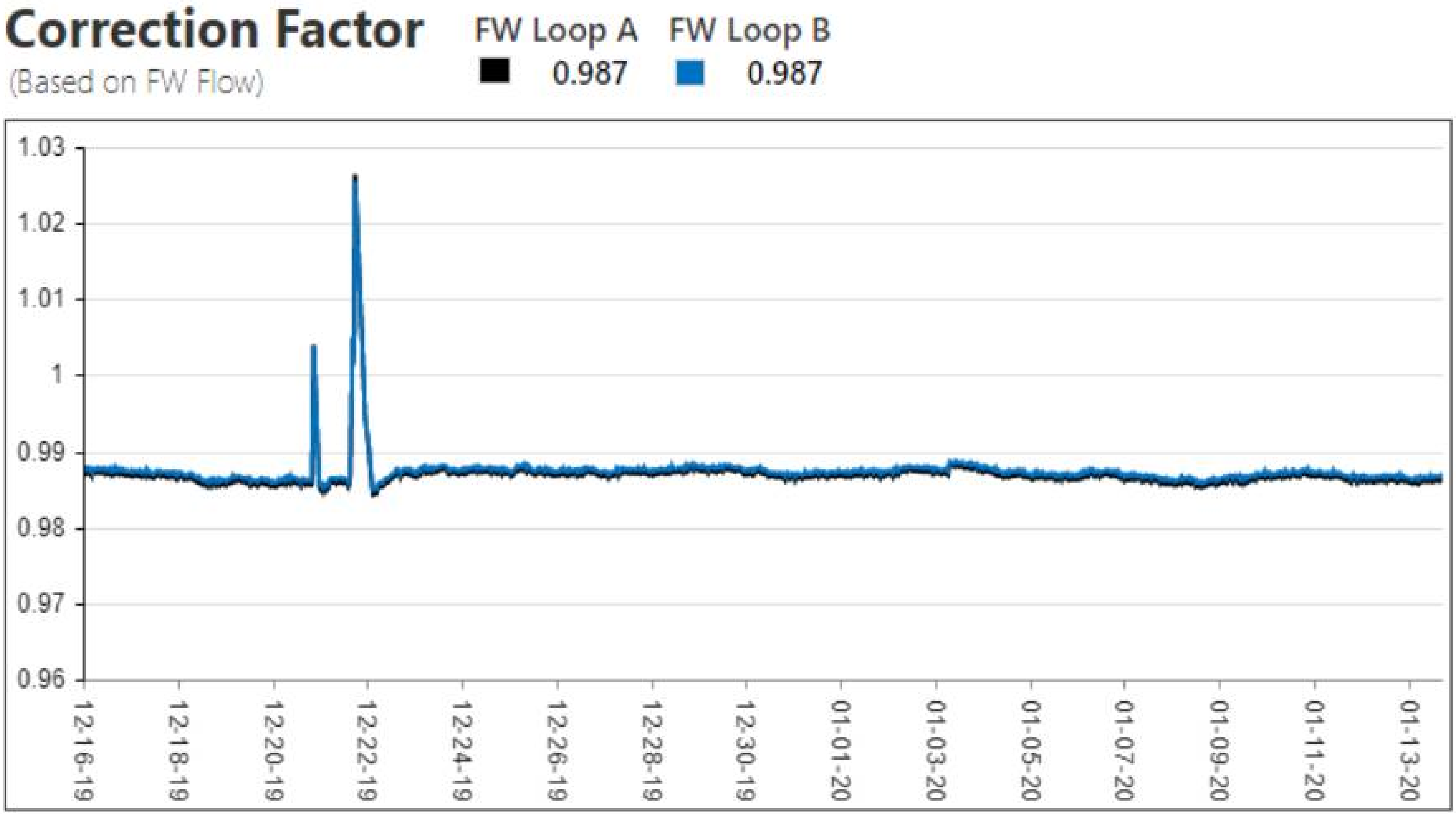
Simple Example of DVR

- Example of DVR Calculation
- Determination of Reconciled Values
- Uncertainty Determination
- Quality Control of the DVR Process
- Individual Parameter Quality Measurement
- Overall Process Quality Measurement
- Summary of Quality Control

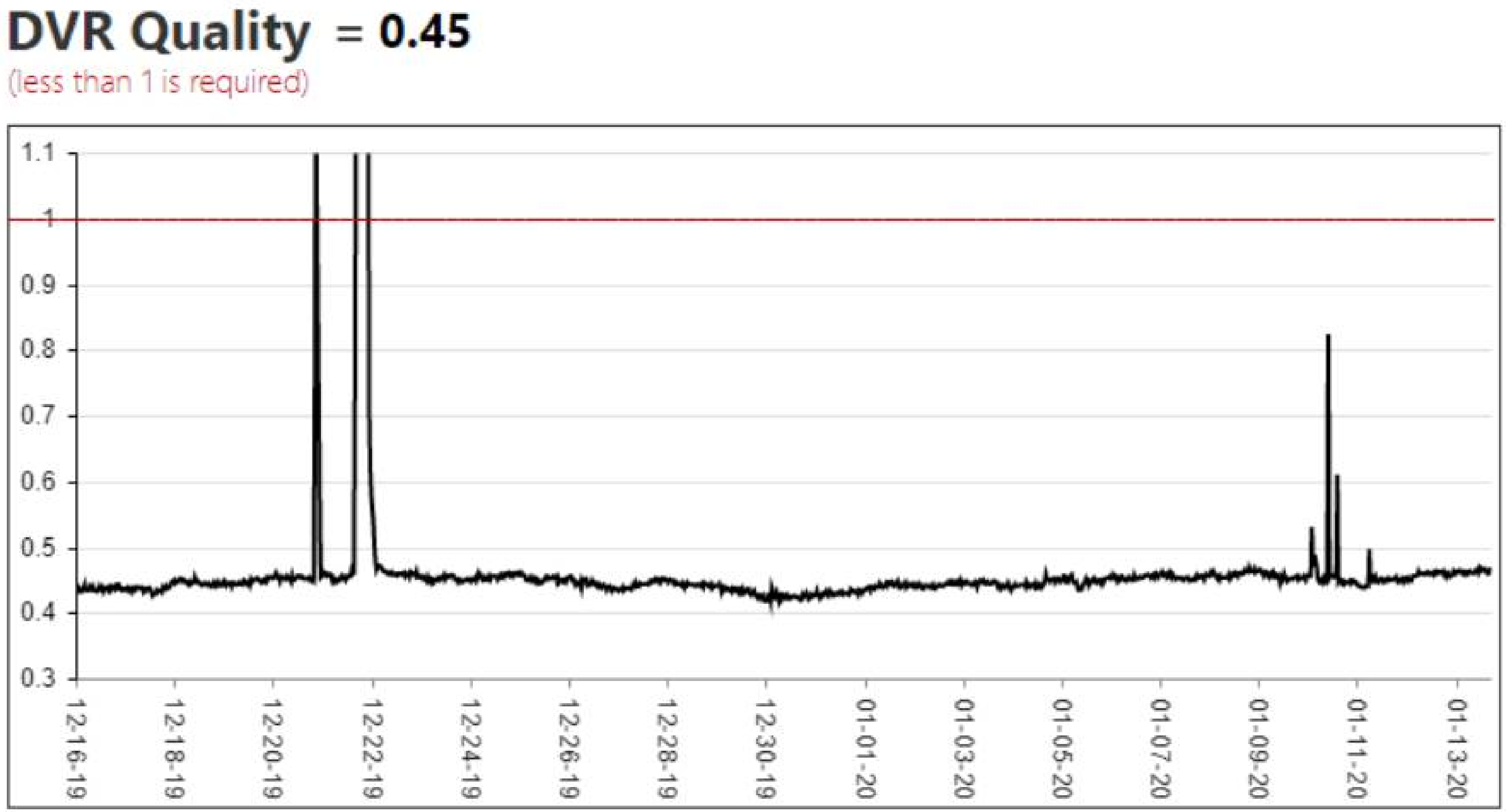
DVR Solutions

- **Reconciliation**
  - Objective Function = $\sum \left\{\frac{measured\ value - reconciled\ value}{standard\ deviation}\right\}^2 \rightarrow minimum$
- **Quality control for the whole process**
  - Quality $= \frac{Objective\ Function}{95\%\ quantile\ of\ Chi^2} < 1$
- **Quality control for each measurement**
  - Single Penalty $= \frac{(measured\ value - reconciled\ value)^2}{\max(correction\ unc.^2, \frac{measurement\ unc.^2}{10})} * (1.96^2) \leq 3.84$
- Measurements with Single Penalty values equal to or exceeding 3.84 (95% confidence interval in terms of variance) are considered suspect

Example Feedwater Flow Correction Factors



Example DVR Quality (continued from previous slide)



Example Key Performance Indicators (more current continued from previous slides)

CLINTON DVR DISPLAY

Start Date: 1/8/18 5:00
End Date: 1/0/00 0:00

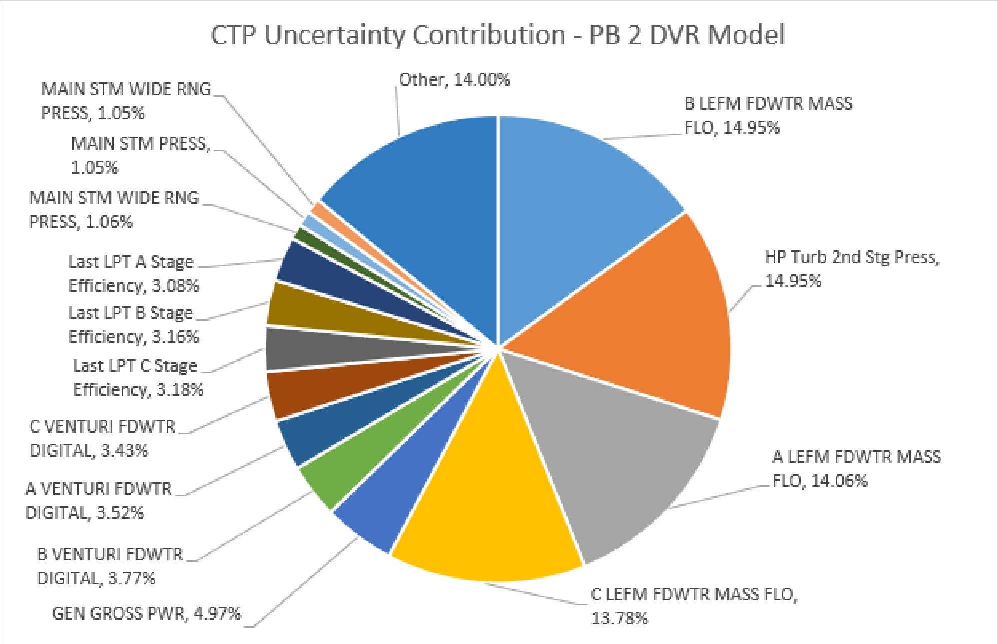
OVERVIEW
DVR QUALITY LIST
FLAGGED TAG LIST

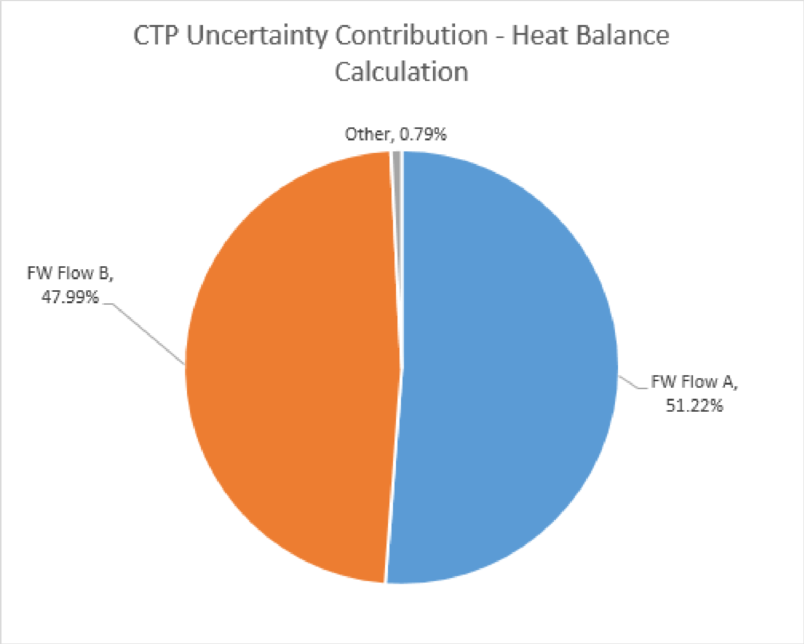
Correction Factor *(Based on FW Flow)*	FW Loop A	FW Loop B	Total Uncertainty
	0.9894	0.9898	0.579%

	Measured Value	Reconciled Value	Reconciled Uncertainty	Units
RX Thermal Power (10 min)	3415.68	3378.66	0.579%	*MW*
Feedwater Temperature	423.51	423.52		*° F*
Total Feedwater Flow	14.7333	14.5807		*MLB/HR*
1st Stage Pressure	664.16	664.35		*PSIG*
Gross Generation	1117.09	1116.82		*MW*

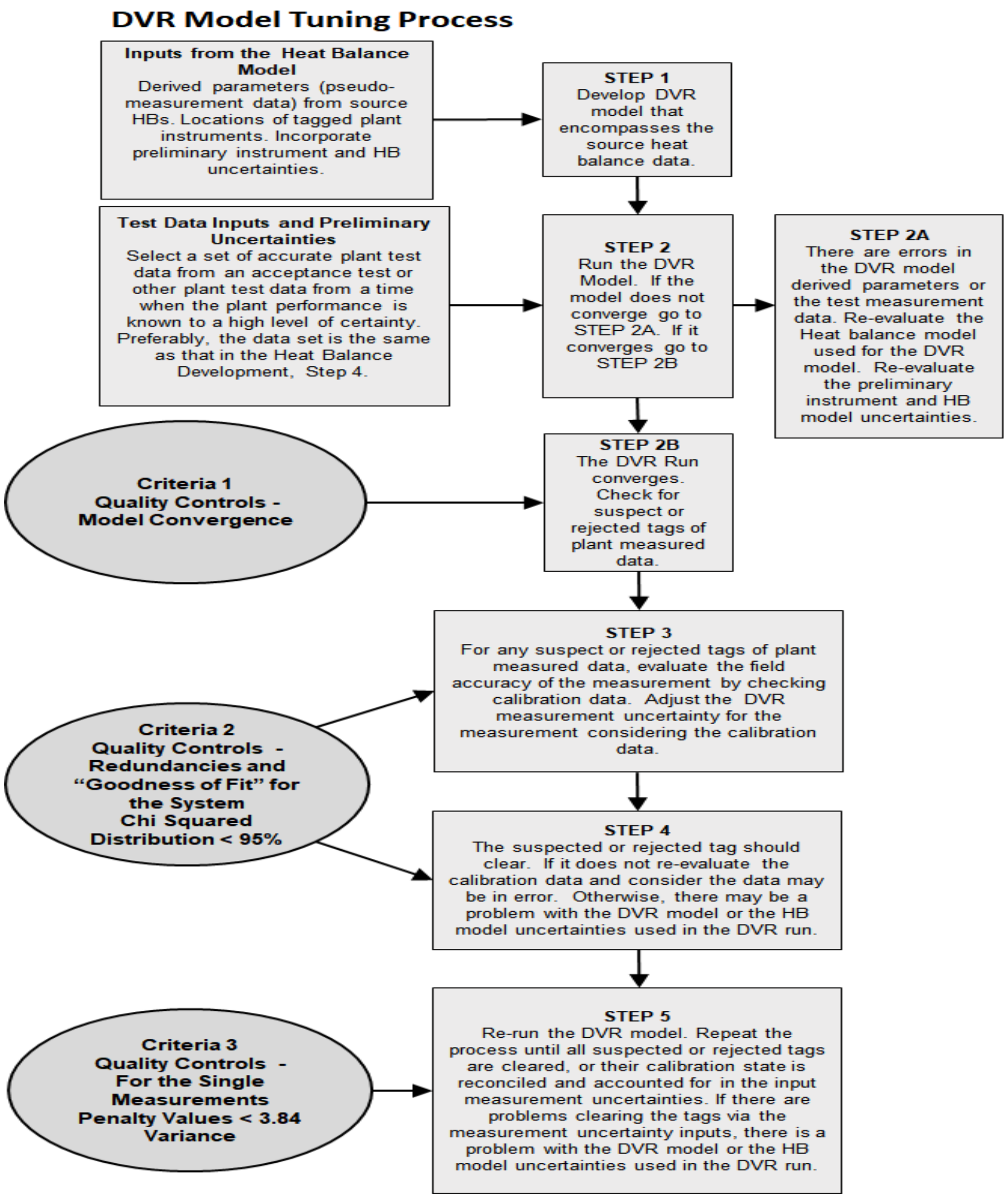
DVR Quality *(less than is 1 required)*	0.8181
# of Flagged Tags *(penalty > 3.84)*	5

Peach Bottom CTP Contribution Comparison

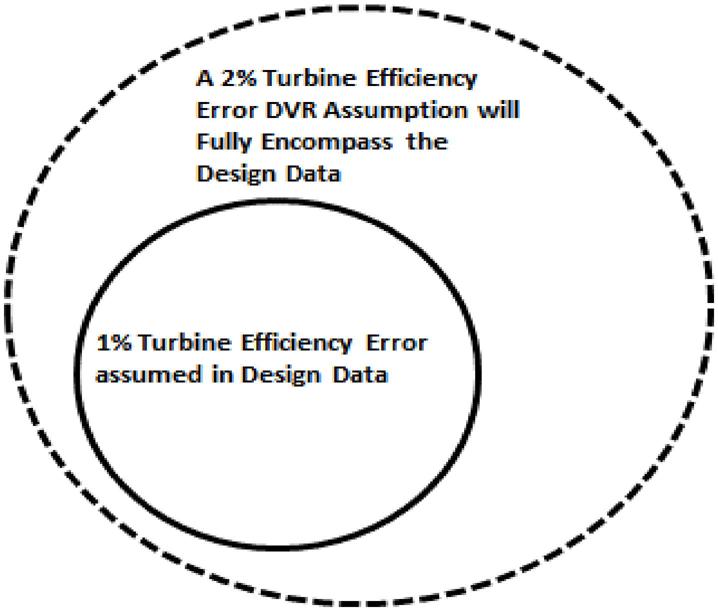




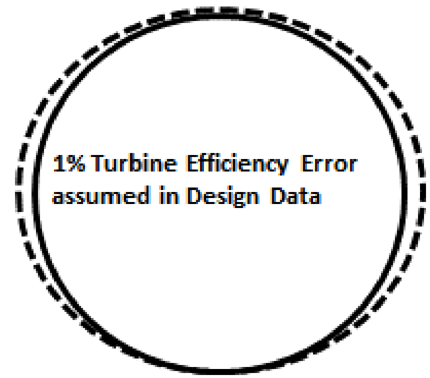
Example DVR Model Tuning Process



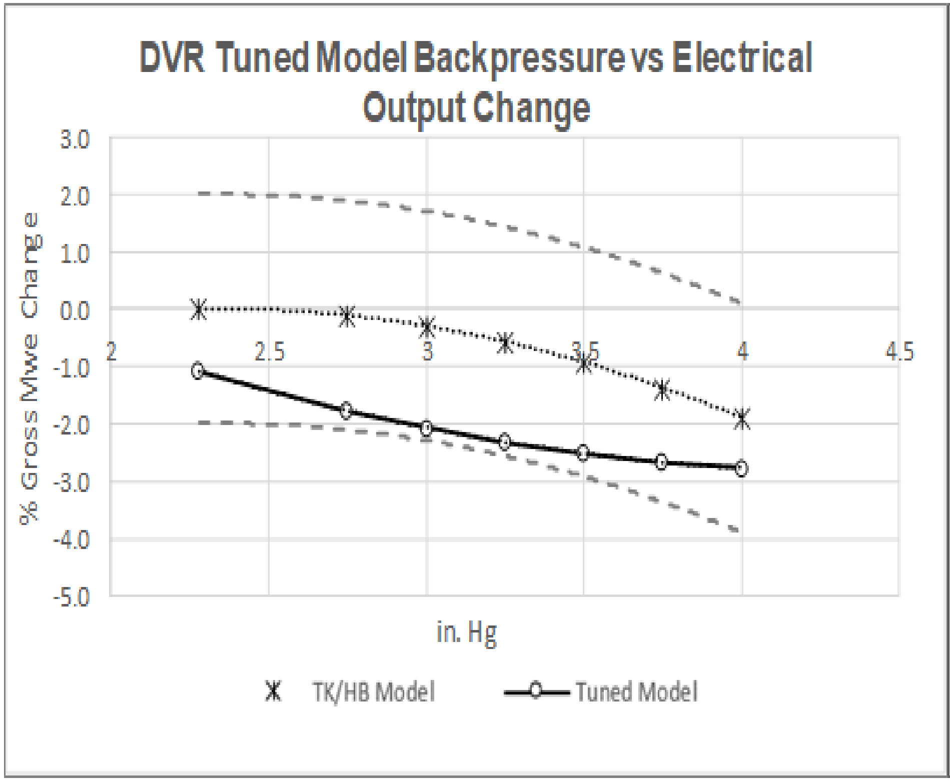
Model Tuning Process and Assumptions

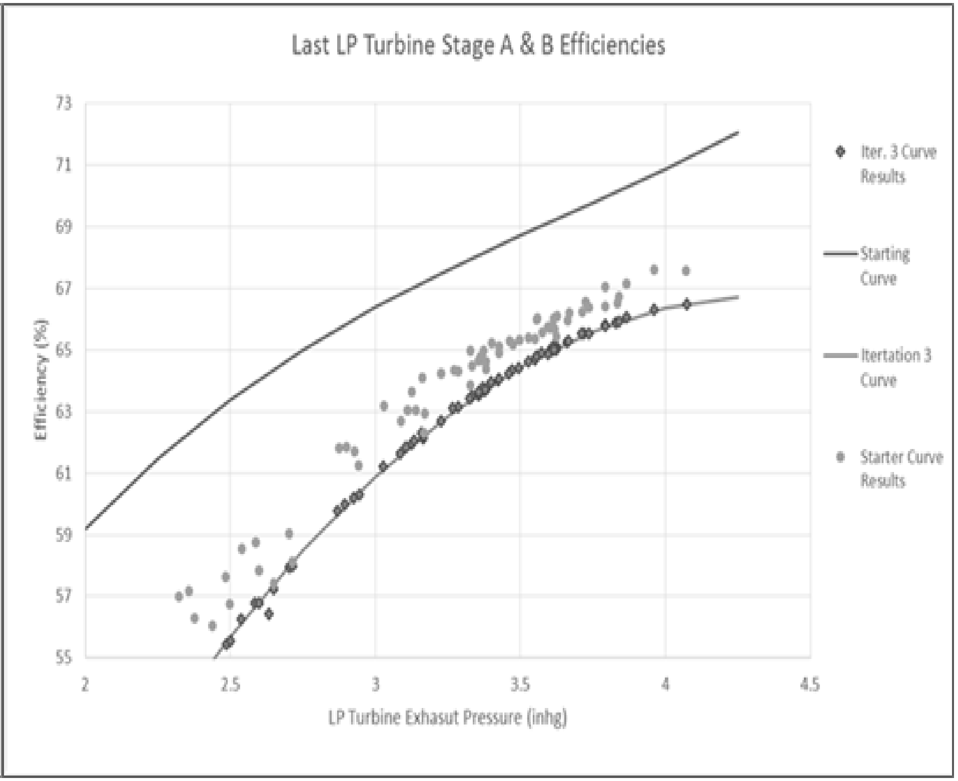


As the DVR process proceeds the estimated Turbine Efficiency Error used in DVR may be reduced to values approaching the Design Data

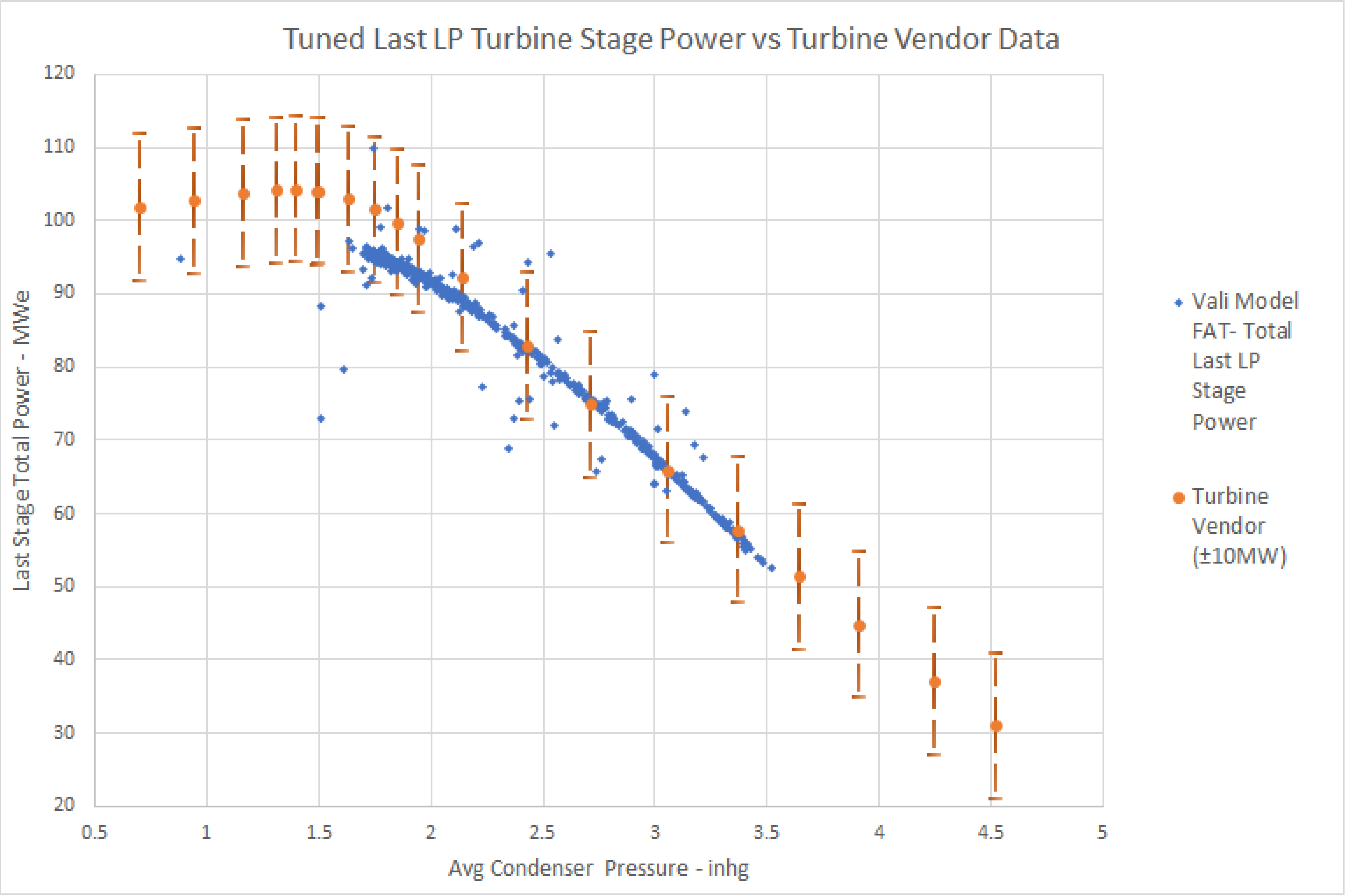


Tuned DVR Model Compared to Vendor Data and LP Turbine Efficiency Curve Iterations

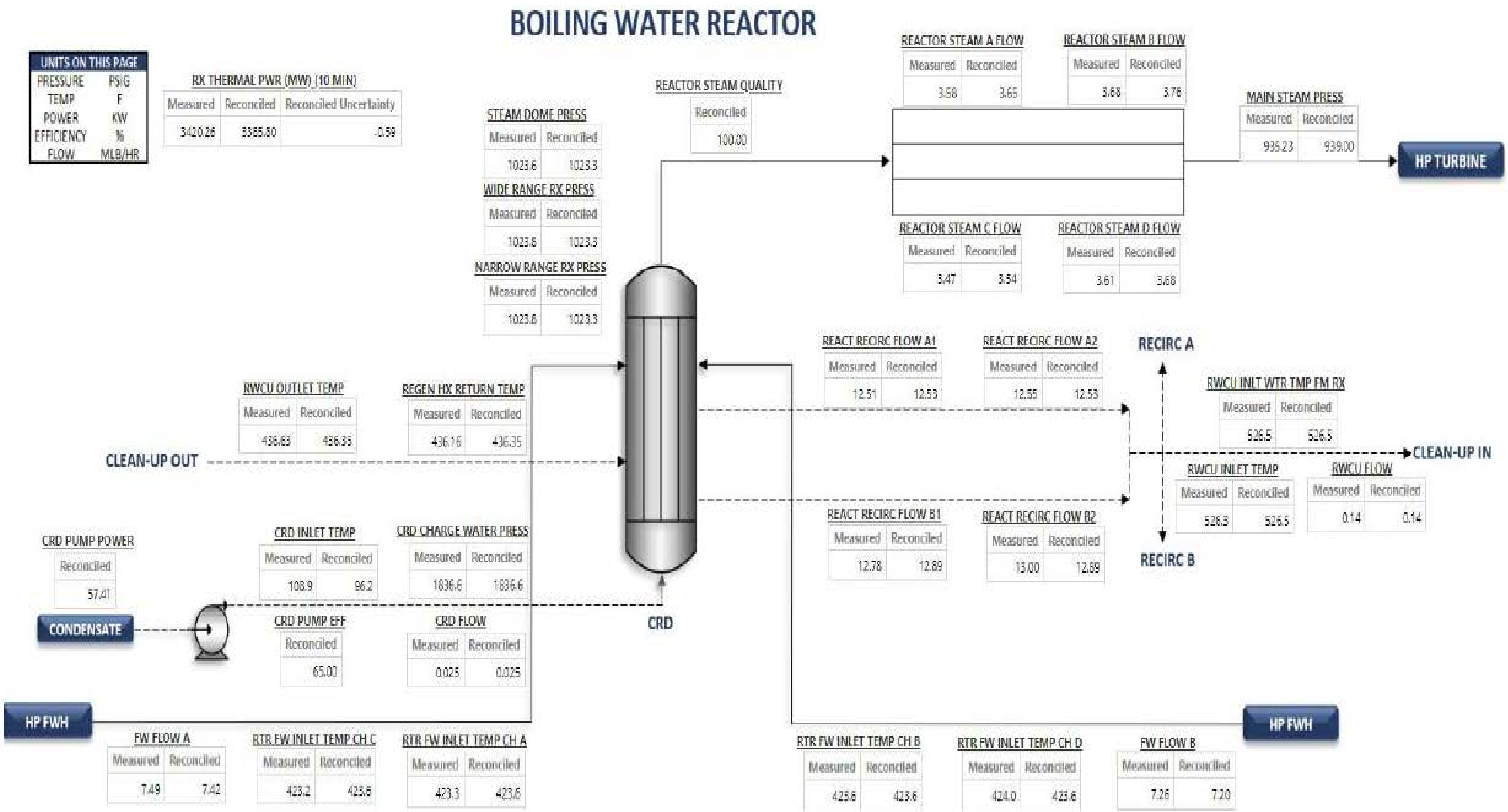




Low Pressure Last Stage Power



Measure/Reconciled Example BWR



Other Topical Report Sections Not Discussed Today

- See Outline in Topical Report Summary
- Introduction
- Benchmarking and Operating Experience Detailed
- Application of DVR Power Plant Data
- Demonstration Application
- DVR Failure Modes Evaluation
- Off Normal Operations
- DVR Reliability
- LCO Conditions
- Limitations
- Conclusions, References, Appendices

Topical Report

- Timeline
- Interfaces
- Request for Fee Waiver
- Proprietary Information

Wrap Up

- Summary
- Staff Questions

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