U.S.NRC

United States Nuclear Regulatory Commission

Protecting People and the Environment

Public Meeting on Digital Condition Monitoring and Maintenance and Diagnostic (M&D) Centers

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Introduction

NRC regulations include requirements that ensure safety-related equipment can perform its intended function when required

- 10 CFR 50.65 establishes requirements for monitoring the effectiveness of maintenance at nuclear power plants, the 'Maintenance Rule"
- 10 CFR 50.55a incorporates reference code ASME OM-1, including inservice testing requirements

Advanced Condition Monitoring (ACM) is a proactive maintenance approach that uses real-time data and models to assess component, system, or process status

- Data can be obtained from advanced sensors (vibration, pressure, temperature, ultrasound, etc) and transmitted digitally for processing
- Models, ranging from simple thresholds to machine learning algorithms and digital twins, use real-time data and historical examples to detect abnormalities and diagnose the causes

ACM for Inservice Testing

- Inservice Testing (IST) is:
  - Traditionally prescriptive,
  - Requires periodic testing
  - Utilizes limited condition monitoring diagnostics tools

- Advanced Condition Monitoring (ACM) technologies offer
  - Digital real-time monitoring of SSC health
  - Continuous performance-based assessments

- NRC's recent work explored ACM technologies and use cases:
  - ML24305A162, Assessment of Condition Monitoring Methods and Technologies for Inservice Inspection and Testing of Nuclear Power Plant Components, October 2024
  - ML251951282, Technical Considerations in the Application of Advanced Condition Monitoring for Inservice Testing Programs, July 2025

*

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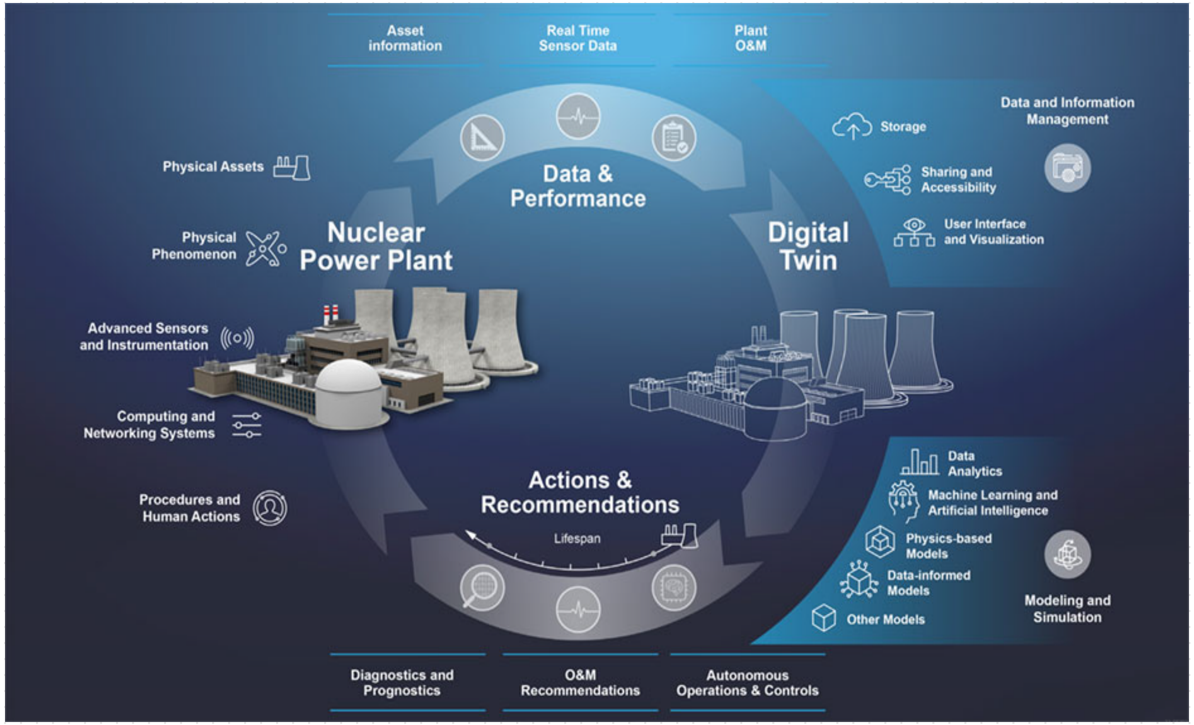
**Image courtesy of https://www.powermag.com/asme-operation-and-maintenance-inservice-testing-program-ensures-nuclear-component-operational-readiness/*

Digital Twins

A Digital Twin is a virtual representation of a component, process, or system that may use various models and operating data to produce insights about the physical counterpart

- Maintains real-time state representation and has capacity to provide novel insights
- Possible enhancements in five categories
  1. Information
  2. Communication
  3. Integration
  4. Analysis
  5. Control
- NRC recently issued a report on digital twins: ML25135A029, Technical Assessment of the Application of Digital Twin and Prognostic Tools for Condition Monitoring, May 2025



RIGA

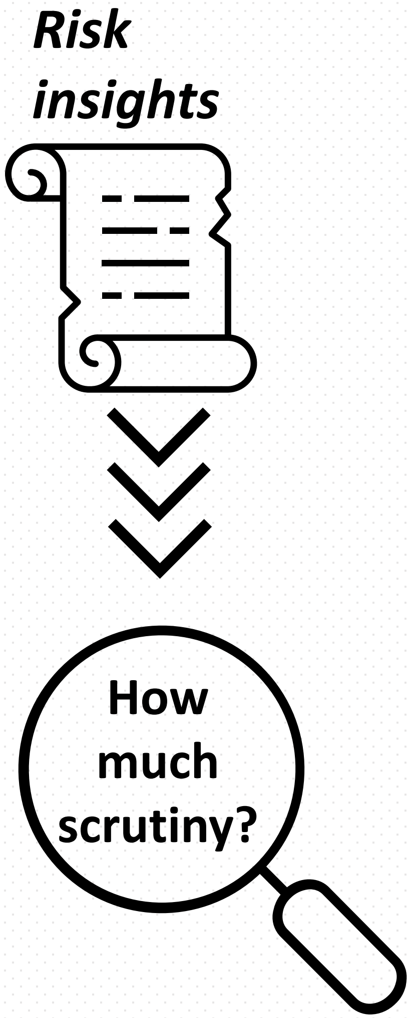
A Risk-Informed Graded Approach (RIGA) helps inform regulatory scrutiny of CM based on safety significance

<u>Components are assessed on four factors</u>

1. SSC risk significance per 10 CFR 50.69 (RISC-1 -> RISC-4)
2. CM function (Descriptive, Diagnostic, Predictive)
3. Failure significance (Incorrect action, malfunction)
4. Technology/methodology maturity (proven/novel)

NRC recently issued a report exploring this approach:

- ML26056A138, On the Application of a Risk Informed Graded Approach for Advanced Condition Monitoring Programs, February 2026



Current Work

- Machine-Learning for Condition Monitoring
  - Developing potential framework for evaluation of ML-assisted plans for condition monitoring of passive components
    - Levels of autonomy
    - Reliability
    - Explainability
- Check Valve Condition Monitoring
  - Alternate to quarterly testing
  - Investigating methods
  - Developing evaluation criteria

Endorsement Efficiency

- Industry landscape requires swift action
- Finalize agency stance prior to final vote
- Enhance existing RG process for LWRs under 50.55a
  - Earlier engagement and parallel concurrence
  - Codes and standards with heavy conditions
- ANLWR codes and standards (not in rulemaking)
  - Direct Regulatory Guide without Comments
    - Unconditioned/uncontroversial codes and standards
  - Direct Regulatory Guide with Comments
    - 30-day post promulgation period
    - Conditioned codes and standards
    - Ex. ASME OM-2 endorsement in RG 1.220

Past Work

<u>RES has published five reports in the last 2 years on condition monitoring</u>

1. ML24305A162, Assessment of Condition Monitoring Methods and Technologies for Inservice Inspection and Testing of Nuclear Power Plant Components, October 2024
2. ML25135A029, Technical Assessment of the Application of Digital Twin and Prognostic Tools for Condition Monitoring, May 2025
3. ML251951282, Technical Considerations in the Application of Advanced Condition Monitoring for Inservice Testing Programs, July 2025
4. ML2523A274, Investigation of Machine Learning Approaches for Condition Monitoring of Boiling Water Reactor Recirculation Pumps, September 2025
5. ML26056A138, On the Application of a Risk Informed Graded Approach for Advanced Condition Monitoring Programs, February 2026

Please Save Questions for the Discussion

Jake Farber, Ph.D.
Research Scientist
Idaho National Laboratory

May 19, 2026

AI-Driven Technologies for Condition Monitoring and Decision Support

LRS #: INL/MIS-26-92372

LWRS LIGHT WATER REACTOR SUSTAINABILITY

Light Water Reactor Sustainability Program

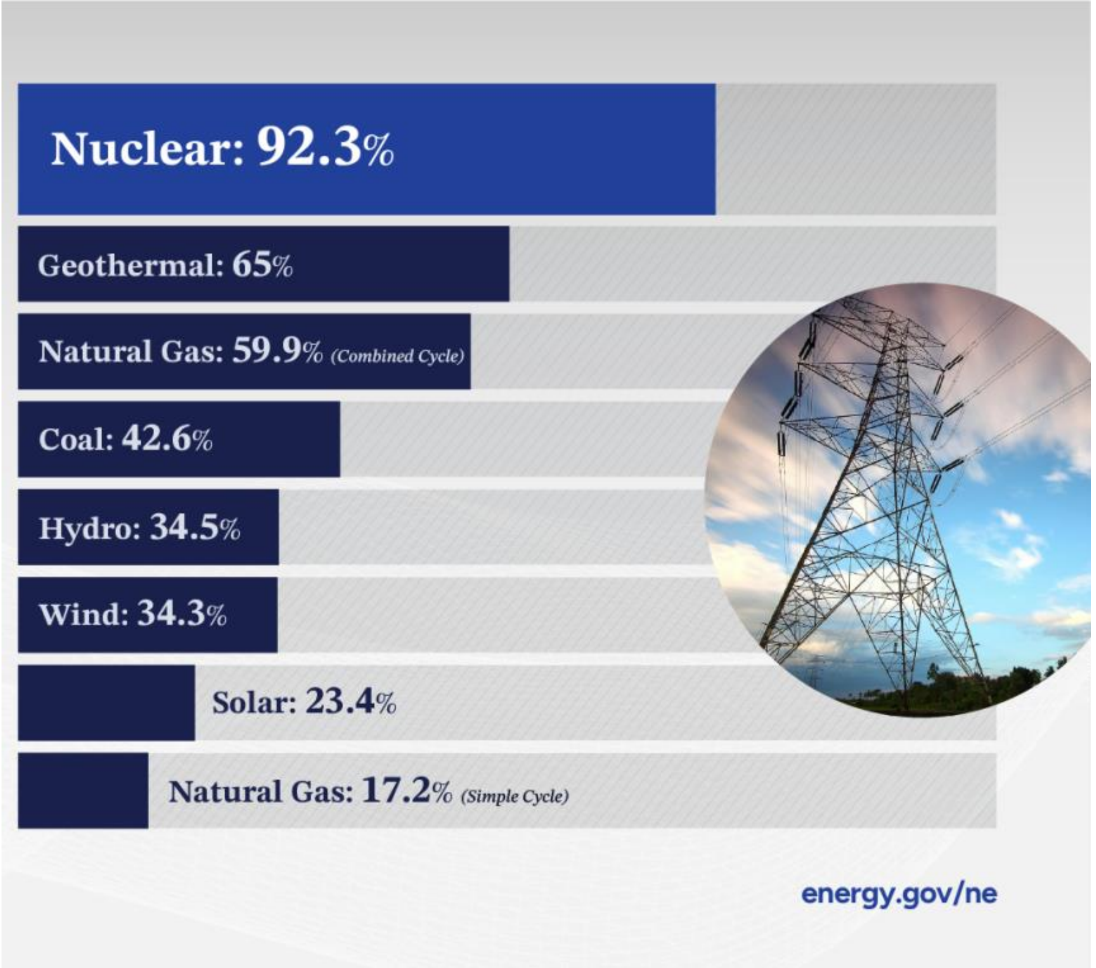
- **Objectives**: Provide federally funded nuclear technology and expertise to drive energy dominance, expand nuclear capacity, and enhance operational efficiency.
- **Value Proposition:** De-risks technology adoption by demonstrating what is possible and the potential for success, allowing utilities to focus on implementation rather than R&D investment.
- **FY26**: $1M+ invested in remote monitoring technologies to further enhance capabilities.

Motivation

- Nuclear power already leads all energy sources in terms of capacity factor (>92% [DOE, 2024]), yet further gains increase grid electricity output, strengthen grid reliability, and improve economics for utilities and customers.
- Traditional alarm-based monitoring detects problems only near the point of failure, leaving little time for planned intervention and risking costly forced derates or unplanned outages.
- Advanced condition monitoring predicts equipment degradation prior to failure, enabling timely intervention and protecting plant availability.

Capacity Factor by Energy Source, 2024

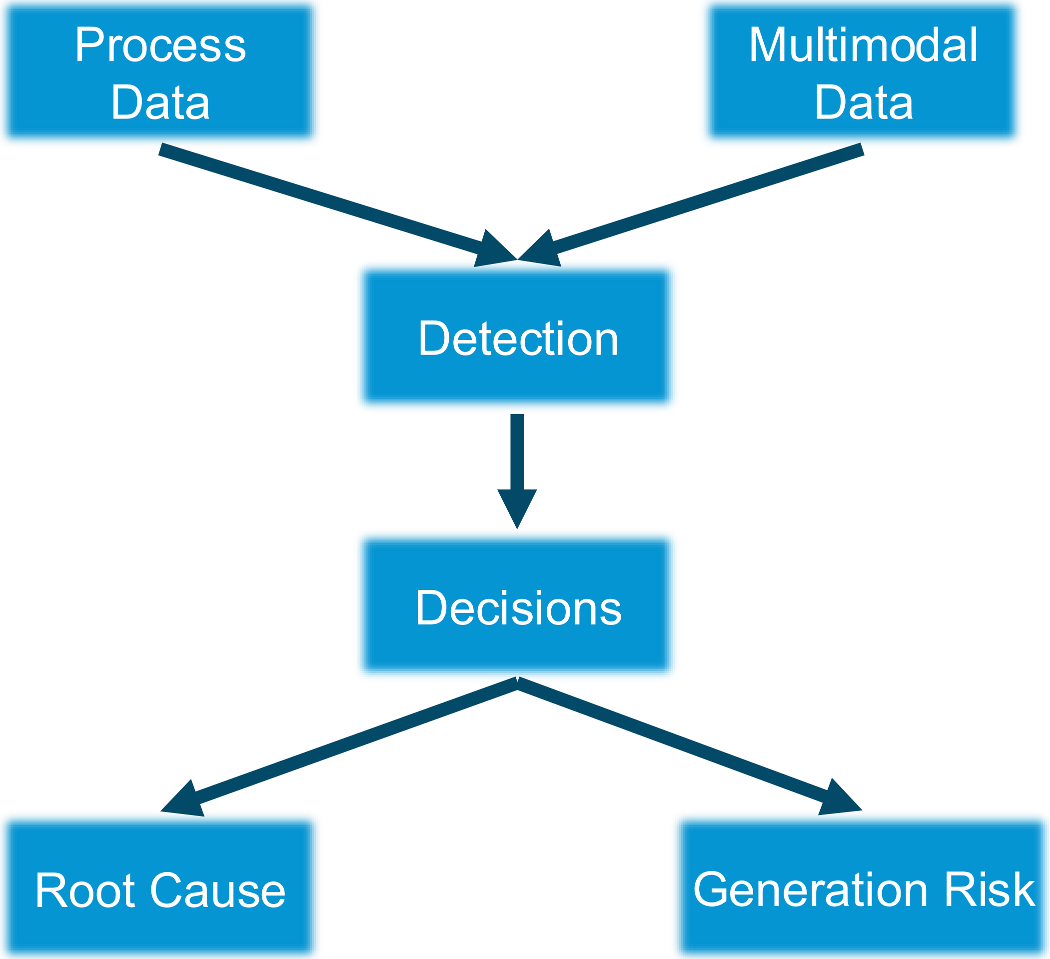
Source: Energy Information Administration



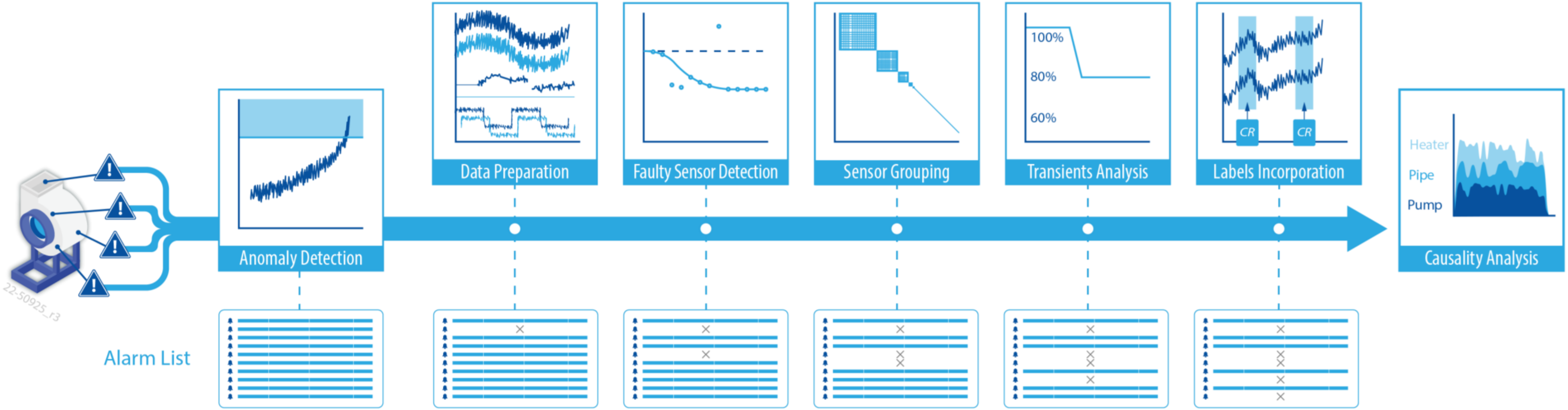
https://www.energy.gov/ne/articles/what-generation-capacity

From Detection to Decision: A Scalable Framework for Condition Monitoring

- Anomaly detection is the foundation, using process data to proactively detect equipment degradation.
- Integrating multimodal data (text, audio, video) can improve said detection and add needed context to further support decision making.
- Once anomalies are detected, the next challenge is decision support — understanding what happened, why, and what it costs.
- Economic impact quantification of equipment degradation closes the loop, enabling risk-informed maintenance and operational decisions.



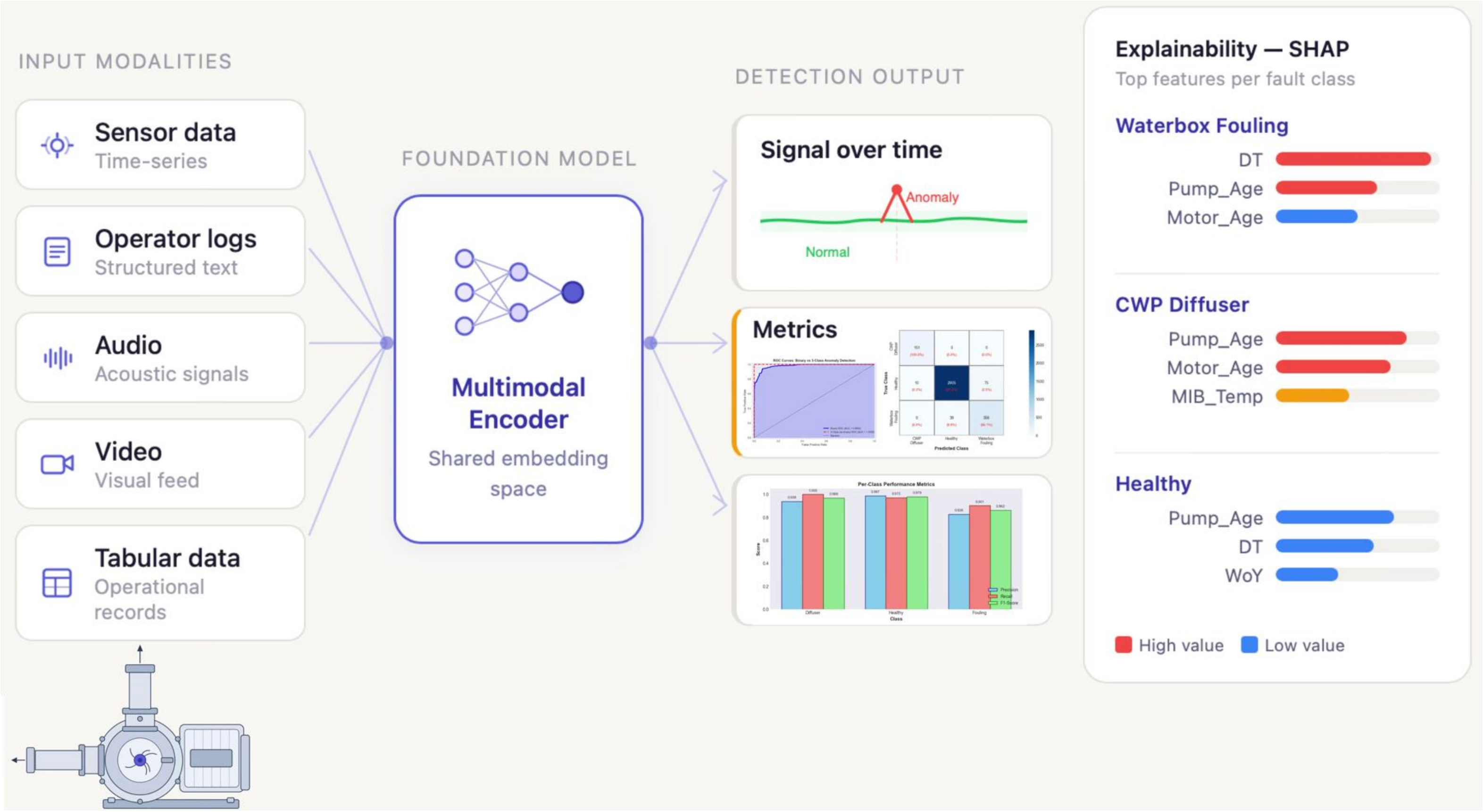
ALARM provides equipment-agnostic anomaly detection that scales across plant systems and facilities with little site-specific configuration.



ALARM: Automated Latent Anomaly Recognition Method

Foundation models incorporate diverse plant data types by integrating sensor readings, logs, and reports into a unified analytical framework.

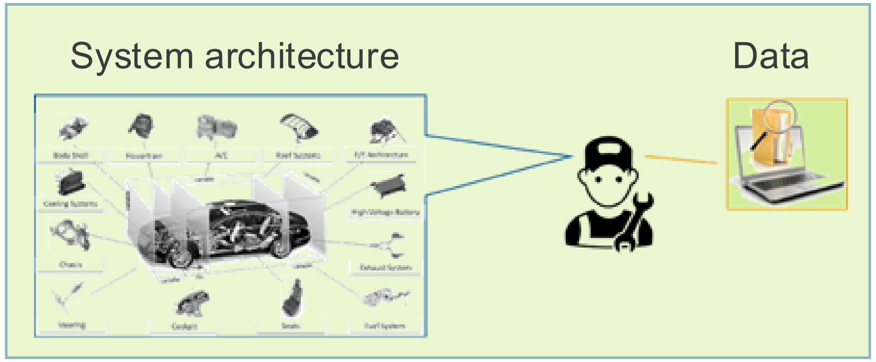
- Emerging AI foundation models can process large-scale, multimodal plant data simultaneously, identifying patterns across data types that traditional single-source methods may miss.
- Outputs are designed with explainability in mind, providing operators and reviewers with transparent, interpretable results.

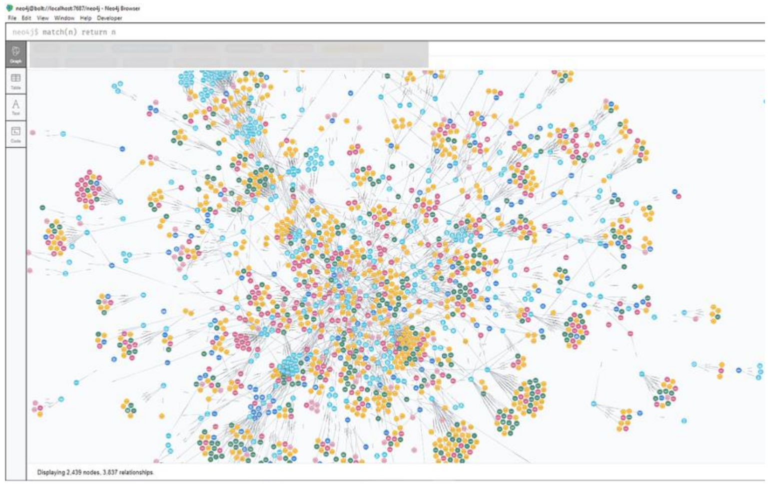


An AI co-pilot architecture drives root cause analysis through causal reasoning, delivering ranked, explainable hypotheses with explicit supporting evidence.

- Root cause analysis is labor-intensive, memory-dependent, and requires retrieving and analyzing large volumes of heterogeneous data.
- An AI architecture co-pilots system engineers through a repeatable Hypothesize → Test → Compare → Decide workflow.
- Knowledge management retrieves and organizes relevant data into a knowledge graph, capturing the semantic role of each element.
- Causal reasoning leverages system architecture, component dependencies, and historical records to constrain the search space and evaluate evidence for and against each candidate hypothesis.

- Anomalies
- SOE logs, alarm logs
- CRs and WOs
- Past RCAs and ECAs
- SOPs, FMEAs
- Supply chain records





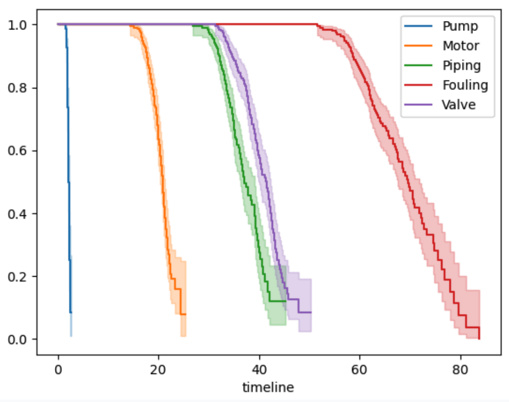
Integrating uncertainty quantification with economic modeling drives smarter, risk-informed maintenance and asset management decisions.

Layer 1
Survival Analysis

Failure time distribution
Weibull/lognormal

Hazard function λ(t)
Instantaneous failure rate over time

Survival function S(t)
P(safe operation past time t)

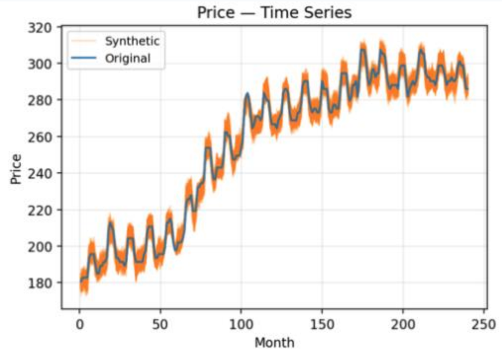


Layer 2
Economic Models

Component cost
Repair, replacement & labor

Downtime cost
Lost generation & capacity revenue

Regulatory risk
Fines, compliance & shutdown costs

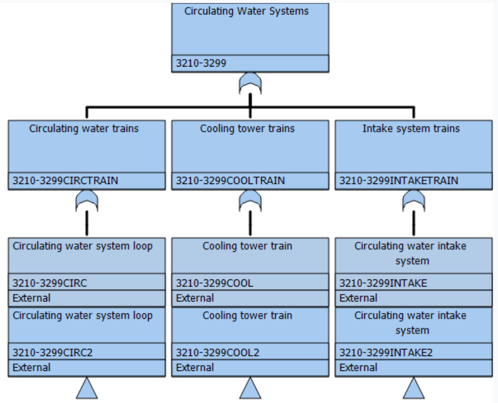


Layer 3
Risk Propagation (GRA)

Loss of Feedwater
Pump, valve failure

Turbine Trip
Loss of oil to the turbine bearing

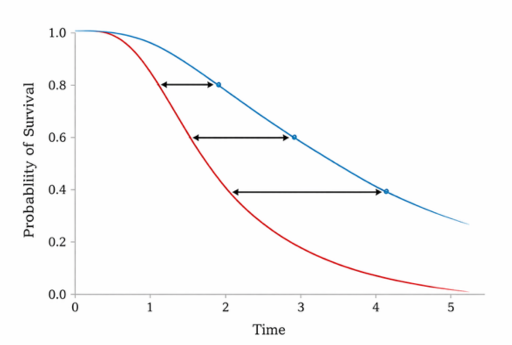
Loss of Primary Flow
Pump, valve failure



Layer 4
Risk Metrics

Time at Risk
Duration in degraded state → prioritize maintenance

Risk at Time
Magnitude during degradation → balance cost



Quantify Degradation Costs → Evaluate Risk Tradeoffs → Schedule Maintenance Optimally

Conclusions

- These technologies mark a shift from reactive, alarm-based monitoring to proactive, predictive condition assessment across plant systems.
- Moving beyond detection, they enable data-driven decision support — translating monitoring results into meaningful operational decisions that optimize capacity factors and strengthen grid reliability.
- Explainable, evidence-based outputs ensure that results are interpretable and actionable for operators and reviewers alike.
- Taken together, detection, root cause analysis, and generation risk assessment form a comprehensive framework to support both the existing and future nuclear fleet.

Questions?

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LWRS LIGHT WATER REACTOR SUSTAINABILITY

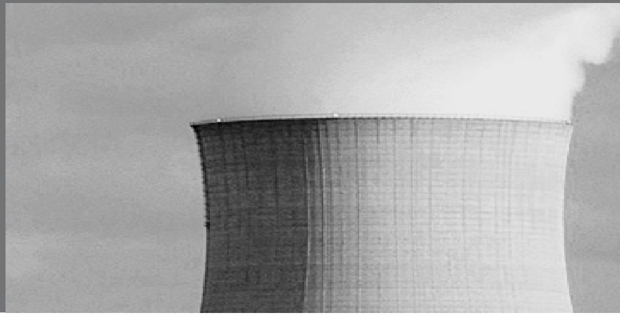
Sustaining National Nuclear Assets

lwrs.inl.gov


Leveraging Condition Monitoring for Improved Equipment Reliability

Austin Crook, Curtiss-Wright

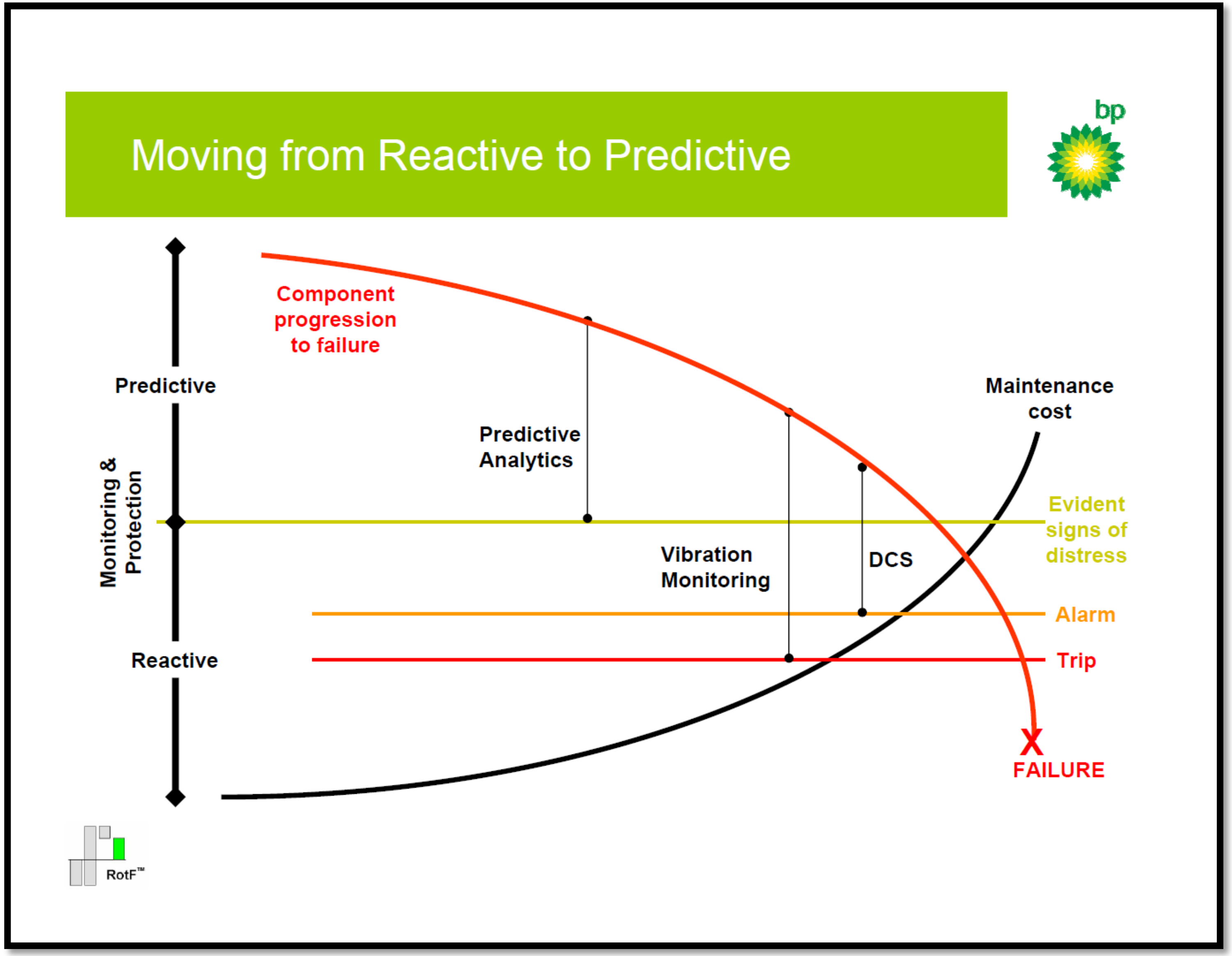
Scott Nedrow, Curtiss-Wright



Abstract

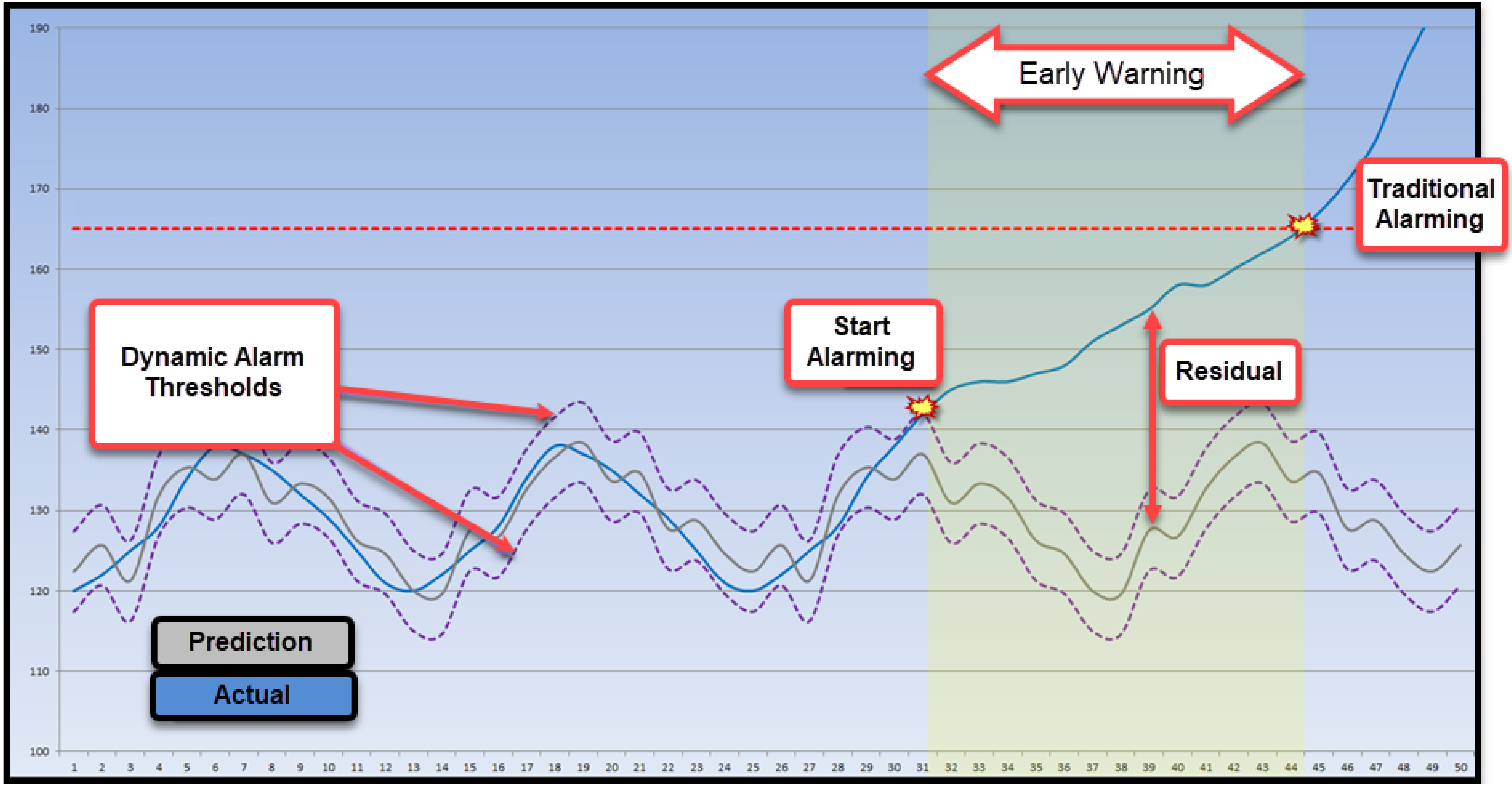
- Condition monitoring software tools play a critical role in preventive maintenance by enabling early detection of developing equipment faults.
- Regular use of these systems allows operators to identify subtle anomalies—such as elevated bearing temperatures—before they escalate into significant failures.
- Minor deviations, which are not always immediately recognized or prioritized, can be found using condition monitoring.

The Goal



Source:
BP Refining Technology: N. Kroutikova, L. Marinai, L. Natarajan, Zaid Rawi, X. Xu, J. Jones, L. Kassie, P. Lahr, *et al* (plus numerous site contacts)
BP IT&S Chief Technology Office: D. Lafferty, P. Stone, B. Tookey *et al*

Condition Monitoring vs Traditional Alarming



Contribution to Your Bottom Line

- **Leverage investment in data acquisition and storage to produce actionable warnings of equipment degradation and provide:**
  - an efficient way of managing process degradation information for equipment and systems
  - a way to reduce control room alarms by addressing equipment and instrument problems early
  - reduced likelihood of catastrophic failures resulting in injury or loss of property
  - the ability to shift unplanned outages into planned maintenance work
  - a means to schedule material and labor proactively to address known faults

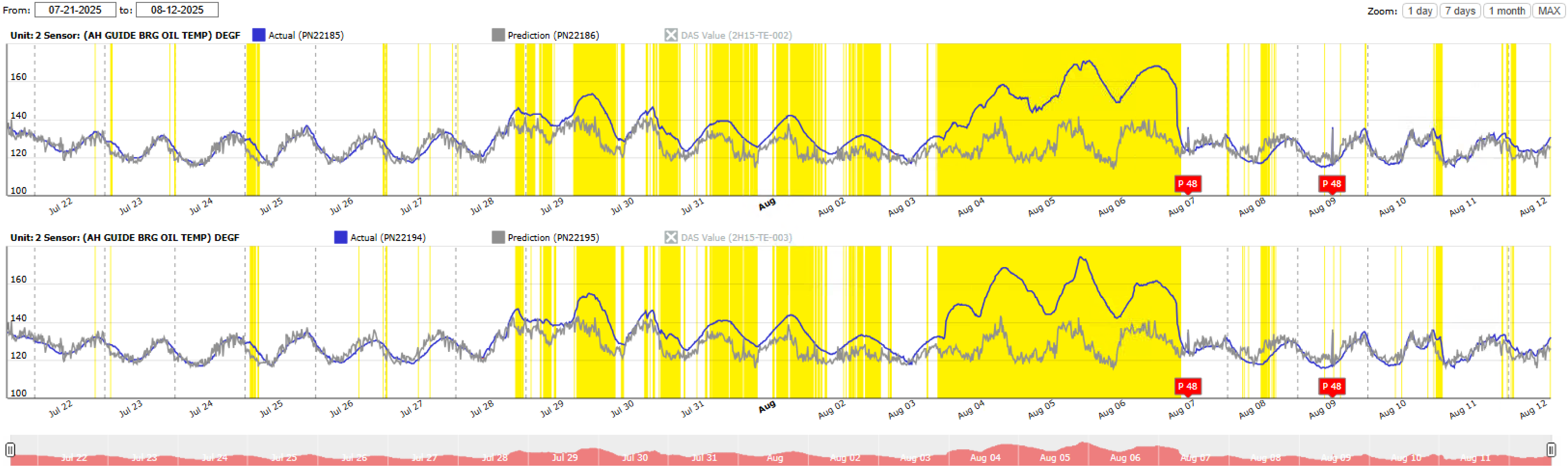
M&D approach

- Review existing models
- Observe and report any change in Models
- Update issues after initial report
- Update existing model tuning if necessary
- Meetings with Plant Engineers in charge of M&D
- Construct additional models as necessary

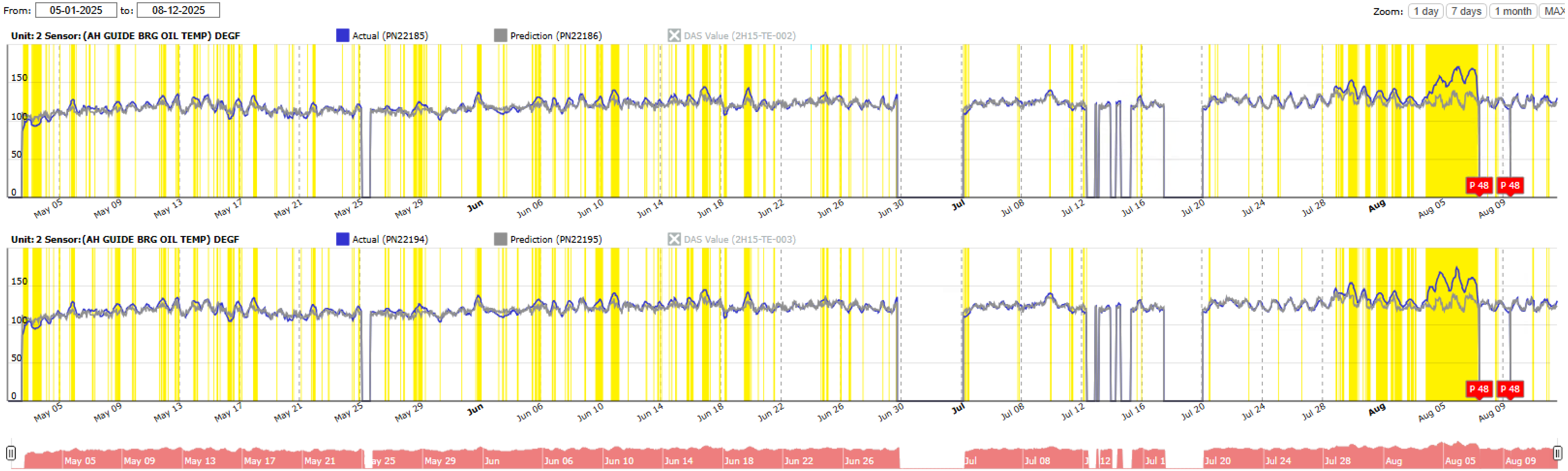
Guide Bearing Oil Pump Case Study

- AH Support Bearing Oil Temperature increased by around 20 DEG F
- Plant was alerted and asked to see if cooler fan was running or if the cooler is valved in.
- "B" guide bearing oil pump indicated running on the DCS but it was not running locally. Started A pump and oil temperature dropped.
- "B" pump had been turned on but tripped off shortly after and did not give an alarm.

Guide Bearing Oil Pump Case Study



Guide Bearing Oil Pump Case Study



CURTISS-WRIGHT

Other Catches

- Hotter than normal bearing temperature where the solution is to backflush the cooling water and filter
- Small pattern deviations on problems before they become big problems
- Flatlined instruments
- Unreliable sensors

M&D Problems

- Communication
- Plant Operations are unknown
- Lack of follow up and follow through
- Not enough time

Questions?

For more information contact:

Austin Crook, Curtiss-Wright

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ARPA-E and Commercial Partner:

US NRC Public Meeting

Centralized Monitoring and Actionable Diagnostics for Nuclear Plant Equipment Health

May 19, 2026

Presented By: ***Giancarlo Lenci, Metroscope Inc.***

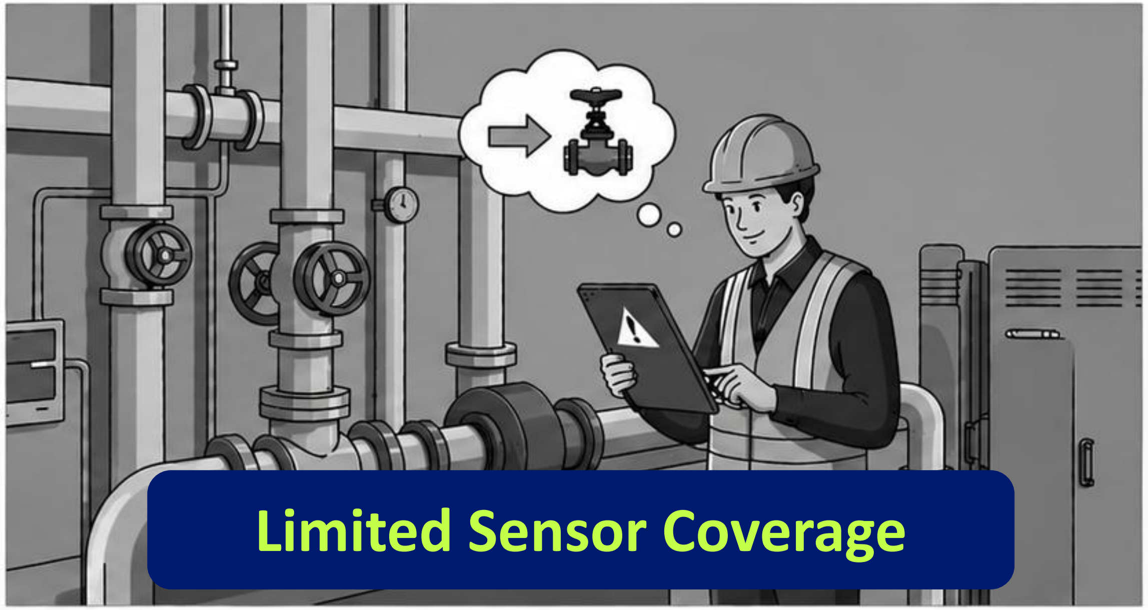
CBM Driver Challenge: **Given a Warning, Identify the Action**

Plant Workflow

- Sensor data
- Alert
- Triage
- Cause Confirmation
- Risk Weighting
- Work order
- Field action

Common Industry Pain Points

Uncertainty in Troubleshooting



Limited Sensor Coverage

Limited Risk-Based Prioritization Tools

Alert Noise

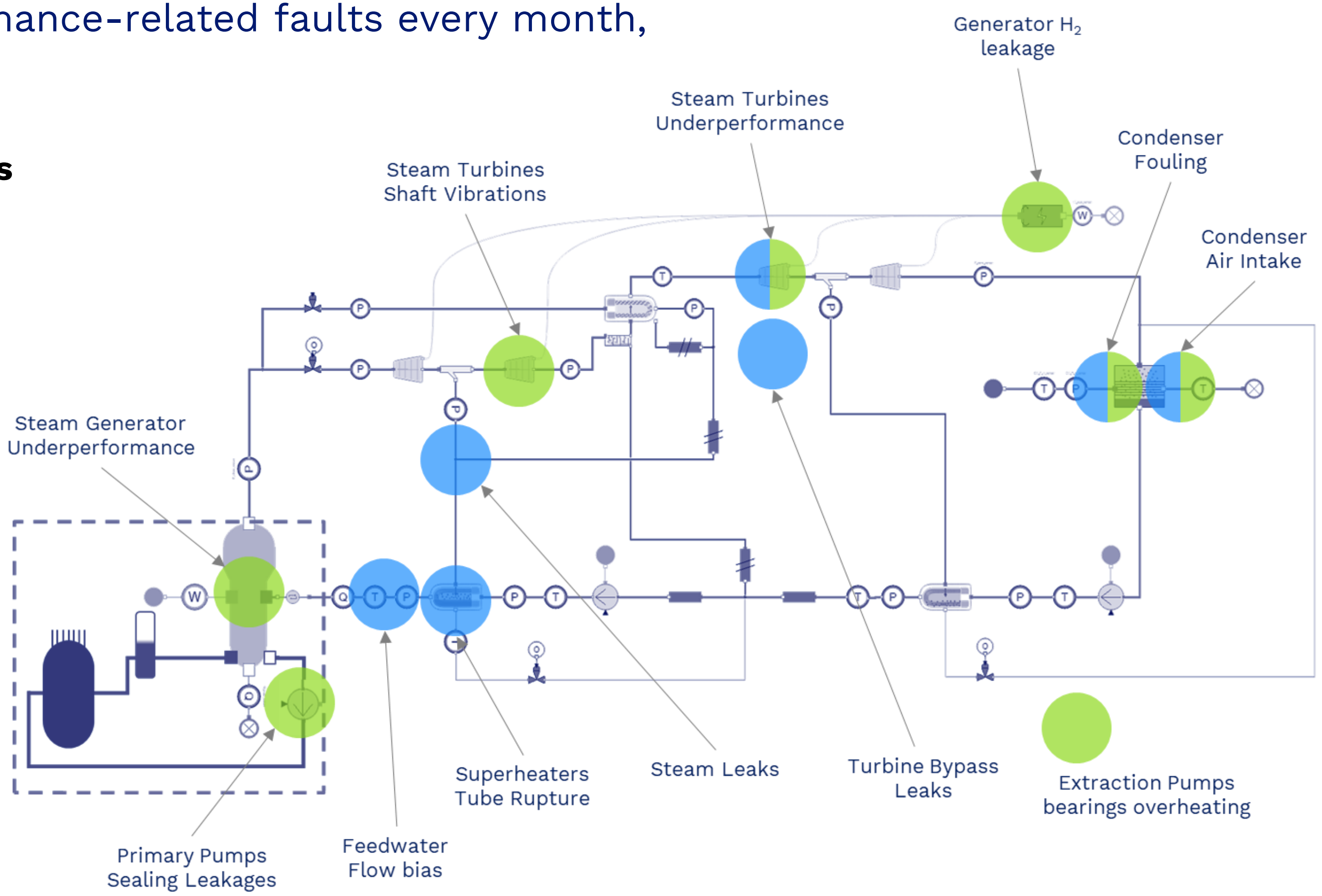
Reliability and Performance

Plants experience on average 5 performance-related faults every month, leading to an average 5+ MWe loss

Metroscope M&D technology identifies faults for condition-based maintenance and plant performance

Main Reliability Threats

Main Performance Issues



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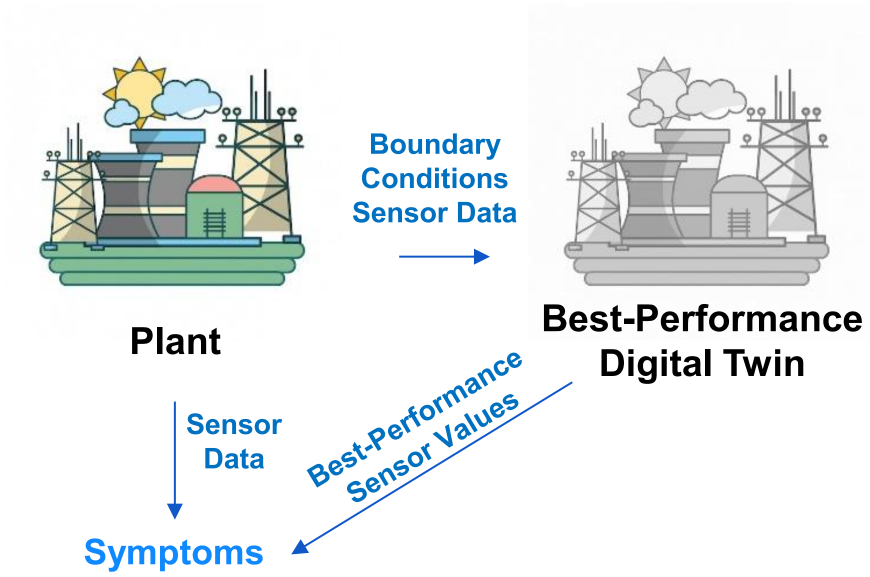
Simultaneous Holistic Diagnostics

Level 1:
Symptom/Anomaly Tracker

Identifies when sensor data are outside of healthy operation.

Does not diagnose faults.

Commonly encountered in the industry with statistical or physical models.



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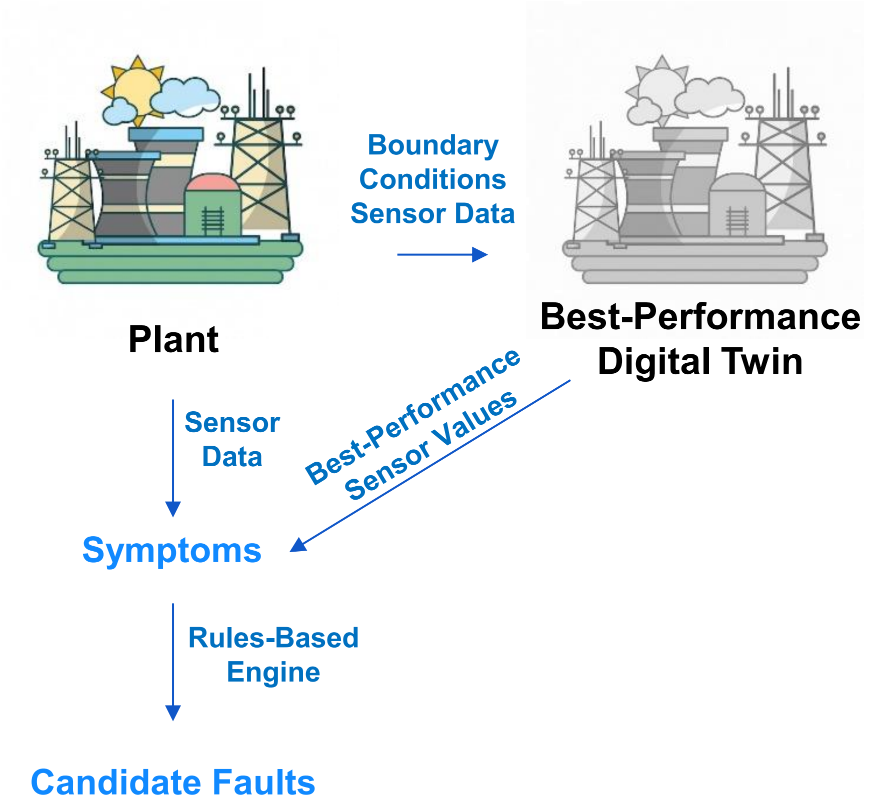
Simultaneous Holistic Diagnostics

Level 2:
Rules-Based Engine

Uses rules, often binary and based on thresholds, to determine faults from symptoms.

Typically, does not diagnose simultaneous faults or take advantage of weak signals from all the modeled sensors.

Available based on EPRI 3002020803.



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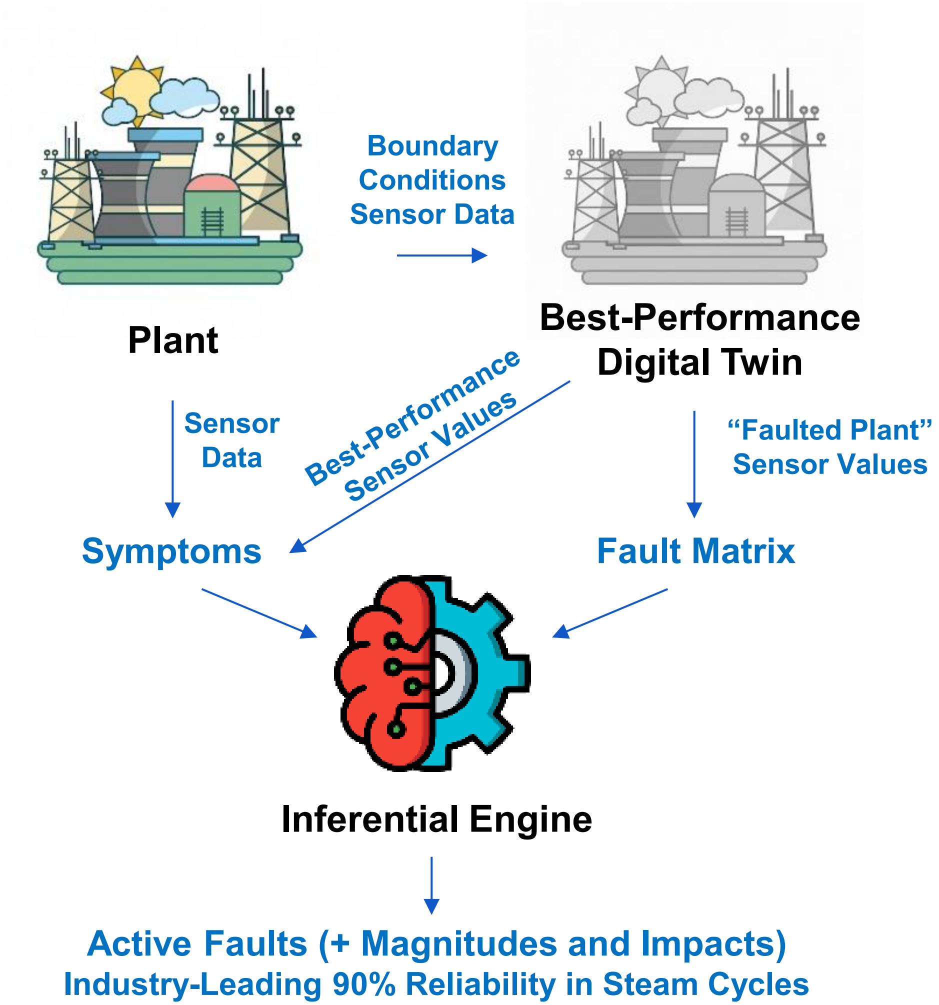
Simultaneous Holistic Diagnostics

Level 3: Simultaneous Holistic Diagnostics

Diagnoses simultaneous faults using full-system weak signals.

Achieves high reliability and precise magnitudes and impacts.

Unique to Metroscope technology, deployed at 80+ plants worldwide.



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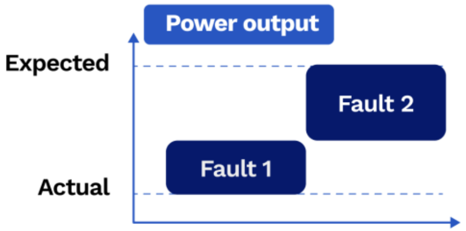
SOLUTION: ONE MULTI-MODEL PLATFORM

Performance Diagnostics



- Steam cycle loss identification
- Physics-based model

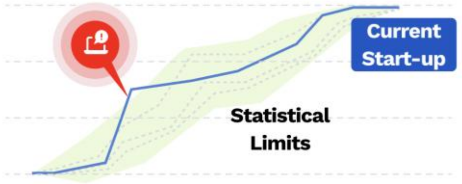
Capacity Forecast

- Weather-based power output forecast (ambient derate)
- Uncertainty quantification

Anomaly Detection

- Early detection of equipment issues
- Fleet of Machine Learning Models

Transients Monitoring



- Detection of anomalies in transient phases (start-ups and shutdowns)

Operations

Live monitoring

Real-time loss detection

Maintenance decisions

Corporate

Fleet-level views

Aggregated insights

Programmatic maintenance

Data Scientists

In-app Model building & Python lab

Model design, training and supervision

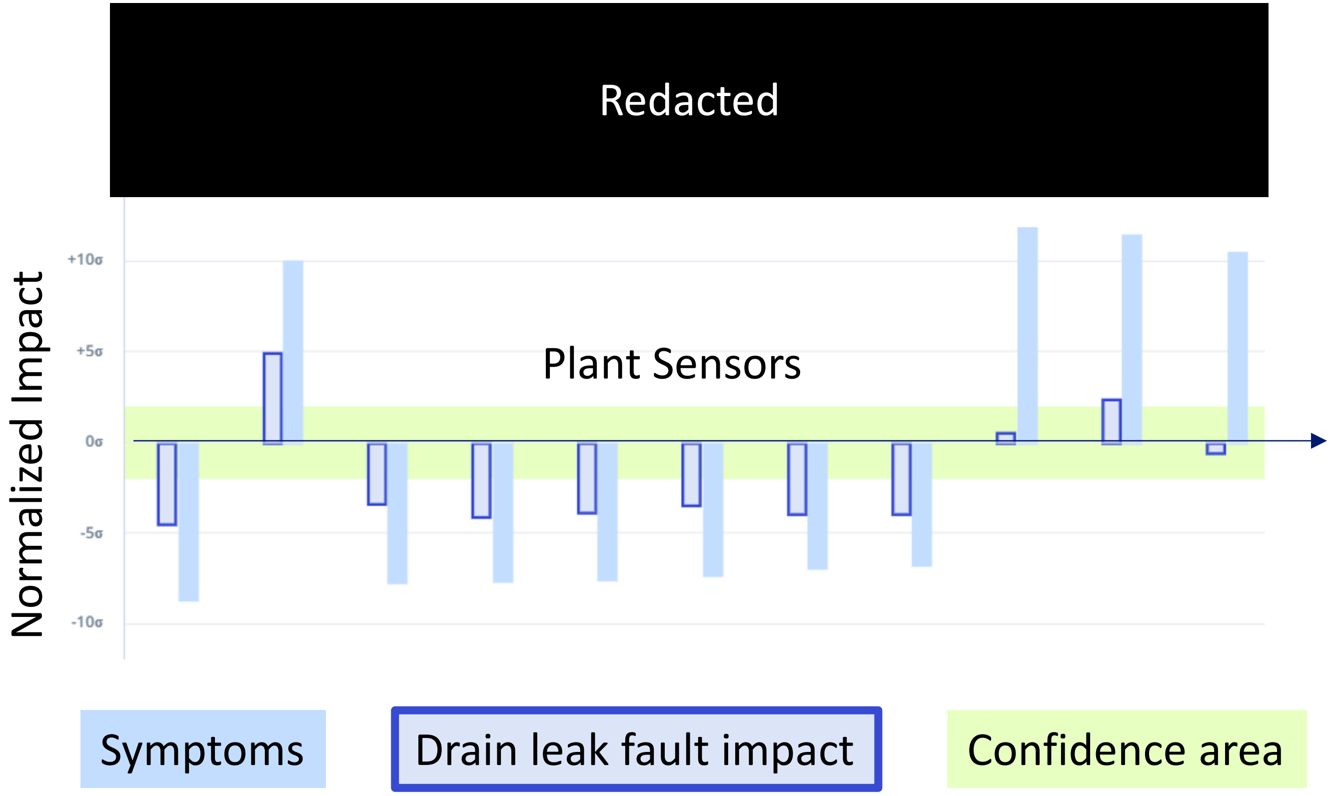
Custom data analyses

Passing Steam Turbine Drain Valve: Quasi Steady Detection is Not Enough

- Steam turbine drain valve is opened temporarily during normal steam turbine startup
- Quasi-steady diagnostics detected an unexpected loss of 6MW through deviations in pressure and temperature around the high-pressure steam turbine after startup
- The loss was attributed to a drain leak that was quantified but not pinpointed

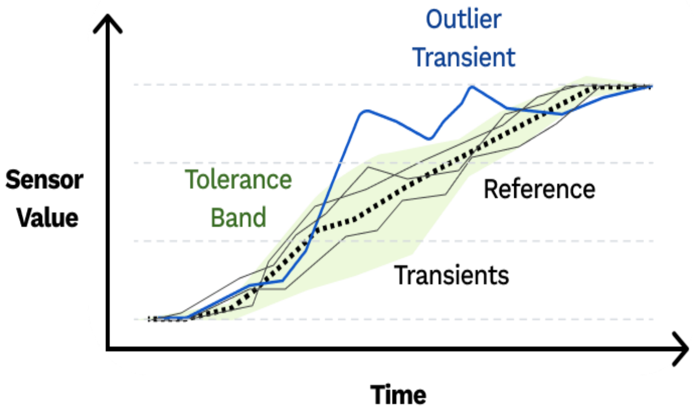
Questions:

- Which valve?
- What sequence caused the issue?

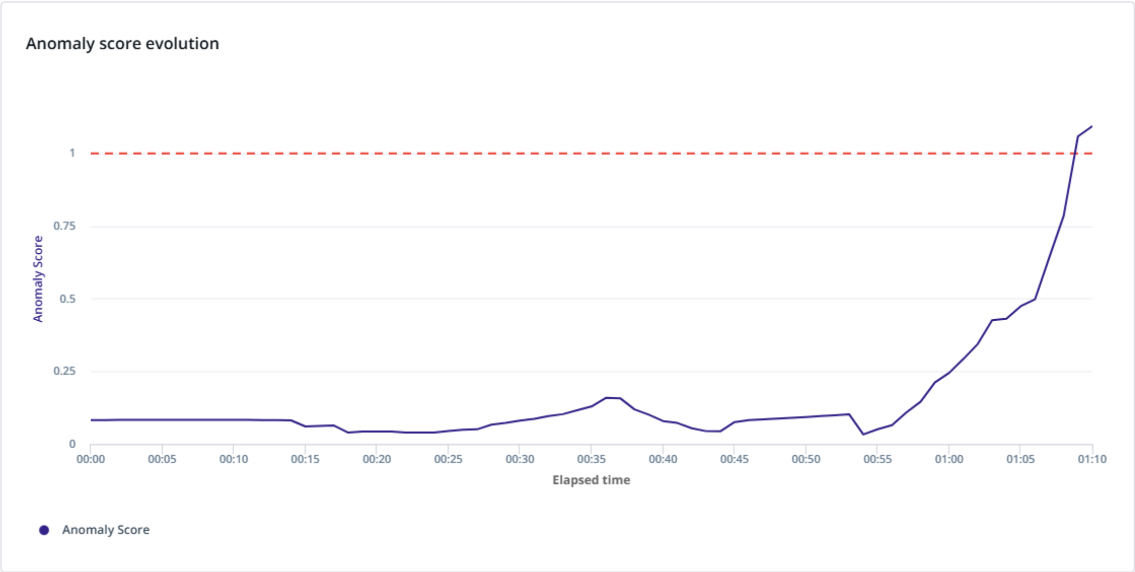


Addressing with Transient Model

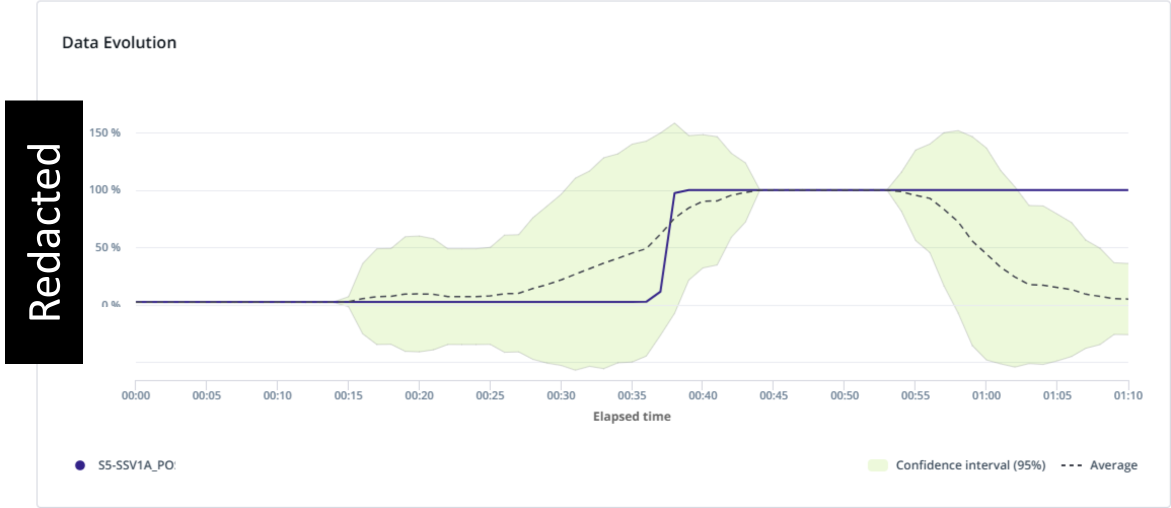
- A model was monitoring the drain valve positions during start-ups
- Alerts were generated at the same times as steady Diagnostics
- The tool identified three specific drain valves that remained open after start-up
- Operators used the tools to rapidly identify the problem and close the valve, recovering 6 MWe



Transient Module Overview



Evolution of the anomaly score



Evolution of the drain valve opening in comparison to the reference trend

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ARPA-E Project

Increase Output Power

Deliver high-value nuclear plant uprates overcoming limitations of data validation and reconciliation (DVR) solutions.

Reduce Operating Costs

Keep nuclear plants competitive by reducing operations and maintenance costs in safety-related auxiliary systems.

Figure from: ANS Nuclear Newswire

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Critical Needs Addressed

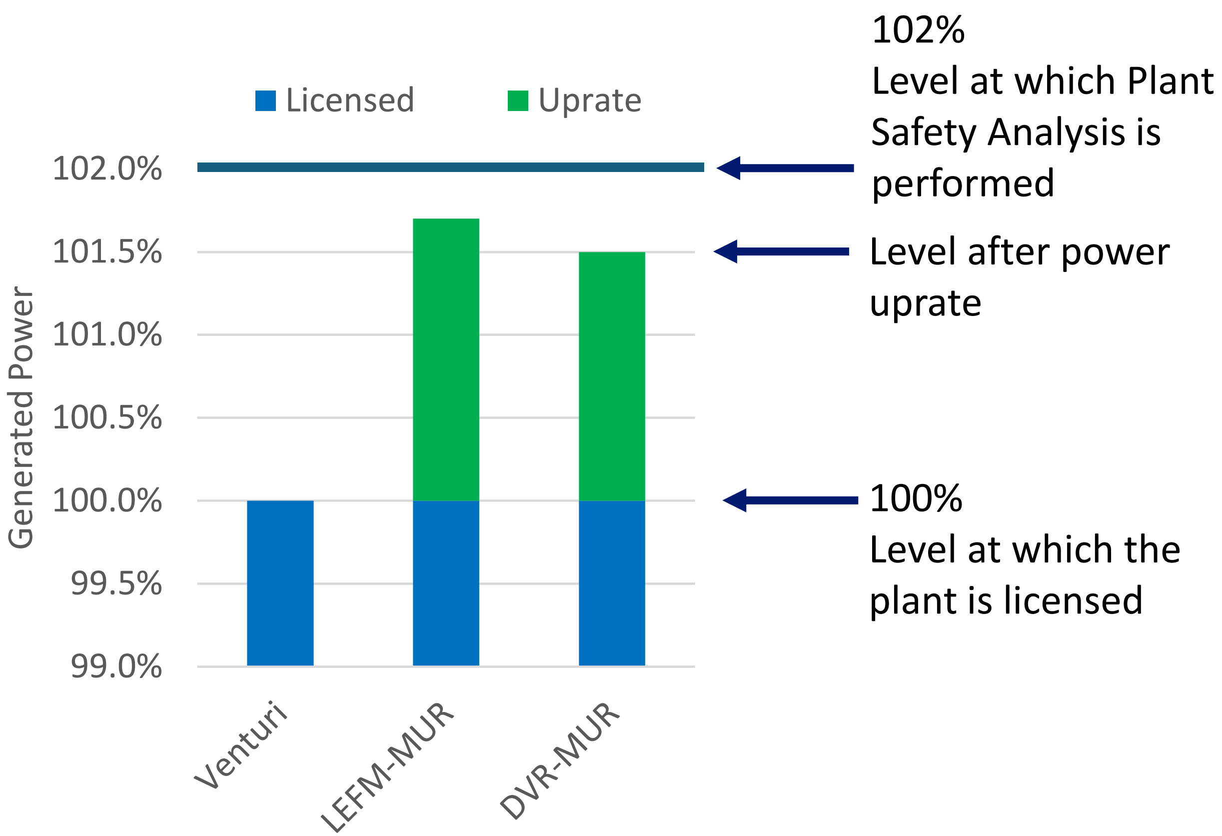
Increase Output Power

Deliver high-value nuclear plant uprates overcoming limitations of data validation and reconciliation (DVR) solutions.

Reduce Operating Costs

Keep nuclear plants competitive by reducing operations and maintenance costs in safety-related auxiliary systems.

DVR Uprates, approved by NRC in 2024, can provide extra power at low cost



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Critical Needs Addressed

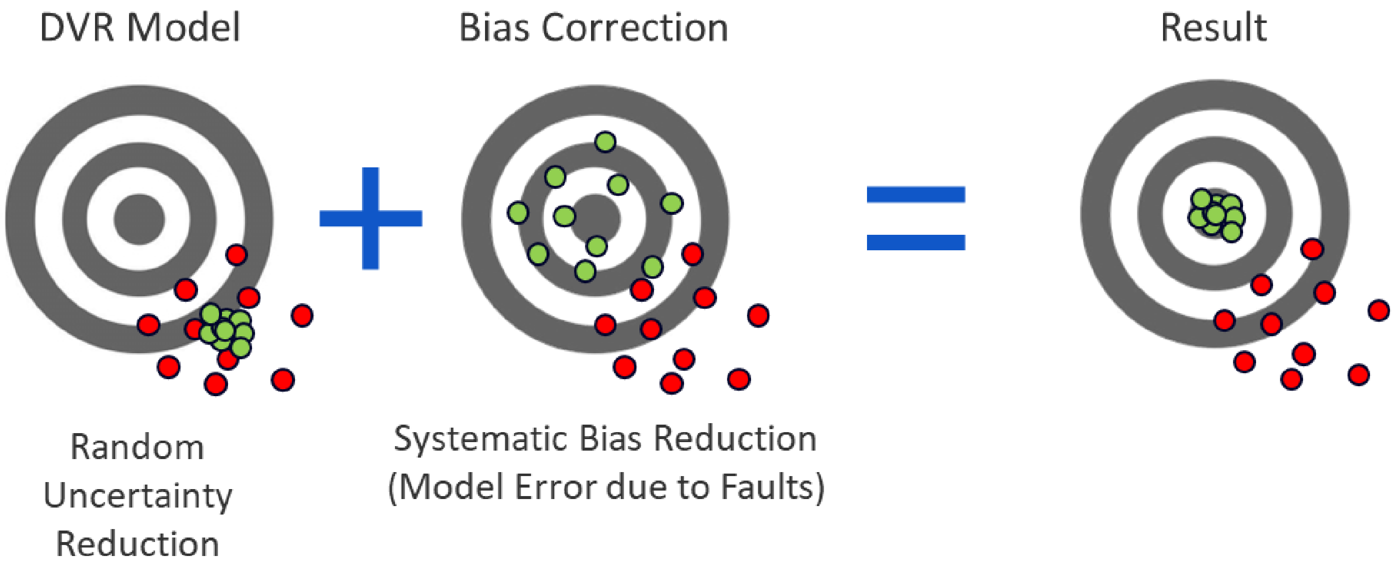
Increase Output Power

Deliver high-value nuclear plant uprates overcoming limitations of data validation and reconciliation (DVR) solutions.

Reduce Operating Costs

Keep nuclear plants competitive by reducing operations and maintenance costs in safety-related auxiliary systems.

Demonstrating Fault-Tolerant DVR at a US BWR in 2026



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Critical Needs Addressed

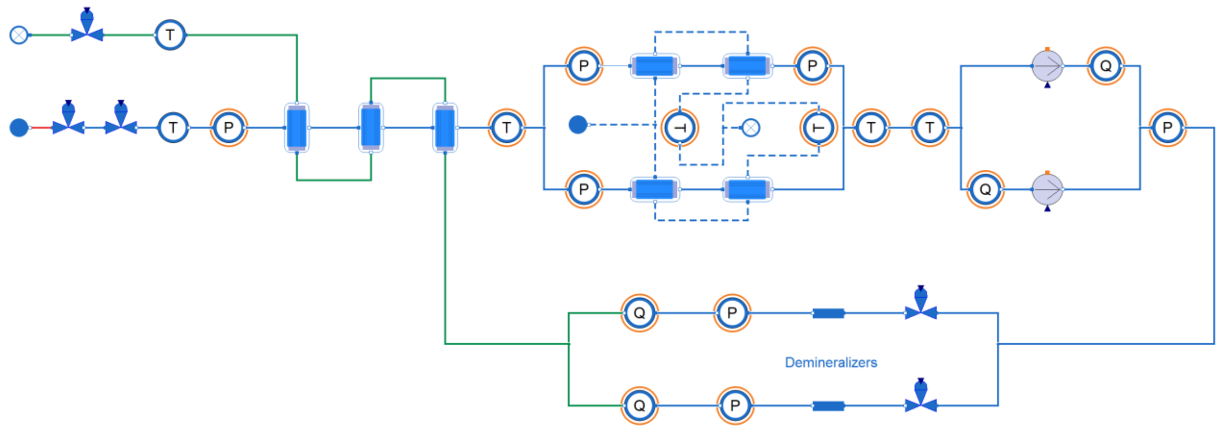
Increase Output Power

Deliver high-value nuclear plant uprates overcoming limitations of data validation and reconciliation (DVR) solutions.

Reduce Operating Costs

Keep nuclear plants competitive by reducing operations and maintenance costs in safety-related auxiliary systems.

✓ Demonstrated Auxiliary System Holistic Diagnostics at a US BWR



RWCU Sensor Diagram (Anonymized)

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The Next Gap: Diagnosis ≠ Decision

Today:

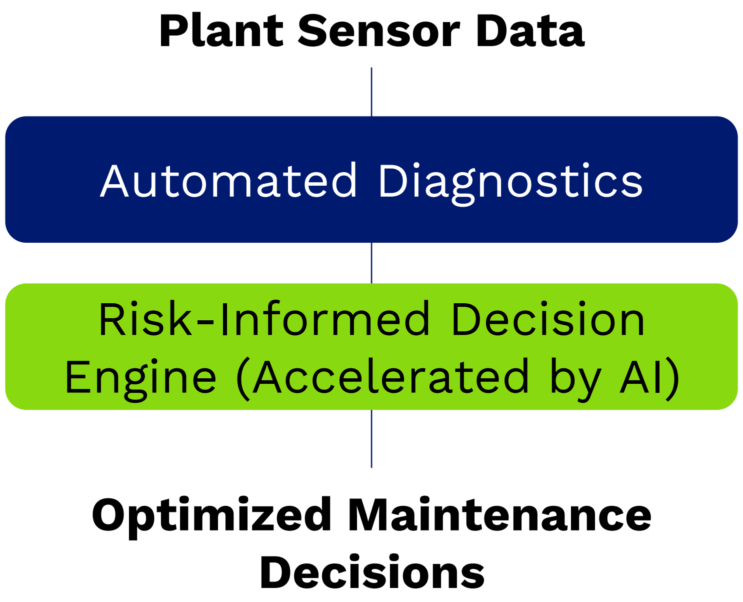
Manual triage after the alert

- Diagnostic alert arrives
- Engineer judges severity from experience
- Risk weighting is mostly qualitative
- Work is scheduled by calendar availability
- Decision trail is hard to audit

Proposed Path:

Risk-informed decision layer

- Convert symptoms into failure-mode hypotheses
- Quantify confidence, consequence, and false-positive cost
- Recommend what to do, when, and why
- Trace evidence from sensor reading to work order
- Give leadership a plain-English decision view



Vision: a Diagnostics-to-Decision Workflow

Sensors & Symptoms → Diagnostic Engine → Failure-Mode Hypothesis → QRA / Risk Model → Risk-Ranked Action

For maintenance engineers

An explainable ranked list of next actions by diagnostic confidence × consequence. Less triage, more fixing.

For plant leadership

A defensible link from condition monitoring spend to enterprise risk reduction. KPIs that finance can read without translation.

For Risk Analysts (e.g., safety or generation risk in nuclear plants)

An auditable evidence package that lets demonstrated diagnostics capability update risk inputs — reducing unwarranted conservatism.