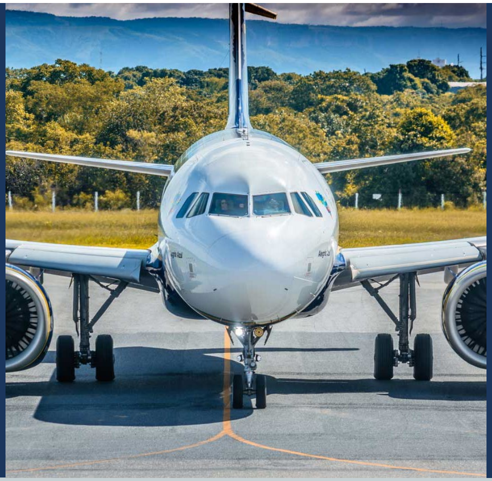


Digital Tools for Power Uprates: Using DVR and PEPSE to Enhance MUR and Performance Studies

Derek Horn | Greg Alder

Content

- Overview / Motivation
- What is Data Validation and Reconciliation (DVR)?
- Why is this Technology Important to Thermal Performance?
- PROCESSPLUS® Software
- Using DVR for Measurement Uncertainty Recapture (MUR) Uprates
- Utility Roadmap for Implementation of DVR
- PEPSE Power Uprate Studies
- Conclusion / Q&A

- **BTB Jansky and Curtiss-Wright have teamed up to provide enhanced on-line thermal performance monitoring based on data validation and reconciliation (DVR).**
- **The purpose of this presentation is to introduce DVR and demonstrate its thermal performance benefits and use with power uprates by walking through several examples.**
- **DVR key benefits:**
  1. **Generates contradiction-free (reconciled) plant data** to serve as an input for successive applications such as process simulation, plant performance monitoring, advanced pattern recognition, etc.
  2. **Power recovery** with reconciled correction factors for feedwater flow and temperatures
  3. **Increased reactor power accuracy and Measurement Uncertainty Recapture (MUR)** in nuclear power plants

Overview | Motivation (2)

- **Nuclear power plants are equipped with a large number of sensors (pressure, flow, temperature, etc.).**
- **All plant instruments are susceptible to measurement error (manufacturing defect bias, equipment installation, instrument drift, component aging, etc.).**
- **This introduces challenges /contradictory information when performing process monitoring, troubleshooting, and/or optimization of plant operations.**
- **Software models often need to be trained. However, if the data being fed into these models is not error free, injection of systematic biases may be introduced, leading to in inaccurate outcomes – "garbage in, garbage out."**

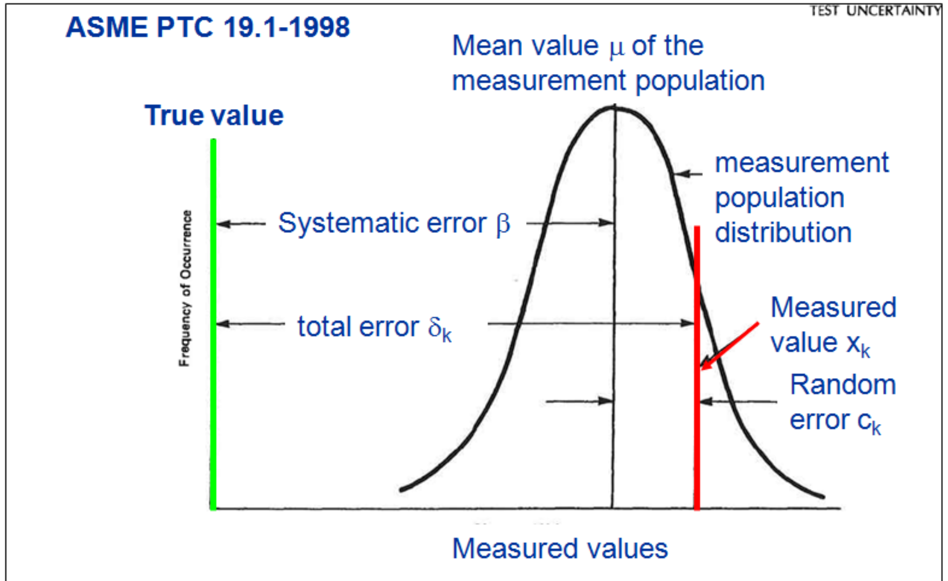

FIG. 4.1 ILLUSTRATION OF MEASUREMENT ERRORS

All plant instruments are susceptible to measurement error

What is DVR?

- **DVR is a software-based methodology that reconciles and validates quality-assured (quality assurance is part of the methodology) measurements and measurement uncertainties of *existing*, installed plant instruments.**
- **DVR combines first principles of thermodynamics with measurement uncertainty from additional plant instrumentation beyond feedwater flow to calculate core thermal power (CTP).**
- **DVR consists of an evaluation of data available from multiple sources and methods to determine the most likely value of a parameter. By combining information from physical models and sensor measurements, knowledge of the state of the system or measurements can be improved, leading to more accurate plant monitoring.**
- **Implementation of a process using a higher number of instruments to determine the most probable CTP results in less plant susceptibility to single instrument failure. This action, in turn, reduces the risk of exceeding a licensed CTP limit or operating below the licensed limit, thus losing generation.**
- **It provides Nuclear Power Plants with the ability to correct important process measurements to the most probable value with traceable uncertainty at 95% confidence interval.**
- **Example:**

Plant measurement:	1000 kg/s (no uncertainty defined; accuracy not defensible)
DVR value:	995 kg/s ± 7 kg/s (traceable and defensible uncertainty)

- **DVR/PDR Introduction movie available at: https://player.vimeo.com/video/1083925701?dnt=1**

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Why is this Technology Important to Thermal Performance?

The primary benefits of DVR are:

1. Increased process measurement accuracy
2. Detection of critical instrument drift
3. Reduced measurement uncertainties
   (When applied to thermal performance related measurements, there is an opportunity for significant MW_e output optimization.)

DVR Primary Output	Specific Measurement Affected	Program Application	Thermal Performance MWe Output Recovery
Increased process measurement accuracy	Increased accuracy of process information from plant data	Accurate machine learning modeling	Enhanced Plant Optimization
Detection and reconciliation of Critical Instrument Drift	Detection/Correction of Feedwater Flow measurement error	Reactor Power Calibration (Production and Safety Benefit)	Forced Loss Avoidance/ MWe Output Recovery
Reduced measurement uncertainties at 95% confidence interval	Reduction of Feedwater Flow measurement uncertainty	Future recapture of License penalties associated with Reactor Power Measurement Uncertainty (MUR)	Improved Heat Rate

Additional Thermal Performance Applications:
Identification/quantification of cycle isolation losses; quality assured component performance monitoring; warranty testing

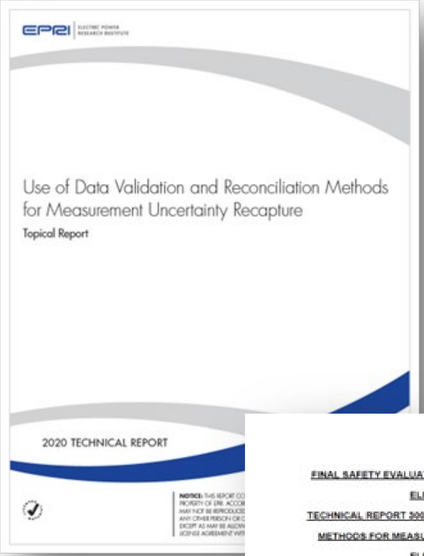
NRC Approval of DVR for MUR

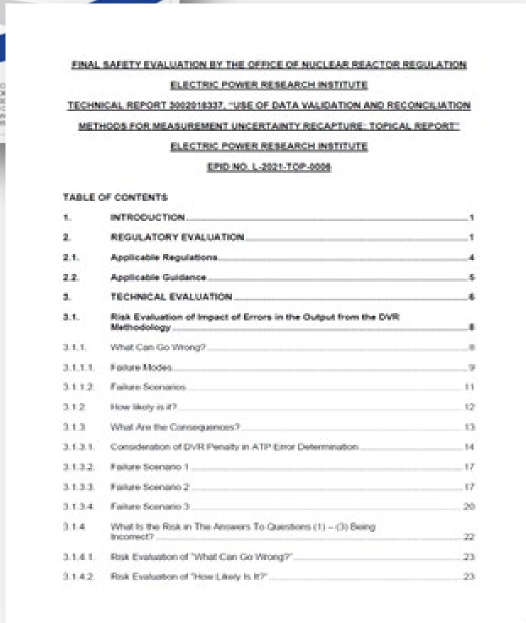
- **NRC Form 896, “A Topical Report Verification,” and NRC Form 897, “Topical Report Withholding Determination,” proprietary information withholding determination for the *Electric Power Research Institute Report 3002018337, "Use of Data Validation and Reconciliation Methods for Measurement Uncertainty Recapture: Topical Report.”***

- **The Topical Report, Revision 0-A (Non-Proprietary Version), Use of Data Validation and Reconciliation Methods for Measurement Uncertainty Recapture is now available in ADAMS using the link below:**

  https://adamswebsearch2.nrc.gov/webSearch2/main.jsp?AccessionNumber=ML23285A308 [adamswebsearch2.nrc.gov]

DVR Topical Report





FINAL SAFETY EVALUATION BY THE OFFICE OF NUCLEAR REACTOR REGULATION

ELECTRIC POWER RESEARCH INSTITUTE

TECHNICAL REPORT 3002018337, "USE OF DATA VALIDATION AND RECONCILIATION METHODS FOR MEASUREMENT UNCERTAINTY RECAPTURE: TOPICAL REPORT"

ELECTRIC POWER RESEARCH INSTITUTE

EPID NO. L-2021-TOP-0006

TABLE OF CONTENTS

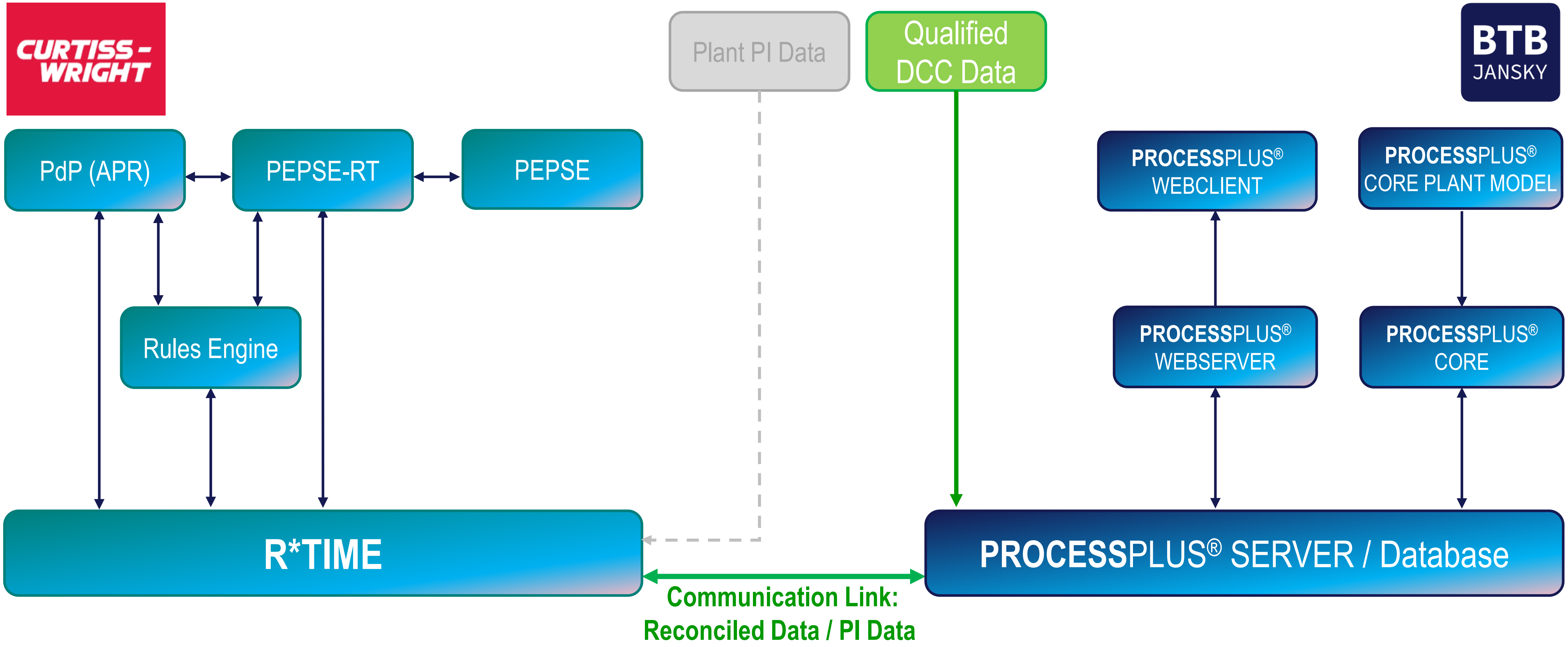
Safety Evaluation concludes that *"…there is reasonable assurance that the DVR method as described in EPRI TR 3002018337 can be used to determine the CTP and the CTP uncertainty, provided all DVR conditions and limitations have been satisfied."*

- Contains description of the methodology, discussion on uncertainty settings and uncertainty propagation, and DVR sensitivities and failure modes
- Table of overall schedule
- Safety evaluation conclusion
- 11 conditions and limitations in the SE that will need to be addressed by a licensee in their LAR

Timeline

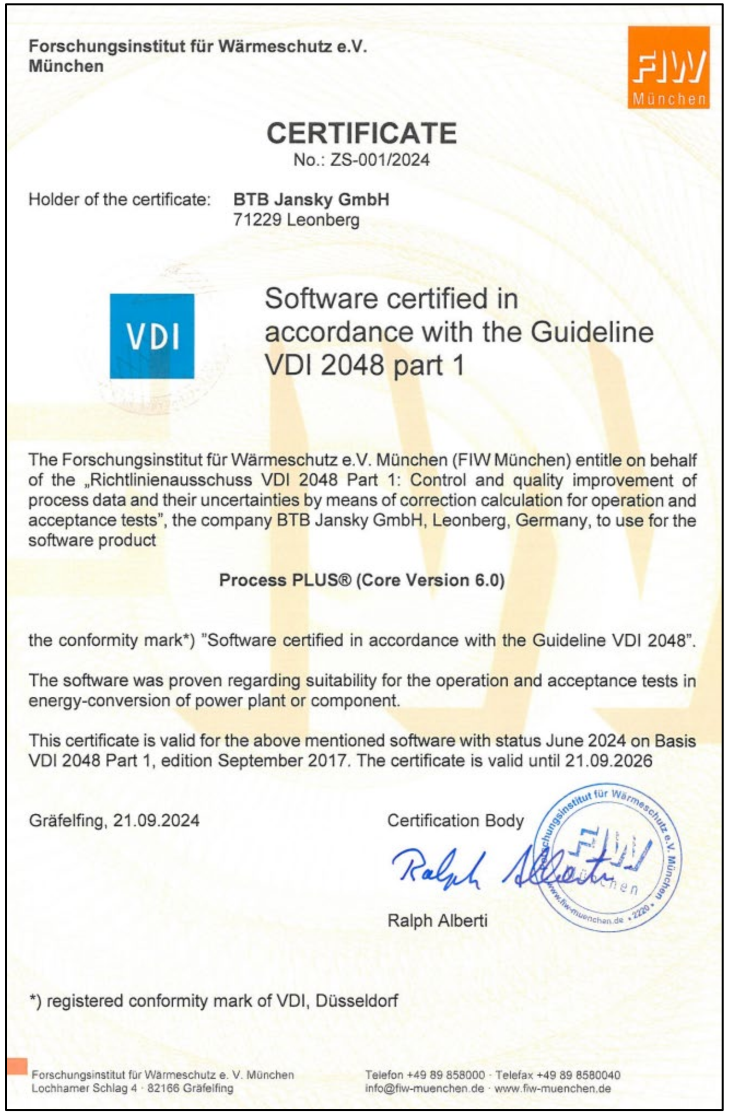
Date	Event
November 2020	DVR Topical Report released by EPRI
May 2022	First round of RAIs received from NRC
September 2022	Audit meeting with NRC
December 2022	Second round of RAIs received from NRC
May 2023	Draft safety evaluation from NRC
June 2023	ACRS meeting
August 2023	Final safety evaluation from NRC

System Architecture



PROCESSPLUS® Software

- **BTB Jansky developed the proprietary data validation and reconciliation system (DVR) PROCESSPLUS® Core 6.0**
- **BTB Jansky developed the platform and software-independent PROCESSPLUS® WebClient**
- **BTB Jansky and PROCESSPLUS® Core 6.0 received the “VDI 2048 part 1, edition 2017-09” certification as the first company world-wide in 2018. Recertified 2020, 2022, 2024 (valid for 2 years).**
- **The VDI 2048 standard was published first in 2000. The new release was published in 2017. The main differences between these releases are:**
  - Adding “Appendix B: Criteria catalogue for certification in accordance with VDI 2048”
  - Certification valid for 2 years
- **Dr. M. Langenstein is a member of the VDI 2048 committee since 2003 and has worked on this standard as one of the main authors**


Forschungsinstitut für Wärmeschutz e.V.
München

FIW München

CERTIFICATE
No.: ZS-001/2024

Holder of the certificate: BTB Jansky GmbH
71229 Leonberg

VDI

Software certified in accordance with the Guideline VDI 2048 part 1

The Forschungsinstitut für Wärmeschutz e.V. München (FIW München) entitle on behalf of the „Richtlinienausschuss VDI 2048 Part 1: Control and quality improvement of process data and their uncertainties by means of correction calculation for operation and acceptance tests“, the company BTB Jansky GmbH, Leonberg, Germany, to use for the software product

Process PLUS® (Core Version 6.0)

the conformity mark*) "Software certified in accordance with the Guideline VDI 2048".

The software was proven regarding suitability for the operation and acceptance tests in energy-conversion of power plant or component.

This certificate is valid for the above mentioned software with status June 2024 on Basis VDI 2048 Part 1, edition September 2017. The certificate is valid until 21.09.2026

Gräfelfing, 21.09.2024

Certification Body

Ralph Alberti

*) registered conformity mark of VDI, Düsseldorf

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PROCESSPLUS® Customers

NUCLEAR POWER PLANTS (PWR, BWR, CANDU, VVER)

Barakah 1-4	United Arab Emirates (UAE)
Beznau A/B	Switzerland
Borssele	Netherlands
Bruce A1-A4/B5-B8	Canada
Brunsbüttel	Germany
Cofrentes	Spain
Diablo Canyon 1/2	USA
Emsland	Germany
Fermi 2	USA
Forsmark 1/2/3	Sweden
Gösgen	Switzerland
Grafenrheinfeld	Germany
Gundremmingen B/C	Germany
Isar 1	Germany
Koeberg 1	South Africa
Krsko	Slovenia
Leibstadt	Switzerland
Mihama 3	Japan
Neckarwestheim 1/2	Germany
Ohi 1/2/3/4	Japan
Paks 1/2/3/4	Hungary
Philippsburg 1/2	Germany
Takahama 1/2/3/4	Japan
Tihange 2	Belgium
Unterweser	Germany

FOSSIL POWER PLANTS

Emsland (Gas)	Germany
Gersteinwerk (Coal)	Germany
GK Mannheim (Coal)	Germany
Henkel IKW (Coal)	Germany
Kaucuk /Synthos (Gas)	Czech Republic
Kirov 3 (Gas)	Russia
Lausward (Gas)	Germany
LyondellBasell IKW (Gas)	Germany
Mosenergo KW 21-9 (Gas)	Russia
Permskaya 2/3 (Gas)	Russia
Pocerady 2/3/4/5/6 (Coal)	Czech Republic
Rheinhafen RDK (Gas)	Germany
Westfalen (Coal)	Germany
Wacker Chemie (Gas)	Germany
Walsum 10	Germany

OIL/GAS PIPELINES

Atlas Pipelines (Gas)	USA
Mero (Oil)	Germany

PROCESSPLUS® is applied in 70+ power plant units worldwide.

Evaluation of Various Feedwater Flow Measurement Methods

- **Evaluating Different Feedwater Flow Measurement Methods with DVR**

Evaluation Method	Standard Measuring Device	Country
Radioactive Tracer	Venturi/Nozzle	Switzerland
Non-radioactive Tracer (CHEMTRAC) UFM CALDON Clamp-on System	Venturi/Nozzle	Belgium
UFM CROSSFLOW AMAG Clamp-on System	Venturi/Nozzle	US
UFM CALDON LEFM System	Venturi/Nozzle	Spain
Other UFM Clamp-on System	Venturi/Nozzle	Canada

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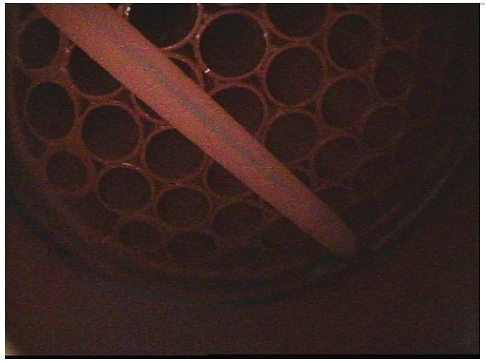
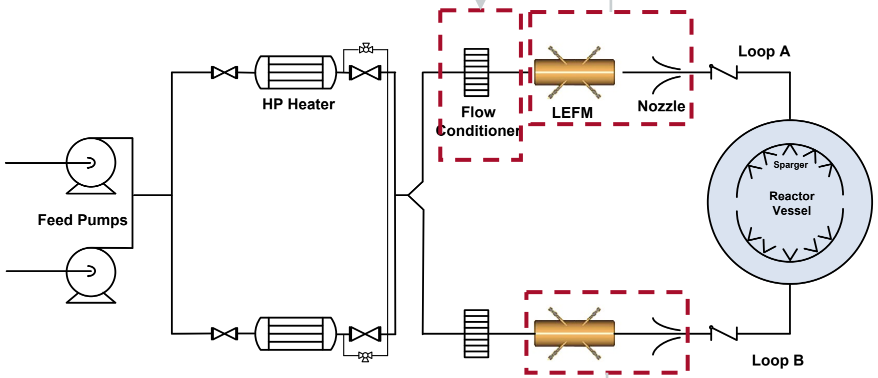
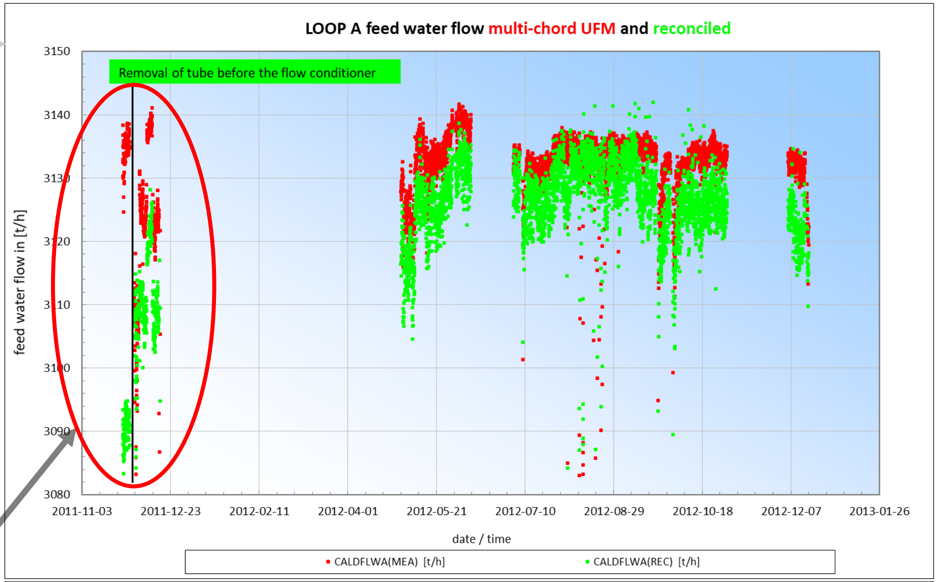
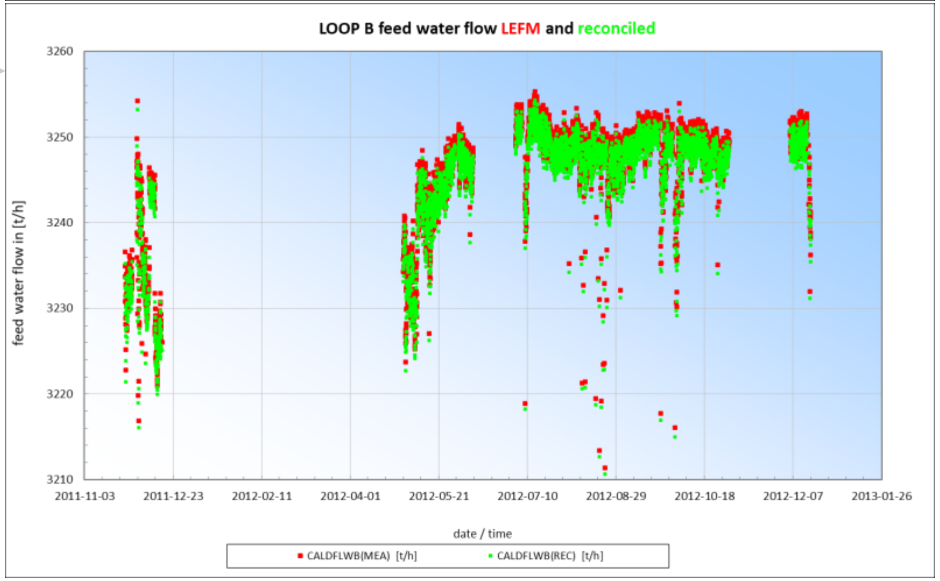
OPEX | Detection of Feedwater Measurement Error (LEFM)







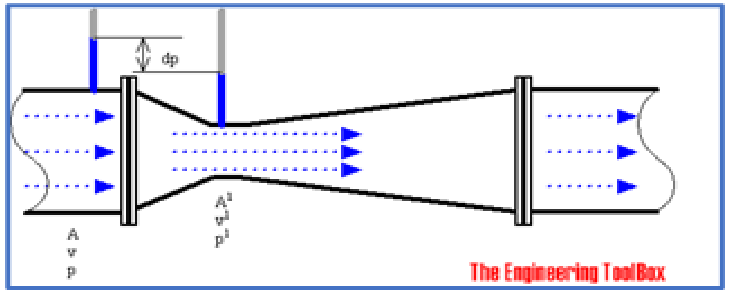


In this example, timely detection led to immediate repair of upstream straightener, recovering 8MWe and total production loss.

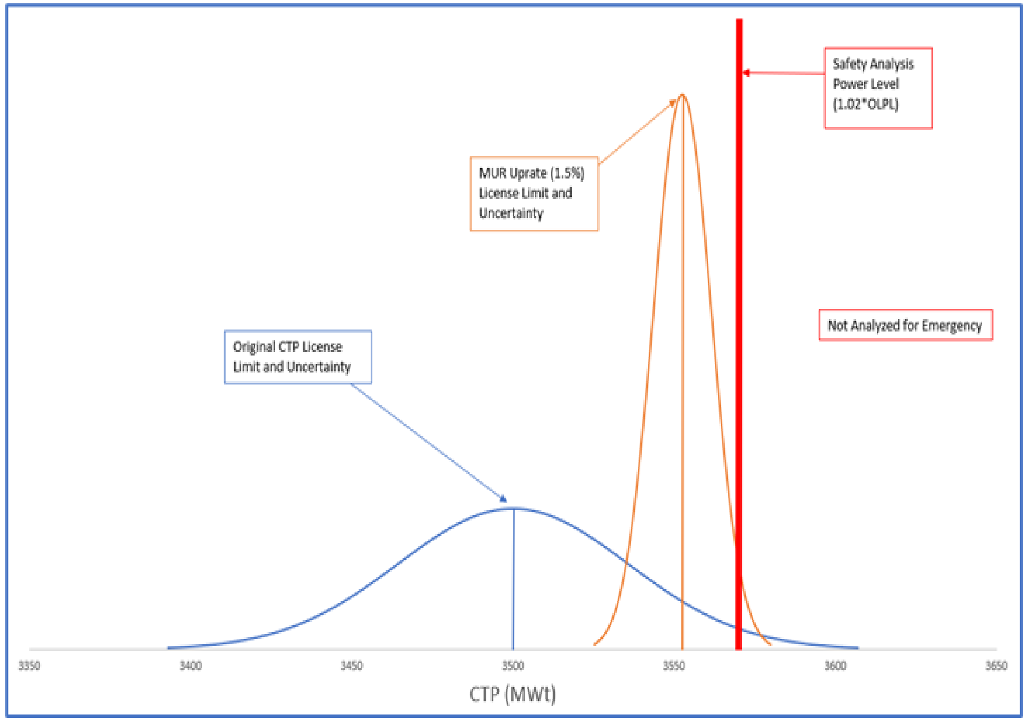
DVR provided early detection of a change in the Loop A feedwater flow measurement by the state-of-the-art multi-chord ultrasonic meter.

Measurement Uncertainty Recapture (MUR) Uprates

- **10 CFR Part 50 Appendix K: "…it must be assumed that the reactor has been operating continuously at a power level at least 1.02 times the licensed power level (to allow for instrumentation error)…" "An assumed power level lower than the level specified in this paragraph (but not less than the licensed power level) may be used provided the alternative value has been demonstrated to account for uncertainties due to power level instrumentation error."**

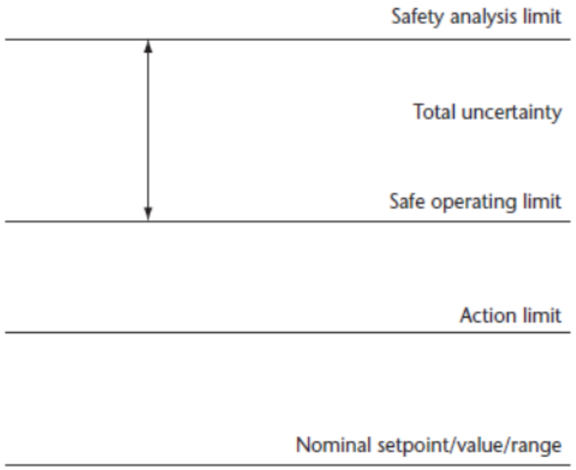


  - Ultrasonic flow meters provided reduced uncertainty and therefore provided basis for MUR uprates (57 out of 93 units in US approved for MUR)
  - DVR provides similar reduction in uncertainty without necessarily requiring additional instrumentation



DVR Application for MUR

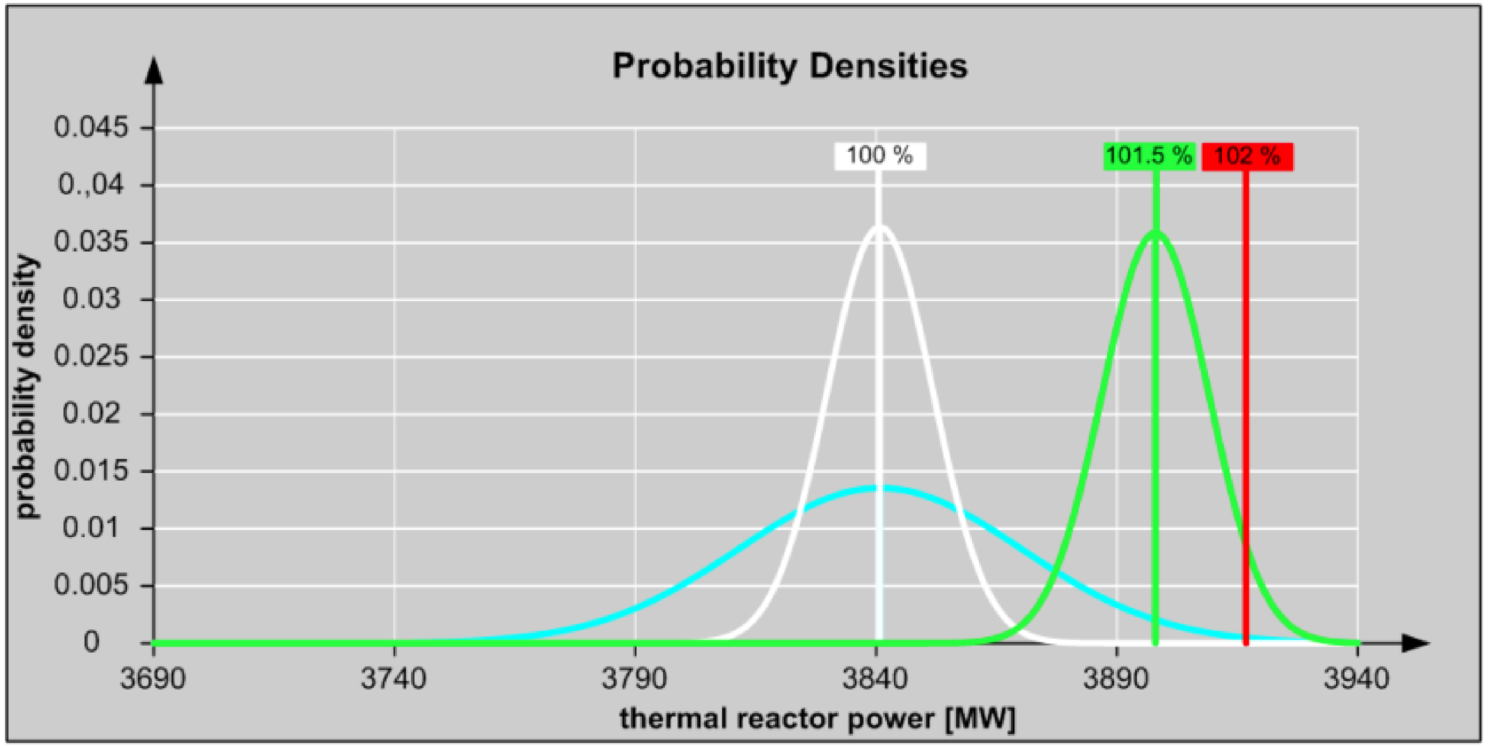
- **Historically, MUR has been implemented based on high-accuracy ultrasonic flow meters.**
- **DVR offers an alternative methodology to demonstrate confidence in measurement uncertainty.**
  - If DVR is used to calculate the critical reactor power measurement uncertainties, and these uncertainties can be demonstrated to be less than the Utility's license's measurement uncertainty penalties, an application could be made to the Regulator to recapture some of the measurement uncertainty penalty.
  - DVR has been approved for MUR in Germany, and recently approved in the United States.



By reducing the total uncertainty, measurement uncertainty penalties can be recaptured so that the safe operating limit can be increased.

Regulator Approved MUR Application at KGG

Measurement Uncertainty Recapture (MUR)



thermal reactor power	calculated from	probability for 'value < 102 %'
100 %	measurements	99.51 %
100 %	reconciled values	99.9999999982 %
101.5 %	reconciled values	95.453 %

Regulator **approved** a 1.5% measurement uncertainty recapture based on DVR.

Next Steps for Licensees

- **Plants that have not yet performed a MUR uprate**
  - License Amendment Request (LAR) will need to be submitted, including information that addresses the SER
  - Need fully developed online DVR models and supporting documentation
  - Uprates of 1.5 to 1.6%, depending on plant instrumentation
    - For a 1200 MWe plant, this equates to 12-17 MWe increase in generation (about $3-4 million increase in revenue per year)
- **Plants that have already performed a MUR uprate**
  - Potential to use DVR to determine correction factors for their ultrasonic flow meters (power recovery)
  - May be potential for additional small uprates – additional licensing input required

Why DVR?

- DVR eliminates systematic errors and reduces uncertainties
- The DVR method has been accepted by the NRC in 2024 for power recovery and MUR uprates
- DVR does not require any additional plant instrumentation
- DVR generates correction factors for feedwater flow rate and feedwater temperature
- DVR replaces traditional methods such as clamp-on or in-situ ultrasonics, deaerator mass balance or PTC 6 tests
- DVR represents the state-of-the-art Digital Twin Technology

Conclusions

- **Validation of process data with DVR provides improved confidence in plant measurements**
- **The DVR technology (PROCESS**PLUS®**) is certified according to the German DVR technical standard VDI 2048**

- **Thermal Performance Related Applications of DVR**
  - Improved process simulation and thermal performance monitoring with FAMOS
  - Quality-assured plant performance and component monitoring
  - Power recovery with DVR correction factors
  - Measurement Uncertainty Recapture (MUR) guaranteed at 1.5 – 1.6%
  - Cycle isolation loss identification

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Using Thermal Performance Modeling Software for Effective and Accurate Evaluation of EPUs and MURs in Nuclear Power Plants

Background

- Many nuclear power plants are currently engaged in EPU (Extended Power Uprate) studies, which include equipment replacement or refurbishment to increase generation.
- Additionally, this can include power increase from MURs (Measurement Uncertainty Recapture) via LEFM or DVR technologies.
- To provide the best predictions of a plant’s response to these modifications, thermal performance software modeling is used.

Background (2)

- **The models provide the best prediction of plant response and are a valuable part of the design process**
- **This includes interactions with potential equipment vendors by providing the plants with a tool to evaluate vendor claims on performance improvements**
- **This presentation explains the steps to collect information and develop models to provide the most accurate representation of a plant's behavior for EPU and MUR studies**
  - The plant modeling software applied in this presentation is PEPSE. PEPSE is an off-line thermal performance software package used in the nuclear industry with the features needed to perform these studies

PEPSE is a registered trademark of Curtiss-Wright Corporation

CURTISS-WRIGHT

What are the steps?

- Data Collection
- Data Validation
- Model Development
- Tuning Models to Plant Data
- Developing the Tuned Model
- Running EPU and MUR Case Studies

Step 1: Data Collection

- What data do I use?
- Where do I get it?
- How much data?

Step 1: Data Collection | What data do I use? Where do I get it?

- Any existing PEPSE model for the unit
- Turbine manufacturer's thermal kit and heat balance diagrams
- Plant Historian point list
- Plant reactor power calculation
- Condenser, Reheater, Feedwater Heater design data
- Condenser tube plugging information
- Piping and instrumentation drawings
- Periodic performance reports (monthly summary, charts and graphs distributed for generation reporting, etc.)
- Plant modification history
- Plant data, multiple sets
- List of known issues in the plant that need to be accounted for in plant data tuning
- Pump curves containing head and efficiency for the condensate, condensate booster, and feedwater pumps
- Circulating Water conditions for Summer/Winter studies
- Circulating water inlet temperature vs Gross Output for comparison after tuning to plant data

Step 1: Data Collection | How much data?

- **Select maximum loads**
  - Summer and Winter max capacity tests
  - Select a 1-2 hour duration, no transients, stable plant operation
  - 1- to 5-minute data collection frequency

Step 1: Data Collection

- **Boundary Conditions**
  - MWth
  - MWe
  - S/G (PWR or Reactor (BWR) steam out moisture or quality, and pressure)
  - Circulating water temp and flow
  - Condenser back pressure(s)
  - Atmospheric Pressure

- **Plant Data**
  - Turbine pressures – 1st stage, HP exhaust, LP inlet
  - Extraction pressures – at turbines or feedwater heaters
  - Pump discharge pressures and temperatures
  - MSR outlet pressures and temperatures
  - Feedwater heater outlet and drain Temperatures
  - Make-up, CRD and blowdown flows
  - Others as available

Step 2: Data Validation

- Accuracy?
- What do I do with it?

Step 2: Data Validation | Accuracy? What do I do with it?

- **Validation of the collected plant data is critical for preparation to tuning the model's plant behavior by reducing measurement uncertainties**
- **For the 1 hour of collated data, max capacity checks – winter and summer**
- **Checks for flatline, noisy sensors, etc.**
  - Minimum and Maximum
  - Average
  - Standard Deviation / Average (%)
  - 2-sigma check
    - Average +/- 2 X Standard Deviation

	U1 (P6CM\	U1 (E031) N	U1 (E025)	U1 (
	MWT	MW	MW	M
Min	**3505.998**	**1176.13**	**1175.32**	**2.9**
Max	**3517.623**	**1182.049**	**1179.83**	**2.9**
Average	**3511.233**	**1178.933**	**1176.989**	**2.9**
STDEV/AVG	**0.11%**	**0.14%**	**0.12%**	**(**
7/28/2024 0:00	3508.187	1178.335	1176.05	2.9
7/28/2024 0:05	3510.215	1176.13	1178.13	2.9
7/28/2024 0:10	3505.998	1178.219	1175.32	2.9
7/28/2024 0:15	3512.582	1178.219	1178.86	2.9
7/28/2024 0:20	3512.719	1179.147	1177.27	2.9
7/28/2024 0:25	3513.357	1182.049	1176.29	2.9
7/28/2024 0:30	3517.063	1180.076	1179.83	2.9
7/28/2024 0:35	3514.814	1179.612	1176.29	2.9
7/28/2024 0:40	3507.623	1177.755	1176.05	2.9
7/28/2024 0:45	3509.053	1179.96	1175.81	2.9
7/28/2024 0:50	3507.787	1178.103	1176.05	2.9
7/28/2024 0:55	3509.009	1177.291	1175.93	2.9
7/28/2024 1:00	3517.623	1181.237	1178.98	2.9

Step 3: Model Setup

- **Detailed model of the generating unit is developed**
  - Model is "Load Generalized" using vendor heat kits to operate from VWO down to low load (25-50%)
- **Each load is benchmarked to ensure accuracy and repeatability**
  - Generation: 0.1%
  - Pressures: 0.5 psi
  - Enthalpies: 1 Btu/lbm
- **This includes the development of models using design information from heat exchanger specification sheets**
  - Simplified design mode feedwater heaters
  - HEI mode condensers
  - Design mode reheaters and external drain coolers

Step 4: Tuning Models to Test Data

- **Subsequently, the models are tuned using instrumentation representing historical plant operating data and incorporating any changes since design, including plant degradation.**
- **The validated data is entered into PEPSE controls to calculate:**
  - Condenser and feedwater heater heat transfer coefficient tuning factors
  - Turbine bowl flow coefficients
  - Extraction line and component pressure drops

Step 5: Developing the “Tuned” Model

- **The calculated tuning factors for the winter and summer are then entered into the model**
  - Use curves (PEPSE schedules) for tuning factors
  - Use PEPSE special streams for pressure drops or within components
    - Type 7 streams are ideal for EPU and MUR studies because they are based on volumetric flow.
  - Use caution with EPU and MUR studies with extrapolation. Check behavior and predictions for reasonable output
  - Be aware the throttle valve will be passing more flow, often exceeding 12%, which will impact the pressure drop.

Step 6: Running EPU and MUR Case Studies

- **Before making case studies for EPU and MUR, test the model well at current plant conditions**
  - Taking equipment out of service (feedwater heaters, etc.)
  - Take heater strings out of service
  - Check cold and hot circulating water temperature plant historical limits
  - Change thermal power and steam conditions and review results
- **Running case studies for EPU and MUR, test the model results**
  - Condenser back pressure
  - Feedwater flow and final feedwater temperatures
  - Pump, turbine, MSR behavior
  - Stream pressure drops – this can have a large impact with the predictions at higher flows

Summary

- Thermal performance models are an effective tool for evaluating EPU and MUR power uprates
- Besides providing generation, the post uprate model results include key performance indices as well as steam and water properties needed for design evaluations
- Generation of heat balance diagrams with pre and post power uprate information can be used in discussions within the utility, contractors and equipment vendors
- Results are accurate if model development and data validation efforts are thorough

Thank you!

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