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Proceedings of the Workshop on Condition Monitoring and Structural Health Management for Nuclear Power Plants

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EXECUTIVE SUMMARY

The Office of Nuclear Regulatory Research at the U.S. Nuclear Regulatory Commission (NRC) has an ongoing research effort to assess the regulatory viability of digital twins for nuclear power plants. As part of this activity, the NRC held a virtual workshop on condition monitoring and structural health management for nuclear power plants. The workshop was hosted by Idaho National Laboratory and was held on November 28–29, 2023.

The 2-day workshop was composed of four technical and panel sessions with 20 presenters from a wide range of national and international organizations, including national laboratories, universities, government agencies, nuclear vendors, and advanced reactor developers. Technical presentations and panel sessions covered a broad technical scope including industry application of DT-enabling technologies for condition monitoring and predictive maintenance, diagnostic and prognostic tools for condition monitoring and structural health management, inservice testing and inspection, reliability integrity management considerations for advanced reactors, and emerging technologies for condition monitoring and structural health management.

The workshop had three main purposes: (1) to gain a better understanding of industry activities and perspectives with respect to the application digital twin enabling technologies and prognostic tools for condition monitoring of nuclear power plant components, (2) facilitate the exchange of knowledge and research activities on topics such as on-line monitoring techniques, predictive maintenance, structural health monitoring, diagnostic and prognostic health management, and (3) become aware of these enabling technologies and how these technologies could be used for life cycle management of plant components.

In the opening session, on Tuesday, November 28, Ms. Michele Sampson, Director of Division of Engineering, NRC Office of Nuclear Regulatory Research, made the introductory remarks. Technical sessions followed by panel discussion on specific topics took place on Tuesday and Wednesday. Some major takeaways from the workshop are as follows:

- There is significant interest in DT technology applications for condition monitoring of active and passive systems, structures, and components in currently operating and future nuclear power plants.
- Each DT enabling technology has challenges and considerations, such as qualification requirements for advanced sensors and instrumentation, verification and validation and uncertainty quantification for advanced modeling and simulation, explainability and trustworthiness for AI/ML; thus, early engagement with regulators is encouraged.
- Application of advanced technologies for condition monitoring is expected to overlap with regulatory aspects in the near future, such as meeting in-service inspection and in-service testing requirements and safety assessment.

- Increased collaboration and coordination among stakeholders would enable information sharing, developing common solutions to shared challenges, and developing guidance and standards for application of DT technologies in condition monitoring.
- DT technology could be a novel source of trusted information on performance monitoring and prediction, process optimization, and regulation. The technology serves as a tool for general integrated data sharing among vendors, licensees, regulators, and the public. Such an information source could both build public trust and improve regulatory efficiency.
- Workshop participants identified several topics related to DT technology and safety that would be of interest for collaborative research:
    - Develop advanced sensors and an approach for optimizing instrumentation for condition monitoring using DTs
    - Develop diagnostics and prognostics models capable of running in real time as part of condition monitoring DTs
    - Develop tools to characterize the interface between condition monitoring DTs and human operators and end users
    - Establish a community of practice with a specific focus on developing guidelines for addressing regulatory aspects of condition monitoring DTs.

All presentation slides from this workshop are available in the NRC's Agencywide Documents Access and Management System, under Accession No. ML24008A291.

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ACRONYMS

AI	Artificial intelligence
ANL	Argonne National Laboratory
ASME	American Society of Mechanical Engineers
AWS	Amazon Web Services
BPV	Boiler and Pressure Vessel
DT	Digital twin
EPRI	Electric Power Research Institute
JSME	Japanese Society of Mechanical Engineers
LWR	Light-water reactor
LWRS	Light water reactor sustainability
ML	Machine learning
NDE	Nondestructive evaluation
O&M	Operations and Maintenance
PRA	Probabilistic risk assessment
RCP	Reactor Coolant Pump
RCS	Reactor Coolant System
RIM	Reliability Integrity Management
ROI	Return on investment
SFR	Sodium-cooled fast reactors
SG	Steam Generator
SHM	Structural Health Monitoring
VAM	Vibro-acoustic modulation

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Workshop on Condition Monitoring and Structural Health Management for Nuclear Power Plants

1. DAY 1 PRESENTATIONS

1.1 Session 1: Applications of Digital Twin Enabling Technologies for Condition Monitoring & Predictive Maintenance

This session set the stage for the workshop with presentations and discussions on digital twins (DTs) for online monitoring in nuclear power plants. The speakers represented advanced reactor developers, technology vendors, national laboratory researchers, and regulators. The key observations from this session are as follows:

- Ongoing efforts include developing proof-of-concept technology for a centralized operations-and-maintenance (O&M) strategy with plant support center for prioritizing asset monitoring
- Criticality assessment could determine priority of asset monitoring using DT
- Real-time capability of a condition-monitoring DT is highly significant during startup, shutdown, and transients
- Predictive capabilities in DT could recommend timely corrective actions
- Current NRC efforts are focused on preparing to make a reasonable assurance finding on the use of DT technologies at nuclear power plants.

1.1.1 Digital Twin Enabling Technology for Online Monitoring in Advanced Reactors – Ian Davis, Plant Monitoring & Diagnostics Engineering Manager, X-Energy

This presentation covered X-energy's Maintenance Strategy at a high level for the Xe-100 plant. The Xe-100 Maintenance Strategy includes a balanced and optimized combination of predictive, condition-based, preventive, and reactive maintenance activities. In addition, this presentation discussed X-energy's plans for handling large volumes of process data generated at Xe-100 plants and how modern approaches to big data enable a more efficient maintenance workforce.

1.1.2 Digital Twins as Applied to New Reactor Designs Focusing on Predictive Maintenance – Brian Golchert, Principal Engineer, Westinghouse

This presentation focused on DTs as applied to new reactor designs focusing on predictive maintenance. For existing plants, DTs are "back fitted" meaning that one builds the models, the reduced order model, and then ties them to existing operational data. For new designs, operational data (beyond proof-of-concept experiments) does not exist. A "blue sky" approach was presented to leverage the capabilities of simulation and improve the design process for new designs as well as using existing tools for predictive maintenance.

1.1.3 Condition Monitoring at Nuclear Plants - Current Technology and 2030 Outlook – Eric Helm, General Manager, Metroscope

This topic presented a summary level view of current monitoring and diagnostics objectives and tools which were then contrasted with new objectives for small modular reactors (SMRs) and advanced reactors. The conclusion highlighted the need for a shifted focus on diagnostics, modeling, and inference technology to meet new industry demands.

1.1.4 Online Monitoring Using Cloud-Based Applications – Cody Walker, Research Scientist, Idaho National Laboratory

This presentation described comparing cost and capabilities of cloud-based resources to other currently available resources to predict the condition of a safety relief valve as well as the architecture to connect a nuclear power plant to cloud computing resources, such as Azure and Amazon Web Services (AWS), and its predictive capabilities.

1.1.5 NRC Regulatory Aspects for Nuclear Digital Twins – Thomas G. Scarbrough, Senior Mechanical Engineer, U.S. NRC

This presentation focused on the regulatory role of the NRC staff in reviewing and approving any DT/ML/AI approaches used to meet the NRC regulations for the safe operation of nuclear power plants. Notably, NRC regulatory staff efforts are focused on preparing to make a reasonable assurance finding on the use of such technologies at nuclear power plants.

1.2 Session 2: Diagnostic and Prognostic Tools for Condition Monitoring and Structural Health Management

Overview: This session presented ongoing efforts at national laboratories, DT developers, and monitoring and diagnostics centers in diagnostics and prognostics capabilities for currently operating and future reactors. The key observations from this session are as follows:

- Current efforts are focused on demonstrating how condition monitoring can improve reliability, prioritize maintenance issues, and enhance operational efficiency
- Some industry efforts are focused on cost-benefit analysis of using DT technologies for condition monitoring
- Virtual sensors technology based on real-time integration of data-based models and physics-based models could enable diagnostics with optimized sensor infrastructure
- Ongoing research and development efforts sponsored by the Department of Energy are focused on DT development, machine learning (ML) models for non-safety systems, and visualization capabilities at currently operating fleet.

1.2.1 Successful Application of Condition Monitoring Technologies into Nuclear Power Plants – Greg Alder, Director Plant Optimization, Curtiss Wright

This presentation overviewed the commercial application of condition monitoring technologies for nuclear power plants including thermal performance improvement, equipment reliability monitoring, diagnosing plant issues, and degradation.

1.2.2 Digital Twins for Prognostics and Health Management in Nuclear – Naresh Iyer, Principal Machine Learning Scientist, GE Research

This talk summarized key findings of a recent ARPA-E program (GEMINA) targeting the application of AI-assured preventive maintenance DTs (PMDTs) toward reducing O&M costs for SMRs. The presenter showed a cost-benefit framework and analysis to help prioritize components when developing PMDTs and estimate a return on investment (ROI) from developing and applying PMDT technologies. The same framework is used to further demonstrate how employing AI-assurance techniques with help further reduce O&M costs over and above the baseline approach of migrating schedule or preventive maintenance to AI-driven predictive analytics.

1.2.3 Predictive Tools for Maintenance Optimization: Heat Exchanger Tube Failure Case – Richard Vilim, Nuclear Science and Engineering Division Department Manager, Plant Analysis, Control and Sensors, Argonne National Laboratory

This presentation described a condition monitoring framework for optimizing maintenance scheduling for nuclear plant systems and how a DT is used to predict the health for components and structures. Methods and validation results for diagnosing incipient signs of component failure and equipment degradation and work on the ongoing application to light-water-reactor feedwater-tube failure was described. Work on the ongoing application to light-water-reactor feedwater-tube failure was also described.

1.2.4 AI/ML Research to Support Plant Modernization – Craig Primer, LWRS Pathway Lead, Idaho National Laboratory

This presentation provided an overview of some research and development efforts currently underway within the Department of Energy's Light Water Reactor Sustainability (LWRS) program and presented focus areas that included data architecture and analytics as well as using ML for material management, equipment monitoring, and anomaly detection; natural language processing and computer vision for O&M; and addressing explainability of AI/ML.

1.2.5 Nearly Autonomous Management and Control in Advanced Reactors – Abhinav Gupta, Center for Nuclear Energy Facilities and Structures, NC State University, Director

This presentation provided a brief overview of recent research conducted at the Center for Nuclear Energy Facilities and Structures for developing AI/ML-based solutions for condition assessment of piping systems and described an ongoing Electric Power Research Institute (EPRI)-sponsored project on experimental validation of new developments including a demonstration of a piping system DT.

2. DAY 2 PRESENTATIONS

2.1 Session 3: Inservice Inspection and Reliability Integrity Management Considerations for Advanced Reactors

Overview: This session focused on presenting an overview of the American Society of Mechanical Engineers (ASME), BPV Code, Section XI, Division 2, Reliability Integrity Management (RIM) for life cycle management of plant components. The presenters discussed challenges and issues with implementing RIM for advanced reactors and explored the nondestructive examination and monitoring needs for inservice inspection of advanced reactors. The key observations from this session are as follows:

- Limited accessibility to liquid-sodium retaining components in sodium-cooled fast reactors (SFR) present unique challenges in meeting inservice inspection requirements
- Ongoing cooperation between ASME and Japanese Society of Mechanical Engineers (JSME) is focused on developing fitness-for-service code for SFRs
- Identifying material degradation mechanisms for specific materials and operating environments is the key starting point for implementing a RIM approach
- A model-based approach using probabilistic risk assessment (PRA) models could be developed for assigning system reliability targets through PRA models.

2.1.1 Development of Fitness-For-Service Code for Sodium-Cooled Fast Reactors – Shigeru Takaya, Principal Researcher, Japan Atomic Energy Agency

This presentation focused on developing a fitness-for-service code for SFRs. Note that SFRs are one of Generation IV nuclear energy systems and are now being developed throughout the world, including in the United States and Japan. Developing inservice inspection requirements suitable to SFRs is crucial to maintain nuclear power plant safety and suppress operation costs. SFRs have several desirable features such as excellent compatibility between purity-controlled sodium and structural materials while traditional volumetric and surface tests are not as easily performed as in light-water reactors due to the limited accessibility to liquid-sodium retaining components. Recently, the fitness-for-service code for SFRs is being developed through the cooperation between ASME and JSME. An overview of deliverables and current activity was also presented.

2.1.2 Introduction to ASME Section XI, Division 2 Reliability and Integrity Management (RIM) – Tom Roberts, Principal Officer, POMO18 Consult LLC

This presentation provided an overview of RIM, what is RIM and why it is needed for advanced reactors, a detailed description of the RIM process, specific monitoring and inspection challenges associated with advanced reactors, and how RIM could potentially address some of those challenges.

2.1.3 Reliability and Integrity Management Program – Challenges and Opportunities – Chris Wax, Principal Technical Leader, EPRI

This presentation’s goal was to expand upon the discussion of RIM programs and identify areas where industry guidance can supplement the ASME BPV Code to provide avenues for more effective and consistent program framework. The areas where challenges or gaps are identified can be clarified to support a reactor designer’s understanding of how their design decisions can impact RIM programs (and vice versa), support a future reactor owner’s ability to effectively implement a RIM program to reduce materials degradation impacts, as well as provide clarity and consistency for future regulator reviews of RIM programs. This presentation did not identify all the gaps (nor did it have complete answers for those that have been identified), but it was seen as a starting point for a coordinated industry effort to effectively and efficiently implement the RIM program.

2.1.4 Assessment of Component Level and Plant Level Reliability Target Allocation to Support RIM – Diego Mandelli, R&D Scientist, Idaho National Laboratory

This presentation focused on the RIM program as applied to advanced reactors. It showed a few effective methods to allocate reliability targets at the plant, system, and asset level by relying on plant PRA models as well as methods to demonstrate that the implemented RIM strategies (e.g., type and frequency of surveillance intervals) confidently assure the planned reliability targets.

2.1.5 Nondestructive Evaluation (NDE) and Structural Health Monitoring (SHM) Needs for Emerging Reactor Technologies – Pradeep Ramuhalli, Distinguished R&D Staff Member & Ryan Meyer, Research Engineer, Oak Ridge National Laboratory

This presentation overviewed the technological advances around a nondestructive evaluation (NDE) and structural health monitoring for emerging reactor technologies. These technological advances have the potential to address some aspects of the RIM process and qualification requirements for these technologies.

2.2 Session 4: Emerging Technologies for Condition Monitoring & Structural Health Management

Overview: This session highlighted use cases of some emerging technologies, such as advanced sensors, data analytics, ML, and AI, as part of DTs for condition monitoring in current and future reactors. The discussion focused on opportunities, challenges, gaps, and regulatory considerations of using DT technologies for condition monitoring. The key observations from this session are as follows:

- Condition-monitoring DT use cases include a wide range of advanced sensors and instrumentations such as vibro-acoustics, piezoelectric accelerometers, vibration integrity monitoring, self-powered neutron detectors, eddy-current flow monitors, and embedded wireless sensors
- Several emerging sensor and instrumentation technologies, especially for advanced reactors, such as SFRs, are currently in development and testing stages
- Early regulatory engagement would enable faster adoption of condition-monitoring DT technologies.

2.2.1 AI-ML Application for Structural Health Monitoring in Nuclear – Vivek Agarwal, Distinguished Staff Scientist, Idaho National Laboratory

This presentation discussed applying AL and ML to structural health monitoring in nuclear power plants. AI and ML techniques are applied to passive assets (like concrete, secondary piping system, and others) and active assets (like pumps, motors, generators, and others) for aging management and health monitoring, respectively in nuclear power plants. In this effort, a physics-informed ML approach was developed for health monitoring of concrete structures containing reactive aggregates using the vibro-acoustic modulation data. The developed approach was used to detect, localize, and estimate the extent of degradation in concrete structures due to alkali-silica reaction. The project outcomes were demonstrated on concrete specimens with different reactive aggregates, reinforcements, and slab sizes.

Overall, the developed approach is generic and extendable to other degradation modes in concrete. In addition to structural health monitoring, ongoing research on risk-informed predictive maintenance strategy enables nuclear power plants to transition from labor-intensive, cost-prohibitive preventive-maintenance strategy to a scalable predictive maintenance strategy. Researchers demonstrated integrating advanced data analytics, natural language processing, ML, AI, physics-informed modeling, risk models, and visualization techniques in this research. The developed approach is scalable across different plant assets and across the fleet. In collaboration with the nuclear industry, the research developed and demonstrated three aspects of AI technologies: performance, explainability, and trustworthiness. This effort provided advancements in (1) application of AI/ML in nuclear power plants for predictive maintenance, (2) user-centric visualization interface, and (3) quantitative and qualitative measures to achieve explainability and trustworthiness of AI/ML technologies.

2.2.2 Sensor to Support Online Monitoring in Advanced Reactors – Jorge Carvajal, Fellow Engineer, Westinghouse

This presentation focused on the potential application of advanced sensors for advanced reactor component condition monitoring. Some of the sensor technologies discussed were digital metal impact monitoring for loose part monitoring within the Reactor Coolant System (RCS), vibration monitoring for Reactor Coolant Pump (RCP) and control rod drive mechanism, eddy-current Steam Generator (SG) tube monitoring, and ex-core and in-core neutron flux detectors.

2.2.3 Online Monitoring to Enable the Long-term Health of Molten Salt Reactors – William Doniger, Postdoctoral Appointee - Chemical & Fuel Cycle Technologies Division, Argonne National Laboratory

This presentation discussed Argonne National Laboratory's work on online monitoring to enable the long-term health of molten-salt reactors. Key monitoring capabilities were discussed including salt chemistry, corrosion, particulate matter, and nuclear material accountancy. In-line electrochemical and optical monitoring approaches are key to achieving at or near real-time assessment of structural health. At-line salt sampling technologies facilitate more traditional analytical chemistry approaches while mitigating physical or radiological hazards to the operator. Examples of deployment in laboratory and industrial applications were also discussed.

2.2.4 Progress Toward Practical Sensor Solutions for Online Monitoring of Advanced Reactors – Luke Breon, Senior Technical Leader, EPRI

This presentation outlined the state of nondestructive evaluation sensors for high-temperature applications as well as work underway at EPRI in identifying and assessing the capabilities of such sensors for emerging reactor designs. Recent, relevant EPRI publications were also discussed. This presentation covered key results of a recent sensors workshop held jointly by EPRI, INL, and MIT and discussed a planned effort to assemble a platform to facilitate holistic industry collaboration relevant to sensors for high-temperature and high-radiation environments to help build, vet, and maintain a roadmap for sensor developments.

2.2.5 Radiation-Endurance Advanced Sensor Systems for Online Monitoring in Nuclear Power Plants – Dan Xiang, Vice President/Founder, X-Wave Innovations

Ultrasonic sensors have a long and successful history for sensing and characterizing materials, including measuring various physical parameters for process control, as well as detecting and characterizing the degradation and damage in materials and structures. Although there are numerous types of ultrasonic sensors capable of measuring various properties of interest, only a few ultrasonic sensors can survive the high temperature and high irradiation in nuclear reactor environments. It remains challenging to develop ultrasonic sensors to perform online monitoring in high-radiation and high-temperature environments.

This presentation reported on the development of a high-temperature, radiation-endurance ultrasonic transducer and its applications in sensing physical parameters and structural condition monitoring. This sensor consists of high-temperature, radiation-endurance, piezoelectric elements and designed structures made of inorganic materials. It has been tested under elevated temperatures up to 800˚C as well as unclear irradiation (gamma and neutron) for an extended period with highly stable and repeatable output signals. This ultrasonic transducer was further adapted into advanced sensor systems and incorporated with specifically designed multi-channel data acquisition hardware and application software along with AI and ML toolbox to extend its applications for online monitoring of structural degradation and damage in nuclear power plants.

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Appendix B
Presentation Slides

Clean • Safe • Secure • Affordable

Digital Twin Enabling Technologies for Online Monitoring in Advanced Reactors

Ian Davis, Plant M&D Engineering Manager

November 28, 2023

X-energy at a Glance

Founded in 2009

13 years of investment and development

Rockville, MD Headquarters

Rooted in the nuclear community with proximity to the DOE and Nuclear Regulatory Commission (“NRC”)

50+ Years of R&D

Built upon years of R&D in high temperature gas reactors

~400+ Employees

Leading Gen IV nuclear development and licensing team

$1.2bn Federal Funding

Selected for DOE's Advanced Reactor Demonstration Program

~$610mm Investment

Capital invested to date with $120 million of committed capital

Reactor: Xe-100

We’re focused on Gen-IV High-Temperature Gas-cooled Reactors (HTGR) as the technology of choice, with advantages in sustainability, economics, reliability and safety.

Reactor: Xe-Mobile

To address the need for ground, sea and air transportable small power production. We’ve developed reactor concepts with potential civilian government, remote community and critical infrastructure applications.

Fuel: TRISO-X

Our reactors use tri-structural isotropic (TRISO) particle fuel, developed and improved over 60 years. We manufacture our own proprietary version (TRISO-X) to ensure supply and quality control.

Space Applications

NASA, DOE, and DOD are exploring our technology and fuel for nuclear thermal propulsion and fission power for the lunar surface.

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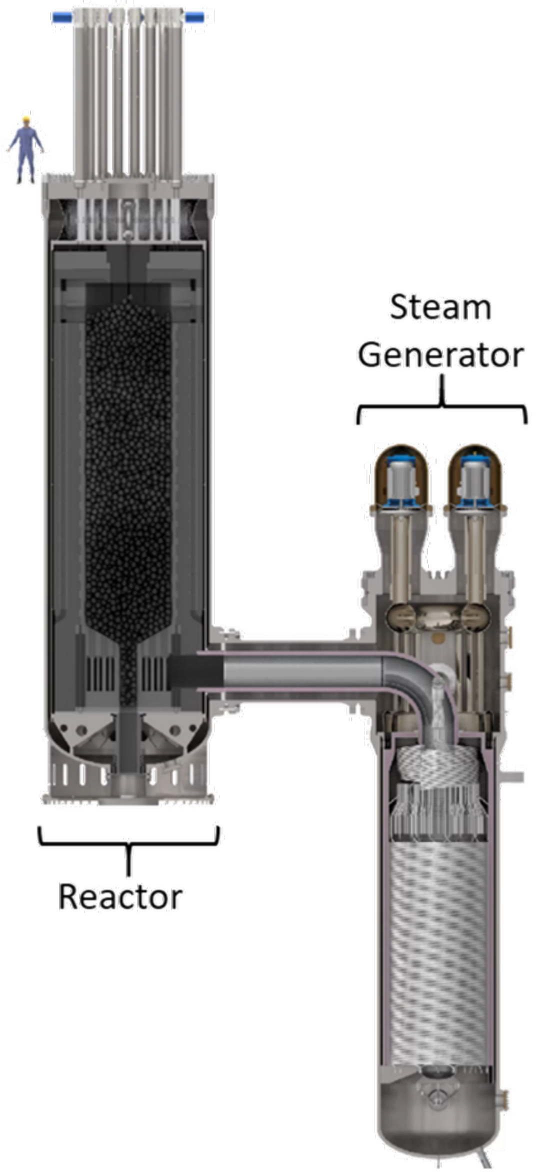
The Xe-100 Design Solution

- Proven High-Temperature Pebble Bed Reactor
- Derived from over 50 years of design and development to significantly reduce costs to enable competitive deployment
- Online refueling through an automated continuous fuel handling system
- Versatile Nuclear Steam Supply System (NSSS) that can be deployed for electricity generation and/or process heat applications
- Conservative design that does not require new material development and or code cases
- Steam pressure and temperature designed to provide steam to multiple Commercially Off The Shelf (COTS) Steam Turbine / Generator sets (typically those used in Combined Cycle Power Plants)



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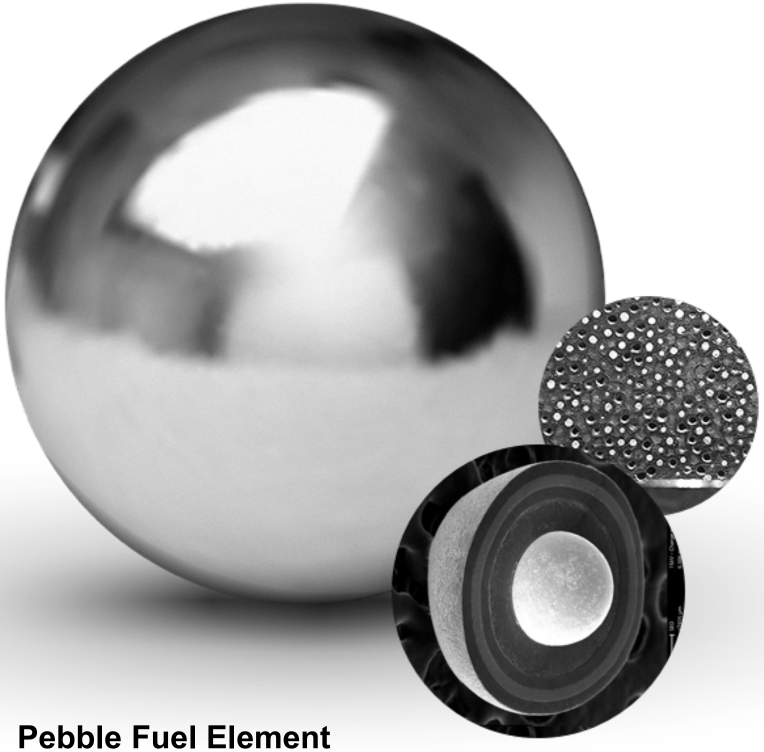
Intrinsic Safety: Our Fuel

Physics, not mechanical systems, ensures 100% safety



Pebble Fuel Element
(60mm)

TRISO Fuel particle
(≈1mm)

- The U.S. DOE describes TRISO fuel as **“the most robust nuclear fuel on Earth,”** it retains waste and fission products within the fuel during ALL conditions, even worst-case accidents and cannot melt.

- We manufacture our own proprietary TRISO encapsulated fuel (TRISO-X) to ensure supply and quality control.

Why is this important?

- No safety related power or operator action required to ensure safety.
- TRISO fuel has 40+ years of prototype and full-scale demonstration reactors. **This is a proven safety approach.**
- The low reactor power density and self-regulating core design (i.e., if cooling stops the core shuts down), ensures the reactor is intrinsically safe.

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Progression of Maintenance

Effectiveness ↑

Predictive

Simple
Advanced (AI/ML)

ML model forecasts pump bearing failure in 3 months.

Condition-based

Continuous
Automated Readings
Automated Analysis

APR software notifies staff of instrument drift

Instrumented
Automated Readings
Manual Analysis

Engineer trends process variables over time

Operator Rounds
Manual Readings
Manual Analysis

Leak detected during Operator Round

Preventative

Calendar-based
Runtime-based

Oil Analysis every 3-6 months on pump motors

Reactive

“Break-fix”
Run-to-failure

Instrument Loop Replacement upon failure

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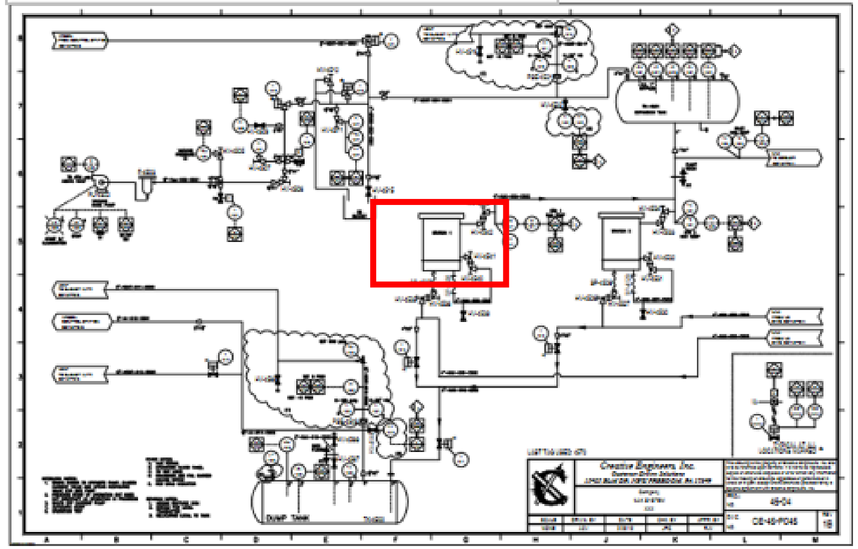
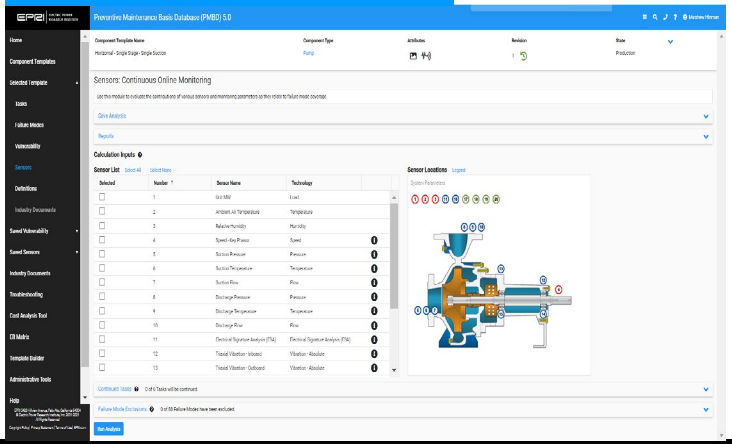
Collaboration b/w SE's, Maintenance, I&C and M&D (and EPRI)

Maintenance Analysis



Asset Criticality Assessment

EPRI Resources



Monitored Asset List

Asset Criticality Ranking	Asset Classification	MDMS Monitoring Level	Monitoring Method	Direct Monitoring System	Monitoring Group
37.63	Run to Maintenance	Level 3: Optional		PEMS	M&D
37.63	Run to Maintenance	Level 3: Optional		PEMS	M&D
37.63	Run to Maintenance	Level 3: Optional		PEMS	M&D
37.63	Run to Maintenance	Level 3: Optional		PEMS	M&D
37.63	Run to Maintenance	Level 3: Optional		PEMS	M&D
37.63	Run to Maintenance	Level 3: Optional		PEMS	M&D
37.63	Run to Maintenance	Level 3: Optional		PEMS	M&D
37.63	Run to Maintenance	Level 3: Optional		PEMS	M&D
37.63	Run to Maintenance	Level 3: Optional		PEMS	M&D
37.63	Run to Maintenance	Level 3: Optional		PEMS	M&D
33.67	Important	Level 3: Optional		DCS, MDMS	M&D
17.15	Important	Level 3: Optional		DCS, MDMS	M&D
17.15	Important	Level 3: Optional		DCS, MDMS	M&D
13.75	Important	Level 3: Optional		DCS, MDMS	M&D
13.75	Important	Level 3: Optional		DCS, MDMS	M&D
13.75	Important	Level 3: Optional		DCS, MDMS	M&D
13.75	Important	Level 3: Optional		DCS, MDMS	M&D
13.75	Important	Level 3: Optional		DCS, MDMS	M&D
21.00	Important	Level 3: Optional		DCS, MDMS	M&D
21.00	Important	Level 3: Optional		DCS, MDMS	M&D
21.00	Important	Level 3: Optional		DCS, MDMS	M&D
42.50	Critical	Level 1: Essential		DCS, IPS, MDMS	M&D

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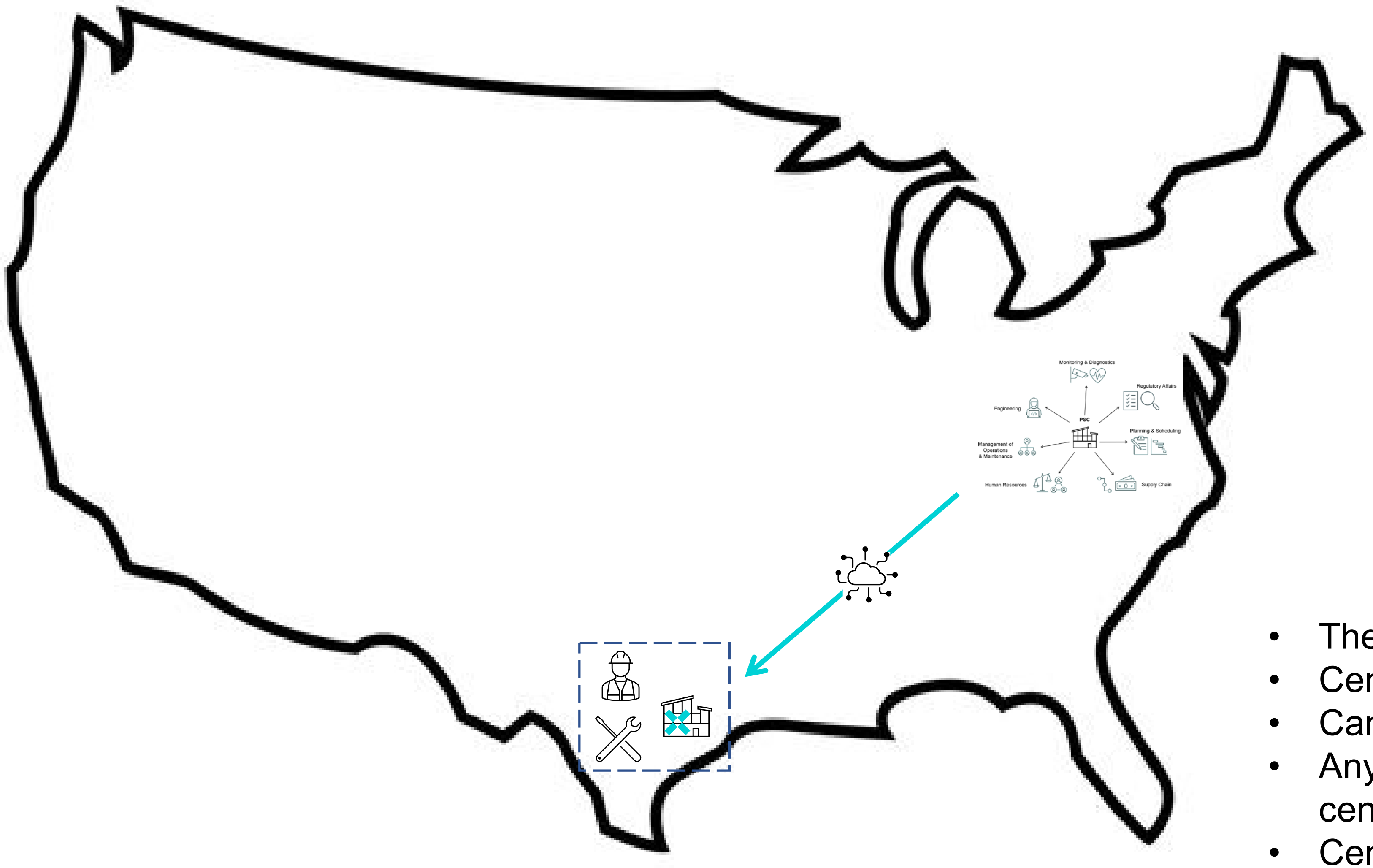
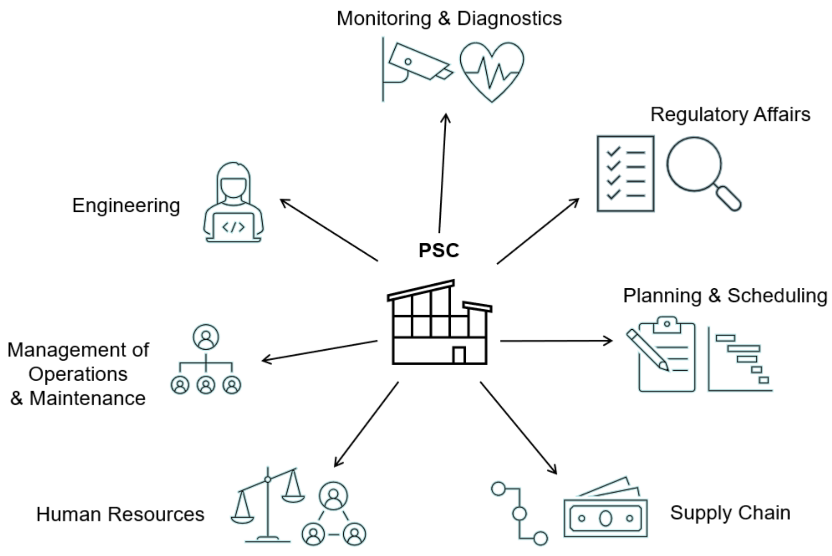
Centralized O&M Strategy with the Plant Support Center (PSC)





- The PSC is location agnostic.
- Centralizing certain staff reduces O&M costs.
- Can support multiple Xe-100 sites.
- Any staff that can be centralized, WILL be centralized.
- Centralized staff will NOT conduct field maintenance.

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Modern Data Infrastructure Enables Condition Monitoring

Securely…

Move – Collect and transfer data from the plant(s)

Store – Place that data in a secure environment for the life of the plant

Transform – Clean and organize the data for easy analytics and visualization

Visualize – Create visualizations for plant staff (e.g., M&D Analysts, Maintenance Technicians, Engineers, Licensing, Regulators, Customers, Executives, etc.

Analyze – Use the data for both basic & advanced analytics, trending, model building and training, performance & maintenance optimizations

Data Protection: Security is paramount. Appropriate security measures will be woven through the components of our system. We will treat all data with care and have measures in place to prevent adverse situations.

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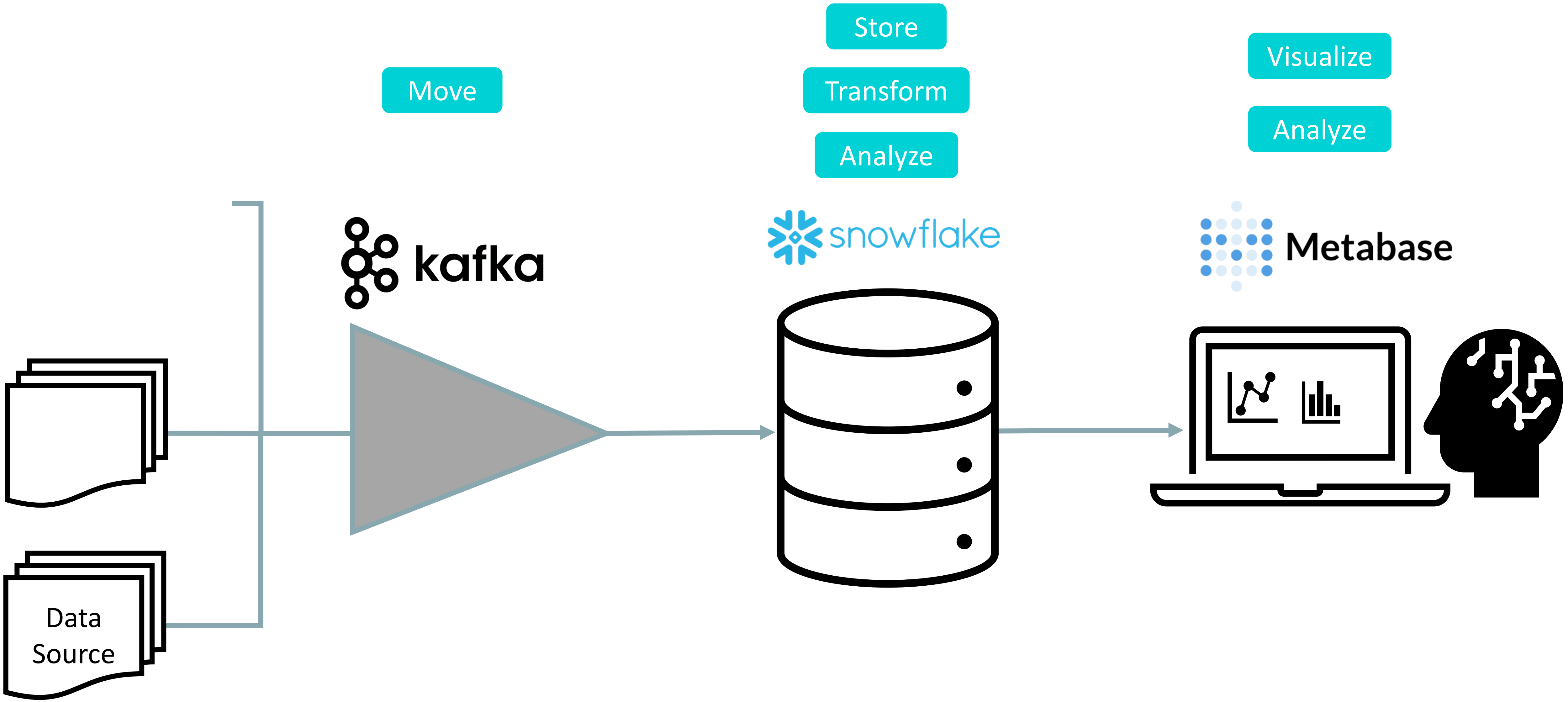
X-energy Proof of Concept Data Pipeline



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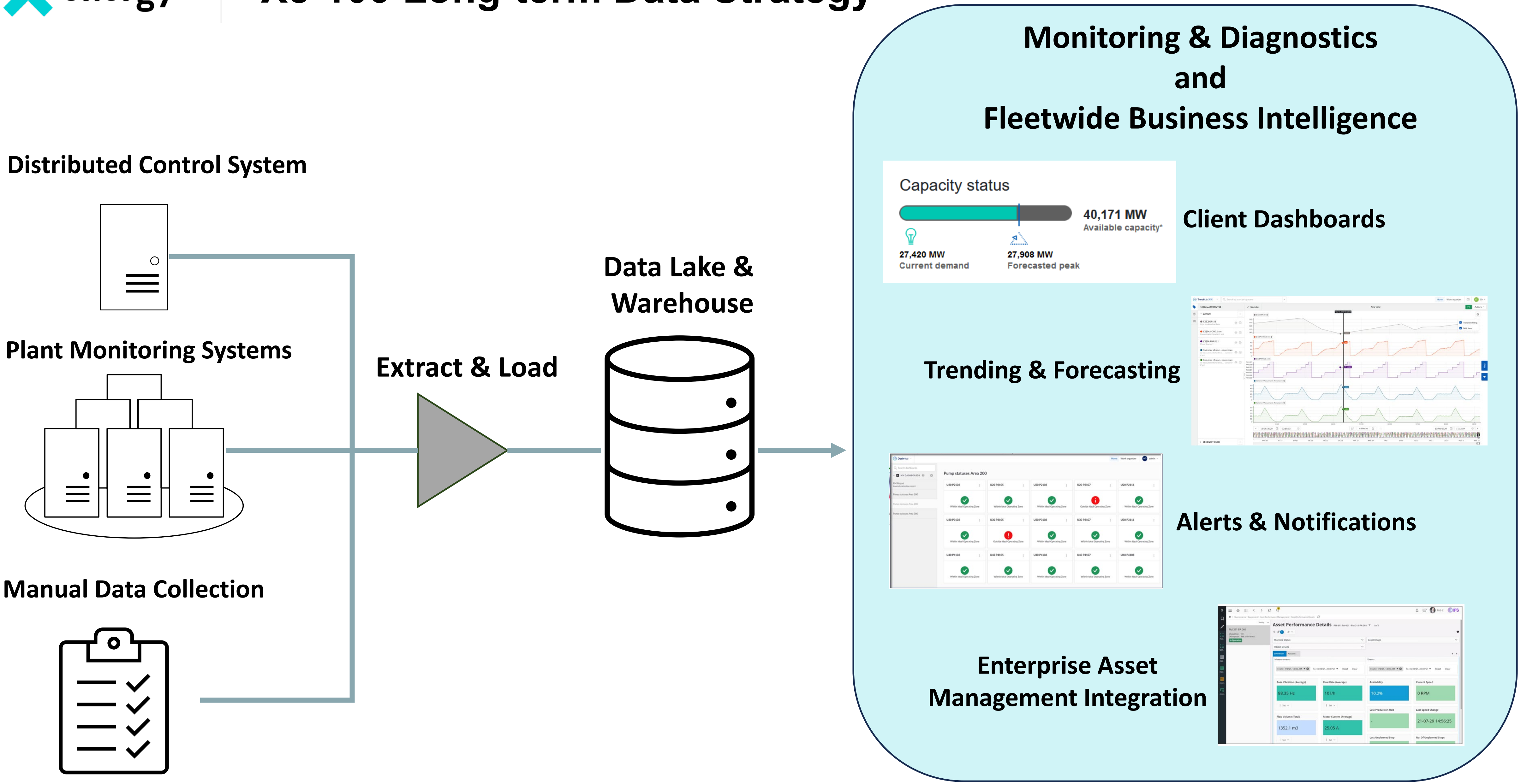
Xe-100 Long-term Data Strategy



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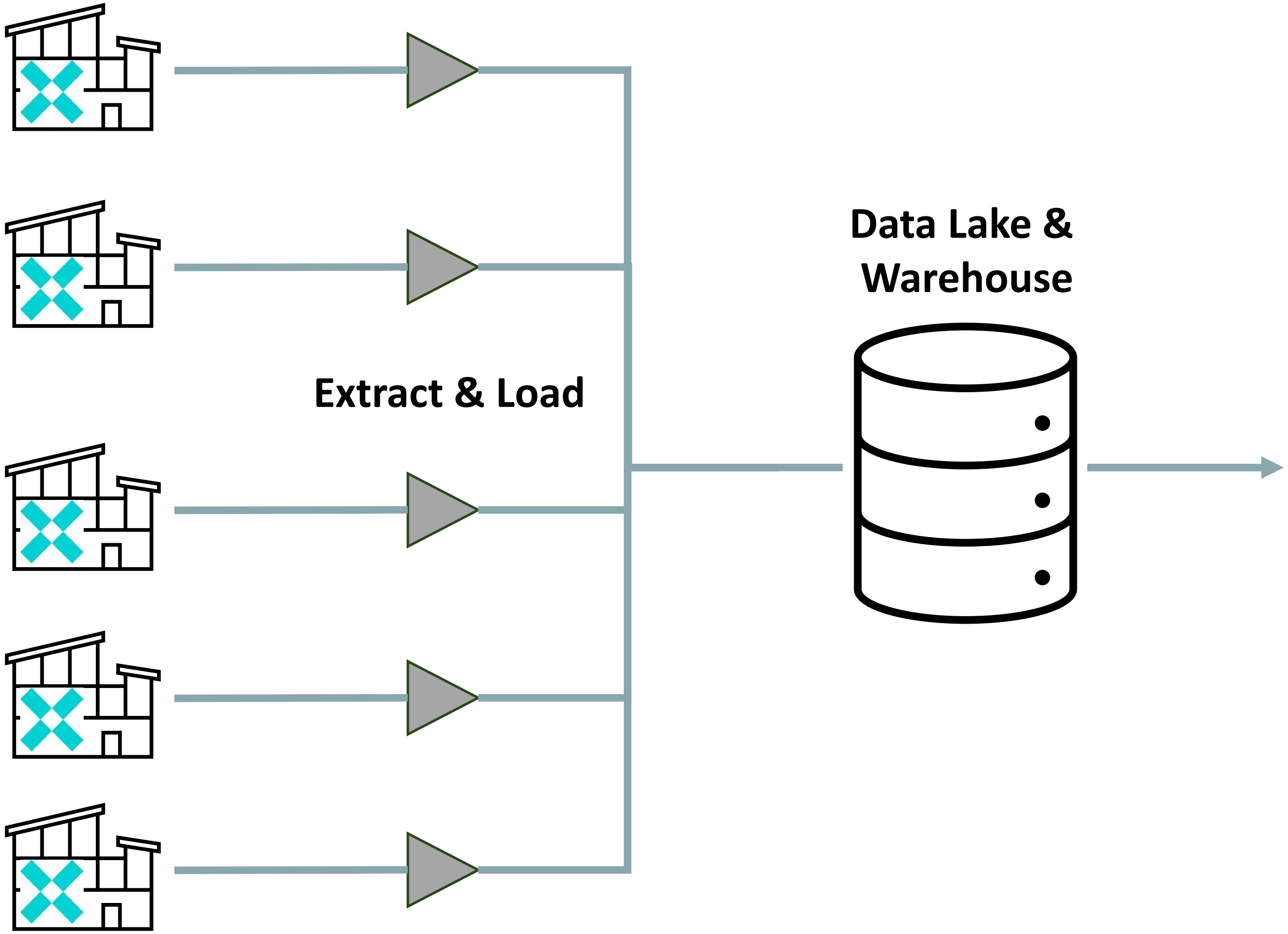
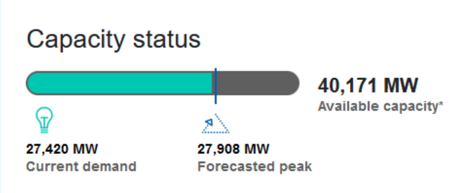
Xe-100 Long-term Data Strategy

Xe-100 Plants

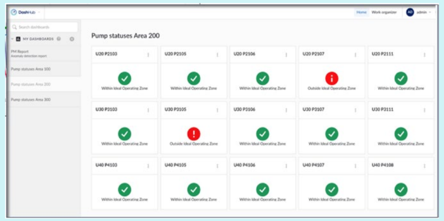


Monitoring & Diagnostics and Fleetwide Business Intelligence



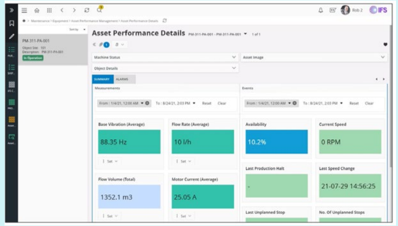
Client Dashboards

Trending & Forecasting



Alerts & Notifications

Enterprise Asset Management Integration



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Clean • Safe • Secure • Affordable

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Digital Twin as Applied for New Reactor Designs Focusing on Predictive Maintenance

Brian Golchert

Principal Engineer, Westinghouse

Virtual Workshop of Condition Monitoring and Structural Health Management for Nuclear Power Plants, November 28-29, 2023

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together

we advance technology & services to power a clean, carbon-free future.

- Customer Focus & Innovation
- Speed & Passion to Win
- Teamwork & Accountability

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Introduction

- The development of new reactor designs present an opportunity to leverage new 'digital' tools
- Digital twins and AI/ML are often mentioned to potentially accelerate/improve new design development and implementation
- However, the 'value' of these new tools is often unclear and not documented.

- This presentation will focus on potential applications of digital twins to new designs (with emphasis on predictive maintenance) and will hope to present some of the potential value of these applications

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Take a step back, what is a Digital Twin?

- Multiple, diverse definitions exist for digital twins
- For this work, let us assume a digital twin is some combination of simulation coupled with live data that runs really, really fast and allows for prognostication of future events based on past history and simulation
- This has been done for years (simulators and other focused analysis/simulation) but has been recently been sped up to near real time.

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What can a Digital Twin do?

- A digital twin links key design parameters with (potentially virtual) sensors
- This allows a simultaneous coupling of live data, simulation and machine learning.
- Properly designed, a digital twin can predict future states…

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Assessing the Value of a Digital Twin

- The eVinci program (as well as many other new designs) has a series of experiments designed to prove/verify some of the underlying concepts related to the commercial eVinci design
- Westinghouse has a pending federal funding award (ARPA-E Meitner Plus Up funding) to show the value associated with a digital twin of the 'first' completed eVinci experiment (Electrical Demonstration Unit [EDU])
- The lessons learned from this work will then be applied to the next test reactor and then to the commercial units (including predictive maintenance)

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Size Considerations

- Existing nuclear power plants are HUGE
- One can 'easily' build a digital twin of a single component (pump, valve, heat exchanger, etc.) because those components are physically separated from each other
- For new designs, particularly micro-reactors, this is not often the case
  - Requires more intimate coupling of neutronics, structural, and fluids
  - This coupling should include material degradation effects (both structural and thermal) due to the high temperatures and fluence

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New designs do not have operational data

- A lot of ‘predictive’ tools in the nuclear industry rely on existing operational data including many predictive maintenance software
- This operational data does not exist for new designs
- One can only leverage so much data from first of a kind testing

- What does one do?

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Start from Simulation and then Update

- Lots of tools are available to model nuclear systems but no one really ‘trusts’ them without experimental justification
- To build an initial digital twin of a new design, it is suggested that one perform coupled detailed structural, reactor physics, and fluid dynamical analysis of the system.
- This will allow correlations (reduced order models) to be built between sensor locations and key design parameters.
- Building these reduced order models allows almost near real time execution of the digital twin

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Next step

- Once one has a simulation based a digital twin complete, then the test facility (and/or commercial unit) starts providing sensor readings.
- It is expected that these reduced order models based on these sensor readings might require adjustment/improvement.
- From a Westinghouse perspective, it is expected that something like a Bayesian interpretation of the sensor data related to the reduced order models would be used to adjust these relationships between the sensor readings and the key design parameters.

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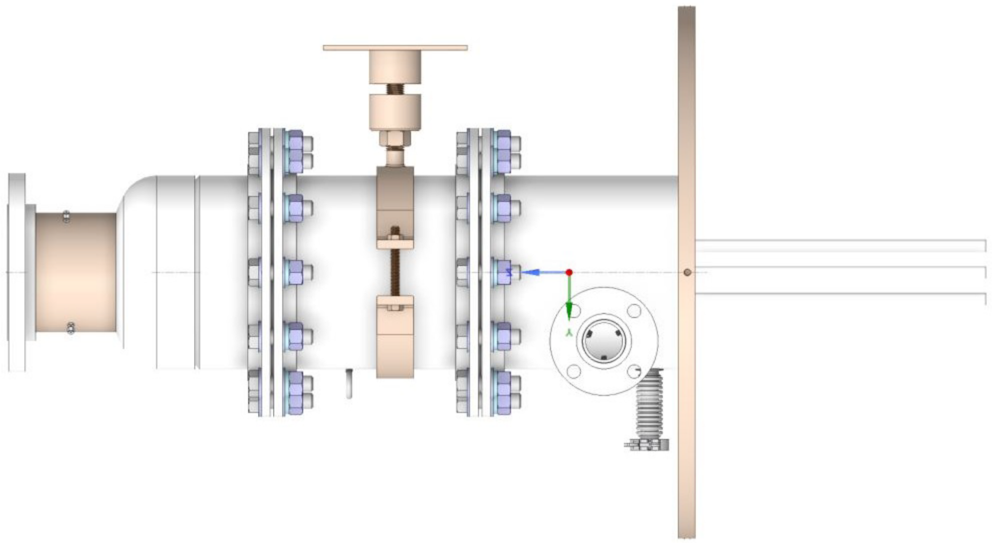
Example: Electrical Demonstration Unit (semi proof of concept)

- The commercial eVinci design has multiple ‘snowflakes’ (hexagons) that use heat pipes to remove heat generated in the core block
- The EDU has one seven heat pipe hexagon
- The image to the right is a CAD image of the EDU



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Electrical Demonstration Unit

- More than 70 thermocouples,
- More than 40 heaters (their amperage is now a sensor)
- 7 heat sinks (heat pipes which link directly to the experimental design parameters)

- As was previously mentioned, there needs to be a different approach to build a digital twin for a micro-reactor as opposed to a commercial unit
- Digital twins for commercial unit components are relatively independent but with 70 thermocouples, 40 heat sources and 7 heat sinks in a small test facility, each sensor can be reading the influence of multiple heat sources/sinks
  - This effect may apply to the commercial unit as well

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Design requirement(s)

- Now that the locations of the sensors have been determined, how do these measurements relate to design requirements?
  - (Note that a digital twin built after the design phase cannot usually evaluate functional requirements which are often geometric)

- Design requirements are frequently a temperature or pressure limit.

- Design requirements for test facilities are often different than for a commercial plant

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Design requirements (cont)

- Since EDU was a 'proof of concept' that heat pipes can transfer the heat, there are very few measurable design requirements.

- With the ARPA-E Plus Up work will just start with temperature measurements (related to the design requirement on the previous slide)

- Once the sensors and design requirement have been determined, Reduced Order Models (ROM) are created based on:
  - Simulation results
  - A part of the experimental data is used to build the ROM

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ROM creation

- A lot of ‘sensor’ data is now available to correlate to design requirements
  - An over-determined system

- ROM ‘can’ be built for each sensor for each design requirement but this leads to a really complex system
  - For test reactors and microreactors, the temperature measured at one sensor does not just measure the heat from one heat source/sink
  - Optimization tools are required at this point to develop importance functions to develop the ROM

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Calibrating ROM with test data

- It cannot be assumed that the simulation based reduced order models will completely/accurately represent the test/operational data.
- Hence, a method needs to be in place to ‘improve’ the ROM.
- Bayesian inference can be used starting with simulation data to update the ROM to more accurately reflect the operational performance.
- The test data that was not used to build the ROM is then fed into the twin as ‘live’ sensor data for further calibration

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Extending the thought process

- In theory, digital twins are ‘useful’ when data exists
- However, one can make the argument that digital twins are extremely cost effective (provide value) during the design cycle
  - Use simulation to reduce tests
  - Use existing commercial software like ANSYS OptiSlang to optimize design parameters such as sensor placement/location that may lead to reduced maintenance costs
- This thought paradigm can be extrapolated from test facilities to commercial design and then backed up by digital twins based on test facilities

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Take a step back and think about it

- In the 'old' days, everyone designed experiments and new reactors based on subject matter expert knowledge (the SMEs are our original digital twins)

- Suppose, our experts said we need 70 thermocouples but simulation only shows you need 50?
  - Leveraging a digital twin can lead to significant cost savings in the design process and in predictive maintenance costs.

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Using a Digital Twin for Predictive Maintenance

- Once you have built it, a digital twin that can effectively monitor the performance of your system/component/design
- As the digital twin monitors the sensor readings and update the ROMs, the ‘deviation’ between the sensor reading and the ROM prediction becomes the first indicator of an issue with a component potentially requiring preventative maintenance
  - Care must be taken when updating the ROMs.
    - Is the ROM just being re-calibrated or is the sensor data indicating there might be an issue?
    - Malfunctioning sensor?
  - It may not be prudent to update the ROMs if there is an issue with the component or the sensor.

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Adding on to the Digital Twin for Predictive Maintenance

- One of the key benefits is that a digital twin can run fast
- However, running tools that can perform analyses to determine the potential effect of deviations tend to run slow so they cannot directly included in the digital twin
- However, these tools can be on ‘standby’
  – If a significant deviation is noted by the digital twin, the current operating state could be evaluated
- Adding a little additional computation and some statistical inference, one can potentially compute when a component/system may fail based on the current state. Examples:
  – Using xLPR would be a one way of predicting weld failure (which would lead to predictive maintenance adjustments)
  – Using Neutron Noise technology from sensors outside of the vessel to determine if there is an issue inside the vessel

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A trained digital twin is a powerful tool to help with predictive maintenance for new designs

- Building a system model that is continually updated based on operational data provides a lot more ‘comfort’ to trust the results
- Since simulation (with reduced order models) can possibly be run off-line faster than real time, it is possible to predict potential future states before they actually occur.
- This leads to ‘trends’ in component behaviour that could be utilized to improve a preventative maintenance
- In addition, changing operating conditions (as part of autonomous control) could lead to cost effective changes in operating conditions.
- Caveat emptor: A digital twin/predictive maintenance is only as good as the sensor data

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Questions?

Condition Monitoring at Nuclear Plants
Current Technology and 2030 Outlook

Virtual Workshop on Condition Monitoring and Structural Health Management for Nuclear Power Plants

Presented by Eric Helm, Giancarlo Lenci

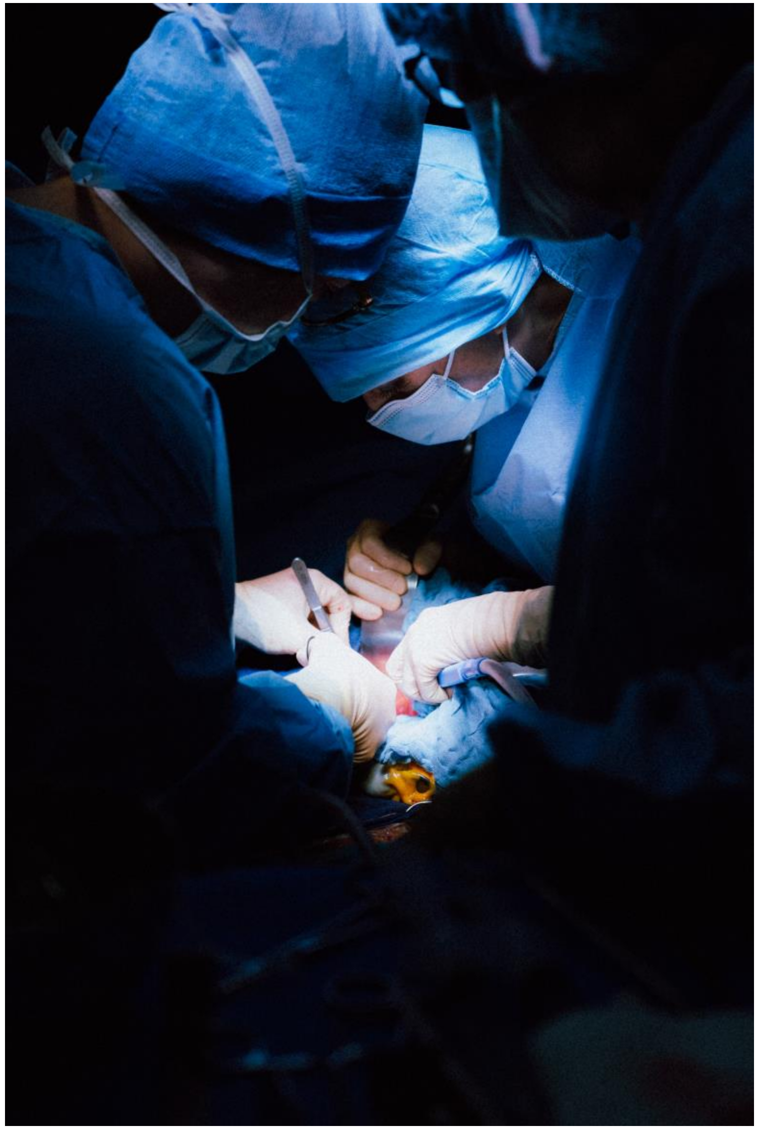
Nov 28, 2023

The High Stakes of Condition Monitoring at Nuclear Plants

What is the cost of a wrong or late diagnosis?

Areas affected:

- Reliability
- Availability
- Performance
- Repairs
- Component replacements
- Asset life



Condition Monitoring of the Plant State

Uses Knowledge of Simultaneous Equipment Problems

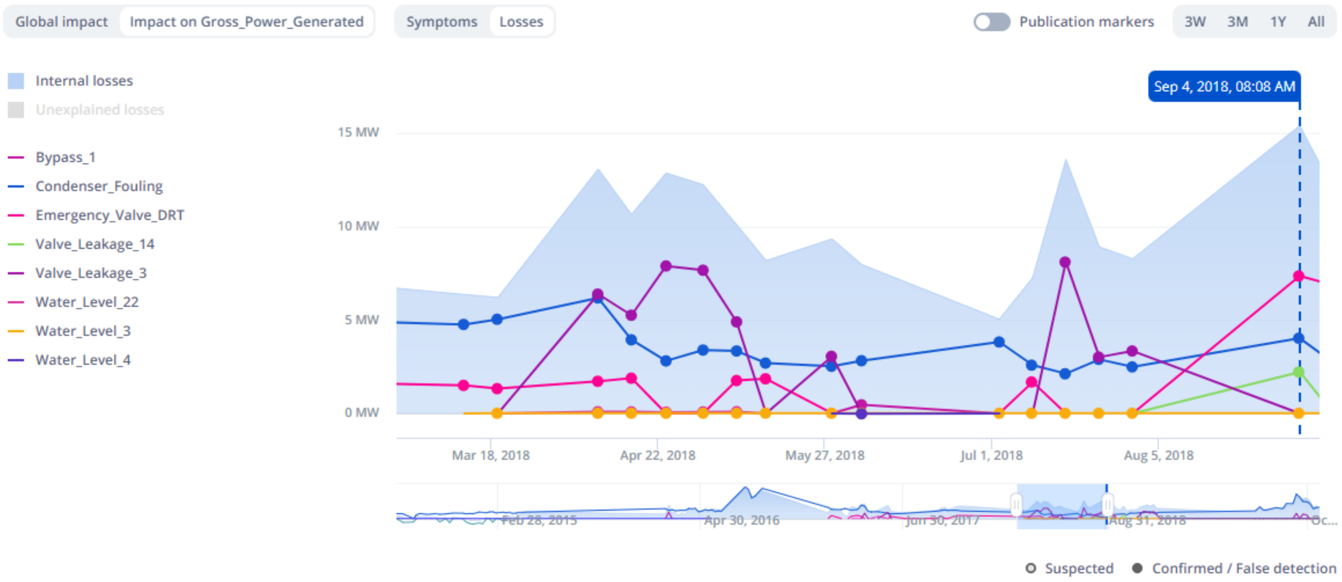
Steam cycles of nuclear plants typically run with **3-5 active faults**

Condition monitoring requires looking for new faults **while knowing the state of active faults**

Metroscope Technology: **Physics-based** models with an **AI engine** determine plant state quantifying faults and their impacts metroscope

Conclusions-First Software Technology

Physics-Based, AI-powered, embeds a plant-tailored quantitative fault matrix



Automated Diagnosis of Simultaneous Faults

Embedded investigation tools, collaborative workflow

70 plant units and growing, 87% accuracy at catching faults

Industry M&D Challenges Today

And How Metroscope Addresses Them

M&D Challenge	Impact on Plant	Metroscope Approach
Burden of data volume and complexity	Analyzing large volumes of sensor data leads to slower decision-making	AI and digital twin technology efficiently summarizes diagnoses live
Stretched for availability of staff with **knowledge and expertise**	Need for specialized knowledge limits the speed and accuracy of fault identification	Automation and embedded OE provides training basis not a burden
Manual **root cause analysis** is time consuming and error prone	Leads to prolonged operation at reduced efficiency	Inferences automatically identify faults accurately reducing time and errors
Instrument uncertainty creates doubt	Uncertainty in measurements leads to inaccurate diagnostics and more verification actions	Digital twin tuned against as-built plant and distinguishes faults from sensor drift
Late diagnosis leads to expensive corrective action	Unplanned or long outages and greater damage leads to high repair costs	Early detection minimizes costs and increases overall efficiency

Use Case:
Emergency Valve DRT Opening

Challenge

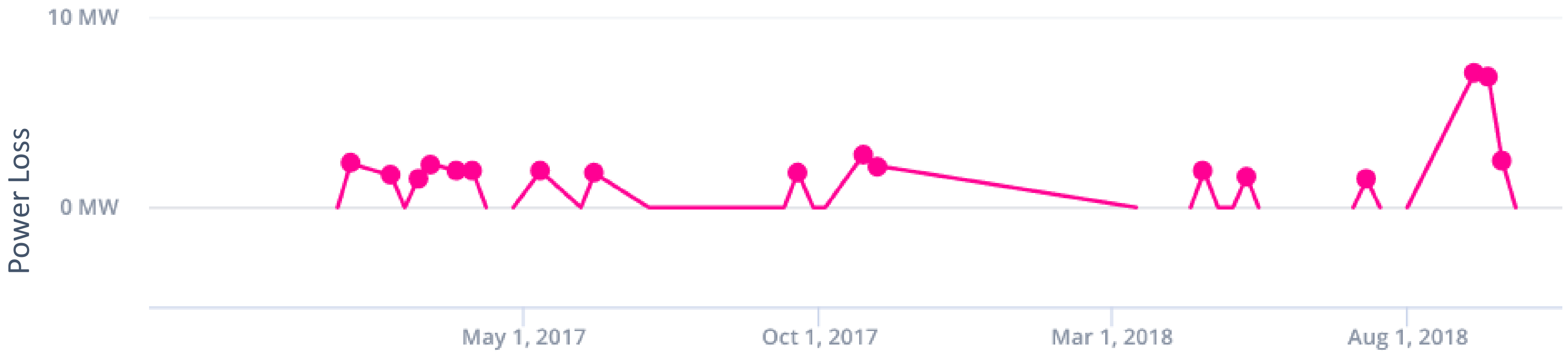
- 19 months of unexplained losses
- ~2MWe → ~30000 MWh losses

Metroscope solution

- Detection of an unknown leak
- Automatic calculation of overall impact
- Monitoring the evolution of the fault
- Maintenance evaluation

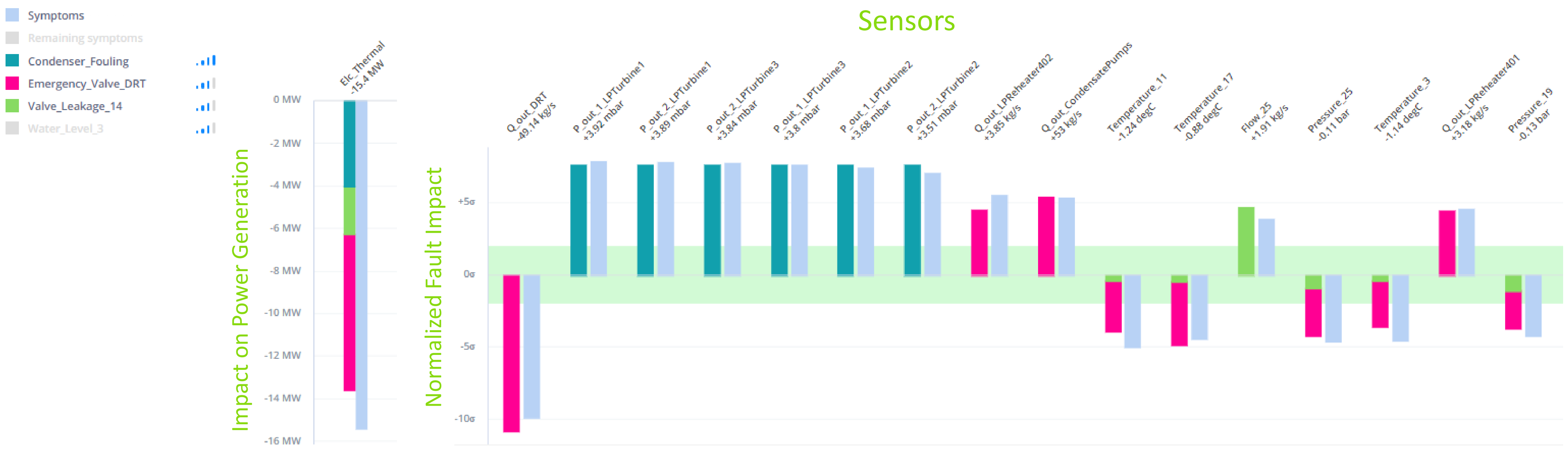
Benefits

- ~$1.4 M of savings
- Fleet knowledge of failure mode



Inference Result is Explainable and Actionable

1. Plant State is understood in terms of fault causes
2. Fault magnitudes and impacts are quantified physically
3. Symptoms are explained in terms of simultaneous faults



Use Case:
Heat Exchanger Tube Rupture

Challenge

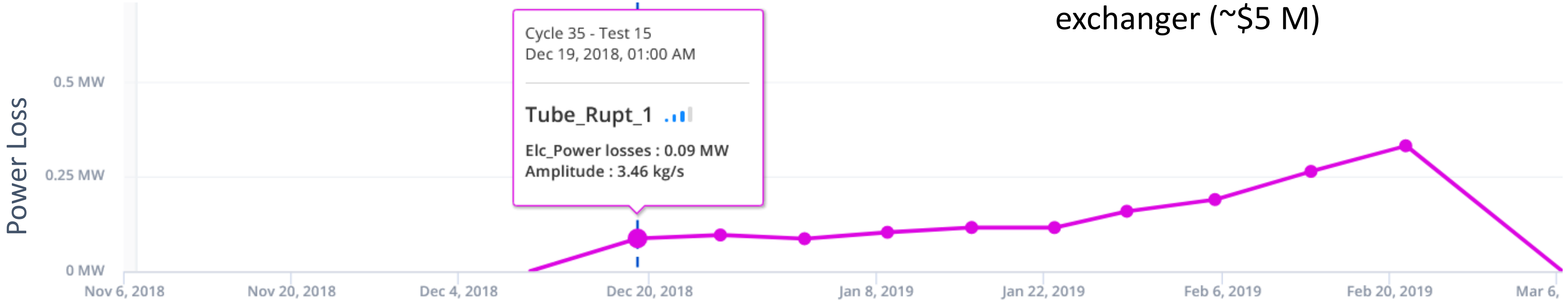
- Detection at 9 kg/s is typical
- HP Feedwater heater tube bundle damage accelerates quickly

Metroscope solution

- Early-stage detection - Tube rupture was detected successfully at just 3 kg/s

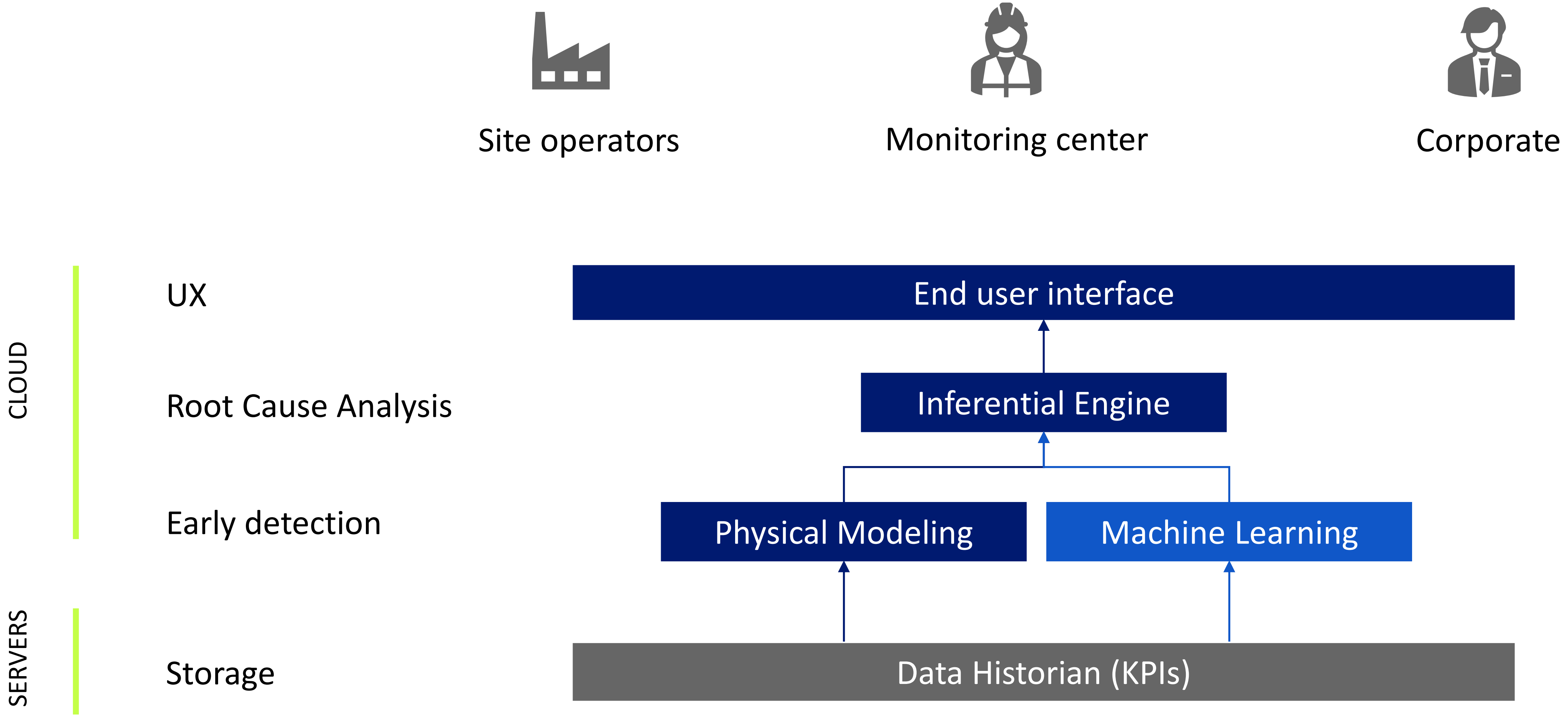
Benefits

- Optimize maintenance planning and timing, time to better prepare for outage
- $80 K/unit/year
- Extend the life of the heat exchanger (~$5 M)



A Framework for Condition Monitoring

With Inference as a Central Step



Overview of Commonly Encountered Plant Tools

Aiming at O&M Cost Reduction

	Monitoring			Diagnostics	
Goal	Detect Problems Early	Characterize Condition		Identify Causes of Anomalies	Rule out Other Explanations
Impact	Reduce impact and cost	Reduce Maintenance (Condition-Based)	Optimize Planning	Speed up Action	Eliminate Wasted Action
Commonly Encountered Tool	Pattern Recognition / Anomaly Detection	EAM - Component Health Index		Single Fault Tree Analysis	Plant knowledge

Areas of Industry-Wide Tool Improvement

Seeking a More Comprehensive Condition Monitoring

	Monitoring			Diagnostics	
Goal	Detect Problems Early	Characterize Condition		Identify Causes of Anomalies	Rule out Other Explanations
Impact	Reduce impact and cost	Reduce Maintenance (Condition-Based)	Optimize Planning	Speed up Action	Eliminate Wasted Action
Commonly Encountered Tool	Pattern Recognition / Anomaly Detection	EAM - Component Health Index		Single Fault Tree Analysis	Plant knowledge
Improvements	Improved models	Remaining Useful Life Calculations		Highly accurate fault inference (automation)	

2030 Outlook: Advanced Reactor Goals

	Monitoring		Diagnostics	
Goal	Design sensors and models to monitor in place of inspection	Automate orders and supply chain actions	Automated plant fault state and impacts estimated	
Impact	Fewest manual inspections / PMs	Lowest effort planning and work order execution	Speed up Action	Semi-automate operator action

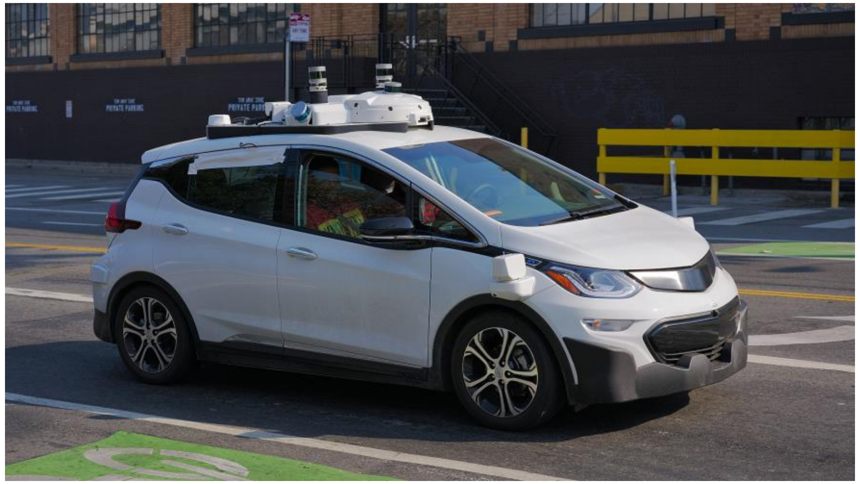
What Tools are Needed?

Modeling Ecosystem + Diagnostic Inference

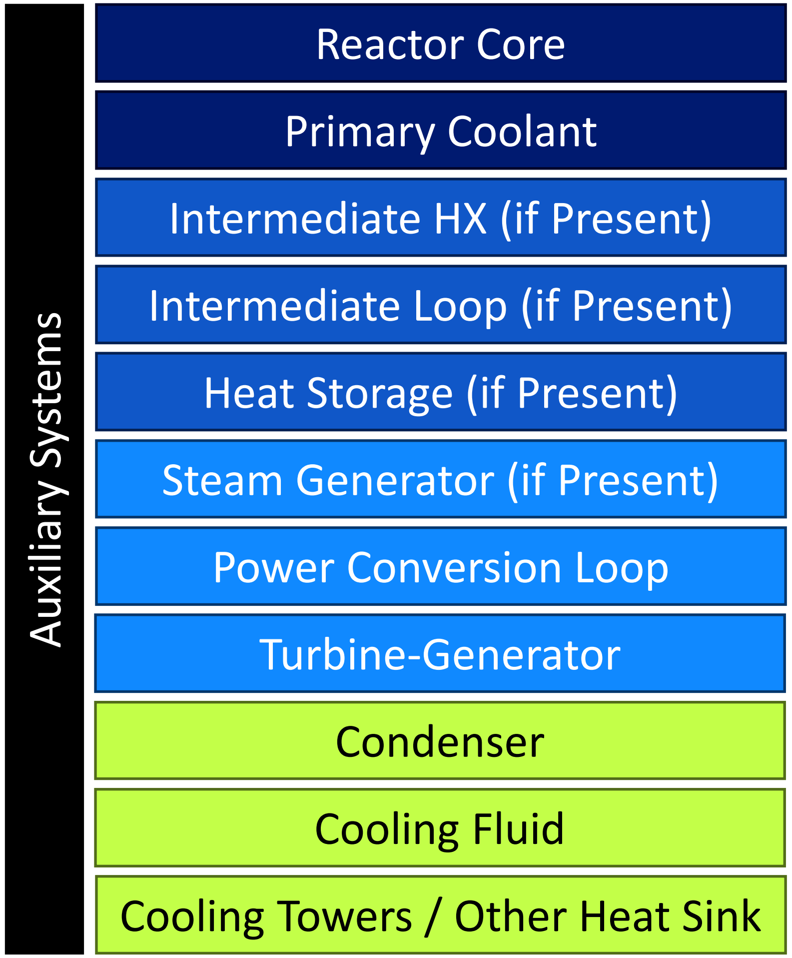
The Path toward Autonomous Operations

- Nuclear systems already use automation to maintain key variables around setpoints
- The challenge is to execute smart autonomous decisions in case of mode transitions or faults

→ Idea: build upon existing automated diagnostics technologies to inform autonomous operations

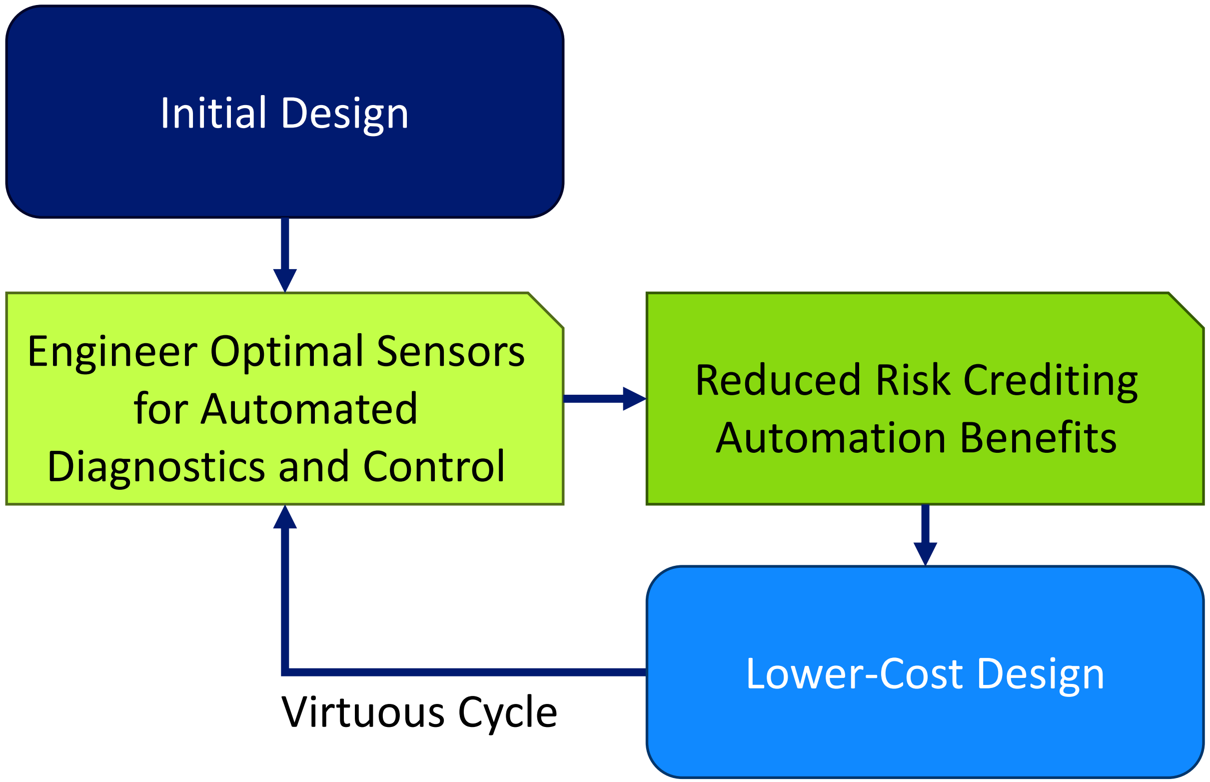


Next Steps for Advanced Reactors



- Envision optimal sensor placement and full process coverage from Metroscope, including auxiliary systems
- Achieve automation or semi-automation, including:
  - Maintenance
  - Controls
- Implement advanced control strategies rather than simple state machines to prevent wear from frequent maneuvers

Virtuous Cycle: Designing for Automation



- Much greater savings than retrofitting an existing design
- Virtuous cycle of design simplification due to progressive risk reduction
- Savings in construction, operation, and maintenance

Conclusions

- Condition monitoring in the steam cycle requires simultaneous fault diagnosis
- Metroscope technology automates diagnosis via physical modeling and AI
- Autonomous operations need technologies that are aware of the plant's state, including faults
- Technologies that are broken by faults would not be helpful
- Savings can be substantial if the technology is baked into design, due to risk reduction
- Needs a modeling ecosystem and appropriate types of inference for full coverage of failure modes

Cody Walker, PhD

Research Scientist at
Idaho National Laboratory

November 20, 2023

Online Monitoring Using Cloud-Based Applications

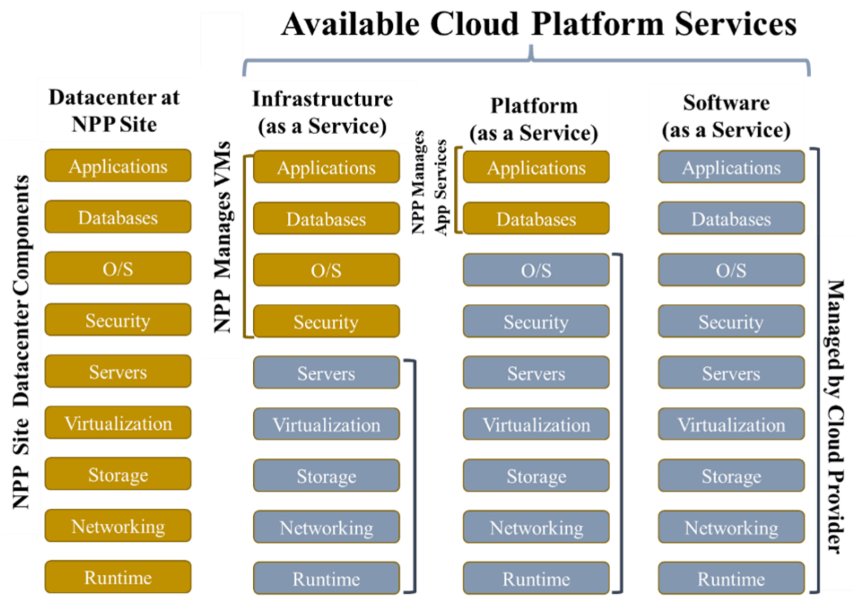
Idaho National Laboratory

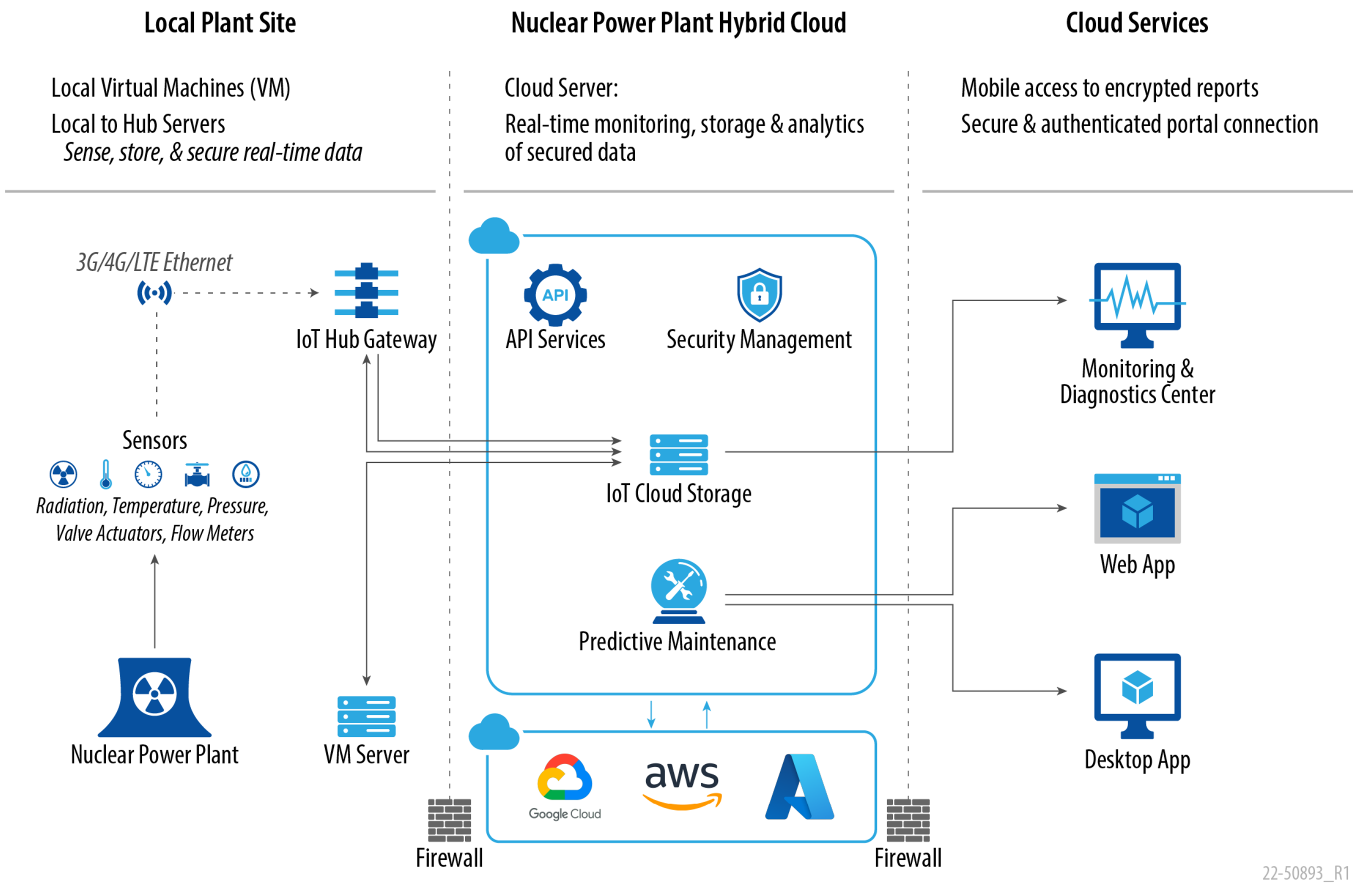
Outline

- Architecture for nuclear power plant-to-cloud computing
- Safety relief valve problem
- Online model training
- Speed testing
- Predictive capabilities
- Overall costs

Online Monitoring Using Cloud Services Will Require Additional Sensors, Systems and Choices

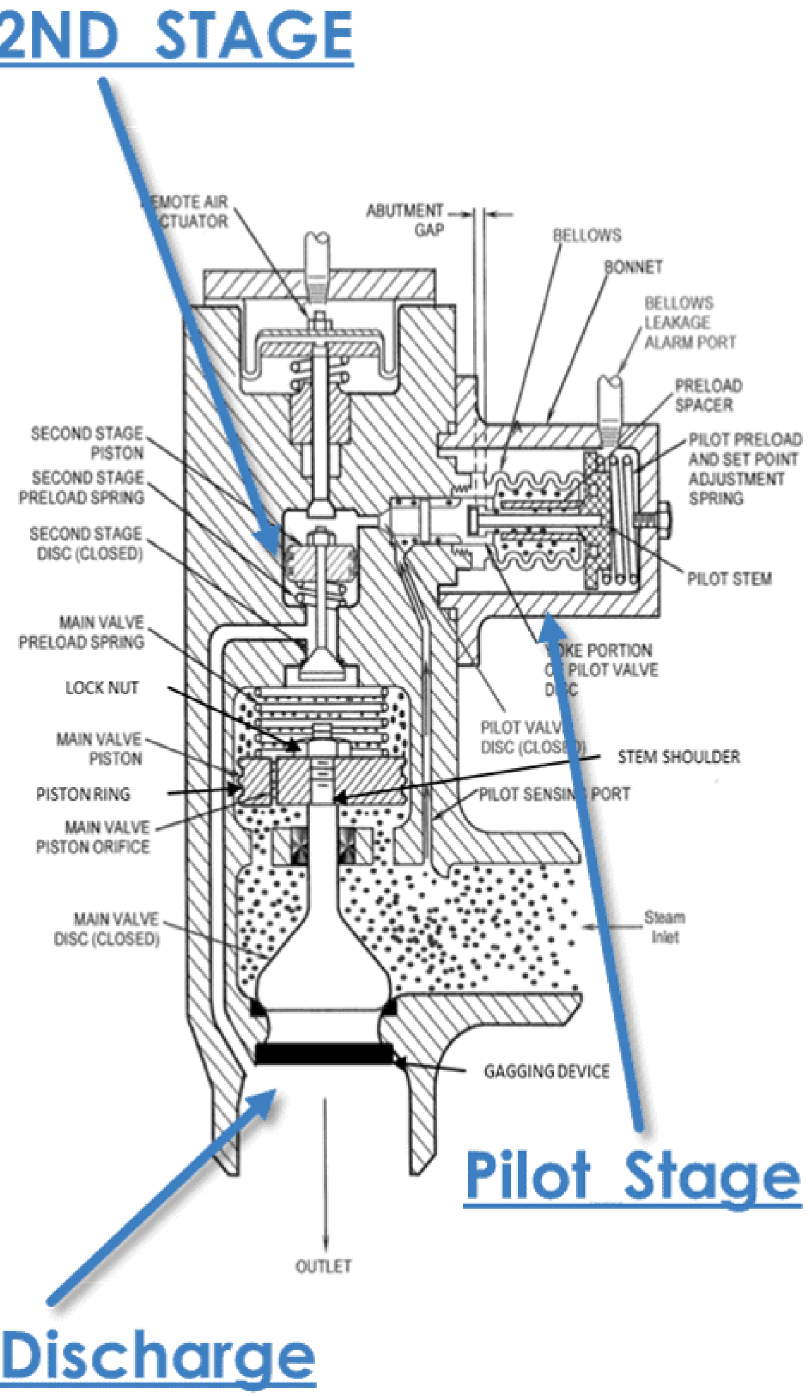
- The end-goal of online monitoring is predictive maintenance
- Cloud computing may be a cheaper way to achieve that goal





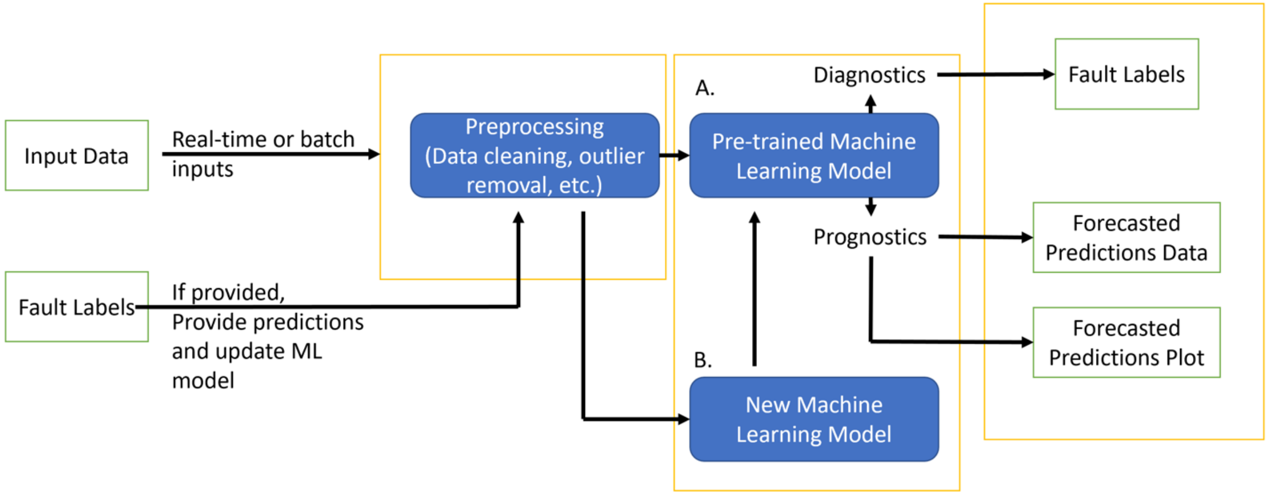
Monitoring a Safety Relief Valve (SRV) Using Multiple Thermocouples.

- SRVs (also known as a pressure relief valve) are highly reliable, nonpowered ways to relieve pressure
- Used in systems that may build up pressure under accident conditions
- Common stressors include:
  - Wear (mechanical stress, cavitation, corrosion, erosion)
  - Temperature (rate of corrosion, spring rate, etc.)
- Data were taken over 14 months
- Monitoring locations include pilot stage, second stage valve body, and downstream discharge.



A/B Model Testing Allows for Continual Updating While Maintaining a Stable Model for Use.

- Models for this research:
  - Feedforward Neural Network (FNN)
  - Long Short-Term Memory (LSTM)
- Preprocessing cleaned the data before model training or updating
- Pre-trained Model A is used to diagnose the current state of health and to predict future parameter values
- Model B is Model A but it is being continually updated with new data
- Model B eventually replaces Model A and a new model begins updating.



Cloud Computing has Elastic Resources and Can Scale Up or Down Depending on Demand

Resources Compared

	Local	HPC (CPU)	HPC (GPU)	Microsoft Azure
Processor	Intel CITM i7-9700 CPU @ 3.00 GHz	2 Intel Xeon 8268 CPUs @ 2.90 GHz 24 cores per CPU	NVidia Tesla V100 32 GPU	28–112 Gb Memory 8–32 Cores
Installed RAM	32 Gb	8 Gb RAM per core	32 GB RAM	14 Gb Memory

Resources Had Comparable Results

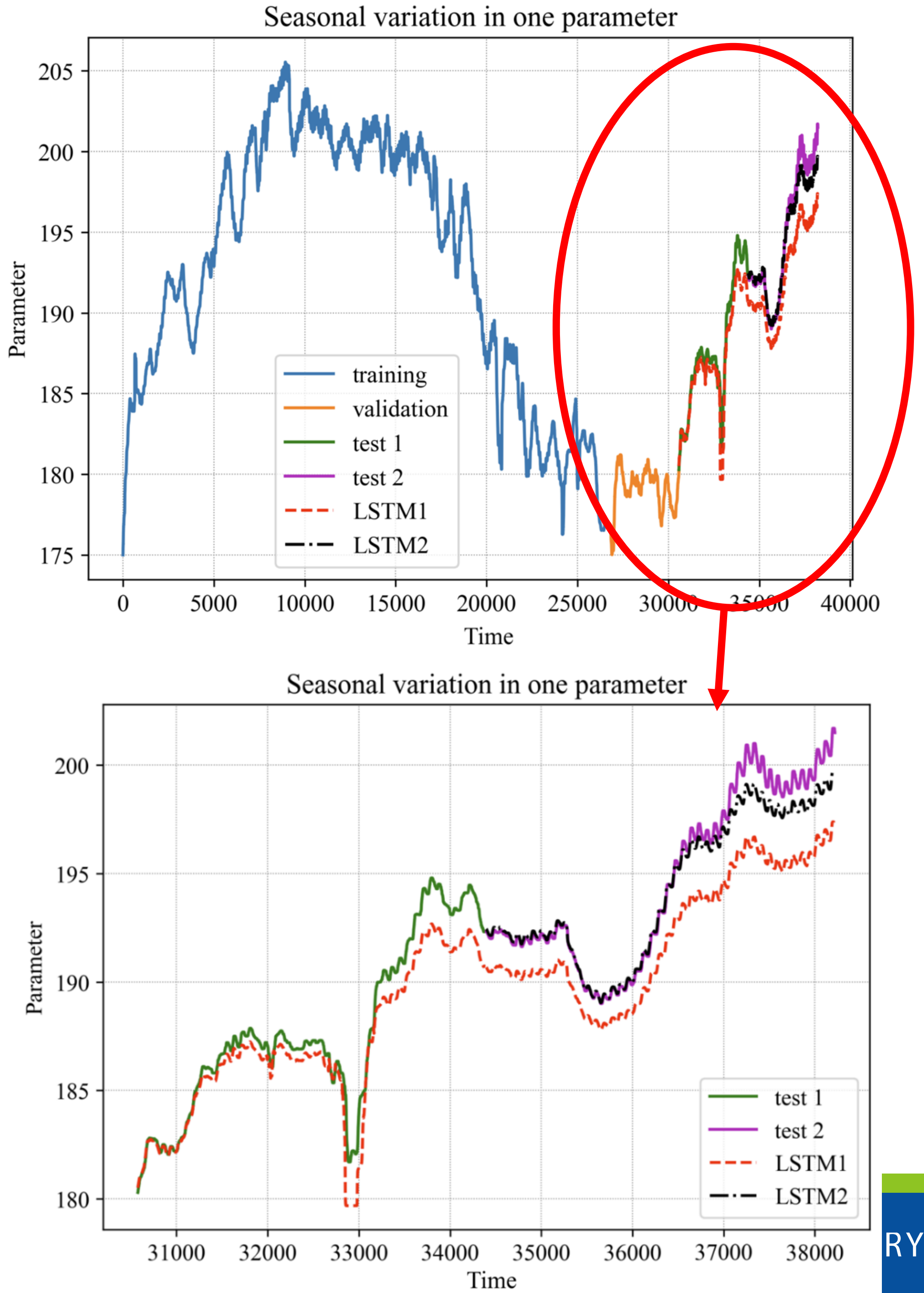
Cloud Computer Speed Testing (in seconds)					
Test	**Local**	**HPC (GPU)**	**HPC (CPU)**	**HPC (multi-CPU)**	**Azure**
Loading Data	3.26 ± 0.10	2.87 ± 0.02	N/A	N/A	14.67 ± 0.29
Preprocess	34.89 ± 0.10	37.94 ± 0.02	N/A	N/A	38.00 ± 0.29
Train FNN 1	8.09 ± 2.01	27.57 ± 5.59	7.18 ± 1.97	11.14 ± 2.51	7.12 ± 2.14
Update FNN 2	0.97 ± 0.06	2.62 ± 0.2	1.04 ± 0.027	—	1.07 ± 0.03
Train LSTM 1	103.67	89.62	126.68	162.47	96.07
Update LSTM 2	8.78	7.76	14.5	—	8.72

Updated Models Reduced Data Drift

A/B Model Testing		
Test	**FNN (RMSE)**	**LSTM (RMSE)**
Model 1 Test A	1.361 ± 0.679	1.411
Model 1 Test B	2.559 ± 1.264	2.792
Model 2 Test B	0.593 ± 0.300	0.504

Updating Models with Recent Data Reduces Model Drift

- A large seasonal component can be seen in the temperature measurement
- Model A was trained on the first 10 months of data, validated in 1.5 months, and tested on ~1.5 months
- Model B was also trained on Test 1 before being tested on Test 2
- Results show that updating with more recent data can reduce model drift when using time series data.



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Current Prices for Cloud Computing Could Be Cost Effective for On-line Monitoring

Current Estimated Costs to Maintain On-site Diagnostics

Hardware	Number of Items Saved	Item Cost	Total Cost	Annual Costs	Monthly Costs	Assumptions
Servers	18	$4,500.00	$81,000.00	$16,200.00	$1,350.00	Replaced every 5 years
Network Elements (e.g., routers)	30	$800.00	$24,000.00	$4,800.00	$400.00	Replaced every 5 years
Software						
Commercial Software	Base Cost	$200,000.00	$200,000.00	$30,000.00	$2,500.00	Maintenance contracts
Purpose-Built Software	Base Cost	$500,000.00	$500,000.00	$75,000.00	$6,250.00	Contract programming
IT Support Staff Average Salary	17	$150,000.00	$2,550,000.00	$2,550,000.00	$212,500.00	—
Offsite Backup	—	—	—	$3,600.00	$300.00	—
Cybersecurity	—	—	—	$20,000.00	$1,666.67	—
Operational Staff	35	$150,000.00	$5,250,000.00	$262,500.00	$21,875.00	Fraction of their time
Manual Sensor Reading	8	$85,000.00	$680,000.00	$680,000.00	$56,666.67	Headcount for manual sensor reading/ recording
Facilities Costs						
Electricity	—	—	—	$300,000.00	$25,000.00	Yearly cost of electricity
Total	—	—	—	$3,942,100	$328,508	—

Estimated Installations to Enable Cloud Computing

Total Cloud Costs	Initial Costs	Annual Costs
Sensors	$300,000.00	$136.00
In-building Network	$1,131,480.00	$176,278.00
Network Aggregation Equipment	$50,000.00	$15,000.00
Installation and Cloud Set-up	$600,000.00	$60,000.00
Total	$2,081,480.00	$251,414.00

Estimated Reoccurring Costs

Direct Cloud Costs	Cost	Number of Applications	Total
Storage of 500 Gb/year	$567.00	25	$ 14,175.00
Total Model Retraining	$28,152.00	25	$703,800.00
Application Hosting	$6,000.00	25	$150,000.00
IT Personnel	$150,000.00	10	$1,500,000.00
—	—	Total	$2,367,975.00

Total Cost Comparison

Cost Comparison	Current Onsite Cost	Cloud Cost
Installation Cost	N/A	$2,081,480.00
Annualized Cost	$3,942,100.00	$2,619,389.00

Acknowledgements

Walker, C.M., Agarwal, V., Nistor, J., Ramuhalli, P. and Muhheim, M., 2023. ***Assessment of cloud-based applications enabling a scalable risk-informed predictive maintenance strategy across the nuclear fleet*** (No. INL/RPT-23-74696-Rev000). Idaho National Laboratory (INL), Idaho Falls, ID (United States).

This report was made possible through funding from the U.S. Department of Energy (DOE)'s Light Water Reactor Sustainability Program. We are grateful to Jason Tokey of DOE, and Bruce P. Hallbert and Craig A. Primer of Idaho National Laboratory (INL) for championing this effort. We thank John Shaver of INL for the technical editing of this report.

Idaho National Laboratory

Battelle Energy Alliance manages INL for the U.S. Department of Energy's Office of Nuclear Energy. INL is the nation's center for nuclear energy research and development, and also performs research in each of DOE's strategic goal areas: energy, national security, science and the environment.

NRC Regulatory Aspects for Nuclear Digital Twins

Thomas G. Scarbrough

Office of Nuclear Reactor Regulation

U.S. Nuclear Regulatory Commission

November 2023

Regulatory Aspects related to DT Technology

- **The regulatory role of the NRC staff will be to review and approve any DT/ML/AI approaches used to meet the NRC regulations for the safe operation of nuclear power plants.**
- **NRC regulatory staff efforts are focused on preparing to make a reasonable assurance finding on the use of such technologies at nuclear power plants.**
- **Along those lines, the NRC staff can best focus our current efforts if we are able to obtain information via early engagement on the possible applications of these technologies.**
- **The more prepared the NRC staff are for a particular type or method of application, the more efficient and effective the NRC staff can be in terms of time and resources to reach our safety finding.**

U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment

Implementation of DT Technology Background

- **NRC specifies regulatory requirements for applicants and licensees of nuclear power plants to establish IST programs for pumps, valves, and dynamic restraints (snubbers) to provide reasonable assurance of operational readiness to perform their safety functions in nuclear power plants that use water in their cooling systems.**
- **ASME established provisions for IST programs for pumps, valves, and dynamic restraints that perform safety functions for water-cooled reactors in the ASME OM Code.**
- **NRC incorporates by reference ASME OM Code in 10 CFR 50.55a with applicable conditions for water-cooled nuclear power plants.**
- **Current US water-cooled nuclear power plants typically operate for 18 to 24 months before shutting down to perform refueling activities and to test components that cannot be tested during plant operation.**

U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment

Implementation of DT Technology Current Activities

- **Some new and advanced designs of nuclear power plants vary significantly from current water-cooled reactors with less opportunities for testing components during plant operations or refueling outages.**
- **Condition monitoring rather than specific testing of components might be needed or proposed by new and advanced reactor applicants or licensees based on the reactor design or operations.**
- **ASME is preparing a new OM-2 Code for IST programs in new and advanced reactors for components that (1) generate, allow, throttle, or isolate fluid flow; (2) provide pressure relief; or (3) establish dynamic restraint to ensure the structural integrity of piping systems and their components.**
- **Scope of OM-2 Code is broader than pumps, valves, and dynamic restraints for ASME OM Code because new and advanced reactors might use different components than current water-cooled reactors.**
- **OM-2 Code allows condition monitoring of components that could include DT technology where justified by applicant or licensee and approved by NRC.**

Implementation of DT Technology
Future Activities

- **ASME is planning to issue new OM-2 Code in 2024.**
- **NRC is preparing a Regulatory Guide to accept ASME OM-2 Code with applicable conditions.**
- **Applicants and licensees for new and advanced reactors may specify use of ASME OM-2 Code as accepted in the NRC regulatory guide for IST programs in their licensing applications.**
- **Applicants and licensees for new and advanced reactors may propose the use of DT technology as part of their IST condition monitoring programs for review and approval by the NRC.**
- **Licensees of current water-cooled nuclear power plants might request use of ASME OM-2 Code as part of their IST programs.**

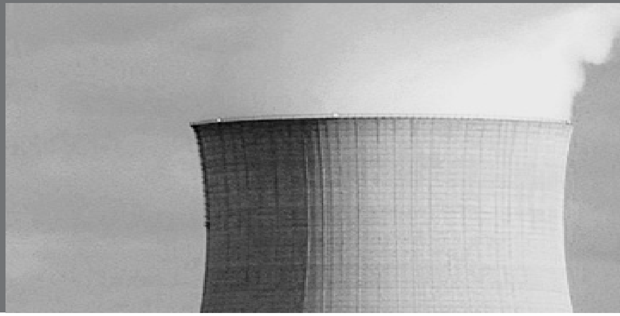
Acronyms

- **AI/ML: Artificial Intelligence / Machine Learning**
- **ASME: American Society of Mechanical Engineers**
- **CFR: Code of Federal Regulations**
- **DT: Digital Twins**
- **IST: Inservice Testing**
- **NRC: U.S. Nuclear Regulatory Commission**
- **OM Code: Operation and Maintenance Code**

QUESTIONS?

Successful Application of Condition Monitoring Technologies into Nuclear Power Plants

NRC-INL Workshop – November 28, 2023



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Curtiss-Wright – Long History of Innovation

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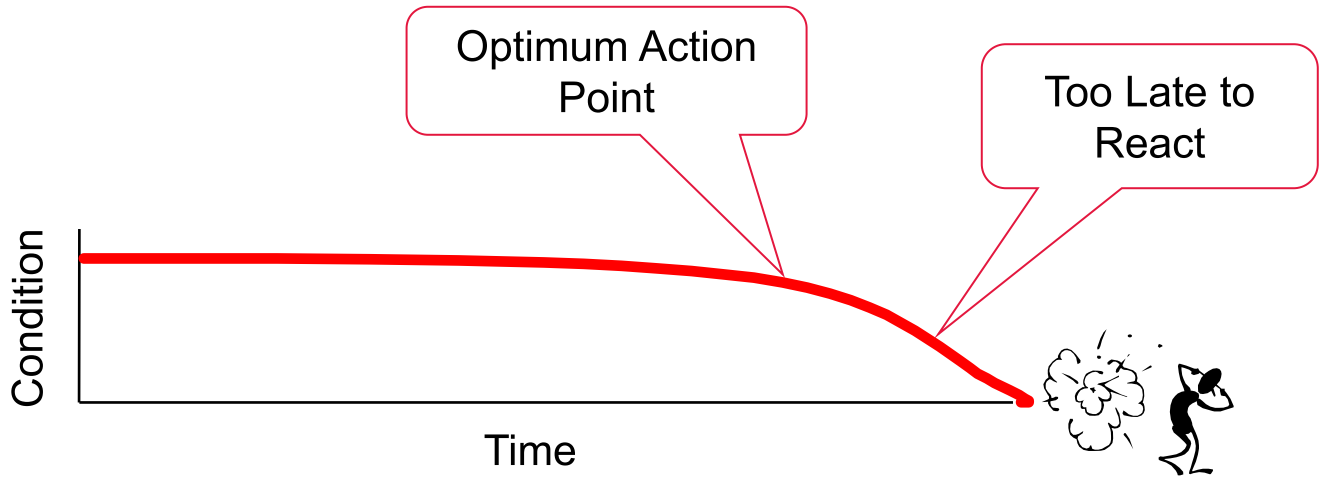
Envisioning the Possibilities – Condition Monitoring

“Having a longer reaction window gives us time to plan for maintenance and repairs. That’s the brass ring we’re ultimately striving for: we want to get out of reaction mode and into predictive mode.”

We went from 27 engineers down to four, but we needed advanced software technology to make it possible. The best megawatts saved are the ones you don’t lose in the first place. The Curtiss-Wright tools generate information to prevent a shutdown or minimize power reductions.”

“I’m surprised an open 3” valve would lose that much generation, but that’s the highest value steam we’ve got that was blowing through it so it makes sense.”



Everything was running well until it wasn’t!

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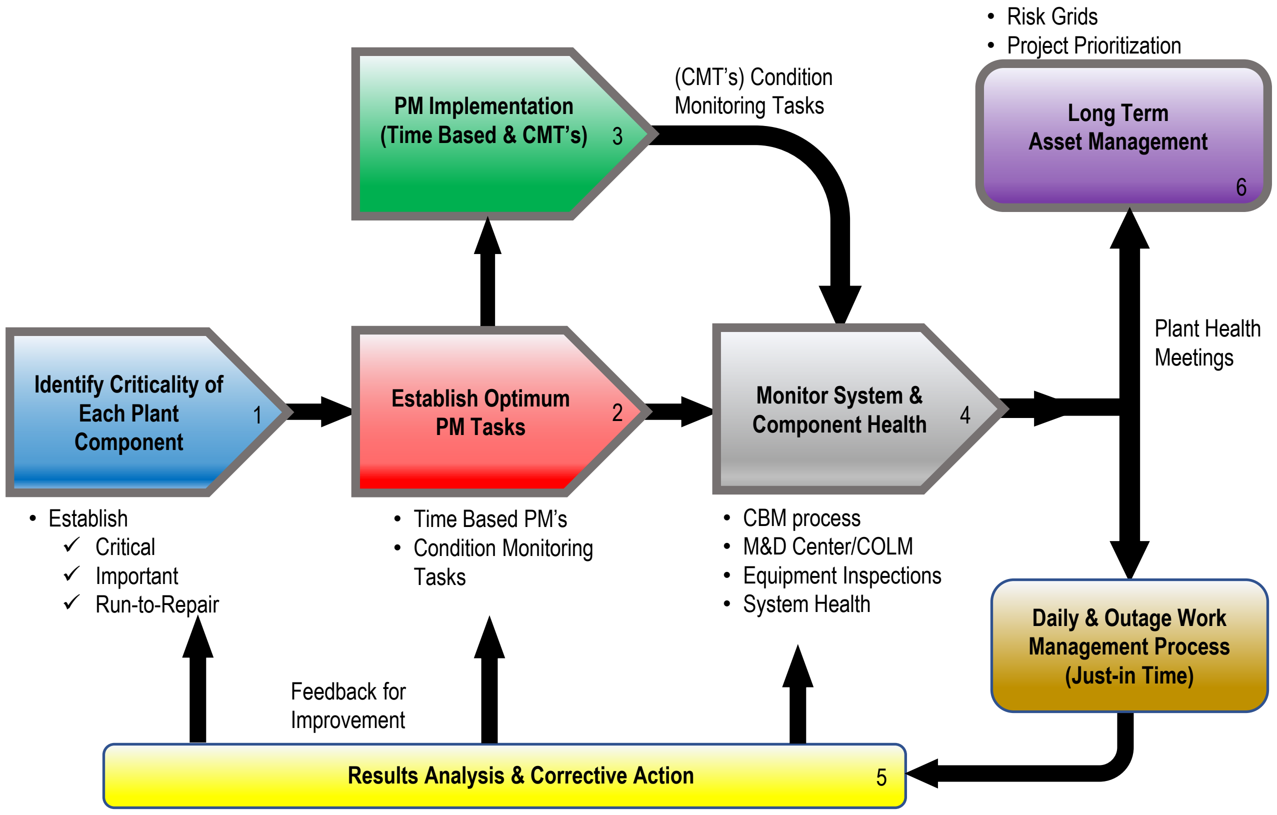
Achieving the Possibilities – Condition Monitoring Process

"The process of monitoring a parameter of condition in machinery in order to identify a significant change which is indicative of a developing fault."

-- Wikipedia



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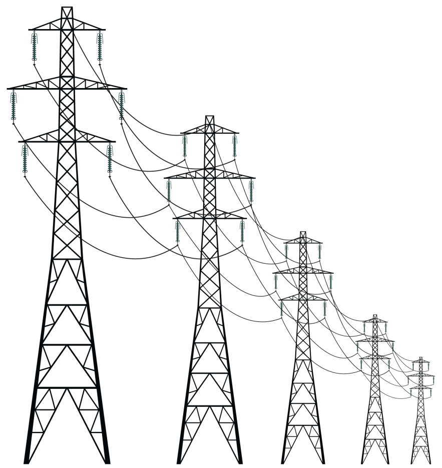
Achieving the Possibilities – Drivers

- **Business Drivers**
  - Client assets
  - Advanced, competitive technology
- **Outcomes: Condition Monitoring**
  - Improve reliability and availability
  - Lower maintenance costs
  - Increase MW production
  - Diagnostics and asset health management
  - Prioritizes maintenance issues



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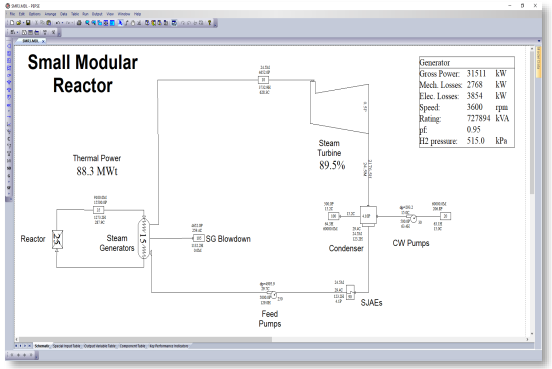
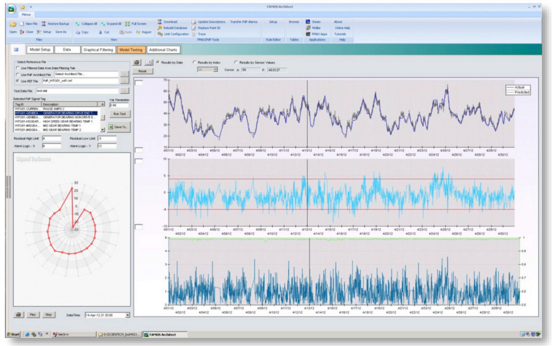
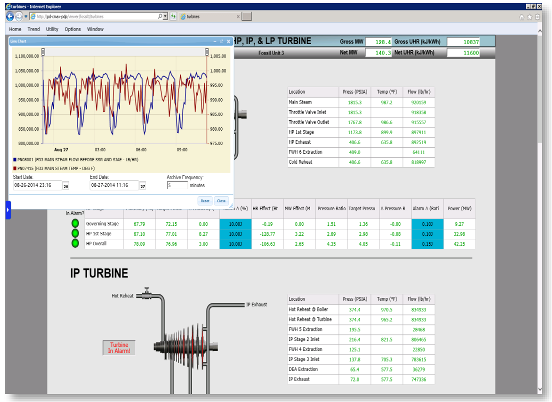
Achieving the Possibilities - Awareness

- **The starting point: Awareness!**
- **Understanding the Business Model**
  - Regulated and De-regulated
  - Operation and Maintenance Support
  - Management Commitment
- **Data Quality / Reliability**
- **Mechanisms for Early Fault Detection and Resolution**
- **Asset Risk Management**







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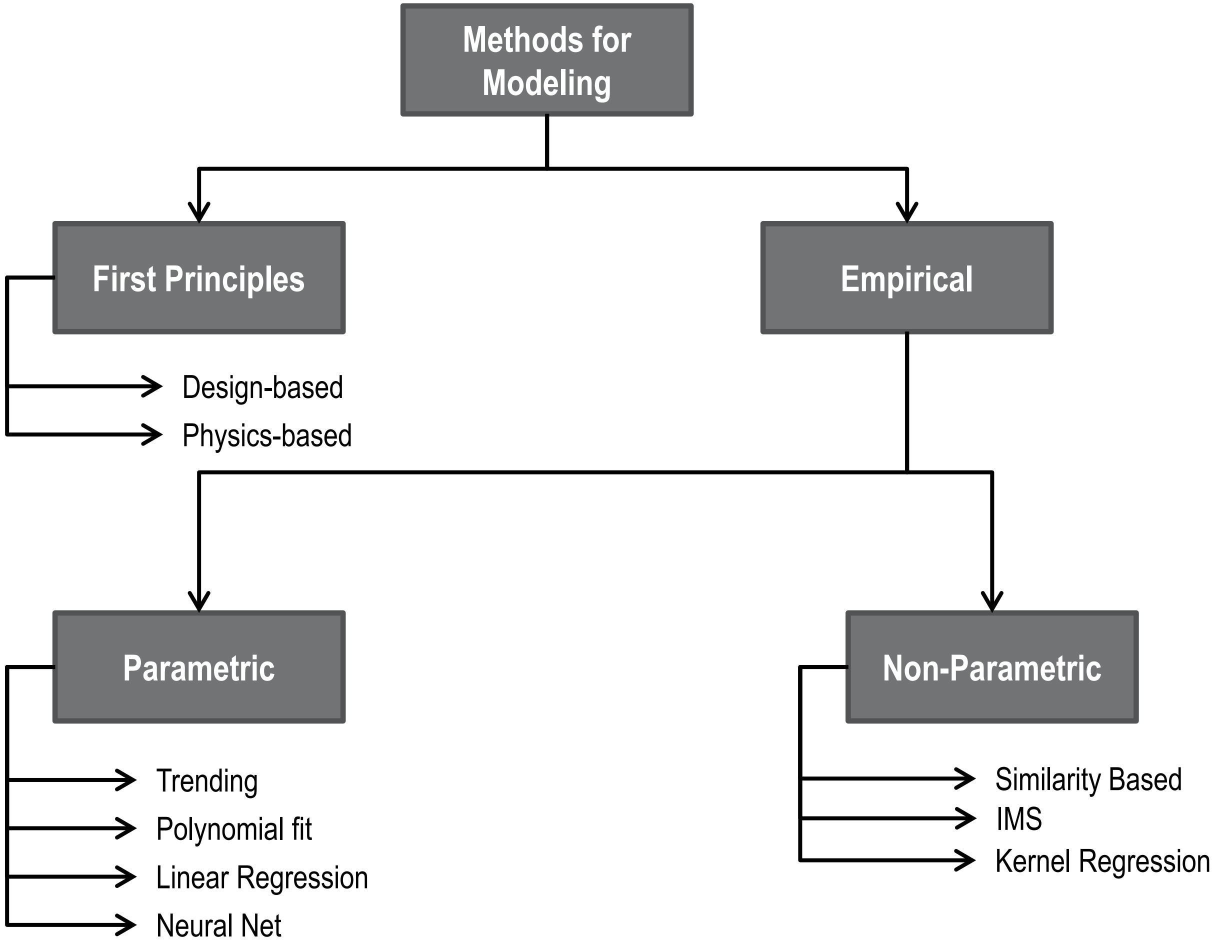
Achieving the Possibilities - Modeling Methods



Achieving the Possibilities - Curtiss-Wright's FAMOS Suite

- **Fleet Asset Management & Optimization Solutions**
  - An integrated solution set
  - Applications for analyzing and optimizing plant performance
  - Condition monitoring and predictive analytics
  - Insight and analytics into critical plant data

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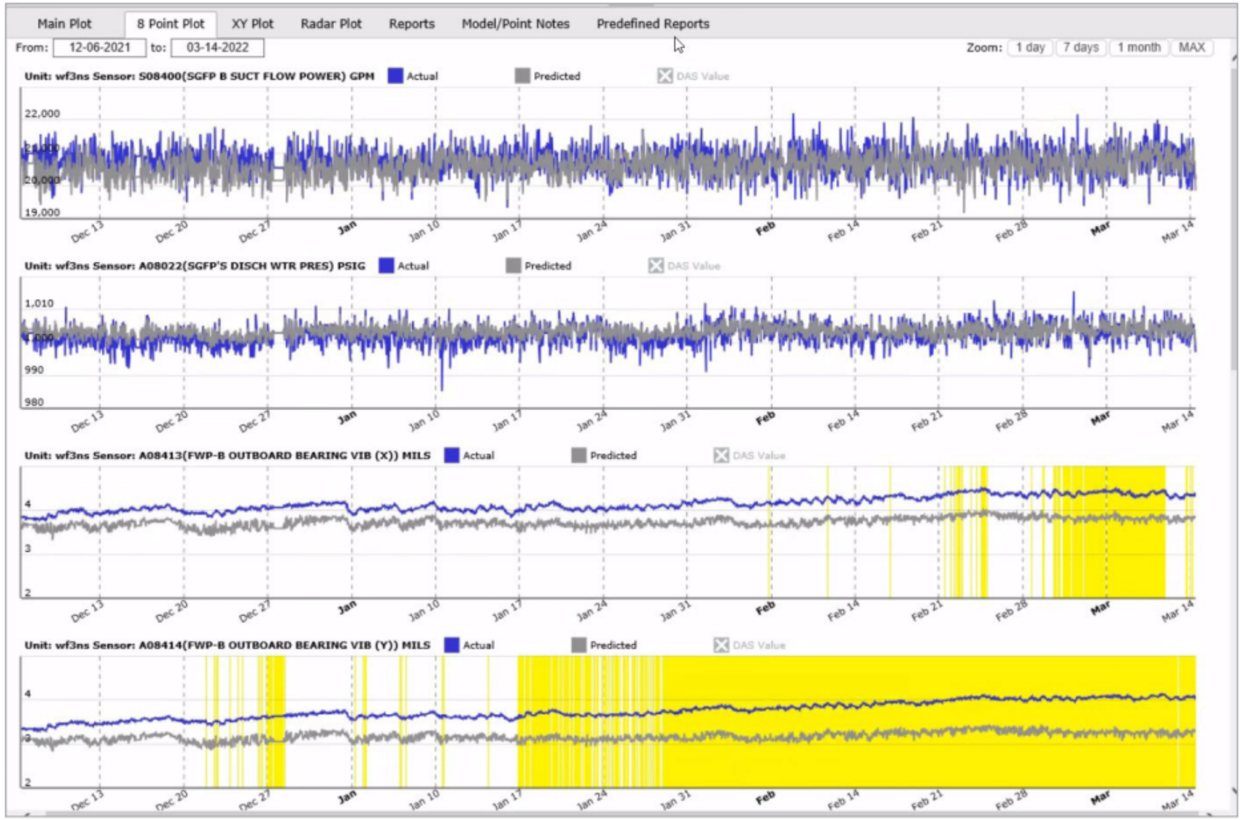
Condition Monitoring Catch – Nuclear Fleet #1

- **Steam generator feedpump outboard bearing failing**



A PdP display that shows an outboard bearing vibration in alarm.

"Having a longer reaction window gives us time to plan for maintenance and repairs. That's the brass ring we're ultimately striving for: we want to get out of reaction mode and into predictive mode."
– FAMOS customer

www.cw-connect.com/resources/curtiss-wright-receives-entergy-premier-vendor-award-implementation-condition-monitoring

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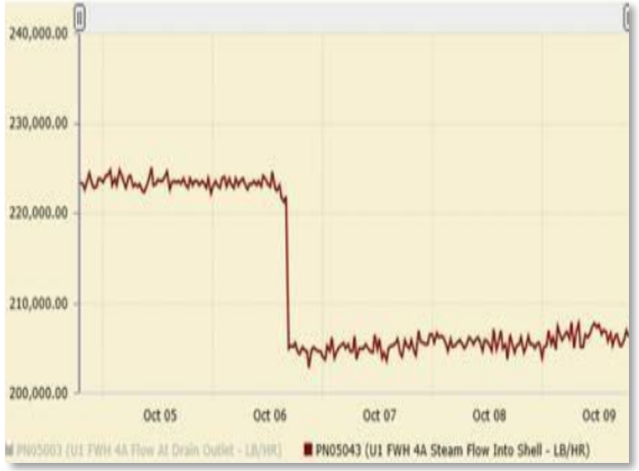
Condition Monitoring Catch – Nuclear Fleet # 2

- **Software Predicated Best Achievable Performance – FWH 4A:**
  - Generation: 1112.8 MWe
  - Extraction Steam Pressure to FWH 4A: 142.8 psia
  - FWH Shell Steam Pressure 135.4 psia
- **Software Simulated FWH 4A Bellows Leakage:**
  - Generation: 1106.5 MWe
  - Extraction Steam Pressure to FWH 4A: 140.0 psia
  - FWH Shell Steam Pressure 127.74 psia

"We went from 27 engineers down to four, but we needed advanced software technology to make it possible. The best megawatts saved are the ones you don't lose in the first place. The Curtiss-Wright tools generate information to prevent a shutdown or minimize power reductions."
– FAMOS customer



www.cw-connect.com/resources/case-study-exelon

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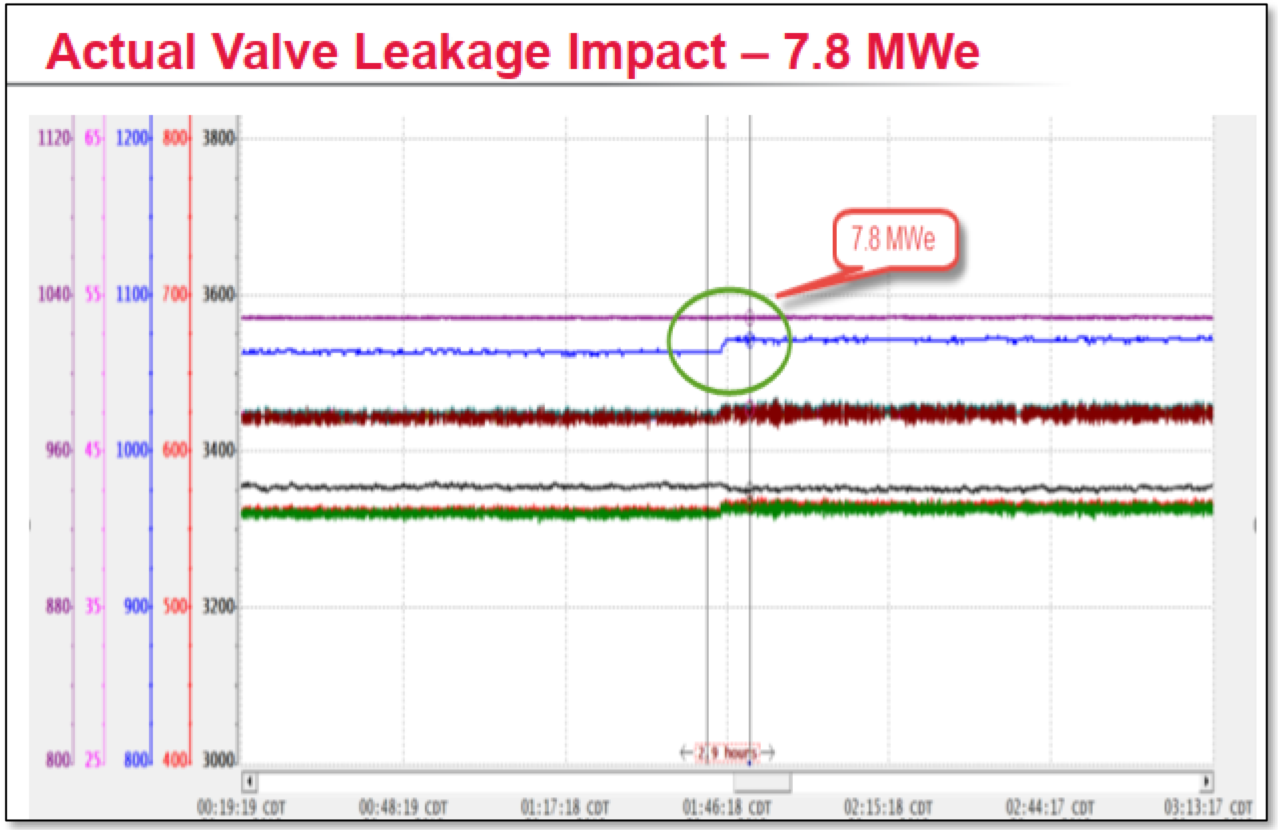
Condition Monitoring Catch – Nuclear Fleet #3

- **Main steam bypass valve open – 8MW impact**



"I'm surprised an open 3" valve would lose that much generation, but that's the highest value steam we've got that was blowing through it so it makes sense."
– FAMOS customer

www.cw-connect.com/resources/video-cycle-isolation

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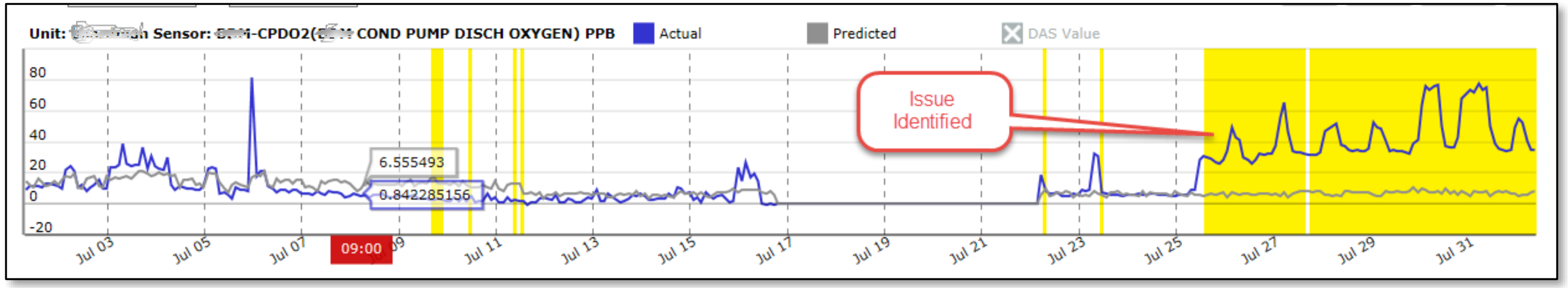
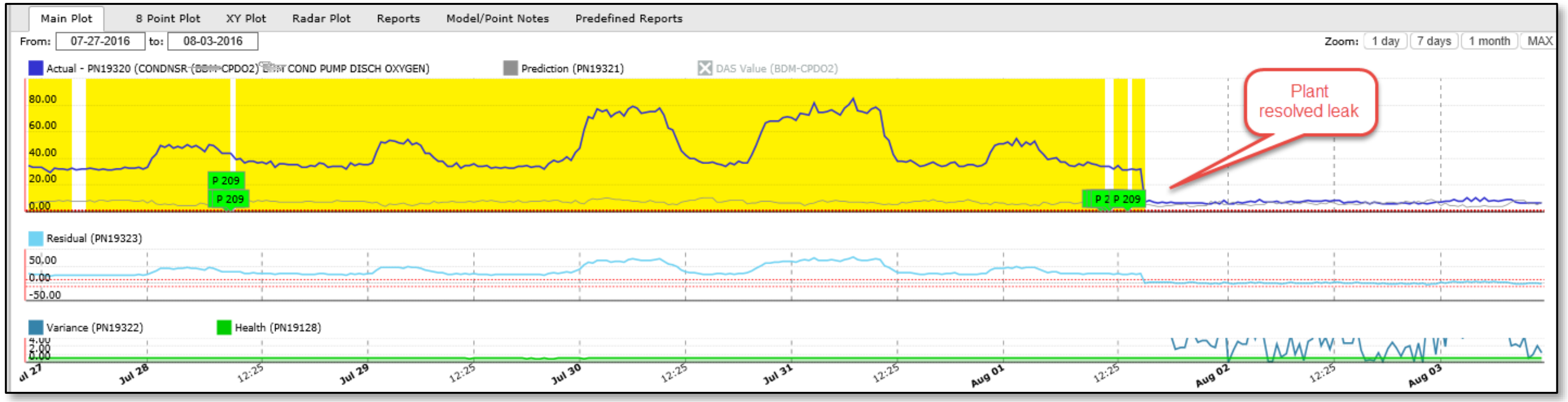
Dissolved O2 in Condensate from Leak at Condensate Pump





“Before we acquired FAMOS, we had a reactive approach for resolving issues. Now FAMOS is our primary solution for performance monitoring and diagnostics, and we can catch issues before they cause equipment to fail. We are more proactive and much more productive because we can analyze how well equipment is performing before problems occur.”
– FAMOS Customer

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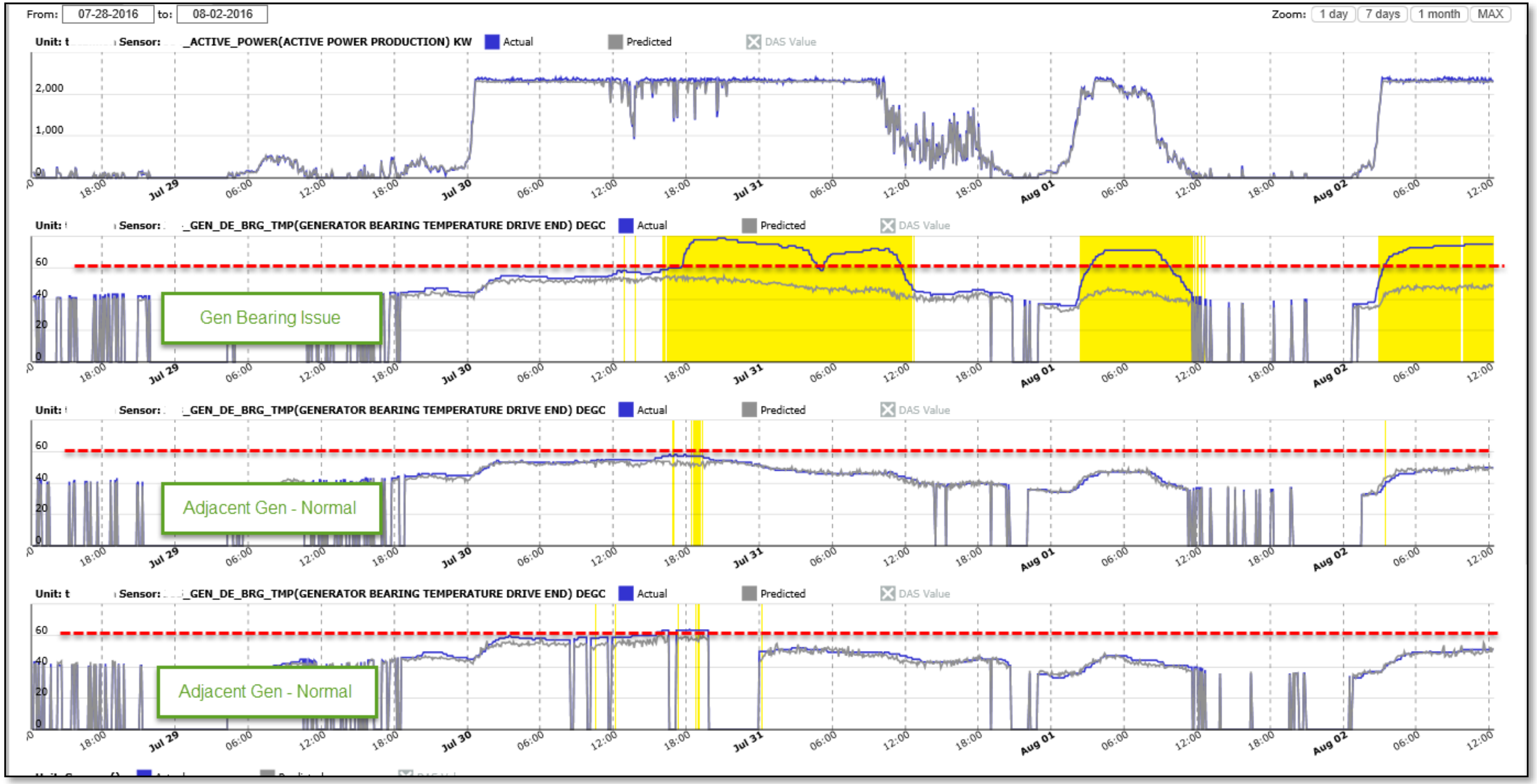
Generator Bearing Issue



www.cw-connect.com/solutions/performance-operations/famos/equipment-anomaly-detection

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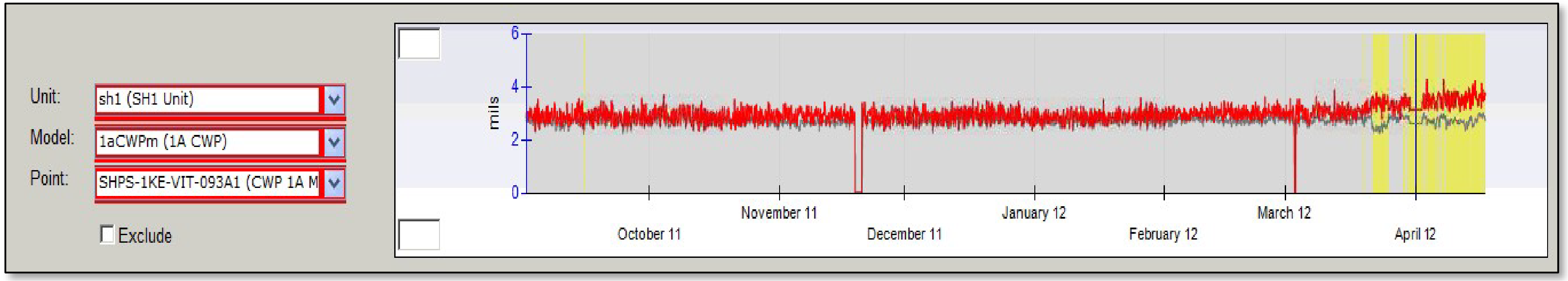
Ignoring Condition Monitoring Alerts

You Don’t Want…

Your Face Here

Example – Ignored Catch Results

- The CWP 1A Motor CH A Vibration began trending up in March. In April, it was noted by PdP that the vibrations increased ~1 mil above normal and were continuing to rise.



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Cooling Water Pump Vibration – Ignored Catch Results

- After returning the unit to service following an outage, the vibrations continued to ramp higher. In September, the CW pump studs failed due to fatigue and the pump was forced offline, resulting in a two-day outage. Loose pump supports and worn-out anchors were found by plant staff after the outage.

- PdP found the anomaly and noted that there was an issue with the pump six months prior to the actual failure and even prior to the scheduled outage. The replacement energy costs for the forced derate and subsequent additional outage, was $1,204,158.

The Possibilities are Endless – Condition Monitoring

"Having a longer reaction window gives us time to plan for maintenance and repairs. That's the brass ring we're ultimately striving for: we want to get out of reaction mode and into predictive mode."

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The Power of Condition Monitoring!

- **Extends equipment lifespans by catching and addressing problems early.**
- **Minimizes unplanned downtime, saving both time and money.**
- **Enhances safety by reducing the changes of equipment failures leading to accidents.**

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Digital Twins for Prognostics and Health Management in Nuclear

Presented at

Virtual Workshop on Structural Health Management for Nuclear Power Plants

Session 2: Diagnostic and Prognostic Tools for Condition Monitoring and Structural Health Management

Wednesday, November 28, 2023

Presenter: Dr. Naresh Iyer, Principal Scientist, GE Research

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Agenda

- Context setting
- GEMINA program: an overview
- Cost analysis for prioritizing development of PMx Digital Twins
- Humble AI: assurance-based Digital Twins to enhanced cost savings
- Summary and conclusions

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Context Setting

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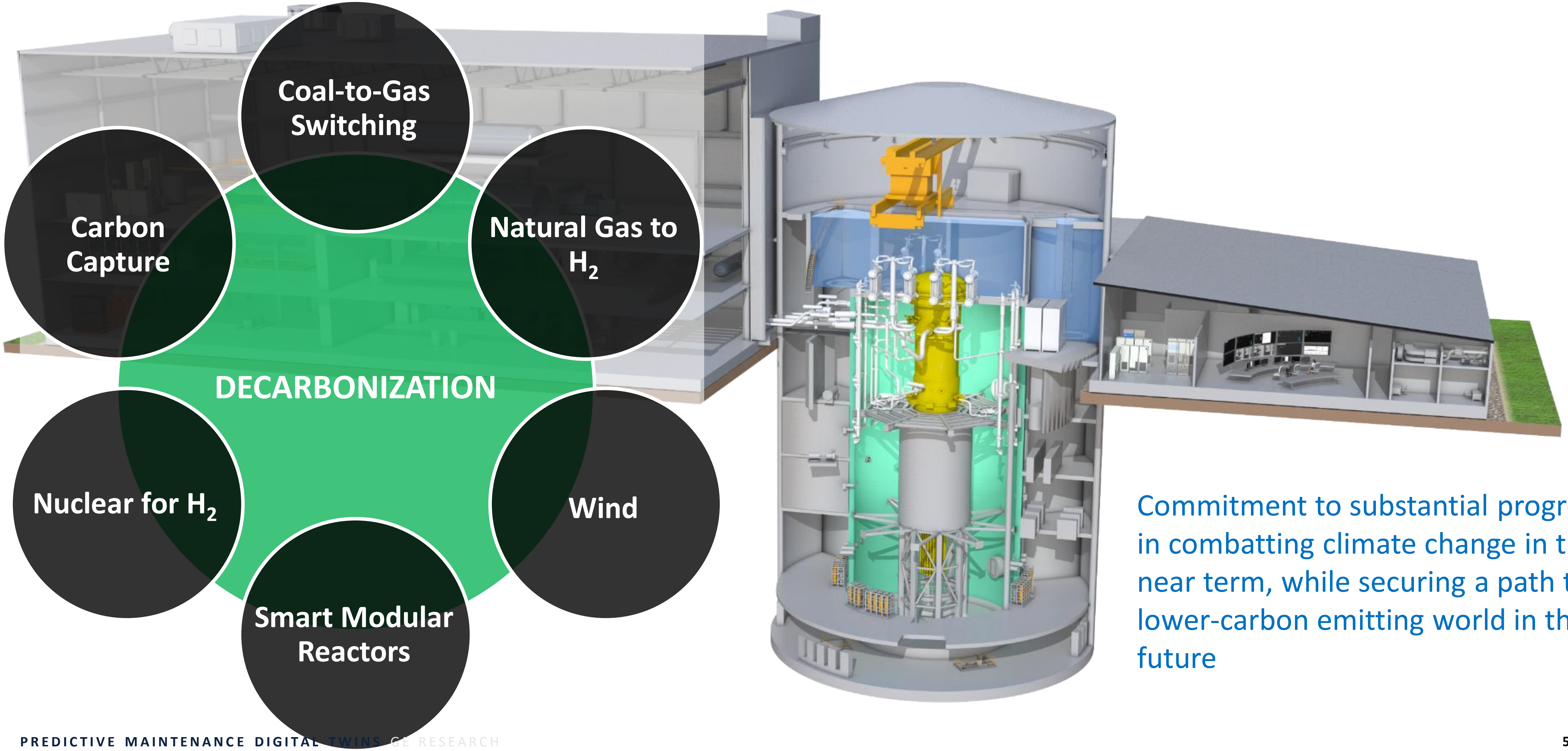
Decarbonization

front and center of GE's energy transition strategy



Commitment to substantial progress in combatting climate change in the near term, while securing a path to lower-carbon emitting world in the future

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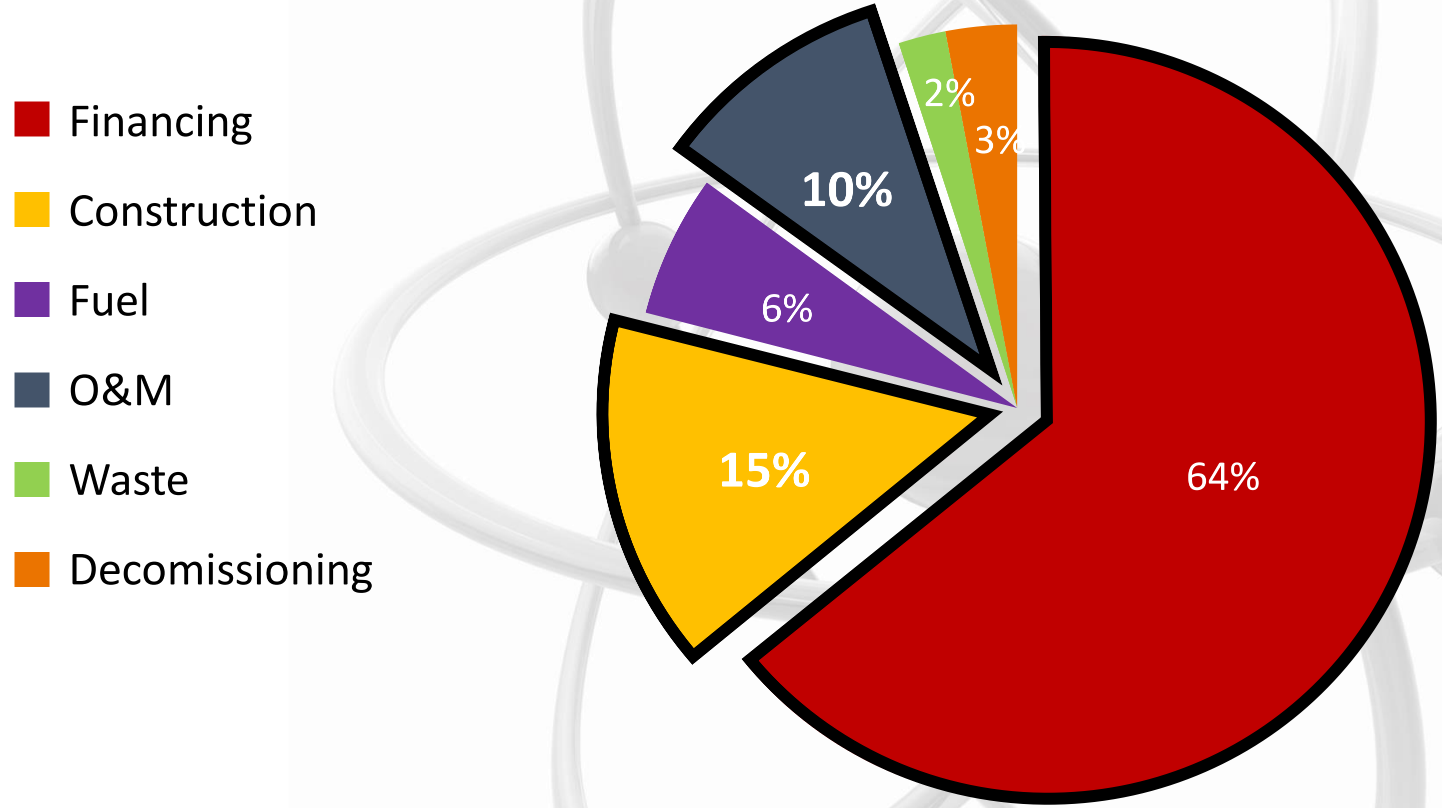
But… Nuclear needs to be cost competitive for adoption



Three Reasons

1. High LCoE (One of a kind plants are expensive)
2. Nuclear Waste &
3. Safety impressions

A MAJOR CHUNK OF NUCLEAR ELECTRICITY COSTS COMES FROM CAPEX & OPEX

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Reducing CAPEX & OPEX in future BWRX-300 Fleet

DESIGNED TO
MITIGATE LOCA

COMPETITIVE
LCOE

REDUCED
STAFF

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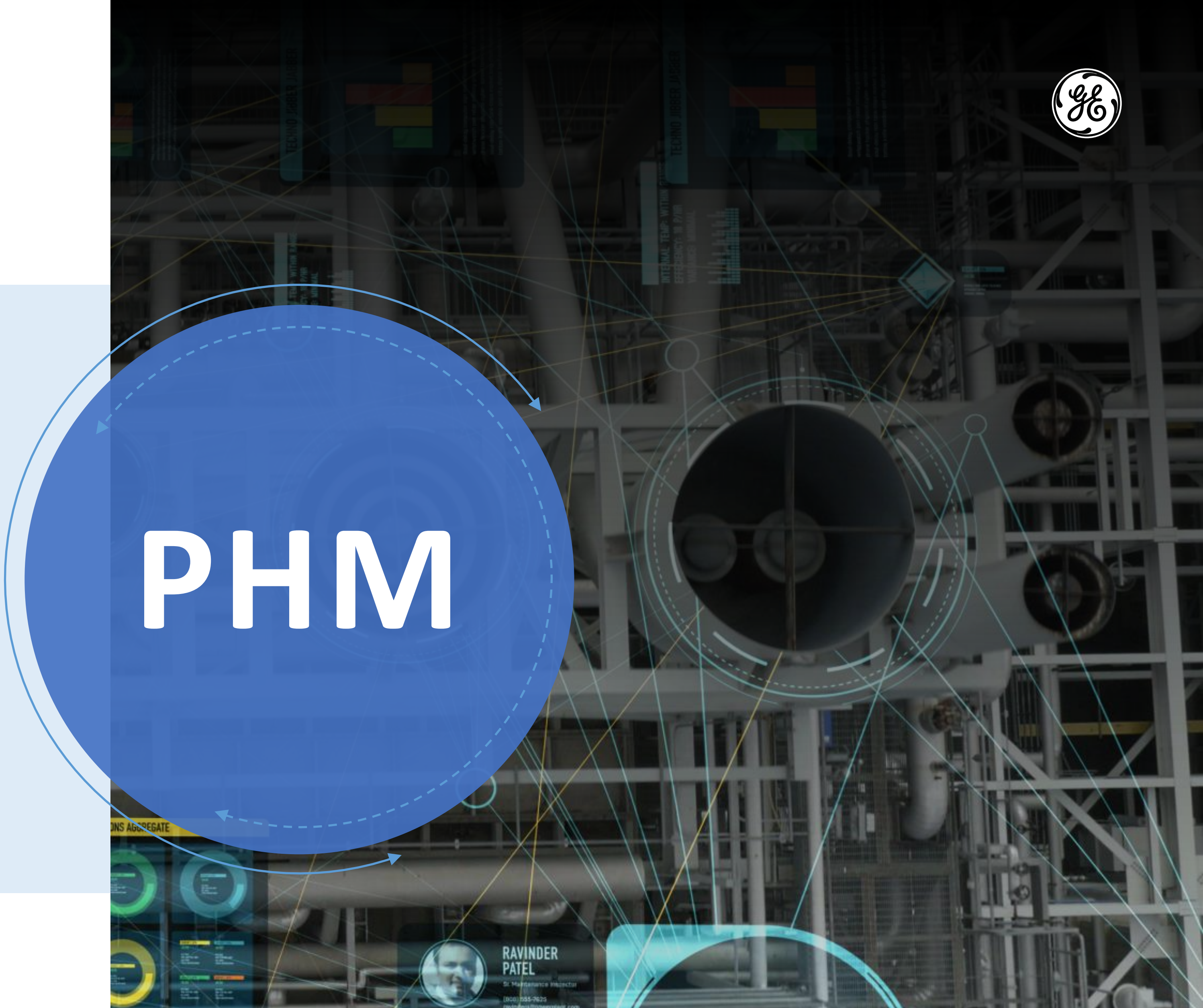
O&M cost reduction

- **Remote monitoring**
- **Predictive maintenance**
- **Automation**
- **Optimized scheduling and central crews**



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GEMINA: overview

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AI-enabled Predictive Maintenance Digital Twins

for Advanced Nuclear Reactors

ARPAE GEMINA

Carbon free nuclear energy can be cost-competitive…

O&M costs can be reduced through AI and automation…

…IF we can mature AI to be trustable for nuclear applications!

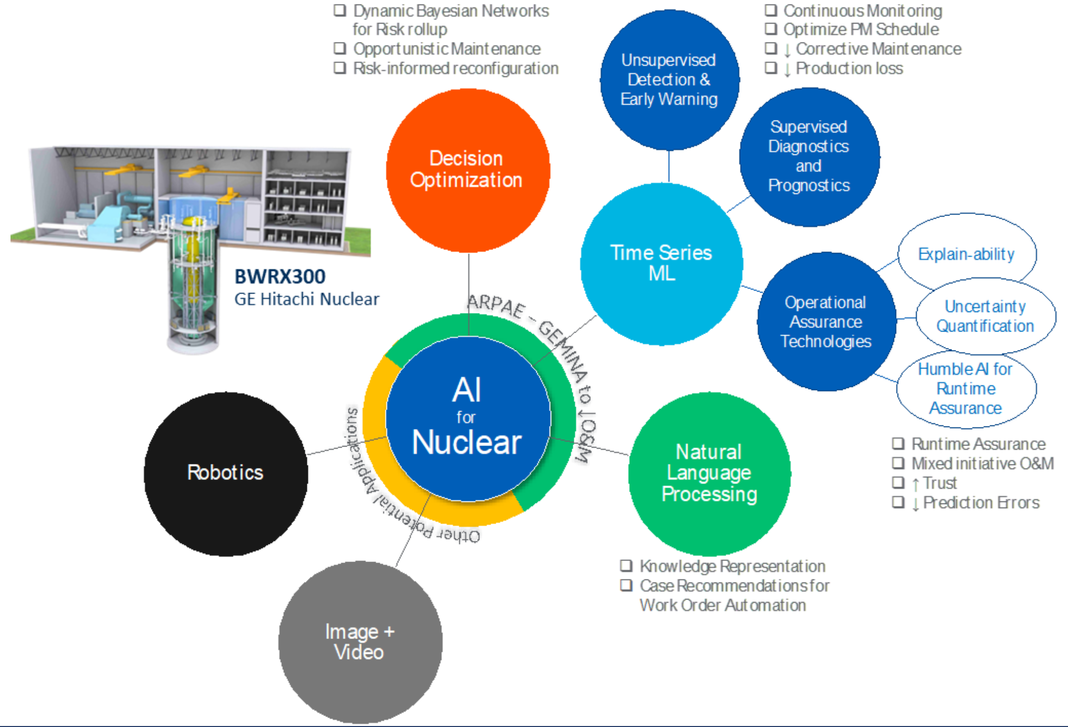
PROGRAM IMPACT

AI-enabled predictive maintenance **to reduce O&M labor costs to $2/MWh** in an Advanced Nuclear Reactor

PROGRAM TARGETS

Metric	From	To *(estimated)*
Automation ↓ labor costs	*None*	Automated workorders … ↓ Planning staff by 50% (10FTE) Online calibration … ↓ Tech staff 75%, admin 25% (16FTEs)
Predictive Maintenance ↓ labor & mat'l	*Alarms*	↓Forced outages & trips … AI-driven predictive algorithms ↓ Labor headcount 35%
Runtime Assurance	*Human*	Humble & explainable AI … quantify uncertainty to establish trust in the models & encourage automation

TECHNOLOGY SUMMARY



Technology Summary

- **Reactor Operations –** Physics-informed machine learning, sensor optimization
- **Reactor Health –** Causal, humble & explainable AI for predictive maintenance
- **Decision Making –** Autonomous risk-informed decisions for reconfiguration & maintenance

TEAM

THE UNIVERSITY OF TENNESSEE KNOXVILLE

OAK RIDGE National Laboratory

Constellation

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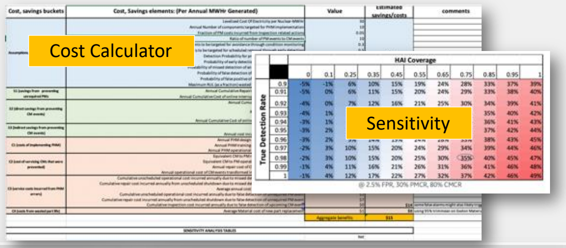
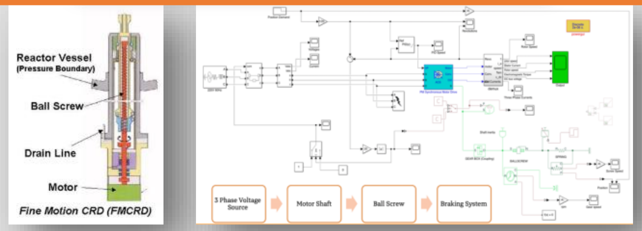
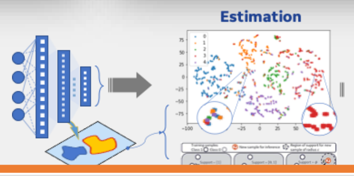
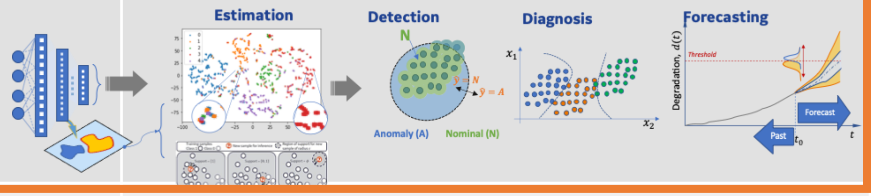
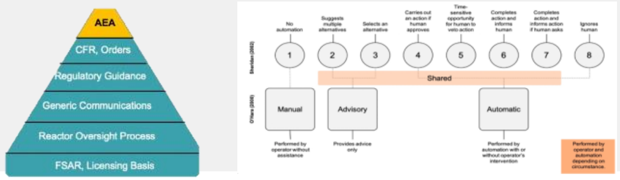
Approach and Outcomes

	WHAT	WHY	CAPABILITIES	
	Cost impact model	• Prioritization based on maintenance (labor and material) costs • Derive performance targets for health algorithms to achieve net positive ROI	• Real cost data from existing fleets over several years • System level as well as plant level ROI analysis • Sensitivity analysis w.r.t. various assumptions or estimates	
	Operational/Health Digital Twins for servo driven FMCRD mechanism	• Servo driven mechanisms are new designs with limited ops experience • FMCRDs key means to accomplish load following, i.e. heavier usage	• Allows to inject relevant failure modes under realistic operational profiles • Effects of noise and varying severity levels	
	Health Twins	• Early detection allows for opportunistic maintenance • Minimize CMs, reduce PM frequencies	• A number health twins under development (see next chart) as applicable to BWRX-300	
	Humble-AI (HAI) for runtime assurance	• How much to trust a prediction in the runtime • Evidence based explanations	• HAI for all types of health prediction methods • Actionable predictions	
	Assessment of current regulatory guidance towards DTs	• Understand current guidance As applicable to predictive maintenance digital twins • Identify gaps and constraints	• Comprehensive analysis • Active discussions with NRC, EPRI, and other OEMs	

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Component Selection

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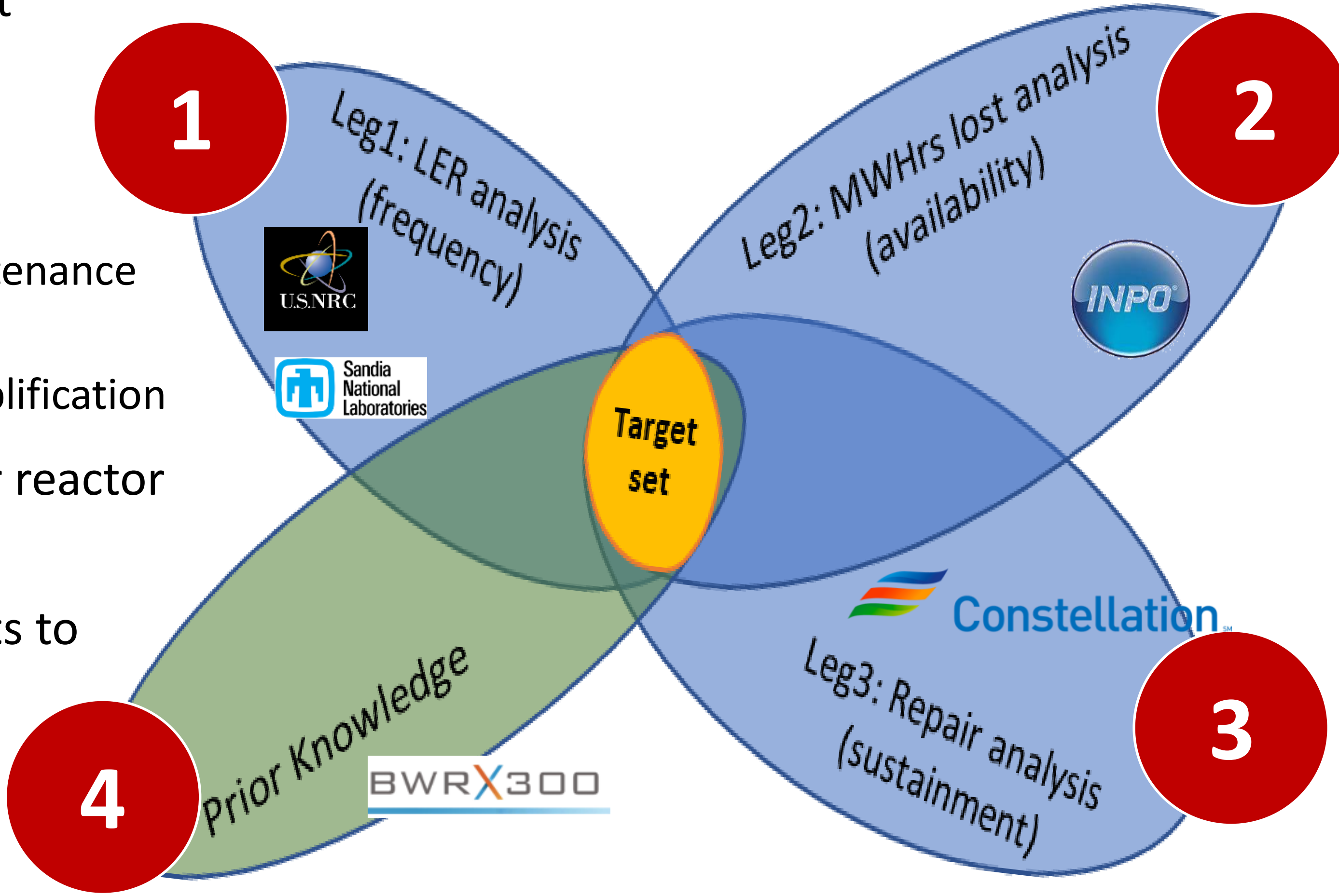
Predictive Maintenance Target Selection

Focused on Nuclear Power Generation

- Target component selection from 3 independent analyses:
  - ✓ Leg 1: Frequency analysis from operational data
  - ✓ Leg 2: Downtime analysis from operational data
  - ✓ Leg 3: Corrective action cost analysis from maintenance data
  - ✓ ….and prior knowledge of BWRX300 design simplification
- Down select critical components from above for reactor and BOP
- ID critical failure modes for selected components to target for modeling



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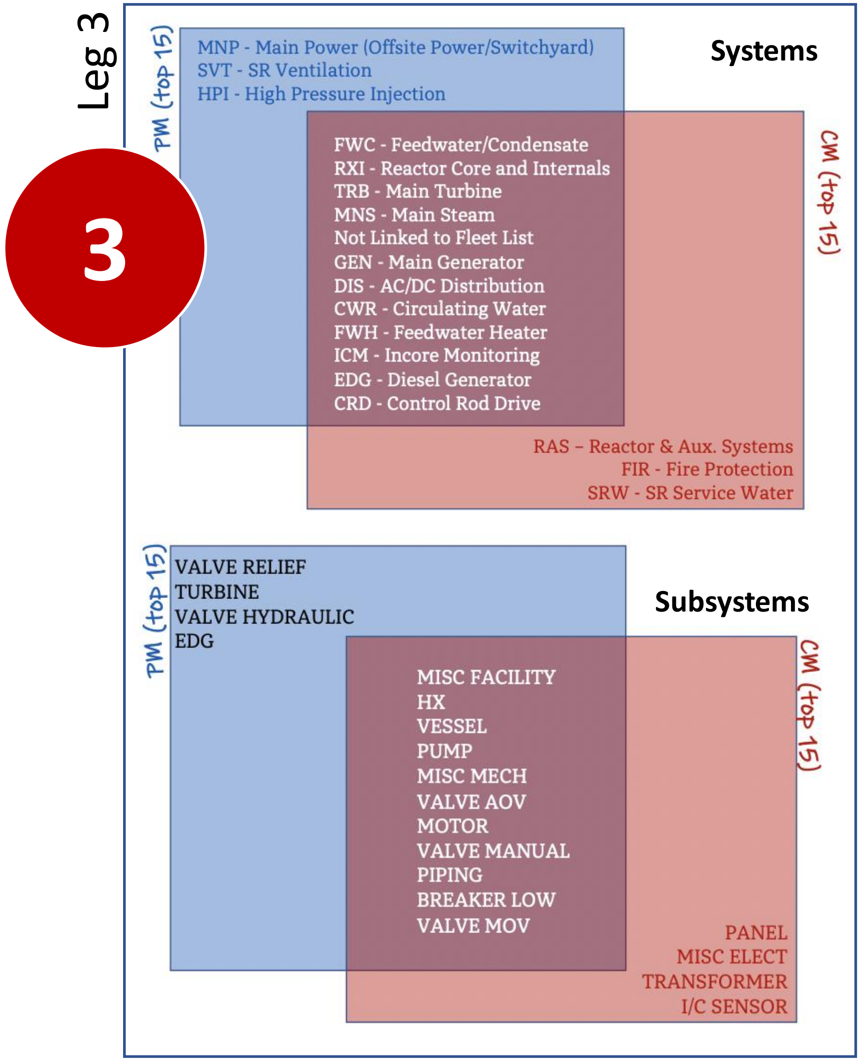
Target Selection - Outcome



1 2

Leg 1+2

- Condensate System + Heat exchanger, condenser, steam generator
- Condenser System + Heat exchanger, condenser, steam generator
- Control Rod Drive System + Rod drive mechanism, hydraulic control unit
- Feedwater System+ Pumps, eductors
- Feedwater System+ Valves, dampers
- Main Generator Output Power System + Transformers, shunt reactors
- Main Generator System + Generators, inverters, motor generators
- Main Turbine System + Turbines (steam, gas)
- Main/Reheat Steam System + Valves, dampers
- Medium Voltage Power Sys. (601V-35kV) + Transformers, shunt reactors
- Nuclear Fuel Services System + Fuel assembly

4

BWRX300 Design

& suspect vulnerabilities

Initial focus

1. FMCRD
2. Valves
3. FW pump
4. I&C
5. Heaters & Heat exch.

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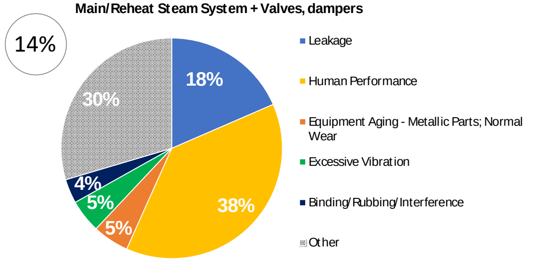
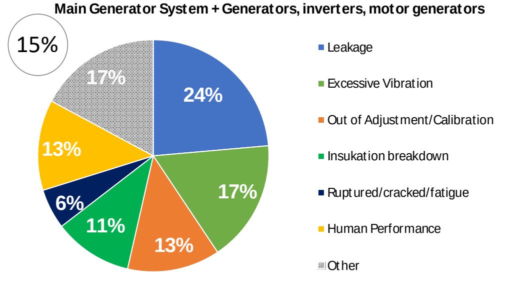
Failure Causes for Top Offenders

Analysis of INPO reports of Existing BWR fleets

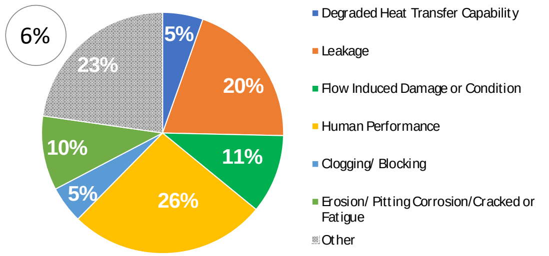
Main/Reheat Steam System + Valves, dampers



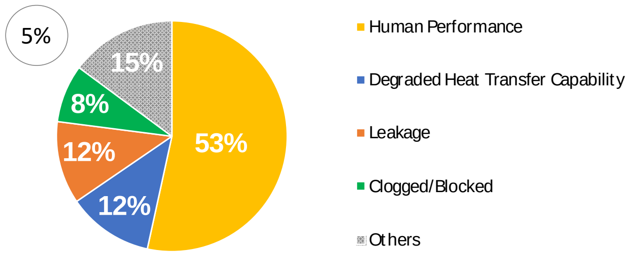
Main Generator System + Generators, inverters, motor generators



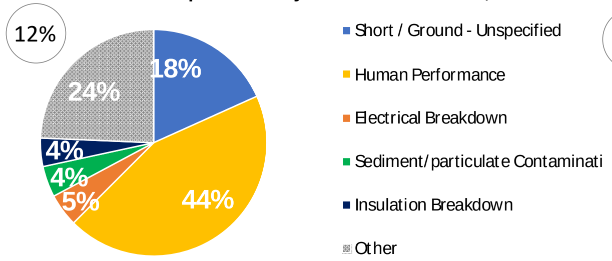
Condensate System+Heat exchanger, condenser, steam generator



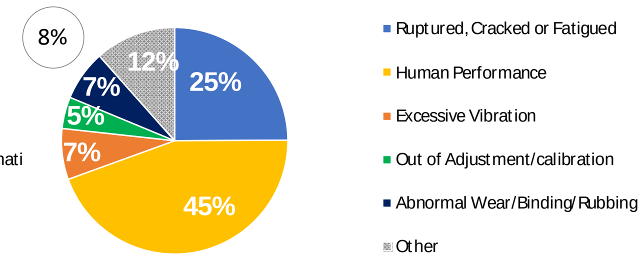
Condenser System+Heat exchanger, condenser, steam generator



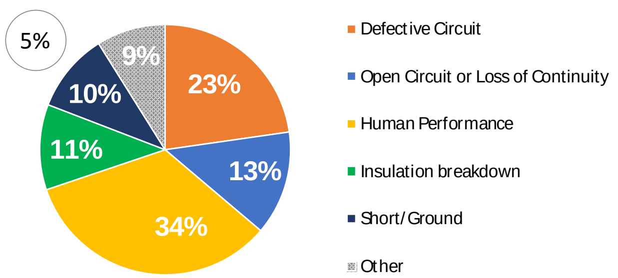
Main Generator Output Power System + Transformers, shunt



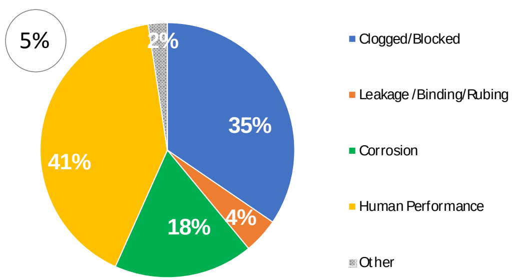
Main Turbine System+Turbines (steam, gas)



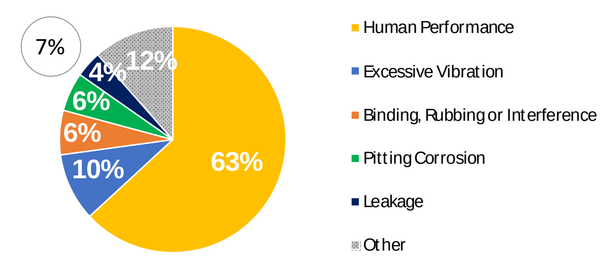
Medium Voltage Power Sys. (601V-35kV) + Transformers, shunt



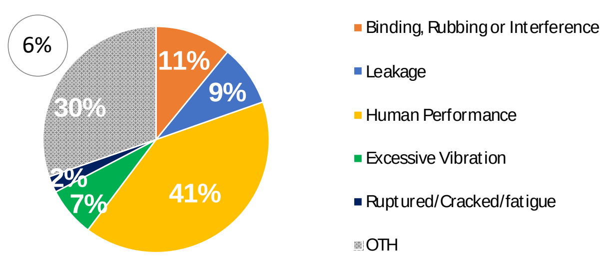
Nuclear Fuel Services System + Fuel Assembly



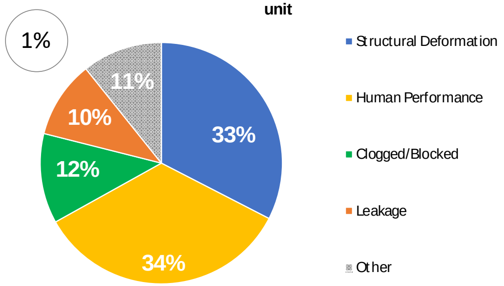
Feedwater System+Pumps, eductors



Feedwater System+Valves, dampers



Control Rod Drive System + Rod drive mechanism, Hydraulic Control unit



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Cost analysis for PMx

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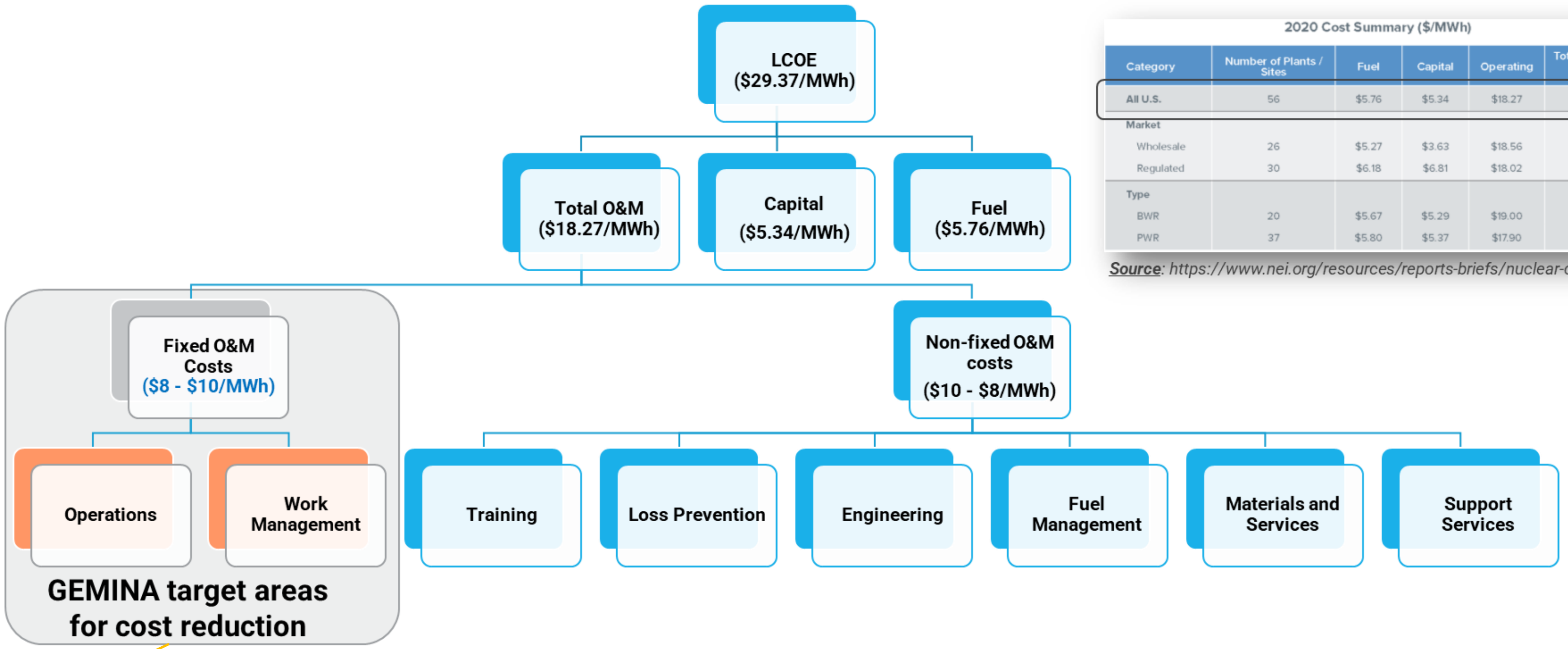
GEMINA: Cost inefficiencies and targets

The need for an ROI analysis for AI-based PMx



2020 Cost Summary ($/MWh)

Category	Number of Plants / Sites	Fuel	Capital	Operating	Total Generating (Fuel + Capital + Operating)
All U.S.	56	$5.76	$5.34	$18.27	**$29.37**
Market					
Wholesale	26	$5.27	$3.63	$18.56	**$27.46**
Regulated	30	$6.18	$6.81	$18.02	**$31.02**
Type					
BWR	20	$5.67	$5.29	$19.00	**$29.96**
PWR	37	$5.80	$5.37	$17.90	**$29.07**

__Source__: https://www.nei.org/resources/reports-briefs/nuclear-costs-in-context

- Primary goal of the program is to bring this cost down to under $2/MWh
- AI-based Predictive Maintenance is a critical driver
- Key question is whether expected savings from PMx are even achievable?

Need ROI analysis for PMx

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PMx Cost Impact Analysis

Formulation

Net savings from application of PMx strategies

$$S = (S_1 + S_2 + S_3) - (C_1 + C_2 + C_3 + C_4)$$

where,

S_1 : savings from reducing unnecessary PvMx or calendar-based scheduled maintenance (PvMs)

S_2 : savings from preventing online failures requiring corrective Mx (CMs)

S_3 : savings from preventing secondary damage from online failures

C_1 : costs of developing and implementing PMx solutions

C_2 : costs from maintenance and other actions taken from failure prognostics

C_3 : costs from errors in component condition-assessment

C_4 : costs from wasted useful life of components

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Data for cost modeling

Actual cost data for system/asset of interest

Multiple years of actual Mx cost data across multiple sites, multiple units, of similar generation capacity

Costs categorized by multiple groupings

- Preventive Mx v/s Reactive Mx costs
- Material v/s Labor costs
- System v/s subsystem Mx costs

Multiple years of data capturing actual operational costs of unscheduled outage events at these sites

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PMx Cost Impact: Outcomes

ASSUMPTIONS
- Designed Generation Capacity: ‘N’ MW
- Capacity Factor : 0.94
- Available PM catch ratio* = 30%
- Available CM catch ratio* = 80%

** Catch-ratios = fraction of events that are feasible for detection and avoidance using AI-based PMx*

Baseline AI-based PMx

- Coverage = 100%
- True Detection rate for PMDT = 80%
- False Detection rate for PMDT = 5%

→ Expected O&M Cost Savings = 19% - 27%

PM Catch-Ratio	CM Catch-ratio: 0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
0	0%	3%	6%	9%	13%	16%	19%	22%	26%	29%	32%
0.1	0%	4%	7%	10%	13%	17%	20%	23%	26%	30%	33%
0.2	1%	4%	8%	11%	14%	17%	21%	24%	27%	30%	34%
0.3	2%	5%	8%	12%	15%	18%	21%	25%	28%	31%	34%
0.4	3%	6%	9%	12%	16%	19%	22%	25%	28%	32%	35%
0.5	3%	7%	10%	13%	16%	19%	23%	26%	29%	32%	36%
0.6	4%	7%	10%	14%	17%	20%	23%	27%	30%	33%	36%
0.7	5%	8%	11%	14%	18%	21%	24%	27%	31%	34%	37%
0.8	5%	9%	12%	15%	18%	22%	25%	28%	31%	34%	38%
0.9	6%	9%	13%	16%	19%	22%	26%	29%	32%	35%	38%
1	7%	10%	13%	17%	20%	23%	26%	29%	33%	36%	39%

AI-based PMx with High Confidence Coverage

- High confidence coverage = 75%
- True Detection rate for high confidence PMx = 98%
- False Detection rate for high confidence PMx = 2.5%

→ Expected O&M Cost Savings = 25% - 37%

PM Catch-Ratio	CM Catch-ratio: 0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
0	0%	4%	8%	12%	16%	20%	23%	27%	31%	35%	39%
0.1	2%	6%	10%	14%	18%	22%	26%	29%	33%	37%	41%
0.2	4%	8%	12%	16%	20%	24%	28%	32%	35%	39%	43%
0.3	6%	10%	14%	18%	22%	26%	30%	34%	37%	41%	45%
0.4	8%	12%	16%	20%	24%	28%	32%	36%	40%	43%	47%
0.5	10%	14%	18%	22%	26%	30%	34%	38%	42%	45%	49%
0.6	12%	16%	20%	24%	28%	32%	36%	40%	44%	48%	51%
0.7	14%	18%	22%	26%	30%	34%	38%	42%	46%	50%	53%
0.8	16%	20%	24%	28%	32%	36%	40%	44%	48%	52%	56%
0.9	18%	22%	26%	30%	34%	38%	42%	46%	50%	54%	58%
1	20%	24%	28%	32%	36%	40%	44%	48%	52%	56%	60%

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Humble AI: assurance-based AI

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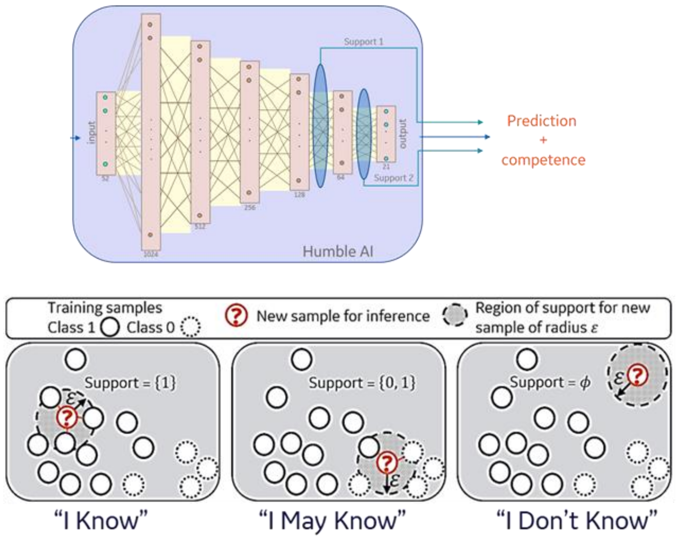
Detection versus confident detection

*Humble AI: Justification-based reliability for ML models**

The most confident predictions find reliable support in feature spaces



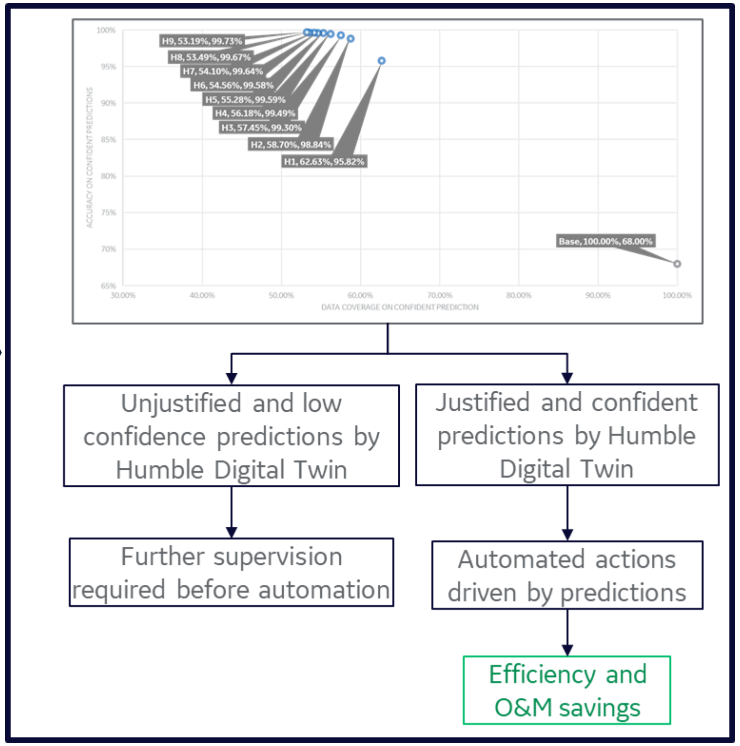
(a): the idea of neighborhood-based support in one or more latent spaces to infer the epistemic status of a classification

Ground Truth: 2
Belief / Classification: 2
Epistemic Status: IK [2]

Ground Truth: 4
Belief/Classification: 4
Epistemic Status: IMK [4, 9]

Ground Truth: 7
Belief/Classification: 1
Epistemic Status: IMK [1, 7]

(b): 3 examples of outcomes from applying epistemic classification to the digit classification problem using MNIST dataset



* Iyer, N., Virani, N. and Yang, Z., 2020, April. Justification-based reliability in machine learning. In Proceedings of the AAAI Conference on Artificial Intelligence (Vol. 34, No. 04, pp. 6078-6085)

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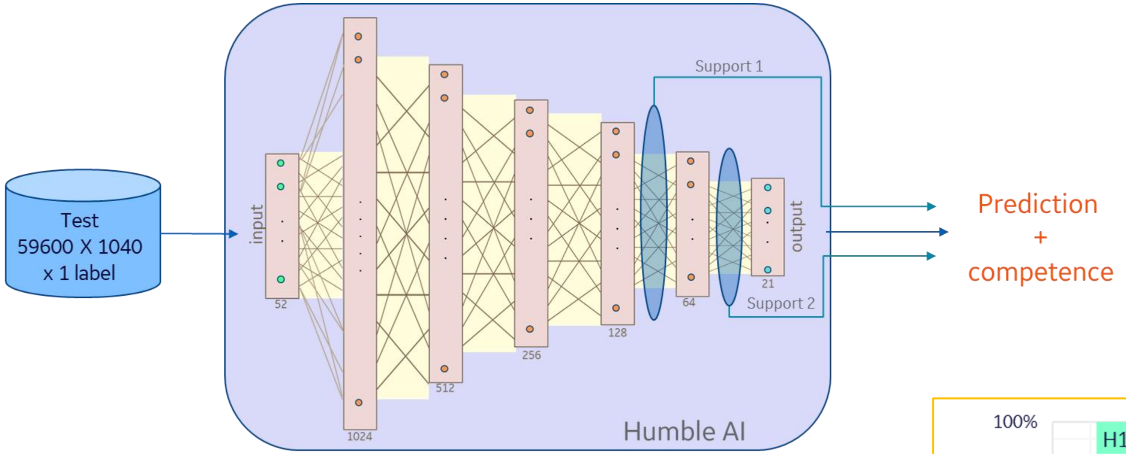
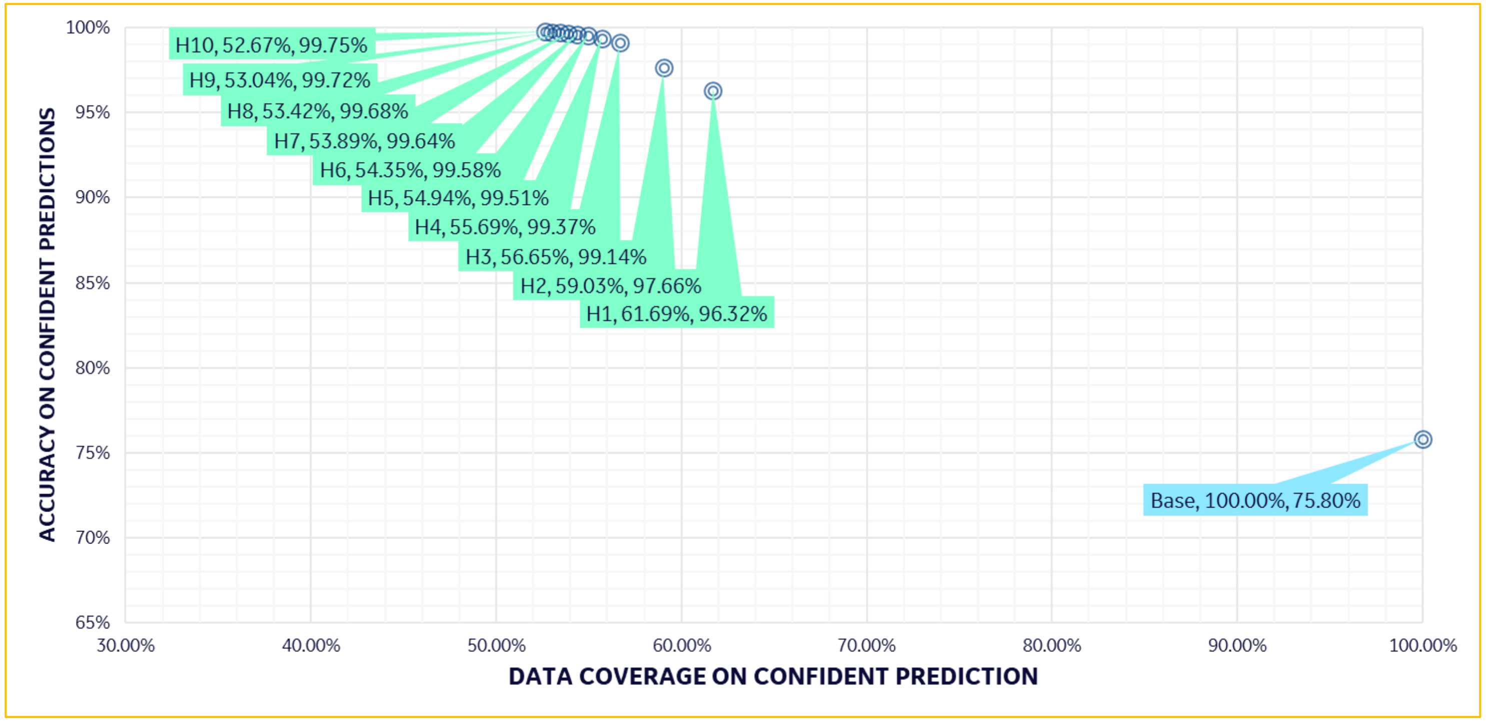
Time-series fault classification [TEP Dataset]





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Summary and Conclusions

- A critical barrier to the adoption of nuclear power tends to be cost
- Digital Twins to enable Predictive Maintenance are critical to impacting O&M costs
- A key barrier to the implementation of AI-based PMx Digital Twins tends to be lack of tools to reliably model and verify the savings
- The talk described a tool/model developed to carry out a cost-benefit/ROI analysis of implementing AI-based PMx Digital Twins
- Stratifying decision making according to high-confidence versus low-confidence predictions helps significantly improve savings from AI-based PMx
- Investments in technologies that assess reliability of AI predictions are very beneficial since it helps significantly improve magnitude of expected cost-savings relative to baseline model

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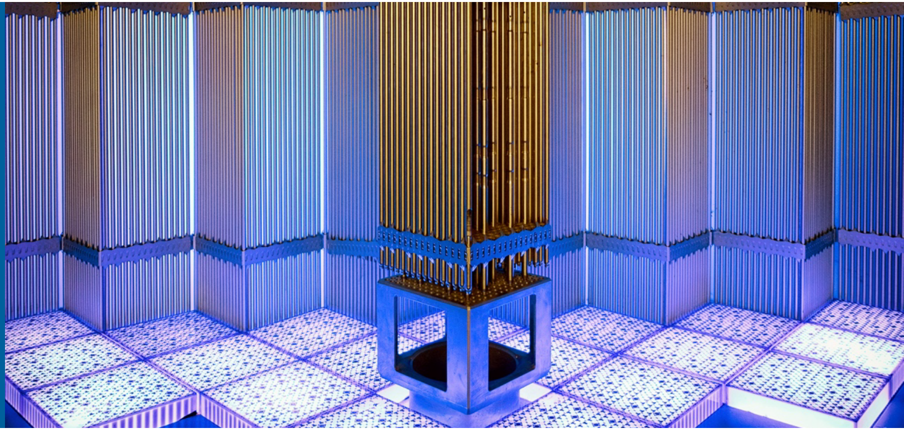
GE

PREDICTIVE TOOLS FOR MAINTENANCE OPTIMIZATION: HEAT EXCHANGER TUBE FAILURE CASE



R. VILIM, Y. LI, A. DAVE
Nuclear Science and Engineering Division
Argonne National Laboratory

Condition Monitoring and Structural Health Management for Nuclear Power Plants Virtual Workshop

November 28, 2023

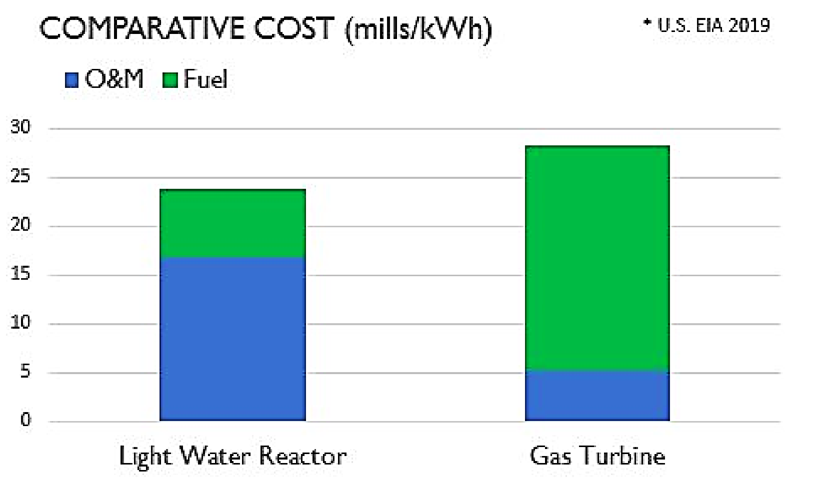
U.S. DEPARTMENT OF ENERGY
Argonne National Laboratory is a U.S. Department of Energy laboratory managed by UChicago Argonne, LLC.

ECONOMICS AS A DRIVER OF ADVANCED O&M

Need to develop advanced maintenance strategies

- Current O&M costs are not competitive, and scheduling of related tasks is not optimal with respect to electricity generation demands
- Flexible operation while potentially improving revenue can stress the plant and increase O&M costs
- Need to pursue alternative opportunities

Current Fleet in US is Not Competitive on an O&M Basis



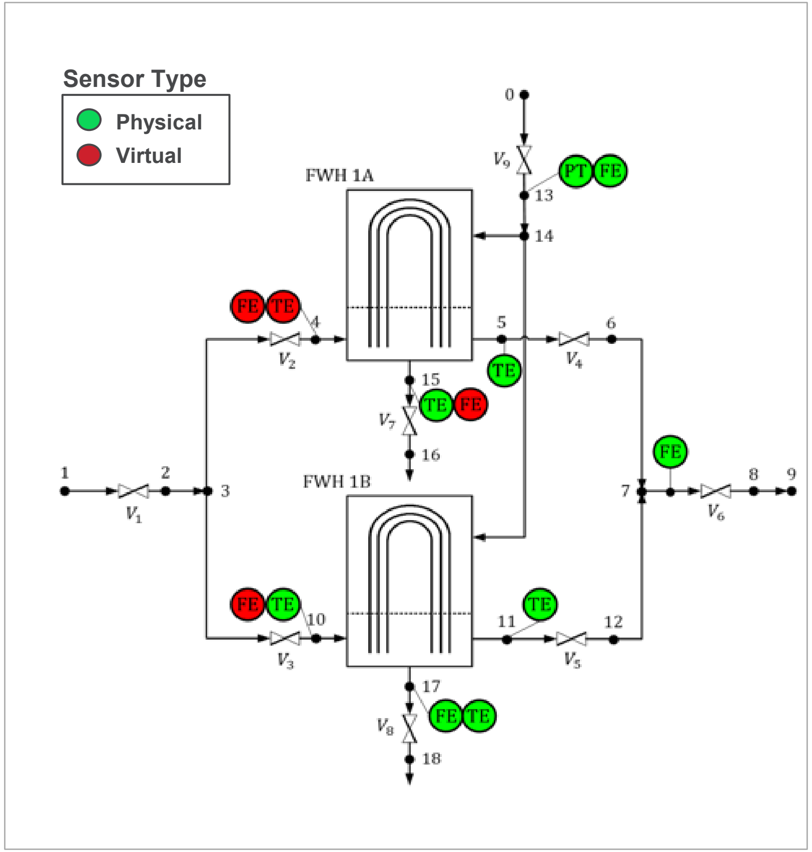
WHAT ARE THE OPPORTUNITIES?

- **Automate procedures that are now performed manually for greater efficiency**
- **Consolidate these advanced capabilities in a remote monitoring center for cost savings**
- **Stage development in a progression of advanced capabilities**
  - Health monitoring
  - Remaining useful life prediction
  - Maintenance schedule optimization

HEALTH MONITORING

Virtual sensors – Inter-Component

- Obtain more information from sensors by taking a system level approach to monitoring
- Create “virtual” sensor readings from knowledge of system P&ID
- Build system level model from P&ID and then solve for process variables not available as measurements i. e. virtual sensors
- Use to improve reliability and specificity of component health diagnosis

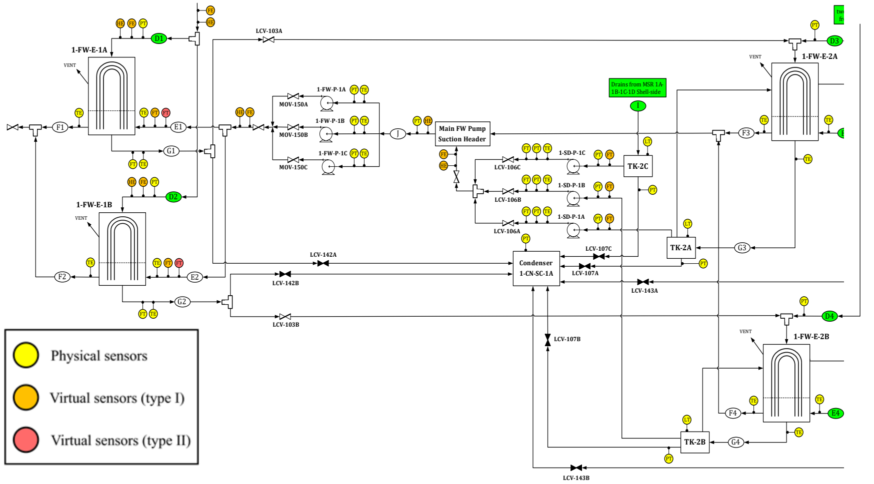


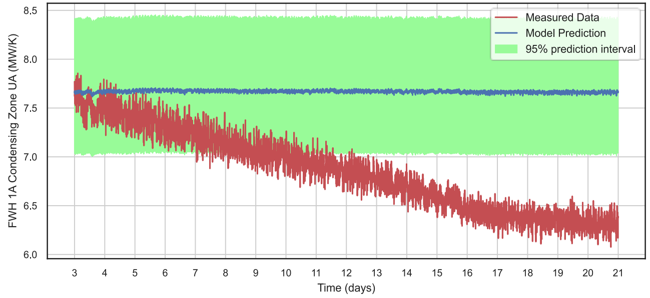
Virtual Sensors Created from P&ID for Two Parallel FW Heaters

HEALTH MONITORING

System level monitoring

- Diagnostics for system rather than individual components
  - Fewer sensors needed
  - Greater fault specificity
- Move from standalone component diagnostics to an engineered plant system having tens of components
- Actionable fault diagnoses generated for the system rather than simple detection of an anomaly





HP Heater tube fouling diagnosed

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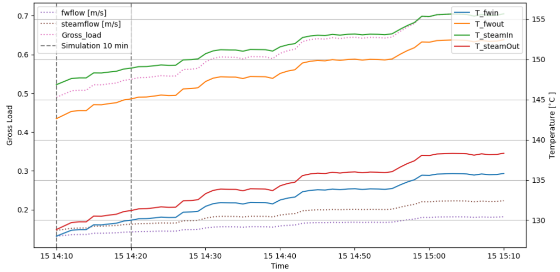
HEALTH MONITORING

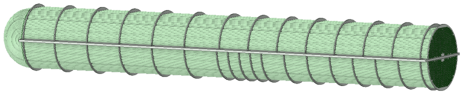
Virtual sensors – Intra-Component

- Need to predict conditions within component
- Collect measured operating history as boundary conditions
- Distribute boundary condition based on geometries
- Calculate intra-component state based on CFD simulations

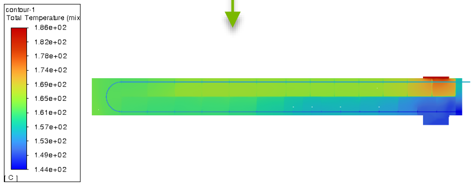
Measured operating history



Geometry–based boundary condition distribution



Intra-Component state



Virtual Sensors

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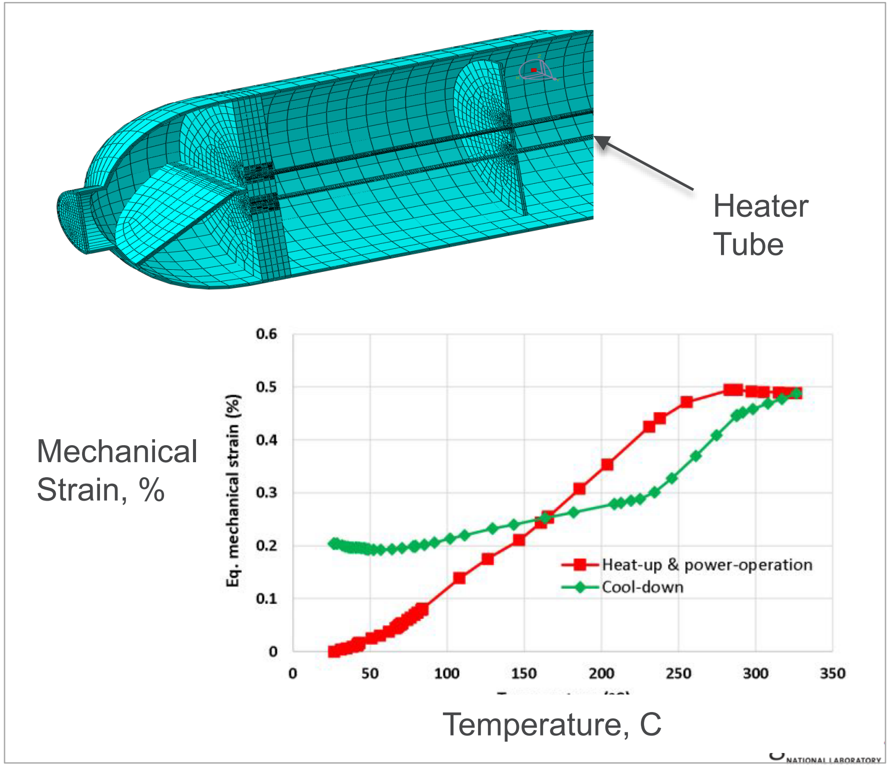
PREDICTION OF REMAINING USEFUL LIFE

Mechanistic tracking of degradation

- High temperature operation and cycling can lead to material damage
- Obtain material damage prediction from high fidelity fluid-structure simulation
- Need to turn this into a real-time prediction of component health for use in reducing inspection frequency and informing inspection location

Model for predicting FW heater tube low cycle fatigue



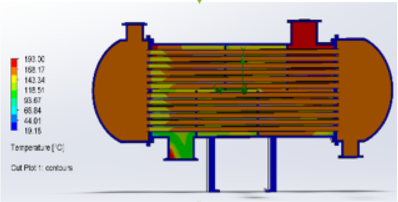
PREDICTION OF REMAINING USEFUL LIFE

Reduced order model for mechanistic degradation

Degradation Captured By Surrogate Model

High-fidelity simulation → Surrogate model

Model Input
1. Operation History
2. Possible initial tube conditions



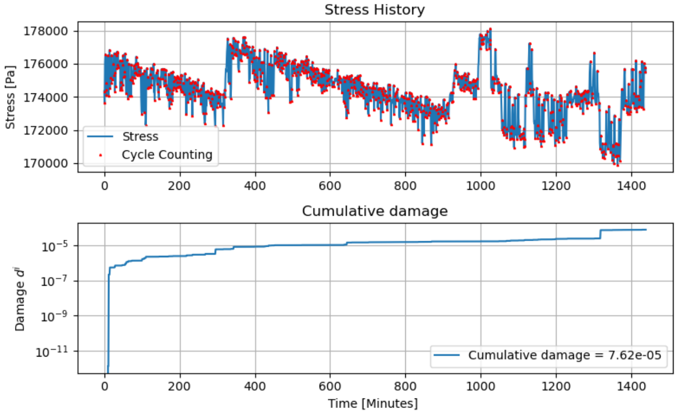
Model Output
1. Transient-spatial physical quantities
2. Degradation characteristics

Feature Extraction
1. Physics-based features
2. Data-driven features with physics

Surrogate Construction
1. Correlation between features and degradation
2. Uncertainty propagation

Different Conditions
1. Configurations/designs
2. Operational history

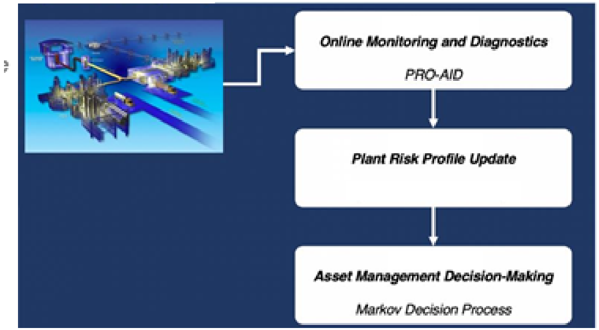
Remaining Useful Life Estimated Based on Cumulative Damage



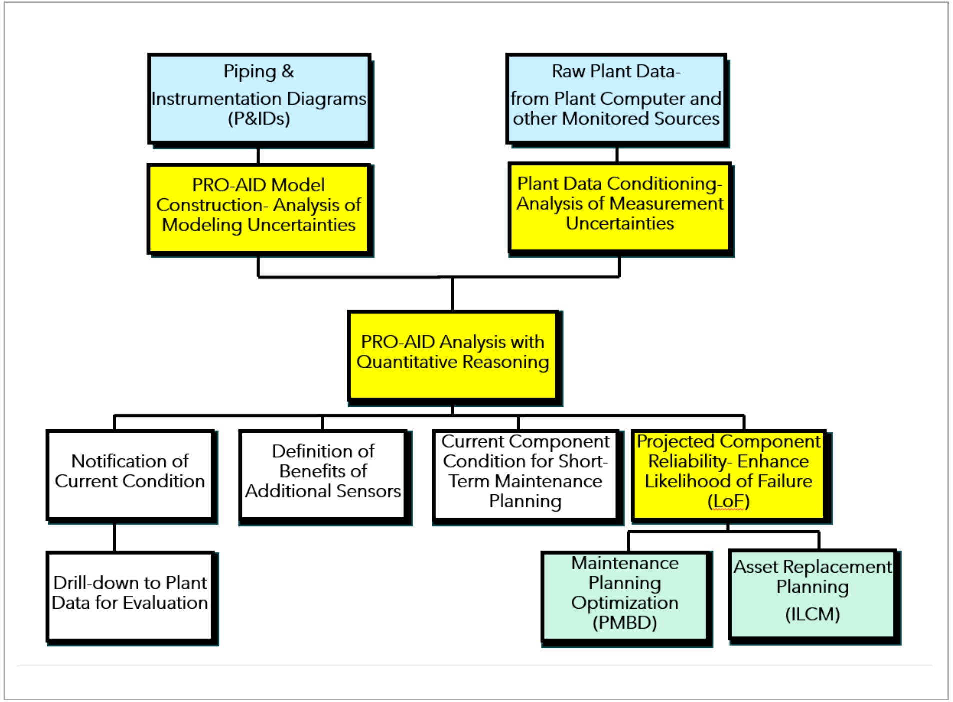
MAINTENANCE SCHEDULE OPTIMIZATION

How it all fits together

- Maintenance and asset management procedures executed on a periodic basis are an over expenditure of resources
- Schedule maintenance on an as-needed basis to reduce work orders for cost savings
- Developed Markov Decision Process that optimizes execution of maintenance tasks



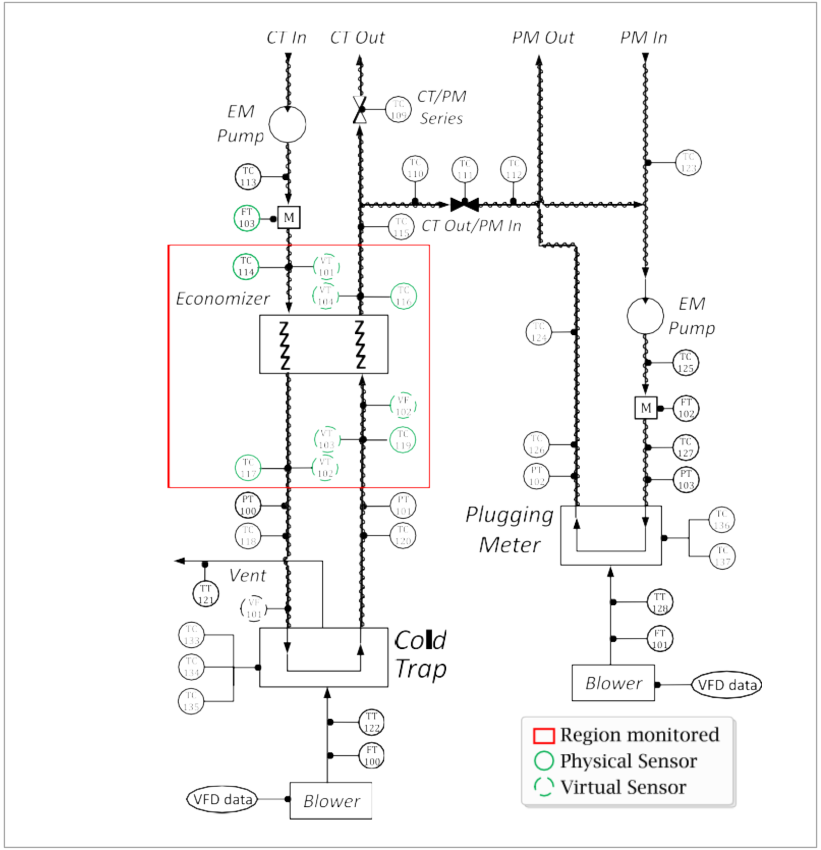
Sequential flow tasks in maintenance scheduling



Tasks enabling optimization of maintenance Scheduling [LPI Inc. 2020]

REMOTE MONITORING CENTER

- Feed sensor data to a remote monitoring and diagnostic center
- One engineer can monitor multiple systems in multiple plants
  - Current anomaly detection paradigm has an engineer monitoring a single system



P&ID for Digital Twin Fault Diagnosis Algorithm and Remote Monitoring Center

Argonne NATIONAL LABORATORY

SUMMARY

- **Automate procedures that are now performed manually for greater efficiency**
- **Consolidate these advanced capabilities in a remote monitoring center for cost savings**
- **Stage development in a progression of advanced capabilities**
  - Health monitoring
  - Remaining useful life prediction
  - Maintenance schedule optimization

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https://www.anl.gov/nse/ai-ml

AI/ML Research to Support Plant Modernization

Craig Primer
Plant Modernization Pathway Lead

November 2023

Overview of Plant Modernization Pathway

The LWRS Program **Plant Modernization** pathway conducts R&D, **provides guidance for full-scale implementation** and **communicates the results** to other nuclear power stakeholders that significantly reduce the technical and financial risks of modernization

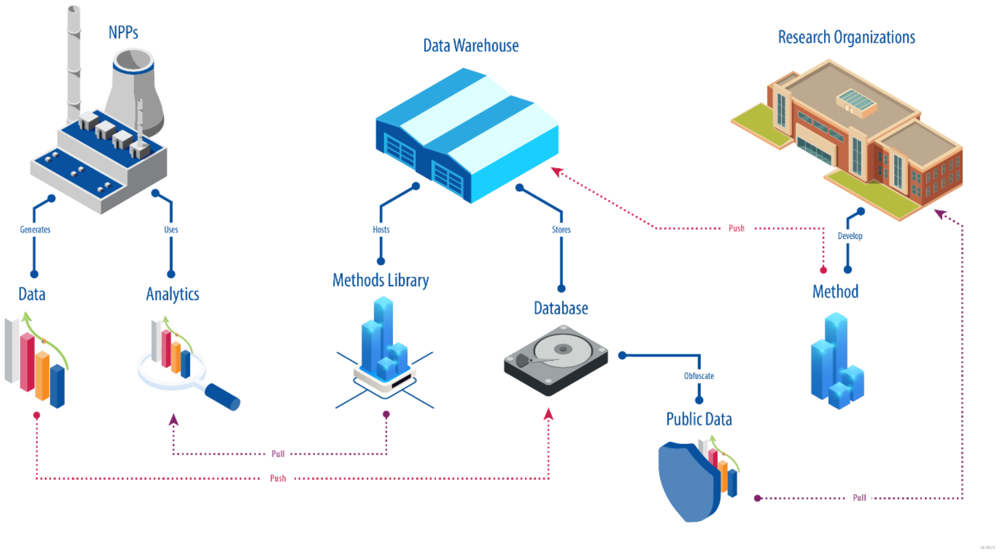
Plant Modernization Research Objectives and Goals

Objectives	Develop modernization solutions that improve reliability and economic performance while addressing the US nuclear industry's aging and obsolescence challenges			Deliver a sustainable business model that enables the US nuclear industry to remain cost competitive
Research Areas	I&C Architecture (Digital Infrastructure)	Data Architecture & Analytics	Human & Technology Integration	Integrated Operation for Nuclear
Outcomes	A multi-layered, sustainable digital foundation to enable Plant Modernization	Advanced monitoring, and data processing to replace labor-intensive plant support tasks	Tools and methodologies that maximize efficiency while ensuring safety and reliability are maintained	LWR fleet electric market competitiveness

Goal - Extend life and improve performance of existing fleet through modernized technologies and improved processes for plant operation and power generation

Data Architecture & Analytics

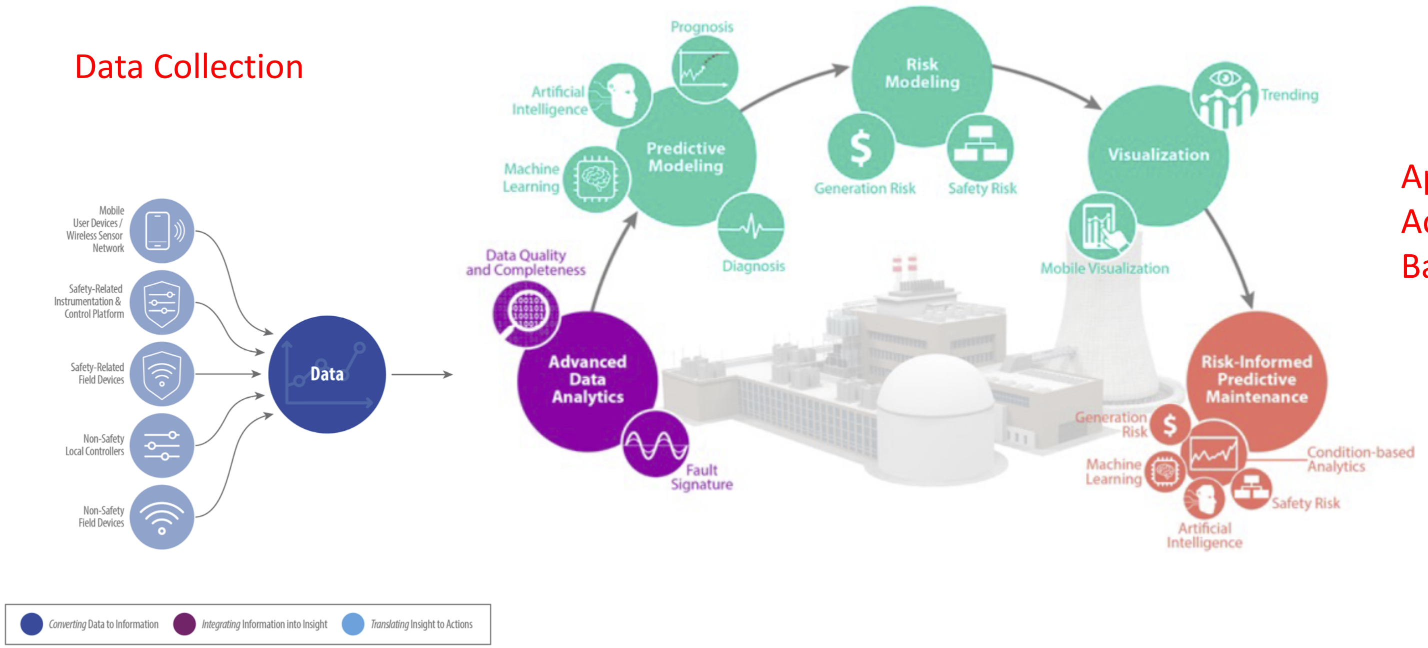
Eliminating unnecessary O&M costs by automating and optimizing critical support activities



Data Management

Data Analytics

Data Collection



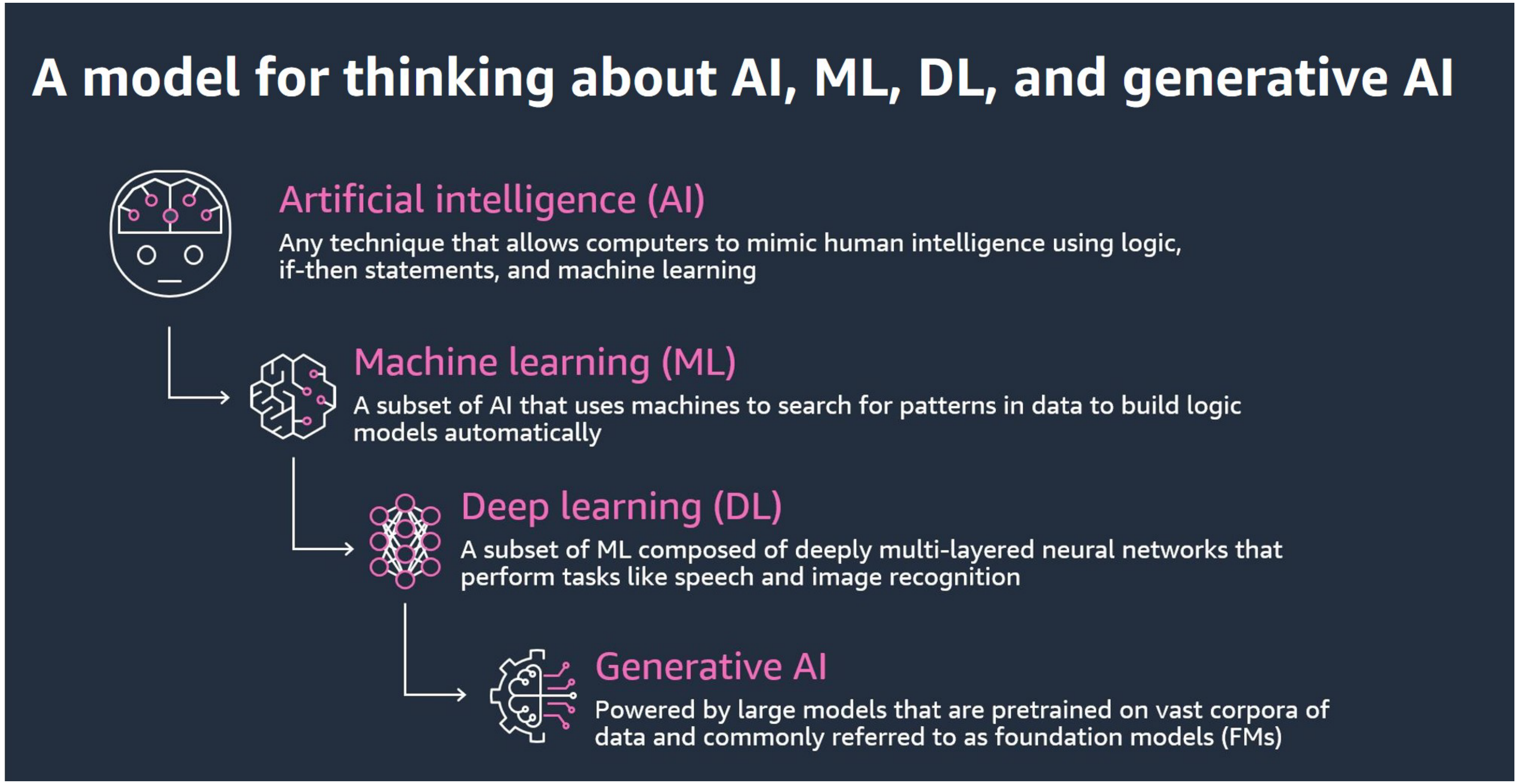
Appropriate Action Taken Based on Data

AI/ML Research Focus Areas

ML for Material Management
ML for Equipment Monitoring
ML for Anomaly Detections

NLP Applications
Computer Vision Applications

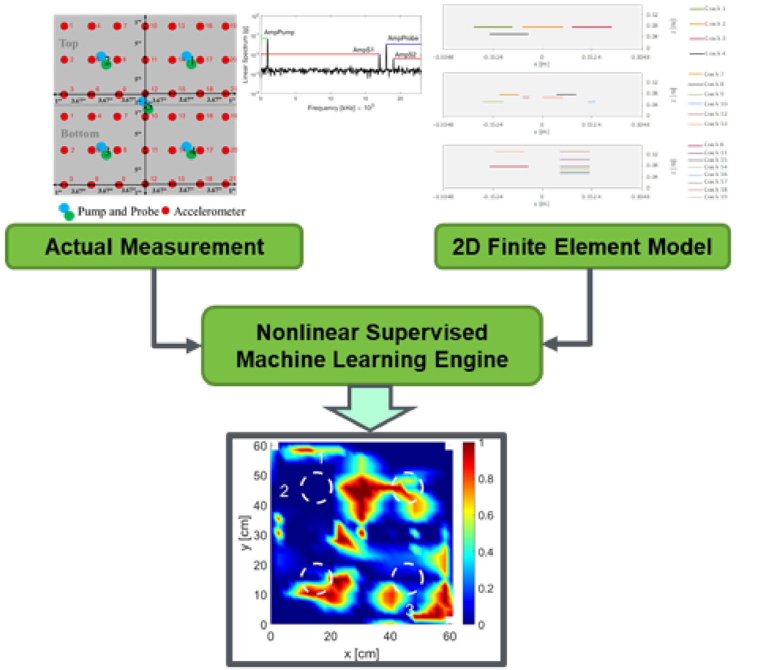
AI/ML Explainability



Overview of AI, ML and subsets of ML

Digital Twin Informed ML for Material Management

Developed technology to locate and estimate alkali-silica reaction (ASR) damage using physics-informed machine learning approach

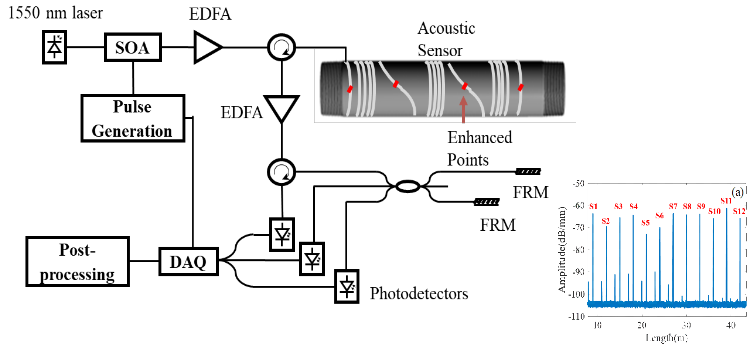


Physics-informed machine learning damage map due to ASR

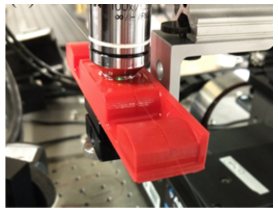
[Concrete Structure Health Monitoring Using Vibroacoustic Testing and Machine Learning, INL/EXT-20-59941]()

Digital Twin and Deep Learning Model used in Secondary Piping Degradation Detection Research

Low-Cost Phase-Sensitive Distributed Fiber

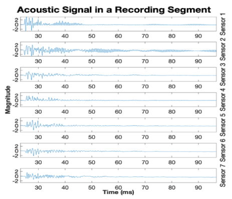


FS-laser Direct Writing

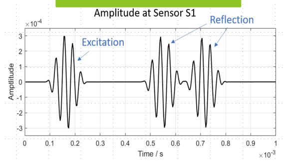


Digital Twin and AI

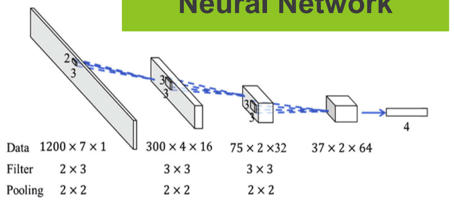
Sensor Data



DT Data



Deep Learning Neural Network

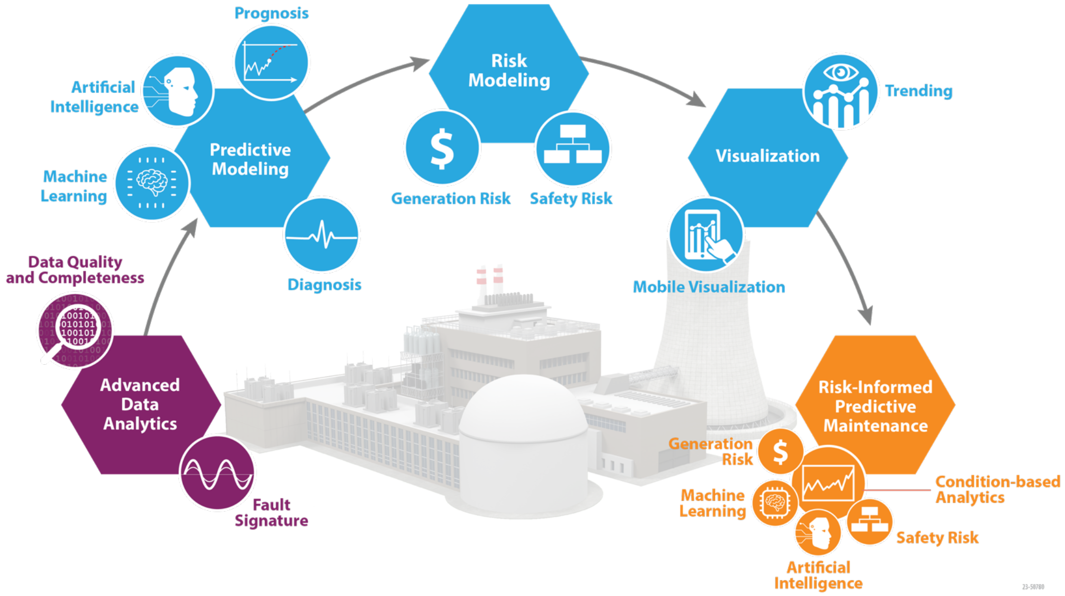


[Concept for Integrated Multi-Modal Online Piping Monitoring System along with Data Fusion and Advanced Data Analytical Algorithms Using High- Resolution Fiber Optics Sensors, INL/EXT-20-59810]()

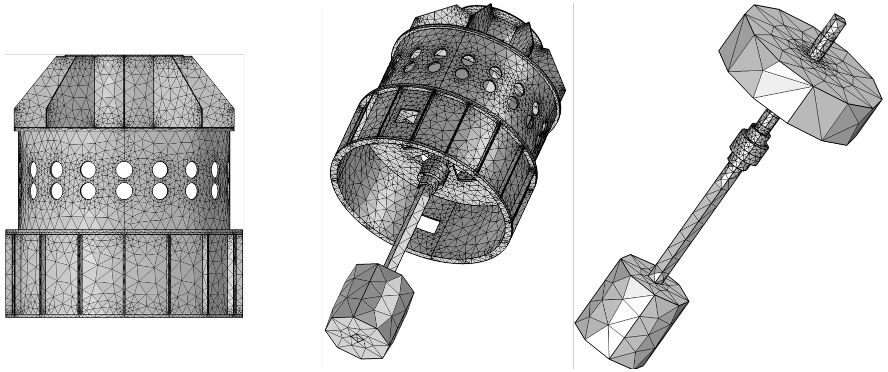
ML for Equipment Monitoring

- Developed a scalable risk-informed predictive maintenance strategy using machine learning approaches, risk modeling, visualization, and multi-band heterogeneous wireless architecture.
- Developed a hybrid model of circulating water pump (CWP) motor (basis for digital twin) to capture different operating dynamics.

Scalable Technologies Achieving Risk-Informed Condition-Based Predictive Maintenance Enhancing the Economic Performance of Operating Nuclear Power Plants, INL/EXT-21-64168



Risk-informed Predictive Maintenance Strategy


Physics-based model of CWS

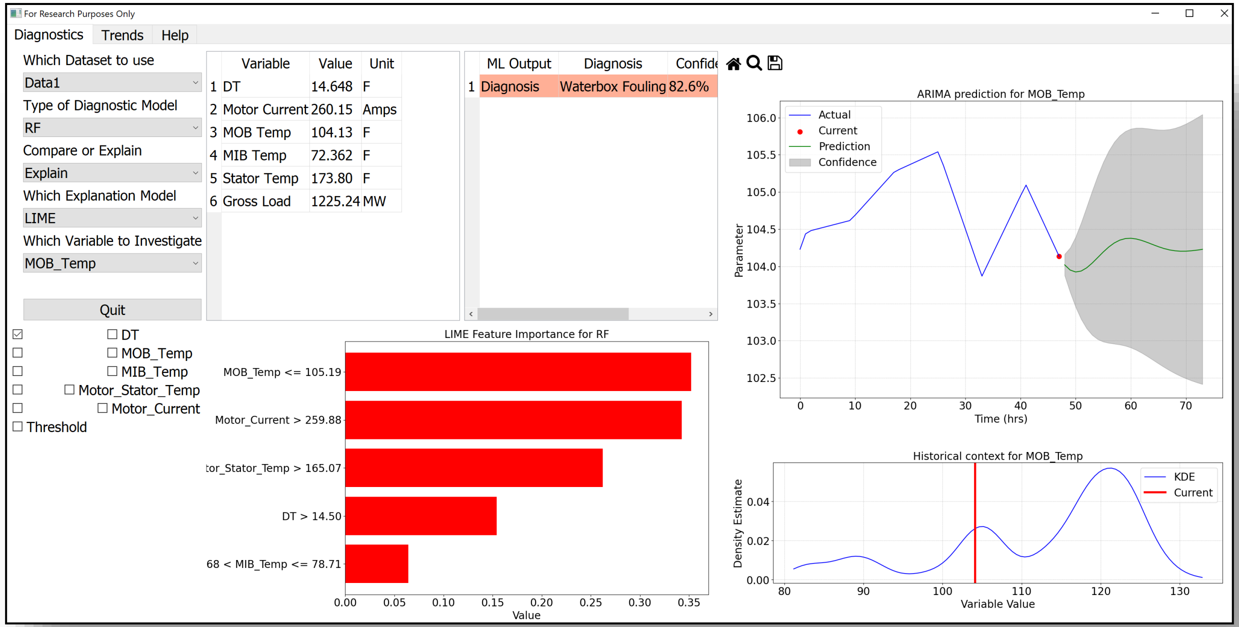
AI/ML Explainability

LWRS Program researchers developed methods to address the explainability, performance, and trustworthiness of AI/ML to enhance the interpretability of outcomes.

One method uses objective metrics like Local Interpretable Model-agnostic Explanations (LIME) and Shapley Additive Explanations (SHAP).

Another method employs user-centric visualization of AI/ML outcomes together with objective metrics to support expert interpretation.

In collaboration with Public Service Enterprise Group (PSEG), Nuclear LLC, performed initial demonstration of the technical basis on circulating water system (CWS) for a waterbox fouling problem.



User-centric visualization with performance and explainability metrices

Explainable Artificial Intelligence Technology for Predictive Maintenance, INL/RPT-23-74159

AI/ML Applications for Anomaly Detection

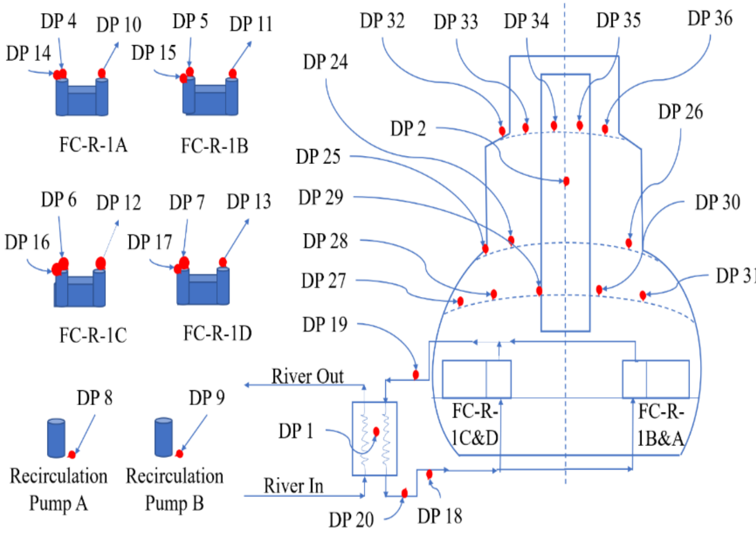
- Unsupervised ML Methods
  - Developing equipment-agnostic anomalies detection methods by holistic inference of process conditions

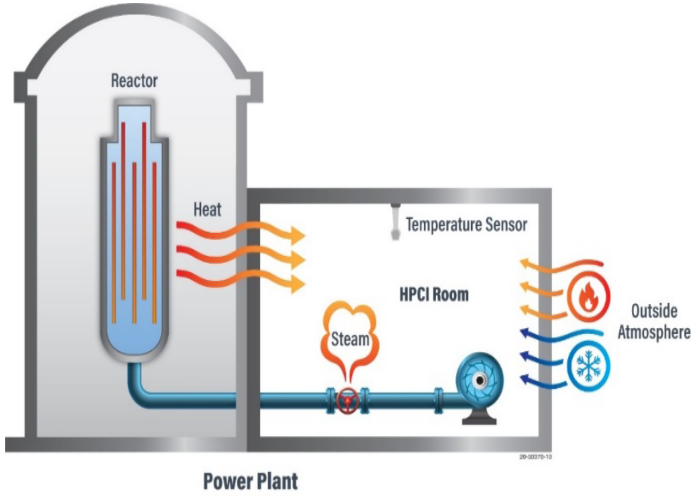
Extending Data-Driven Anomaly Detection Methods…, INL/RPT-23-73933
Software - Automated Latent Anomaly Recognition Method, (ALaRM)

- Semi-Supervised ML Methods
  - Developing methods to couple text-mined information from sparse condition reports to equipment and process sensors data for equipment and process reliability analysis

Feature Extraction for Subtle Anomaly Detection Using Semi-Supervised Learning, Annals of Nuclear Energy, vol. 181, pp. 109503, 2023
https://doi.org/10.1016/j.anucene.2022.109503

Recurrent neural networks were used to predict dry well cooling fan failure using surrounding sensors





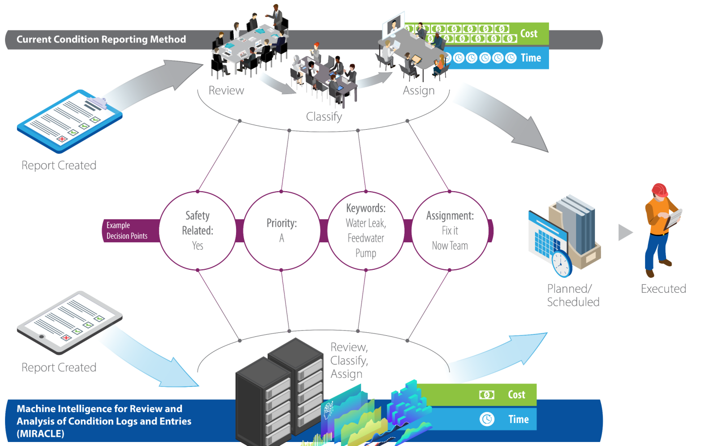
Clustering methods were used to detect High-Pressure Coolant Injection (HPCI) system steam leak

NLP Applications for Process Improvement

- Natural Language Processing and Deep Learning Methods:
  - Demonstrating and evaluating the automation of the condition reports screening process (which is the review and classification of condition reports according to their impact on nuclear safety).
  - Evaluating the automation of document review, sampling, trending, analysis, and reporting.

- Natural Language Processing and Clustering Methods:
  - Developing an inventory optimization method by coupling work demand information with parts inventory to reduce the minimum stocking requirements.

Condition report screening is a process that involves several staff on daily or bi-daily basis for several hours a week.



Software: Machine Intelligence for Review and Analysis of Condition Logs and Entries (MIRACLE)

Developing AI/ML methods to optimize the stocking requirements in a plant

Explainable Artificial Intelligence Technology for Predictive Maintenance, INL/RPT-23-74159

Computer Vision Applications for Process Improvement

- Computer Vision and Deep Learning Methods:
  - Developing methods to automatically identify a fire in a video stream to augment the effectiveness of the fire watch program
  - Developing and evaluating the automation of logging analog gauges (i.e., a method to recognize gauges in oblique angles and read their values)
  - Demonstrating methods for drones to autonomously recognize and navigate their environment in a nuclear power plant.

Example of AI/ML's ability to accurately identify fire and smoke.

Automating Fire Watch in Industrial Environments through Machine Learning-Enabled Visual Monitoring, INL/EXT-19-55703
Software - Modelling Framework for Fire and Smoke Detection in Imagery

Automated gauge reading impacts a wide spectrum of activities in a plant including operator rounds, gauges calibration, and peer verification, and improves data fidelity for online monitoring.

Patent - Automated Gauge Reading And Related Systems, Methods, And Devices

Drones can automate several activities in a plant including operator and security rounds, and inspections of hazardous locations.

Software - Route-operable Unmanned Navigation of Drones (ROUNDS)

AI/ML Research Summary

ML for Material Management
ML for Equipment Monitoring
ML for Anomaly Detections

NLP Applications
Computer Vision Applications

AI/ML Explainability

Artificial intelligence, machine learning, associated methods and data handling techniques are relatively new in the nuclear power industry.

- Show great promise for automating many manually performed activities
- Are demonstrating new approaches to enhance efficiency

Collaborative efforts with owner-operators and others emphasize many non-safety uses.

- Adoption must align with the nuclear safety culture of the industry.
- Some uses demonstrate ability to rapidly transition to safety important uses.

Trust in automation, understandability affect usability.

- Human factors issues in AI/ML implementation vital to adoption and safe use.

LWRS LIGHT WATER REACTOR SUSTAINABILITY

Sustaining National Nuclear Assets

lwrs.inl.gov

Deep Learning Solutions to Health Management of Nuclear Mechanical Systems

Abhinav Gupta
Director, CNEFS

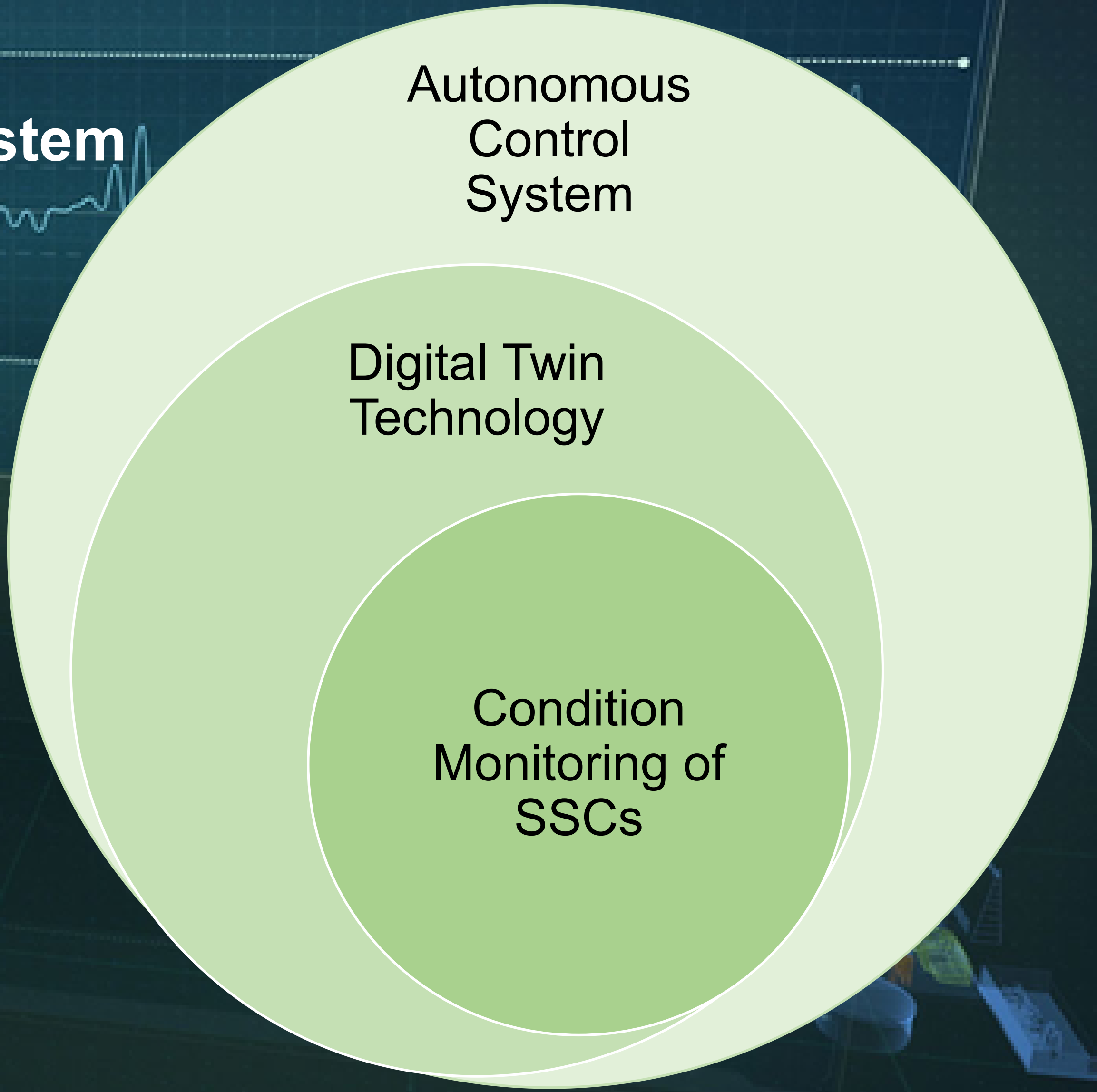
Harleen Sandhu, Saran Bodda

Center for Nuclear Energy Facilities & Structures
North Carolina State University
Raleigh, NC 27695-7908

Autonomy in Advanced Nuclear Reactors

Development of a Nearly Autonomous Management and Control (NAMAC) System for Advanced Reactors

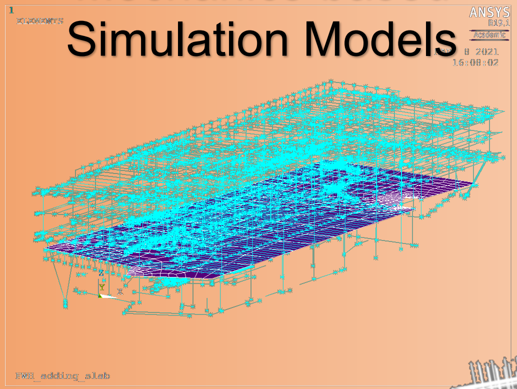
NAMAC, "Development of a Nearly Autonomous Management and Control (NAMAC) System for Advanced Reactors," (2018) URL NAMAC - ARPA-E



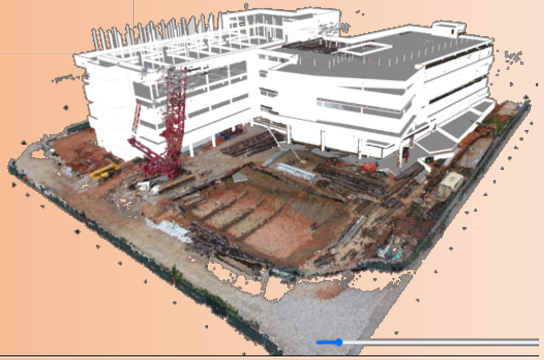
Resource: https://www.industryweek.com/technology-and-iiot/article/22026918/where-do-digital-twins-fit-in

As-Built v/s As-Designed Digital Twin

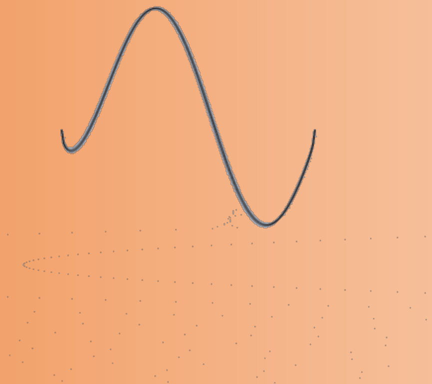
Mechanics-based Simulation Models



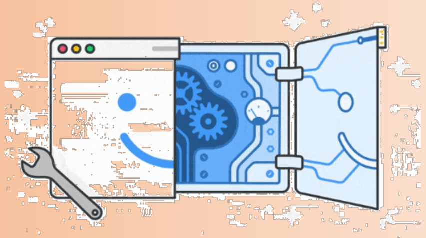
As-Built Design



Sensor Data



Maintenance History

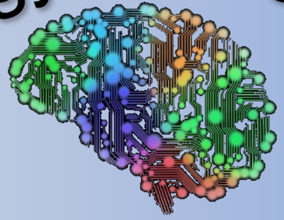


Digital Twin

PROGNOSIS

DIAGNOSIS

Strategy Assessment



Source: *https://enviosystems.com/2021/03/01/how-digital-twins-can-help-reduce-global-carbon-emissions/*

Importance of Condition Monitoring

- December 2021, maintenance checks on the primary circuit of Civaux 1 revealed stress corrosion cracking (SCC) near the welds on pipes of the safety injection system.

- 12 reactors shut down as a result of the issue – for investigation or repair.

- EDF had to lower its 2022 nuclear output forecast yet again in November 2022, to 275-285 terawatt-hours (TWh) extension of four reactor outages for repairs linked to corrosion problems.
  (Resource: https://www.reuters.com/business/energy/edf-says-leak-civaux-reactor-not-due-welding-2022-11-08/)

- Another SCC was found in Penly power plant in early 2023, "a crack extending over 155 mm, or about a quarter of the circumference of the piping". *(Resource: https://www.lemonde.fr/en/economy/article/2023/03/08/large-crack-discovered-on-nuclear-power-plant-further-complicates-situation-for-france-s-edf_6018624_19.html)*

The Civaux nuclear power plant (Image: EDF)

Resource: https://www.world-nuclear-news.org/Articles/French-regulator-gives-update-on-corrosion-issue

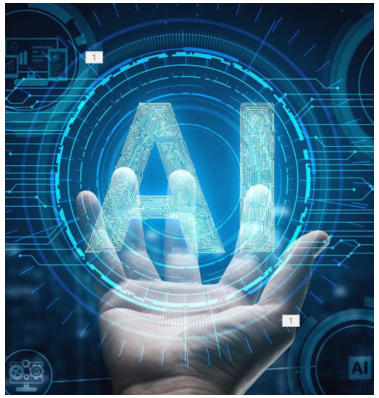
Degradation in Nuclear Piping Systems

- Flow-assisted Corrosion and Erosion
- Stress and Fatigue due to operational vibrations

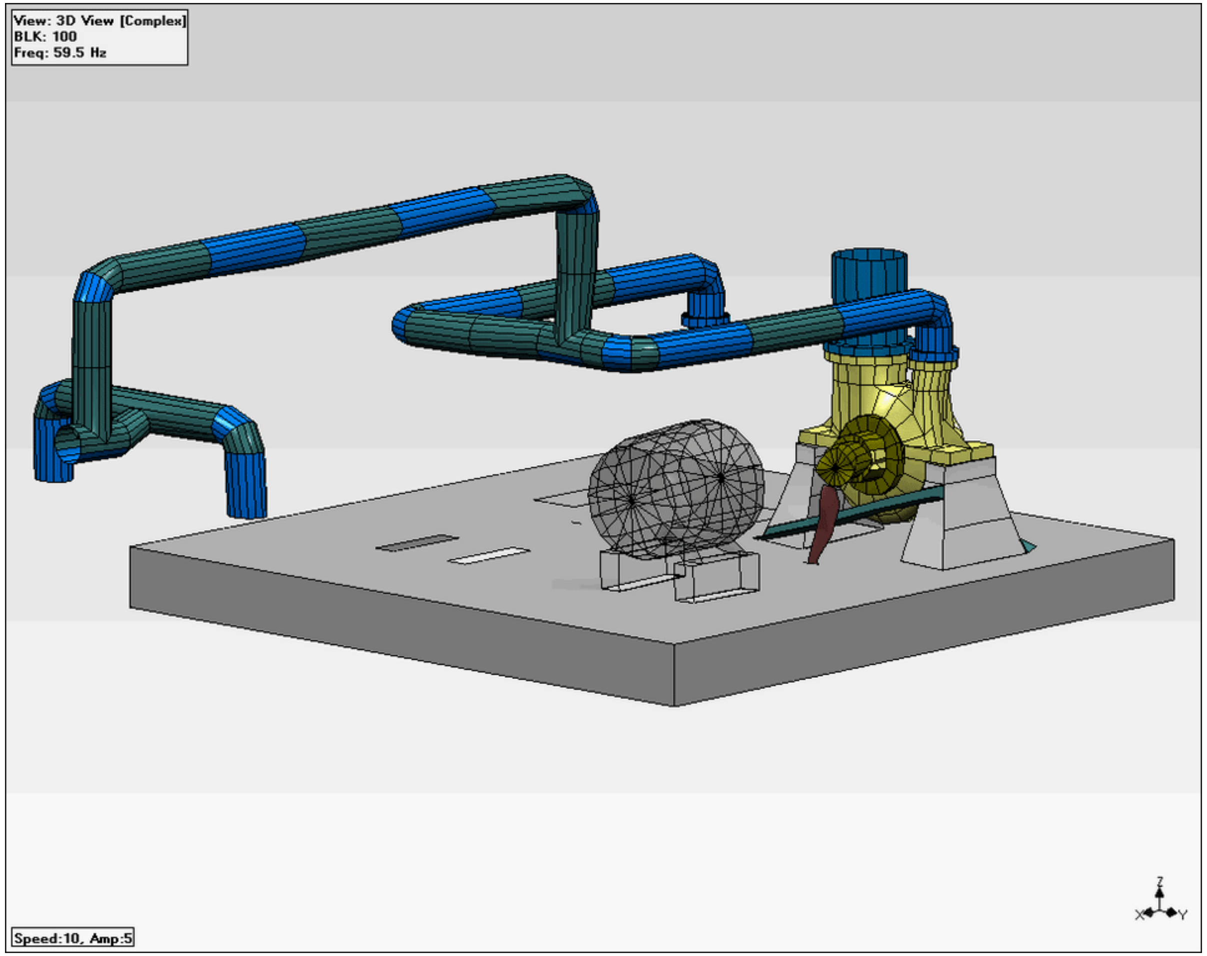
Resource: K. M. Hwang, H. Yun, and C. K. Lee, "Development of New Methodology for Distinguishing Local Pipe Wall Thinning in Nuclear Power Plants," World Journal of Nuclear Science and Technology, vol. 2, no. 4, Oct. 2012, doi: [10.4236/wjnst.2012.24030](https://doi.org/10.4236/wjnst.2012.24030).

Corresponding reduction in structural stiffness

- 25% thickness reduction ***Minor***
- 50% thickness reduction ***Moderate***
- 75% thickness reduction ***Severe***



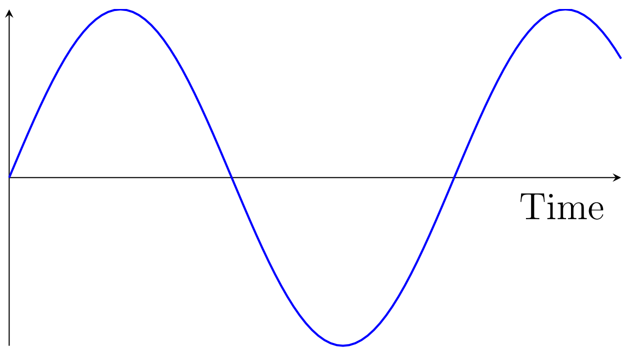
Operational Pump Loads



Resource: https://www.mechsol.com/case-study/nuclear-generator-stator-cooling-pumps-specialized-vibration-testing/

Pump-induced vibrations in pipe systems:

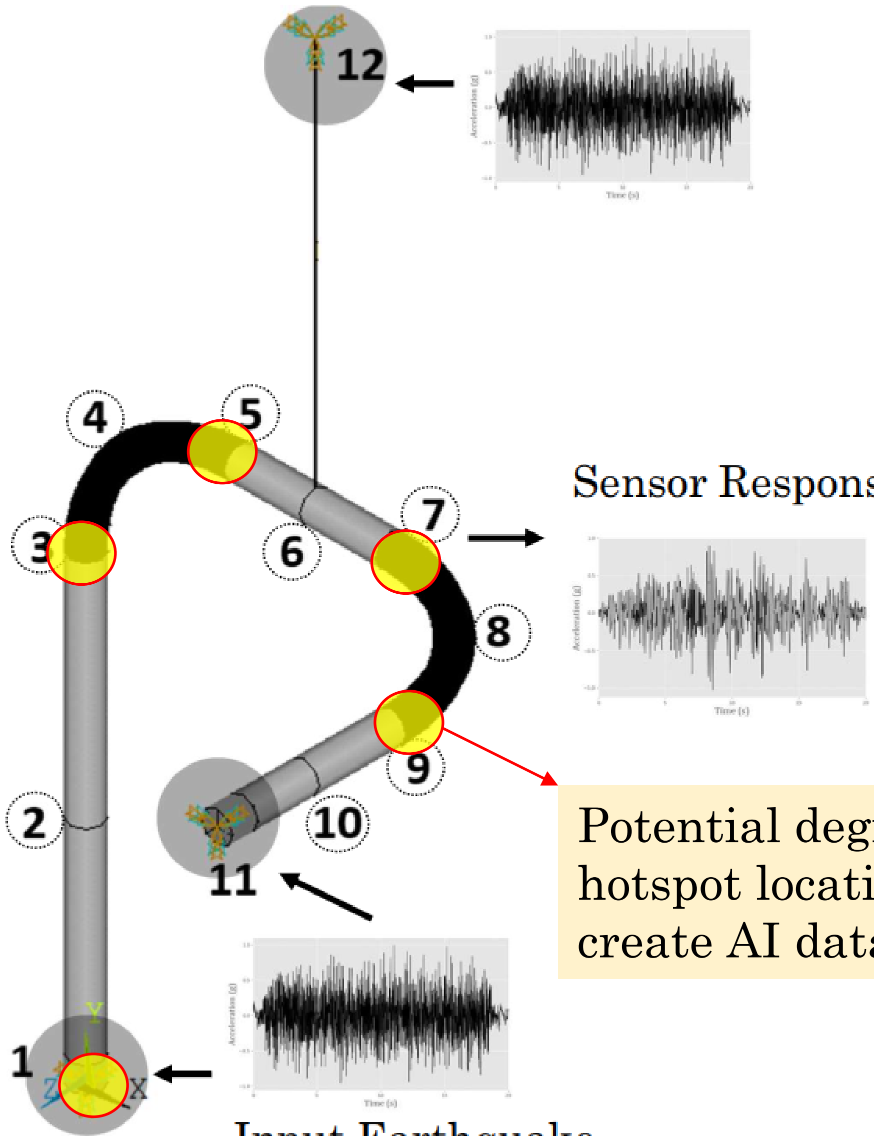
- *Harmonic in nature*
- *Large amplitude of vibration*
- *Frequency of the harmonic excitation depends on the pump speed in RPM.*



Equation of motion: $[M]\{\ddot{U}\} + [C]\{\dot{U}\} + [K]\{U\} = f(t)$

Harmonic load function: $f(t) = F\sin(\omega_f t)$ or $F\cos(\omega_f t)$

Simple Piping System



Sensor Response

Potential degradation hotspot locations to create AI database

Input Earthquake

Uncertainty in Degradation Severity

Minor

[20% – 30%]

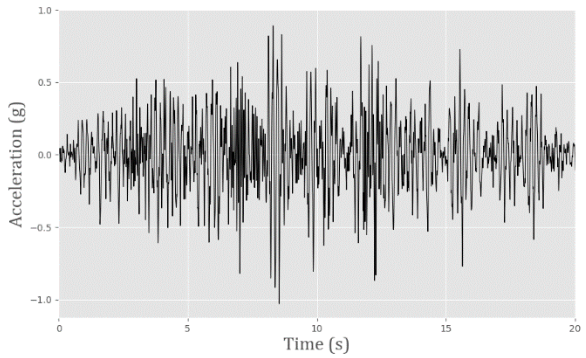
Moderate

[45% – 55%]

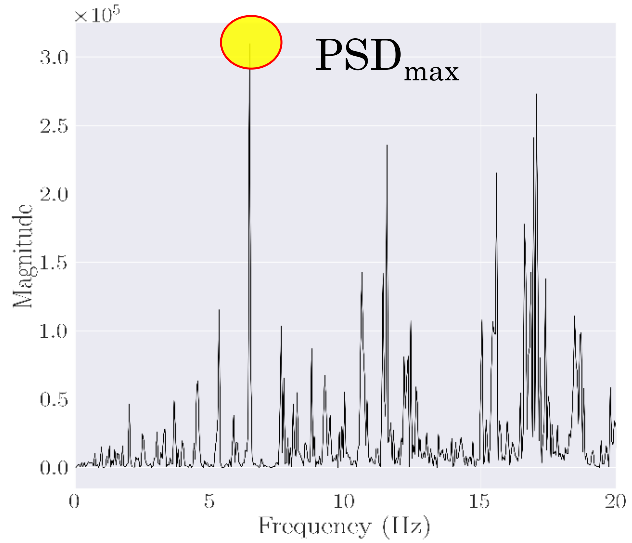
Severe

[70% – 80%]

Acceleration-time series



Power Spectral Density



Initial Implementation of MLP ANN

Training feature	Accuracy of predicting degraded locations
PSD_{max}	45%

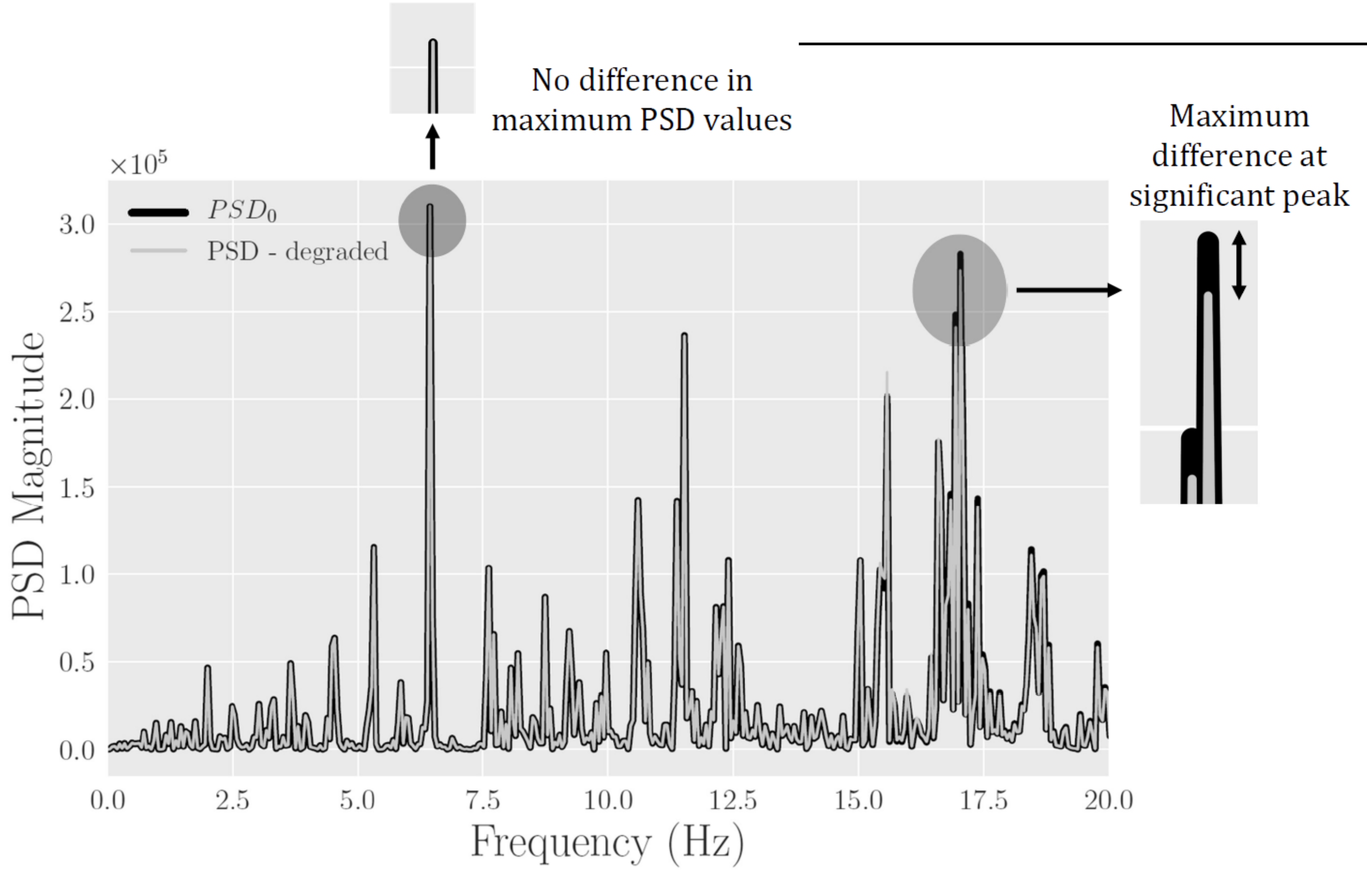
Next Steps:

1 | Explore signal processing and feature extraction for better degradation sensitive quantities

2 | Investigate MLP ANN architecture and key parameters

3 | Develop a sensor placement strategy

Signal Processing and Feature Extraction

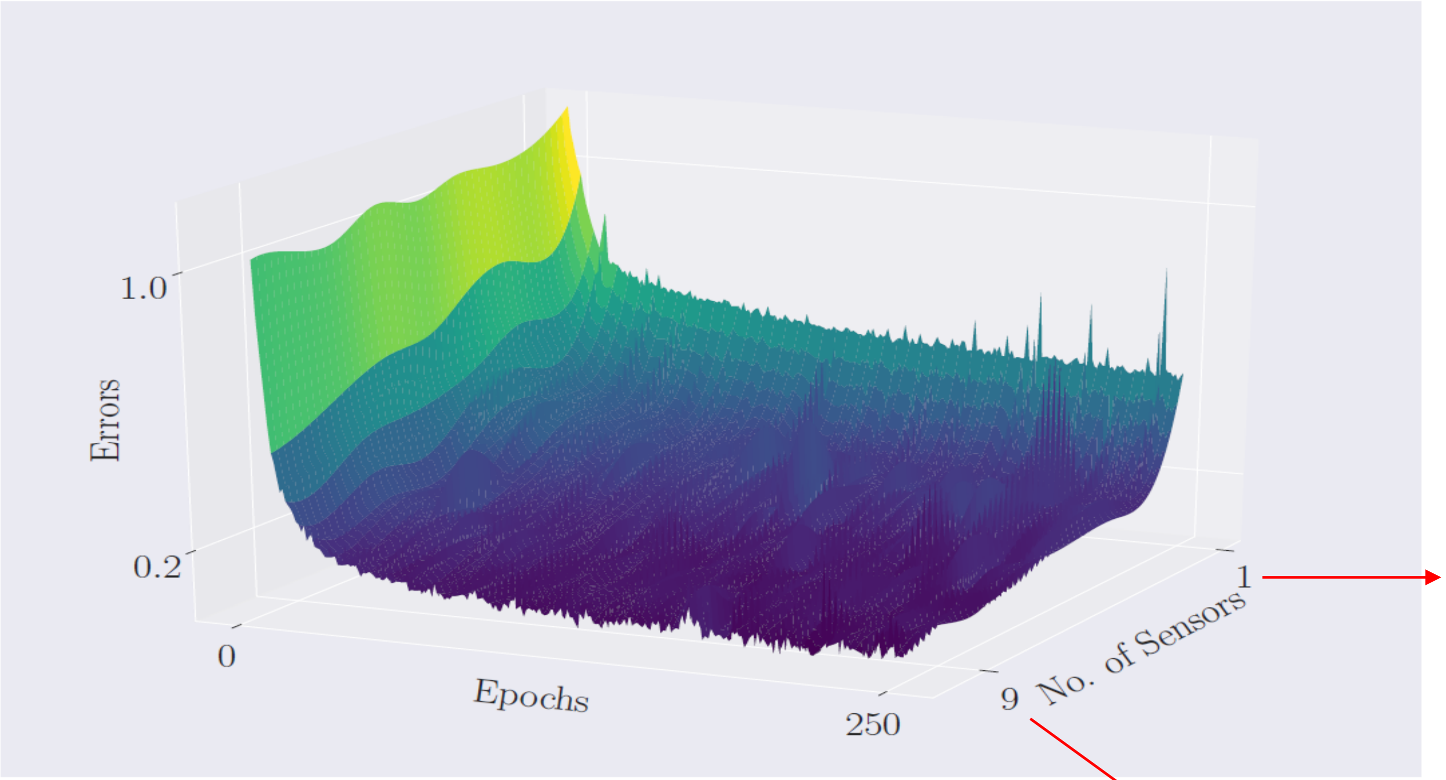


Unlike existing SHM studies, where a considerable difference is noted at peak values of response

Vector of Degradation Sensitive Quantities

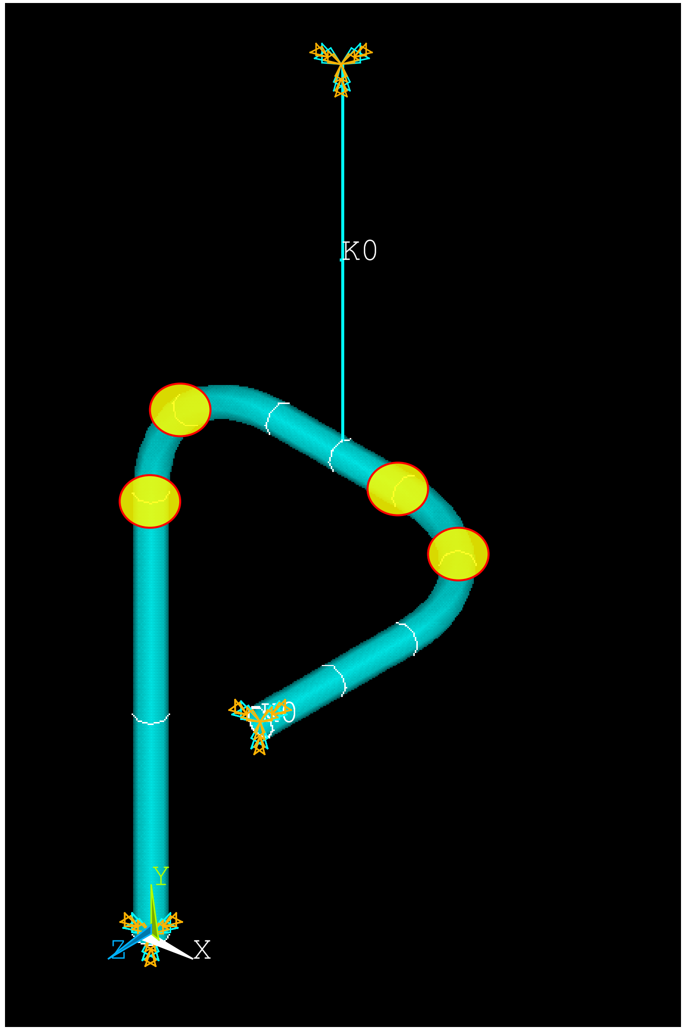
$$\left[\mathrm{PSD}_{\max},\ \Delta_{\max}\mathrm{PSD},\ \omega_{\Delta},\ \mathrm{PSD}_{0,\Delta} \right]$$

Sensor Placement Strategy



High errors
Low cost

Low errors
High economical and computational cost



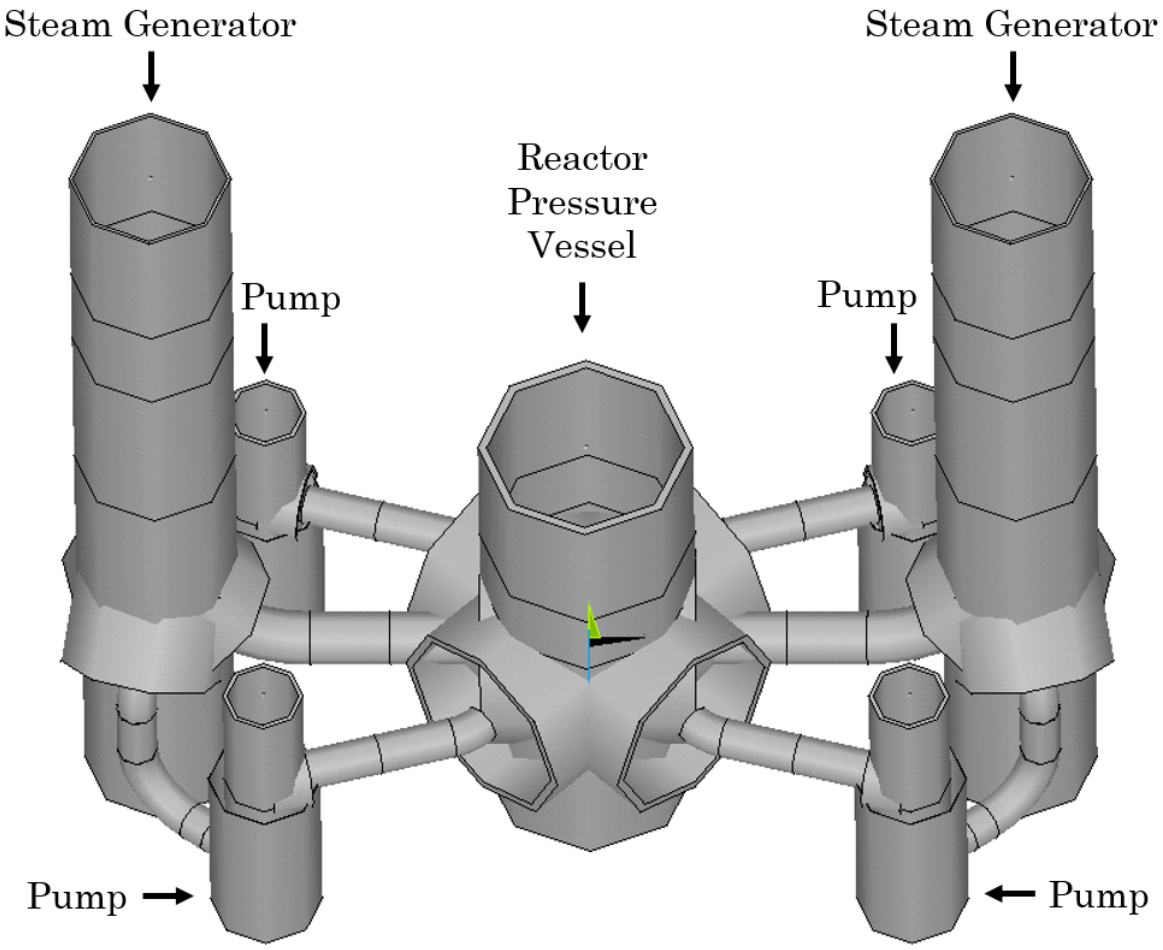
- Considered 4 sensor locations at the elbow joints (most sensitive to degradation), instead of all the 9 sensors.

Results from Simple Piping System

ANN Model	Predict Locations	Predict Locations and Severity
1 QoI (PSD_{max}) 9 Sensors	45%	29%
Vector of 4 QoIs 9 Sensors	97% ↑	97% ↑
Vector of 4 QoIs 4 Sensors	96% ↓	96% ↓

*QoI: Quantity of interest

Realistic Piping-equipment System

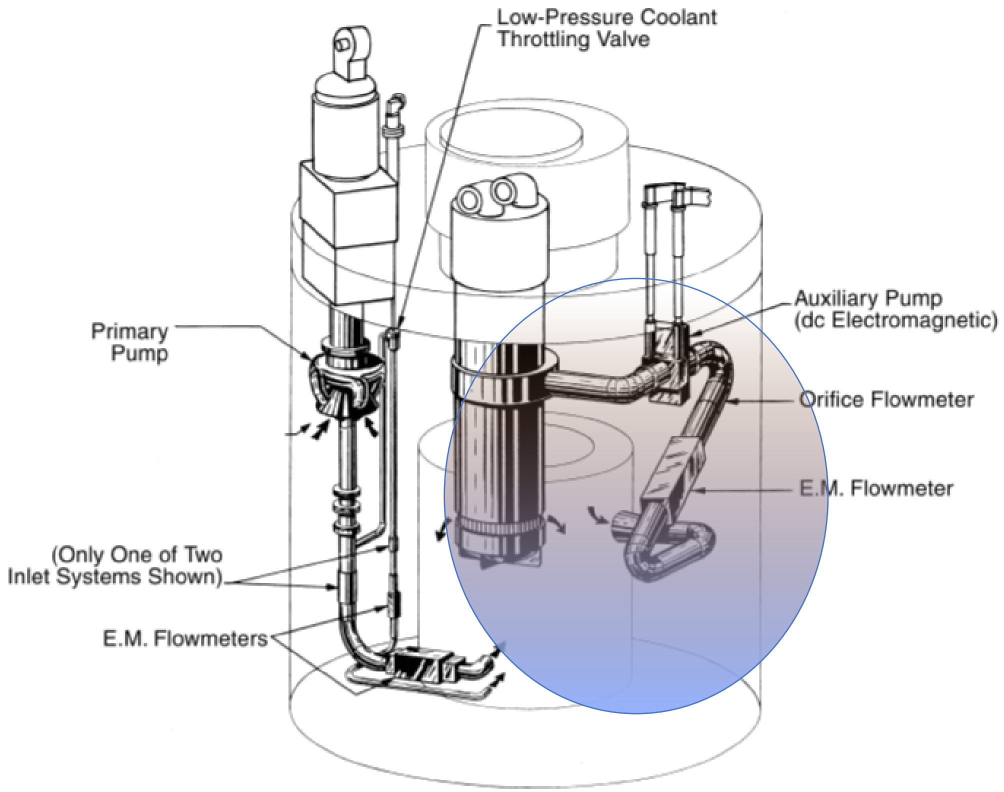


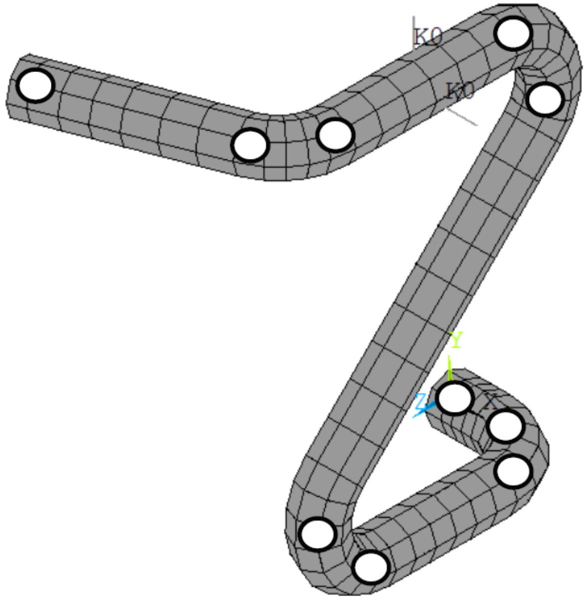
Representative of US Nuclear Regulatory Commission NUREG/CR-1677 Vol. 1, Problem 4

ANN Model	Predict Locations	Predict Locations and Severity
1 QoI (PSD_{max})	14%	5%
Vector of 4 QoIs	99% ↑	99% ↑

*QoI: Quantity of interest

EBR-II Z Piping-equipment System





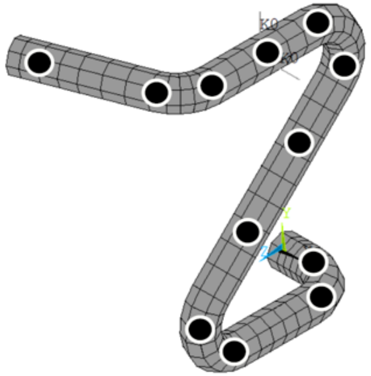
Hotspot degradation locations at elbows and nozzles

- Experimental Breeder Reactor II (EBR-II) was built in 1964 and decommissioned in 1994 by ANL.
- Sodium-cooled fast reactor

ANN Model	Predict Locations	Predict Locations and Severity
Vector of 4 QoIs	99%	97%

*QoI: Quantity of interest

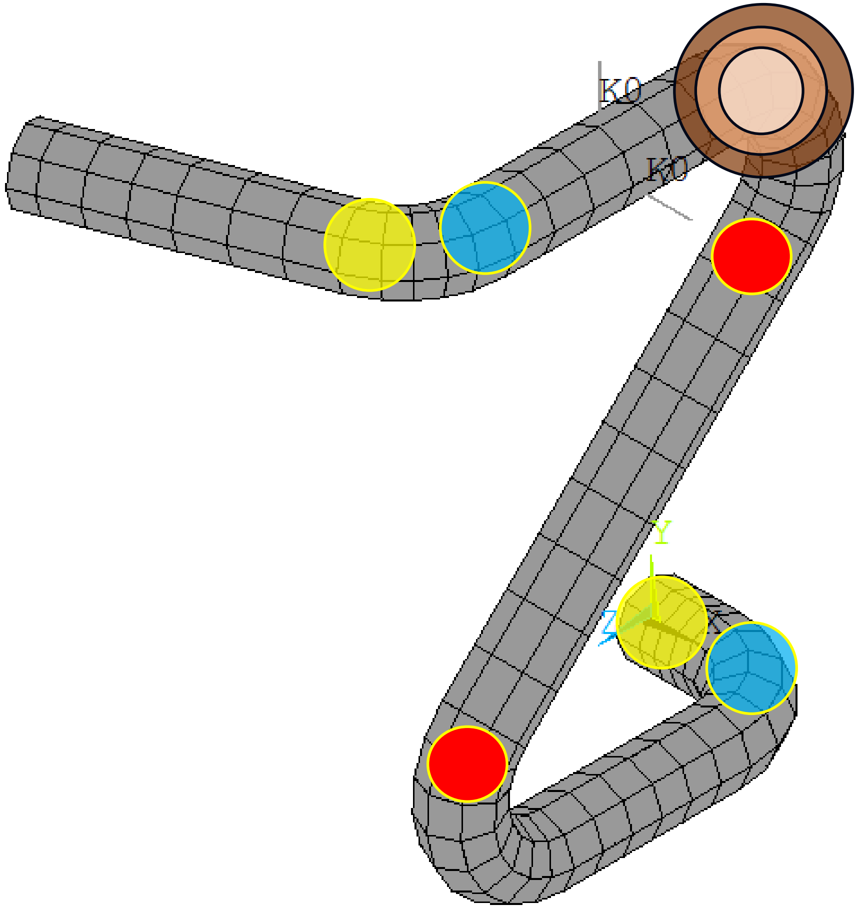
Results from EBR-II Z Piping System



No. of sensors	ANN Model	Predict Locations	Predict Locations and Severity
12	1 QoI:PSD_{max}	86%	74%
	Vector: 4 QoIs	99%	97%

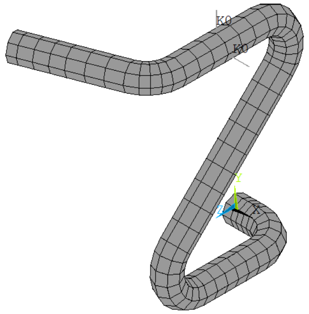
*QoI: Quantity of interest

Cases that were predicted erroneously



	12 sensors	8 sensors

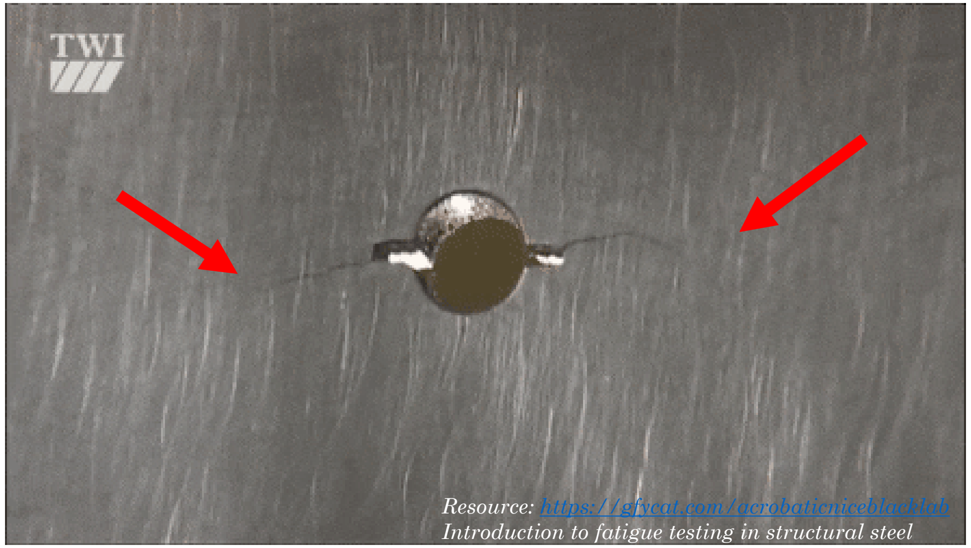
< 2% of total 630 test cases



Detect degraded locations and severity

Provide recommendations to avoid high-cyclic fatigue

Fatigue



Resource: https://gfycat.com/acrobaticniceblacklab
Introduction to fatigue testing in structural steel

- Continuous vibrations over long periods of time can cause fatigue to build up at certain structural discontinuities of the piping-equipment systems.

- **Fatigue** is the weakening of a material caused by **cyclic loading** that results in progressive, brittle and localized structural damage.

- Once a crack has initiated, each loading cycle will grow the crack a small amount.

- This can occur even when:
  the cyclic loading stresses $<$ the material's yield strength.

Strategic Recommendations for Operator Actions

Diagnosis:

Predict degraded location and severity

↓

Transmissibility Ratio plots

↓

Obtain stresses in high T.Ratio range

↓

Obtain pump operating speed at maximum stress

↓

Check “safe” values as per ASME Design Criteria for fatigue

↓

Potential recommendations

1

Avoid pump speeds at 882 RPM

$N = 3 \times 10^5$

$P = 882$ RPM

2

Pump operation at 882 RPM

Allowable hours: 6

$$h = \frac{N}{P \times 60} \approx 6$$

Development of Diagnostic Digital Twin for Piping System

NCSU: Abhinav Gupta and Kevin Han
EPRI: Bruce Greer and Hasan Charkas

NC STATE UNIVERSITY

EPRI

Critical Need

- Commercial nuclear power industry is actively seeking tools and methods to optimize construction activities and reduce operations and maintenance (O&M) costs.
- Digital twins (DTs) are promising tools that offer updated representations of structures, utilizing various data types.
- Further demonstrations of DTs' effectiveness are needed to promote their widespread adoption in the nuclear industry, unlocking diverse applications.

Potential Impact

Objectives of this project are to:

- Reduce cost and time due to design changes and improve the visibility of design changes.
- Detect degraded locations based on indirect sensor measurements.
- Diagnose and classify degradation severity as minor, moderate, or severe.

Project Innovation and Approach

North Carolina State University will conduct an exploratory project to demonstrate the various steps needed in the development of a digital twin on a piping system and to develop a computational framework for assessing degradation mechanisms. To achieve the high-level objectives, the following framework will be implemented.

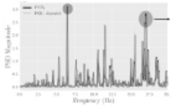
Design Piping System Using BIM

→ Scanning and Virtual Inspection

→ Convert "As-Built" BIM into FE model

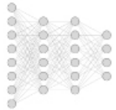
→ Sensor Optimization

→ Feature Extraction and Training Data for DT



→ Trained DT and Experimental Test Data

→ Prediction Degradation Using Deep Learning



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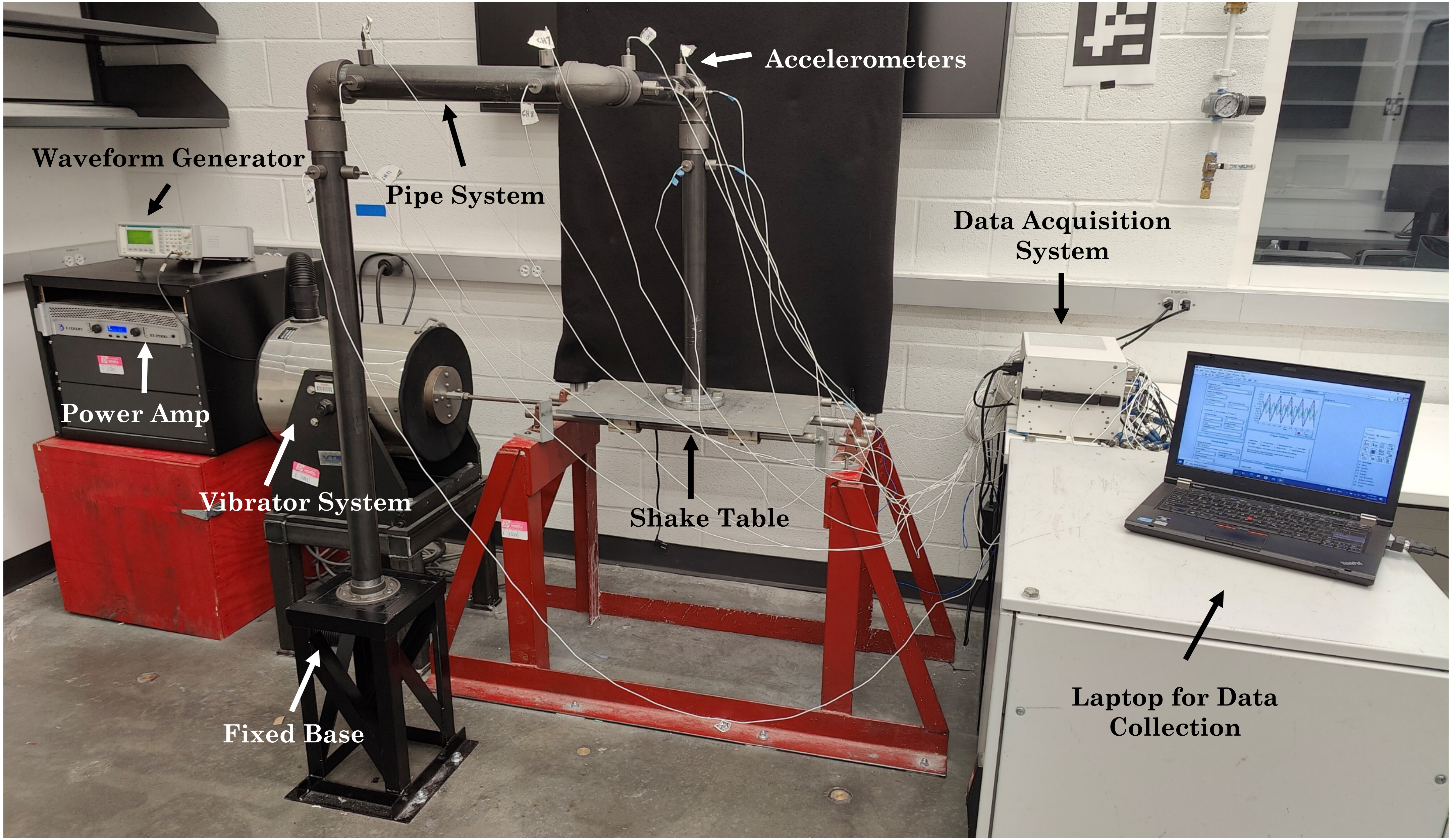
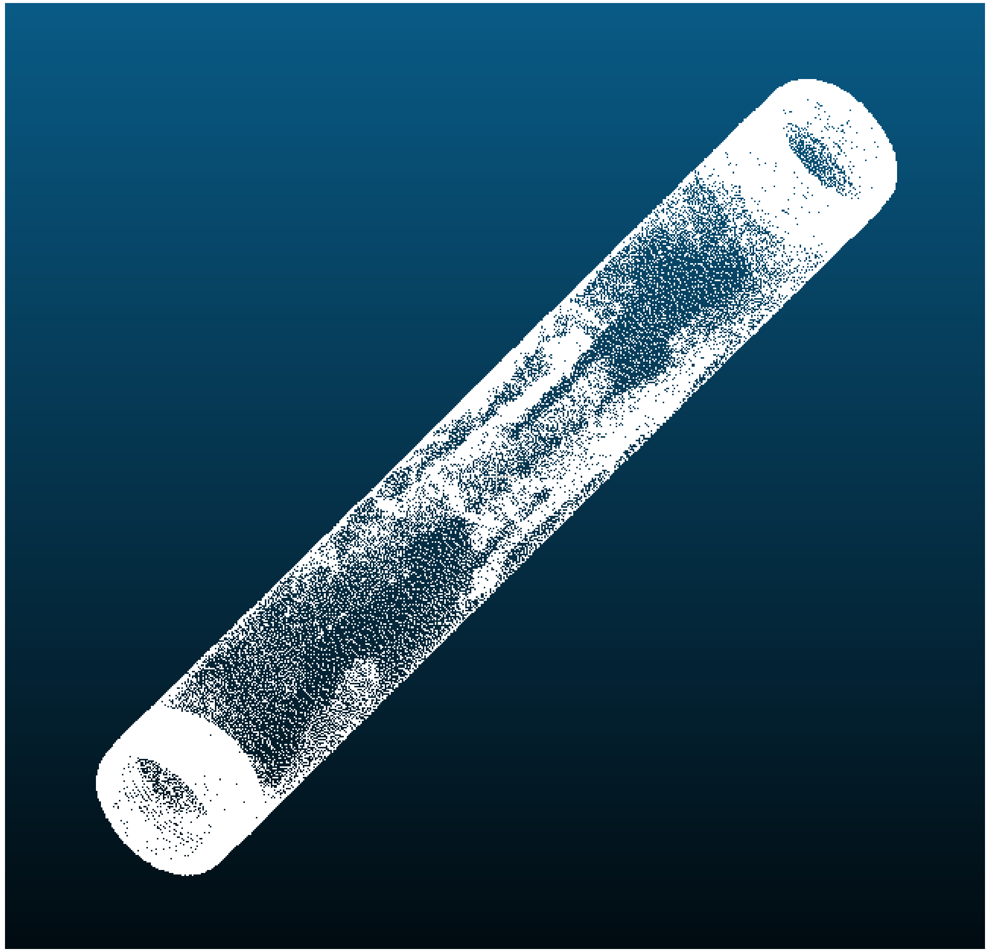
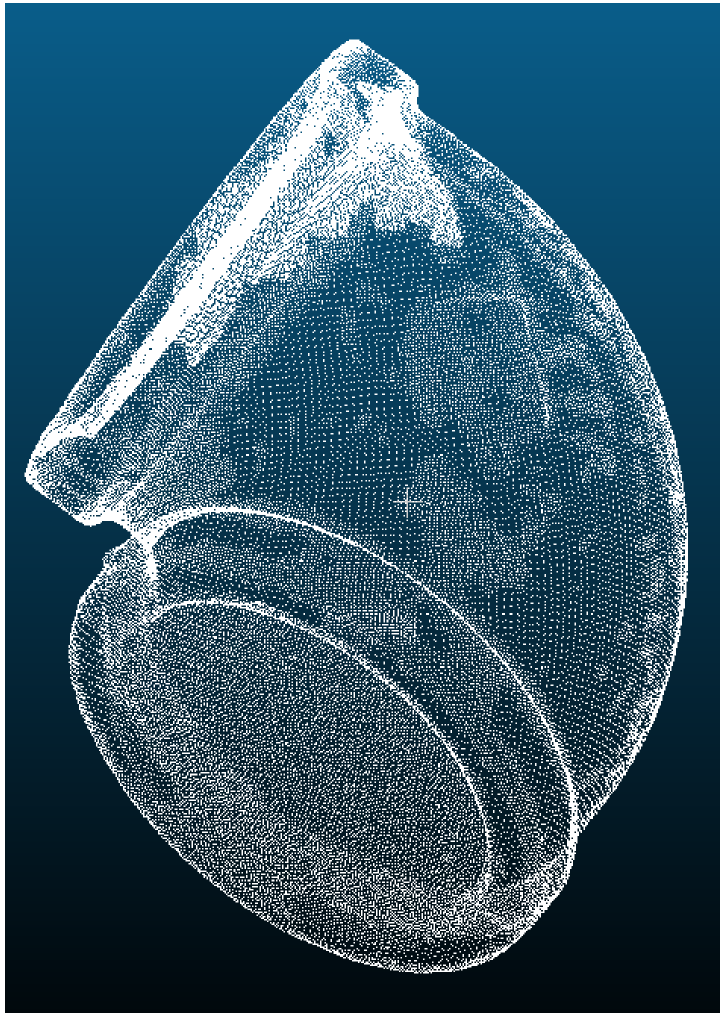
Lab Setup


Accelerometers
Waveform Generator
Pipe System
Data Acquisition System
Power Amp
Vibrator System
Shake Table
Fixed Base
Laptop for Data Collection

Overlays of BIM and 3D Scans of Pipe Parts

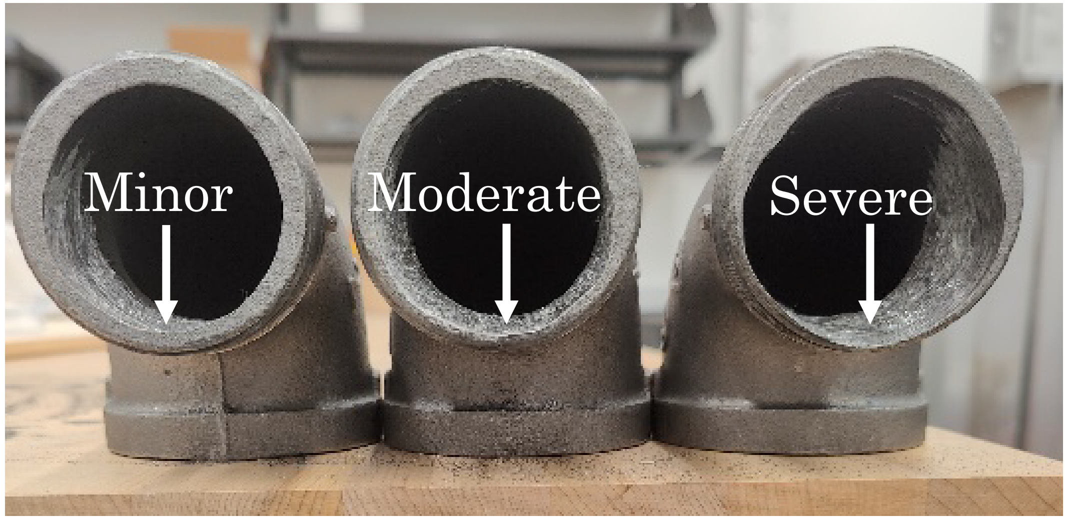


18” Pipe



Elbow

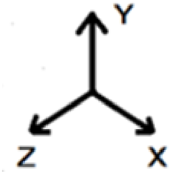
Degradation Implementation



Sources of Error in Experimentation

Experimental Setup

- Piping system assembly
- Accelerometer alignment



Shake Table Loading

- Heat effects

Data

- Noisy, insufficient data
- Non-uniform degradation

Conclusions

- Illustrated benefits of using the proposed vector of degradation sensitive features versus a single quantity

- The condition monitoring framework can predict degraded locations and severity from the simulated sensor data with more than **95%** accuracy.

- Proposed a cutting-edge technique to combine the condition monitoring framework with fatigue-life assessment for nuclear piping-equipment systems, by providing a strategy-based recommendation on “safe” pump operating speeds and duration.

Ongoing Research

- Validation of experimental sensor data with simulated sensor data
- Signal processing and feature extraction of non-stationary signals
- Training with simulated data (large database) and testing with experimental data.

Thank you!

Any Questions?

Virtual Workshop on Condition Monitoring and Structural Health Management for Nuclear Power Plants

November 28-29, 2023

Development of Fitness-For-Service Code for Sodium-Cooled Fast Reactors

Shigeru TAKAYA

Fast Reactor Cycle System R&D Center

Japan Atomic Energy Agency

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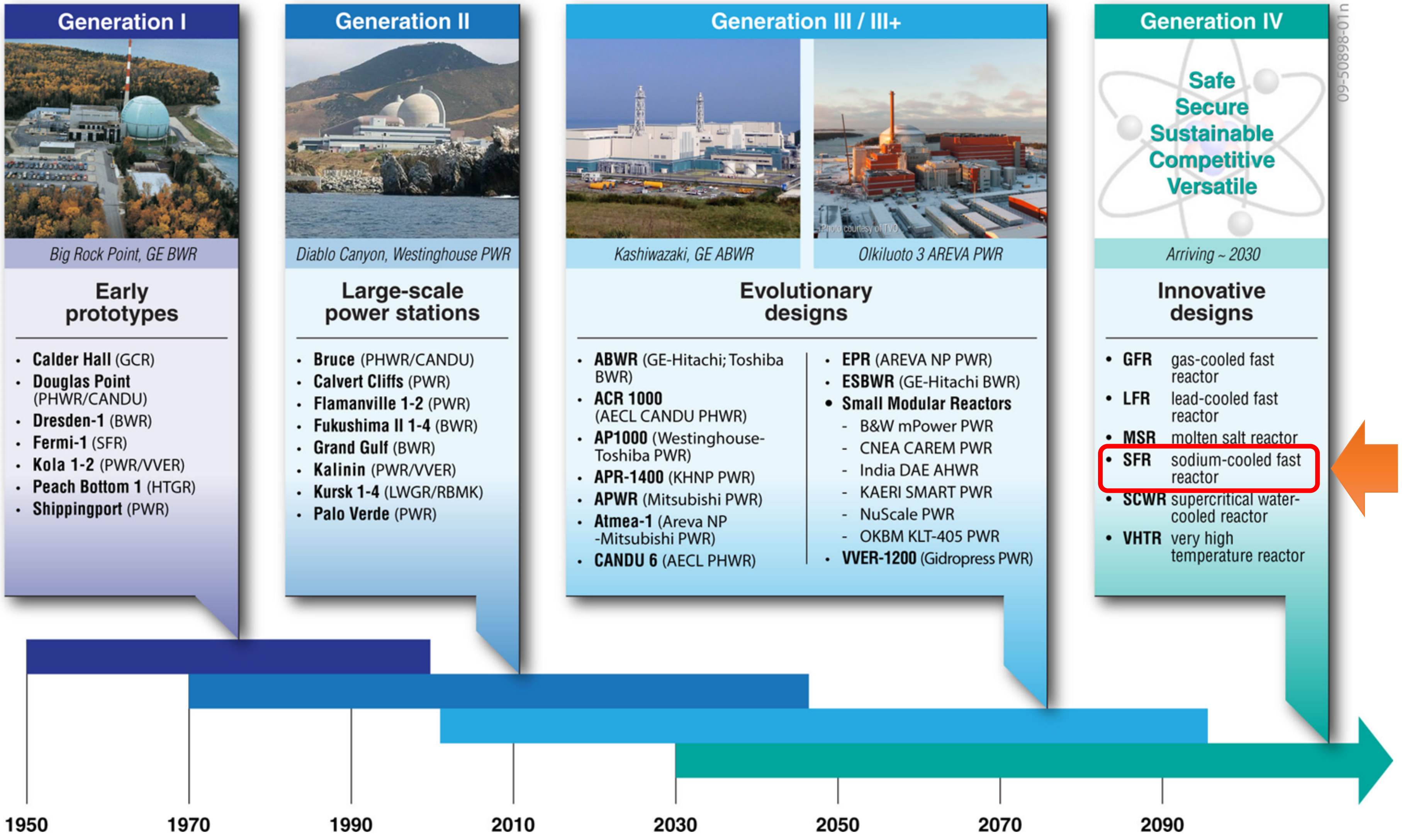
Development of Sodium-Cooled Fast Reactors (SFRs)



Generation IV International Forum
https://www.gen-4.org/gif/jcms/c_40962/home

Importance of Fitness-for-Service (FFS) Code

- In-Service Inspection rules provided by FFS code are **important for safe and stable operation of plants**.
- **Effective and efficient ISI** is crucial **to suppress operation cost** which is one of major power generation cost factors.
- ISI rules also **affect design** of nuclear power plants because the accessibility to the components where ISI is required needs to be considered appropriately in the design.

ISI rules need to be developed rationally by considering relevant features of reactor type and design of an individual nuclear power plant.

Features of SFRs

- SFRs have several different features from the conventional Light Water Reactors (LWRs).
- It is not reasonable to apply the ISI rules of conventional LWRs to SFRs directly.

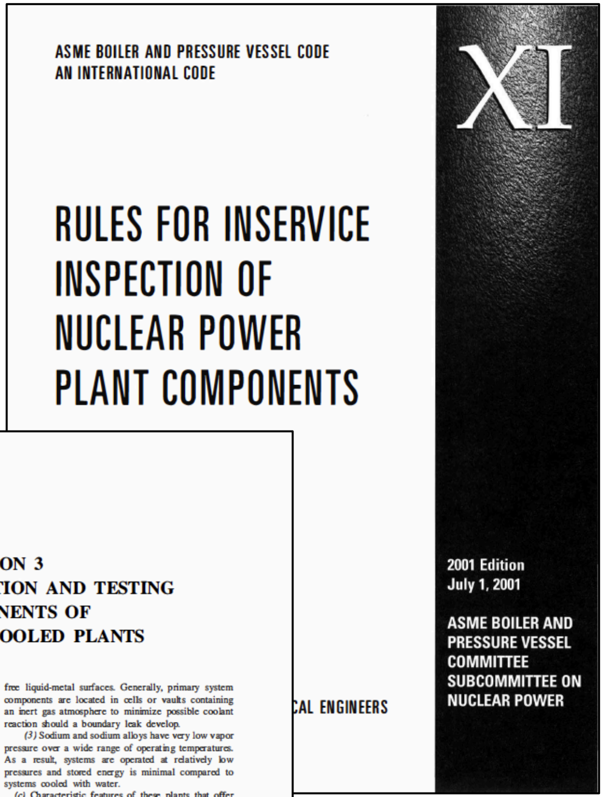
Difficulty in conducting traditional NDE ⇨ **Negligible corrosion, low pressure, easy detection of leaked sodium**

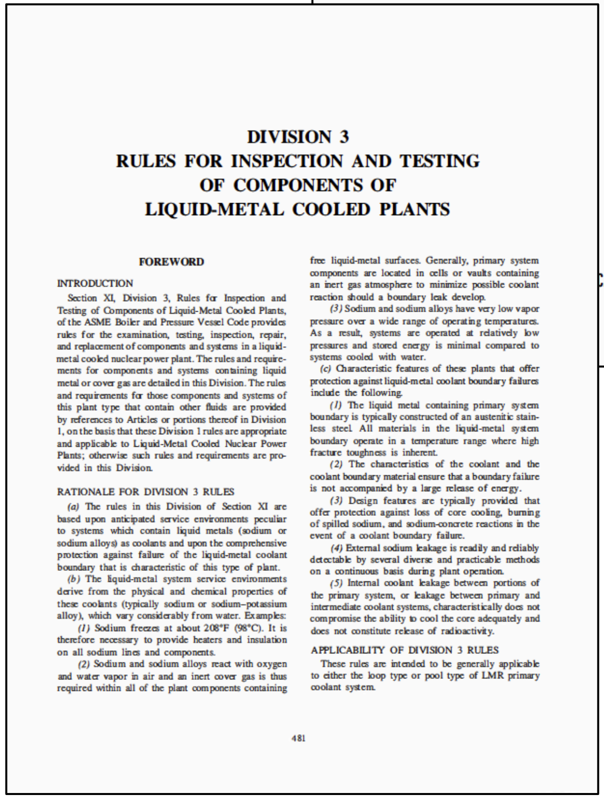
		LWR（PWR）	SFR（Monju）	Features of SFRs
Operating Conditions				
	Coolant	Water	Sodium	・Opaque and chemically active ・Excellent compatibility with structural materials
	Reactor Outlet Temp.	~320℃	~530℃	・Operation in Creep regime
	Difference in Temp. between Reactor Outlet and Inlet	~30℃	~130℃	・High thermal stress
	Operating Pressure	~16 MPa	~1 MPa	・Low pressure
Dimensions（Reactor Vessel）				
	Inner Diameter	~4 m	~7 m	・Large diameter
	Thickness	~200 mm	~50 mm	・Thin wall thickness
	Inner Diamter／Thickness	~20	~140	・High ratio

Previous FFS Code for SFRs

- Historically, ASME Boiler and Pressure Vessel (B&PV) Code, **Section XI, Division 3**, existed until the 2017 edition.
- It was developed as part of the Clinch River Breeder Reactor Plant Project in the U.S..
- The code revision was suspended due to the cancellation of the project, thus several parts, including acceptance standards for examinations of Class 1 Components, were left as being in the course of preparation.

It was practically difficult to apply it to SFRs.





DIVISION 3
RULES FOR INSPECTION AND TESTING
OF COMPONENTS OF
LIQUID-METAL COOLED PLANTS

FOREWORD

INTRODUCTION

Section XI, Division 3, Rules for Inspection and Testing of Components of Liquid-Metal Cooled Plants, of the ASME Boiler and Pressure Vessel Code provides rules for the examination, testing, inspection, repair, and replacement of components and systems in a liquid-metal cooled nuclear power plant. The rules and requirements for components and systems containing liquid metal or cover gas are detailed in this Division. The rules and requirements for those components and systems of this plant type that contain other fluids are provided by references to Articles or portions thereof in Division 1, on the basis that these Division 1 rules are appropriate and applicable to Liquid-Metal Cooled Nuclear Power Plants; otherwise such rules and requirements are provided in this Division.

RATIONALE FOR DIVISION 3 RULES

(a) The rules in this Division of Section XI are based upon anticipated service environments peculiar to systems which contain liquid metals (sodium or sodium alloys) as coolants and upon the comprehensive protection against failure of the liquid-metal coolant boundary that is characteristic of this type of plant.

(b) The liquid-metal system service environments derive from the physical and chemical properties of these coolants (typically sodium or sodium–potassium alloy), which vary considerably from water. Examples:

(1) Sodium freezes at about 208°F (98°C). It is therefore necessary to provide heaters and insulation on all sodium lines and components.

(2) Sodium and sodium alloys react with oxygen and water vapor in air and an inert cover gas is thus required within all of the plant components containing free liquid-metal surfaces. Generally, primary system components are located in cells or vaults containing an inert gas atmosphere to minimize possible coolant reaction should a boundary leak develop.

(3) Sodium and sodium alloys have very low vapor pressure over a wide range of operating temperatures. As a result, systems are operated at relatively low pressures and stored energy is minimal compared to systems cooled with water.

(c) Characteristic features of these plants that offer protection against liquid-metal coolant boundary failures include the following.

(1) The liquid metal containing primary system boundary is typically constructed of an austenitic stainless steel. All materials in the liquid-metal system boundary operate in a temperature range where high fracture toughness is inherent.

(2) The characteristics of the coolant and the coolant boundary material ensure that a boundary failure is not accompanied by a large release of energy.

(3) Design features are typically provided that offer protection against loss of core cooling, burning of spilled sodium, and sodium-concrete reactions in the event of a coolant boundary failure.

(4) External sodium leakage is readily and reliably detectable by several diverse and practicable methods on a continuous basis during plant operation.

(5) Internal coolant leakage between portions of the primary system, or leakage between primary and intermediate coolant systems, characteristically does not compromise the ability to cool the core adequately and does not constitute release of radioactivity.

APPLICABILITY OF DIVISION 3 RULES

These rules are intended to be generally applicable to either the loop type or pool type of LMR primary coolant system.

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Development of ISI Rules for SFRs in ASME and JSME

- **Code Case to Sec. XI, Div. 3** (~2017)
  - ASME/JSME Joint Task Group for **System Based Code (SBC)** was established in 2012 in the ASME B&PV Code Committee.
  - **Code Case N-875** that provides alternative ISI requirements, including acceptance standards, to Sec. XI, Div. 3 was developed based on the SBC concept, and was issued in 2017.

- **FFS Code for SFRs in JSME** (~2021)
  - **FFS code for SFRs** was concurrently being developed in JSME as well as **Leak-Before-Break (LBB) Assessment Guidelines for SFRs**, and their first edition were approved in 2021.

- **Provisions Specific to SFRs for New Sec. XI, Div. 2** (On going)
  - New Sec. XI, Div. 2 covering all types of nuclear power plants was issued in the 2019 edition. **Based on the results of the activities above in ASME and JSME**, provisions specific to SFRs are **now being developed.**

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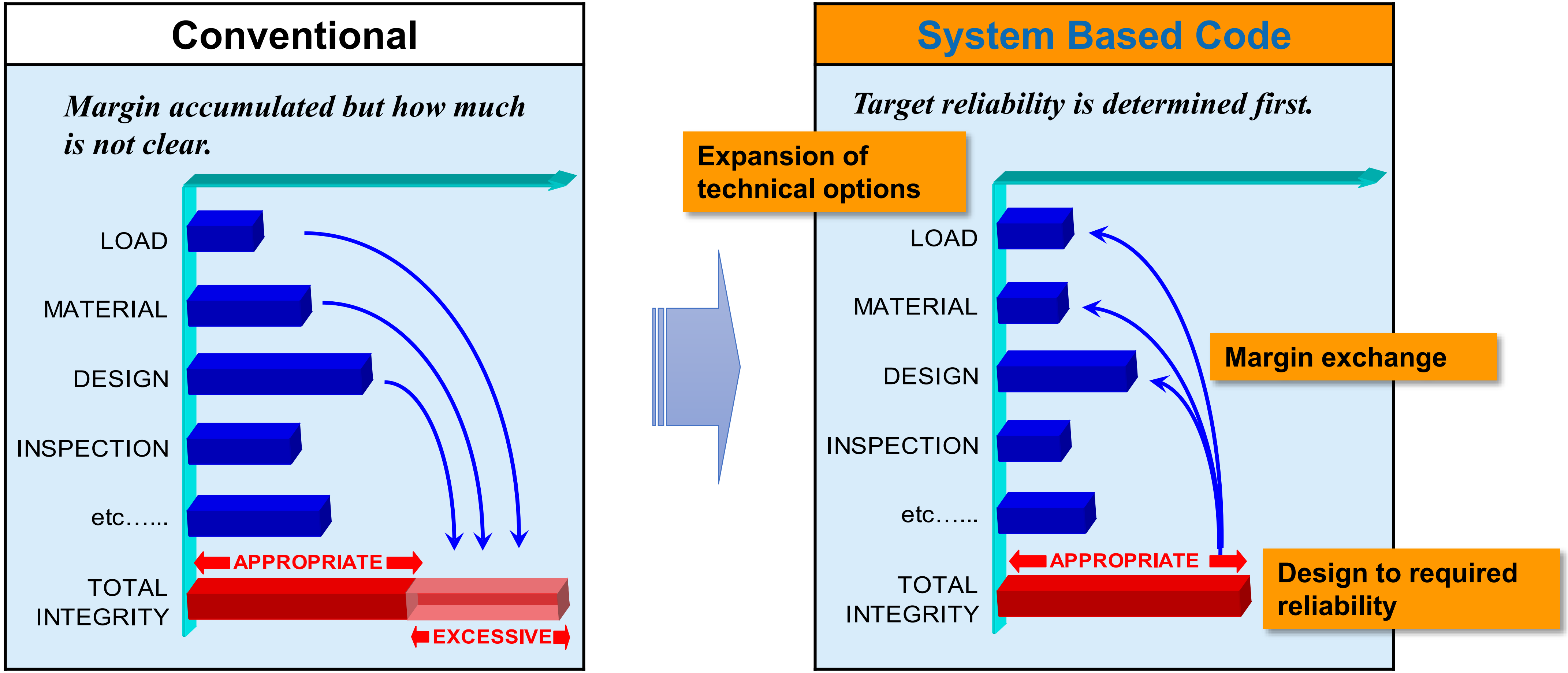
System Based Code Concept



Asada, Y., Tashimo, M. and Ueta, M., 2002, “System Based Code—Principal Concept,” Proc. 10th International Conference on Nuclear Engineering, ICONE10-22730.

Alternative ISI Requirements to Sec. XI, Div. 3

Conditions developed by using the SBC concept

Examination category	Section XI, Division 3	Code Case N-875
Liquid-metal-retaining welds in Class 1 vessels protected by guard vessels	▪ Continuous monitoring ▪ VTM-2	▪ Continuous monitoring*
Liquid-metal-retaining welds in Class 1 vessels not protected by guard vessels	▪ Continuous monitoring ▪ VTM-2	▪ Continuous monitoring*
Liquid-metal-retaining welds in Class 1 piping protected by guard pipe or tank (Heat transport loop piping)	▪ Continuous monitoring ▪ VTM-2	▪ Continuous monitoring*
Liquid-metal-retaining welds in Class 1 piping not protected by guard pipe or tank (Heat transport loop piping)	▪ Continuous monitoring ▪ VTM-2	▪ Continuous monitoring*
Internal components	▪ VTM-3	▪ None

* Acceptance standards were newly prepared.

Alternative ISI Requirements to Sec. XI, Div. 3 (Cont’d)

➢Acceptance Standard for Continuous Monitoring

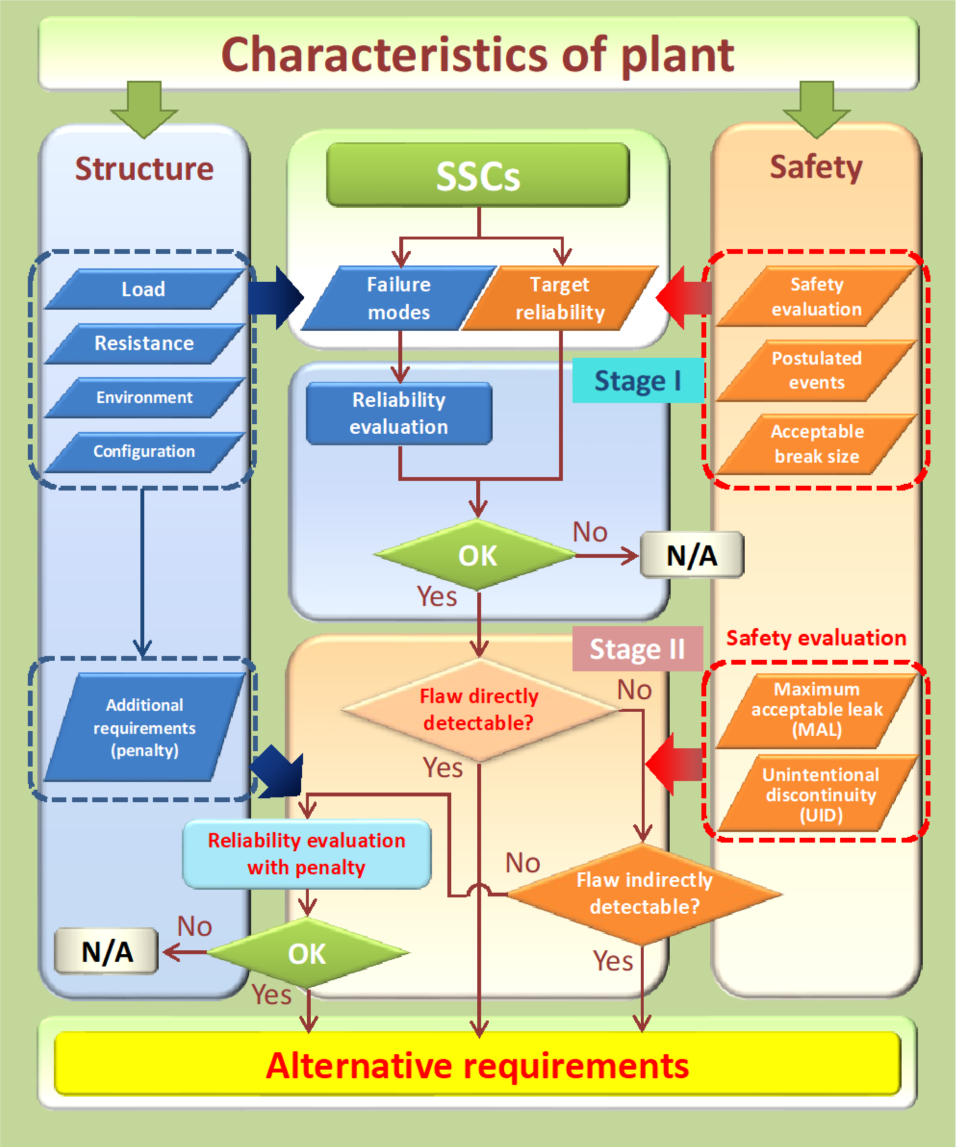
Once leakage is indicated, it is required to conduct a confirmation of leakage in accordance with the procedure predetermined by the Owner. If the confirmation takes longer time than the determined time, it is conservatively evaluated that the leakage is confirmed.

- **In case of confirmed:** Immediate shutdown of the system
- **In case of unconfirmed:** Repair of the leak detectors to meet the minimum percentage of required working leak detectors

Alternative ISI Requirements to Sec. XI, Div. 3 (Cont’d)

➢ **Conditions for application of the alternative ISI requirements based on the SBC concept**

- **Stage I:** Structural reliability evaluation
  - *It shall be shown that the SSC has the **reliability equals to or greater than Reliability Target without ISI**.*
- **Stage II:** Evaluation of detectability of flaws
  - *It is ensured to shut the plant down safely **before the flaw reaches the maximum acceptable size**.*
  - *Either direct or indirect detection. **Flexible selection of suitable ISI technologies** according to the plant features*



Alternative ISI Requirements to Sec. XI, Div. 3 (Cont'd)

➢ Determination of Failure Modes

- Degradation mechanisms that can potentially produce flaws during service is evaluated based on the list of potential degradation mechanisms provided in the CC as well as operating and research experience.
- Failure modes are determined based on the identified degradation mechanisms.
- Failure modes not addressed in the design code are also considered, if necessary.

Table 1
Degradation Mechanisms Criteria

Degradation Mechanism		Degradation Features	Attribute Criteria	Susceptible Regions
TF		crack initiation and propagation	– potential for mixing of hot and cold fluids at core outlet, – potential for liquid level turbulence, – potential for inflow of cold fluid to hot outlet plenum during a scram transient, OR …tential for relatively rapid temperature change	base metal, heat affected zone (HAZ), and welds

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JSME FFS Code for SFRs

➢ General Rules, and ISI Requirements of Class 1 Components and their Supports are provided in the 1st Edition approved in 2021.

Parts examined		ISI requirement
Primary coolant boundary welds	Sodium retaining parts	▪ Continuous monitoring (CM-1) For small diameter pipe ▪ Continuous monitoring (CM-2)
	Cover gas retaining parts	▪ Continuous monitoring (CM-3)

Distinction based on influence of failure

- Leak detection sensitivity high enough to demonstrate Leak-Before-Break (LBB) is required for CM-1 for ensuring the shutdown of the plant in safe.

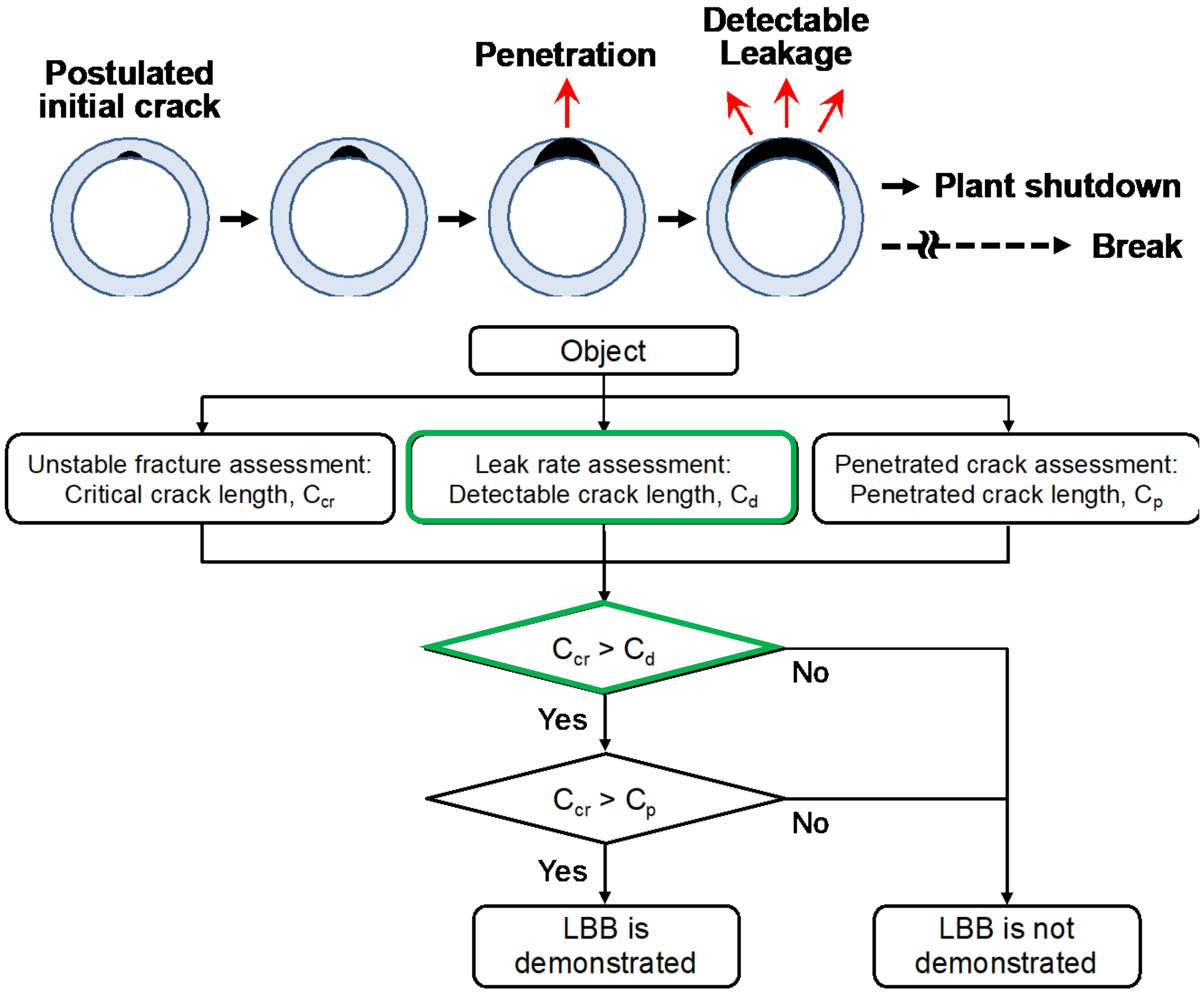
LBB concept applied to ISI

- LBB Assessment Guidelines for SFRs were also developed at the same time.

JSME LBB Assessment Guidelines for SFRs

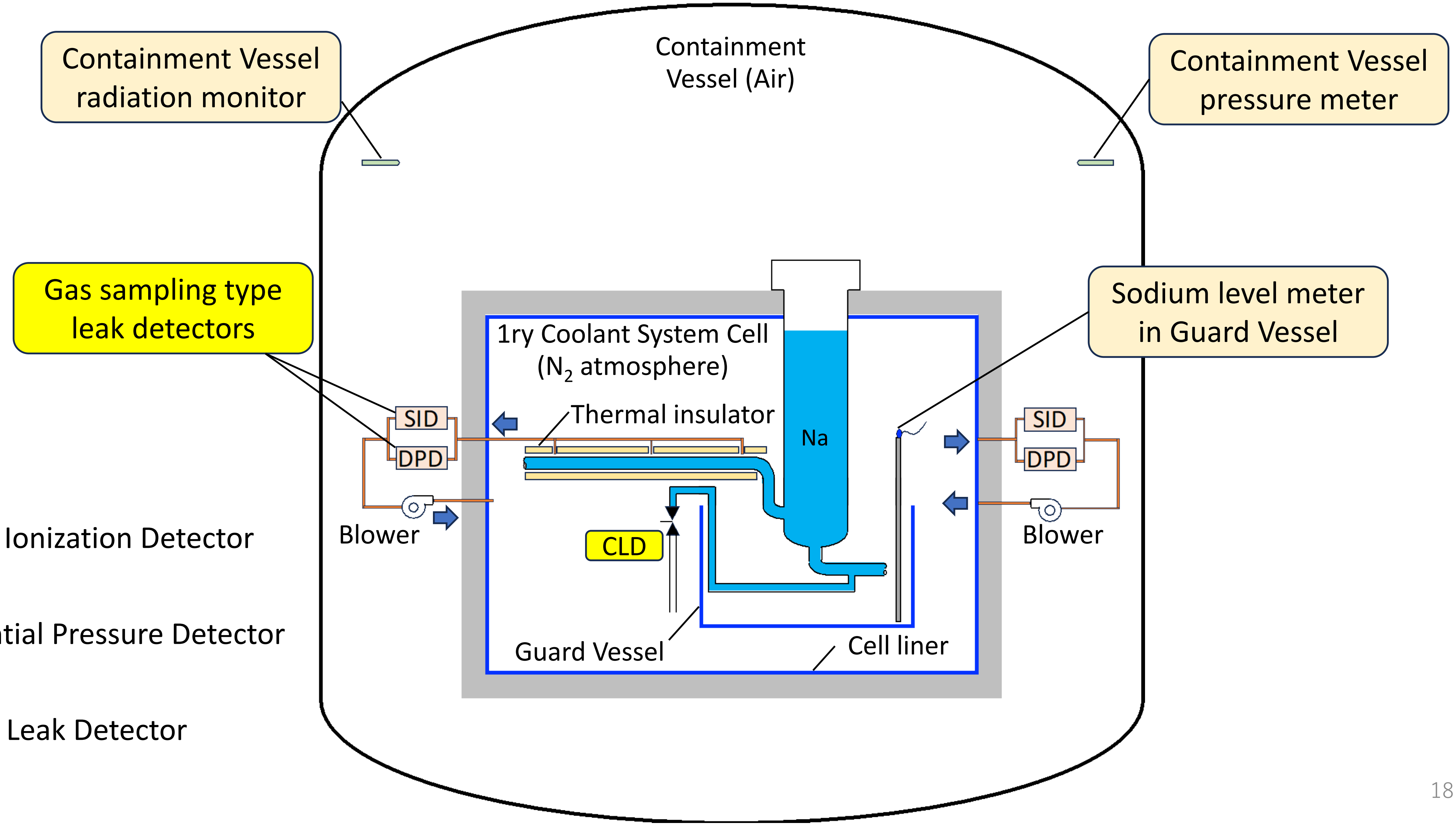
Developed by considering the following features of SFRs:

- **Operation at elevated temperatures**
  - Effect of crack growth by Fatigue-Creep damage
- **Usage of liquid sodium as a reactor coolant**
  - Leak rate assessment method for sodium
- **Low pressure system**
  - Applicability to components with large diameter and thin wall thickness
  - Secondary stress is dominant.



The sensitivity is to be determined so that C_d is smaller than C_{cr}.

Installation of Sodium Leak Detectors (Example)



SID:
Sodium Ionization Detector

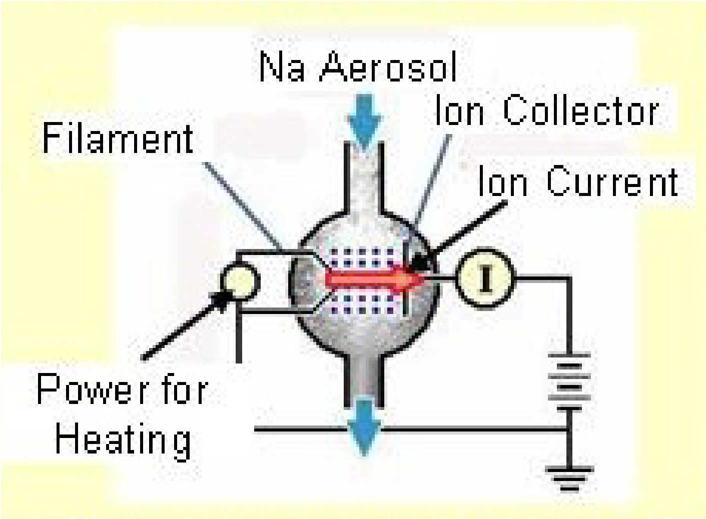
DPD:
Differential Pressure Detector

CLD:
Contact Leak Detector

Sodium Leak Detectors (Examples)

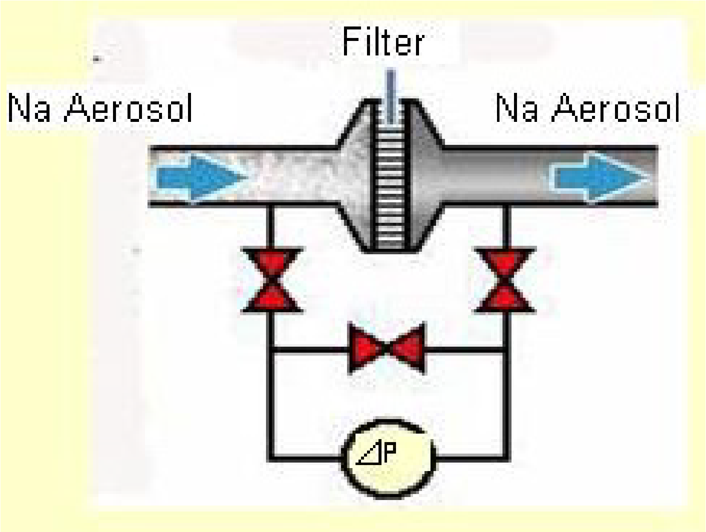
- **SID (Sodium Ionization Detector)**

  Best suitable to detect sodium leak in the inert gas atmosphere (Sensitivity: ≧1 × 10^{-10} g Na/cc)



- **DPD (Differential Pressure Detector)**

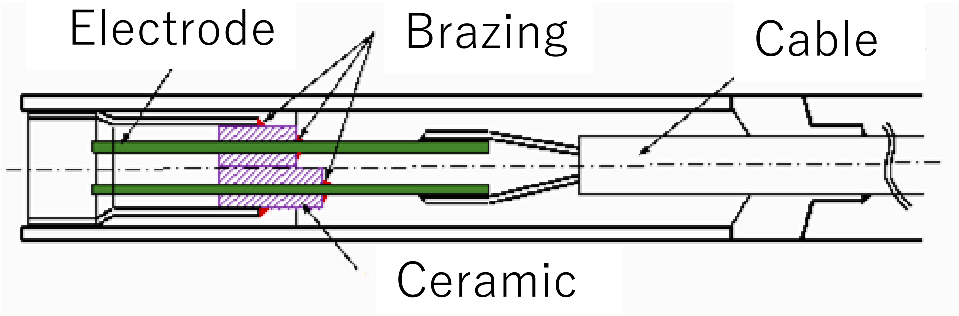
  Applicable to either the inert gas or air atmosphere.



http://www.cea-jaea-collaboration.net/napocket/pocketbook/page37.html

- **CLD (Contact type Leak Detector)**

  Applied to portions where leaked sodium accumulates such as valves and bottom of tank.



https://jopss.jaea.go.jp/search/servlet/search?5065316

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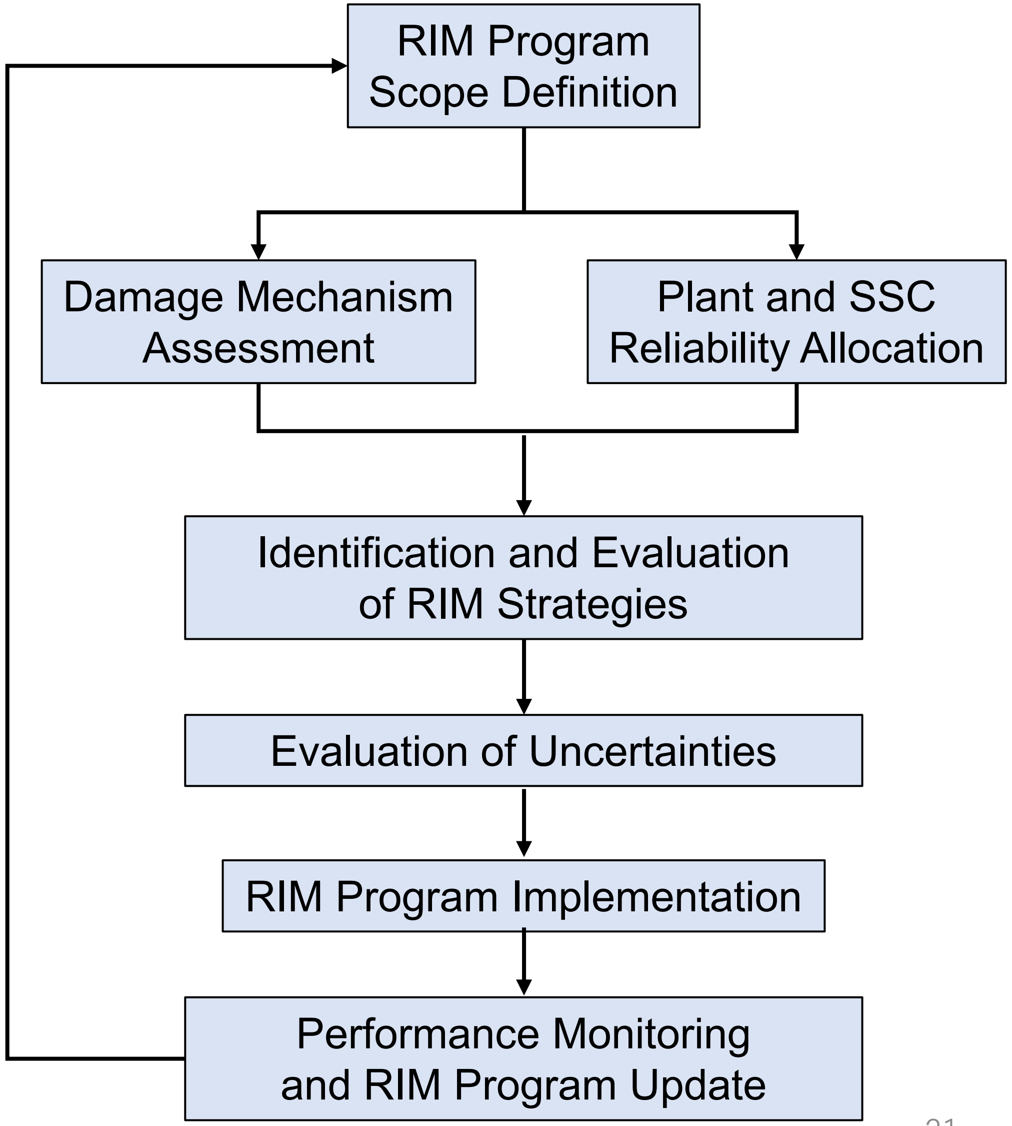
Proposal of Provisions Specific to SFRs for Sec. XI, Div. 2

ASME Sec. XI, Div. 2, "Reliability and Integrity Management (RIM)"

- **New** fitness-for-service code **for all types of nuclear power plants** published in 2019
- **Basic concept shared with SBC** (Several key parts of CC N-875 were incorporated in Div. 2)
- **Technology-neutral** requirements with supplements for specific types of nuclear reactors (currently only for LWR and HTGR)
- Development of **the supplement for liquid-metal (Sodium) cooled reactors** is now one of the **top priority** action items of Sec. XI committee.
- ASME/JSME Joint Working Group on RIM Processes and SBC has prepared **draft provisions based on ASME Sec. XI, Div. 3, CC N-875, and JSME FFS codes as well as LBB Assessment Guidelines for SFRs**, and the draft is now under consideration by WGs.



Summary

- SFRs are expected as Generation IV nuclear energy systems.
- Effective and efficient ISI is crucial for safety, stable operation, and economic efficiency. Thus, ISI rules needs to be determined by considering relevant features of SFRs.
- The following FFS codes for SFRs have been developed as the result of the collaboration between ASME and JSME so far.
  - Code Case N-875 in ASME
  - FFS Code & LBB Assessment Guidelines for SFRs in JSME
- Currently, for the new Sec. XI, Div. 2, provisions specific to SFRs are being prepared based on the results above by the continuous collaboration between ASME and JSME.

Introduction to ASME Section XI, Division 2 Reliability and Integrity Management (RIM)

USNRC - DOE - INL
WORKSHOP ON STRUCTURAL HEALTH MANAGEMENT FOR NUCLEAR POWER PLANTS
NOVEMBER 28 - 29, 2023

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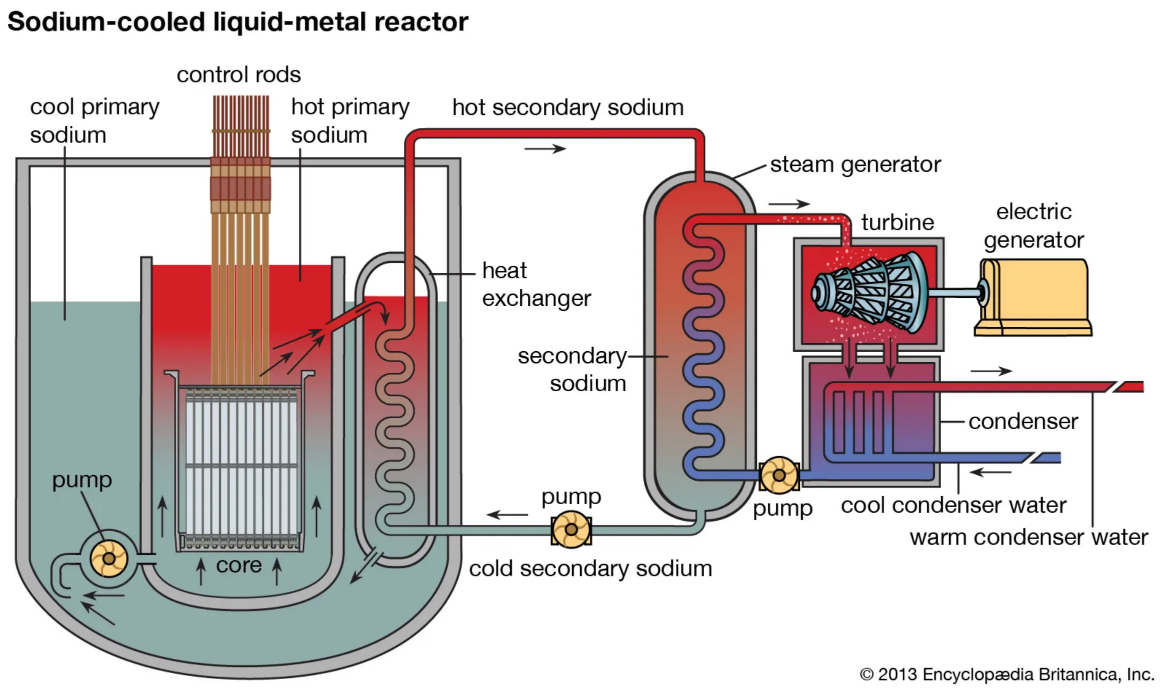
Today’s Topics

- Outline the process of Reliability Integrity Management (RIM)
  - What is RIM and why it is needed for advanced reactors?
- The RIM process concepts.
- Operational (monitoring) inspection challenges for advanced reactor designs.
- Example of RIM use & application of MANDE.

Outline of RIM

- Section XI, Division 2 Reliability Integrity Management (RIM) overview.
- What is RIM?
- Why is RIM essential to AR*, SMR* and MR* **designers** and not just to future Owners/Operators?
- What is important about RIM that AR, SMR & MR **designers** should consider throughout the design phase?
- How do Risk Informed Performance Based approaches integrate into the RIM process?



*
- AR = Advanced Reactors.
- SMR = Small Modular Reactors (i.e., <=300 MWe per unit) independent of technology
- MR = Micro Reactors (Info Link) https://www.energy.gov/ne/articles/what-nuclear-microreactor

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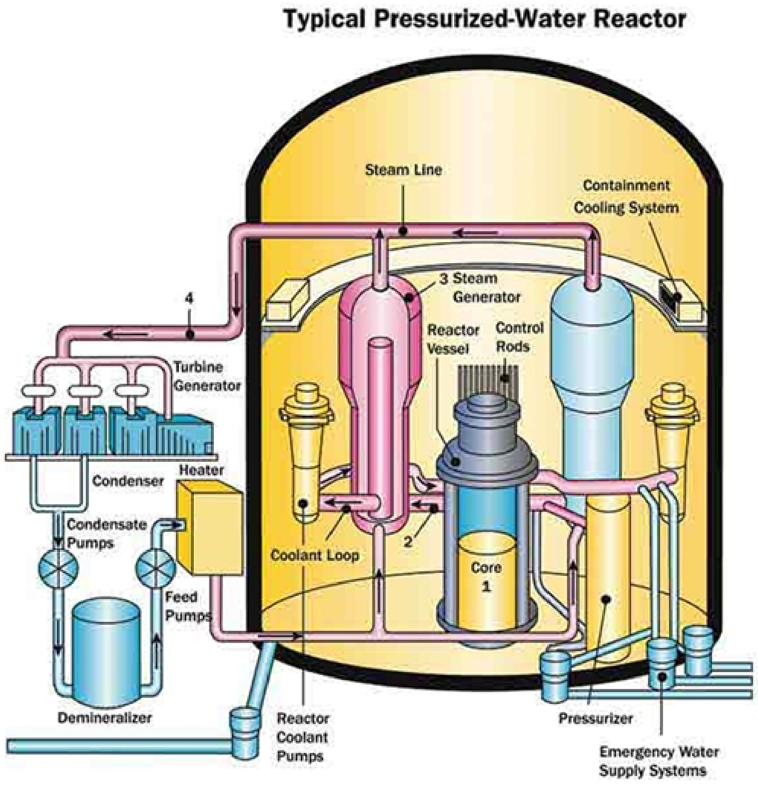
Challenges for Advanced Design Reactors - Historical Perspective

- ASME Section XI Division 1, and similar international inservice inspection standards (e.g., French RSE-M), are **<u>not well suited</u>** for most advanced design reactors currently in development.

- ASME Division 1 was developed primarily for light water reactor technology (e.g., BWRs & PWRs).

- ASME XI Division 1 tends to be "weld centric" in terms of what is inspected.



Reliability Integrity Management (RIM)

An ASME Section XI Sub-Group – developed the new ASME XI Division 2 Reliability Integrity Management (RIM)

- RIM is a detailed **process** to establish operational monitoring criteria for expected degradation mechanisms that are expected to occur, regardless of the reactor technology, (e.g., Molten Salt, HTGR, Liquid Metal, etc.)

  - RIM is "technology neutral" process – applicable to any reactor design and technology.

  - RIM criteria may be established by deterministic or probabilistic methods.

  - RIM requires Monitoring and NDE **(MANDE)** to be assigned to SSC, based on credible degradation mechanisms in concert with an SSC's contribution to risk for safe plant operation.

LINK TO WEBPAGE

https://aris.iaea.org/

Reliability Integrity Management Basic Process Overview Concepts

During design and operations

1. RIM scope definition and SSC selection based on PRA

INPUTS:
- Licensing & Safety Requirements
- Plant Level PRA
- SSC Level PRA Contribution to Risk

During design and operations

2. Degradation Mechanism Assessment

INPUTS:
- Assess Damage Mechanisms (DMs) relevant to the specific technology.
- Examples - creep, corrosive coolants, deterioration of non-metallics, such as graphite.

During design and operations

3. Plant and SSC Reliability Target Allocation

INPUTS:
- Selected SSC Reliability Target value feeds into the required System and Plant Required Reliability needed to meet safety objectives.
- Established by Frequency/Consequence (F/C) Curve

During design and operations

4. Identification and establishment of RIM strategies and MANDE

INPUTS:
- MANDE is selected to monitor or inspect for DMs relevant to the specific reactor technology.

Reliability Integrity Management Basic Process Overview Concepts

During design and operations

5. Evaluation of Uncertainties

INPUTS:
- Both PRA models as well as selected MANDE have associated uncertainties.
- These uncertainties must be accounted for to assure the fidelity of the required reliability of an SSC to meet its performance objectives,

During operations

6. RIM Program implementation

INPUTS:
- Program is initially implemented based on initial PRA, assigned RT values and selected MANDE.

During operations

7. Continuous monitoring and RIM Program and MANDE updates

INPUTS:
- As the plant is operated, the RIM program is updated and adjusted using the same processes employed during the initial development of the RIM Program but using newly gained insights from OE.

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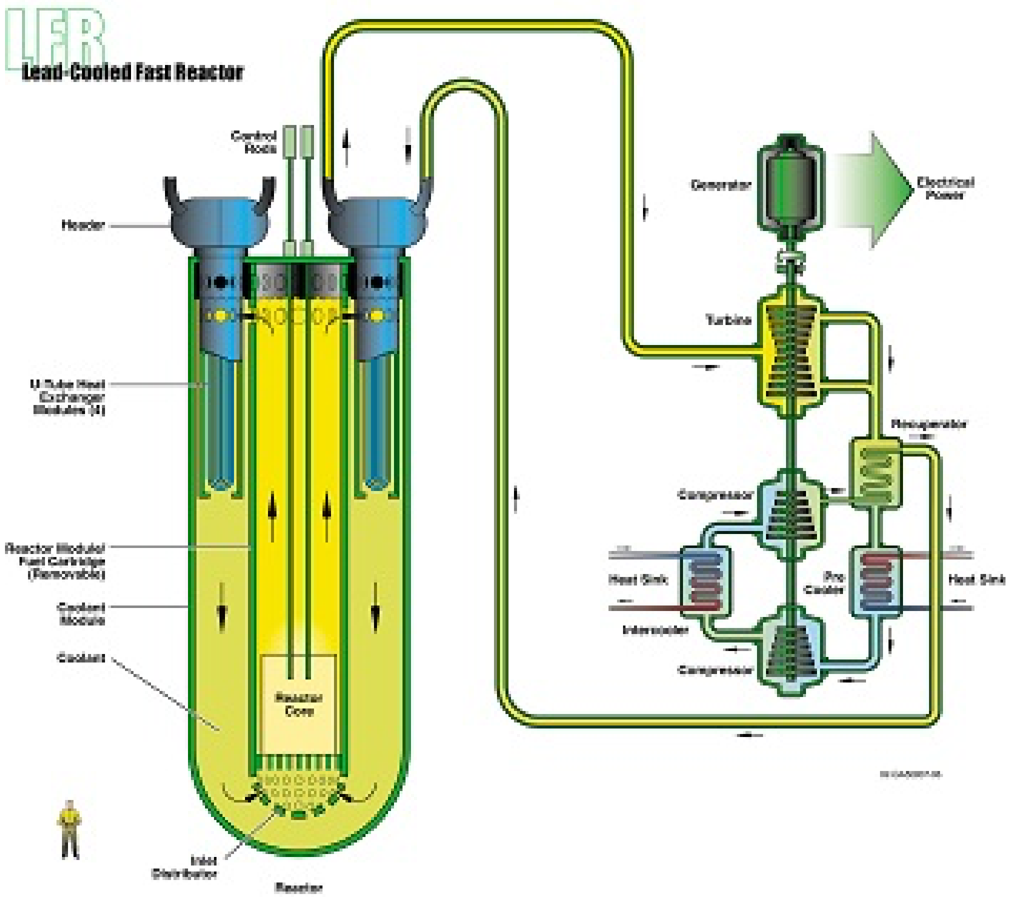
RIM Process Description: Part I (During Design)

- **<u>Any SSC</u>** that could affect plant reliability must be scoped into the RIM program.

    - Non-Safety Related SSC* classified under historic SSC classification guidance as Non-Safety Related, but that are **<u>deemed risk significant</u>**, are required for inclusion in the RIM programs.

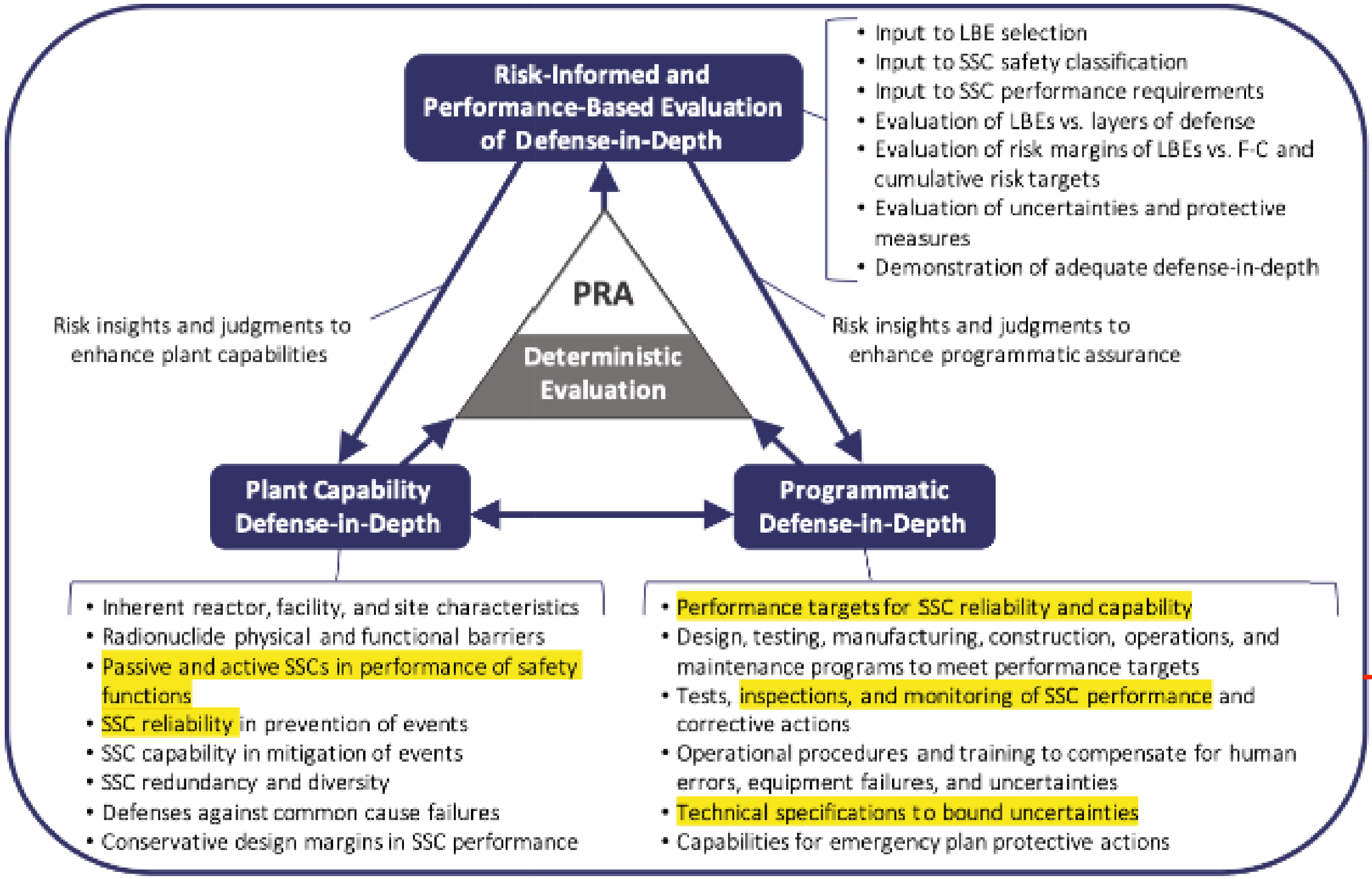
- This contrasts with the existing ASME XI Div. 1 Class 1, Class 2, Class 3, Class MC, Class CC, etc. ISI approach, with each class having different graduated criteria based on the Class of an SSC, rather than its risk significance.

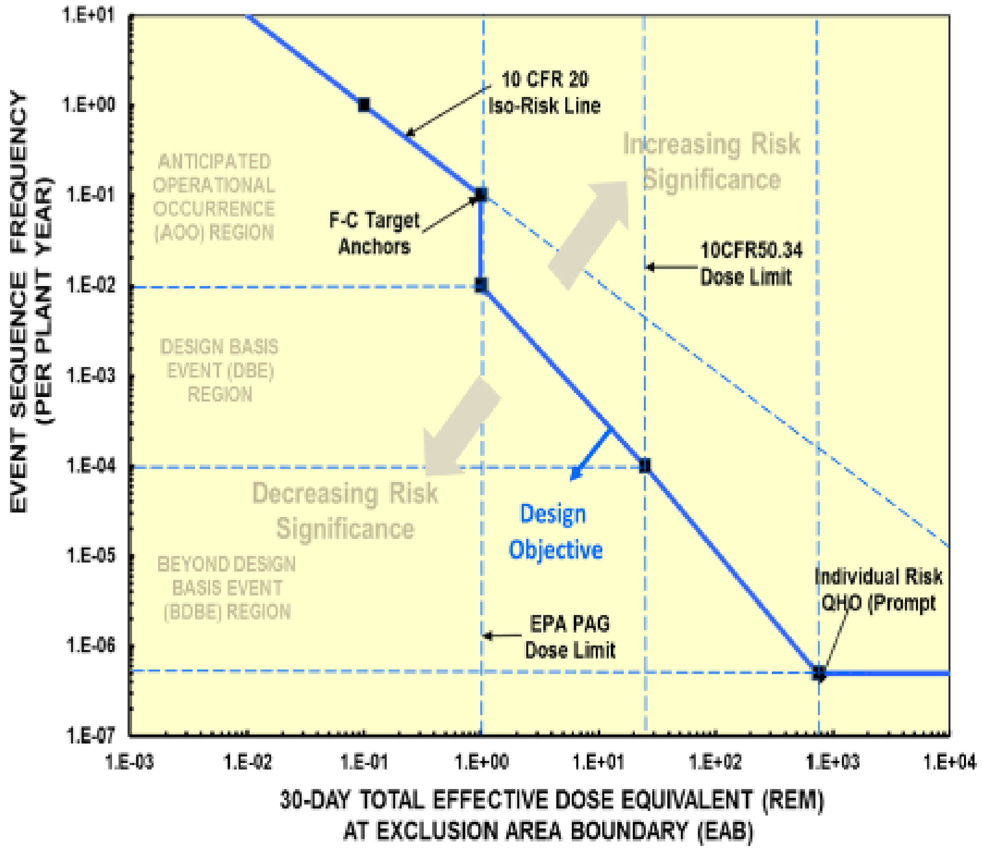


* Using NEI 18-04 guidance such SSC would be classified as Non-Safety Related with Special Treatment (NSRST)

RIM Process Description: Part I (During Design)

A ranking for risk contribution, known as a **Reliability Target Value**, is assigned to each SSC.





Figures from NEI 18-04

RIM Process Description: Part I (During Design)

- As part of initial design as well as during operations, SSCs that are deemed risk significant are scoped into the RIM Program.
  - This determination is established by the RIM Expert Panel (RIMEP)
  - RIMEP must use accepted PRA criteria to make this determination at the plant, system and SSC level.
  - This applies to passive components that would not normally be considered in traditional PRA evaluations.
- A ranking of relative risk, known as a **Reliability Target Value**, is assigned to each SSC.

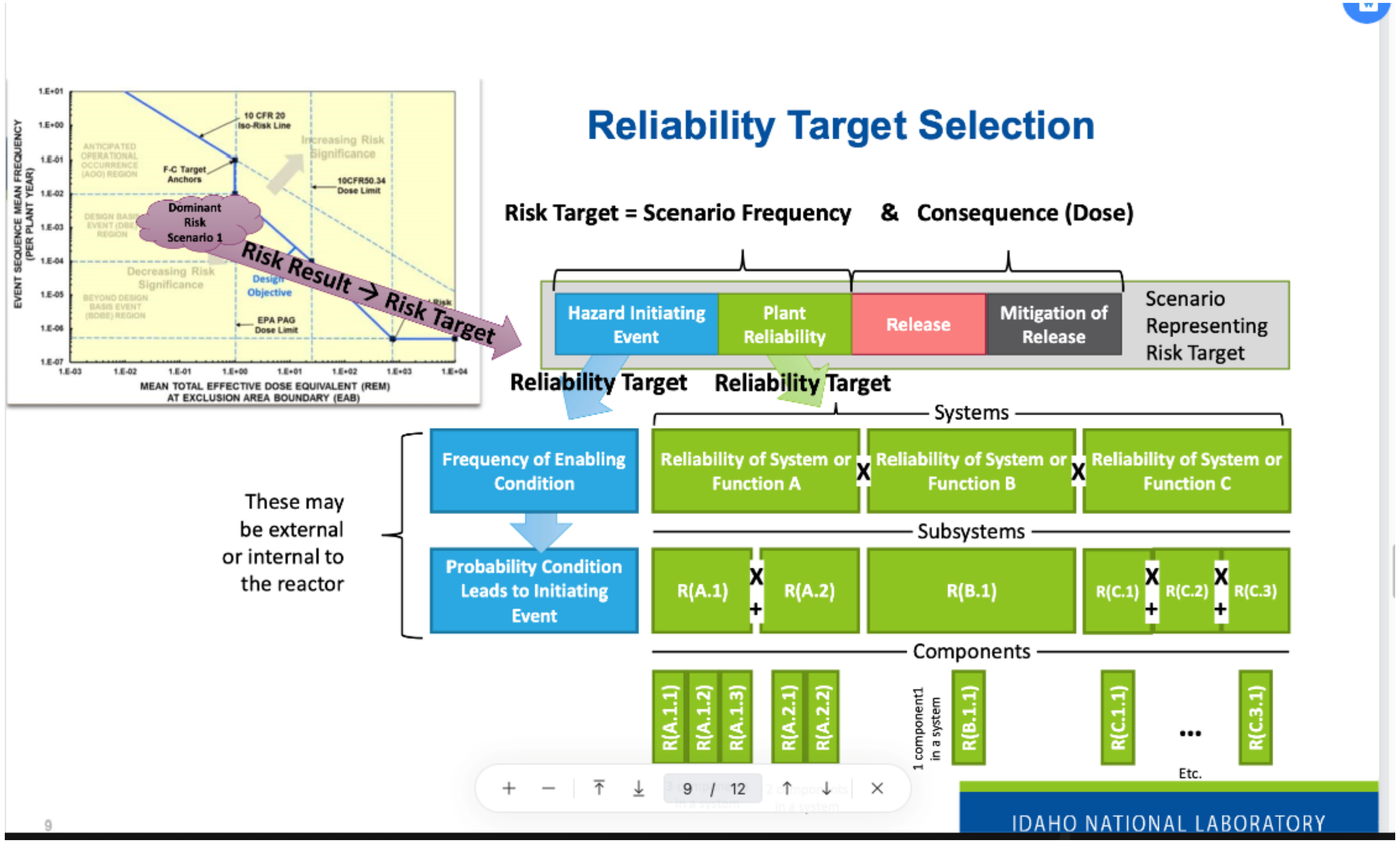


Figure from INL Report INL/PT-22-68899 Link: https://inldigitallibrary.inl.gov/sites/sti/sti/Sort_64127.pdf

RIM Process Description: Part I (During Design)

- An SSC's **Reliability Target** value is the assigned numerical index that must be maintained for an SSC within the program to assure it will:
  - Perform its required function over its expected life cycle
  - Not challenge safe plant operation or reduce overall Plant or System Reliability criteria

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RIM Process Description: Part I (During Design)

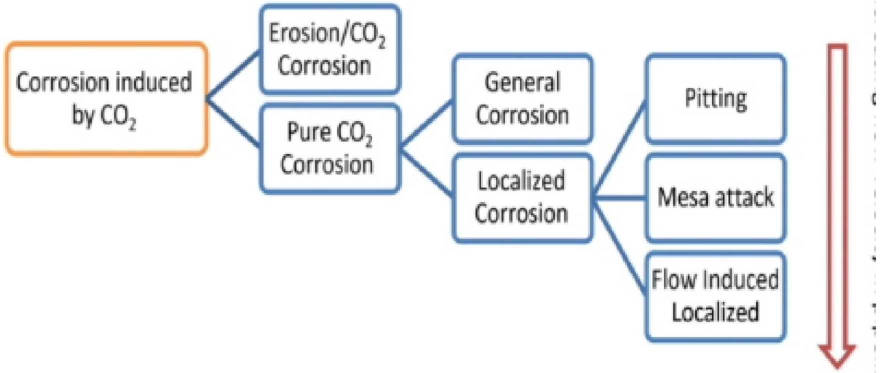
- As part of the RIM process, the RIMEP and a second RIM prescribed expert panel called the MANDE Expert Panel (MANDEEP) are required to perform an SSC Degradation Mechanism Assessment (DMA)
  - The DMA establishes what credible degradation mechanisms might apply to an SSC for a specific reactor technology over the life of the SSC (e.g., Creep, Stress Corrosion Cracking, Flow Induced Vibration, coolant chemistry excursions, etc.).

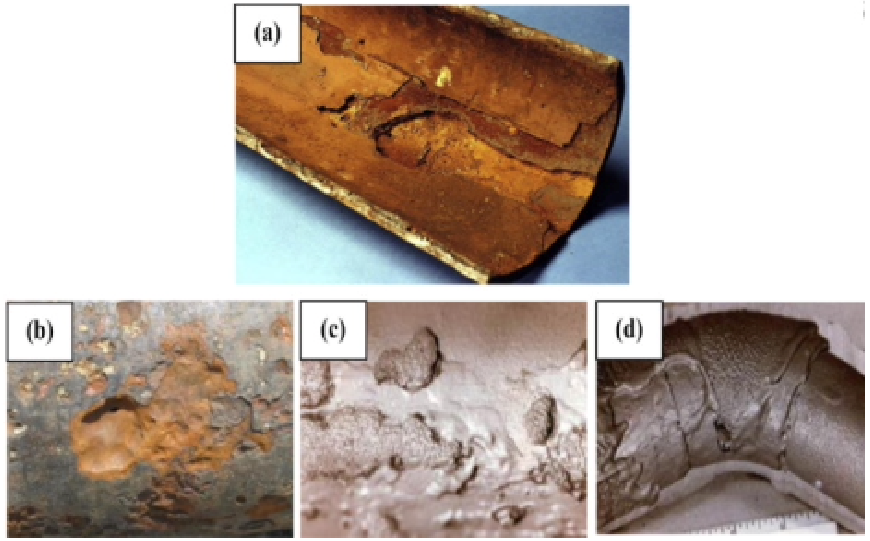
Table VII-1.2-1 Degradation Mechanism Attributes and Attribute Criteria (LWR) (Cont'd)

Degradation Mechanism		Attribute Criteria	Degradation Features and Susceptible Regions	Table VII-1.3.3-1 Examination Category (as appropriate)
FS (cont'd)	FAC	– Carbon or low alloy steel piping with Cr <0.5% (some literature indicates 0.1%) and – Wet steam environment (i.e., two-phase flow) or – Any high-purity water environment coupled with – Low levels of dissolved oxygen – And flow (there is no known practical threshold velocity below which FAC will not occur) [reference: T. M. Laronge, M. A. Ward, "The Basics and Not so Basics of Water Corrosion Processes Altered by Flow Changes," CORROSION/99, paper 99345, NACE International, Houston, TX (1999)] – Accelerated further by turns in the flow path and – Low or very high pH – Fluid flow present >100 hr/yr	wall thinning can initiate in welds, HAZ, and base metal at the component inner surface affected locations can include regions where the potential for FAC degradation has been identified FAC can occur over extensive portions of the component inner surface Degradation growth is relatively slow, and through-wall degradation is not expected within an inspection period	A, B, D, F, J, O
	PE	– Solid Particle Erosion (SPE) is damage caused by particles transported by the fluid stream rather than by liquid water or collapsing bubbles. In contrast to liquid impingement erosion, the necessary velocities for SPE are low, approximately 3 ft/sec. SPE also requires the presence of particles of sufficient size, typically >0.004 in. (100 microns). – Erosion rate decreases in ductile materials rapidly with decreasing particle size below 0.004 in. (100 microns).	Wall thinning can initiate in welds, HAZ, and base metal at the component inner surface. "Hard materials" (e.g., Stellite) offered only modest improvement over carbon steel. The Inconel alloys offered only a very modest improvement over carbon steel. Unless exotic materials are used (i.e., ceramics), there is no material solution to SPE. Susceptible regions include valve internals, nozzles, and the steam turbine. Degradation growth is relatively slow, and through-wall degradation is not expected within an inspection period.	B, D, F, J

RIM Process Description: Part I (During Design)

- The RIMEP and MANDEEP are responsible for determining and assigning MANDE
- Any MANDE selected must be **<u>“performance demonstrated”</u>** before being used.
- This assures that any MANDE selected is effective in detecting the degradation mechanism.
- RIM is **<u>not focused exclusively on weld examinations</u>**. Any credible degradation mechanism must be accounted for in MANDE selection (e.g., general corrosion).





NOTE: Some reactors have used CO2 as a coolant

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RIM Process Description: Part I (During Design)

- MANDE that is assigned is chosen for the purpose of detecting credible degradation mechanisms expected to occur in a particular reactor technology.

- Because DMs may not be limited to just weld locations, MANDE application needs to be accounted for in the design of an AR to employ RIM.

- Based on the previous example of corrosion phenomena in a CO2 environment, a system may need to be outfitted with installed transducers to be able to detect changes in wall loss due to general corrosion effects.

- Regardless of the method of MANDE selected, a provision of RIM is that MANDE must be performance demonstrated.

    - That is to say, what is the **“confidence level”** of the MANDE chosen to be able to reliably detect changes in wall thickness of any SCC exposed to CO2 as in the noted example.

Advanced Reactor Designer Considerations Summary:

- Integrating RIM considerations during efforts is essential and should include:
  - Establishing what the population of risk significant SSCs are for inclusion of the RIM Program,
  - Determining credible degradation mechanisms for RIM scoped SSCs,
  - Assigning Reliability Target values for SSC,
  - Demonstrating MANDE selected for SSC within the RIM Program.

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RIM Process Description: Part II (During operations)

- RIM is an on-going "Living Program".
- It applies over the entire plant life cycle of risk significant SSC:
  - The periodicity for prescribed MANDE is based on several factors :
    - Expected SSC degradation mechanisms,
    - Required Reliability Target value assigned to an SSC and,
    - Operating conditions (e.g., longer fuel cycles than PWR or BWR)

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RIM Process Description: Part II (During operations)

As operating experience is gained, the RIM Program must be updated.

- RIM can therefore be thought of as an **ongoing aging management program.**

- As OE is obtained, the same seven RIM process steps used during design must be used to update and maintain the RIM program over the life of the SSC.

Summary

- Advanced nuclear reactors have varied designs and intended purposes.
  - Alternative approaches to existing ISI activities was needed to accommodate these technologies.
  - Nuclear technology is moving to designs other than commonly employed LWRs.
  - Some planned reactors to be used in applications other than power production (e.g., medical isotope production, desalination, industrial process heat, etc.)
  - RIM was developed accommodate these new designs and applications.

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Reliability and Integrity Management Programs

Challenges and Opportunities

Chris Wax

Principal Technical Leader

November 29, 2023

Workshop on Structural Health Management of Nuclear Power Plants

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Overview

Operating Environments for Advanced Reactors

Materials Management Programs

Passive Component Condition Monitoring

RIM Process Challenges and Opportunities

RIM Process Phases

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Operating Environments for Advanced Reactors

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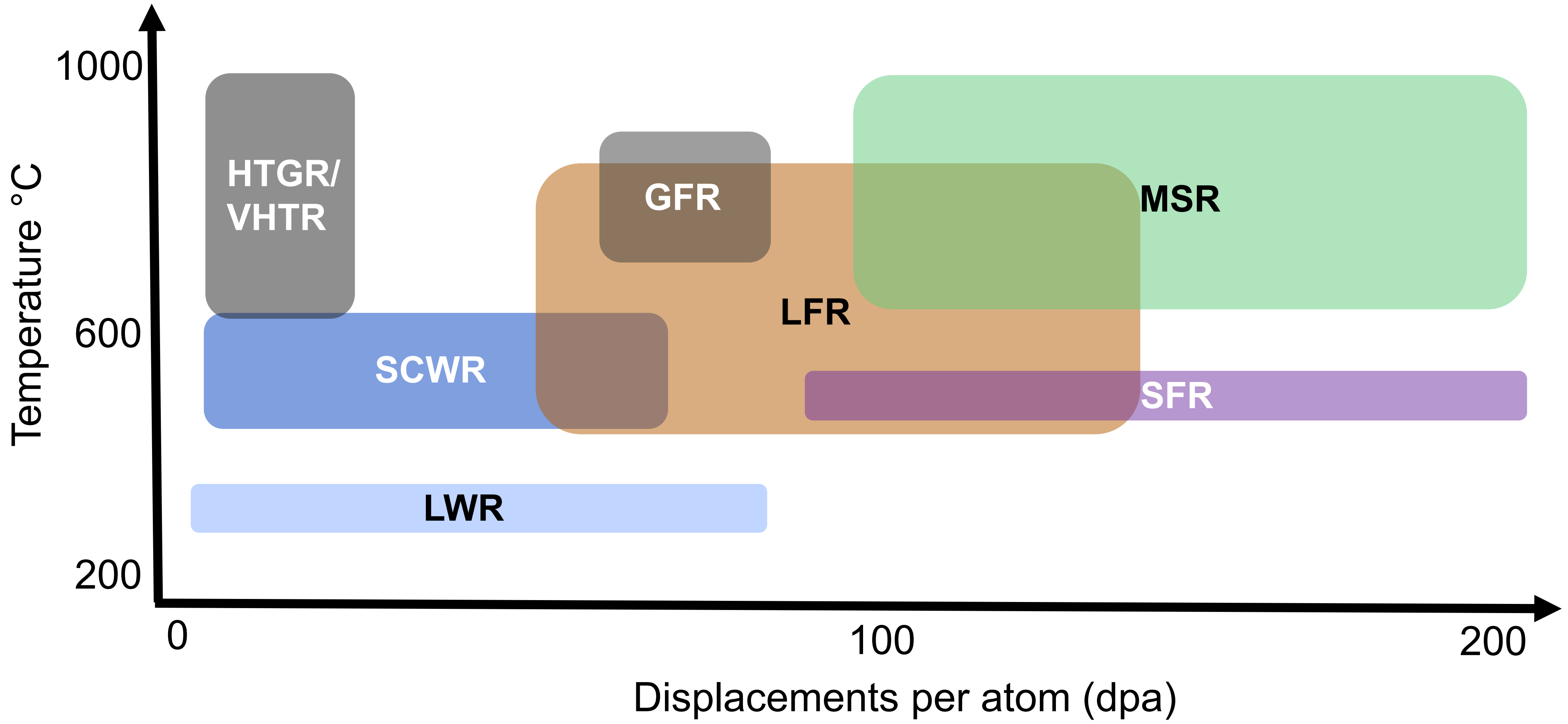
New Fuels, Coolants, Conditions = New Material Challenges



Adapted from Y. Guerin, G. S. Was, and S. J. Zinkle. *Materials Challenges for Advanced Nuclear Energy Systems*. MRS Bulletin V34(1), (2009).

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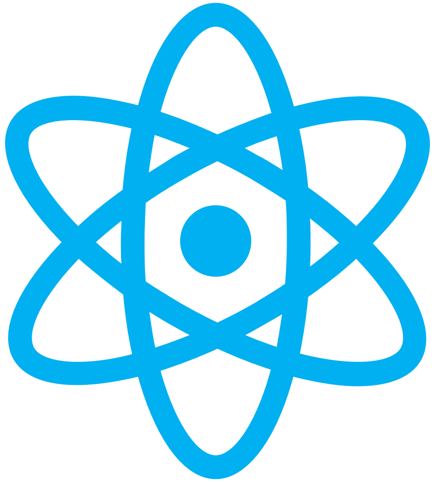
The Challenge for Advanced Reactors

High Temperature Materials Qualification

Materials Testing in New Reactor Environments

Materials Management Programs to Ensure Operational Integrity



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Materials Management Programs

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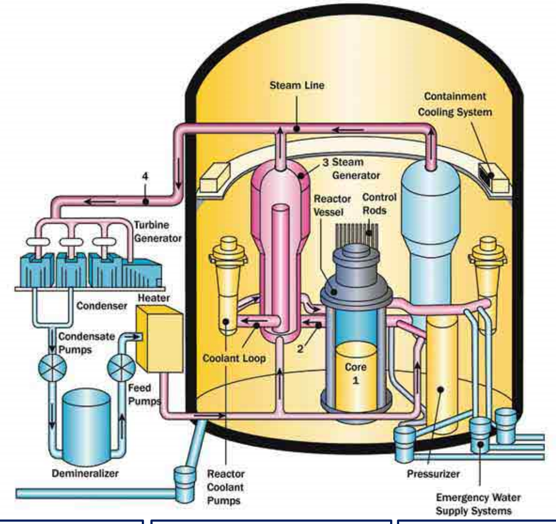
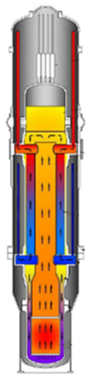
Materials Management Programs

- For the operating, light-water reactor fleet, license holders use a deterministic approach to assure as-designed safety margins through a selection of mandated examinations and tests
  - ASME Section XI, Division I
    - Developed and evolved with over 50 years of operating experience guiding the requirements
  - NEI 03-08 Materials Initiative
    - Industry requirement, endorsed by NRC, to proactively manage aging and degradation of materials
- To support a broader range of reactor specifications/designs, a performance-based alternative approach to define examinations and tests is now available
  - ASME Section XI, Division II

Typical Pressurized-Water Reactor

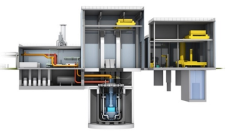


Water-Cooled Reactors

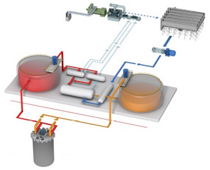


Schematic of the small modular light-water reactor (lwSMR) power module by NuScale

Sodium Fast Reactor

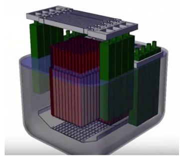


Design rendering of the Natrium reactor, TerraPower's SFR

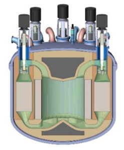


Natrium's integrated molten salt thermal storage loop, enabling 150% power peaking

Molten Salt Reactors

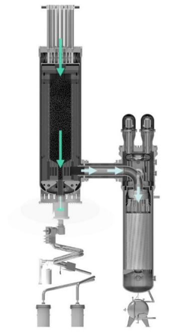


Rendering of Moltex's stable salt reactor, which burns spent LWR fuel.



Rendering of Southern Co. and TerraPower's molten chloride fast reactor.

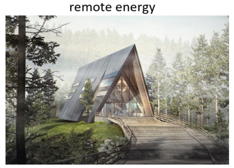
High-Temperature Gas-Cooled Reactor



Rendering of the Xe-100, X-Energy's pebble-bed HTGR.

Microreactors

Design rendering of Westinghouse's eVinci microreactor supplying remote energy



Artist's rendering of Oklo's microreactor power plant

The legacy Section XI, Division I ISI program requirements is a poor fit for many new designs

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Reliability and Integrity Management Process

Challenges and Opportunities

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RIM Program – Challenges and Opportunities

- ASME Section XI, Division 2 provides a general overview of the RIM Process
  - It is not meant to be a prescriptive definition of the program, rather a framework for a technically justified process to identify strategies to preclude, mitigate, or reduce materials degradation impacts

- Further definition of pieces of the process can support the industry in creation of consistent programs and make for more effective and efficient regulatory review
  - These areas tend to fall outside of, or go beyond, the purview of the Code

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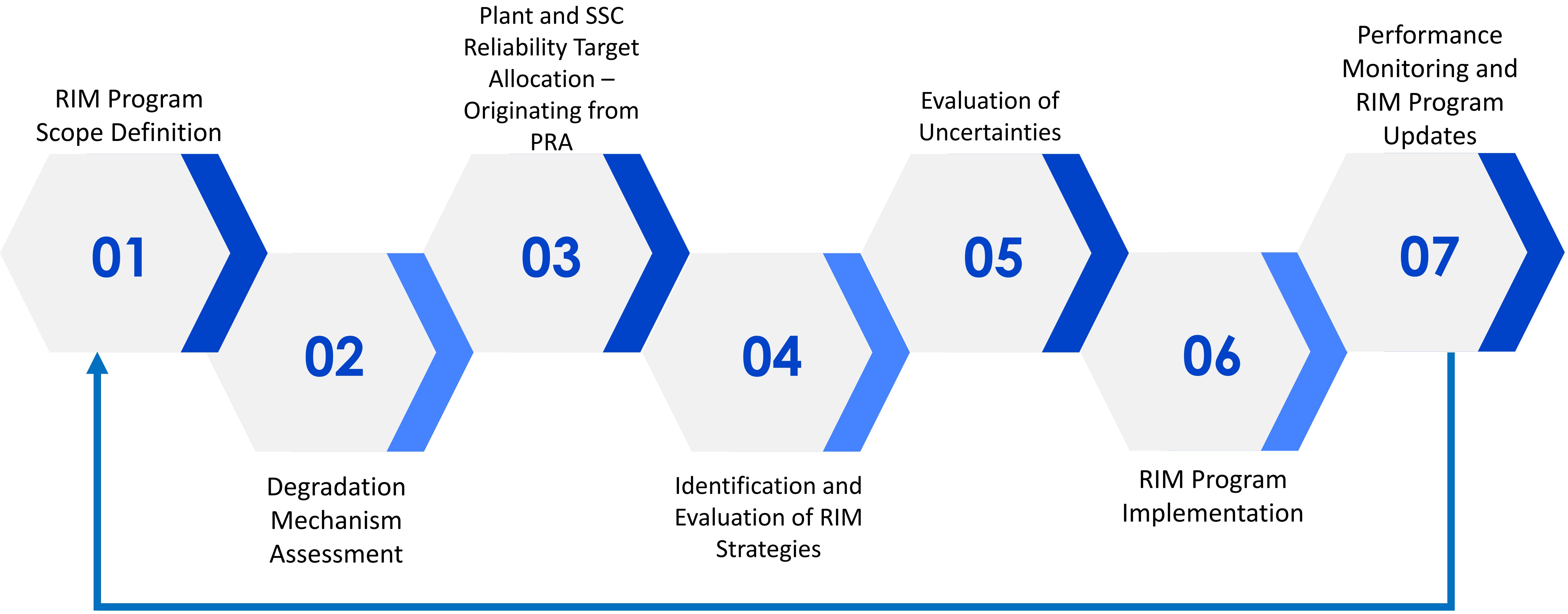
Advanced Reactor Materials Management - The RIM Process

ASME Section XI, Division II



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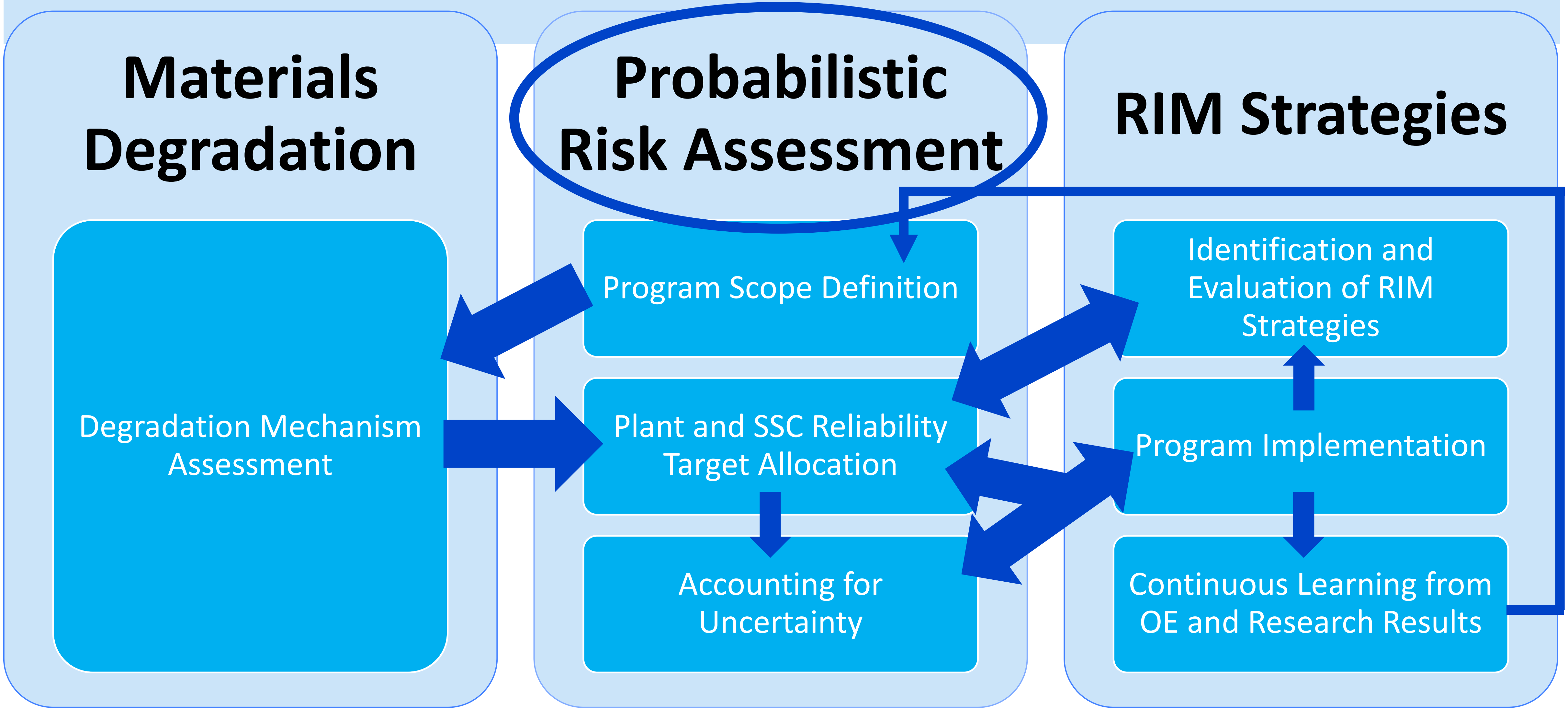
RIM Process



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RIM Program – Materials

Challenges

High Temperature Alloys

Only 6 codified for Class A service in Section III, Division

Mechanical qualification does not include environmental compatibility

Materials Degradation in Advanced Reactor Environments

Knowing where to inspect, what to inspect for, and how often to inspect - understanding of the mechanisms and how they manifest is pivotal

Nonmetallic Materials

New class of materials necessary for some advanced reactor technologies

May be used as moderator and/or structural components

Opportunities

High Temperature Alloys

Can we utilize the RIM program to allow for expedited deployment, even though environmental gaps may be present?

Materials Degradation in Advanced Reactor Environments

Materials Degradation Matrices, Issue Management Tables, and prioritized research

Nonmetallic Materials

ASME Section III Task Group on Graphite Design Analysis

ASME Section III Working Group on Nonmetallic Design and Materials

ASME Section XI Nonmetallic Component Degradation and Failure Monitoring Task Group

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RIM Program – Probabilistic Risk Assessment

Challenges

Scope Identification

What risk metrics will the new technologies use? Core Damage Frequency (CDF)/Large Early Release Frequency (LERF) may not be appropriate

Risk-Informed and Performance-Based

Initial PRA is important and understanding how each of the passive component reliability targets impact risk is pivotal

Circular process of identifying reliability target, selecting RIM Strategy, and assessing risk impact

Reliability Target Allocation

Correlation of qualitative condition monitoring to quantitative failure probability

Opportunities

Scope Identification

Industry and Regulator need to further define appropriate risk metrics to support scope identification

Risk-Informed and Performance-Based

Slight paradigm shift from current fleet experience – building off risk-informed processes that have been successful in past

Consistent approach to assessing risk impact and identifying/accounting for uncertainties

Reliability Target Allocation

PRA workshop to identify a consistent approach to efficient utilization of the PRA and reliability target allocation

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RIM Program – RIM Strategies

Challenges

RIM Strategy Definition/Selection

Design decisions, material selections, chemistry requirements, monitoring and non-destructive examinations (MANDE), evaluation methodologies, modeling techniques, and more

Advanced Monitoring and NDE Techniques

Novel approach development needed to support unique operating environments

Advancing sensor and monitoring methodologies for high temperature applications

Performance Demonstration

Current NDE is demonstrated for effectiveness and accuracy to ensure modalities detect degradation

New process for novel approach demonstration required

Opportunities

RIM Strategy Definition/Selection

Aggregate strategies to support expert panel selection

High temperature flaw evaluation techniques Code activities – design inputs vital

Advanced Monitoring and NDE Techniques

Integrated and coordinated industry effort to advance technology capability and readiness (Luke to cover more)

Performance Demonstration

Defining the process to clarify requirements for demonstration of MANDE effectiveness will support the industry and Regulator

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RIM Process Phases

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RIM Process Phases

Design

RIM is NOT a design code, rather an input to be accounted for

- Review the design and designate RIM inputs, as applicable – Program can be built based off design decisions, assuming site is built as-designed
- RIM Strategies during the design phase may include influencing materials selection and manufacturing techniques to preclude or reduce likelihood of future degradation

Construction

Validation and documentation of "design program" inputs

- Materials selection and proposed fabrication practices match design proposal
- Field change notices or applicable repairs that occur during construction shall be captured
- Capture necessary pre-service inspection results

Operation

Final validation of the inputs from the design and construction phases to ensure changes to critical inputs are accounted for

- Reconvene the Expert Panels (including the future RIM Program Owner)
- RIM Program is risk-informed and performance-based – as a living program, OE and research results need to be incorporated into program and necessary revisions performed

Reactor Technology Designer/Vendor RIM EP and MANDE EP

Owner/Operator RIM EP and MANDE EP

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Questions?

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November 29th, 2023

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Assessment of Component Level and Plant Level Reliability Target Allocation to Support Reliability and Integrity Management (RIM)

Battelle Energy Alliance manages INL for the
U.S. Department of Energy's Office of Nuclear Energy

Idaho National Laboratory

RIM: A Two Game Mindset

Type and frequency of surveillance, inspection, and maintenance activities

Home game: Design phase

- **Decision space:** Choose an optimal design and RIM strategy for each SSC → reliability target
- **Objective:** Maximization/minimization of plant level figure of merits (O&M costs, reliability, availability)

Regulatory and/or economic constraints

Advanced reactor design

SSC$_1$

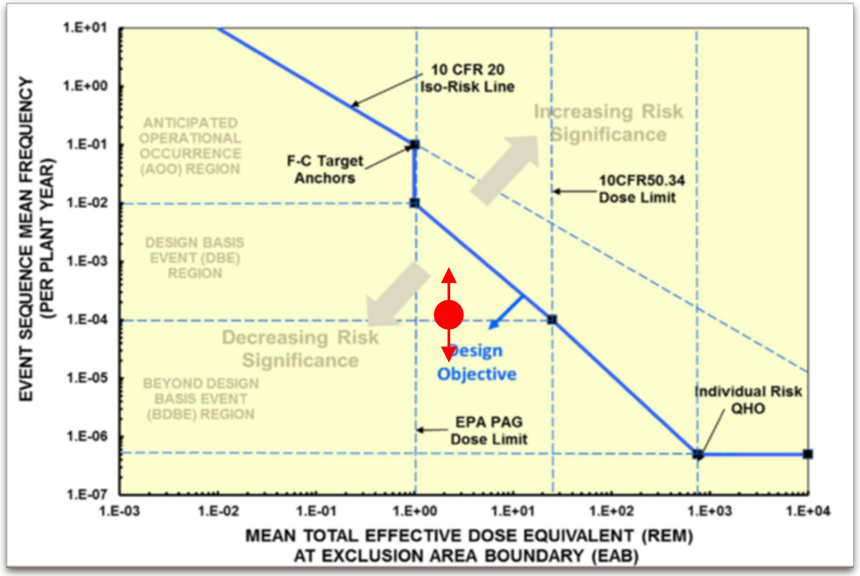
SSC$_2$

SSC$_3$

Reliability engineer perspective

RIM strategy

SSC reliability target



RIM: A Two Game Mindset

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Advanced reactor design

SSC_1

SSC_2

SSC_3

Reliability engineer perspective

RIM strategy

SSC reliability target

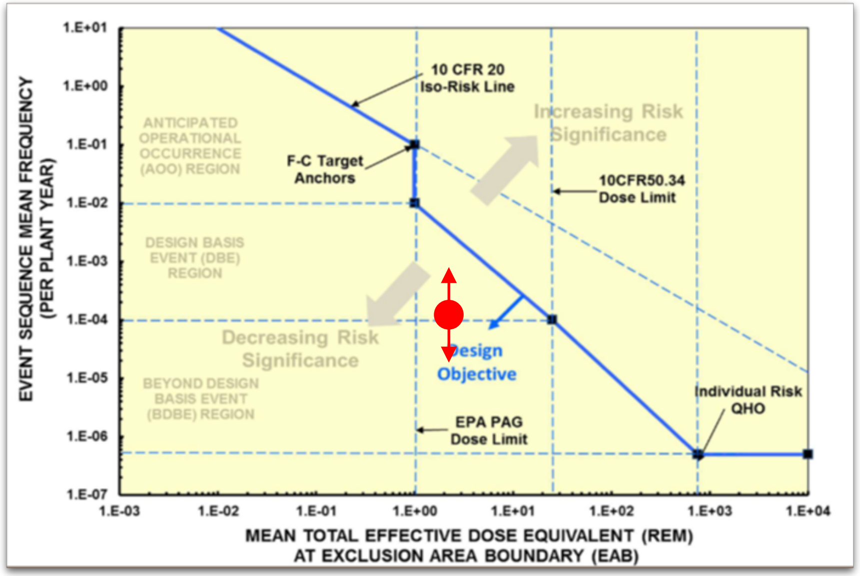
?=

YES: Update RIM strategy

System engineer perspective

Condition based data

Actual SSC reliability performance

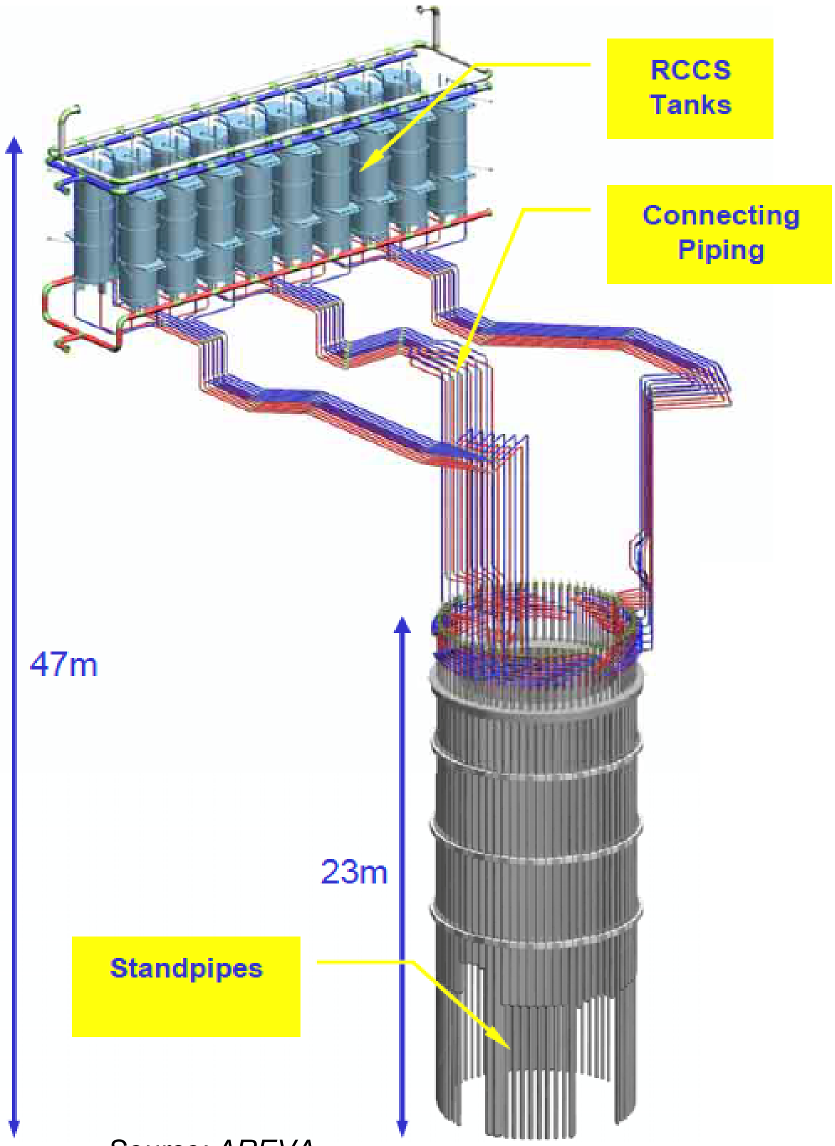


Away game: Operating phase

- **Decision space:** Check reliability performance and update RIM strategy (if needed)
- **Objective:** Demonstrate that RIM strategies assure the planned reliability targets

Home Game: System RIM Optimization

- **System:** Reactor Cavity Cooling System (RCCS) for an HTGR
- **RCCS function**
  - Protects the concrete walls of the reactor cavity
  - Removes thermal radiation from the reactor vessel and releases this heat to atmosphere
- **Design types**
  - Pebble bed modular reactor (PBMR): water cooled
  - High temperature gas-cooled reactor (HTGR): air cooled
- **Starting point:** Reliability modeling performed by K. Fleming in PBMR Passive Component RIM Pilot Study*
- **Our goal**
  - Include RIM economic aspects
  - Identify optimal RIM posture for the RCCS
- **Focus:** Two groups of components
  - Standpipes and connecting pipes



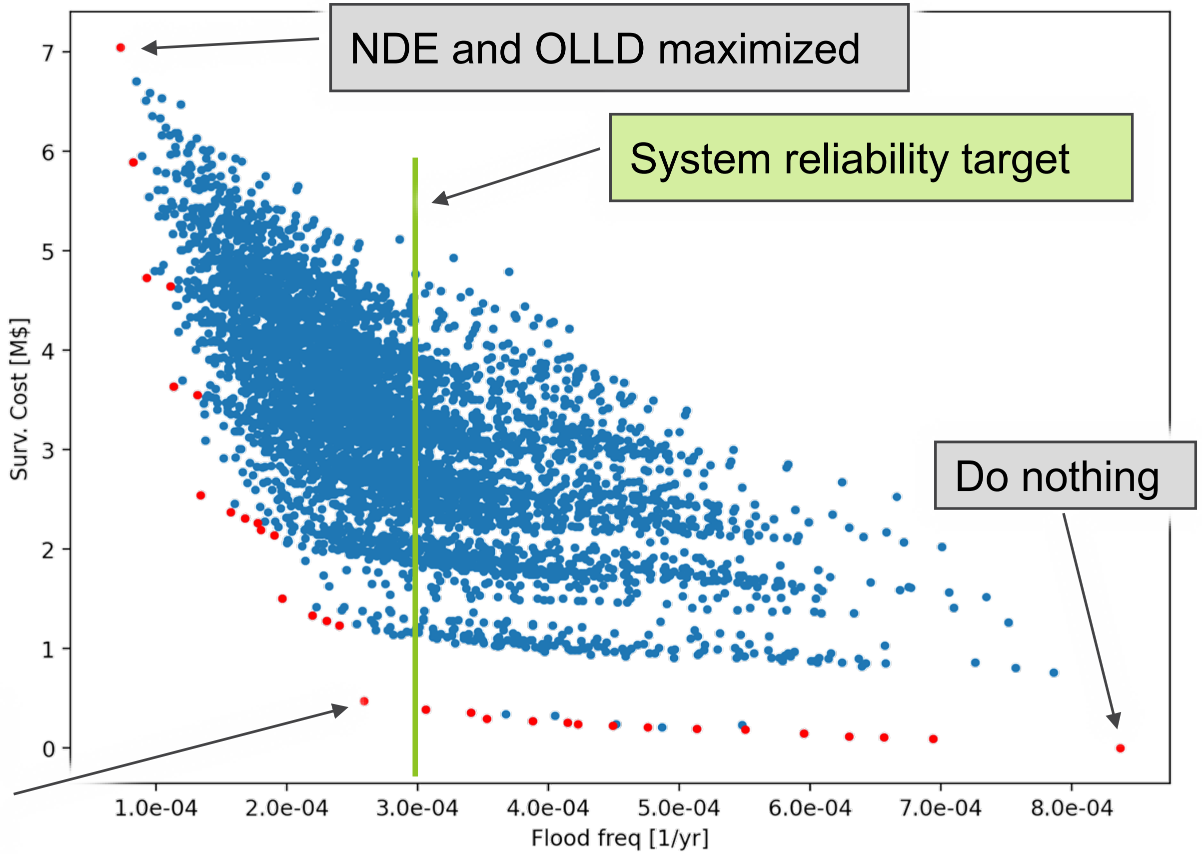
Source: AREVA

*Reference: Karl Fleming, Steve Gosselin, Ron Gamble, “PBMR Passive Component Reliability Integrity Management (RIM) Pilot Study”, Prepared for PBMR (Pty) Ltd., Technology Insights, 2007

Home Game: System RIM Optimization

- **RCCS RIM strategies**
  - Types (Probability of detection [POD])
  - Frequency
- **RCCS inspection cost model**
  - Fixed costs (apparatus and personnel training)
  - Variable costs (per inspection session):
    - Inspection time [per pipe]
    - Number and skills of personnel required
- **Analysis steps**
  - Evaluation of all scenarios
  - RIM scenario = NDE & OLLD option for standing and connecting pipes
    - Number of RIM scenarios: 9801
  - Perform multi-objective optimization
    - Optimal RIM scenarios in the Pareto frontier (red dots)

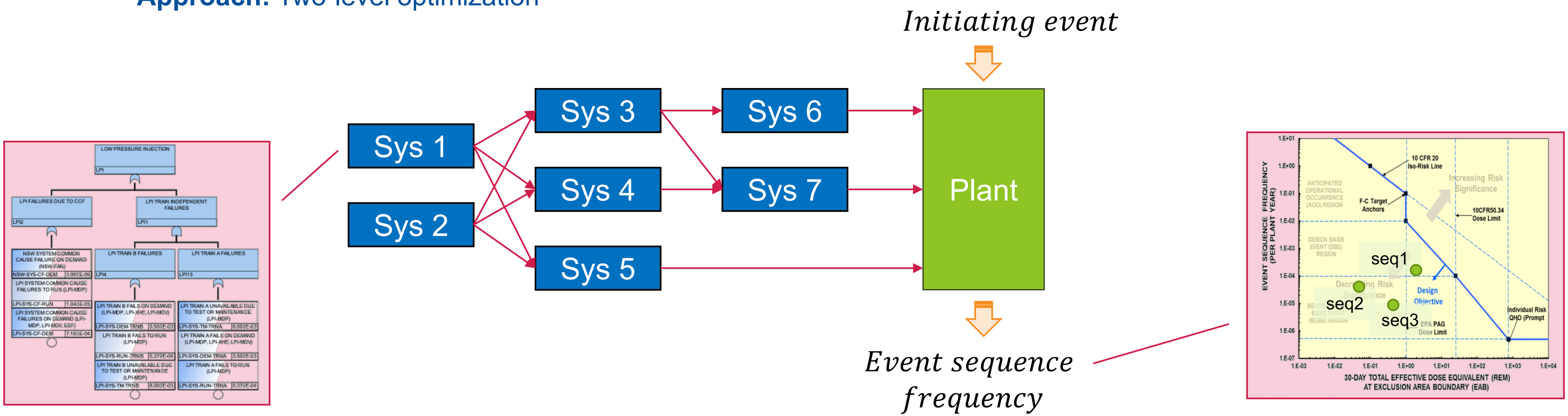
	Non-Destructive Evaluation (NDE)	On-line leak detection (OLLD)
Types	• Phased_array • EddyCurrent + ultrasonic • Do_nothing	• Visual • Imaging_spectra • Do_nothing
Frequency	3,6,9,15 years	1.5, 3, 4.5, 6 years



RAVEN

Home Game: Plant RIM Optimization

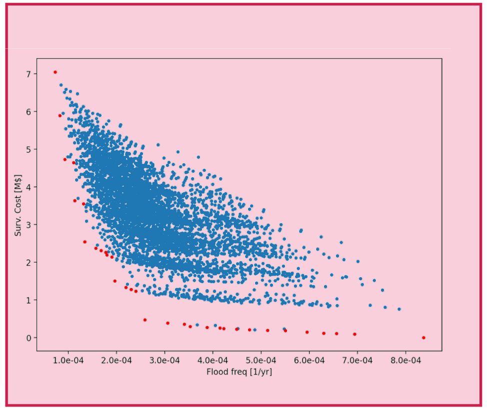
- **Issue in previous application:** How can system reliability target be set?
- **Starting point:** Full plant PRA model
- **Optimization problem**
  - **Decision space:** RIM options for each asset
  - **Objective function:** Minimize costs
  - **Constraint:** Frequency of event sequence
- **Approach:** Two-level optimization

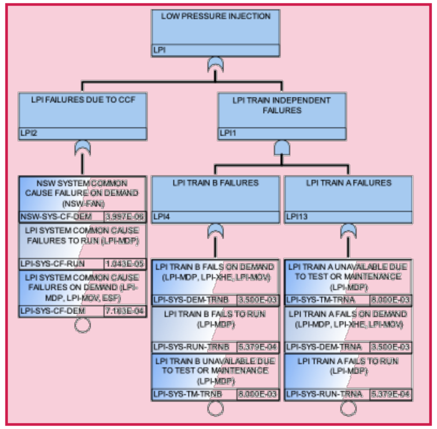


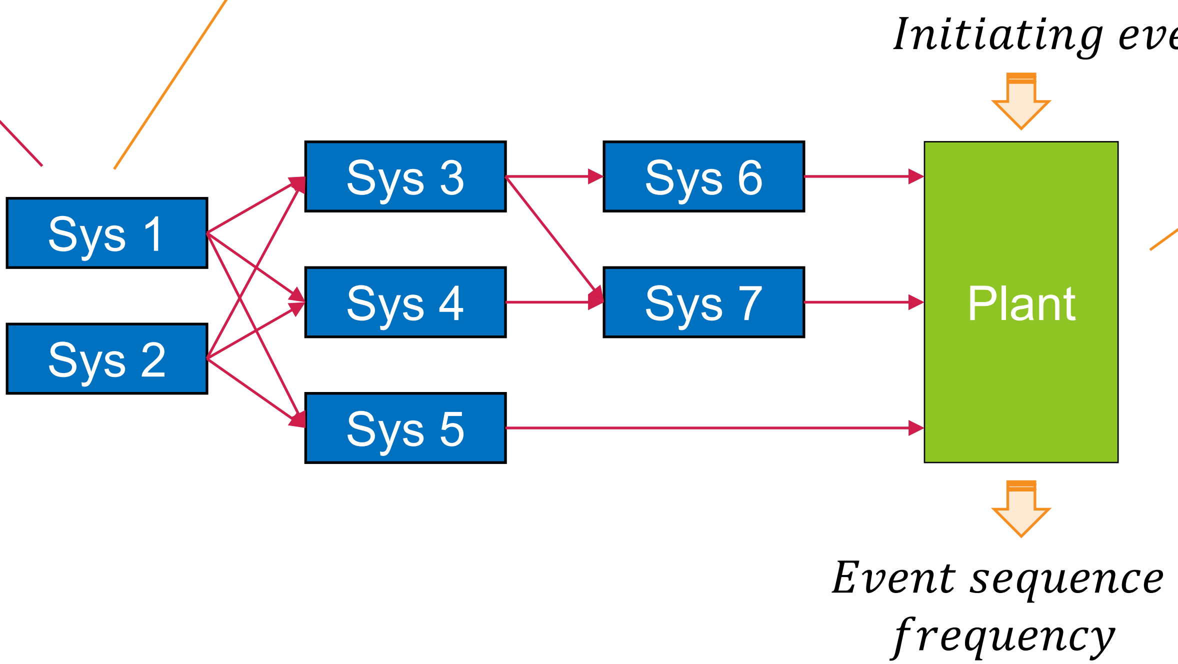
Home Game: Plant RIM Optimization

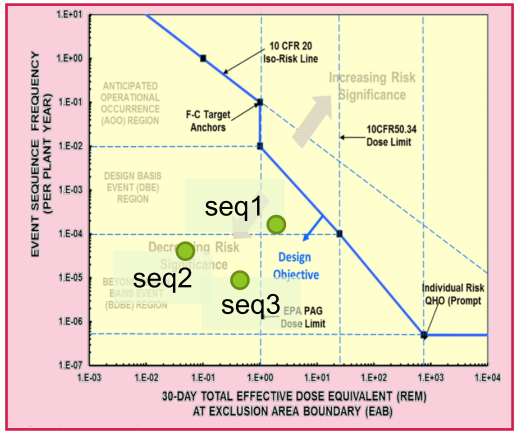
Level 1: Locally optimize each system (failure probability vs. RIM costs)
- Multi-objective optimization
- Model: system fault tree(s) + system cost
- Output: optimal combinations of basic events

Level 2: Event sequence optimization
- Single-objective optimization (genetic algorithm)
- Model: event sequence PRA model
- Decision space: optimal combination of basic events for all systems









Away Game: Plant Is Operating

- **Challenge:** Translate equipment condition-based data into a reliability value
  - To be compared to assigned reliability target

Classes
- Periodic surveillance data
- Continuous on-line monitoring data
- Prognostic data

System engineer perspective

Data types
- Qualitative (e.g., SSC operating or not)
- Quantitative (e.g., temperature or vibration data, NDE inspection, remaining useful life)

Condition based data

Actual SSC reliability performance

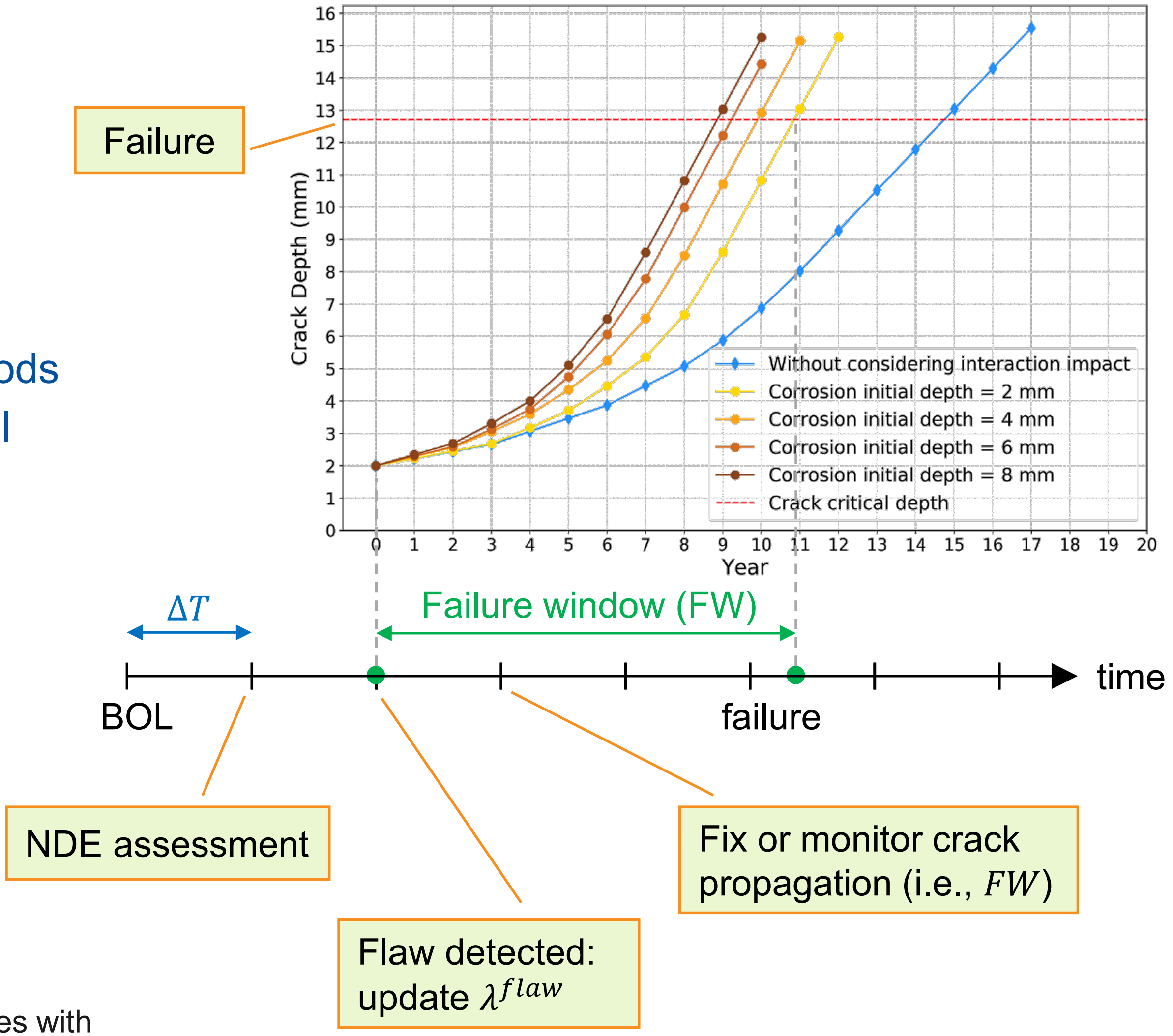
- **Scenario 1:** Periodic assessment of stand-by safety injection pump
  - Data (qualitative): Historic instances of pump performance (i.e., initial start-up and 8-hours operation)
  - Actual reliability performance (e.g., pump failure rate) estimated using Bayesian updating methods
  - Compare estimated and target failure rate
    - Update RIM strategy (e.g., frequency of preventive maintenance)

Away Game: Plant Is Operating

- **Scenario 2:** Periodic NDE assessment of flaws/cracks in piping systems*
  - Data (qualitative and quantitative)
    - Historic instances of identified flaws
    - Crack depth temporal profile
    - Probability of detection (POD) of NDE system
  - Actual reliability performance estimation
    - FW estimated using actual and historic trends
    - λ^{flaw} estimated using Bayesian updating methods
    - Actual reliability performance and SSC physical degradation:

$$\lambda^{act} = f\left(\lambda^{flaw}, FW, POD, \Delta T\right)$$
$$= \lambda^{flaw}(1 - POD)^{\left\lfloor \frac{FW}{\Delta T} \right\rfloor}$$

  - Update RIM strategy (i.e., POD, or ΔT) if needed

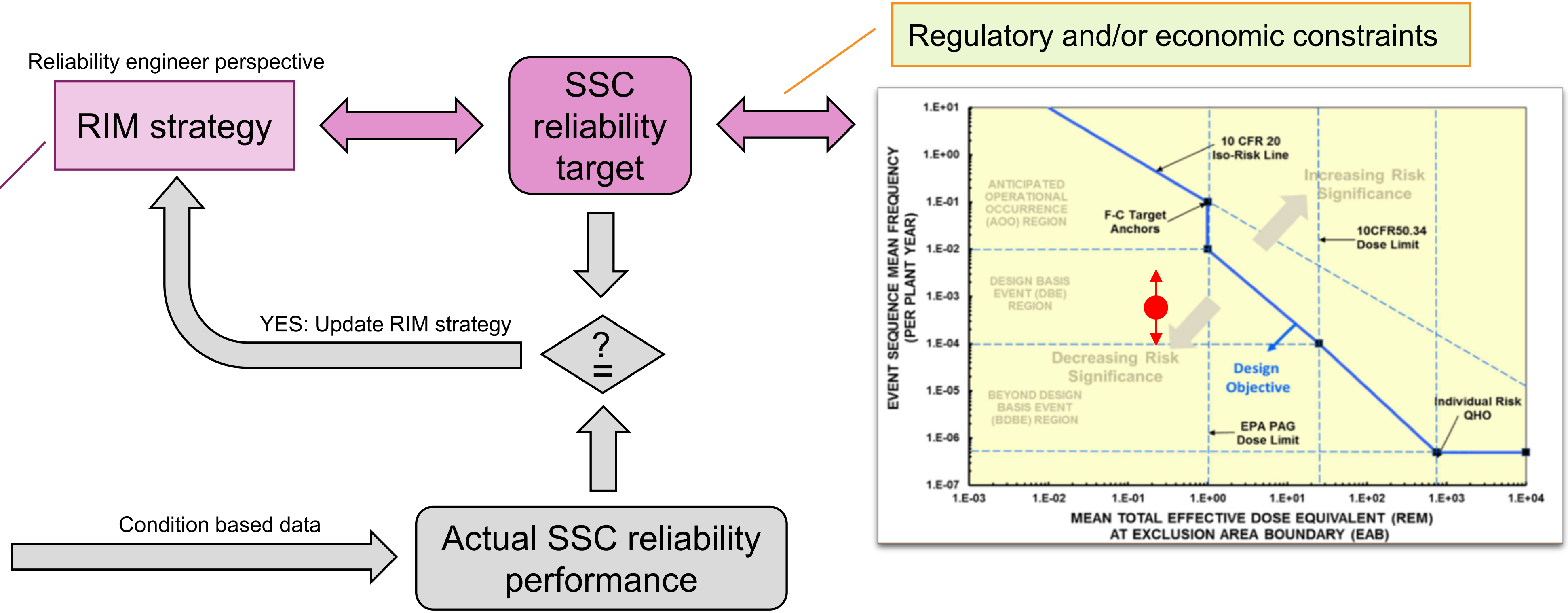


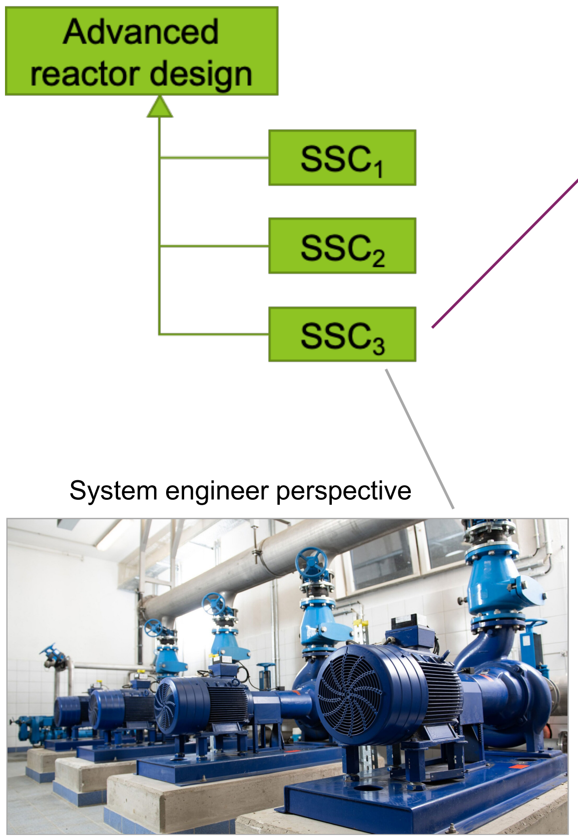
* Xie M., Wang Y., Xiong W., Zhao J., Pei X. (2022). A Crack Propagation Method for Pipelines with Interacting Corrosion and Crack Defects. Sensors (Basel), 22(3):986. doi:10.3390/s22030986.

Summary Of This Talk

Home game: Design phase

- Optimization methods designed to determine an optimal RIM strategy for each SSC (i.e., reliability target)





Away game: Operating phase

- Reliability modeling designed to demonstrate that RIM strategies guarantee the planned reliability targets

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Nondestructive Evaluation (NDE) and Structural Health Monitoring (SHM) for Emerging Reactor Technologies

Pradeep Ramuhalli (ramuhallip@ornl.gov)
Ryan M. Meyer (meyerrm@ornl.gov)

WORKSHOP ON STRUCTURAL HEALTH MANAGEMENT FOR NUCLEAR POWER PLANTS

November 28-29, 2023

Virtual Meeting

ORNL is managed by UT-Battelle, LLC
for the US Department of Energy

U.S. DEPARTMENT OF ENERGY

Outline

- Background
  - Emerging Reactor Technologies
  - In service inspection (ISI) Framework for LWRs
- Needs and challenges for NDE and SHM for Emerging Reactors
- Examples of recent R&D efforts
- Open research needs
- Summary

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ISI Role and Effectiveness for LWRs

- Defense-in-depth: Multi-layered approach to maintaining safety and high reliability
  - No one action, system, or component is depended upon to maintain safety
  - An integrated number of actions, systems, and components with multiple backups
  - In service inspection (ISI) using nondestructive evaluation (NDE) is one component of defense-in-depth
- Effectiveness affected by:
  - Unknown degradation progression rates – failures may occur between planned inspections
  - Variable crack initiation times
  - Degradation outside of initial inspection sample
  - ASME NDE methods applied may not always be targeted for appropriate degradation processes
- Unpredicted (or undiscovered) degradation leads to augmented ISI programs and mandated requirements exceeding those in ASME Boiler & Pressure Vessel Code Section XI
  - Stress corrosion cracking (SCC) in stainless steel (SS) and Alloy 600/82/182 welds
  - Boric acid corrosion
  - Flow-accelerated corrosion
  - Thermal fatigue
  - Other forms

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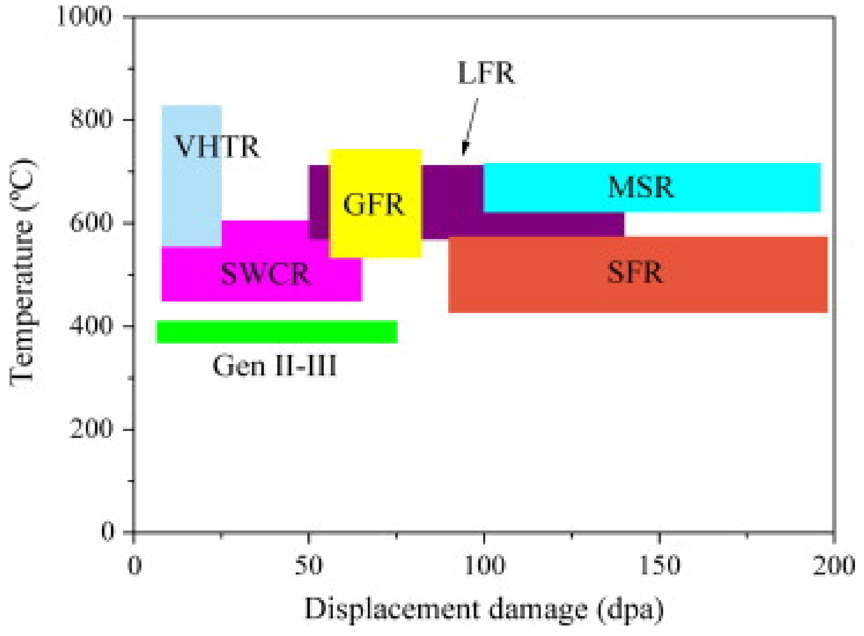
Nominal Operating Parameters of Non-LWRs

		SFR	LFR	MSR	SCWR	GCR
Temperature (^oC)	Core Inlet		290-610	550-650	350	250-587
	Core outlet	704***	465-780	700-1000	625	530-850
	Maximum	~825$^+$, 705^{++}	814$^+$	1300***, 947**	1900$^+$	1238$^+$
	Primary loop (Inlet/outlet)	338/485	405/561	570-650 /700-1000		
	Secondary Loop (Inlet/outlet)	282/443	392/541	450-600 /633-690		
Pressure Range (MPa)	Reactor Vessel	~0.1-0.2	~0.1	~0.1 – 0.5	26	~5-9
Flow Rate (kg/s)	Primary loop	174,128 (l/min)	2150-16200		1418	96-320
Neutron Flux	Peak fast fluence n/cm^2	6.8x 10^{12}* 4.0x 10^{23} (limit)	3.7 x 10^{23}	0.33-1 x 10^{21}* 3 x 10^{23}**		
	Flux (average) n/cm^2-s		2.35 x 10^{15}			
Power density (MW/m^3)	Average	17-210	69		Varies from 67-300	4-6.5

* Reactor vessel
** Graphite moderator
***Coolant maximum
$^+$ Fuel
$^{++}$ Reactor Vessel Wall

Operating Experience for Non-LWR Passive Components

- Sodium reactors
  - Cause: Manufacturing defects, defective welds, fatigue cracking, erosion, sodium deposits, contamination, …
  - Effect: Sodium leak, sodium-water interaction, sodium contamination, level fluctuations, …
- HTR
  - Cause: Material incompatibility, moisture intrusion, manufacturing issues, …
  - Effect: cracking, chloride corrosion, failure of nut/bolts, plugging of pressurization lines, mechanical jamming, …
- LFRs, MSR
  - Cause: Material choice, high coolant velocity, coolant contamination
  - Effect: irradiation hardening, cracking, corrosion/erosion,…
- Issues identified from OE have been largely addressed through design modifications in current concepts and selection of improved materials
  - Some Non-LWR operational concepts also include periodic replacement of critical passive components



J.G. Marques, Energy Conversion and Management, 2010

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Potential NDE and SHM Needs and Issues in non-LWR

- Wide variation in materials
  - Stainless steel, F/M steel, ceramics, graphite, Ni-base superalloys,…
- Locations vary for potential degradation
  - Welds and joints
  - Bends/elbows
  - Tubing
- Data on material performance over non-LWR lifetime is limited
  - Tests ongoing for material qualification, codes and standards development
- NDE and SHM measurement challenges
  - Potential access limitations
  - Measurement parameter sensitivity
  - Deployment issues for in-situ measurements

Components	Materials	Potential Degradation Modes	Desired Measurements
• Reactor vessel • Core structure, shields • Reflectors, absorbers, moderators • Piping and tanks • Heat exchangers, steam generators • Turbines, compressors • Valves, pumps	• Austenitic stainless steel • Ni-base superalloys • F/M steels • ODS F/M steels • Ceramics, composites, polymers • Graphite • Concrete	• Thermal and mechanical fatigue cracking • Creep/irradiation creep/creep-fatigue • Oxidation/corrosio n • Embrittlement • Stress corrosion cracking • Void swelling	• Cracking and corrosion • Creep • Coolant parameters (temperature, pressure, flow, chemistry, level) • Neutron flux • Contamination (coolant and cover gas) • Loose-parts

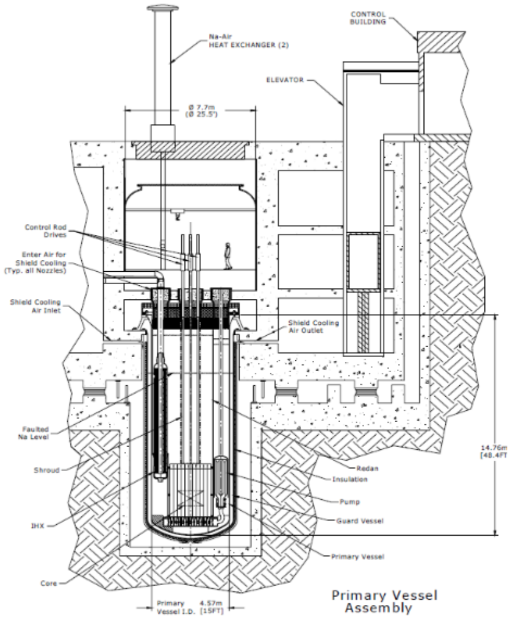
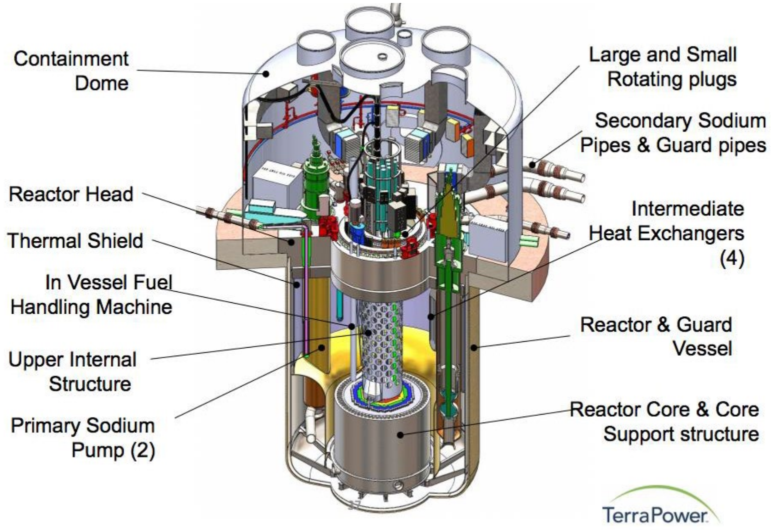


Figure III-2. Primary Plant Systems



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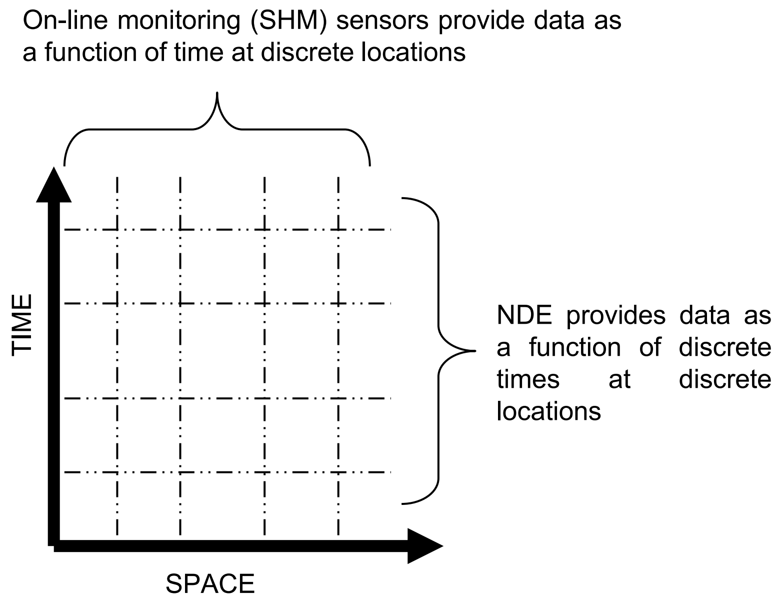
ISI for Reliable Degradation Detection

- Most effective technique - continuously monitor all plant components 100% of the time
- Next best method - examine all components during each refueling outage (or periodically)
  - Not economically viable – plants would spend more time being inspected than making power
  - Would require very large population of skilled NDE and crafts personnel; especially for many plants in simultaneous outages
  - In practice, a subset of components, selected based on risk and OE, are inspected periodically
- Structural health monitoring (SHM) may be needed for Non-LWRs that may have longer refueling cycles
  - Continuous monitoring of a subset of components
  - Component selection based on contribution to risk, and perhaps limited accessibility



Fundamental differences in data structure between Nondestructive Evaluation (NDE) and Structural Health Monitoring (SHM))
(After Thompson [2009])

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SHM Systems for Nuclear Power May Require High Temperature, Rad-tolerant Sensors

- Sensor materials selection is key to subsequent sensor reliability
  - Example: Prior research has shown viability of AlN and BiT composites for high-temp, in-reactor ultrasonic measurements

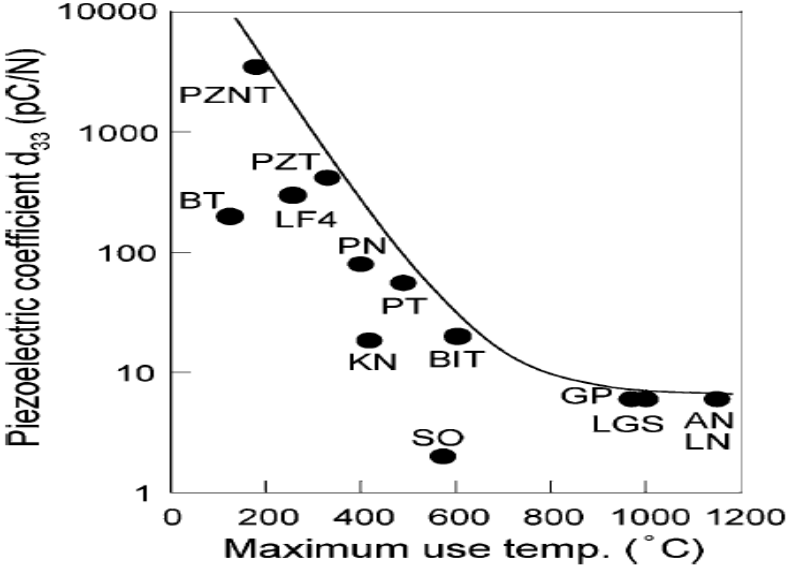
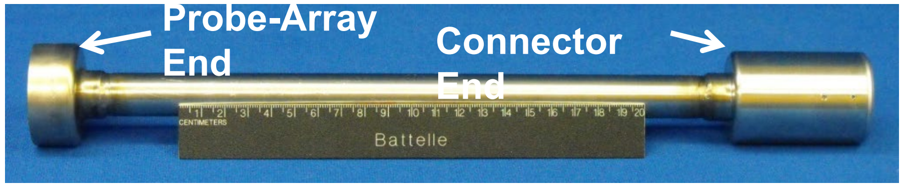
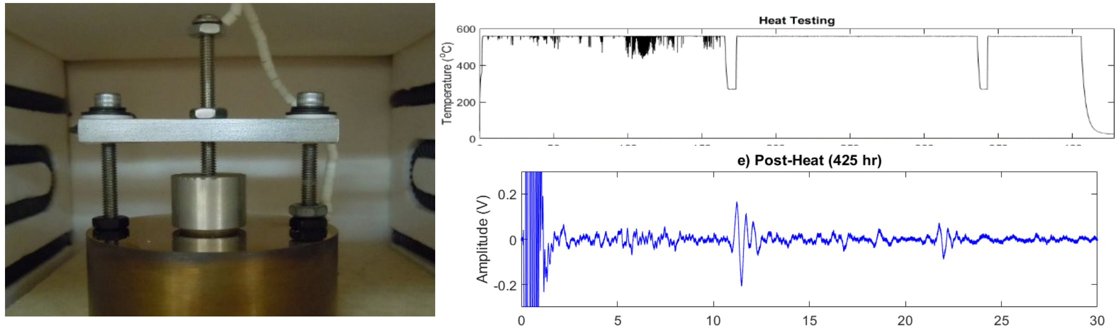


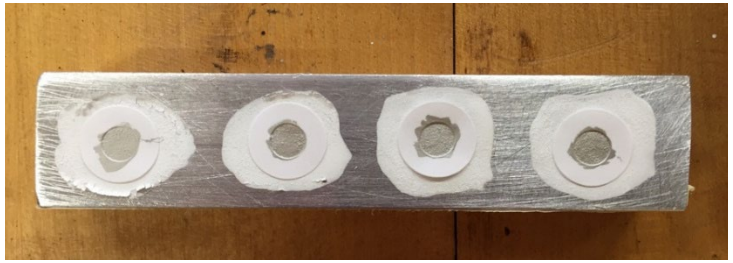
Figure . Relationship between piezoelectric coefficient d_{33} and the maximum use temperature (for most materials, T_C) for piezoelectric ceramics. Reproduced from M. Akiyama, et al, *Advanced Materials* **21** (5), 593-596 (2009).



Under-sodium Viewing Ultrasonic Phased Array (Larche et al 2017)



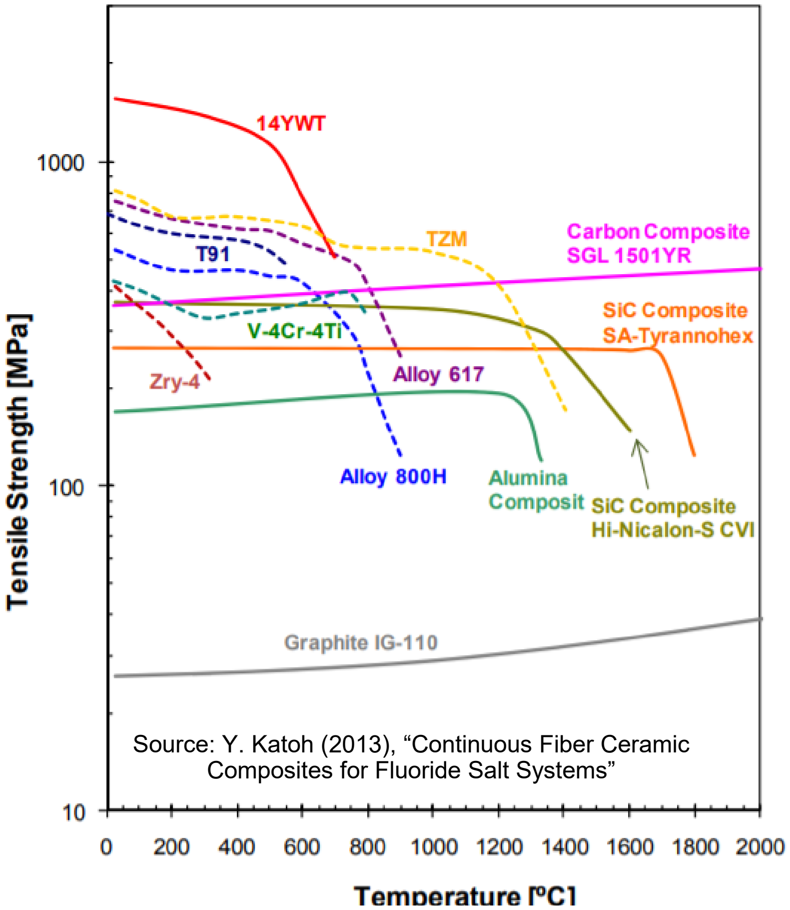
High temperature (>550°C) Monolithic Ultrasonic Transducer (Ramuhalli et al 2018)



Sol-gel High-Temperature Composite Transducers

(courtesy C. Lissenden, B. Tittman)

NDE and SHM Methods for Non-Metallic Non-LWR Components are Needed



Source: Y. Katoh (2013), "Continuous Fiber Ceramic Composites for Fluoride Salt Systems"

Bottom graphite stud of MSRE before (large photo) and after (inset) operation

Source: ORNL-TM-4174

New techniques will be needed for inspecting/monitoring and characterizing materials such as SiC/SiC composites and graphite

Advanced Technologies (AM, AI, …) Enable Robust Structural Health Monitoring of Metals, Concrete, and Composites

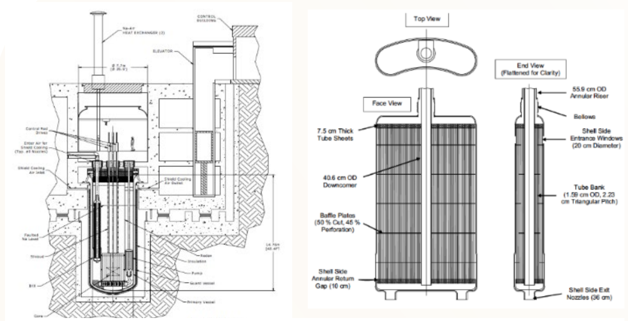
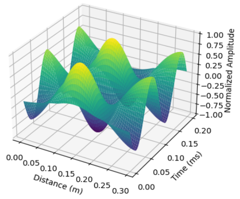
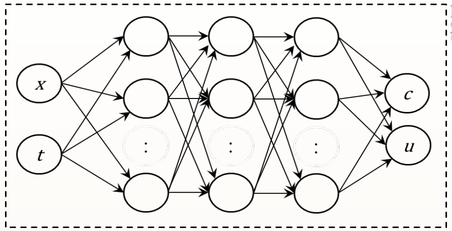


Table III-1. Summary of ISI&M Requirements

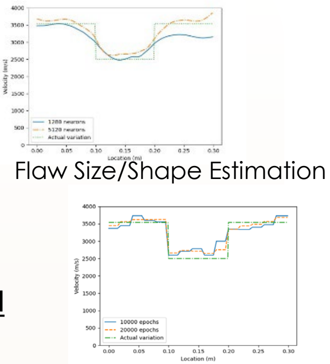
Major Components	ISI		Maintenance		
	Scheduled Inspection	Access	Preventive	Corrective	Access
Control Rod System - Control Rod Drive Mechanism - Control Rod Drive Line	 Not Required Not Required	 N/A N/A	 TBD TBD	 Replace part Replace	 Port (6) Port (6)
Reactor Internals Integrally Welded Structures -Core Support Structure -Core Barrel -Passive Core Restraint -Coolant Flow Ducts & Plenum -Thermal Barrier (Redan)	 Visual (VTM3) (1)	 Ports(3)	 Not planned	 Not planned	 N/A
Internals attached by other than welding	Visual (VTM3) (1)				
Reactor Support - Support Skirt Welds & Bolts	 Visual (VTM3) (2)	Ports & Pit (4)	 NA	 NA	
Reactor & Containment Vessel	Visual (VTM2) (2) CM	7" gap, Ports(5)	NA	NA	NA
Primary EM Pump	CM	N/A	TBD yrs	Replace	Port (6)
IHX	CM	N/A	Not planned	Replace	Port (6)
DRACS	CM	N/A	Not planned	Replace	Port (6)
Reactor Closure - Stationary Deck	 CM,Visual(VTM3)		 NA	 NA	

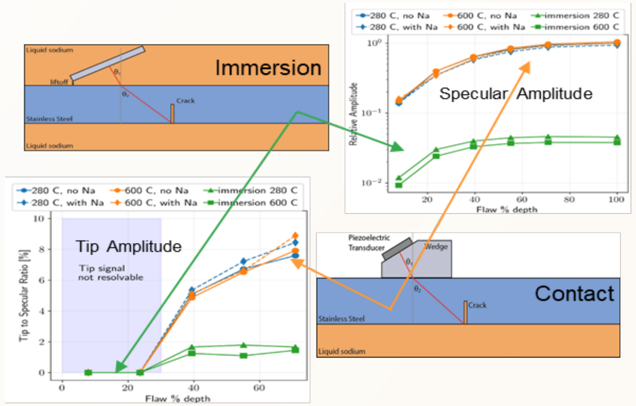
Component Design and Inspection/Monitoring Requirements per Code (if available!)

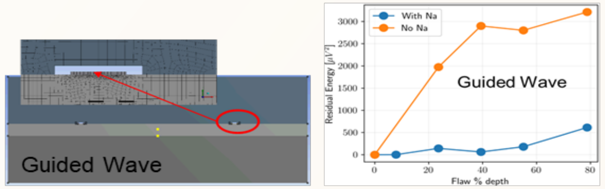




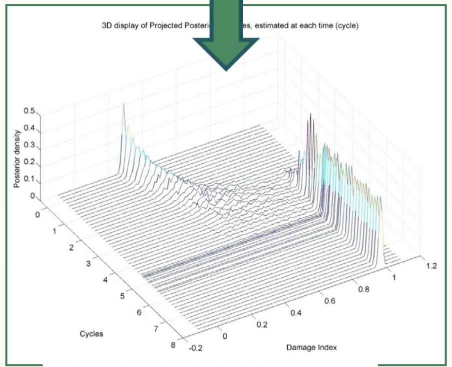
Physics-informed Machine Learning Applied for Structural Component Diagnostics (Rathod et al 2021, 2022)

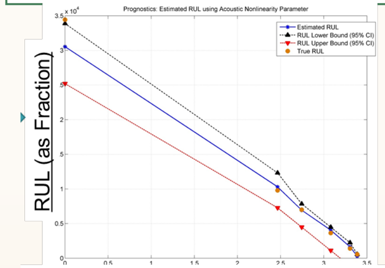






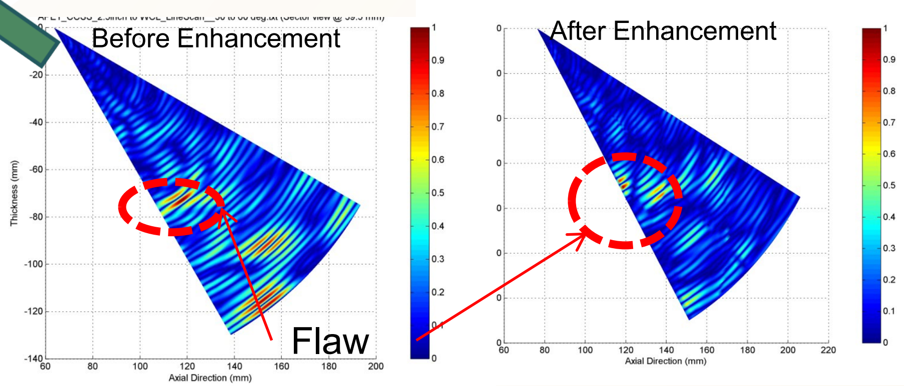
Model based Assessment of Structural Health Monitoring (SHM) (Ramuhalli et al, 2018)



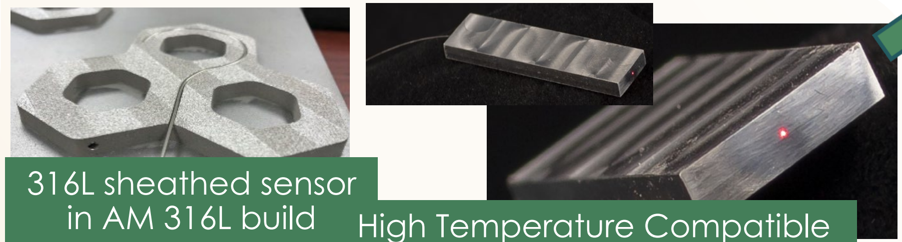


Measurement at Fraction of Remaining Life

Remaining Fatigue Life Estimate for Structural Components (Ramuhalli et al 2012)

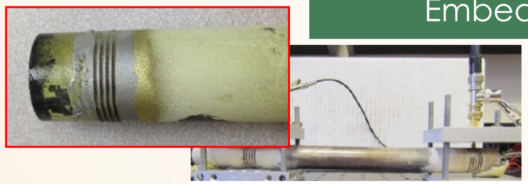


Data Enhancement for Flaw Detection from Ultrasonic Phased Array Measurements (Ramuhalli et al 2010)



316L sheathed sensor in AM 316L build

High Temperature Compatible Embedded Sensors

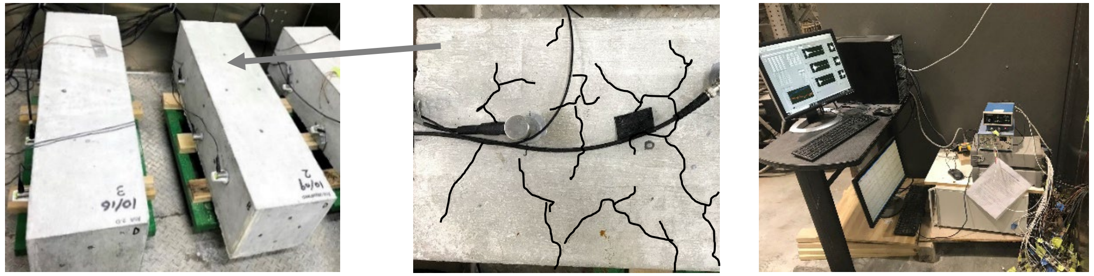


Integrated Sensors for SHM

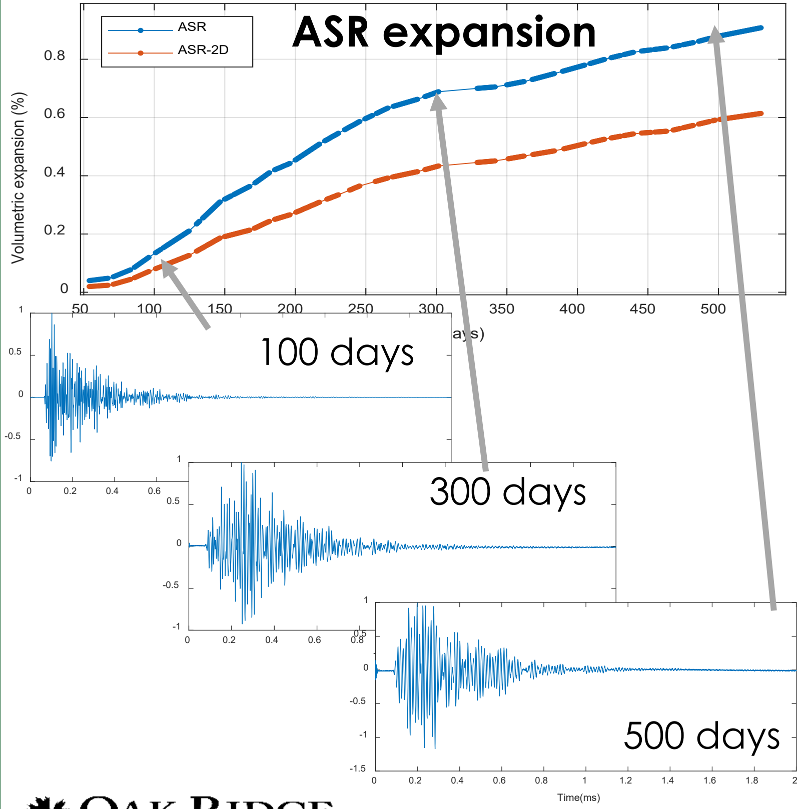
(Courtesy Dr. C. Lissenden, Dr. B. Tittmann (PSU))

Example of AI/ML Application: NDE/SHM of Concrete with Alkali-Silica Reaction(ASR)

- Objective: predict ASR expansion using ultrasonic NDE/SHM
- AI-assisted analysis: Improved ASR expansion prediction compared to baseline analysis (regression)



Ultrasonic NDE of ASR development on concrete mockups



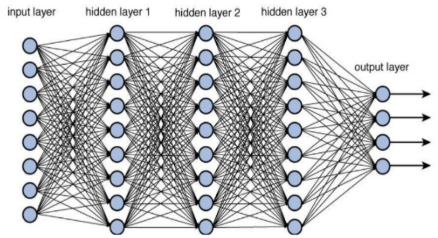
Ultrasonic signals over time

Ultrasonic Velocity

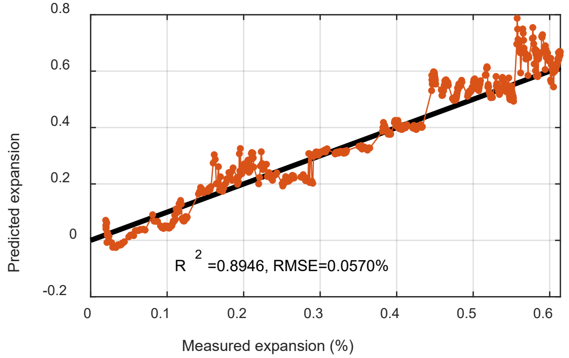
Features

Ultrasonic signals

Machine Learning: ASR Expansion Prediction



ASR Expansion prediction
based on ultrasonic NDE data



H. Sun & S. Sabatino, *Machine Learning for Processing Ultrasonic Data from Long-Term Monitoring of Concrete with Alkali-Silica Reaction (ASR)*, Oak Ridge National Laboratory, ORNL/SPR-2023/2948, 2023

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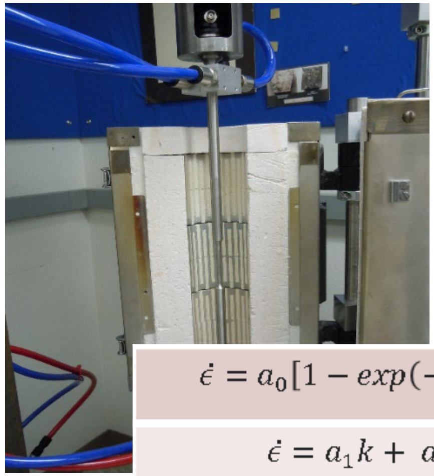
Data-driven and Physics-Inspired Algorithms for Diagnostics and Remaining Life Estimation



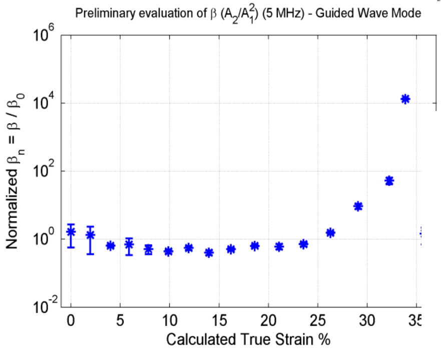
$$\dot{\epsilon} = a_0[1 - exp(-a_1 k)]$$

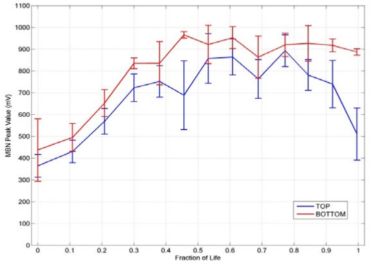
$$\dot{\epsilon} = a_1 k + a_0$$

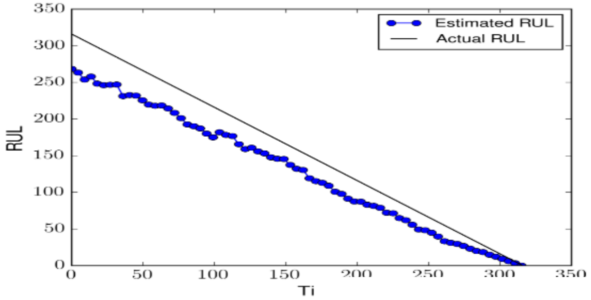
$$\dot{\epsilon} = a_3 k^3 + a_2 k^2 + a_1 k + a_0$$

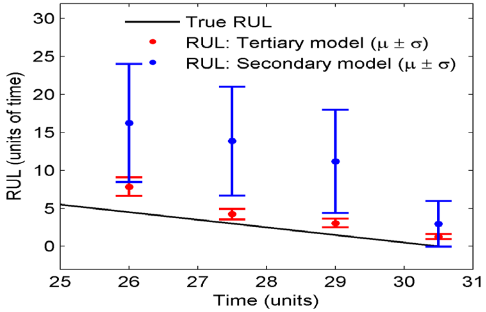
High Temperature Creep: Models and Measurements

Acoustic and Magnetic Measurements

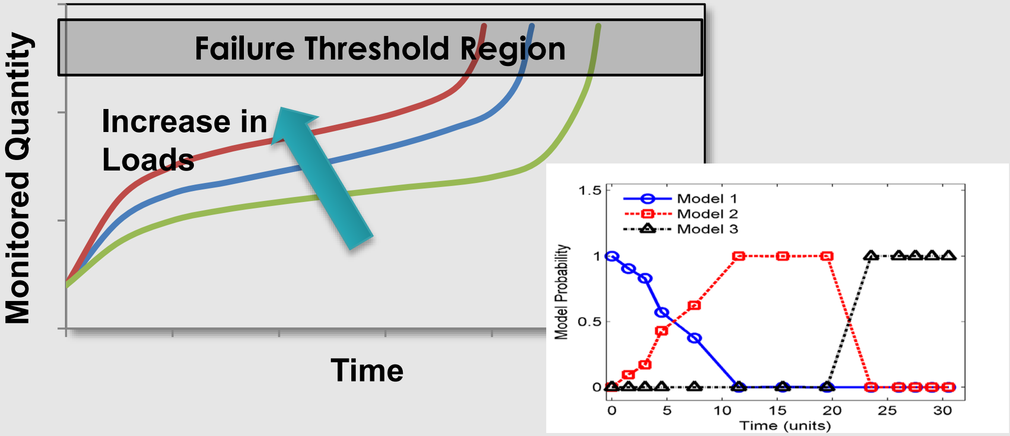








Prognostic Result: RUL



Diagnostic/Predictive Model Selection

Data shown from:
Ramuhalli et al, ANS NPIC-HMIT 2012
Roy, Ramuhalli et al, ANS NPIC-HMIT 2015
Dib, Roy, et al, ANS NPIC-HMIT 2017

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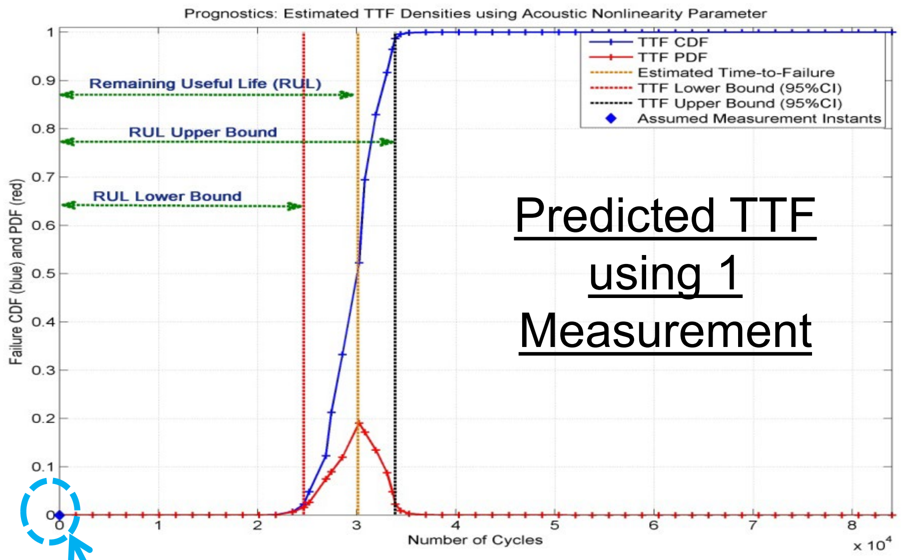
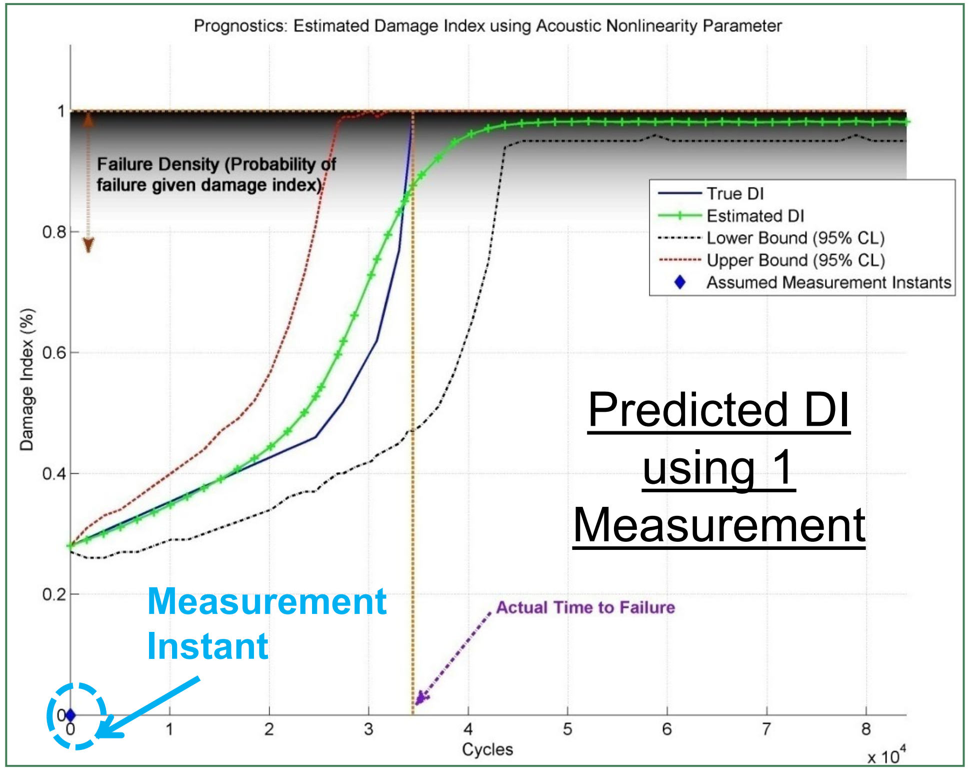
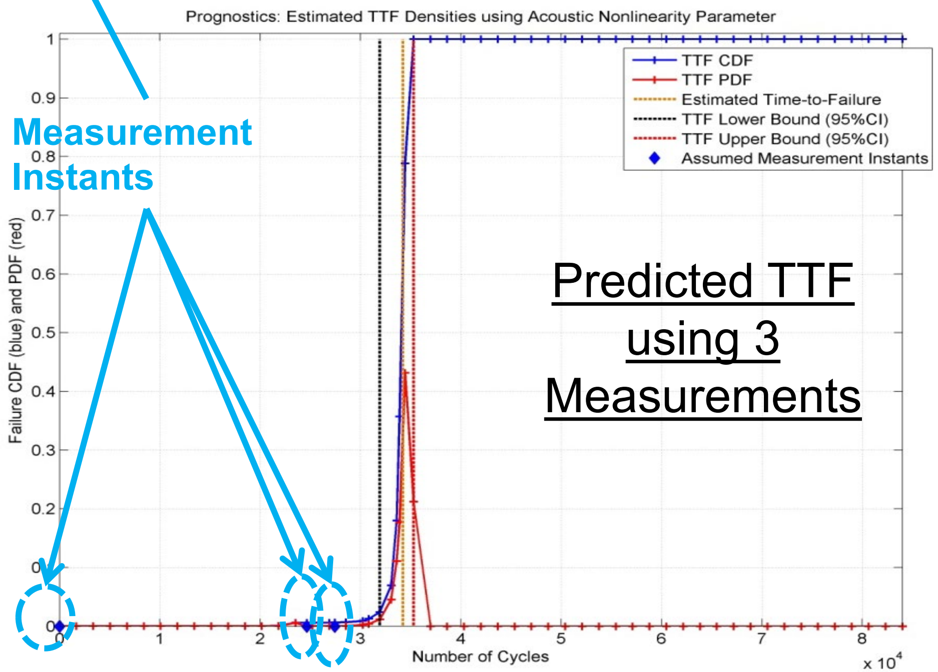
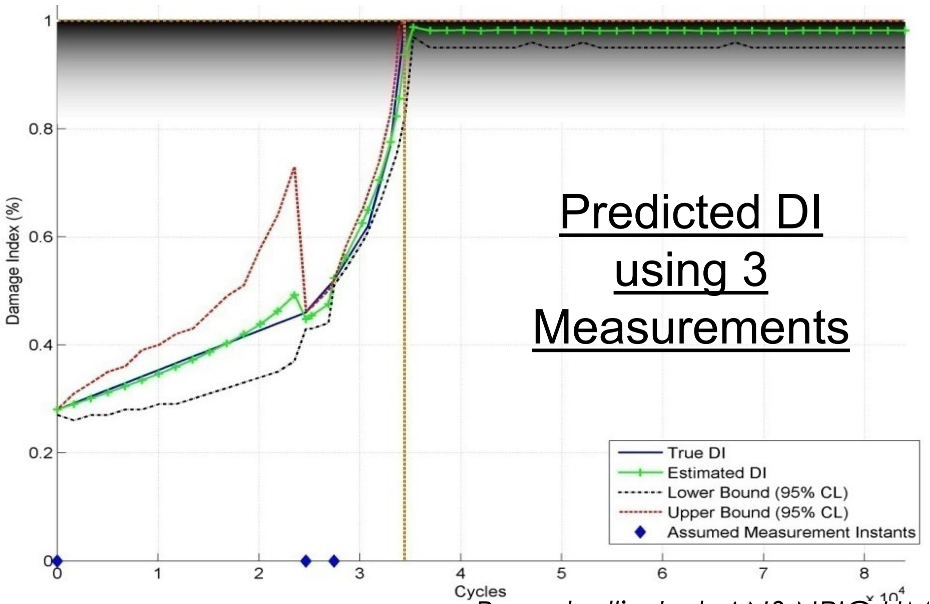
Predicted Time-to-Failure, with Uncertainty, for Fatigue Damage









Ramuhalli et al, ANS NPIC-HMIT 2012

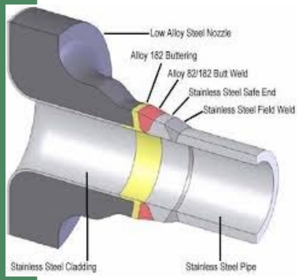
NDE Qualification by Performance Demonstration

- NDE reliability influenced by many factors including equipment, materials and surface condition, flaw size and orientation, procedures, …
- Several studies performed beginning in early 1980s to improve the reliability of UT
- These studies led to the development of a performance demonstration process to qualify UT performed on LWRs
- The requirements for performance demonstration are in Appendix VIII of Section XI, Div. 1
- EPRI administers performance demonstrations for the industry through the performance demonstration initiative (PDI)
  – Qualification of personnel, equipment, and procedures…
  – Performance demonstration to show acceptable level of performance for flaw detection, sizing, and low false call rate

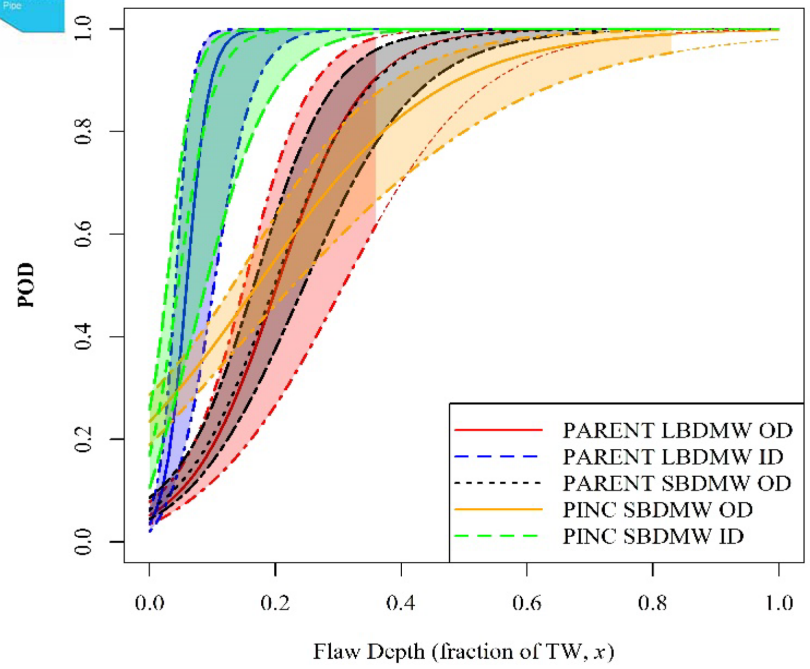
Quantifying Performance of NDE
– Probability of Detection (POD) for Dissimilar Metal Welds

- Program for Inspection of Nickel-alloy Components (PINC) – [NUREG/CR-7019]
- Program to Assess the Reliability of Emerging NDE Techniques (PARENT) - [NUREG/CR-7235 (ML17159A466)]

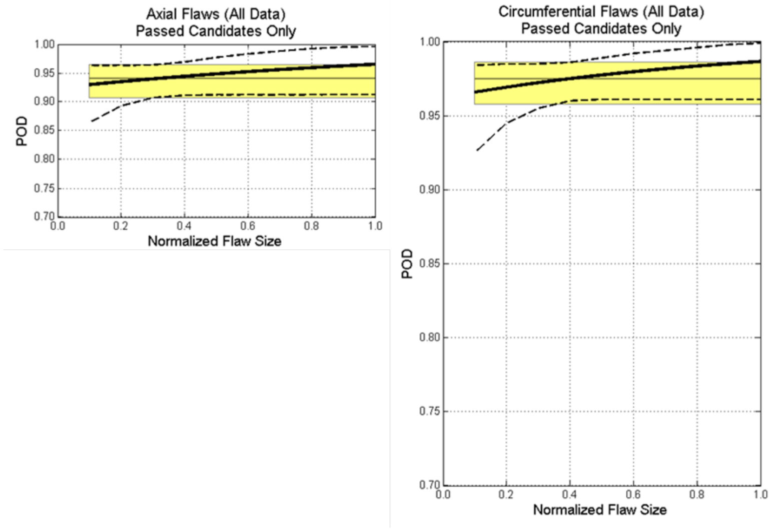
- POD analysis of PDI data is summarized in EPRI report: MRP-262 Rev. 3 (EPRI report number – 3002010988)



Cross-section of nozzle to pipe weld



POD Curves for Flaws in Reactor Pressure Vessel Nozzles



Empirical quantification of performance can be resource intensive

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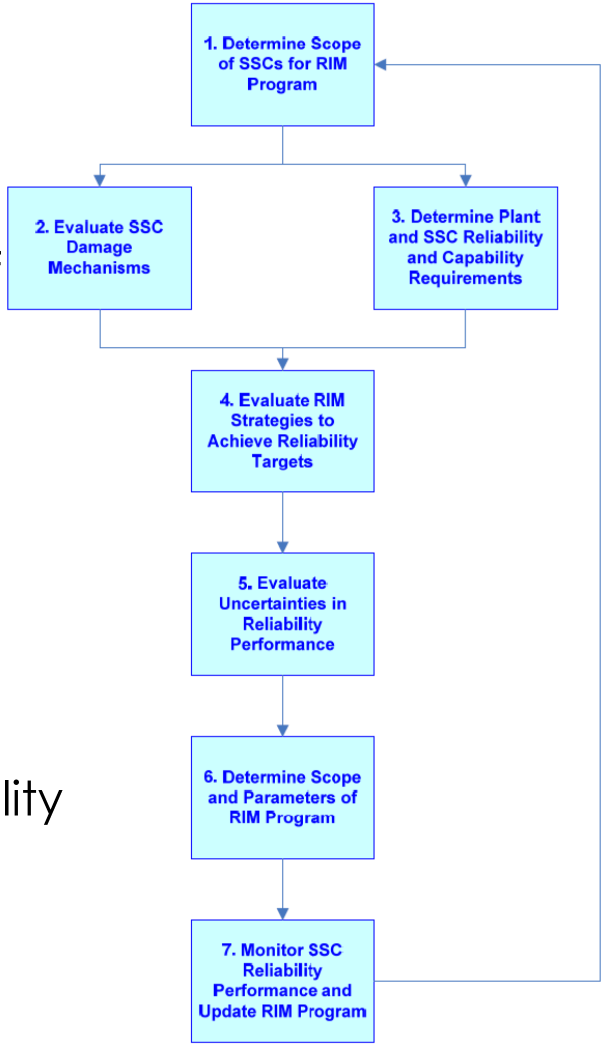
Reliability Integrity Management (RIM)

- Determination of plant and SSC reliability requirements (3)
- Evaluate RIM strategies to Achieve Reliability targets (4)… a variety of strategies could be applied, e.g.
  - Through design…
  - Through operation…
  - Through implementation of monitoring and NDE (MANDE)…
- The ability of proposed MANDE to meet reliability target(s) must be demonstrated
  - This implies quantification of performance and influence on system reliability
- Evaluate uncertainties in Reliability Performance (5)
  - Identify strategies to address uncertainties in RIM strategies to provide added assurance that reliability targets will be met
  - Defense-in-depth philosophy is maintained



From Fleming et al. (2008)*

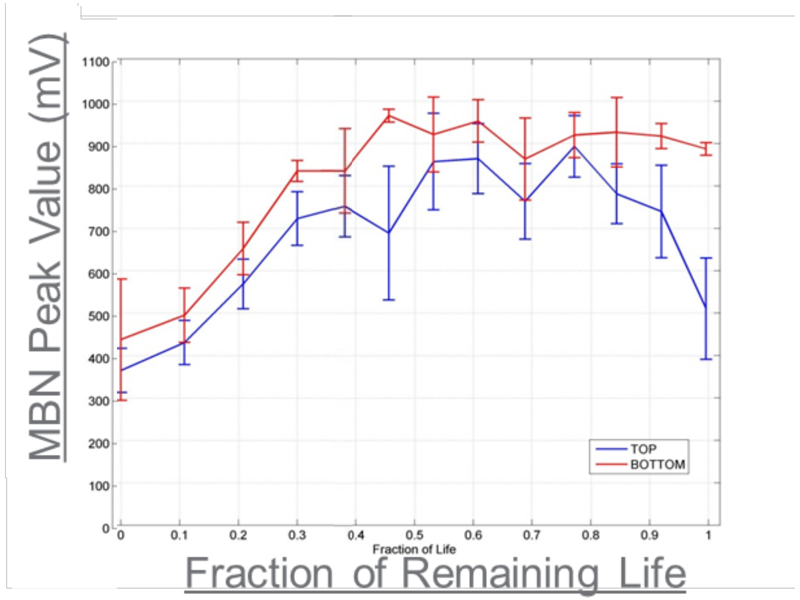
*Fleming, KN, Fletcher, J, Broom, N, Gamble, R, & Gosselin, S. "Reliability and Integrity Management Program for PBMR Helium Pressure Boundary Components." *Proceedings of the Fourth International Topical Meeting on High Temperature Reactor Technology. Fourth International Topical Meeting on High Temperature Reactor Technology, Volume 2*. Washington, DC, USA. September 28–October 1, 2008. pp. 127-133. ASME. https://doi.org/10.1115/HTR2008-58036

Measurements Are Usually Easier than Interpretation

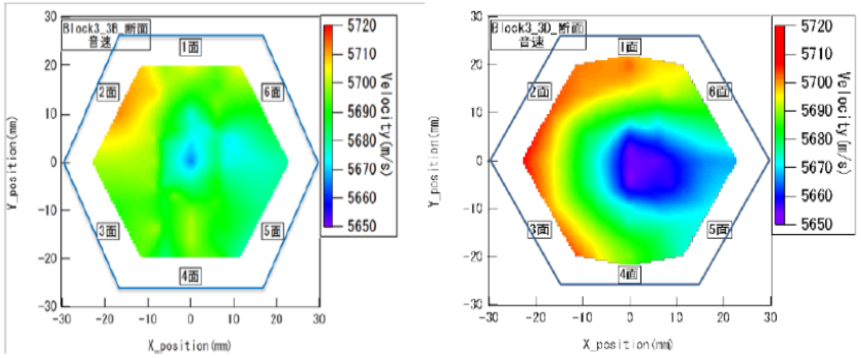
- Most NDE methods for microstructure characterization provide relative and not absolute information
  - Classical inverse problem: non-uniqueness

- Correlative analyses provide vital insights into measurement change with degradation

- Approaches for quantifying material state from NDE/SHM measurements and its remaining useful life are needed



MBN Peak Value Change with Tensile Strain in 304 SS
(Ramuhalli et al, 2015)



Density and Ultrasonic Velocity Change with Dose in Stainless Steel Blocks
Garner et al, INL/CON-14-33001, 2015

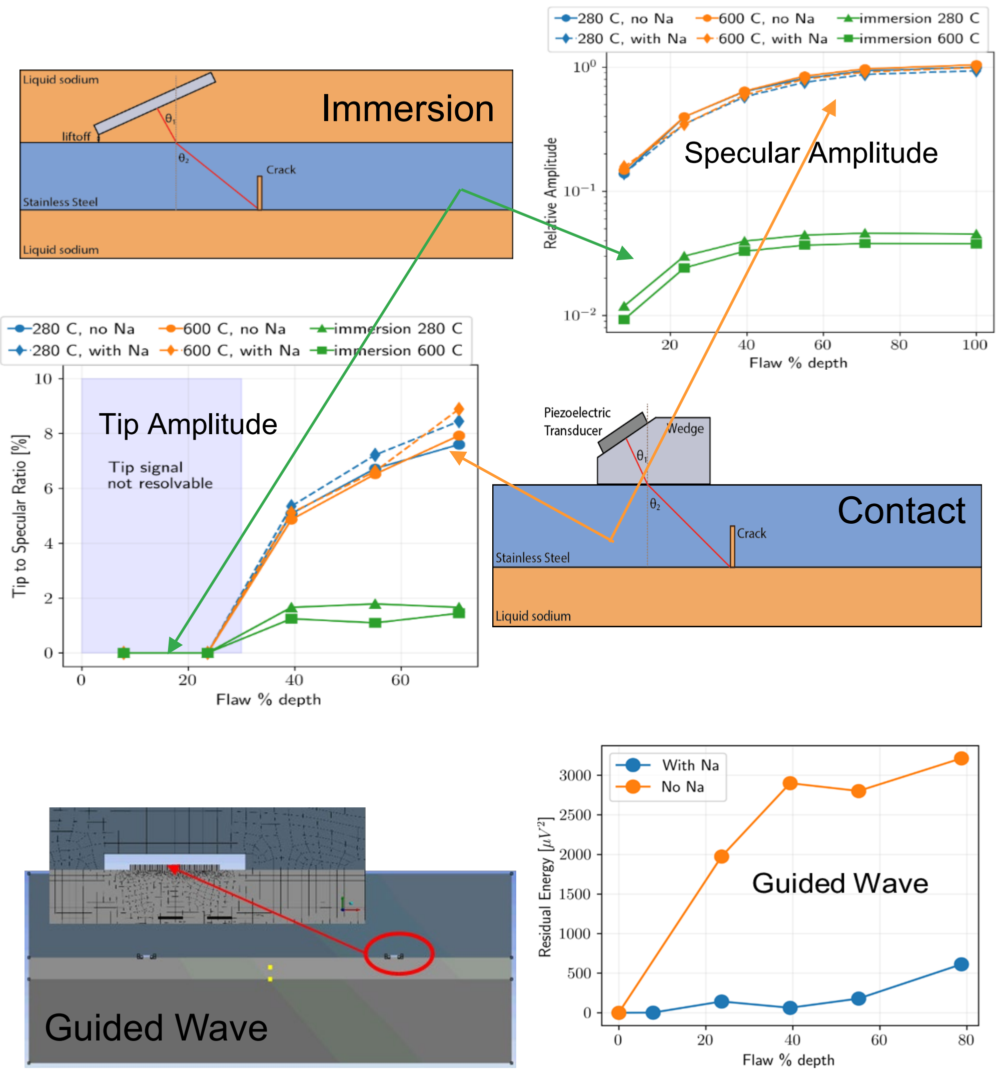
Quantitative Evaluations of NDE/SHM Performance and Reliability Will be Necessary

- Several Factors Conspire to Elevate Importance and Necessary Rigor for Quantitative Treatment of NDE/SHM for Emerging Reactors
  - Desire for increased operational autonomy requires information to be available in a way machines can process
  - Desire to reduce uncertainty in safety margins to improve economics
  - Increased reliance on risk-informed frameworks for decision making

- Performance and Reliability Characterization Drivers
  - Potential novelty and diversity in materials and material microstructure; fabrication history
  - Harsh environments seriously challenge available sensors and instrumentation
  - Delineating effects of multiple stressors
  - Insufficient information for inverse models and damage accumulation models
  - Damage threshold for failure (especially if defining degradation with respect to precursors)

Role of Modeling & Simulation/Digital Twins for Passive Components

- NDE/SHM empirical performance demonstration challenges for emerging reactors -
  - Empirical performance demonstrations for NDE/SHM need to account for operational factors
  - Accounting for potential harsh environmental effects
  - Variation in potential system designs/concepts limits ability to pool resources
- Modeling & Simulation can provide insights to inspection performance
- Digital Twins may provide pathway to incorporate factors associated with reactor operations into quantitative NDE/SHM performance evaluation



Source: Dib et al, IWSHM (2018)

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Ongoing Research Needs for NDE/SHM for non-LWRs

- Quantitative Evaluation of Performance and Reliability of SHM and NDE for various mechanisms
  - Measures of degradation severity or component health are needed
  - Measurement uncertainty quantification and its effect on reliability (account for impact of factors associated with reactor operations)
  - Concurrent damage mechanisms – detection sensitivity and selectivity
  - NDE/SHM of novel materials and AM manufactured materials
- Sensors and instrumentation survivability
  - Online calibration of aging sensors for in-situ monitoring to correct measurement drift
  - Optimal sensor placement for in-situ monitoring
- Inverse methods for quantifying material condition from NDE/SHM, estimating remaining service life
  - Physics-informed AI/ML: Relating material changes to measured quantities and vice-versa, and assessing component health change over time
  - Failure/Acceptance criteria – acceptable and rejectable damage thresholds.
- Human factors
  - Inspection and data analysis can vary with operator
  - Resulting analysis information will need to be presented to operators

Summary

- Emerging reactor concepts present many unique challenges not present with LWR fleet; a greater emphasis on SHM will be present in emerging reactors although it is still applicable to existing fleet of LWRs
- NDE plays (and will continue to play) a critical role in defense-in-depth for nuclear power plants
- Rigorous quantification of NDE/SHM performance is <u>more important</u> and <u>more challenging</u> for emerging reactors
- Performance demonstration of NDE/SHM performance is <u>just as important</u> and <u>more challenging</u> for emerging reactors
- As emerging reactor concepts mature, new challenges to assessing degradation level and growth rates are foreseen; Research (nationally and internationally) is addressing many of these challenges
  - Sensing: what, where, and how to measure; sensitivity & fidelity; applications to non-metals and AM materials
  - Sensors and instrumentation for in-vessel/in-containment use
  - Inverse models for rapid, robust data analysis
  - Qualification of sensors and instrumentation, systems, methods, and procedures and personnel
  - Data and testbeds for testing and qualifying methods and developing analysis methods are necessary

Acknowledgments

- A number of collaborators have contributed to the work presented here, and include staff from ORNL, PNNL, ANL, Bettis, INL, Universities (UT-Knoxville, PSU, WSU, ISU, CSU-LB, WUSTL, Ajou University), and Industry (AMS Corp.)
- A portion of the research presented here was supported by the USDOE Office of Nuclear Energy through the Advanced Reactor Technologies (ART), Nuclear Energy Enabling Technologies (NEET), and the National Scientific User Facility (ATR-NSUF) programs. A portion of the research was supported by the NNSA Office of Defense Nuclear Nonproliferation (NA22). Parts of this work were supported by Ajou University (S. Korea) and USNRC.
- Oak Ridge National Laboratory is managed by UT-Battelle for the US Department of Energy.

Questions?

Vivek Agarwal, PhD
Distinguished Staff Scientist
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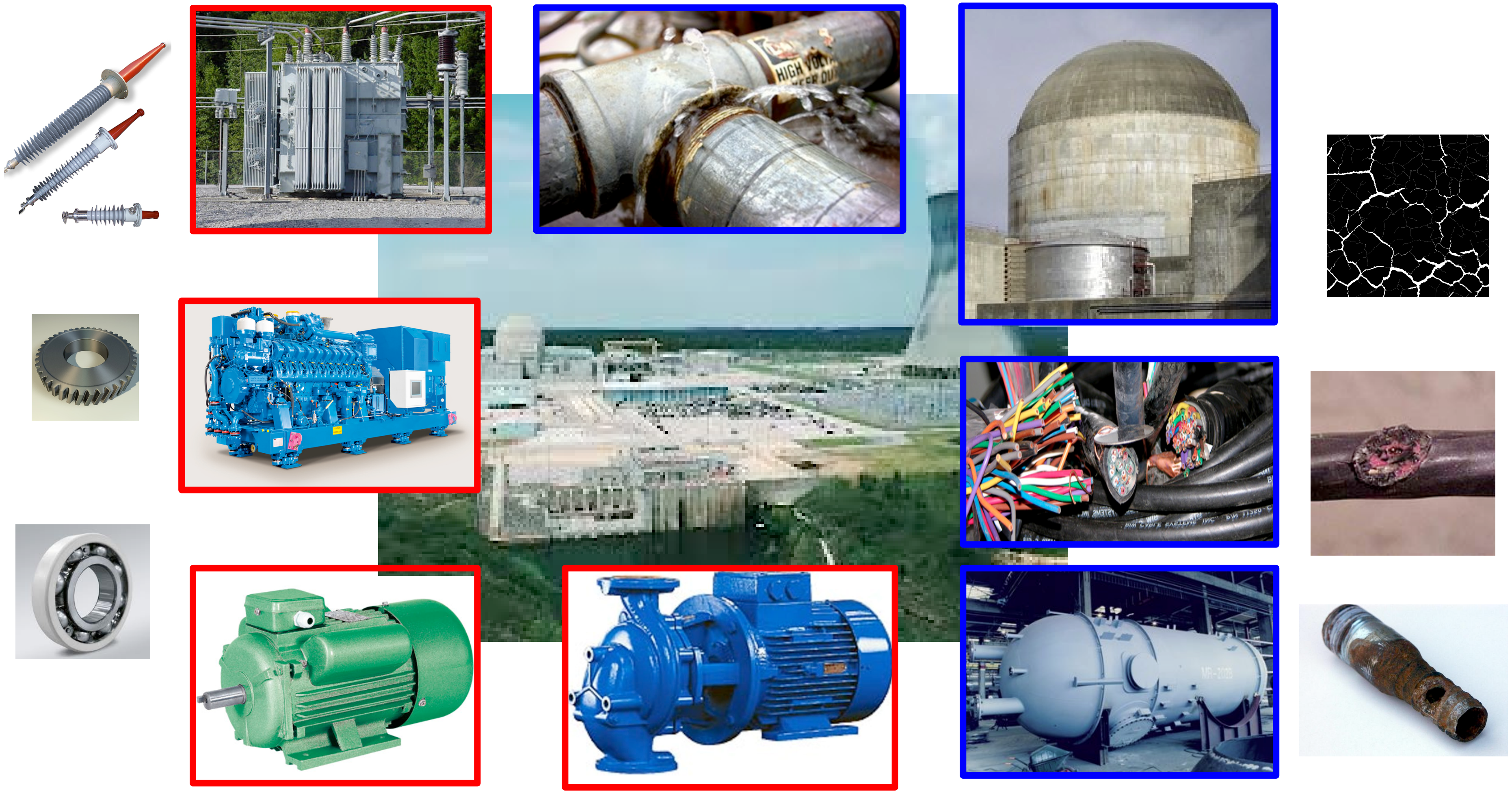
Artificial Intelligence and Machine Learning Applications for Structural Health Monitoring in Nuclear

Virtual Workshop on Condition Monitoring and Structural Health Management for Nuclear Power Plants

November 28-29, 2023

Idaho National Laboratory

Structures, Systems, and Components (SSCs)

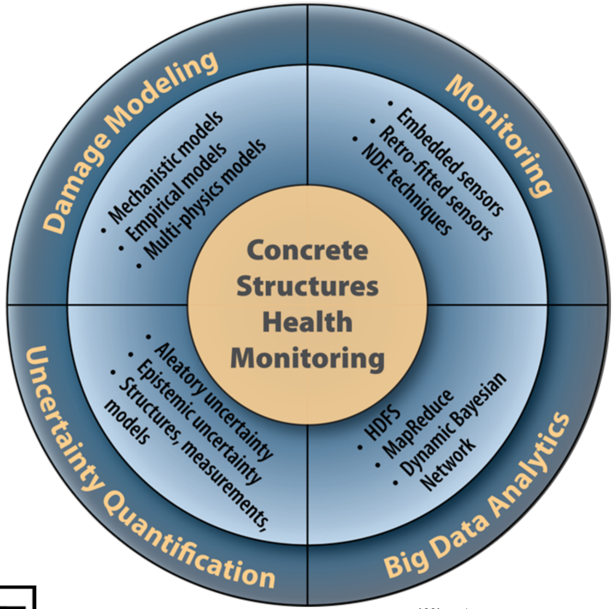


Active SSCs

Passive SSCs

Structural Health Monitoring

- Age-related deterioration of nuclear plant concrete structures might lead to **premature closure** or prevent **second license renewal** process
- Current structural health monitoring (SHM) in the nuclear industry is strictly an **offline process** and lacks application of **advanced technology solutions**
- **Multi-institute concrete SHM** research effort would integrate monitoring techniques to
  - Detect, localize, and estimate Alkali-Silica Reaction degradation mode in concrete structures
  - Develop diagnostic and prognostic models
  - Apply Bayesian technique to integrate different sources of uncertainties
- Concrete SHM research would enable **science-** and **data-based decision-making** on structural health.

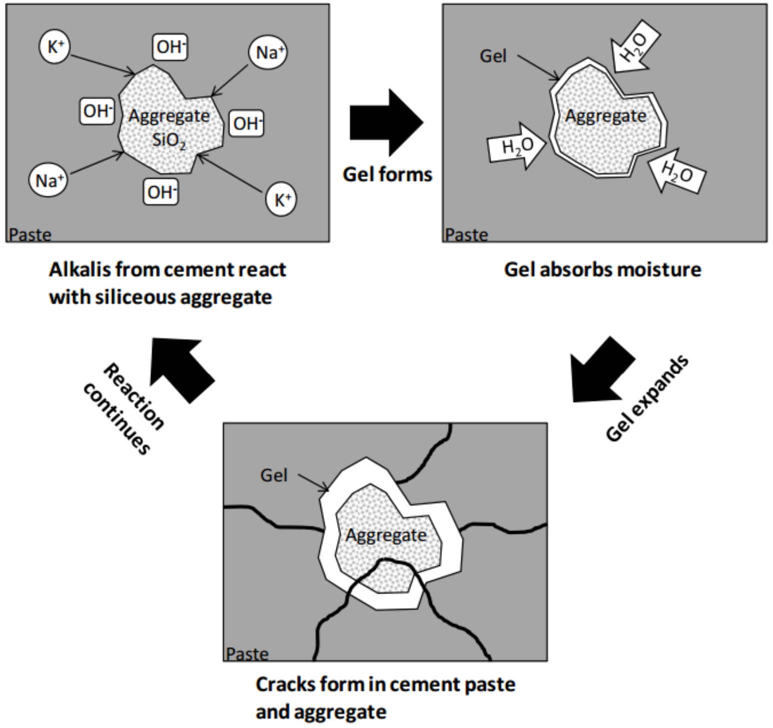


VANDERBILT UNIVERSITY
University of Nebraska Lincoln
University of South Carolina
Georgia Tech
The University of Tennessee Knoxville
The University of
Oak Ridge National Laboratory
INL Idaho National Laboratory
EPRI Electric Power Research Institute

V. Agarwal, G. Cai, A. Gribok, P. Nath, R. Hansley, K. Neal, Y. Bao, S. Mahadevan, “Monitoring, Modeling, and Diagnosis of Alkali-Silica- Reaction in Small Concrete Samples,” INL/EXT-15-36683, September 2015.

Alkali-Silica Reaction (ASR) Degradation

- ASR is an intrinsic chemical reaction that forms a gel in concrete pores, expands, and causes stress and cracking of concrete
- Can be associated with corrosion of steel reinforcement bars and other steel structures embedded in the concrete
- Water containing sulfate or chloride causes ASR



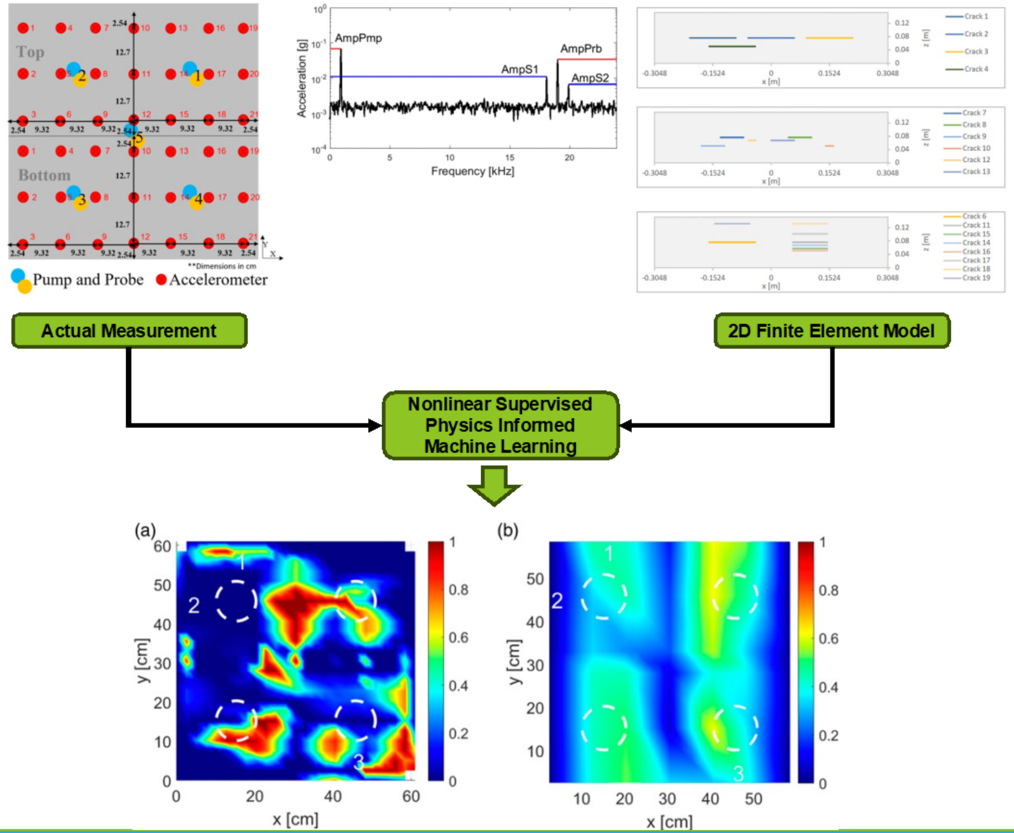
Challenges

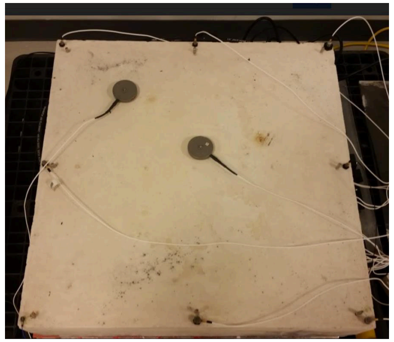
- Extent of ASR occurrence
  - location throughout the plant
  - position within the thickness of the concrete wall
- Extent to which ASR has reduced mechanical properties of concrete

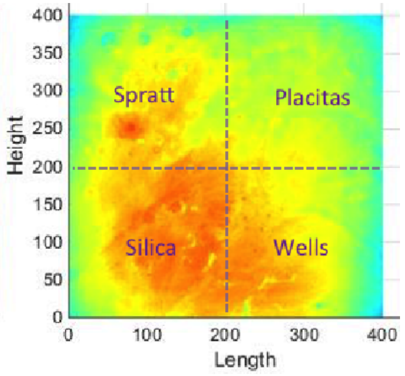
Kreitman, K., 2011, “Nondestructive Evaluation of Reinforced Concrete Structures Affected by Alkali-Silica Reaction and Delayed Ettringite Formation,” M.S. Thesis: University of Texas at Austin, Austin, Texas.

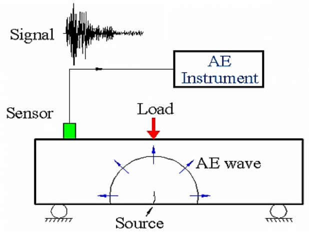
Multimodal Measurements and Automation

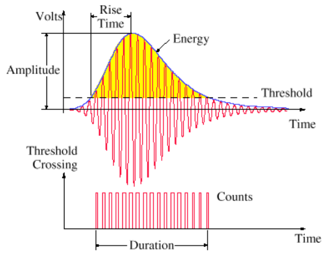
Developed technology to locate and estimate alkali-silica reaction (ASR) damage using physics-informed machine learning approach.

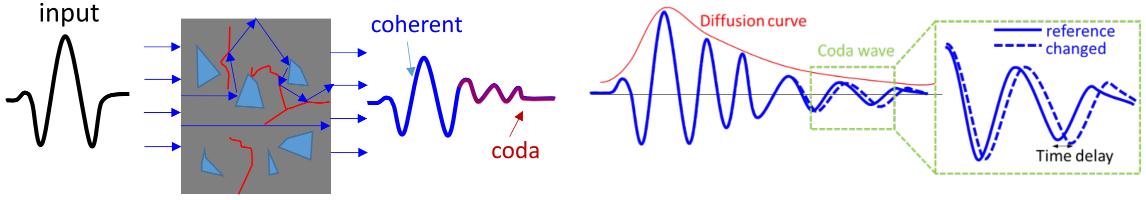








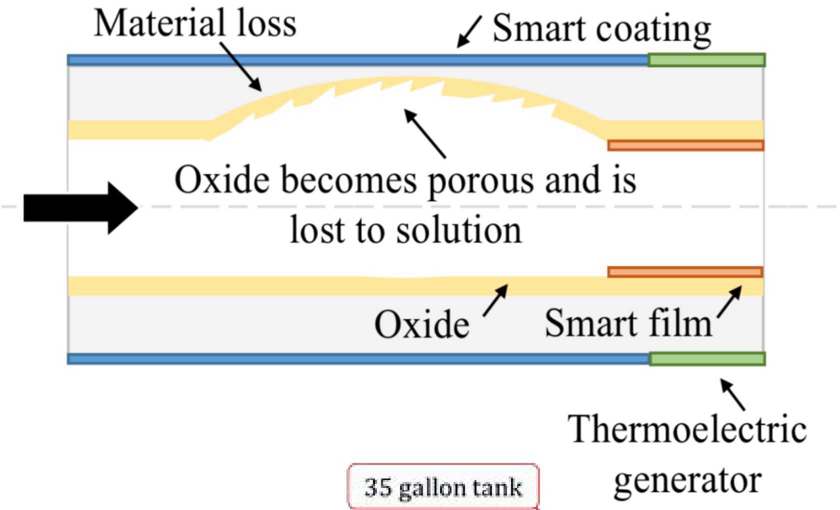


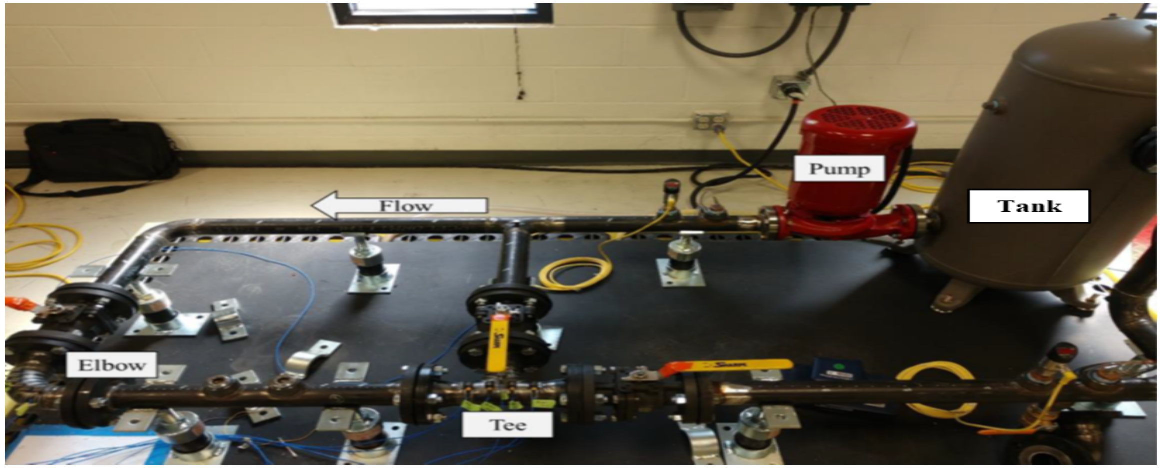


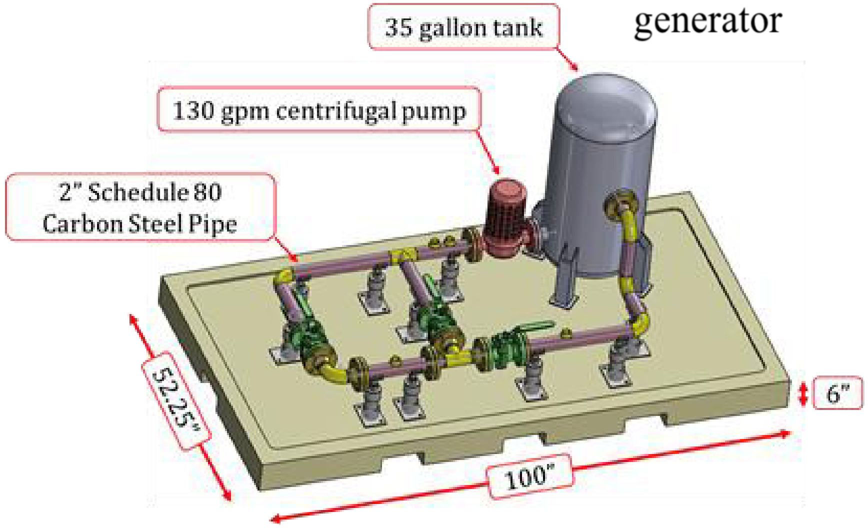
Miele, S., Pranav, K., Mahadevan, S., and Agarwal, V. Diagnosis of Internal Cracks in Concrete Using Vibro-acoustic Modulation and Machine Learning. Structural Health Monitoring Journal, vol. 21, no. 5, pp. 1973-1991, 2022.

Corrosion in Secondary Piping System in Nuclear

- Develop a three-dimensional sensing approach to understand internal wall thinning due to corrosion in secondary piping system
  - Smart film to sense chemo-mechanical state of inner wall of pipe structure.
  - Vibro-acoustic sensing to detect changes to inner wall of pipe due to material loss.
  - Simulate sensing approach on a subscale cooling circuit testbed.



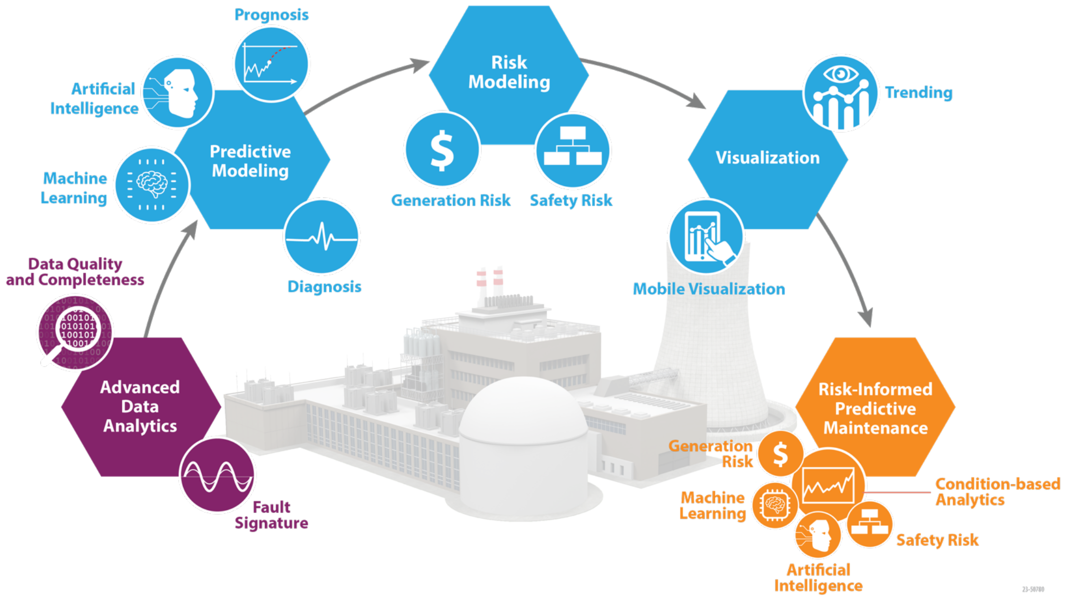




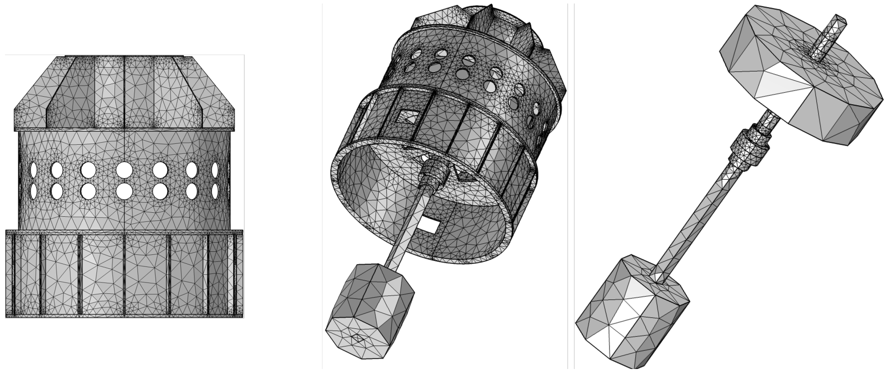
K. A. Manjunatha, V. Agarwal, A. L. Mack, D. Koester and D. E. Adams, "Total Unwrapped Phase-Based Diagnosis of Wall Thinning in Nuclear Power Plants Secondary Piping Structures," in IEEE Access, vol. 10, pp. 113726-113740, 2022.

Predictive Maintenance Strategy

- Developed a scalable risk-informed predictive maintenance strategy using machine learning approaches, risk modeling, visualization, and multi-band heterogeneous wireless architecture.
- Developed a hybrid model of circulating water pump (CWP) motor (basis for digital twin) to capture different operating dynamics.
- INL collaborated with Public Service Enterprise Group (PSEG) Nuclear LLC and PKMJ Technical Services (now part of Westinghouse Electric Company).

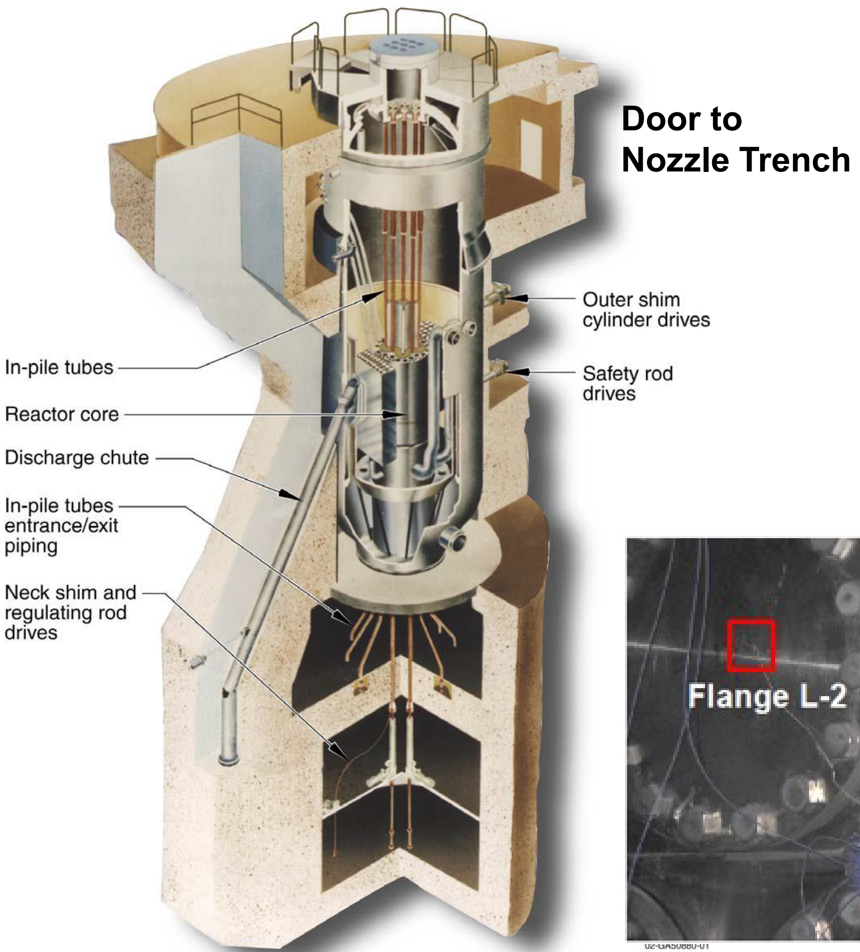


Risk-informed Predictive Maintenance Strategy

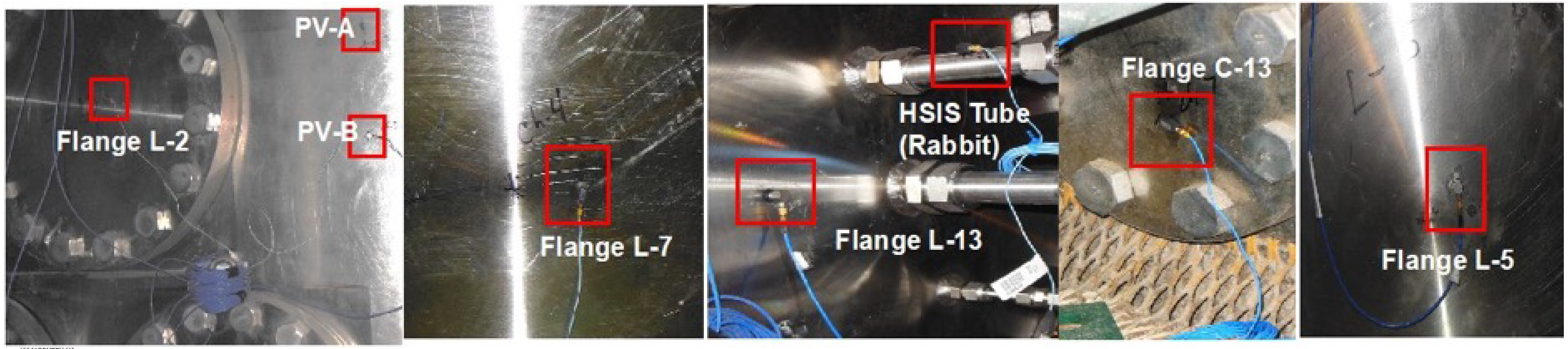

Physics-based model of CWS

V. Agarwal, K. Manjunatha, et al. Scalable Technologies Achieving Risk-Informed Condition-Based Predictive Maintenance Enhancing the Economic Performance of Operating Nuclear Power Plants. INL/EXT-21-64168

Advanced Test Reactor Acoustic Measurement Infrastructure (AMI)

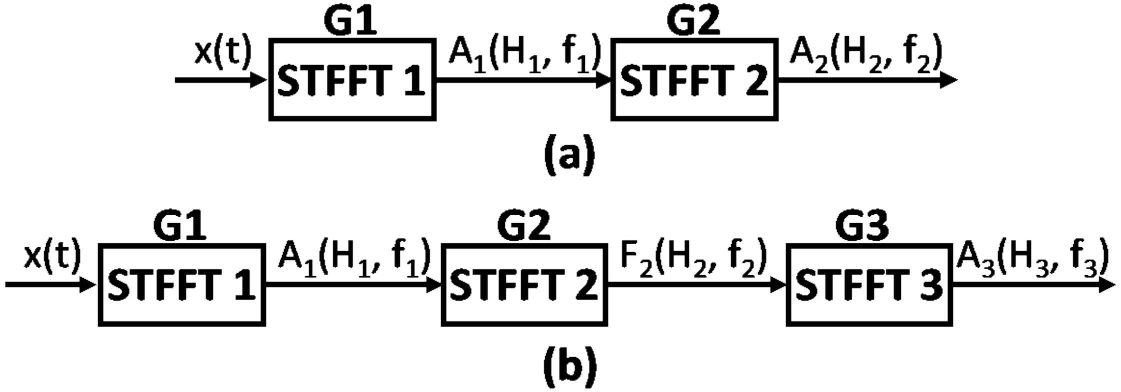


- National Instrument platform for data acquisition
- 8 Channel with piezoelectric accelerometers
- Accelerometers Installed
  - Pressure Vessel
  - Hydraulic Shuttle Irradiation System (HSIS) Piping
  - Flanges (multilevel)
  - Spaced ≈ ¾ of the pressure vessel circumference

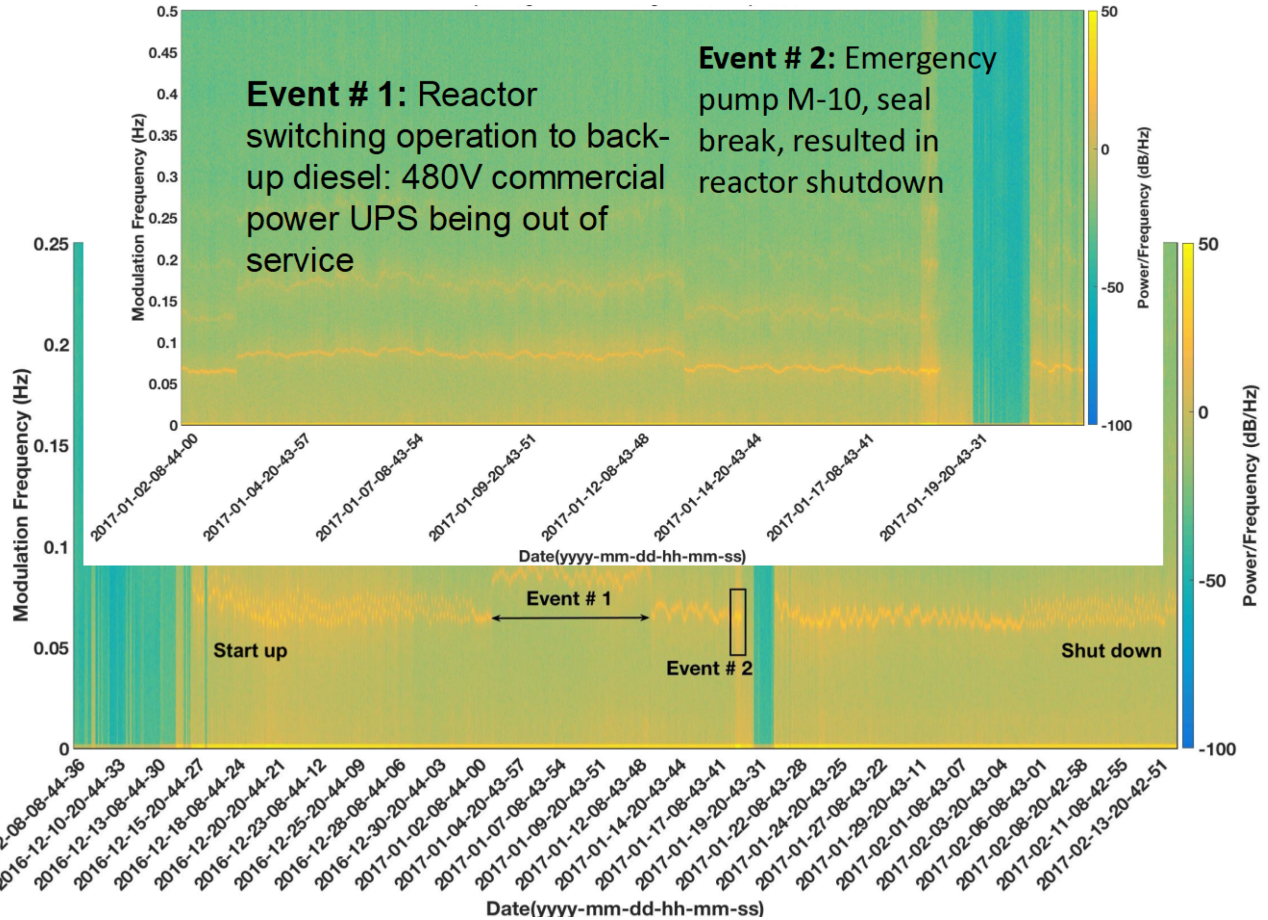


V. Agarwal and J. A. Smith, "Real-time in-pile acoustic measurement infrastructure at the advanced test reactor", *Nuclear Technology.*, vol. 197, no. 3, pp. 329-333, Mar. 2017.

Recursive Short-Time Fast Fourier Transformation (STFFT)

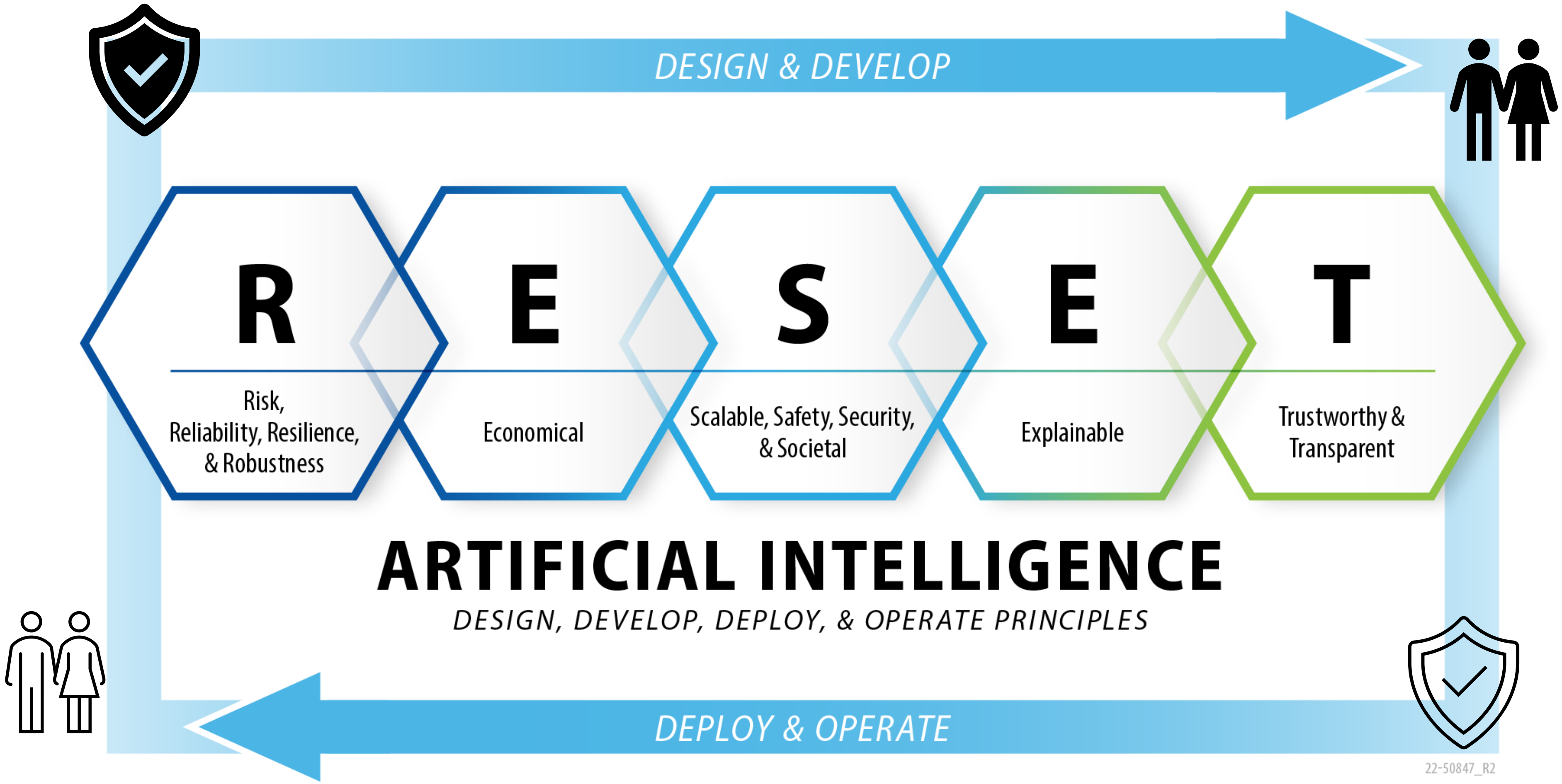


- Application of recursive short-term fast Fourier Transformation allows develop of acoustic signatures of the reactor under different operating conditions
- Application of machine learning approaches to automate diagnosis and prognosis of reactor state of operation
- Enable predictive maintenance strategy and enhance reliability of reactor operation



J. A. Smith and V. Agarwal, "Recursive Use of the Short-Time Fast Fourier Transform for Signature Analysis in Continuous Processes," in *IEEE Transactions on Instrumentation and Measurement*, vol. 72, pp. 1-11, 2023.

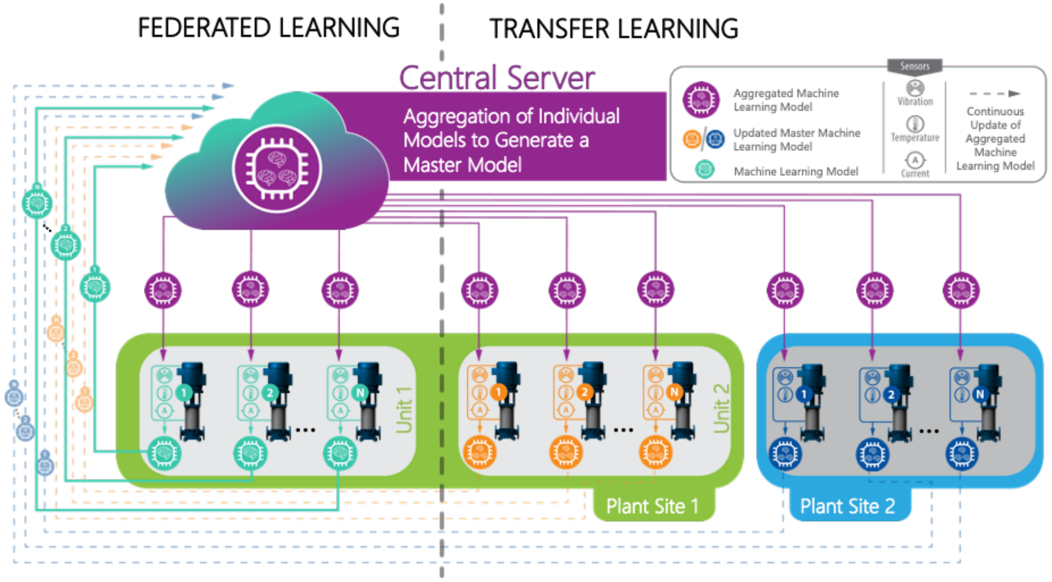
Artificial Intelligence Lifecycle and Guiding Principles



V. Agarwal, C. Primer et al. Data Architecture and Analytics Requirements for Artificial Intelligence and Machine Learning Applications to Achieve Condition-Based Maintenance, INL/RPT-22-70350

Scalability Aspect of AI/ML

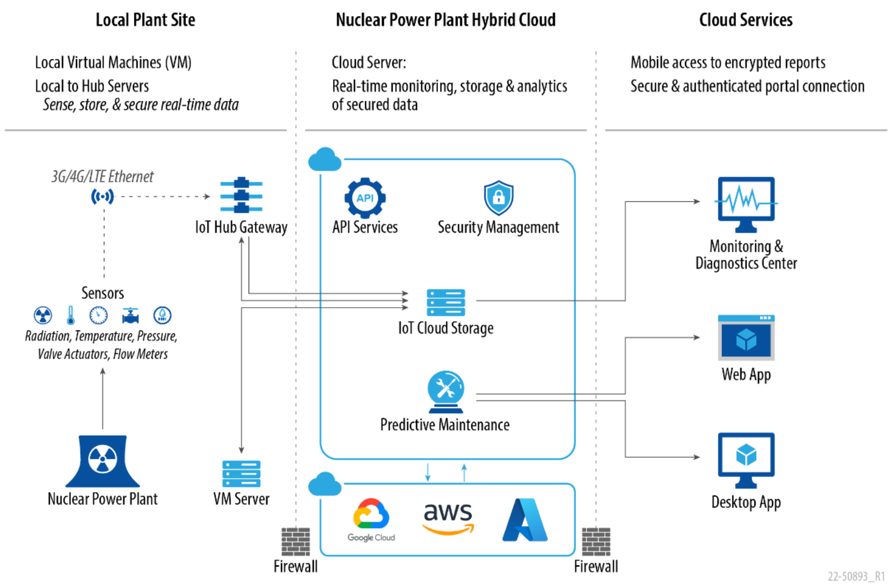
Federated Transfer learning approach would allow nuclear plants to achieve scalability of AI/ML approaches by ensuring data privacy and security. Also enable distributed AI/ML approach for resilience.



Federated Transfer Learning AI/ML Approach

V. Agarwal, K. Manjunatha, et al. Scalable Technologies Achieving Risk-Informed Condition-Based Predictive Maintenance Enhancing the Economic Performance of Operating Nuclear Power Plants. INL/EXT-21-64168

Cloud computing would help achieve cost-effective scalable predictive maintenance strategies to alleviate nuclear power plants from developing onsite storage, computing and analytics capabilities and resources.



Proposed high-level architecture of the hybrid cloud.

C. Walker, V. Agarwal, et al. Assessment of Cloud-based Applications Enabling a Scalable Risk-informed Predictive Maintenance Strategy. INL/RPT-23-74696

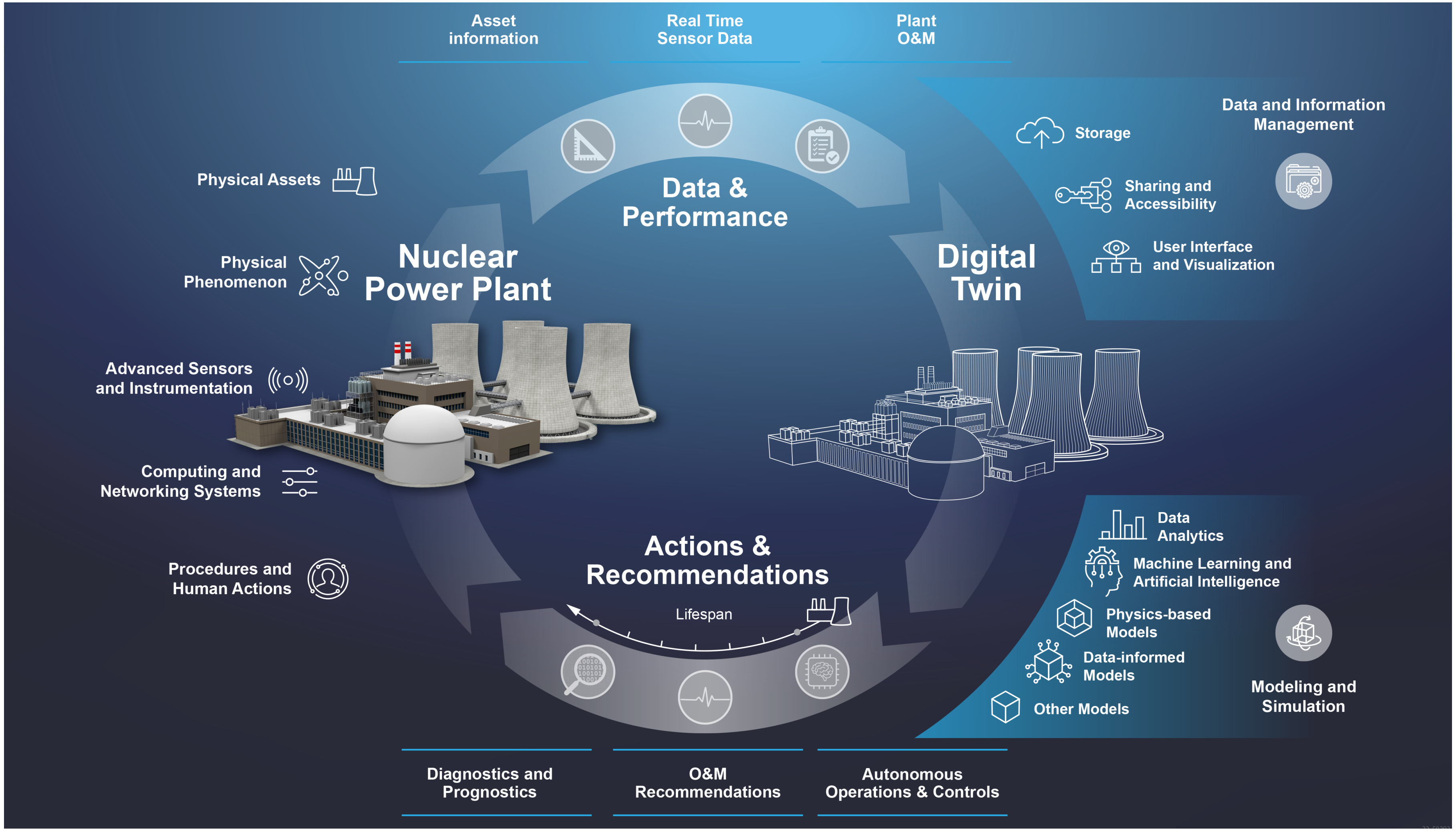
Interpretability of Artificial Intelligence and Machine Learning Technologies for building Trust Among Users

- LWRS Program researchers developed methods to address the explainability, performance, and trustworthiness of AI/ML to enhance the interpretability of outcomes.
- One method uses objective metrics like Local Interpretable Model-agnostic Explanations (LIME) and Shapley Additive Explanations (SHAP).
- Another method employs user-centric visualization of AI/ML outcomes together with objective metrics to support expert interpretation.
- In collaboration with Public Service Enterprise Group (PSEG), Nuclear LLC, performed initial demonstration of the technical basis on circulating water system (CWS) for a waterbox fouling problem.

User-centric visualization with performance and explainability metrices

C. Walker, V. Agarwal, N. Lybeck, A. Hall, L. Lin, R. Hall, R. Boring, T. Mortensen. Explainable Artificial Intelligence Technology for Predictive Maintenance. INL/RPT-23-74159

In Conclusion connecting to the Digital Twin Framework



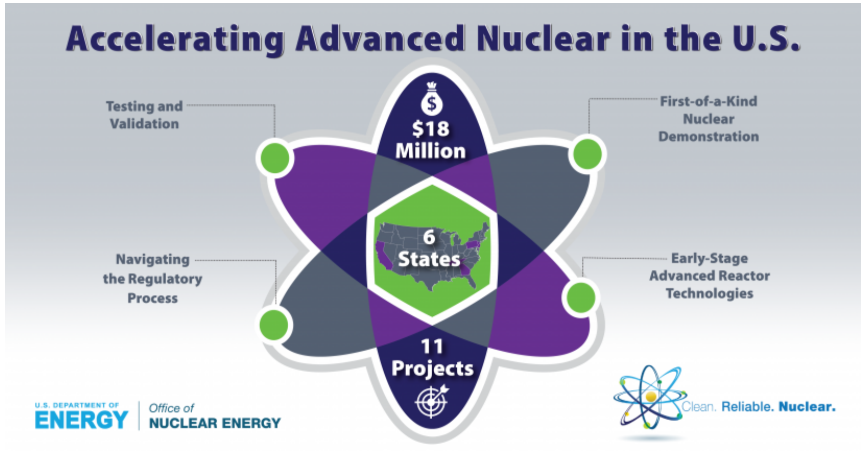
Source: https://www.nrc.gov/reactors/power/digital-twins.html

Acknowledgements

LWRS
LIGHT WATER REACTOR SUSTAINABILITY

U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment

ASI | Advanced Sensors and Instrumentation

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Sensors to Support Online Monitoring in Advanced Reactors

Virtual Workshop on Condition Monitoring and Structural Health Management for Nuclear Power Plants

Jorge Carvajal
Fellow Engineer, Global Technology Department

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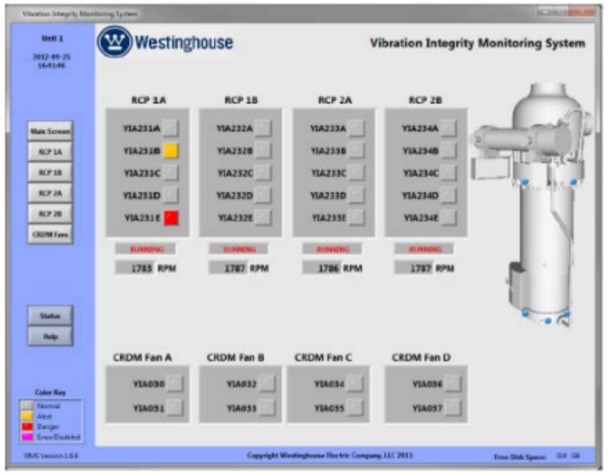
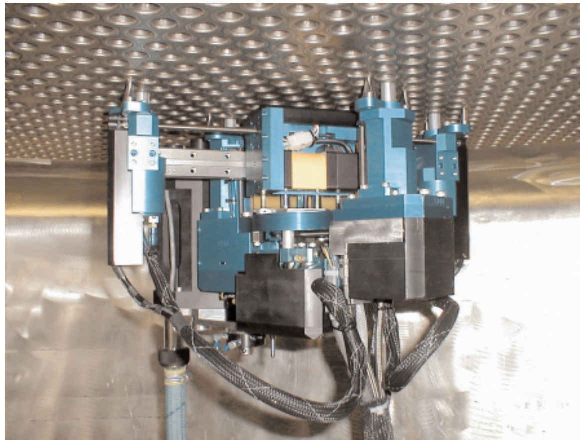
State of Knowledge of On-Line Component Conditioning Monitoring & Structural Health Sensor Types

- Digital Metal Impact Monitoring System (DMIMS): loose parts monitoring within RCS
- Vibration Integrity Monitoring System (VIMS): vibration monitoring for RCP and control rod drive mechanism
- Eddy current SG tube monitoring: steam generator tube inspection
- Neutron Flux noise: remote condition monitoring process using the ex-core and in-core neutron flux detectors



VIMS cabinet


Pegasys Robot


DMIMS cabinet

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Advanced Sensors for On-Line Component Conditioning Monitoring

- Sensors must be able to operate reliably in harsh environments (high temperature and radiation)

- New sensors for Gen III Reactor and Fuel storage applications
  - In-Rod Sensor
  - Dry-Cask applications

- Advanced Reactors (Gen IV and Micro Reactors)
  - Distributed fiber sensing
  - Eddy Current Flow Monitoring System
  - In-Core Neutron Flux Detectors
  - Fuel integrity monitoring system
  - Helium leak detector

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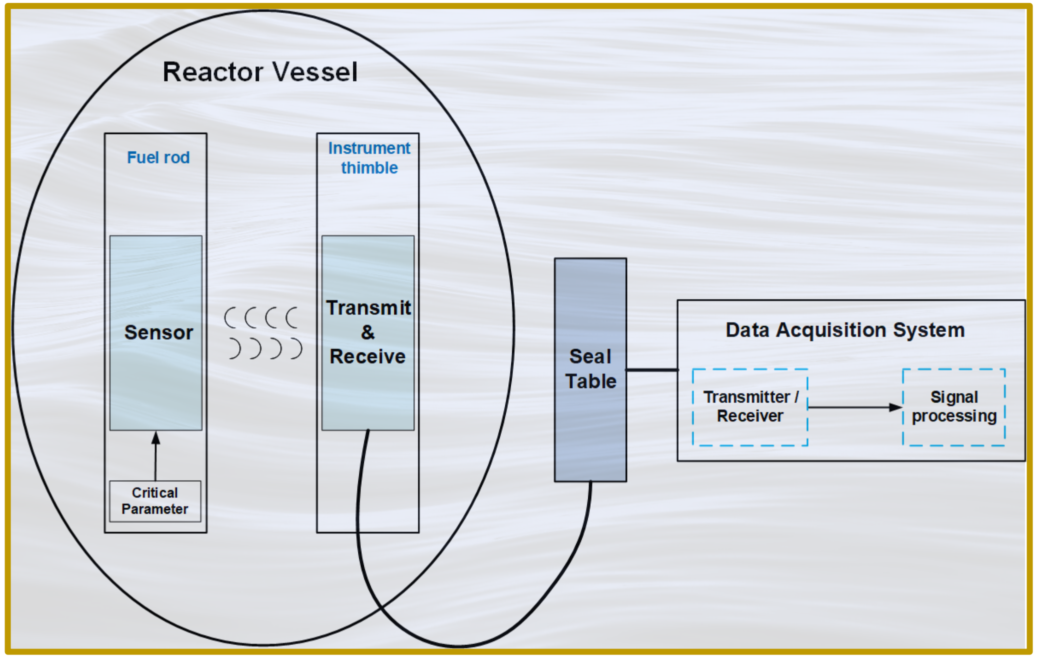
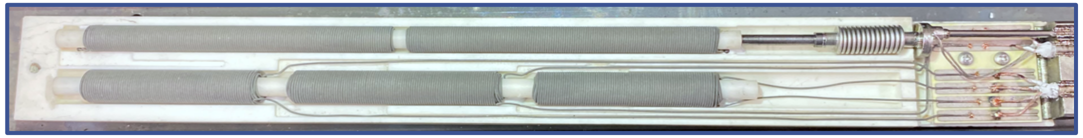
In-Rod Sensor System

- Overview
  - Real-time transmission of critical parameters
    - Center line fuel pellet temperature
    - Rod internal pressure
    - Fuel pellet stack elongation
  - Fuel rod penetration not required
  - Signal wirelessly coupled to transceiver in thimble tube
- Benefits
  - Non-intrusive real-time data instead of the typical "cook and look" significantly accelerates development
  - Reduction or elimination of post irradiation examination



Sensor system plant configuration



Pressure sensor assembly installed at ORNL HFIR

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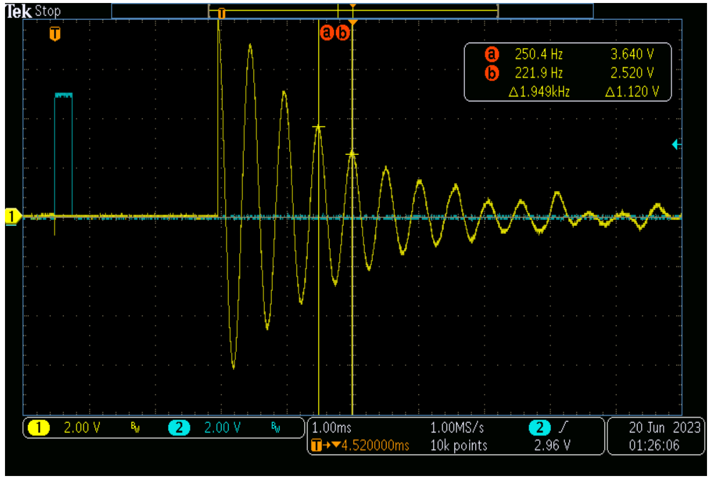
Dry-Cask Sensor System

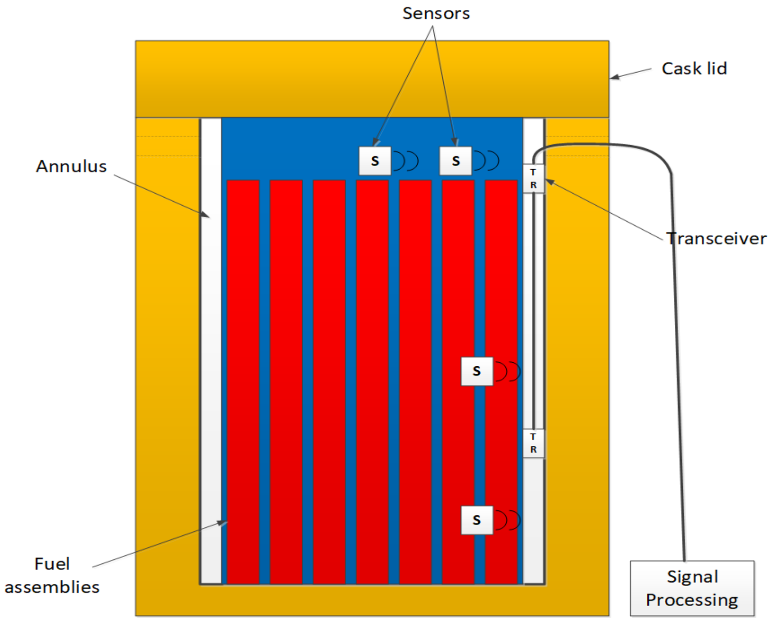
- Overview
  - Wireless transmission of critical parameters (temperature, pressure) without adding penetrations to the spent fuel storage steel cask

- Benefits
  - Provides direct measurements (cladding temperature, pressure) without cask penetration
    - Reduce surveillance
    - Allow direct measurements that may lead to degradation mechanisms (SCC, e.g.)

Transceiver placed in the exterior of the cask while sensor at same elevation inside cask



Sensor response from configuration on the left figure



Sensor system configuration

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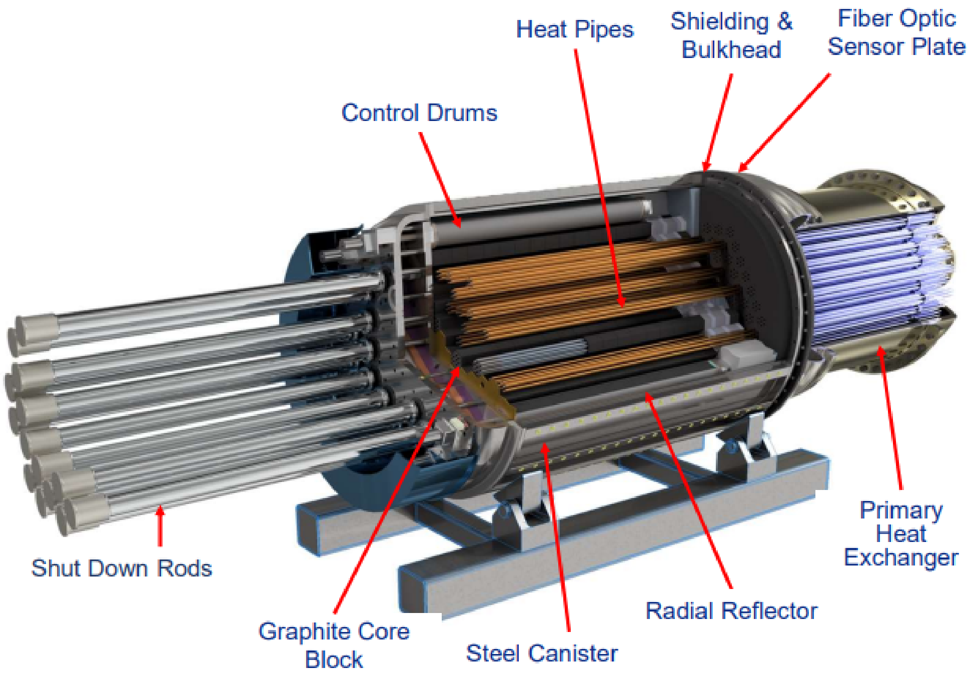
Distributed Fiber Sensing

- Overview
  - Fiber optic sensors can provide measurement such as temperature and strain under harsh environmental conditions
- Benefits
  - Distributed measurements with a single fiber compared to a single measurement from a single sensor
- Applications
  - Heat pipe temperature
  - Spent fuel storage steel canister structural health



eVinci Microreactor

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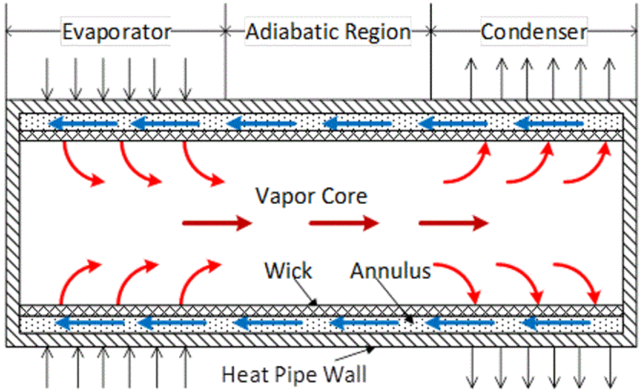
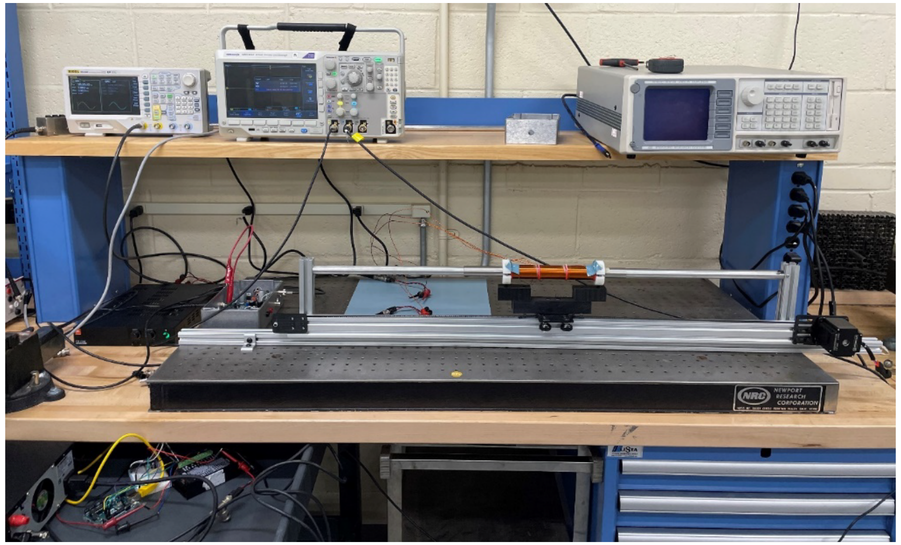
Eddy-Current Flowmeter

- Overview
  - The Eddy Current Flowmeter (ECFM) is an electromagnetic sensor that measures the velocity of liquid sodium flow through the heat pipes of the eVinci Microreactor.
  - A current induced into the center primary coil results in a voltage difference across the secondary coils that is directly proportional to the sodium flow velocity.
- Benefits
  - Near real-time indication of heat pipe failure



Heat pipe sodium flow path



Experimental setup

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Thank you!

Questions?

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NOVEMBER 29, 2023

ONLINE MONITORING TO ENABLE THE LONG-TERM HEALTH OF MOLTEN SALT REACTORS

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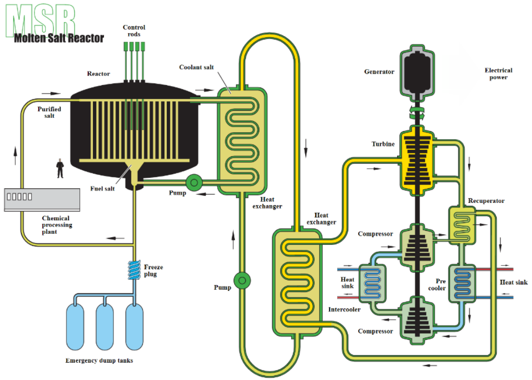
U.S. DEPARTMENT OF ENERGY
Argonne National Laboratory is a U.S. Department of Energy laboratory managed by UChicago Argonne, LLC.

Argonne NATIONAL LABORATORY

ADVANCED EQUIPMENT AND SENSORS FOR MOLTEN SALT SYSTEMS

Molten salt systems present a broad number of operational challenges due to the high temperatures, corrosivity, and radioactivity of the salt media. MSR-relevant equipment and sensors suitable for economical deployment must have excellent longevity, stability, and performance over multi-year durations.

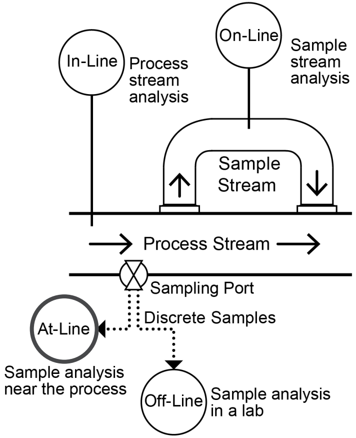
Molten Salt Reactors



Salts under study

Chloride salts
Fluoride salts
Be-bearing salts
U/TRU-bearing salts
- Fuel reprocessing salts
- MSR fuel salts

Process Monitoring Technologies



Each group of sensors has a different range of developmental costs and expected performance profiles.

Hoyt et al. JNMM *(2021)*

MANY TYPES OF MONITORING TOOLS COULD POTENTIALLY SUPPORT MSR OPERATIONS AND STRUCTURAL HEALTH

Under DOE NE's Advanced Reactor Safeguards program we conducted a comprehensive assessment of available monitoring tools relevant to MSRs.

Most technologies are still at an insufficient technology readiness level to permit deployment.

Key monitoring capabilities for MSRs:

- Corrosion
- Salt chemistry
- Particulates
- Nuclear material accountancy

safeguards impact

PM impact

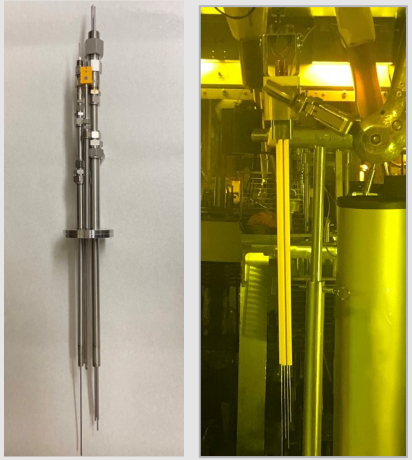
TRL

Molten Salt Process Monitoring and Safeguards Instrumentation

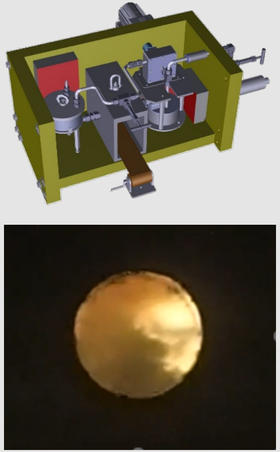
Measurement Type	Sensor Type	Relevance to Process Montoring	Relevance to NMAC	Comments	TRL (for MSR Integration)	PM Impact (1-10)	Safeguards Impact (1-10)
Salt Composition (species concentrations)	Salt Sampler	Measurements of evolving fuel salt and fission product concentrations using a variety of off-line techniques	Off-line measurements of safeguards-relevant actinides	Enables off-line measurements that are higher precision than in situ techniques. Sample handling is challenging. Sampling procedure may create diversion scenarios.	8	6	8
	Electrochemical	In situ monitoring of evolving fuel salt and fission products. In situ monitoring of corrosion products.	In situ monitoring of the concentrations of safeguards-relevant actinides	Potential for noise in high-radiation environment.	6	8	8
	Raman	In situ monitoring of evolving fuel salt and fission products. In situ monitoring of corrosion products.	In situ monitoring of the concentrations of safeguards-relevant actinides	Questionable longevity of optical windows	4.0	8	8
	UV-Vis	In situ monitoring of evolving fuel salt and fission products. In situ monitoring of corrosion products.	In situ monitoring of the concentrations of safeguards-relevant actinides	Transmission measurements will be challenging given the high concentrations of dissolved fuel salt species. Questionable longevity of optical windows	4.0	8	8
	LIBS	In situ monitoring of evolving fuel salt and fission products. In situ monitoring of corrosion products.	In situ monitoring of the concentrations of safeguards-relevant actinides	Possibility for isotopic measurements. Optical access and measurement of consistent samples is challenging.	4	8	8
Isotopics (radiation detection and quantification)	Gamma spectroscopy (e.g., HPGe or microcal)	Off-line analysis of fuel salt and fission product composition (in support of neutronics and burnup assessments)	Off-line analysis of key isotopes	High background radiation. Best suited to off-line sample analysis. On-line detectors can be used for signatures. Microcal will offer significant advantages for resolution compared to HPGe	7	6	8
	Alpha spectroscopy	On-line analysis of fuel salt and fission product composition (in support of neutronics and burnup assessments)	On-line analysis of key isotopes	Laboratory demonstrations; performance at high temperatures questionable	3	5	7
Pressure	Pressure transducers (NaK filled, etc.)	Flow verification. Pump assessment	Signals can be used for signature development.	High PM impact. Necessary for any MSR.	7	10	3
Flow rate	Thermal flow meter	Salt pump verification. Quantification of salt transfers to and from process equipment	Quantification of SNM transfers to and from process equipment	Demonstrations in coolant salts but not in fuel salts	7	8	7
	Ultrasonic fow meter	Salt pump verification. Quantification of salt transfers to and from process equipment	Quantification of SNM transfers to and from process equipment	Demonstrations in coolant salts but not in fuel salts. Transducer lifetime questionable.	7	8	7
	Activiation flow meter	Salt pump verification. Quantification of salt transfers to and from process equipment	Quantification of SNM transfers to and from process equipment	High background radiation may make detection of activated products difficult	4	6	6
Corrosion / Strucutral Metal monitoring	Magnetic susceptibility meter	Measurement of Cr depletion from walls of tubing and piping	Minimal safeguards impact	Early demonstrations only. Only detects Cr depletion.	4	5	2
	Ultrasound	Measurement of material buildup or depletion on walls of tubing and vessels	Assess buildup of possible actinide materials on walls.	Transducer lifetime in high-temperature, high-radiation conditions unclear	4	5	4
Temperature	Thermocouples	Heat transfer assessment; monitoring of operational limits	Signals can be used for signature development. Many other safeguards measurements are dependent on accurate temperature measurements	High PM impact. Necessary for any MSR. Very long-term stability unknown in MSR conditions	8	10	8
	Fiber optics	Heat transfer assessment; monitoring of operational limits	Signals can be used for signature development. Many other safeguards measurements are dependent on accurate temperature measurements	Damage to optical fiber from radiation is a concern	6	8	5
Salt redox potential	Dynamic reference electrode	Assessment of corrosivity of salt and state of dissolved materials	Assessment of state of safeguards-relevent actinide species	Years-long longevity in MSR must be demonstrated	7	7	6
	Optical (Raman, UV Vis)	Assessment of corrosivity of salt and state of dissolved materials	Assessment of state of safeguards-relevent actinide species	Precise determination of redox potential requires full accounting of every salt constituent; optical approaches may not produce accurate results	3	6	6
	Thermodynamic reference electrodes	Assessment of corrosivity of salt and state of dissolved materials	Assessment of state of safeguards-relevent actinide species	Questionable longevity of separator materials in molten salt environment	5	7	6
Volume / Liquid Level	Tracer dilution	Measurement of total salt volume to assess presence of leaks	Measurements of salt volume to enable translation of coenctration measurements into total inventory in salt	Background radiation may make tracer measurements difficult	5	6	7
	Ultrasound	Measurement of salt level (which can be used to estimate salt volume) to assess presence of leaks	Measurement of depth (which can be used to estimate total volume) to enable translation of coenctration measurements into total inventory in salt	Longevity in high temperature, radiation conditions unclear	7	7	7
	Contact depth sensor	Measurement of salt level (which can be used to estimate salt volume) to assess presence of leaks	Measurement of depth (which can be used to estimate total volume) to enable translation of coenctration measurements into total inventory in salt	Possible corrosion issues depending on salt media	7	8	7
	Radar	Measurement of salt level (which can be used to estimate salt volume) to assess presence of leaks	Measurement of depth (which can be used to estimate total volume) to enable translation of coenctration measurements into total inventory in salt	Longevity in high temperature, radiation conditions unclear	7	7	7
Particulate Monitoring	Electrical Resistance Tomography	Monitoring of precipitated solids (to prevent clogging)	Monitoring of precipitated solids to ensure NMAC closure	Only short term demonstrations at present. Can measure particle loading but provides no quantification of particle composition	6	6	7
	Ultrasonics	Monitoring of precipitated solids (to prevent clogging)	Monitoring of precipitated solids to ensure NMAC closure	Not yet demonstrated for molten salt systems. Can measure particle loading but provides no quantification of particle composition	5	6	6
Off-gas monitoring	Optical (Raman)	Monitoring management and release of radioactive material	Mass accountancy for volatile actinide species	Limited amounts of SNM present in off-gas system	5	7	6
	LIBS	Monitoring management and release of radioactive material	Mass accountancy for volatile actinide species	Limited amounts of SNM present in off-gas system	5	7	6
Under-salt Viewing	Ultrasound	Detection of leaks/spills	Maintaining CoK for fuel pins	Important for MSRs with captive fuel salt pins (to enable item counting)	4	4	8
	Video	Detection of leaks/spills	Maintaining CoK for fuel pins	Important for MSRs with captive fuel salt pins (to enable item counting)	4	4	8
Vibration/Accelerations	Accelerometers	Pump health monitoring	Minimal safeguards impact		8	4	1
Valve Position Monitoring	Position Monitor	Valve position confirmation	Confirmation of flow pathway to appropriate process equipment		8	6	5
In-reactor video monitoring	Cameras (CCD, CMOS, etc.)	Detection of leaks/spills within reactor boundary	Detection of off-normal behavior	Longevity questionable	6	5	5

MOLTEN SALT SENSOR SYSTEMS

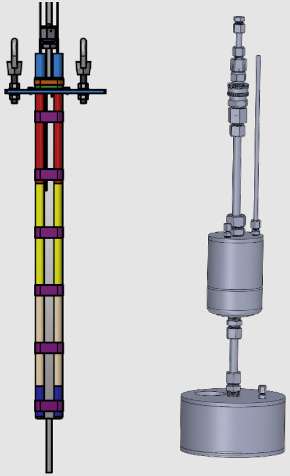
Argonne has demonstrated a variety of monitoring technologies to enable safe operations and material accountancy for nuclear-relevant systems. Deployable sensors for salt composition, redox state, particle concentrations, etc. have been created.



Electrochemical Monitoring of Salt Composition



Windowless Optical Monitoring of Composition



Automated Salt Sampling

Particulate Monitoring

FUNDAMENTAL CHEMICAL MECHANISMS CONTROLLING THE STRUCTURAL HEALTH OF MSRs

Many *thermodynamic* and *kinetic* phenomena govern the evolution of the chemistry within an MSR

- Homogeneous reactions in the bulk salt
- Heterogeneous reactions at the salt/structure interface

The rates of these reactions are controlled by a wide variety of factors

- *Chemical Kinetics*
- *Mass Transfer*
- *Charge Transfer*

The corrosion rate is ultimately controlled by the combined rates of the underlying chemical mechanisms

HOMOGENEOUS REACTIONS

Displacement Reactions
$MgCl_2 + NaOH \rightleftharpoons MgOHCl + NaCl$
$CrCl_2 + FeCl_3 \rightleftharpoons CrCl_3 + FeCl_2$

Decomposition Reactions
$MgOHCl \rightleftharpoons MgO + HCl$
$2SmCl_3 \rightleftharpoons 2SmCl_2 + Cl_2$

Dissolution/Precipitation Reactions*
$MgO \rightleftharpoons Mg^{2+} + O^{2-}$
$Mg \rightleftharpoons Mg(sol.)$

HETEROGENEOUS REACTIONS

Redox Reactions
$Fe^{2+} + 2e^- \rightleftharpoons Fe^0$
$Cr^{2+} + 2e^- \rightleftharpoons Cr^0$
$2H^+ + 2e^- \rightleftharpoons H_2$
$MgOH^+ + e^- \rightleftharpoons \frac{1}{2}H_2(sol.) + MgO(sol.)$

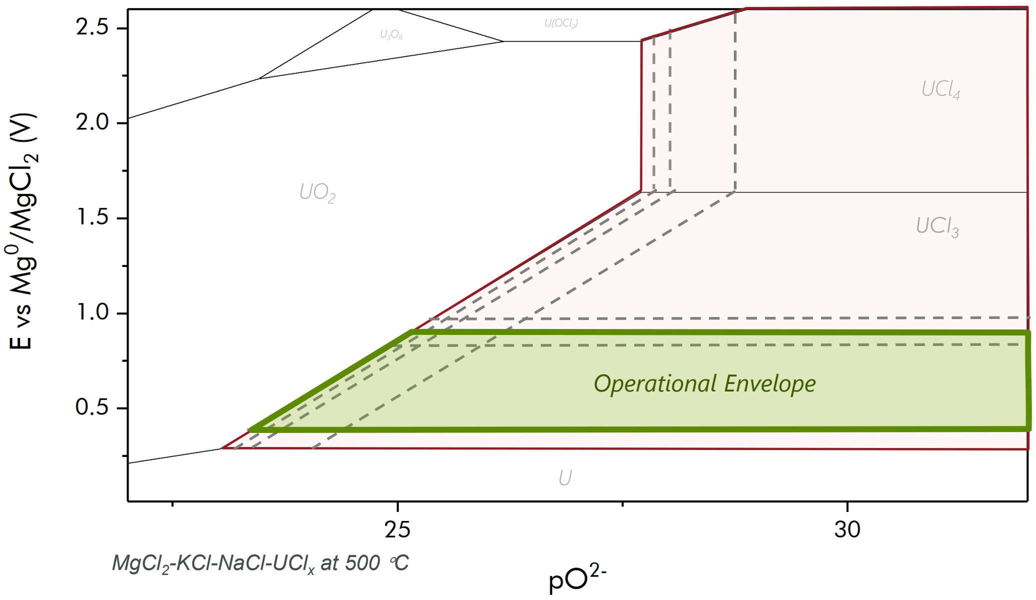
Disproportionation Reactions*
$3M^{2+} \rightleftharpoons M^0 + 2M^{3+}$

Temperature gradient driven transport
$M^0\big\|_{hot\ leg} \rightleftharpoons M^0\big\|_{cold\ leg}$

**Can occur both heterogeneously and homogeneously*

OPERATIONAL ENVELOPES FOR MSR CHEMISTRY

Regions of optimal chemical conditions can be defined in terms of the salt chemistry operational envelope. The operational envelope is constrained by structural metal oxidation at high salt redox potentials, oxide precipitation at high oxide concentrations, and various material interactions at low redox potentials.



Pourbaix diagram and associated operational envelope for Chloride-salt-cooled reactors with dissolved uranium fuel salt.

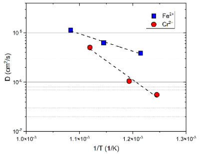
Pourbaix diagram data taken from:
Brown et al. J. Appl. Electrochem. 43 (2013)
Guo et al. J. Electroanal. Chem (2021)
Guillaumont R, Mompean FJ, NEA Amsterdam (2003)
and from recent experiments at ANL

MULTIPHYSICS SIMULATIONS FOR CHEMISTRY AND CORROSION

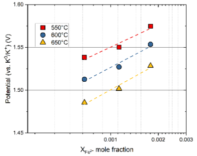
Multiphysics simulations can be used to define the allowable limits of the operational envelope for specific molten salt systems. These simulations are informed by many fundamental thermochemical and thermophysical properties that must be accurately measured.

Salt/Alloy Thermodynamic and Mass Transfer Properties

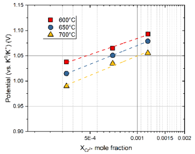
Cr^{2+}, Fe^{2+} Diffusion Coefficients.



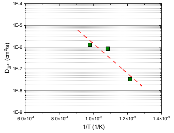
Fe^{2+}/Fe^{0} Thermodynamics



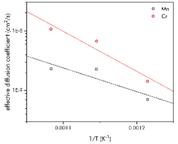
Cr^{2+}/Cr^{0} Thermodynamics



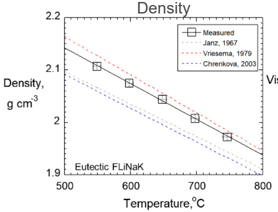
Properties of Corrosion Control Species

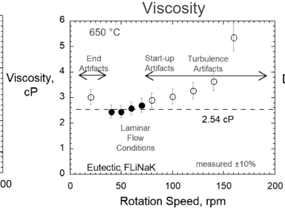


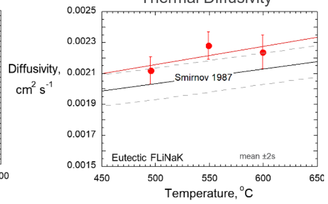
Alloy Properties



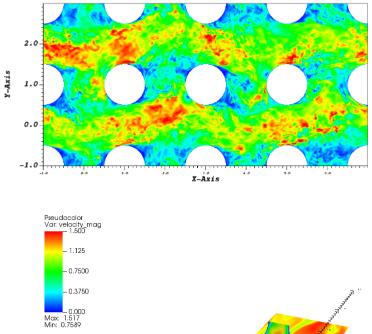
Thermophysical Properties (M. Rose, et al.)

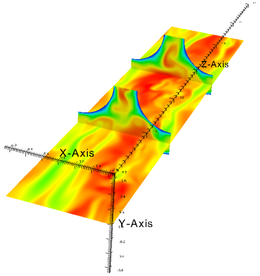


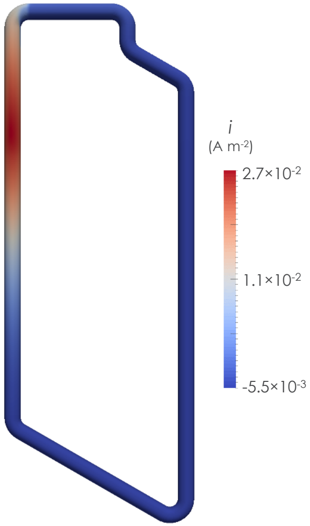




Molten Salt Chemistry Simulations using Argonne's Molten Salt Chemistry and Transport code (MOSCATO)





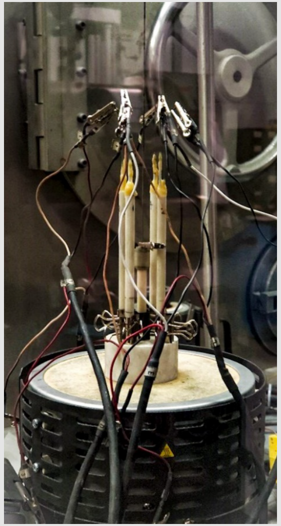


Local Cr depletion/deposition rate

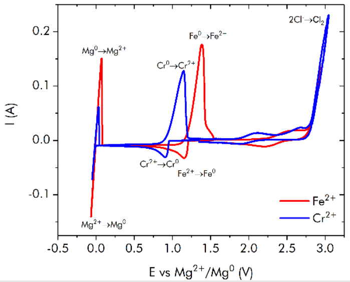
FUNDAMENTAL THERMODYNAMIC DATA FOR SALT-ALLOY SYSTEMS

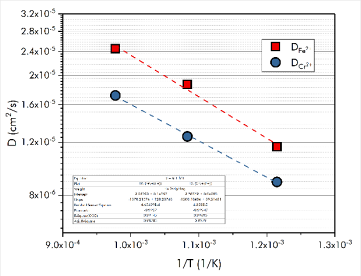
Fundamental properties for the salt and alloy are essential to properly quantify corrosion processes. Accurate thermodynamic properties and rate-controlling diffusion and reaction rate constants must be known.

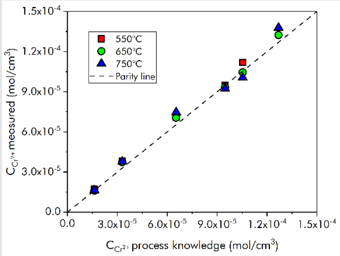
Development of Electrochemical Sensors for Corrosion Products



Fundamental Properties for Corrosion Products





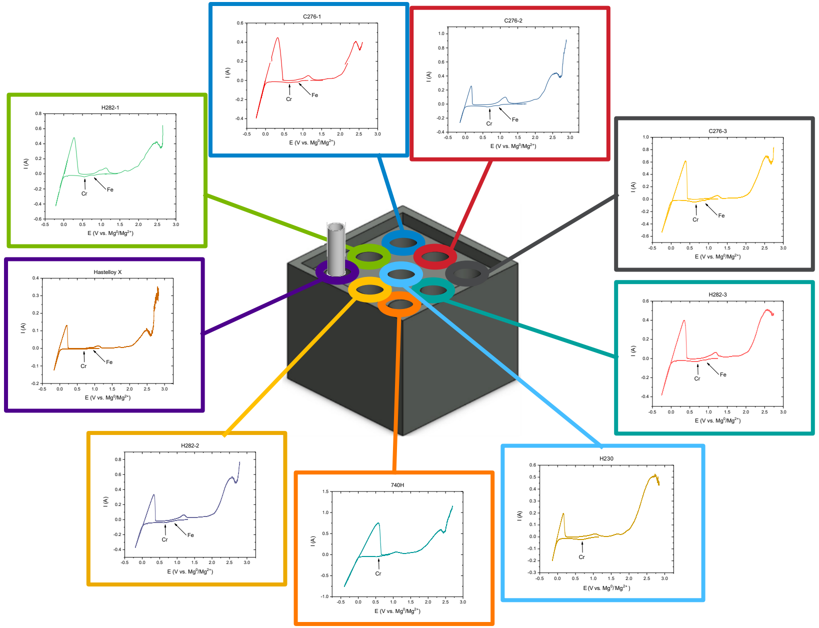


Guo et al. J Electroanalytical Chem (2021)

Typical measurements during Cr^{2+} and Fe^{2+} property testing in $MgCl_2$-KCl-NaCl

HIGH-THROUGHPUT IN SITU CORROSION ASSESSMENTS OF SALT-ALLOY SYSTEMS

- Electrochemical sensors have been deployed in many static salt-alloy systems for monitoring of corrosion.
- Many alloys can be rapidly evaluated in high-throughput static exposure tests.
- In general, the most common corrosion products of ASME code qualified alloys for MSRs are compounds containing chromium, iron, and nickel.

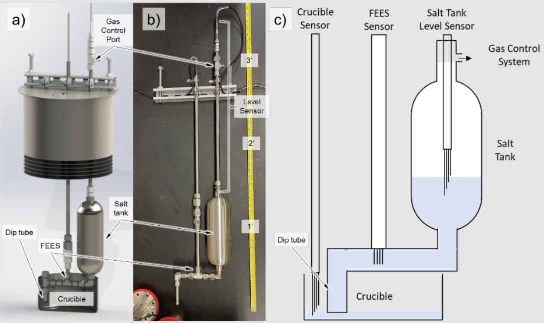


High-throughput salt capsule testing apparatus with in situ monitoring

TESTBEDS FOR FLOW SYSTEM MONITORING

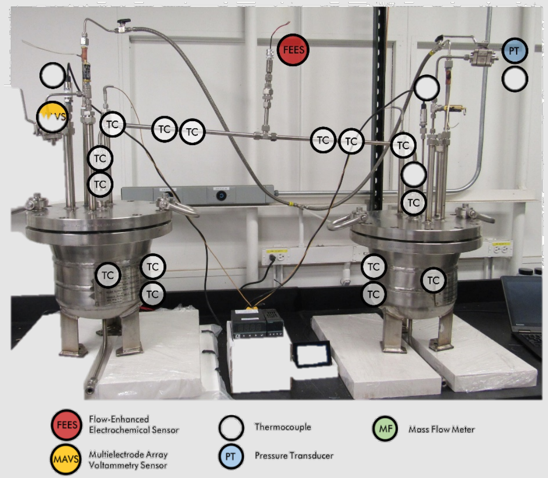
Moving beyond static testing, Argonne has developed Modular Flow Instrumentation Testbeds (MFITs) and other molten salt flow systems to support the development of sensors for in-line and on-line flow conditions.

Mini-MFIT for Coolant Salts



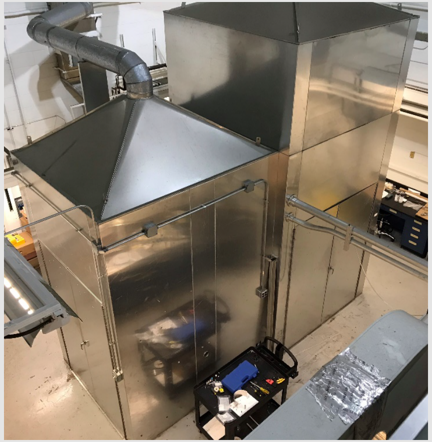
- Flow rates: 0.01 to 0.5 L/s
- Salt level sensor for making flow rate determinations.

MFIT for Fuel-Bearing Salts



- Flow rates: 0.01 to 1 L/s
- Radiological operations: >13 months of active operations in total

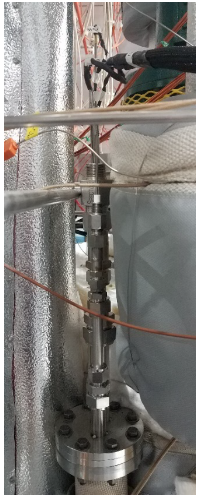
Secondary Effects Loop

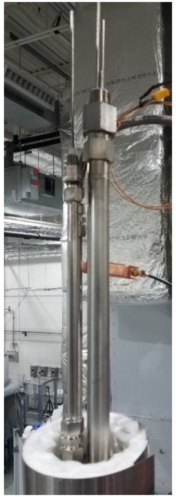


- Engineering-scale flow loop with suite of corrosion monitoring and control capabilities *(coming online soon…)*

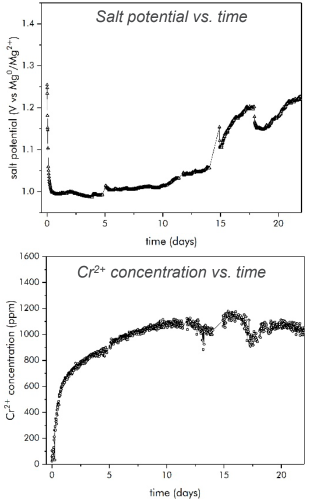
FLOW LOOP MONITORING

Argonne has successfully operated electrochemical sensors in several molten salt loops. Success is contingent on extensive signals processing and shielding measures to achieve noise-free signals in industrial-scale environments.

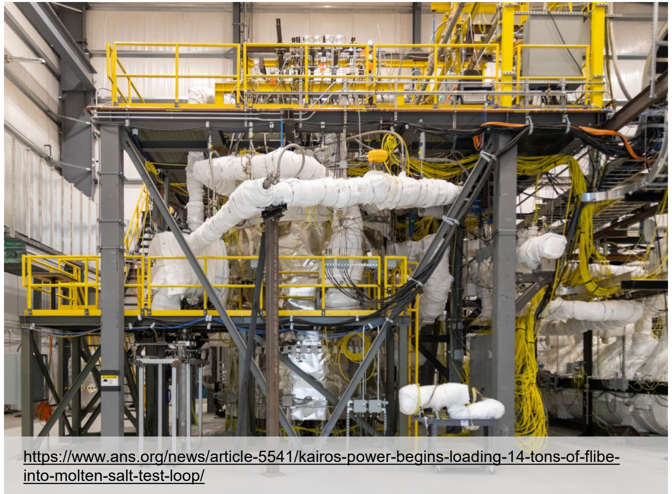


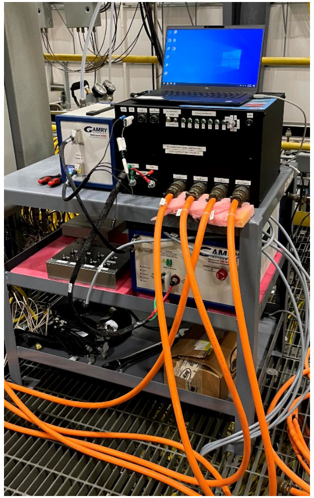


Multielectrode array sensors installed onto the ORNL FASTR loop



Typical data from monitoring of thermal convection loop



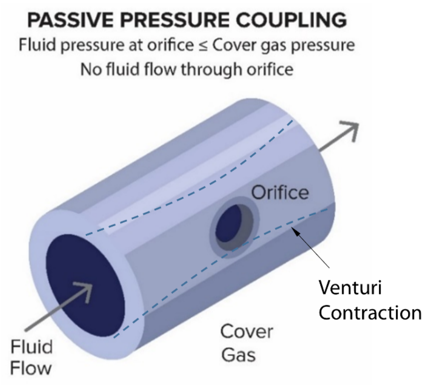


Instrumentation for distributed electrochemical sensors at the Kairos Power Engineering Test Unit

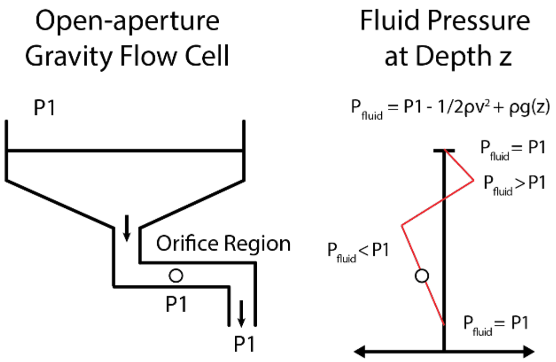
OPEN-ORIFICE GRAVITY FLOW CELL

A windowless optical cell has been designed to enable long-duration on-line spectroscopic monitoring of molten salt compositions

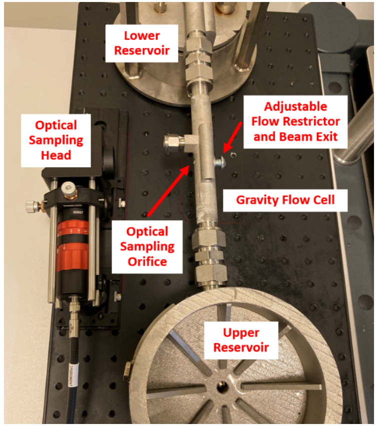
- Gravity flow and Venturi effect prevent fluid flow through holes in flow cell wall
- Orifices provide windowless optical access to fluid flowing in sampling loop



Open-orifice flow cell



Operating Mechanism



Benchtop Raman Spectroscopy Demonstration

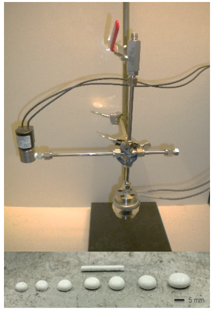
AUTOMATED SALT SAMPLE EXTRACTION

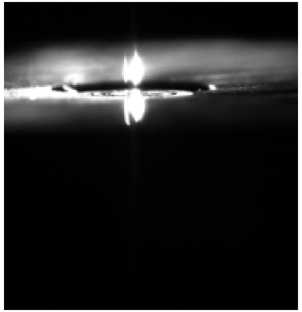
Salt sampling will be a crucial component of molten salt process monitoring and safeguards

Argonne's automated salt sampling technology uses a Helmholtz resonator chamber to generate salt droplets for off-line analysis

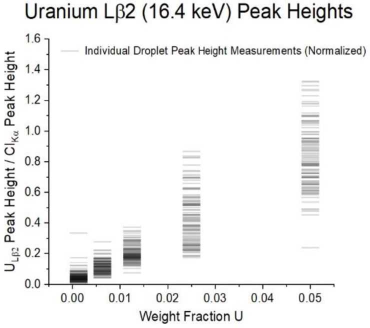
- Consistent sample generation
- Wide range of achievable sample sizes
- No moving parts (freeze valve compatible)
- Reduced containment risks compared to pressure-driven flow

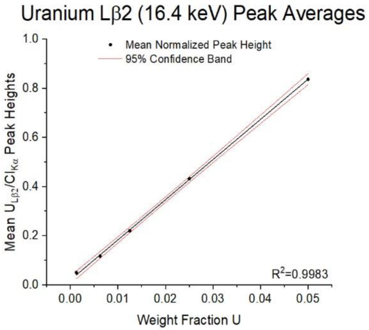
High throughput sampling eliminates errors from inhomogeneity and achieves high accuracy measurements





Batch-operated HR pneumatic salt sample generator



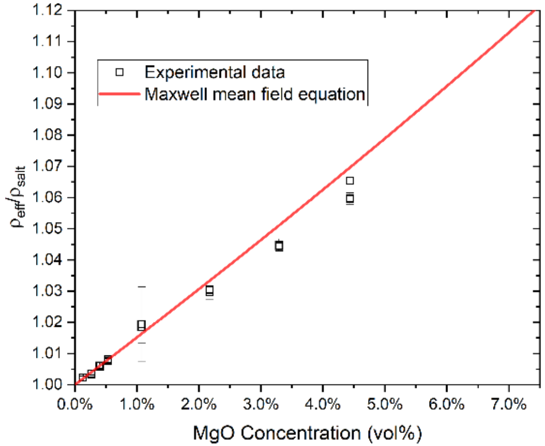


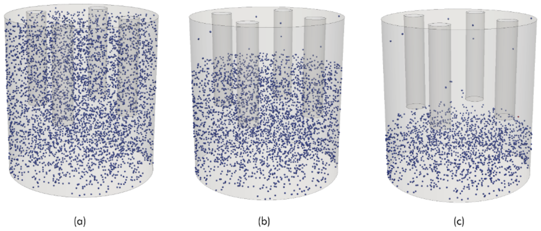
Left: XRF measurements for individual LiCl-KCl salt microsamples with uranium content ranging from 0.125 to 5.0 wt.%. *Right:* Mean peak height values for each uranium concentration.

Launiere et al. United States: N. p.10,416,045 (2019)

PARTICLE MONITORING SENSORS

- Precipitated solids including oxides and noble metals are a significant challenge for MSRs
- Argonne has developed particle monitoring technologies to elucidate the presence of solids within the process media
- The presence of particles can be a substantial challenge for operations of molten salt process equipment
  - Clogging
  - Surface dross
  - Erosion corrosion
- The sensors have been demonstrated over a range from 0.0 to 10% wt% for a variety of oxide materials



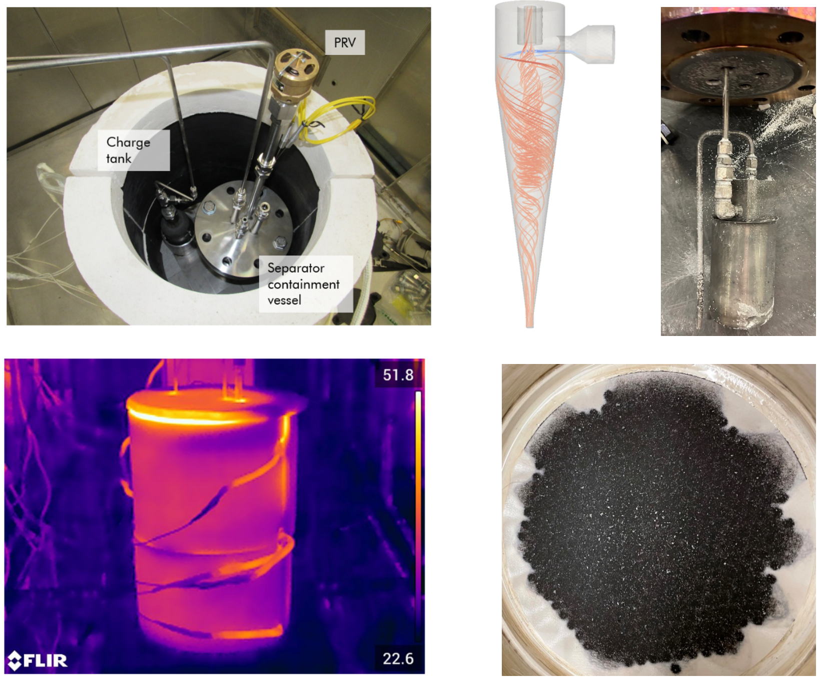


Experimentally measured effective resistivity as a function of particle loading with comparison to theoretically calculated curve (left: full concentration range, right: low concentration range, 0.0 to 1.0 wt%)

Guo et al. ANL/CFCT-23/1 (2022)

VORTEX SEPARATION OF PRECIPITATED PARTICLES

- Particle management is crucial to avoid clogging and erosion corrosion in molten salt reactors
- Generate accelerations of 1000s of g's to facilitate the removal of very small particles from the salt (< 10 micron)
- Argonne has demonstrated these separators as part of a large-scale salt purification flow sheet that includes step-wise dehydration and reactive metal contacting



Salt-particle separator installed onto transfer line under receiver vessel lid

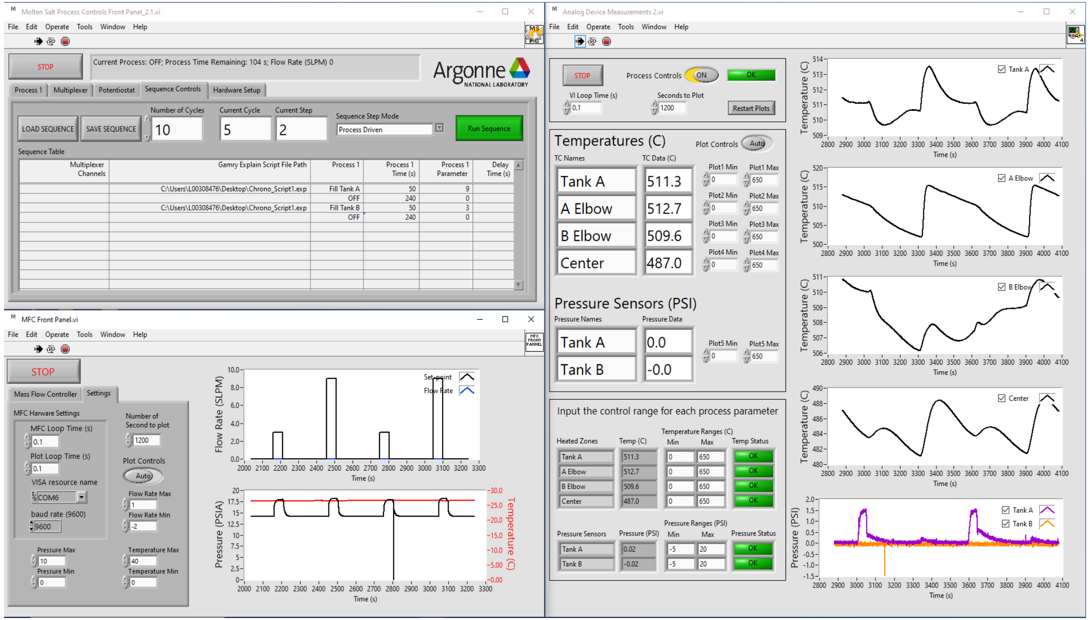
AUTOMATED MONITORING AND CONTROL

Information from multiple types of sensors will ultimately be needed to ensure long-term health of MSRs

Argonne has developed an automated monitoring and control platform called ILEX to enable multimodal monitoring of complex molten salt systems

- Facilitates repeatable flow conditions and sensor manipulation with minimal operator intervention.
  - >1,000 flowing salt experiments completed
  - >3,000 electrochemical sensor measurements recorded since January 2023
- Has been deployed for remote sensor operations at industrial partners

Argonne's ILEX Process Monitoring and Controls Software



DISCUSSION

Monitoring and characterization molten salt coolants will be a crucial to reactor structural health. The exact form that the required monitoring approaches will take will be dependent on many vendor-specific factors.

Many questions remain:

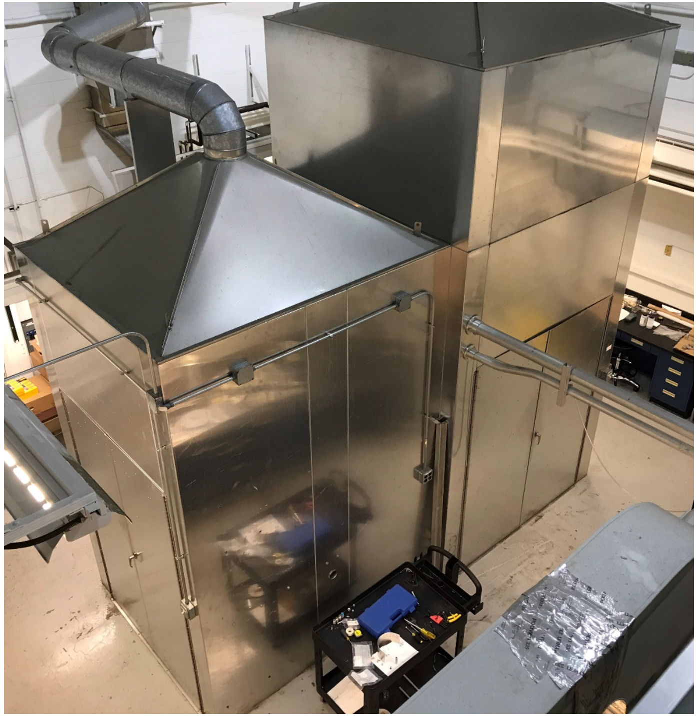
- Where will monitoring need to be done?
  - Primary & secondary coolant systems
  - Hot and cold regions
  - Specific regions of safeguards relevance
- How accurate will the monitoring tools need to be to ensure the salt is kept in the prescribed operational envelope?

CONCLUSIONS

Argonne has developed a wide variety of technologies for MSRs and associated fuel processing systems

Future work is being directed toward:

- Application of multimodal sensors to additional nuclear-relevant fluoride and chloride salts
- Development of additional spectroscopy capabilities within the windowless optical cell
- Development of purification and salt processing systems
- More forced convection studies in the Modular Flow Instrumentation Testbed and in Argonne's engineering-scale flow loop
- Development of novel process chemistries and fuel cycle approaches
- Sensor deployability and user experience improvements



Molten salt flow loop and purification system enclosures

ACKNOWLEDGEMENTS

Funding Sources:

- DOE NE-5
  - MSR Program
  - Advanced Reactor Safeguards Program
  - NEAMS
- DOE NE-4
- GAIN
- DOE EERE Solar Energy Technologies Office
- ARPA-E

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Argonne NATIONAL LABORATORY

U.S. DEPARTMENT OF ENERGY

Progress Toward Practical Sensor Solutions for Online Monitoring of Advanced Reactors

Luke Breon
Senior Technical Leader

NRC/INL Virtual Workshop on Condition Monitoring and Structural Health Management for Nuclear Power Plants
11/29/2023

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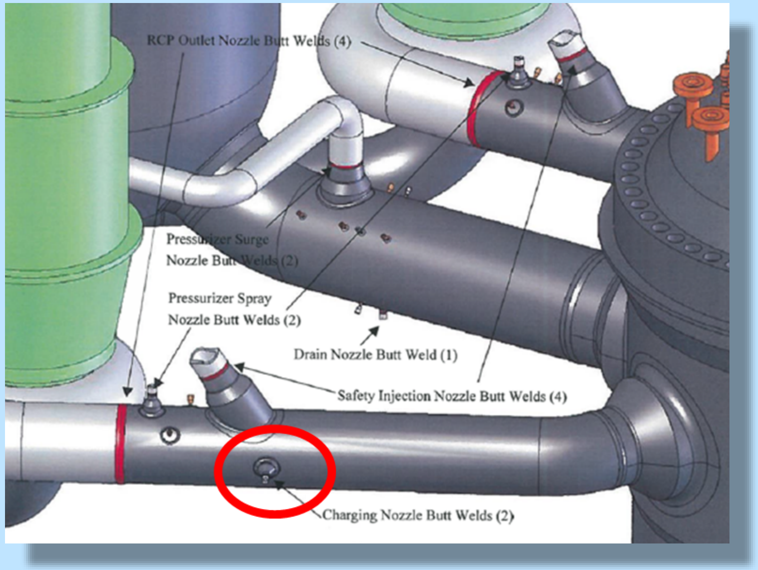
High-Temperature NDE Applications

Up to 200°C

Available with current technology

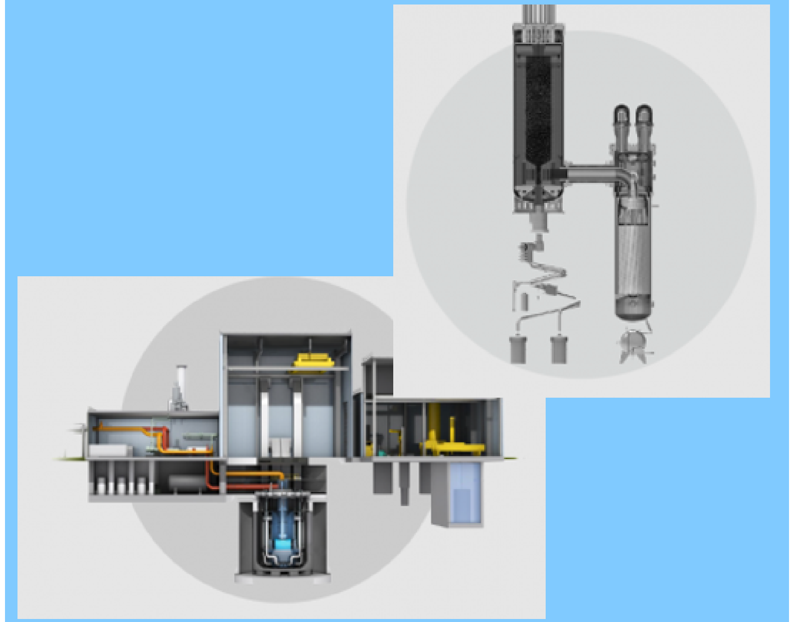
Up to 350°C – LWRS

Monitor Existing cracks:
Do I need to repair now?



~650°C and beyond –advanced reactors

Continuous operations



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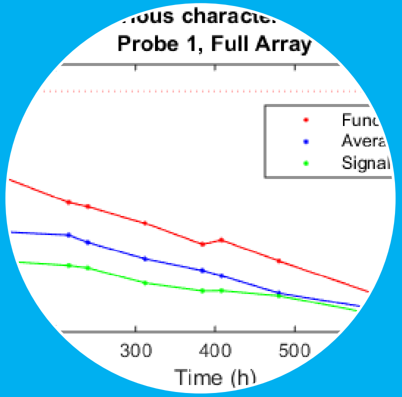
EPRI R&D for High-Temperature Sensors



Explore sensor prototypes

- Thermal limit testing
- Thermal cycling
- Long-term thermal endurance

Guide, promote advanced sensor development

- Directly installed UT for 600 C
- UT phased array for 350 C
- Ultrasonic process sensors

Adhesive mounting and coupling

- Practical bonding & coupling
- Advanced strategy testing
- Limited irradiation testing (NSUF)

Networking with stakeholder communities

- Advanced reactor developers
- Sensor technology developers
- National Labs
- Adjacent industries
- MISSION: ***Sensors***
  - Synergy, non-redundancy, road-mapping

Conducting yearly workshops since 2021

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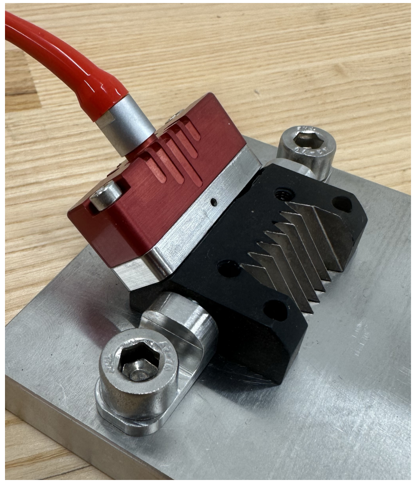
Current Testing

- Bulk-wave ultrasonics up to 1472 °F / 800 °C
- Ultrasonic Phased array up to 662 °F/ 350 °C
- Adhesives up to 700 °F/ 371 °C
- Embedded sensors in flexible circuitry 350 °F / 180 °C
- Ultrasonic process sensors
- NDE alternatives (strain-based FFS)

- High-temperature infrastructure (20+)
  - Box furnaces 2192 °F/ 1200 °C
  - Convection Ovens 932 °F/ 500 °C
  - Hotplate 1472 °F 800 °C



Phased array probe for 350 °C

Bulk Wave Probe for 550 °C

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Selections from Relevant Recent Publications

- 3002026401_Sensors for High Temperature Applications
  - coming 12/2023
- 3002026548_Sensors for Extreme Environments Wireless Dry_Cask Storage Internals Monitoring
  - 2023, free to the public
- 3002026618_The State of Sensors for Advanced Reactor Applications
  - 2023
- 3002023836_Feasibility of Monitoring Fitness for Service by External Component Strain
  - 2022 (3x follow-on efforts)
- 3002018479_Sol-Gel Spray-On Technology for High-Temperature Ultrasonic Sensors
  - 2020, free to the public

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Sensors and Robotics Workshop

Joint EPRI/INL/MIT workshop, October 10 & 11, 2023

Agenda:

- Technical presentations
  - Innovative technology
  - Current sensors
  - Non-LWR fission designs
  - ITER
  - Robotics technologies
  - Manipulators
  - Automation
- Industry open discussions

Attendees: (appx 80)

- Advanced reactor developers
- Sensor Developers
- Robotics technology providers
- Automation technologists
- Support vendors
- National Laboratories
- Universities
- EPRI

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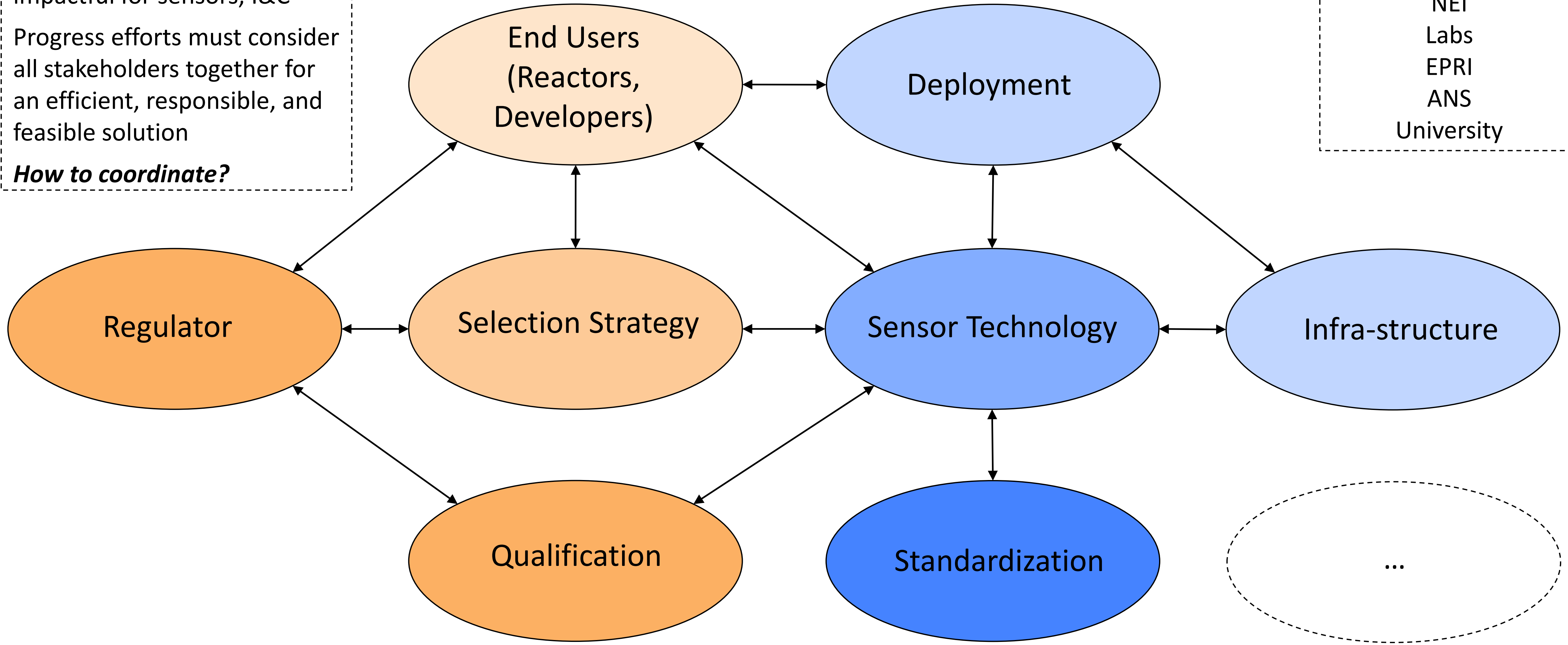
MISSION: ***SENSORs***

Sensor Experts Network to Support Operation of new Reactors

Many stakeholder groups are impactful for sensors, I&C

Progress efforts must consider all stakeholders together for an efficient, responsible, and feasible solution

How to coordinate?



Support Groups:
NEI
Labs
EPRI
ANS
University

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SENSORs Mission & Platform

- Provide technical information exchange among stakeholder groups
  - Raise technical questions and establish holistic context
  - Identify common challenges
- Strategize major development directions
  - Explore potential solution options
  - Solicit buy-in from adjacent stakeholders
  - Combine development goals into synergistic direction
  - Identify standardization opportunities
- Maintain sensors roadmap
  - Touch-base on progress, emerging needs & information
  - Follow technical developments, update gap closure
  - Focus development on the most responsible approach

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Radiation-Endurance Advanced Sensor Systems for Online Monitoring in Nuclear Power Plants

Virtual Workshop on Condition Monitoring and Structural Health Management for Nuclear Power Plants

November 29, 2023

Dan Xiang, Xi Gong, Dheeraj Velicheti, Yizhong Wang, Berkin Uluutku, Hunter Jones, Paolo Lami, Michael Whiteman and Adam Harwood

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Motivation

DOE seeks advanced sensors and sensing technologies, capable of surviving in substantial radiation fields for online monitoring and control of nuclear power plants, and other nuclear applications with demonstrated

- Accuracy
- Reliability
- Resilience
- Ease of replacement and upgrade
- Directly support existing power reactors, test reactors, advanced reactors, and other similar systems.

Our Solution

Radiation Endurance Ultrasonic Transducer (REUT) based sensor systems that sustain high-temperature and radiation environments for nuclear power plants. *<u>REUT design utilizes selected radiation resilient materials, material engineering and harnessing knowledge of acoustic propagation in materials.</u>*

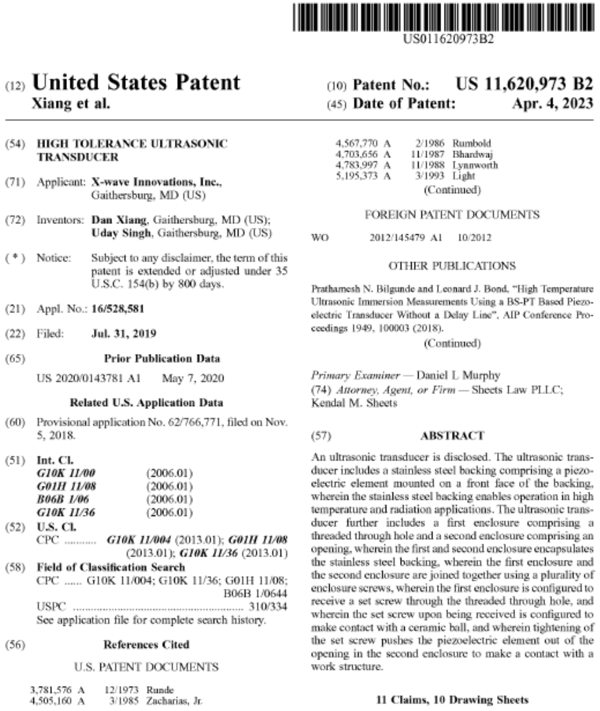
REUT SENSOR TECHNOLOGIES DEVELOPMENT

- REUT sensor design/development
- REUT-based sensor technologies development for nuclear reactors
  - Temperature sensor
  - Multi-point temperature sensor
  - Fluid viscosity sensor
  - Flow rate sensor
  - Liquid level sensor
  - **Structural health monitoring (AE sensor & GW sensor)**
  - **Wireless REUT embedded sensor**
- Single-channel and multi-channel data acquisition development
- Application software and signal processing algorithms development
- Machine learning toolbox development

* DOE SBIR Phase II programs (grant # DE-SC0020019 and DE-SC0021863)

REUT DESIGN & DEVELOPMENT

- Designed, developed and assembled REUT-I and REUT-II prototypes using stainless steel, ceramics and high-temperature piezo element ($LiNbO_3$).
- Designed, fabricated and tested multiple REUT metal backing designs.
- Demonstrated REUT to generate and detect acoustic/ultrasonic signals of different frequencies.
- Demonstrated REUT performance at high-temperature up to 1,000 ^oC.
- Demonstrated REUT performance subjecting to thermal cycles up to 800 ^oC.
- Demonstrated REUT performance subjecting to Gamma irradiation 700 Mrad and fast neutron 10^{15} n/cm^2 for 7 hours



US011620973B2

(12) **United States Patent**
Xiang et al.

(10) **Patent No.: US 11,620,973 B2**
(45) **Date of Patent: Apr. 4, 2023**

(54) **HIGH TOLERANCE ULTRASONIC TRANSDUCER**

(71) Applicant: **X-wave Innovations, Inc.**, Gaithersburg, MD (US)

(72) Inventors: **Dan Xiang**, Gaithersburg, MD (US); **Uday Singh**, Gaithersburg, MD (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 800 days.

(21) Appl. No.: **16/528,581**

(22) Filed: **Jul. 31, 2019**

(65) **Prior Publication Data**

US 2020/0143781 A1 May 7, 2020

Related U.S. Application Data

(60) Provisional application No. 62/766,771, filed on Nov. 5, 2018.

(51) **Int. Cl.**
G10K 11/00 (2006.01)
G01H 11/08 (2006.01)
B06B 1/06 (2006.01)
G10K 11/36 (2006.01)

(52) **U.S. Cl.**
CPC ***G10K 11/004*** (2013.01); ***G01H 11/08*** (2013.01); ***G10K 11/36*** (2013.01)

(58) **Field of Classification Search**
CPC G10K 11/004; G10K 11/36; G01H 11/08; B06B 1/0644
USPC 310/334
See application file for complete search history.

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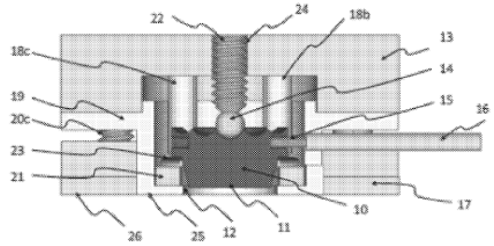
(Continued)

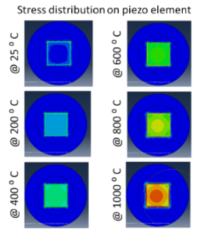
Primary Examiner — Daniel L Murphy
(74) *Attorney, Agent, or Firm* — Sheets Law PLLC; Kendal M. Sheets

(57) **ABSTRACT**

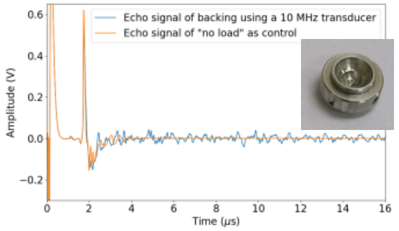
An ultrasonic transducer is disclosed. The ultrasonic transducer includes a stainless steel backing comprising a piezoelectric element mounted on a front face of the backing, wherein the stainless steel backing enables operation in high temperature and radiation applications. The ultrasonic transducer further includes a first enclosure comprising a threaded through hole and a second enclosure comprising an opening, wherein the first and second enclosure encapsulates the stainless steel backing, wherein the first enclosure and the second enclosure are joined together using a plurality of enclosure screws, wherein the first enclosure is configured to receive a set screw through the threaded through hole, and wherein the set screw upon being received is configured to make contact with a ceramic ball, and wherein tightening of the set screw pushes the piezoelectric element out of the opening in the second enclosure to make a contact with a work structure.

11 Claims, 10 Drawing Sheets



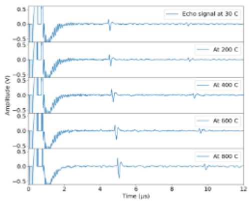


FEA simulation



Backing development

Assembly development



Testing

Improvement

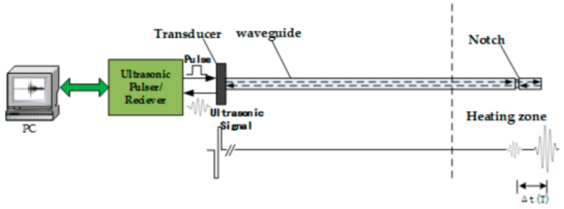
US Patent 11,620,973 "High Tolerance Ultrasonic Transducer"

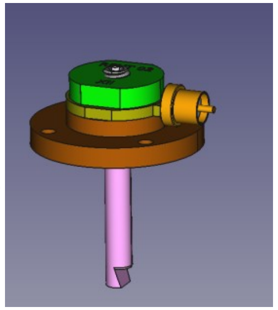
XII Proprietary Information

X-WAVE INNOVATIONS, INC.
Make state-of-the-art obsolete

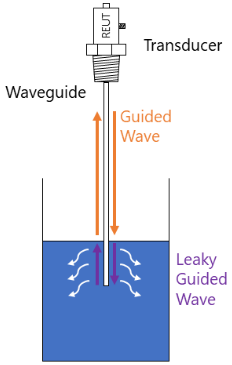
REUT SENSOR SYSTEMS/APPLICATIONS DEVELOPMENT

Temperature sensors

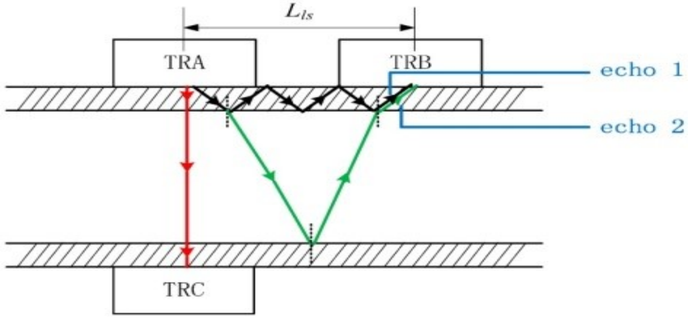




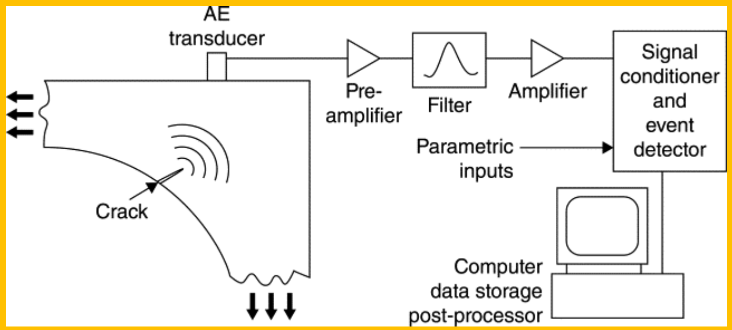
Fluid viscosity and level sensors



Fluid temperature, pressure and flow sensors



Structural health monitoring sensors



XII Proprietary Information

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REUT Structural Health Monitoring (SHM)

Passive AE SHM :

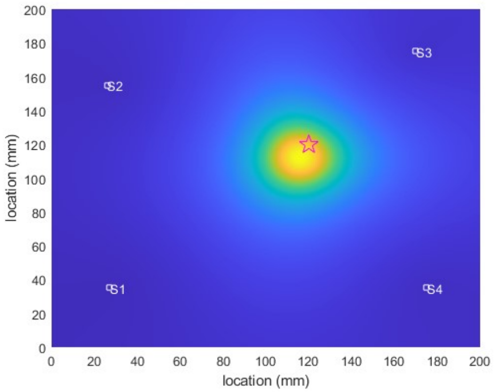
- REUT sensors with ¾″-8 thread mounting
- $LiNbO_3$ and ZnO piezo-element were used
- Signal processing technique were developed for AE monitoring and source localization
- AE sensing and localization were tested for temperatures up to 150ºC

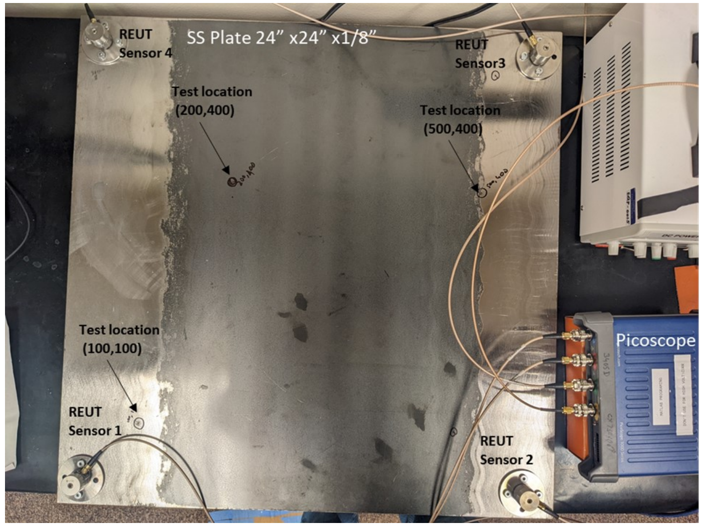
Active Guided Wave SHM :

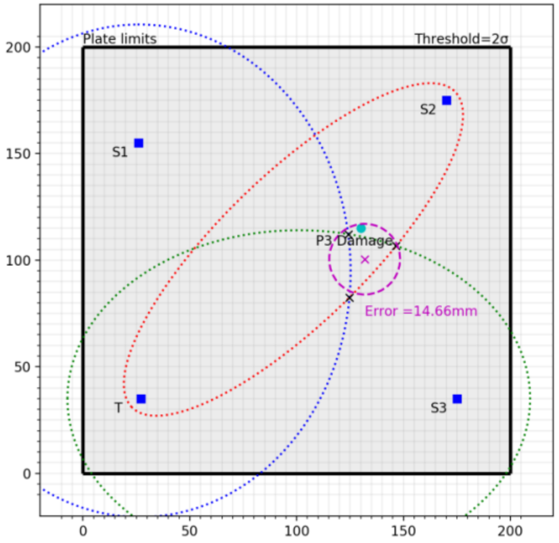
- Same AE setup for GW SHM
- Signal processing techniques were developed to detect changes in the structure and determine damage location.

Benefits:

- Combination of GW and AE sensing for active and passive SHM
- Continuous AE monitoring and damage localization at high temperatures
- Periodic GW SHM to verify the damage and its location
- Easy to install and operate







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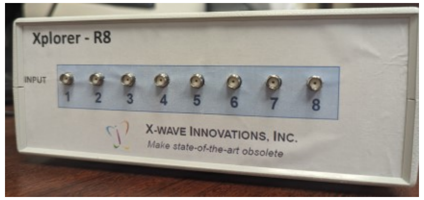
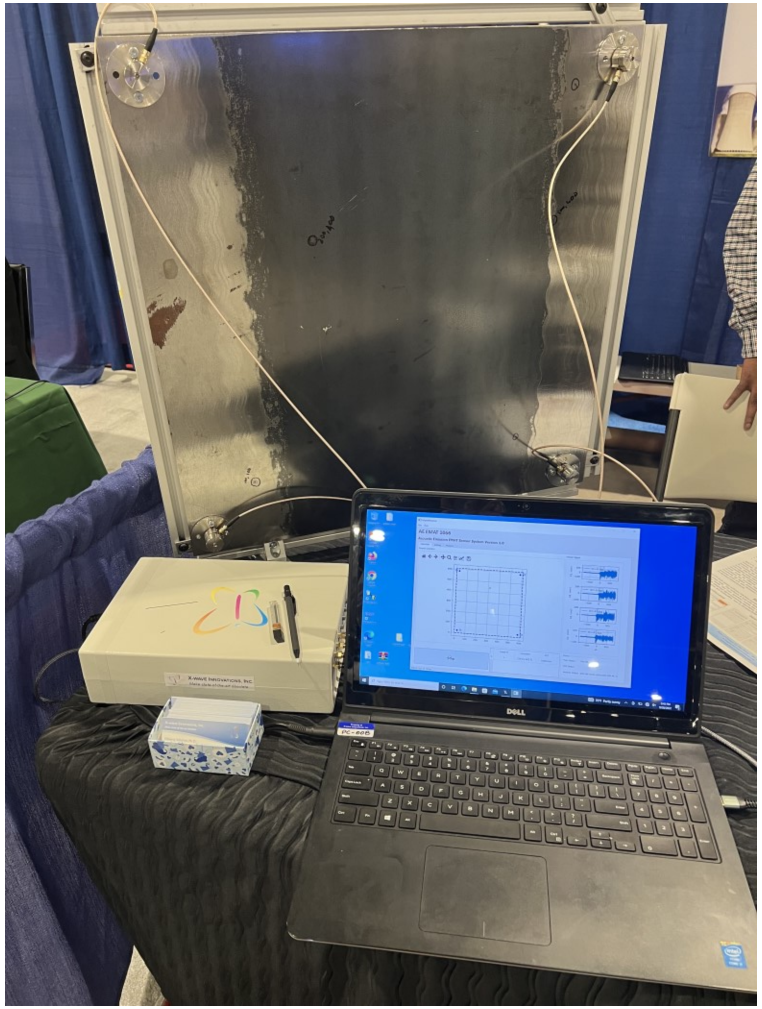
Multi-Channel Data Acquisition Hardware

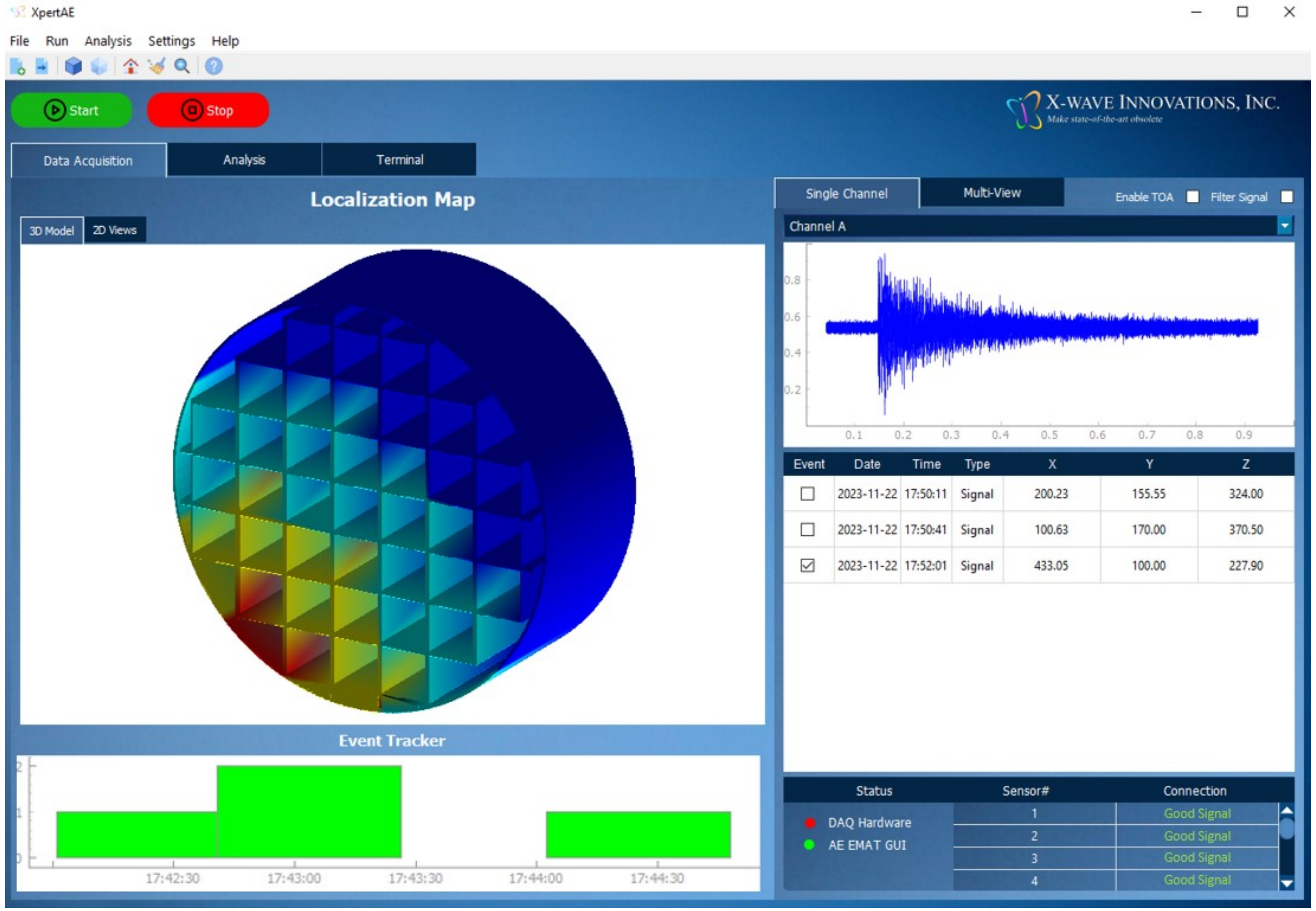
- Passive AE model (Xplore-8R)
- Passive and Active Dual model (Xplore-8TR)
- Support up to 8 transducers
- Up to 8 transducers in receiving mode concurrently
- Transmission mode in Xplore-8TR support up to 8 transducers in sequentially
- Low Noise with EMI Shield and Input / Output Isolation
- Software controlled gain adjustment of receiving amplifier
- Either negative pulse up to 1MHz or arbitrary waveform generator (AWG) up to 1MHz
- On-board high voltage power module and high voltage amplifier
- Computer control of DAQ settings via USB



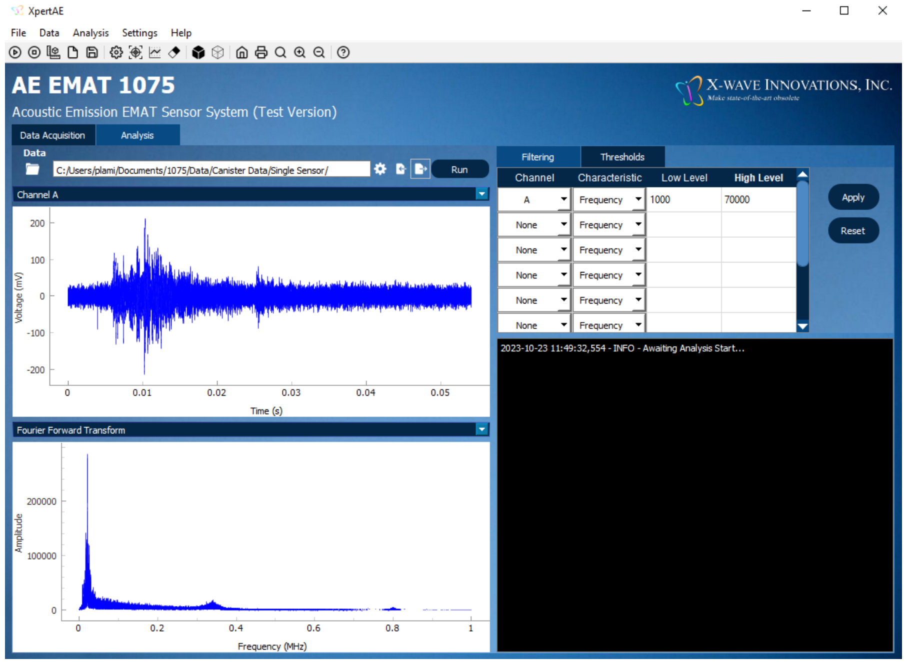


Application Software Development

- SHM software with maximum likelihood estimation provides accurate estimation of damage/defect location.
- Signal processing algorithm automatically estimates the ultrasonic velocity.
- Artificial Intelligence/Machine Learning (AI/ML) toolbox incorporated in the software is able to distinguish true AE from other acoustic events.

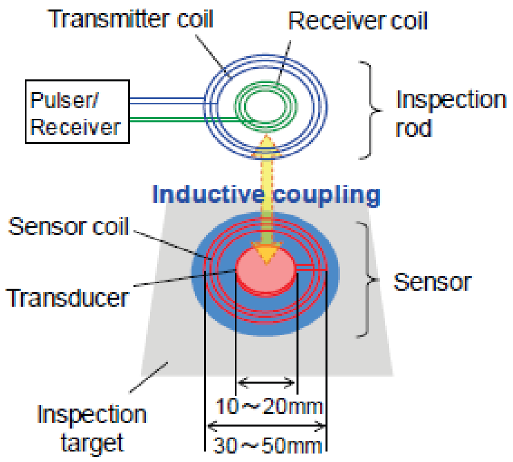


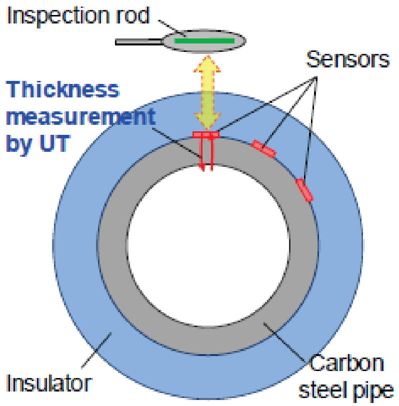
Field Test of CISCC in Spent Nuclear Fuel Dry-Storage Canister

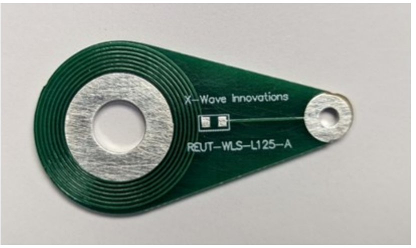


Wireless REUT Development

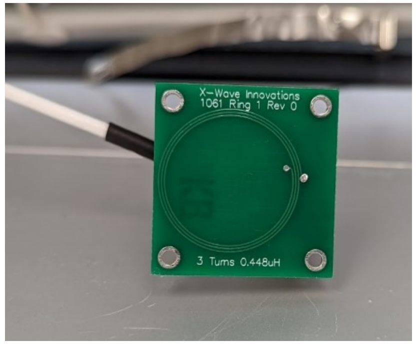
- Developed wireless REUT scheme to eliminate permanent wire connections to sensors
- Reduce sensor system maintenance, especially electrical connections failure
- Wireless wall thickness or material degradation monitoring applications
- Can be adopted for the other REUT applications of temperature, viscosity and GW SHM applications



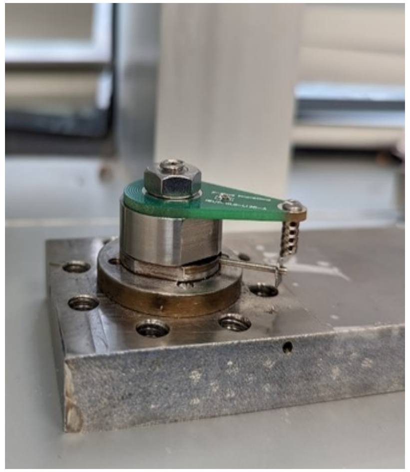


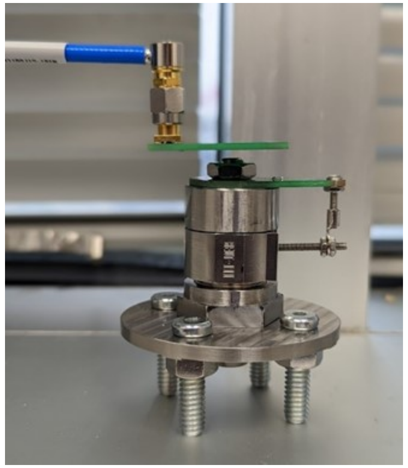


(a) Sensor coil



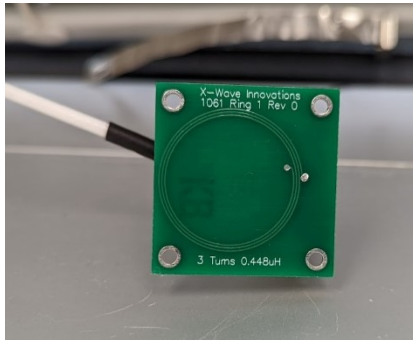
(b) Interrogator coil



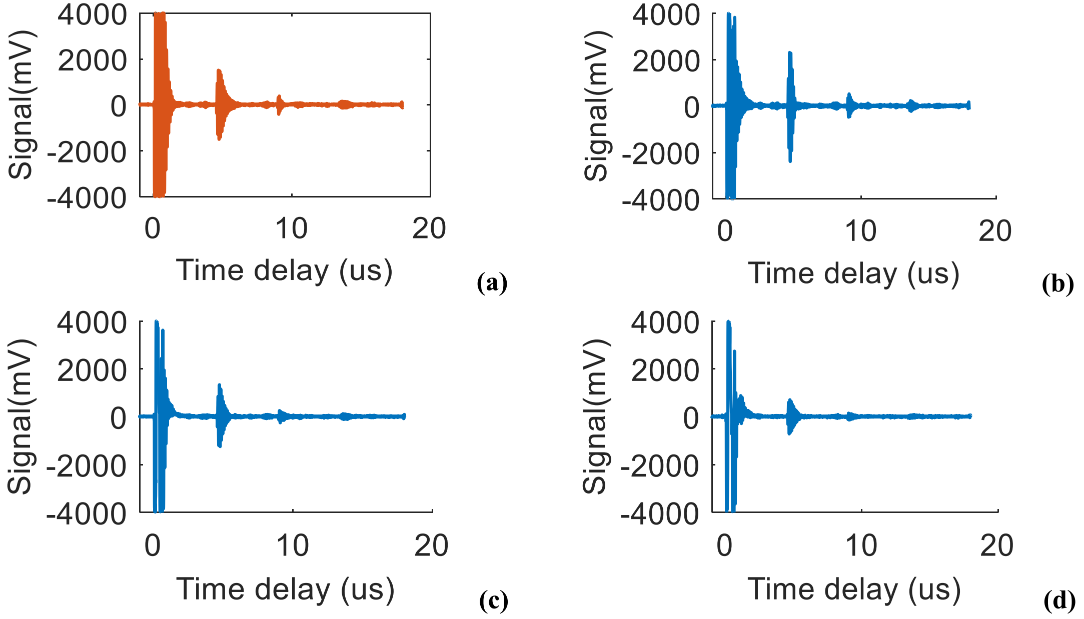


Pending US Patent #63,460,833

Fine tune pulser/receiver coil parameters



Coil 1	Coil Shape	Ring	Inductance	0.8uH
	Coil Diameter	25.4	Resistance	0.084 Ohm
	Number of turns	3	Impedance @ 1kHz	0.084 Ohm
Coil 2	Coil Shape	Ring	Inductance	1.52 uH
	Coil Diameter	25.4	Resistance	0.091 Ohm
	Number of turns	5	Impedance @ 1kHz	0.172 Ohm
Coil 3	Coil Shape	Ring	Inductance	3.2 uH
	Coil Diameter	25.4	Resistance	0.127 Ohm
	Number of turns	8	Impedance @ 1kHz	0.128 Ohm
Coil 4	Coil Shape	Ring	Inductance	4.95 uH
	Coil Diameter	25.4	Resistance	0.145 Ohm
	Number of turns	10	Impedance @ 1kHz	0.148 Ohm



Wirelessly interrogated pulser echo signals captured with interrogation coils in the table: a) coil 1, b) coil 2, 3) coil 3 and 4) coil 4

This wireless REUT sensor system was tested to measure the thickness of two specimens, and an accuracy of 0.005 inches (0.127mm) was achieved.

Single-channel Data Acquisition Device Development

- X-1061 PR
  - Negative pulse: 400 Vp-p max
  - Low-noise amplification
  - Receiver gain: 60dB
- X-1067 PR
  - Adjustable square pulse width
  - Pulse amplitude: 100, 200, 300, 400 Vp-p
  - Operation frequency range: 100KHz – 20MHz
  - Receiver gain: 60dB

Rev. 0

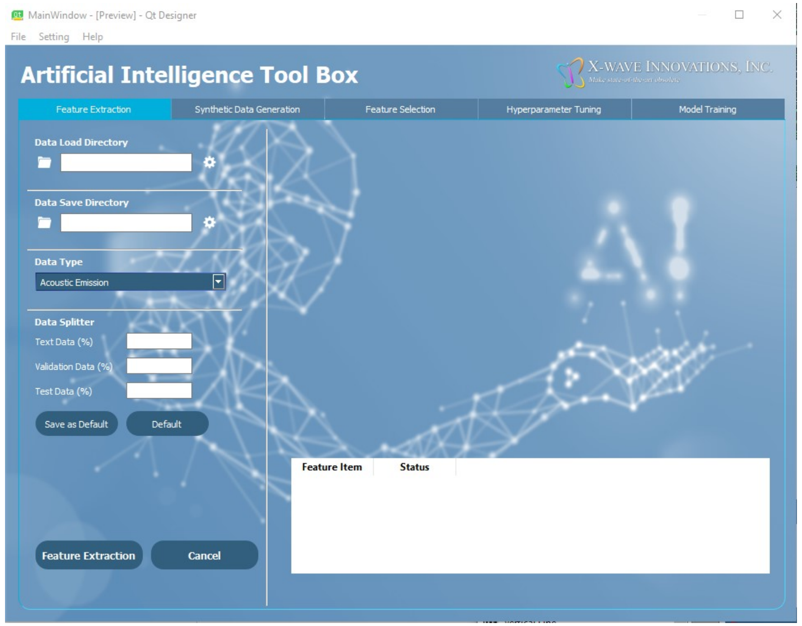
Rev. 1

Both X-1061PR and X-1067 PR can be digitally controlled through a USB port

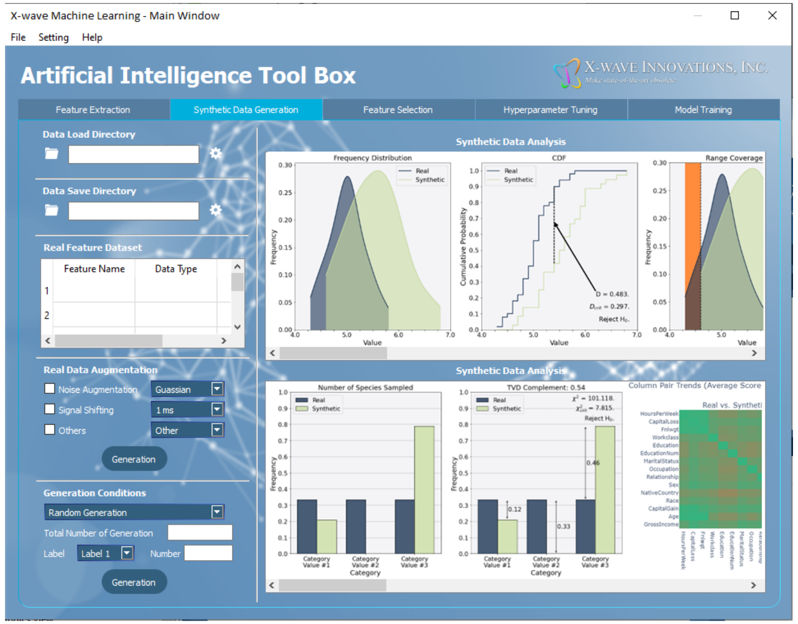
Artificial Intelligence and Machine Learning Toolbox

XII Machine Learning Toolbox:

- **Feature Extraction**
  - Waveform (AE/non-AE) signal feature analysis
- **Synthetic Data Generation**
  - Generate synthetic data for expand dataset and improve ML model performance
- **Feature Selection**
  - Increase model training efficiency and optimize the workflow for following modules
- **Hyperparameter Tuning**
  - Tuning parameters for different ML models and selecting models with better performance on a partial dataset
- **Model Training**
  - Training and validating the selected model with full dataset, provide final ML models for end users



Feature Extraction



Synthetic Data Generation

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Make state-of-the-art obsolete

Take Aways

- The REUT design allows to continuously operate at high-temperature (e.g., 800ºC or higher) and high-irradiation environments of nuclear reactors
- REUT sensor systems are developed and demonstrated for online structural heath monitoring:
  - Passive AE detection of corrosion, cracking, creep, etc.
  - Active GW detection and quantification of defect size, location, etc.
  - Wireless, embedded sensing wall thickness and material property degradation, etc.
- Single-channel and multi-channel data acquisition devices are developed for REUT sensor systems
- Applications software packages with signal processing algorithms are developed for REUT online monitoring applications
- AI/ML toolbox is developed to enhance and expand REUT online monitoring capabilities

XII Proprietary Information

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- Dr. Susan White at Ohio State University Nuclear Reactor Lab (OSU/NRL) for the neutron irradiation test
- Dr. Luke Breon at Electrical Power Research Institute (EPRI) for durability and longevity tests
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