U.S.NRC
United States Nuclear Regulatory Commission
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PROCEEDINGS OF THE WORKSHOP ENABLING TECHNOLOGIES FOR DIGITAL TWIN APPLICATIONS FOR ADVANCED REACTORS AND PLANT MODERNIZATION

Virtual Workshop
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Research Information Letter
Office of Nuclear Regulatory Research

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EXECUTIVE SUMMARY

The Office of Nuclear Regulatory Research (RES) at the U.S. Nuclear Regulatory Commission (NRC) has initiated a future focused research project to assess the regulatory viability of digital twins for nuclear power plants. The objectives of this project are to:

- Understand the current state of the technology and potential applications for the nuclear industry,
- Identify and evaluate technical issues that could benefit from regulatory guidance, and
- Develop infrastructure to support regulatory decisions associated with digital twins.

As a follow-on to the workshop hosted in December 2020 (ML21083A132), RES sponsored the Enabling Technologies for Digital Twin Applications for Advanced Reactors and Plant Modernization 2021 Online Workshop. The workshop was hosted by Idaho National Laboratory (INL) in collaboration with Oak Ridge National Laboratory (ORNL), the Department of Energy's (DOE) Advanced Research Projects Agency-Energy (ARPA-E), and the Electric Power Research Institute (EPRI) and was held September 14-16, 2021.

The 3-day workshop was composed of five technical and panel sessions with 29 presenters from a wide range of national and international organizations, including universities, national laboratories, government agencies, nuclear vendors, nuclear industry, advanced reactor developers, and digital twin developers. With 324 participants from across the globe, the workshop provided a forum for nuclear industry and digital twin stakeholders to discuss the application of digital twins and digital twin enabling technologies such as advanced sensors and instrumentation, data analytics, machine learning and artificial intelligence in the current light water reactor (LWR) fleet and advanced reactor designs. The workshop also included an overview of the next steps toward regulatory realization of digital twins in the nuclear industry.

The workshop had two main purposes: (1) to review and exchange information on the current applications of digital twin enabling technologies, and (2) to identify necessary steps toward regulatory realization of digital twins. The workshop sessions covered the following topics: industry applications to digital twins in nuclear, advanced sensors and instrumentations, use cases of digital twin enabling technologies in nuclear power plants, digital twin enabling technologies in advanced reactor applications, and steps toward regulatory realization of digital twins.

On the first day of the workshop, Tuesday, September 14, 2021, Mr. Ray Furstenau, Director of RES, opened the workshop with introductory remarks and moderated a panel session on industry applications of digital twins in nuclear and Dr. Hasan Charkas from EPRI moderated a technical session on advanced sensors and instrumentations. On the second day of the workshop, Wednesday, September 15, 2021, Dr. Gene Carpenter representing Advanced Research Projects Agency - Energy (ARPA-E) moderated a technical session on use cases of digital twins enabling technologies in nuclear power plants and Ms. Angela Buford, Office of Nuclear Reactor Regulation (NRR), NRC, moderated a technical session on digital twin enabling technologies in advanced reactor applications. On the third day of the workshop, Thursday, September 16, 2021, Mr. Eric Benner, NRR, moderated a panel session on steps toward regulatory realization of digital twins and delivered the workshop closing remarks.

The following are some major takeaways from the workshop:

Technical Challenges/Opportunities

- The nuclear industry and national laboratories have demonstrated interest and are pursuing the use of digital twin technologies and have realized advanced capabilities in preventive maintenance optimization, work order data analysis, anomaly detection and diagnosis, and real-time radiation monitoring.

- There is significant interest/effort in the development of advanced sensor technologies and applications including wireless communication, multi-modal sensing, condition-based monitoring and maintenance, and operation in harsh environments, especially those introduced by advanced reactor designs (e.g., extreme temperature, radiation, corrosivity).

- Many advanced reactor developers are designing plants integrated with digital twins (DTs) throughout their lifecycle to facilitate improved decision making and greater operational flexibilities (e.g., potential dynamic operating envelope).

- Challenges exist in the following areas: real-time reduced-order or surrogate models, data production and integration, virtual prototyping, autonomous control, and sensor requirements.

Regulatory Challenges/Opportunities

- There are three main categories of potential DT use: 1) use by industry for inherent benefits (e.g., improved design, construction, operations and maintenance), 2) use by industry as a tool for regulatory compliance (e.g., licensing submittals, safety analysis), and 3) use as an NRC regulatory tool (e.g., shared source of plant information, enabler of iterative design approvals and just-in-time regulation).

- Industry and regulators need to develop agreed upon guidance and frameworks for acceptance of DT applications that is consistent, explicit, and enables the use of DTs as an additional avenue for meeting the intent of existing regulations.

- One approach to building confidence in DT technology – an important aspect for acceptance and adoption of DTs – is pioneering DT applications with non-safety components or systems and demonstrating acceptable performance prior to safety-related applications.

- DTs have the potential to enhance NRC inspection activities, including automated regulatory compliance testing and on-demand access to high-fidelity plant information.

All presentations slides from this workshop are available in the NRC's Agencywide Documents Access and Management System, under Accession No. ML21342A121.

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1 DAY 1 PRESENTATIONS

1.1 Panel Session 1: Industry Applications of Digital Twins in Nuclear

In this panel, representatives from the nuclear industry provided a perspective on how digital twins technology has been implemented or may be implemented. The panel provided insights of the potential challenges and benefits of the identified digital twins enabling technologies and introduced additional important enabling technologies. Potential industry strategies for accommodating these technologies within the nuclear lifecycle and any new competencies or technical disciplines needed to support digital twin technologies were discussed as well.

Participants on this session presented the following initiatives/perspectives about the industry applications of digital twins in nuclear:

- Xcel Energy discussed their Cap Intelligent Advisor (artificial intelligence (AI) and machine learning (ML)) and Digital Ops Factory programs which facilitates the search, entry, and analysis of data.
- The Electric Power Research Institute (EPRI) presented an update of their ongoing project that aims to explore benefits, challenges, and potential use cases for advanced reactors and will establish industry guidelines, best practices, and recommendations for implementing digital twins in advanced reactor life cycle management.
- Westinghouse Electric Company discussed practical aspects that can be implemented with the correct use of the digital twin technologies.
- Exelon Corporation presented their remote monitoring project. This initiative uses wireless sensors to support plant monitoring.
- The Department of Energy (DOE) Advanced Research Projects Agency-Energy (ARPA-E) presented several initiatives that demonstrate that the use of digital twin enabling technologies can decrease operations and maintenance (O&M) labor cost and map temperatures of reactors components, among other benefits.
- Metroscope introduced their software that diagnosed equipment problems for all types of plant auxiliary systems.

The presentations slides for Day 1 can be found here and in the Agency Documents Access and Management System (ADAMS) under ML21342A122.

Presentations

1.1.1 Innovation Journey to a Brighter Future

Patrick Burke, Vice President of Nuclear Strategy
Xcel Energy

Presentation Overview: This presentation described several initiatives that Xcel Energy is working on to implement the use of ML/AI to facilitate the search, entry, and analysis of operational data. Other potential efforts were discussed.

1.1.2 EPRI's Digital Twin Related Activities for Nuclear Applications

Craig Stover, Program Manager Advanced Nuclear Technology
EPRI

Presentation Overview: During this presentation EPRI discussed in more details the four top innovation areas of interest at this moment. Those are ML and big data, reliable data sharing, digital twinning, and advanced manufacturing. All these areas have great potentials for several possible use cases in the existing and next generation of nuclear power plants.

1.1.3 Westinghouse Perspectives

Scott Sidener, Consulting Engineer, Digital Innovation
Westinghouse Electric Company

Presentation Overview: There was no presentation from Westinghouse. Scott Sidener discussed the company's perspectives on digital twin technologies.

1.1.4 Exelon Nuclear Innovation Projects Overview

Rick Szoch and Tim Alvey
Exelon Corporation

Presentation Overview: Exelon Corporation presented their Innovation Culture and Digital Transformation initiatives. Remote monitoring is their main effort currently, and this project creates a new wireless infrastructure that provides a method to utilize wireless sensors.

1.1.5 ARPA-E GEMINA Portfolio and Digital Twins

Charalampos Andreades, Technology to Market Advisor
ARPA-E

Presentation Overview: ARPA-E introduced the Generating Electricity Managed by Intelligent Nuclear Assets (GEMINA) program and highlighted benefits that digital twins can provide to the industry, including the enabling technologies/capabilities. Dr. Andreades also discussed initiatives that are utilizing digital twin-related technologies.

1.1.6 Digital Twin Monitoring for Advanced Reactors and Plant Modernization

Aurélien Schwartz
Metroscope

Presentation Overview: Metroscope presented their software, which consists of a trusted and reliable digital twin-based program that can diagnose equipment problems for all types of plant auxiliary systems.

1.2 Session 2: Advanced Sensors and Instrumentations

This session includes presentations focusing on advanced sensors and instrumentation with an emphasis on digital twin applications. The presentations demonstrated the development of new sensors and the greater digital integration of existing sensors. A recurring focus included continuous monitoring control system integration. There is a general goal to move to condition-based monitoring. It was noted that advanced sensors still require testing in the more extreme environments found in advanced reactors. Finally, it was shown how virtual sensors with a digital twin can be used to optimize instrumentation and controls (I&C) systems during the design phase.

Presenters in this session discussed the following use cases of digital twins:

- Iterative plant design using digital twins
- Digital twin virtual sensors to optimize instrumentation

Challenge identified by presenters:

- Validation of novel sensor performance under extreme conditions

Presentations

1.2.1 Advanced Sensors and Instrumentation for Digital Twin Applications

Pattrick Calderoni, National Technical Director, Advanced Sensors and Instrumentation Manager, Measurement Science Department
INL

Presentation Overview: The development efforts for advanced sensors were outlined. Advanced sensors include multi-point and multi-modal sensors that must be built to withstand the reactor environment. Advanced sensors will be integrated with control systems to provide real-time data and feedback. Specific sensors were discussed with the predominant feature being high-temperature operation, including in-core neutron flux, high-temperature thermocouples, ultrasonic sensors for temperature measurement and structural health monitoring, and optical fiber-sensors. Wireless technologies and power harvesting were also discussed.

1.2.2 Non-intrusive Temperature and Pressure Wireless Sensor and Transceiver System for Extreme Environment Applications

Jorge Carvajal, Fellow Engineer
Westinghouse Electric Company

Presentation Overview: Ongoing sensor development efforts were reviewed. Wireless sensors for temperature and pressure measurement were presented for use inside sealed fuel rods and inside seal dry storage steel cannisters. The fuel rod sensors would also measure pellet elongation and operate passively. These sensors provide real-time and continuous data. It is suggested that these sensors could be used to increase data availability to accelerate fuel qualification and technical analysis. Efforts are ongoing to test sensors at high temperature and in radiation environments.

1.2.3 Data Analytics and Remote Monitoring Integration

Molly Strasser
Xcel Energy

Presentation Overview: Xcel Energy presented their process for moving to a condition-based monitoring and maintenance scheme. Wi-Fi was installed to connect with sensors and smart devices in the hands of personnel. New sensors were added, and existing analogue gauges were integrated into the digital network. Sensing includes vibration, gauge readers, void monitoring, remote radiation mapping, valve position indication, acoustic monitoring for switchgear and transformers, and continuous thermal imaging. Advanced models were used for processing of continuously collected data.

1.2.4 Digital Twin Impact on I&C Systems Development for Xe-100

Matthew Hertel, Senior Nuclear I&C Engineer
X-enegy

Presentation Overview: The development of I&C systems for Xe-100 was presented. A digital twin was used in lieu of a physical plant. I&C system design was optimized using an iterative process using specifications, transient analysis, and physical systems.

1.2.5 Online Monitoring (OLM) Implementation to Extend Transmitter Calibration Intervals in Nuclear Facilities

Brent Shumaker and H.M. Hashemian
Analysis and Measurement Services Corporation (AMS)

Presentation Overview: Online monitoring for transmitter calibration was presented. It was presented that transmitters were calibrated at every outage, but typically don’t drift in that period. Instead, a condition-based maintenance system using online monitoring was implemented to only calibrate those sensors that had drifted. This system was implemented in Sizewell B since 2005, Vogtle units 1 and 2 since 2018, and the Advanced Test Reactor since 2015.

2 DAY 2 PRESENTATIONS

2.1 Session: Use Cases of Digital Twin Enabling Technologies in Nuclear Power Plant

Even though digital twin technologies have not been fully implemented in the nuclear industry, they are gaining momentum and support. At this moment there are several projects ongoing to implement this technology into the industry. From risk-informed approaches to optimize equipment maintenance to a specific software that use a combination of digital twin and AI to provide a diagnosis, there are several successful cases in the industry where this technology has been deployed. In this session, participants presented concrete examples and use cases of digital twin technologies in the nuclear industry.

Presenters in this session discussed the following use cases of digital twins:

- Preventive maintenance optimization
- Work order data analysis
- Identification of fault signatures
- Development of an automated digital platform
- Detection of high-pressure heater leak
- Detection of condensate collector tank leak
- Detection of condenser losses
- Real-time radiation monitoring network (this case is still in the experimental phase)

Challenges identified by presenters:

- Lack of synchronization
- Lack of good quality data for different fault modes
- Data imbalance
- Lack of model generalization
- Qualification for ML process

The presentations slides for Day 2 can be found here and in the ADAMS under ML21342A123.

Presentations

2.1.1 Integrated Risk-informed Condition-based Maintenance Capability and Automated Platform

Matthew Yarlett, Project Engineer
Westinghouse Electric Company

Presentation Overview: Presentation of the research results of the project between PKMJ Technical Services, INL, and Public Services Enterprise & Group (PSEG) based on development of condition-based monitoring models and integrating those models into a digital platform for use by the nuclear industry. This project integrated advancements in online monitoring and data analytics techniques with advanced risk assessment methodologies. Preventive maintenance optimization, work order data analysis, and identification of fault signatures, among others, were presented as successful accomplishments of the developed technique.

2.1.2 AI Driven Scalable Condition-based Predictive Maintenance Strategy

Koushik A. Manjunatha, PhD Staff Research Scientist
INL

Presentation Overview: Introduction of a decentralized AI approach using heterogeneous data from a nuclear power plant (NPP) asset to deploy condition-based predictive maintenance strategies. The approach is simple and scalable across different assets at the plant site and across the nuclear fleet. Predictive maintenance models, fault signature identification, fault probability were some examples of results that can be obtained using the technique. This presentation also highlighted several challenges that lead to inaccurate model interpretations.

2.1.3 Thermal Performance Management for Nuclear Power Plant with Digital Twins

Christophe Duquennoy, PhD, Nuclear Fleet Thermal Performance Expert
Électricité de France S.A. (EDF)

Presentation Overview: This presentation highlighted use cases on EDF experience. The Metroscope software, which combines a digital twin of the process with AI to perform a diagnosis in operations, is the program utilized by EDF. Early detection of condenser collector tank leaks, condenser loses, and heaters tube rupture are examples of diagnosis activities predicted by the software.

2.1.4 Digital Twin of a Real-time Radiation Monitoring Network

Richard McGrath, Principal Technical Leader in Radiation Safety Group
EPRI

Presentation Overview: This presentation explained the ongoing results of the EPRI's project regarding the use of a digital twin as a real-time radiation monitoring network. This EPRI NextGen RP Project have the potential of optimize the way radiation protection is performed in NPP. The project consists in two phases: Phase 1 - "Demonstration of geophysical application for analyzing radiological survey data", and Phase 2 - "Apply machine learning to geophysical radiological survey application".

2.1.5 Non-destructive Examination (NDE) 4.0 and ML for In-Service Inspections

Iikka Virkkunen, Professor
Aalto University

Presentation Overview: An introduction to a new system that increases the reliability of the use of NDE for inspections through the application of ML. This new procedure can be integrated to existing NDE methods and allow connected systems to aggregate data. Tools like edge computing and ML are vital for the implementation. The biggest hurdle is the qualification of the system.

2.2 Session 2: Digital Twin Enabling Technologies in Advanced Reactors Applications

The NRC is preparing to review and regulate a new generation of advanced non-light water reactors, and this session covers the intersection between digital twin enabling technologies and advanced reactor applications. Many companies are planning to use digital twins not only for operation and maintenance, but also in the design, licensing, construction, and decommissioning phases of the NPP lifecycle. Several different approaches to the use of digital twin technologies have been presented, each involving iterations between experiments, simulations, prototypes, and digital twin models. To fully realize the benefits of digital twins, developers need high-quality training data, high-speed surrogate and reduced-order models that can run in real time, and considerable numbers of legacy and advanced sensors to provide the necessary information to the models so that the digital twin can inform predictive maintenance and optimize operational efficiency.

Presenters in this session discussed the following use cases of digital twins:

- Anomaly detection with ML
- Informing maintenance & security in design space
- Detection (fault or anomaly detection), diagnosis (place faults in classes), and health estimation and forecasting (includes performance prediction)
- Health evaluation and analysis in real-time, semi-autonomous control room, operational reliability and diagnostics, and safety hazard intervention and limiting defense (detect and mitigate cyber threats)
- Recognize and address mechanical and thermal fatigue failure modes which drive O&M activities and costs
- Use of DT to fully model all aspects of the system, from physics to controls to properties controlling the device

Challenges identified by presenters:

- Dealing with the statistically impressive results of ML, which might be individually unreliable
- Lack of good quality data for training algorithms and building the DT
- Integration of heterogeneous models in a DT
- Uncertainty quantification methodology
- Getting right balance between digital and physical models in the development process

Presentations

2.2.1 Xe-100 Digital Twin Technologies Overview

Ian Davis, Senior Digital Twin System Engineer
X-energy

Presentation Overview: X-energy is using digital twin technologies to support the ongoing development of its advanced high-temperature gas-cooled reactor (HTGR) design and plans to use these technologies to support future operation and maintenance of Xe-100 sites. Some of the inherent characteristics of this advanced reactor concept, such as the robustness of the tri-structural isotropic (TRISO) particles that contain the fuel, low power density of the core, and strong negative temperature coefficient of reactivity, reduce safety concerns and offer opportunities for implementation of new technologies. Some of the digital twin tools include three-dimensional models that can be explored with augmented reality/virtual reality (AR/VR) and coupled to the detailed operator training simulator, a plant historian (includes dashboards and visualizations), and custom ML/AI models for aspects such as conducting predictive maintenance and optimizing operational efficiency.

2.2.2 Humble AI for Reliable Machine Learning-Based Health Twin

Dr. Nurali Virani, Lead Scientist
General Electric Company (GE)

Presentation Overview: Machine learning-based health twins can be used for fault detection, diagnosis, or health estimations of physical systems and components. A key aspect of using health twins-based automation for critical industrial infrastructure is the development of characterization regions of reliability and trust as safety and performance are paramount. GE has developed an AI program referred to as “Humble AI” that is aware of its own competence and improves its competence via learning. The crucial element of this program is the model competence evaluation, which analyzes model inputs, model internal representations, and model outputs, and identifies regions of trust, overlap/ambiguity, and extrapolation to get justification-based reliability. The AI was tested using Tennessee Eastman Process simulation data and achieved an overall accuracy of 76% on all the data it was shown; however, on 56% of the data, the AI program had an accuracy over 99%. This highlights the concept that an AI could be used to automate certain aspects of operation and maintenance (where the confidence and accuracy is high) and request human assistance outside of that region of confidence.

2.2.3 Enabling Technologies for Digital Twins Applications for the KP-FHR

Anthonie Cilliers, Senior Management
Kairos Power

Presentation Overview: Kairos Power plans to use robust digital twin technology in several aspects of the Kairos Power Fluoride Salt-Cooled High-Temperature Reactor (KP-FHR). Among these are systems for the following functions: safety hazard intervention and event limiting defense (KP-Shield) to provide a passive, robust, reliable safety shutdown capability; operational reliability and diagnostics (KP-Sword) for active plant control; health evaluation and analysis in real-time (KP-Heart) to provide intelligent health monitoring; semi-autonomous industrial grade human machine interface technology (KP-Sight) for a semi-autonomous control room. Kairos power will carry out the development process as follows: 1) small test facilities, 2) large test facilities, 3) prototypical facilities, and 4) commercial facilities. A key aspect of the design is to minimize the safety envelope using state-based plant information.

2.2.4 High-Fidelity Digital Twins for BWRX-300 Critical Systems

Emilio Baglietto, Associate Professor of Nuclear Science and Engineering
Massachusetts Institute of Technology (MIT)

Presentation Overview: Discussion of the use of high-fidelity digital models using computational fluid dynamics (CFD) to inform maintenance and operational decisions. This is especially useful in new applications that do not have a rich database from which to draw. MIT has been able to demonstrate reduction of operating uncertainty through high-fidelity simulations and accurately predict velocity and temperature fluctuations responsible for fatigue. The STRUCT program developed by MIT was also able to capture complex phenomena driven by the formation and interaction of large turbulent structures that are strongly non-linear and not prone to “lumping” and generalization. Additionally, MIT’s program demonstrated accelerations between 50 and 100 times compared to traditional large eddy simulations. These high-fidelity CFD models can be used to create the surrogate models used by a digital twin.

2.2.5 Molten Salt Loop Development Acceleration with Disturbed Single Crystal Harsh Environment Optical Fiber-Sensors

Michael Buric, Staff Scientist
National Energy Technology Laboratory (NETL)

Presentation Overview: Single crystal optical fibers such as $Y_3Al_5O_{12}$ (YAG) or sapphire are used for distributed temperature sensing to map high-radiation and/or high-temperature environments like liquid-fueled molten salt reactors (LFMSRs). The single crystal optical fiber technology can extend into nuclear harsh environments and provide data to not only guide reactor design and improvement through thermal efficiency, but also inform LFMSR transient response. This technology can be used to gather thousands of data points to map reactor coolant temperatures or other parameters, and preliminary testing indicates accuracy with temperatures up to 1000°C and a standoff distance up to 50 feet.

2.2.6 Digital Twin to Production Reactors, The Simulation Continuum

Bob Urberger, Chief Software Engineer
Radiant

Roger Chin, Software Architect
Radiant

Presentation Overview: Radiant plans on using a digital twin as a common tool between regulators and developers to ensure common sources of information for aspects relevant to them. Throughout the development process, Radiant is advancing their design by using Nuclear Energy Advanced Modeling and Simulation (NEAMS) tools to run high-fidelity multi-physics reactor simulations, and then using the NEAMS results to create reduced- order models for their digital twin software. They iteratively use the high-fidelity NEAMS tools, reduced-order models, hardware-in-the-loop simulations, and subscale or full-scale prototypes to refine both their models and design. Radiant will be able to demonstrate the safety of various operations by using a digital twin run, hybrid simulation run, or full prototype run.

3 DAY 3 PRESENTATIONS

3.1 Panel Session: Steps Toward Regulatory Realization of Digital Twins

This panel is focused on the intersection between digital twins enabling technologies and regulatory activities. Panelists provided their unique perspectives and insights on how digital twin technology may be employed as a tool for both industry regulatory compliance and perhaps the NRC itself as well as insights into the regulatory outcomes, challenges, resources, and gaps, especially those that are unique or novel, associated with digital twin technologies and areas where regulatory processes should be focused to accommodate these technologies.

Presenters in this session discussed the following use cases of digital twins:

- Support visualization with linkage to 3D models with AR/VR, operator simulator training, access to plant historical data, and the development of AI/ML models
- Simulator certification, human factor evaluation, and operator workload reduction
- Support optimized security staffing via security analysis and what-if security scenarios
- Support analysis submitted to NRC for human factor evaluation and staffing
- Standardize internal documentation, provide visualizations, and automate analysis
- Visualization and creation of “virtual sensors” to provide greater insights into the actual plant state
- Enable efficient and lower risk design with an iterative design process, shifts to virtual design space, and hardware-in-the-loop development and testing
- Facilitate the licensing process by structuring documentation and submittal information
- Prediction of future operational states using faster-than-real-time simulation
- Provide greater operational and regulatory flexibility by calculation of a dynamic operating envelope
- Operational anomaly detection
- Use of AI/ML for plant control functions, event prediction, equipment remaining useful life estimates, and sensor drift detection
- Provide common, rich data for industry and regulators

Challenges identified by presenters:

- Establishment of an appropriate regulatory guidance for approval of digital twin technologies and applications such as AI/ML control systems, autonomous systems, dynamic operating envelopes, reduced-order and multi-domain models, and reduced plant safety footprints
- Implement a streamlined regulatory process and appropriate common information interface to enable rapid regulatory response to plant design changes
- Determine appropriate verification, validation, and uncertainty quantification processes for digital twin models

The presentations slides for day three can be found here and in the ADAMS under ML21342A124.

Presentations

3.1.1 Digital Twins – Regulatory Viability

Jeremy Bowen, Deputy Director, Division of Engineering, Office of Nuclear Regulatory Research
NRC

Presentation Overview: Discussion of NRC's ongoing digital twin research activities which include technical preparedness, regulatory readiness, assessment of standards, and communication and knowledge management; digital twin project completed activities, publications, and takeaways thus far, and active and future project tasks.

3.1.2 Xe-100 Licensing Perspectives: Steps Toward Realization of Digital Twins

Tom Braudt, Licensing Engineer
X-energy

Steve Vaughn, Licensing Engineer
X-energy

Presentation Overview: Discussion of Xe-100 digital twin tools and their uses for digital control and monitoring, predictive maintenance, high-fidelity simulator development, human factor engineering, operator workload reduction, training, dose reduction, security, fire detection, and to support plant state awareness in different production modes; plans to use DT help analyze operator workload and staffing methodology for topical report to be submitted to the NRC; and plans to use AI/ML for control, event prediction, equipment remaining useful life estimates, and sensor drift detection.

3.1.3 Using Digital Twins to Support Regulations

Paul Keutelian,
Radiant

Presentation Overview: Discussion of Radiant's vision to make nuclear portable and use DTs to maximize the speed of design iteration; support regulatory intents to protect personnel, the environment, and hardware, and prove the protections; dynamically assess risk and risk-informed decisions; act as a common source of information for both regulators and developers; and standardize internal documentation, provide visualizations, and automate analysis.

3.1.4 Nuclear Energy Institute (NEI) Perspectives on Digital Twins

James Slider, Technical Advisor
NEI

Presentation Overview: Discussion of NEI's purpose and organization; the importance of a common language for DTs; challenges presented by DT model complexity, real-time inputs, and NRC acceptance and usage for regulatory decisions; NEI's promotion of advanced ideas and best practices within the industry; and NEI's goal to work with industry and the NRC to realize the benefits of DT technologies by establishing a predictable regulatory framework for approving DT applications and protecting public health and safety.

3.1.5 Kairos Perspective

Anthonie Cilliers, Senior Manager Instrumentation, Controls and Electrical
Kairos Power

Presentation Overview: Discussion of the Kairos definition of a DT; DT uses to provide virtual plant sensors, operations databases, support for operator training, and data analytics; demonstrations of smaller subsystems such as a molten salt coolant loop and a virtual counterpart to support a faster iterative design process; how a DT facilitates the intersection between regulatory and design spaces and speeds the licensing process; operational phase use of a DT to predict future plant conditions, create a dynamic operating envelope, and detect anomalies; design phase use to DT to more accurately define safety margins and reduce safety-related footprint within a plant; and use of a DT to reduce design risks.

3.1.6 Westinghouse Perspective

Brian Golchert, Principal Engineer
Westinghouse

Presentation Overview: Discussion of costs associated with DT including lack of guidance for related NRC submissions for techniques such as reduced-order modeling and coupling of single-domain models; the need to establish a DT business case; use of DT to support hardware-in-the-loop; use of DT in place of prototypes to reduce design, development, and regulatory costs; and the need for industry and the NRC to develop guidance needed to implement DTs.

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APPENDIX A WORKSHOP ATTENDEES

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APPENDIX B PRESENTATION SLIDES

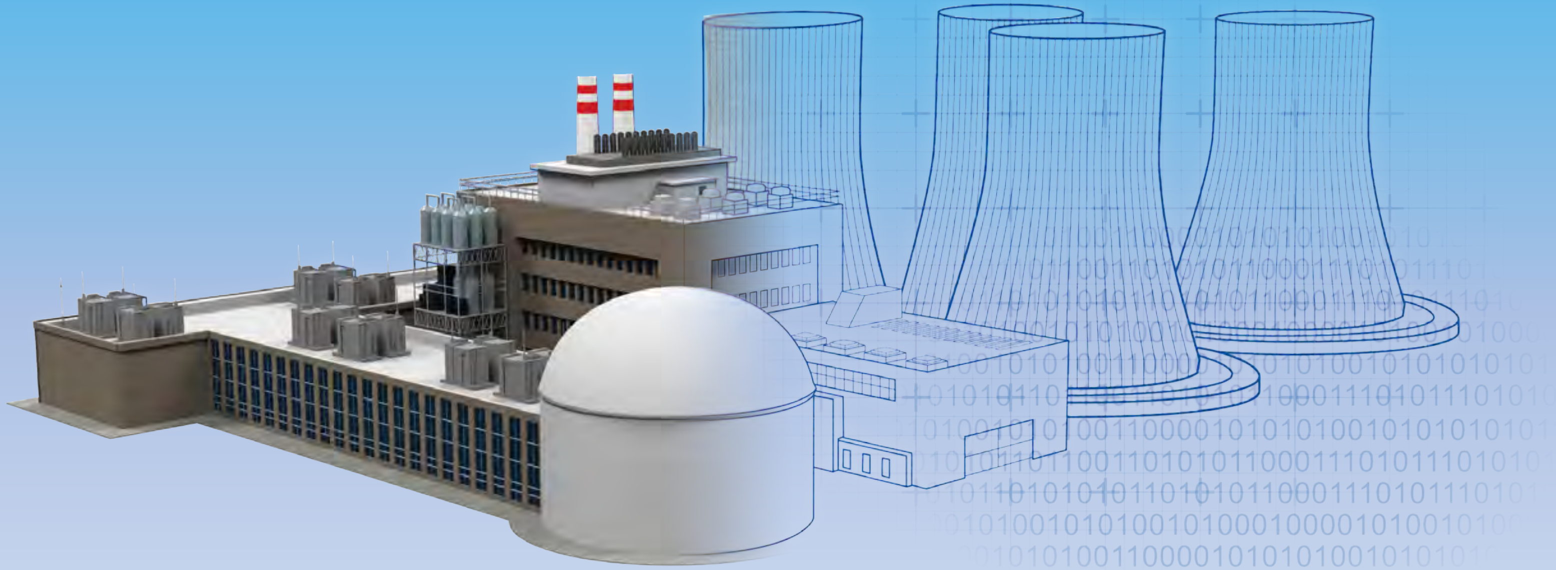
Oak Ridge National Laboratory | INL Idaho National Laboratory | U.S.NRC United States Nuclear Regulatory Commission — Protecting People and the Environment | arpa·e CHANGING WHAT'S POSSIBLE | EPRI ELECTRIC POWER RESEARCH INSTITUTE

Enabling Technologies for Digital Twin Applications for Advanced Reactors and Plant Modernization

Ray Furstenau

Director, Office of Nuclear Regulatory Research

September 14-16, 2021



Future Focused Research (FFR)

- **FFR program supports the NRC vision of becoming a modern, risk- informed regulator**

Objectives

- Close technical gaps ahead of regulatory needs
- Support transformative, innovative ideas
- Follow trends across industry and federal agencies
- Engage with industry, public, government and university communities
- Build new in-house capabilities that will attract and retain top talent

Process

- Open to ideas from across the agency
- Senior Level Staff panel reviews & makes project recommendations
- Monitor and communicate progress via program reviews and seminars

Workshop Overview

Day 1 Tuesday, September 14th		Day 2 Wednesday, September 15th		Day 3 Thursday, September 16th	
11:00 - 11:15	Introduction and Opening Remarks: NRC	11:00 - 12:45	Technical Session *Use Cases of Digital Twin Enabling Technologies in Nuclear Power Plants*	11:00 - 12:45	Panel Session *Steps Toward Regulatory Realization of Digital Twins*
11:15 - 12:45	Panel Session *Nuclear Industry Applications of Digital Twins*				
12:45	Break	12:45	Break	12:45	Closing Remarks: NRC
2:00 - 3:45	Technical Session *Advanced Sensors & Instrumentations*	2:00 - 4:00	Technical Session *Digital Twin Enabling Technologies in Advanced Reactor Applications*		
3:45	Adjourn	4:00	Adjourn		

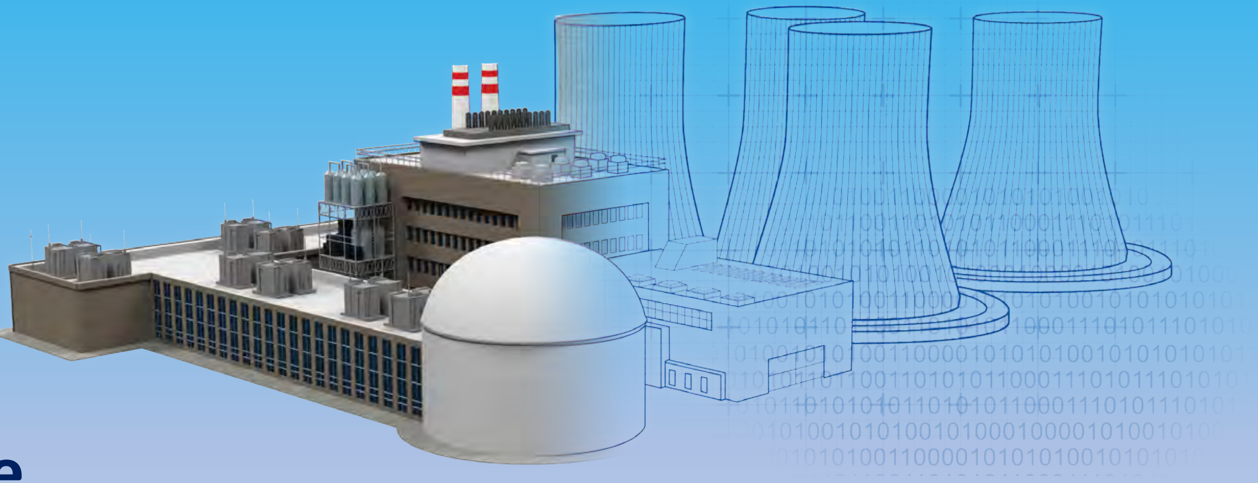
Oak Ridge National Laboratory | Idaho National Laboratory | U.S.NRC United States Nuclear Regulatory Commission *Protecting People and the Environment* | arpa·e CHANGING WHAT'S POSSIBLE | EPRI ELECTRIC POWER RESEARCH INSTITUTE

Nuclear Industry Applications of Digital Twins

Opening Panel Session – September 14, 2021

Moderator: Ray Furstenau, NRC

Patrick Burke, Xcel Energy
Craig Stover, EPRI
Scott Sidener, Westinghouse
Rick Szoch & Tim Alvey, Exelon
Harry Andreades, ARPA-E
Aurélien Schwartz, Metroscope



INNOVATION JOURNEY TO A BRIGHTER ENERGY FUTURE

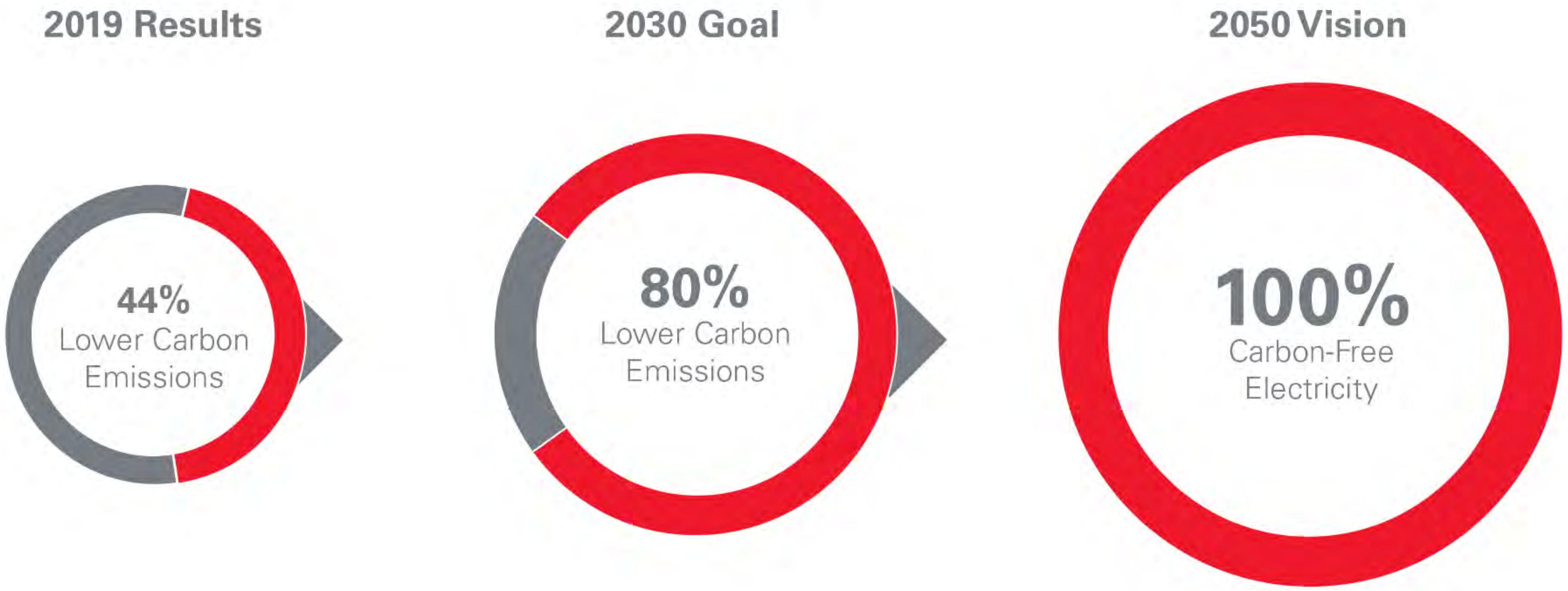
Patrick Burke

Vice President Nuclear Strategy

September 14, 2021

Leading the Clean Energy Transition

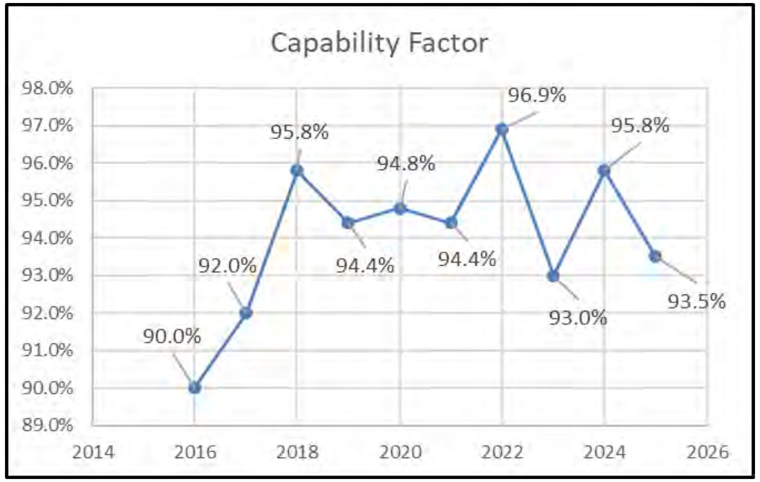
A bold vision for a carbon-free future
Monticello and Prairie Island Nuclear Plants



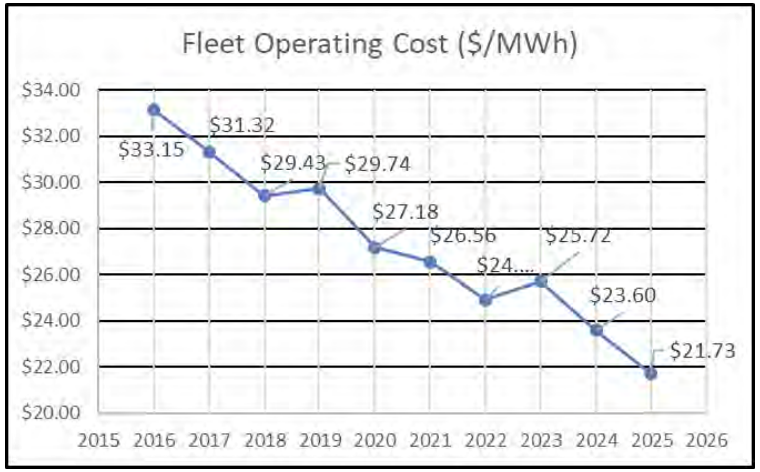
Company-wide emissions reductions from the electricity serving our customers, compared to 2005

Safe, Reliable, and Cost Effective Operation
Through Innovation and Technology

- Safe - High safety metrics & ratings (NRC, INPO)



- Reliable - Capability Factors 90% to 95%



- Cost Effective 33$/Mw to 26$/Mw

Track Record of Innovation

- Cap Intelligent Advisor (AI/ML) and Digital Ops Factory
  - Search, Entry, Analytics
- Automation and Work Management integration – GE APM
  - Wi FI and Sensors and Remote Monitoring
- Early adopters for Organizational Transformation – Fleet Services Model (Operate & Maintain),
- Risk based initiatives, TSTF-425 & 505 and 10CFR50.69
- Security Innovation and Modification
- Outage Improvements (Drones, Communications, etc.)
- Hydrogen production DOE demonstration project (HTSE)
- Flexible Operation – Integration with Wind
- Exploring operational services with NuScale

Future State

- High levels of Safe and Sustainable performance through Technology
- Highly Skilled Multi functional workers that are data and digital fluent
- Services Organization across multiple units leveraging remote technologies
- Automation of analytics and reporting
  - Compliance Validation
  - Daily Ops reports - risk based priorities
  - Real time equipment performance monitoring
  - Reporting automation (MSPI, etc)
- Integrated operations (Flex, H2, Grid Support, Storage)

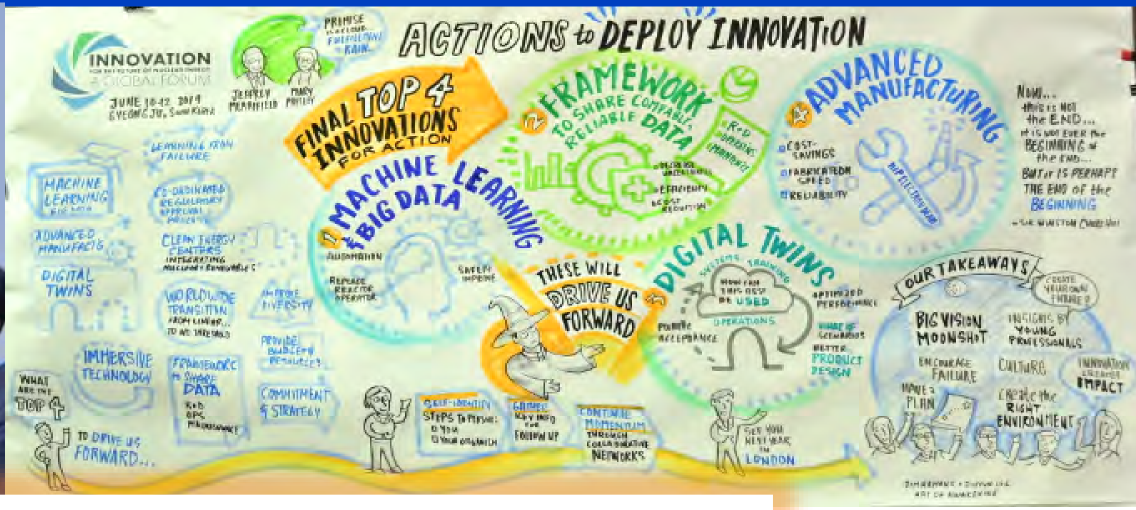
EPRI's Digital Twins Related Activities for Nuclear Applications

An Overview

Craig Stover
Program Manager
Advanced Nuclear Technology (ANT)

September 14, 2021





INNOVATION
FOR THE FUTURE OF NUCLEAR ENERGY
A GLOBAL FORUM

JUNE 10–12, 2019
GYEONGJU, SOUTH KOREA

EPRI IAEA KHNP NATIONAL NUCLEAR LABORATORY NEA



Collaboration to Accelerate the Top 4 Innovations

Machine Learning/ Big Data

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Framework to Share Comparable, Reliable Data

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INNOVATION
FOR THE FUTURE OF NUCLEAR ENERGY
A GLOBAL FORUM

Challenge

Courage

Who should attend?

EPRI and its co-organizers are inviting top innovators and influencers from around the world:

- Movers
- Shakers
- Activists
- Mirrors
- Super-nodes
  Simply healthy restless people

GLOBAL FORUM FOR NUCLEAR INNOVATION 2021

Attendees will leave with ways to:

- Drive innovation using a new network
- Lead a cultural shift in their organizations.
- Inspire and on-board others into the innovation movement for responding to climate change, deep decarbonization, and the energy challenge for the future of nuclear energy.

Role Model

EDF | EPRI ELECTRIC POWER RESEARCH INSTITUTE | IAEA International Atomic Energy Agency | NATIONAL NUCLEAR LABORATORY | NEA NUCLEAR ENERGY AGENCY

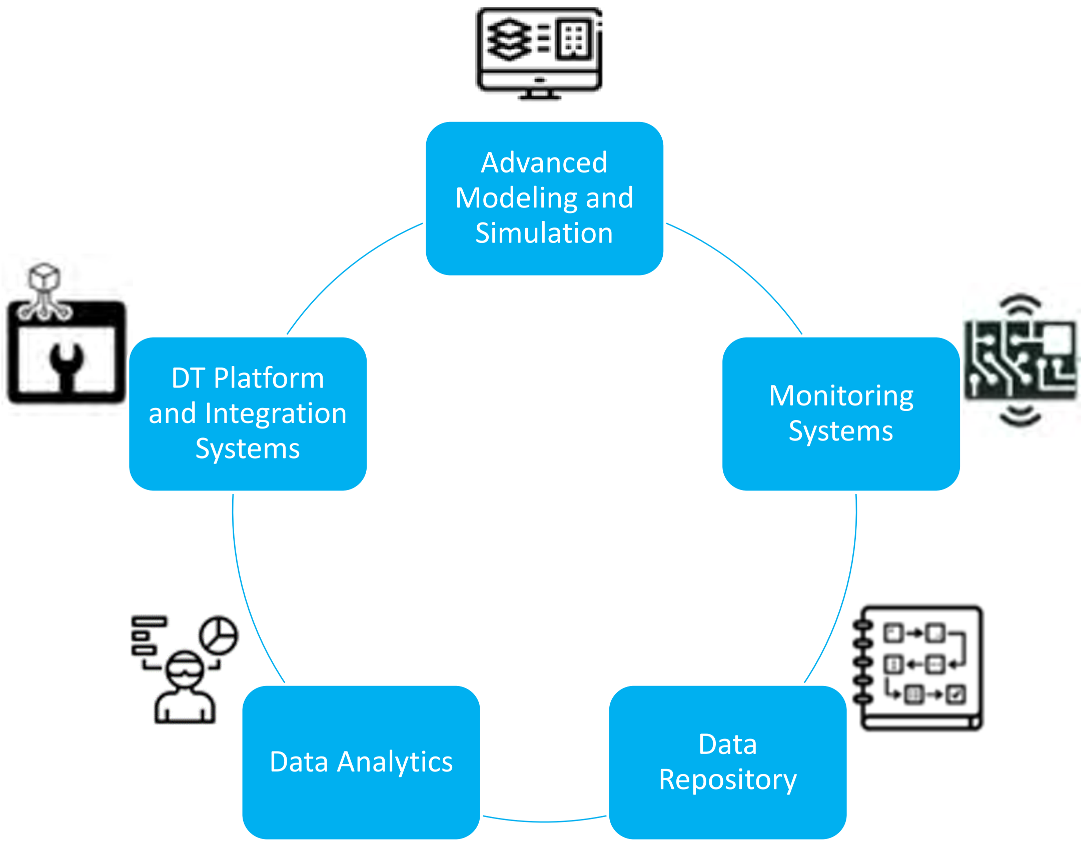
Diversity

Q1/Q2 2022

www.globalnuclearinnovation.com | globalforum@epri.com

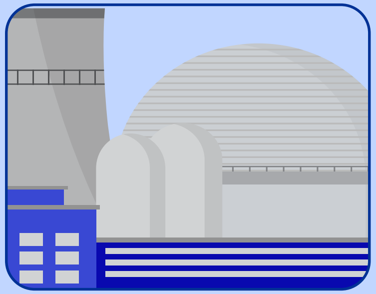
EPRI Digital Twin Engineering Overview

- Formed an internal cross-cutting team for collaboration
- Developed two technical insights document (3002020014) and (3002022555)
- EPRI Digital Twins information video released in December 2020 and another one should be released soon.
- Near term the team is working on the following:
  - What impact do DT applications have on nuclear power plant construction, operation, maintenance and decommissioning?
  - What DT applications can be deployable in the near future?



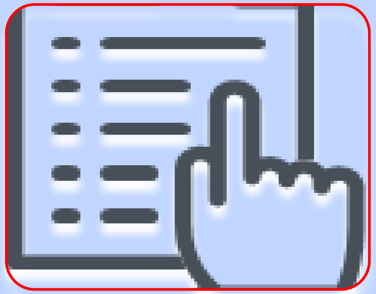
Element of Digital Twins

Digital Twins (DTs) for Advanced Reactors (ARs)



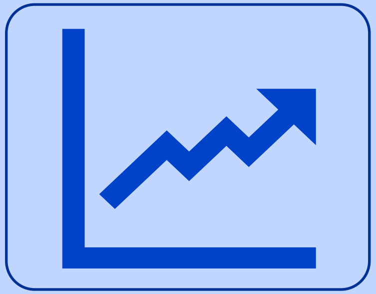
Objective

- Explore benefits, challenges and potential use cases for AR applications
- Establish industry guidelines, best practices and recommendations for implementing DTs in ARs life cycle management



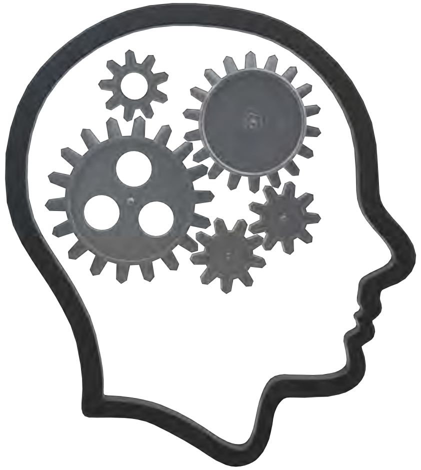
Status

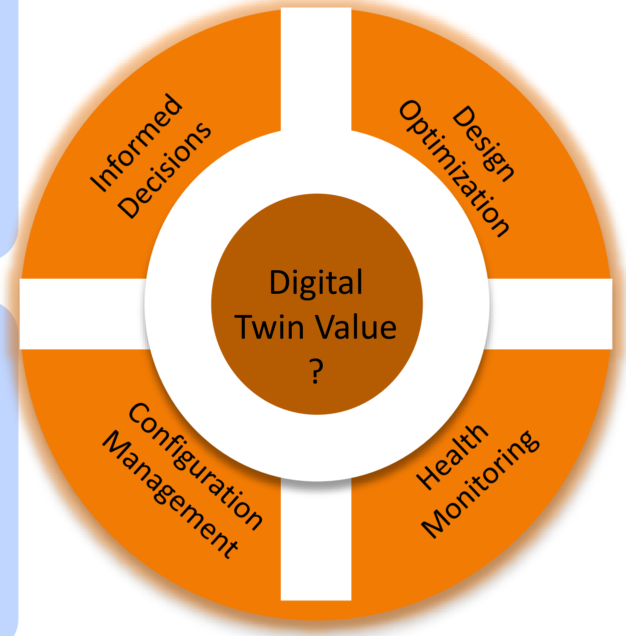
- Summarized use cases for various stages of ARs life cycle
- Developed a framework of DT project phases
- Selected use cases to further develop DT diagrams for them and to understand needed details to deploy them.



Next Steps

- Summarize experiences and recommendations
- Publish in 2022





Digital twins use cases….what are we finding so far?

- The sky's the limit!. Its important to assess
  - Technology readiness
  - Cost and Value
  - Scalability
  - Regulatory acceptance
  - Applicability
- Enabling technologies like AI and ML as well as data analytics are important for ensuring successful DT applications

The key question: where does it make sense to use DTs? (Technology readiness, cost benefits, and priorities)

Description	Target Benefits
Real-Time Construction Sequence Optimization and Front-Running Simulations • A DT based on BIM that integrates 3D geometry, construction sequencing information, cost model, schedule, and so forth, to visualize and simulate detailed work sequencing. • During construction phase, use the DT to perform real-time optimization and front-running simulations informed by monitoring of schedule- and cost-critical parameters (for example, concrete curing; health, efficiency, and productivity of construction equipment; quantities of materials delivered and installed; current weather and forecast; environmental/health hazards; geolocation and biometrics of personnel; status of work products and inspections; supply chain data and predictions; billings from suppliers). • Real-time tracking of critical parameters enables identification and mitigation of suboptimal construction operations. • Front-running simulations provide real-time analysis of the likely consequences/outcomes of construction project events and deviations from the plan; provide construction management with high-fidelity information to support optimal responses to construction deviations.	• Improved efficiency of construction operations. • Optimized costs and schedule. • Early warning of personnel health hazards during construction for improved safety. • Informed ad-hoc decision-making based on knowledge of likely consequences of unplanned events that occur during construction and potential outcomes of mitigating actions.
3D Mapping and Augmented Reality Visualization of Ambient Radiation Levels • Integrate radiation monitoring sensor data with 3D building models to provide real-time, in situ mapping of ambient radiation levels throughout plant. • Equip plant personnel with mobile augmented reality equipment integrated with the ambient radiation maps and personnel location tracking to enable real-time visualization of radiation levels in the field, for example, safety glasses with projected images indicating radioactive "hot spots" to improve implementation of "as low as reasonably achievable" (ALARA) dose management principles. • Use pathfinding algorithms to guide personnel through optimal routes to their destination to minimize personnel dose exposure. • Compare real-time measurements from distributed sensors in plant and dosimeters worn by plant personnel with historical data to provide event-driven alarms and notifications of unexpected and new hot spots, which could be indicative of system faults, leaks, or malfunctions. • Couple personnel location tracking with contamination monitors to facilitate tracking, tracing, and cleanup of contamination sources.	• Enhanced personnel safety, reduced dosage. • Decreased personnel effort for performing radiation surveys manually.


Together…Shaping the Future of Energy™

SCOTT SIDENER

CONSULTING ENGINEER, DIGITAL INNOVATION

WESTINGHOUSE ELECTRIC COMPANY

Exelon Nuclear Innovation Projects Overview

Exelon Generation®

Innovation Culture and Digital Transformation

DATA-DRIVEN INSIGHTS HIGH VALUE DECISIONS

- Extend nExus capability to include digital twin and mobile capabilities
- Data strategy and Big Data Platform capabilities
- Data analytics and AI/ML to achieve value through data-driven decision-making

Direction for 2022 and beyond

INNOVATION CAPABILITY & CULTURE

- Innovation Program with the new Constellation
- Innovation Solution Value Capture and Sustainability

DIGITAL PROCESS TRANSFORMATION

- Implement process transformations to enable annual savings
- Deliver insights and savings through workflow automation with AI & ML

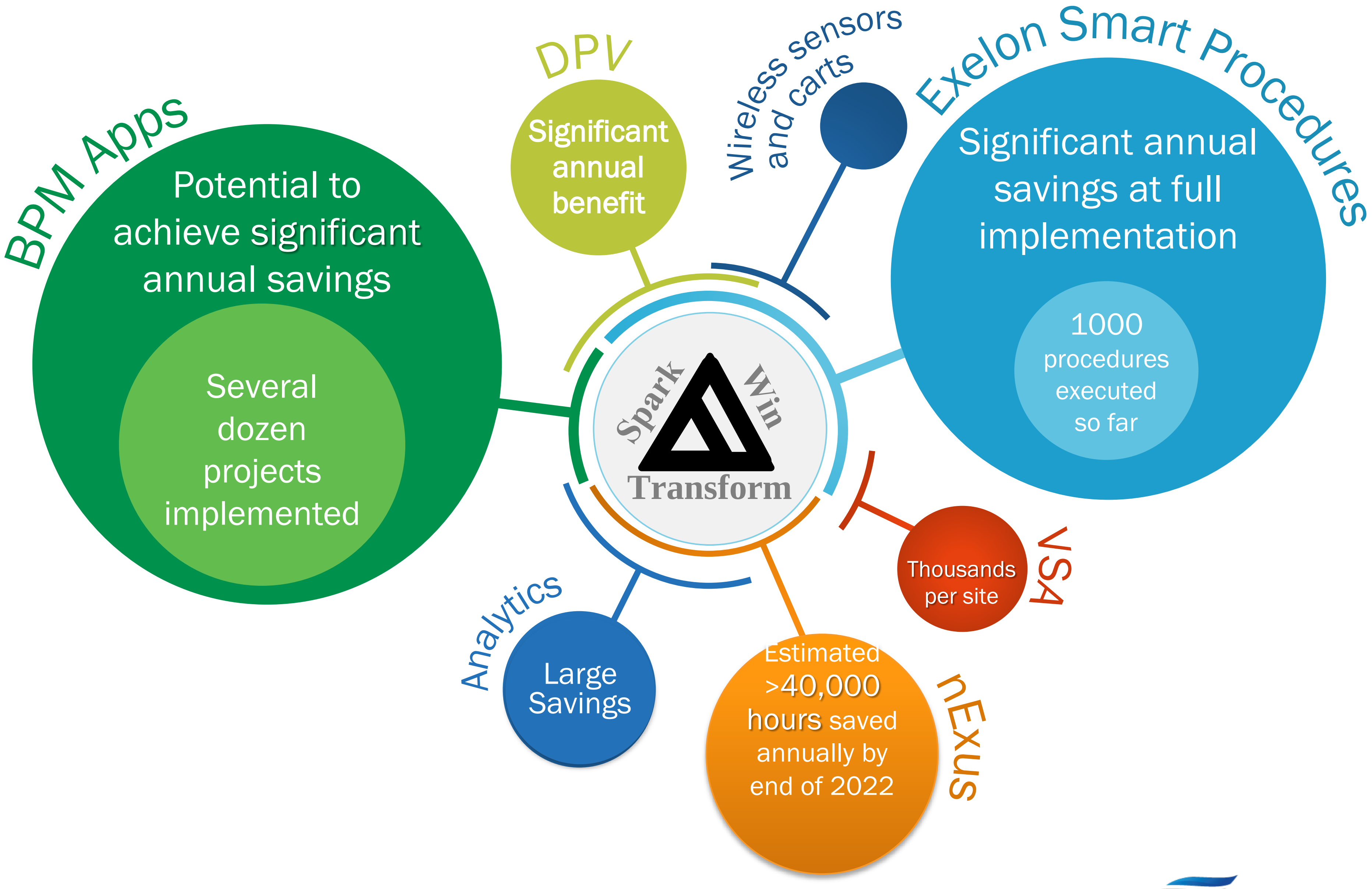
CONNECTED MOBILE WORKFORCE

- Expand Use of Smart Procedures
- Future of Work Instructions

We Have a Burning Platform!!

- Competition with natural gas
- Aging plants
- Plant shutdowns due to economics
- Domestic nuclear construction costs
- Extension of operating life cycles
- Maintaining our domestic nuclear fleet is a matter of national security

Exelon Nuclear Innovation Focus on Value



Exelon Nuclear Innovation – Remote Monitoring

Wireless Sensors

Provides a cost-effective method to enable new innovative ideas

Executive Summary:

Problem – The high cost of running wires and using traditional install is cost prohibited. Most data is collected manually by operator rounds

Solution –State of art communications infrastructure

- Wireless infrastructure that provides a cost-effective method to utilize wireless sensors and enable new innovative ideas and predictive technologies
- Low-cost wireless sensors (design once-install many) installed to improve predictive technology and facilitate elimination of high-cost time-based maintenance
- Reduce the time that it takes from an idea to implementation

Wireless Sensors – Benefits

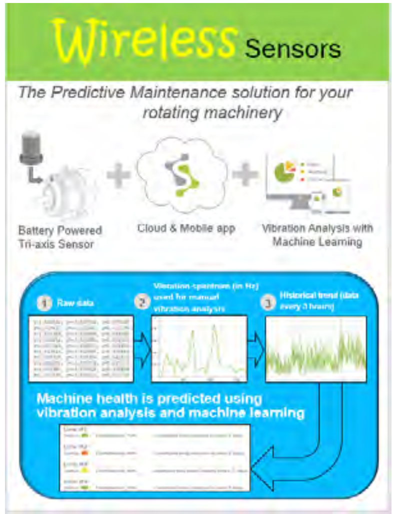
Eliminate unplanned downtime
Identify defects in rotating machines before they happen and eliminate downtime

Real time visibility into health
Provide real-time visibility into machine health; can replace walk around data collection

Monitor inaccessible machinery
Continuous, safe and consistent data collection for remote assets and hazardous locations, reducing exposure

Dose savings
Reduction in Ops & Maintenance rounds

Multi parametric PdM
Leverage multi-parament sensor data to get a holistic view into machine health



Innovative Improvement:

How did the old system work in terms of people, process, and tools?
Traditional sensors required wires. This process can take years to design, plan & install. This process can also cost millions of dollars to complete. This process is very slow & costly, and it never gets done.

How does the new solution work in terms of people, process, tools?
Wireless sensors allow us to rapidly deploy sensors where needed at a much lower cost. These sensors allow us to use design once & install many concept. Wireless sensors can be installed both temporary or permanently installations. They can also be portable or mobile.

New Capabilities:

- Wireless sensors are expected to define and transition to a future state where maintenance on consequential equipment is accomplished "just-in-time". This is enabled via state-of-the-art diagnostic and analytics tools, wireless technologies, and an altered work management strategy.

Application:

- Wireless sensors to support plant monitoring included licensed and unlicensed radio frequency
- Cellular devices to support plant communication
- Connecting devices & sensors to Predix APM

Value:

There are numerous benefits to the ability to connect Internet of Things devices to the corporate network. Ability to utilize a variety of wireless sensors in the field. The ability to capture and transmit image data back to a centralized server where it can be used by a variety of applications.

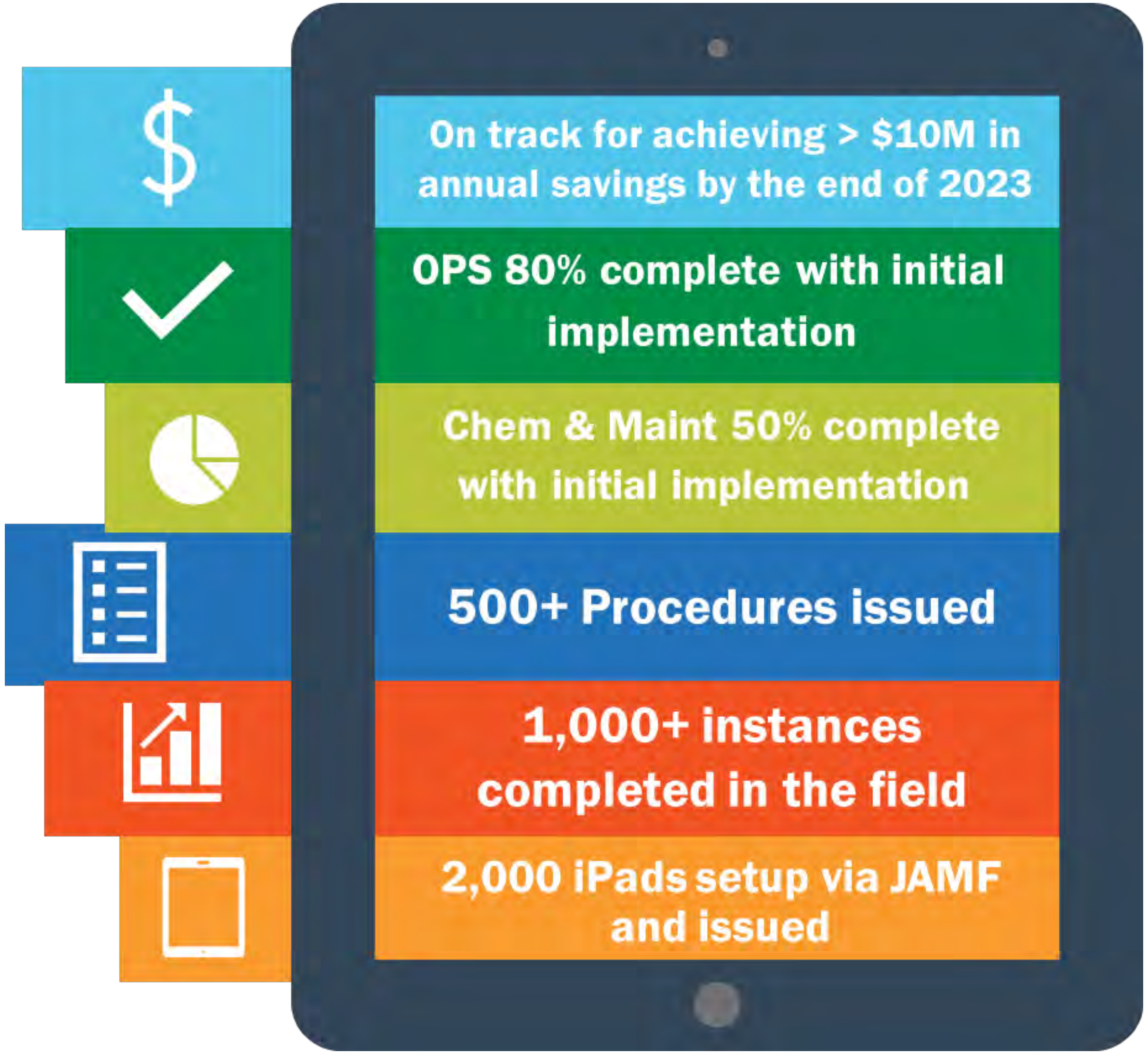
Other Uses or Potential Enhancements:

- Maintenance frequency optimization based on procedure results
- Schedule optimization based on real time task duration
- Connecting procedures to live plant data

Exelon Nuclear Innovation – Remote Monitoring

- Personnel able to perform monitoring from their desk.
- Ability for event-triggered actions: Upon an event, predefined actions can be performed, including camera movement and email notification.
- Cart setup can be potentially stored in the Power Lab and can be sent for simple assembly and setup at the site with hotspot.
- Potential for cost saving by reducing personnel burden and ability to monitor hotspot behavior.

Exelon Nuclear Innovation – Smart Procedures



Exelon Nuclear Innovation Analytic Projects

Potential Opportunities

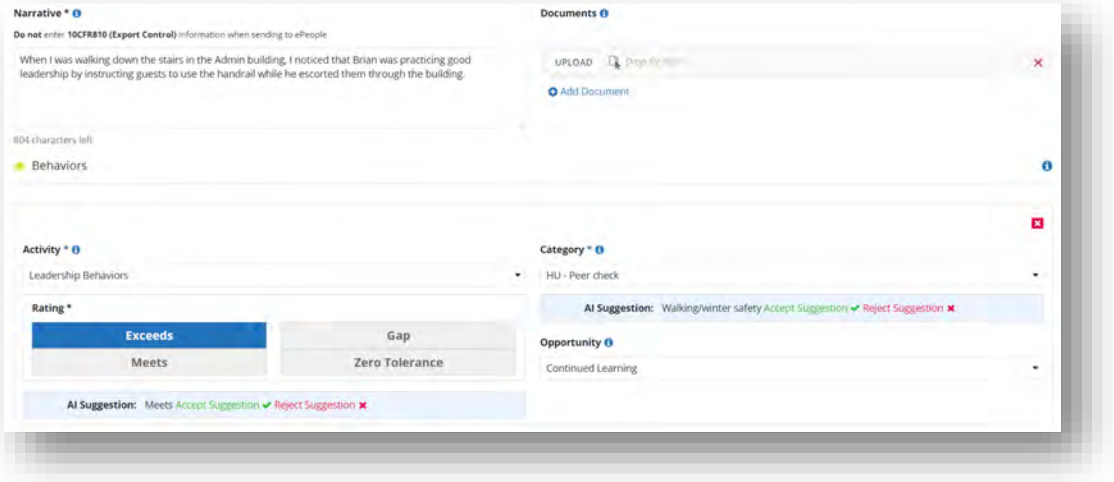
- Full automation of resource intensive processes
- Improved trending and data insight
- Enhanced predictive capabilities
- Process optimization and forecasting

Desired Results

- Reduced operating costs
- Improved accuracy of decision making
- Improve workforce quality of life
- More time working on the "right stuff"

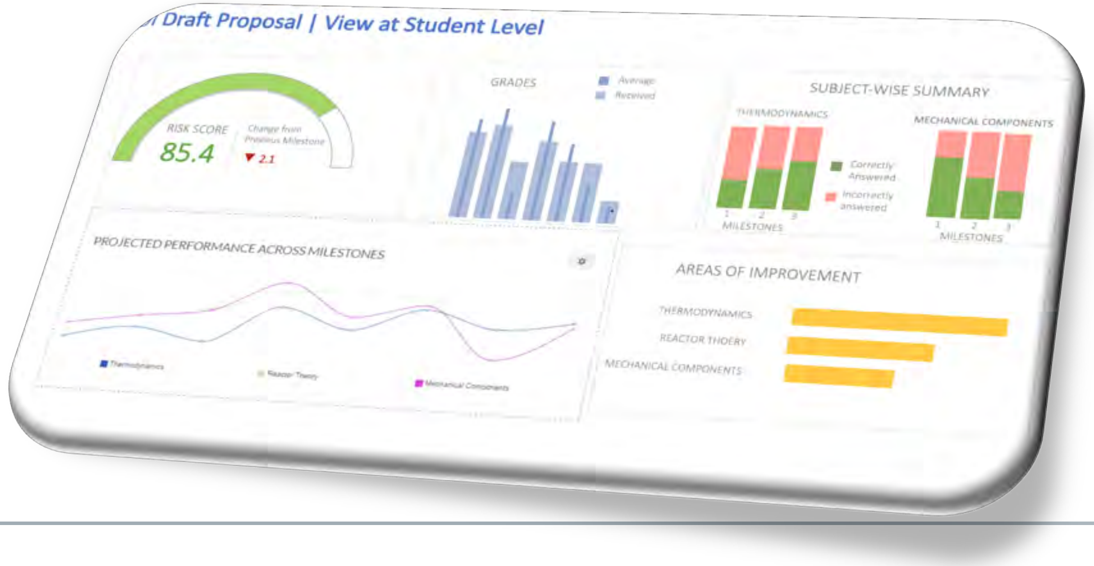
Exelon Nuclear Innovation Analytic Projects

Observation Categorization

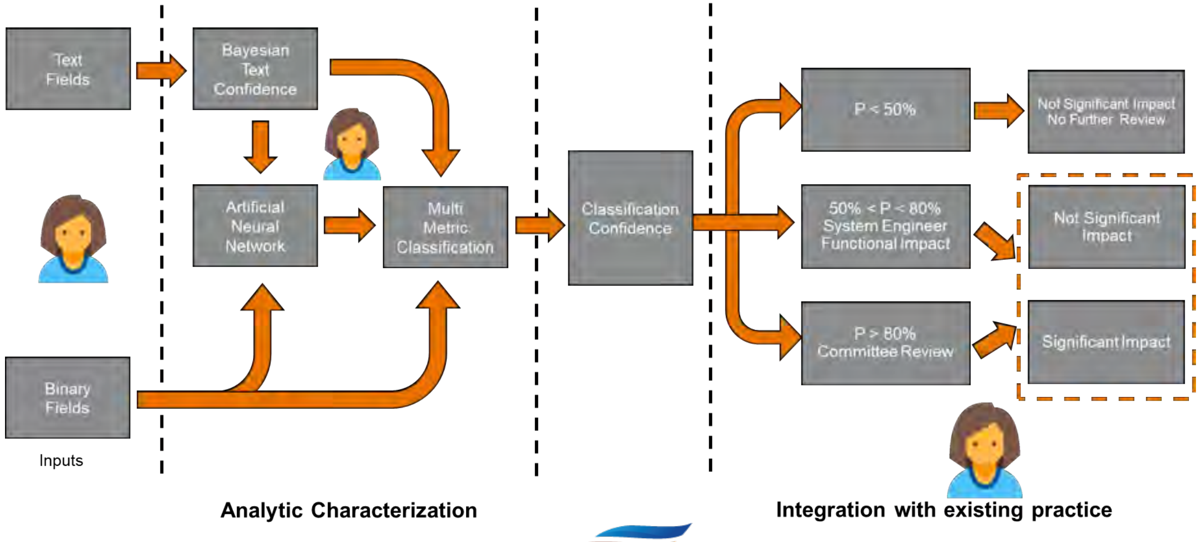


Chemistry Sampling Analytic

Initial License Training Throughput Optimization



Condition Report Screening Automation



Exelon Generation.

ARPA-E GEMINA Portfolio and Digital Twins

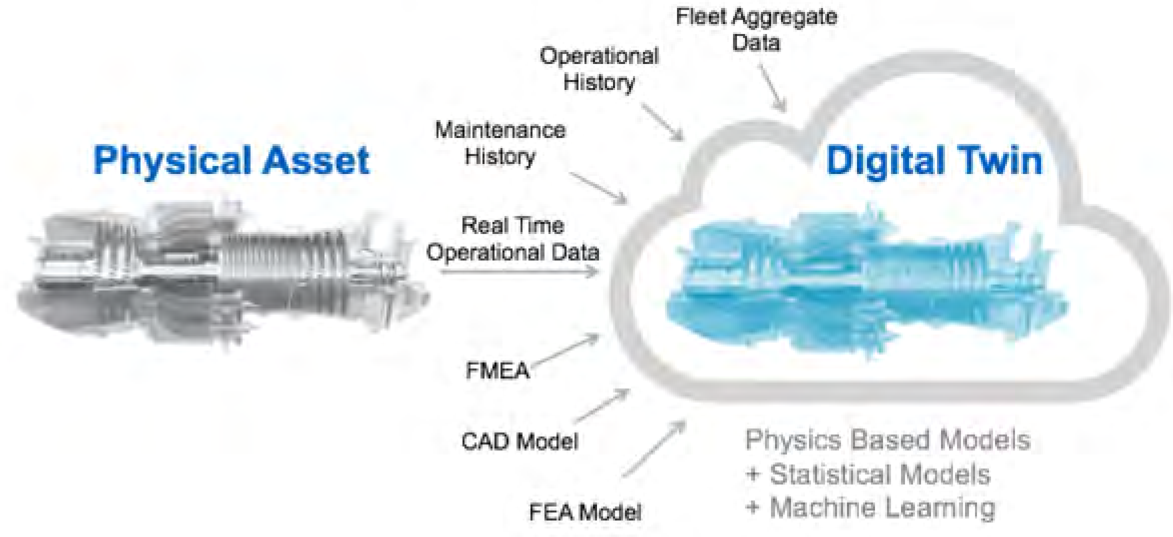
Dr. Harry Andreades
Technology-to-Market Advisor (support contractor to ARPA-E)
Contact: Dr. Jenifer Shafer, Program Director, jenifer.shafer@hq.doe.gov

December 7, 2021

Defining Digital Twins

- Mapping of physical asset models in a digital platform where a virtual digital replica is created

- Consists of three basic building blocks:
  1. 3D models
  2. Simulators
  3. PLM platform to centralize, organize, and manage data



- Continuous updating (sensors) and real-time data analysis to model physical asset

Digital twins provide a range of benefits

- Allow for **optimal operations** and condition-based **maintenance**

- **Time travel**: Allow for manipulation of DT for scenario and what-if analysis without disturbing physical asset (continuously updated data goes beyond static picture)
  - This can also apply during design phase – prior to physical asset launch

- Enables:
  - Rapid design iterations and optimization
  - Remote operations
  - Autonomous power plants
  - Fleet management
  - Performance improvement

Where are DTs applied currently?

Oil & Gas, Gas Turbines (and Combined Cycles), Wind Power, Hydro, etc.

SIEMENS

AVEVA

Bentley

ROLLS ROYCE

AKSELOS

FRAZER-NASH CONSULTANCY

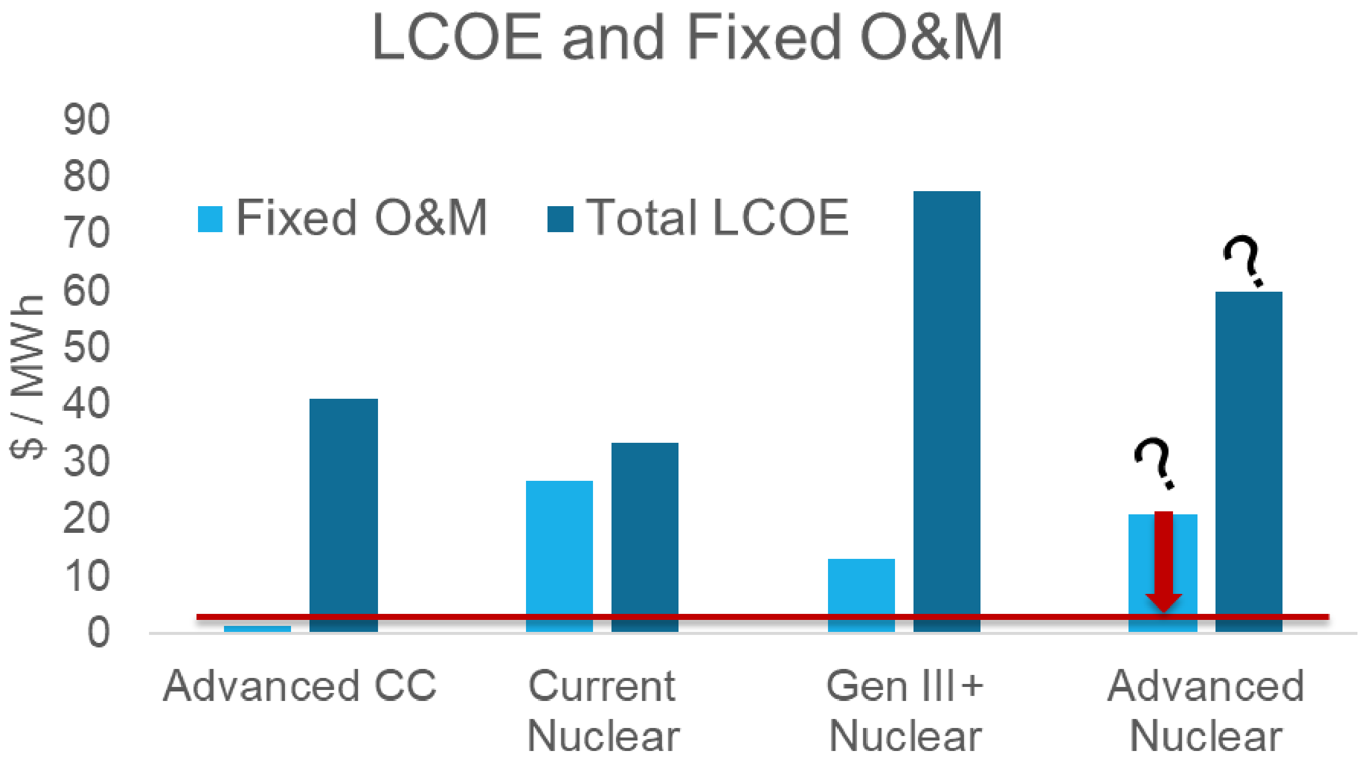
MITSUBISHI POWER

GEMINA (Generating Electricity Managed By Intelligent Nuclear Assets)

- **Goal:** Develop the tools and cost basis for ARs to **achieve fixed O&M costs of $2/MWh** without shifting costs to other parts of LCOE

Awardee teams are developing the following for one or more of the most promising AR designs:

- **Digital twins for advanced reactor systems**
- **Relevant cyber physical systems**
- **O&M approaches for advanced reactors**
- **Cost models and design updates**



ARPA-E teams are building digital tools for ARs and building blocks for DTs

Advanced Reactor Digital Twins

- Massachusetts Institute of Technology; GE Hitachi; GE Research
- moltex clean energy; Argonne National Laboratory
- NC State University; Zachry
- University of Michigan; Kairos Power
- framatome; Argonne National Laboratory
- X-energy®; Zachry; NC State University
- GE Hitachi; The University of Tennessee Knoxville; Oak Ridge National Laboratory; GE Research

Sensors and Data Generation

- Argonne National Laboratory; Kairos Power
- Massachusetts Institute of Technology
- National Energy Technology Laboratory

Construction

- NC State University; INL Idaho National Laboratory

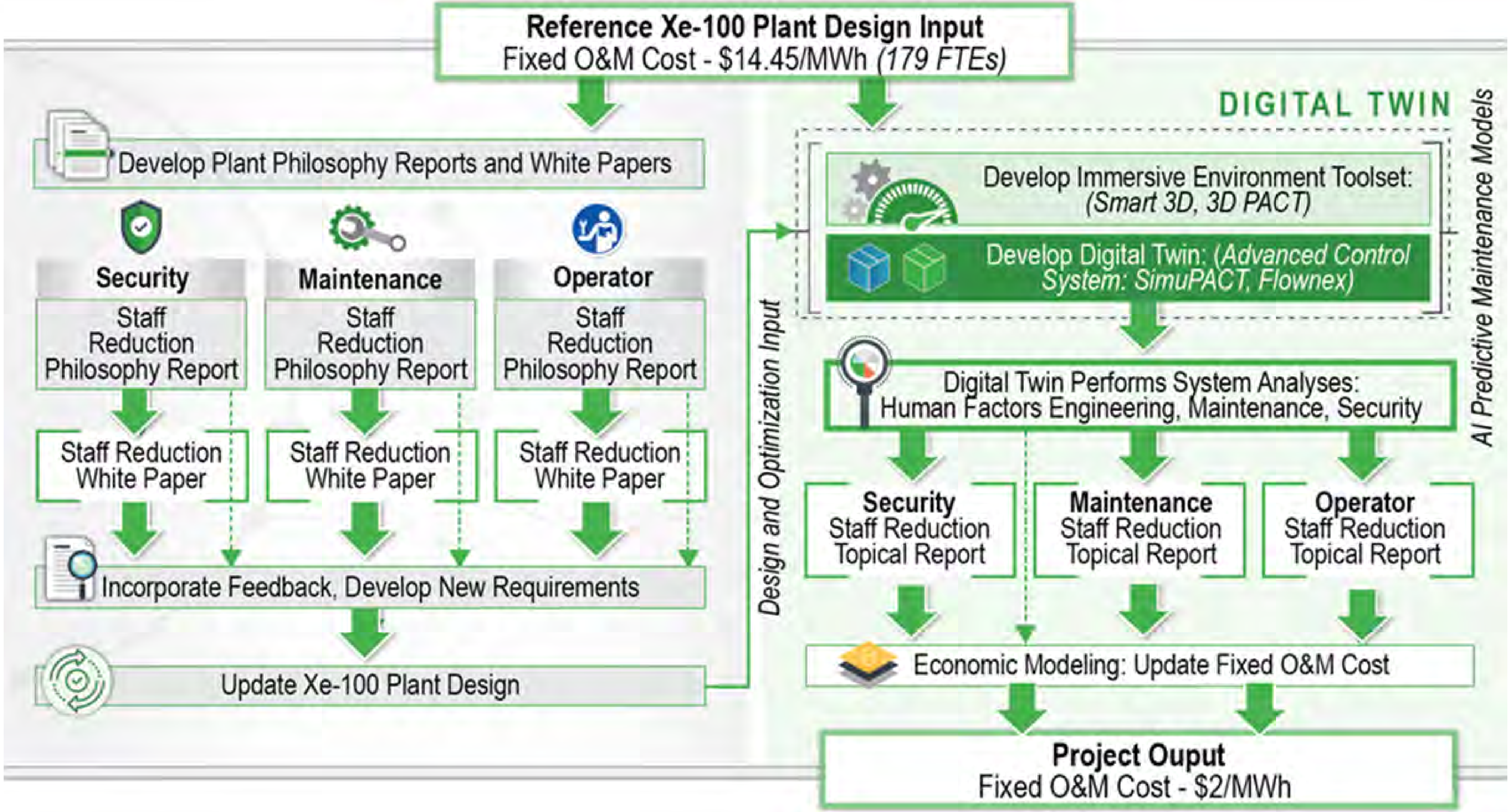
O&M TEA

- EPRI Electric Power Research Institute
- INL Idaho National Laboratory; Massachusetts Institute of Technology

Autonomous Maintenance

- SR Southern Research
- Southern Company; Oak Ridge National Laboratory

X-energy: Advanced Operation & Maintenance Techniques Implemented in the Xe-100 Plant Digital Twin to Reduce Fixed O&M Cost

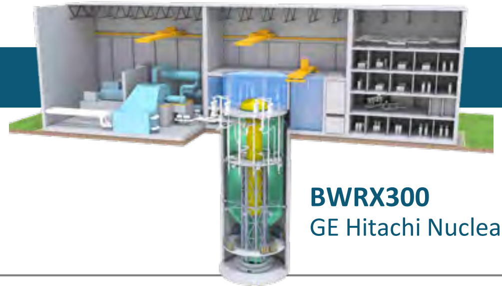


GE – Research: AI-ENABLED PREDICTIVE MAINTENANCE DIGITAL TWINS FOR ADVANCED NUCLEAR REACTORS

Summary

Program Impact

AI-enabled predictive maintenance **to ↓ O&M labor costs**
from $15/MWh to $3/MWh in an Advanced Nuclear Reactor



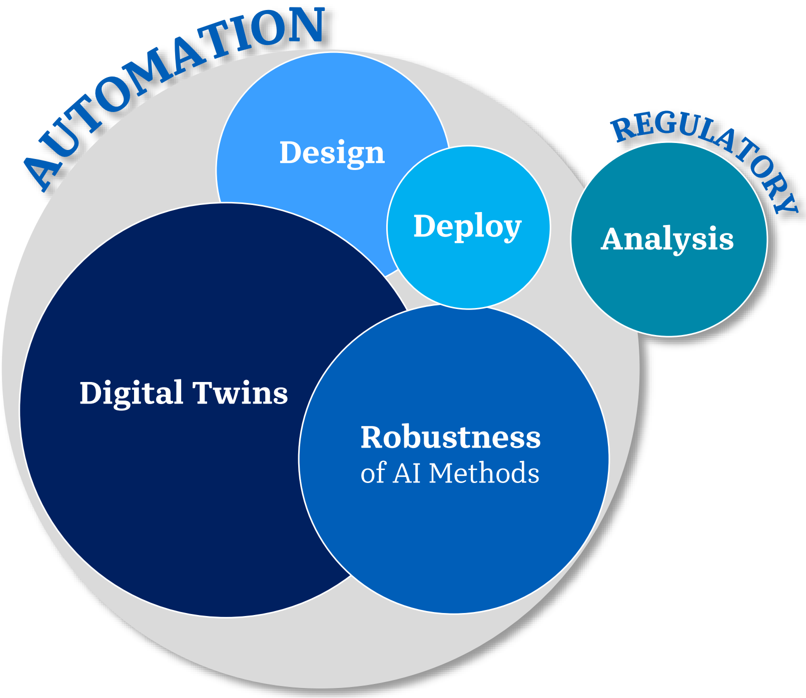
BWRX300
GE Hitachi Nuclear

Program Targets

Metric	From	To
Automation ↓ labor costs	*None*	Automated workorders … ↓ Planning staff Online calibration … ↓ Tech and admin staff
Predictive Maintenance ↓ labor & mat'l	*Alarms*	↓Forced outages & trips … AI-driven predictive algorithms → ↓ Labor headcount
Trust	*Human*	Humble & explainable AI … quantify uncertainty to establish trust in the models & encourage automation

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



ADVANCED REACTOR DIGITAL TWINS

U Michigan: Project SAFARI: Secure Automation for Advanced Reactor Innovation

GOAL

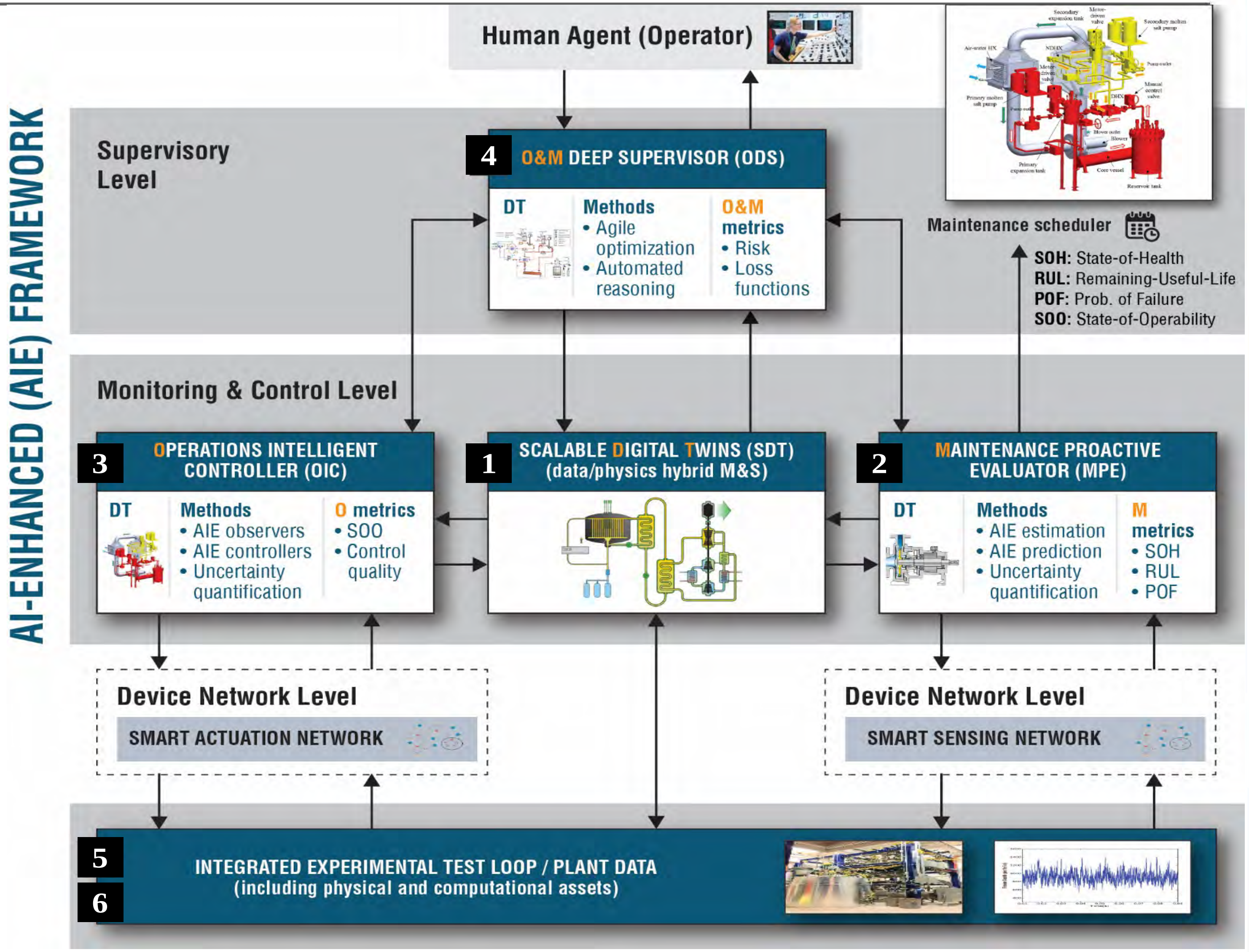
Reduce NPP O&M costs by delivering a capability which will enable smart functionalities in advanced reactor systems including:

- **Autonomous, flexible operations**
- **Predictive maintenance**
- **Agile Design**
- **System and sensors optimization**

DEMO Kairos FHR

END PRODUCT

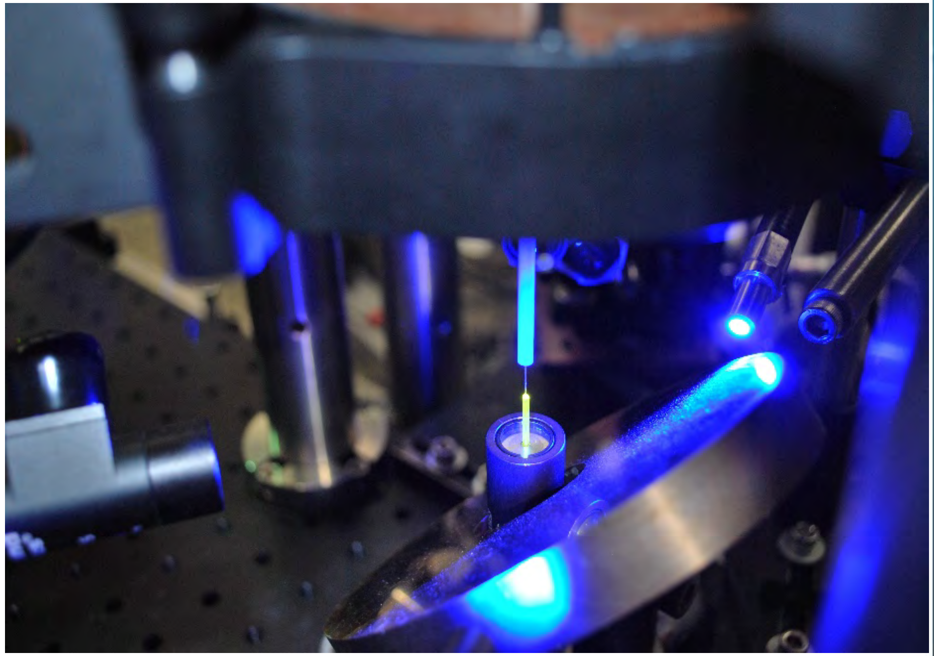
Physics-based, data-enabled, modular and scalable capability that can be extended and applied to any reactor technology



arpa·e CHANGING WHAT'S POSSIBLE

NETL: DISTRIBUTED MOLTEN SALT LOOP SINGLE-CRYSTAL HARSH-ENVIRONMENT OPTICAL FIBER-SENSORS

- Introducing fully-distributed sensing to MSRs
- Growing new cladded single-crystal optical fibers for molten-salt environments
- Gathering thousands of data-points to map reactor coolant-path temperatures or other parameters
- Mapping in-core temperature distributions
- Next-gen sensing replaces single-point sensors like thermocouples
- Providing data to guide reactor design and improvement through thermal efficiency



First successful growth of Cerium YAG fiber by LHPG

SRI: ML FOR AUTOMATED MAINTENANCE OF FUTURE MSR

Create an integrated software and algorithm architecture to "teach" automated systems from simulated data

Why - Autonomous maintenance operations identified as "critical" for next generation MSR

DEFT & SR

Algorithm development

1

Establish baseline, vendor agnostic methodologies

Look to solve two (2) problem sets

1. Robot positioning
2. Tracking via reinforcement learning (RL)

AWS

Component creation, manipulation and "reality - feedback"

4 IRTC

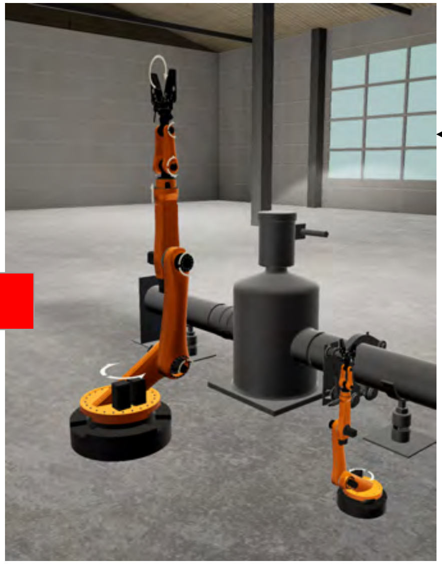
Virtual Construct

SR 2

Physical demonstration 1

Physical Robot

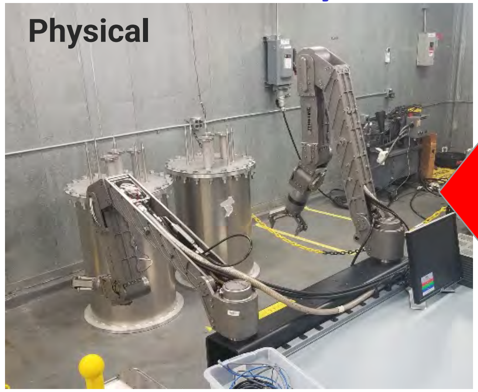
Physical maintenance equipment



Virtual replicates

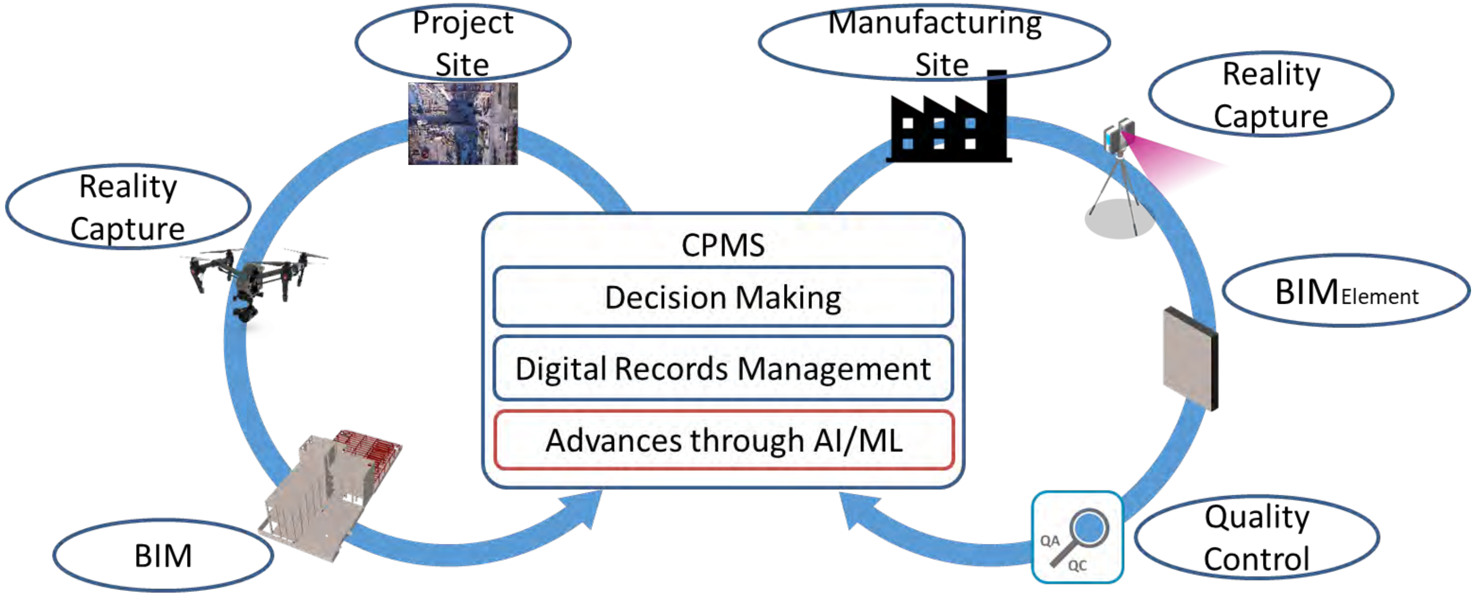
ORNL 3

Physical demonstration 2

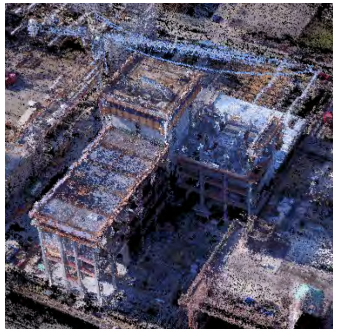


AUTONOMOUS MAINTENANCE

NSCU: A Data-driven Approach to High Precision Construction and Reduced Overnight Cost and Schedule

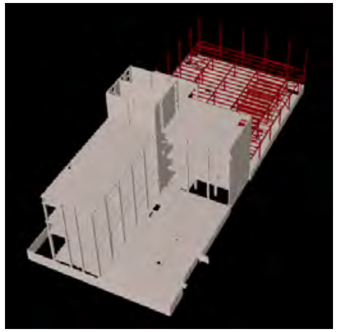


Reality Capture (drone+laser scanner)



+

4D BIM



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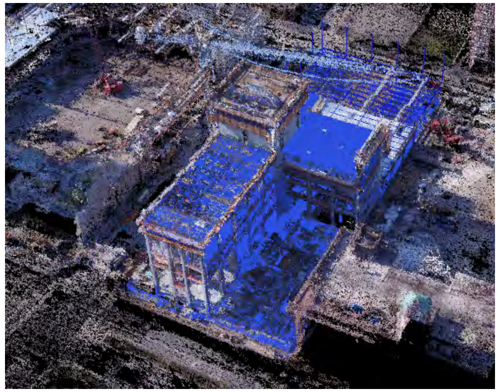
Integrated Project Site Model



CONSTRUCTION

EPRI: BUILD-TO-REPLACE: A NEW PARADIGM FOR REDUCING ADVANCED REACTOR O&M COSTS

- Identify representative SSCs for evaluation of design life implications for cost and performance associated with licensing, construction, operation, maintenance, and decommissioning

- Identify at least two reference advanced reactor (AR) designs to establish baseline O&M cost, enveloping multiple missions and a broad plant parameter envelope
  - Target: small modular light-water reactor and high-temperature gas-cooled reactor as mature technologies,
  - Aspirational goal: extend to a molten salt reactor design

- Define scenarios for reduced SSC lifetimes to evaluate impacts on O&M costs against other categories, including construction and decommissioning

Metric	State of the Art	Proposed
Fixed O&M cost	$20/MWh for light-water reactor (LWR) fleet	< $10/MWh for more mature ARs < $5/MWh for less mature ARs
Design life for major plant components	30 – 40 years for PWR steam generator 60+ years for RPV	Major SSCs < 15 years No life limiting SSCs

SUMMARY

- ARPA-E has a complimentary fission portfolio which targets both capital and operating costs reductions for making advanced reactors commercially competitive

- Digital twins and their enabling technology can be disruptive in changing the design, construction, and operating phases for advanced reactors

- Multidisciplinary capabilities are needed for successful implementation of DTs

- ARPA-E has a strong technology-to-market focus and encourages/enables performers to focus on commercial relevance and commercialization aspects of their technology

- Performer material is from unrestricted/publicly-available info from the annual ARPA-E Nuclear Program Review meeting, and can be found at https://arpa-e.energy.gov/2021-annual-nuclear-review-meeting.

metroscope

Digital Twin Monitoring for Advanced Reactors and Plant Modernization

Webinar - 09/14/2021

Aurélien Schwartz

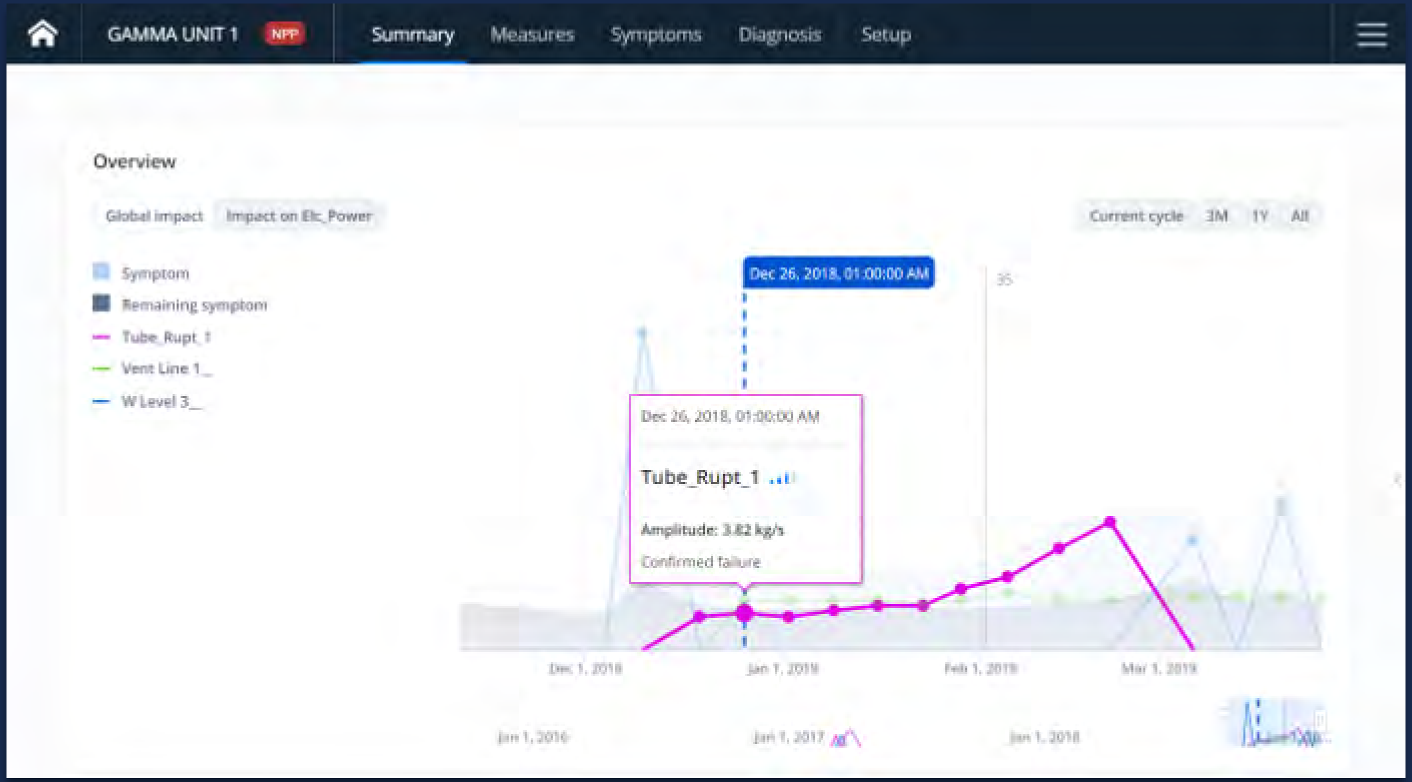
Software company founded in Paris in 2018,
with offices in Germany and the USA
Patented technology originating from the R&D Center of EDF
constituted of more than 2000 researchers

Starting with a usecase

Tube rupture in a High Pressure Feedwater Reheater (Blayais, France)

Automatically detected on Dec 23 with a magnitude of 3kg/s

Fixed at the end of Feb with a magnitude of the leak of 15 kg/s



Key principles

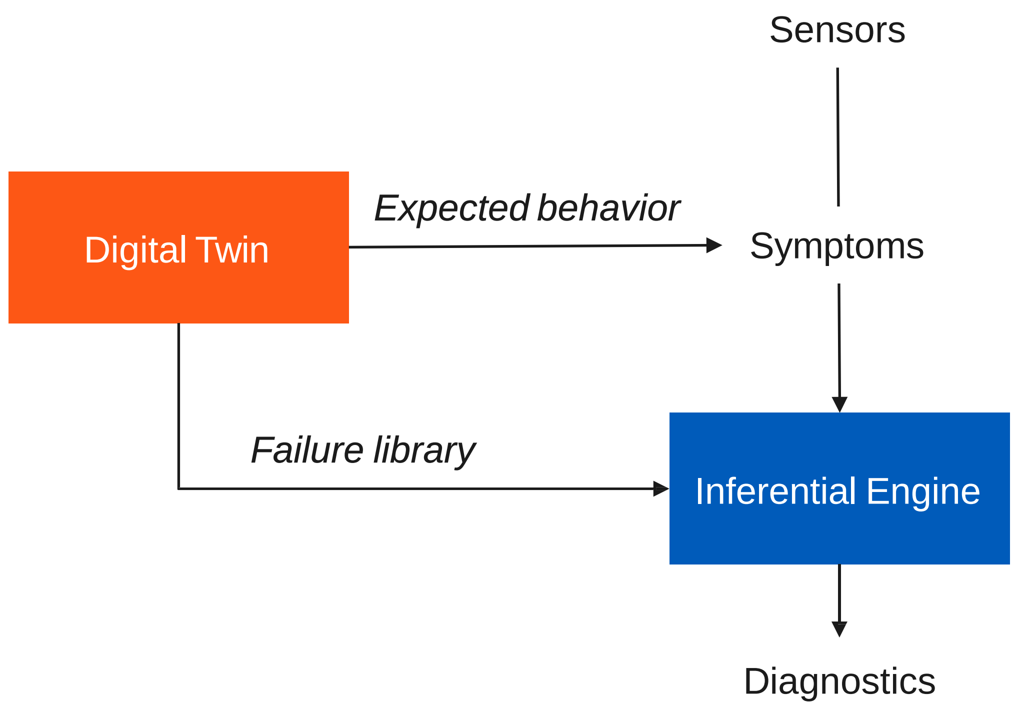
First, we use a model to build live symptoms for the plant

$$measurements - expected\ values = symptoms$$

We then use a failure library embedded in the digital twin to preform a root cause analysis.

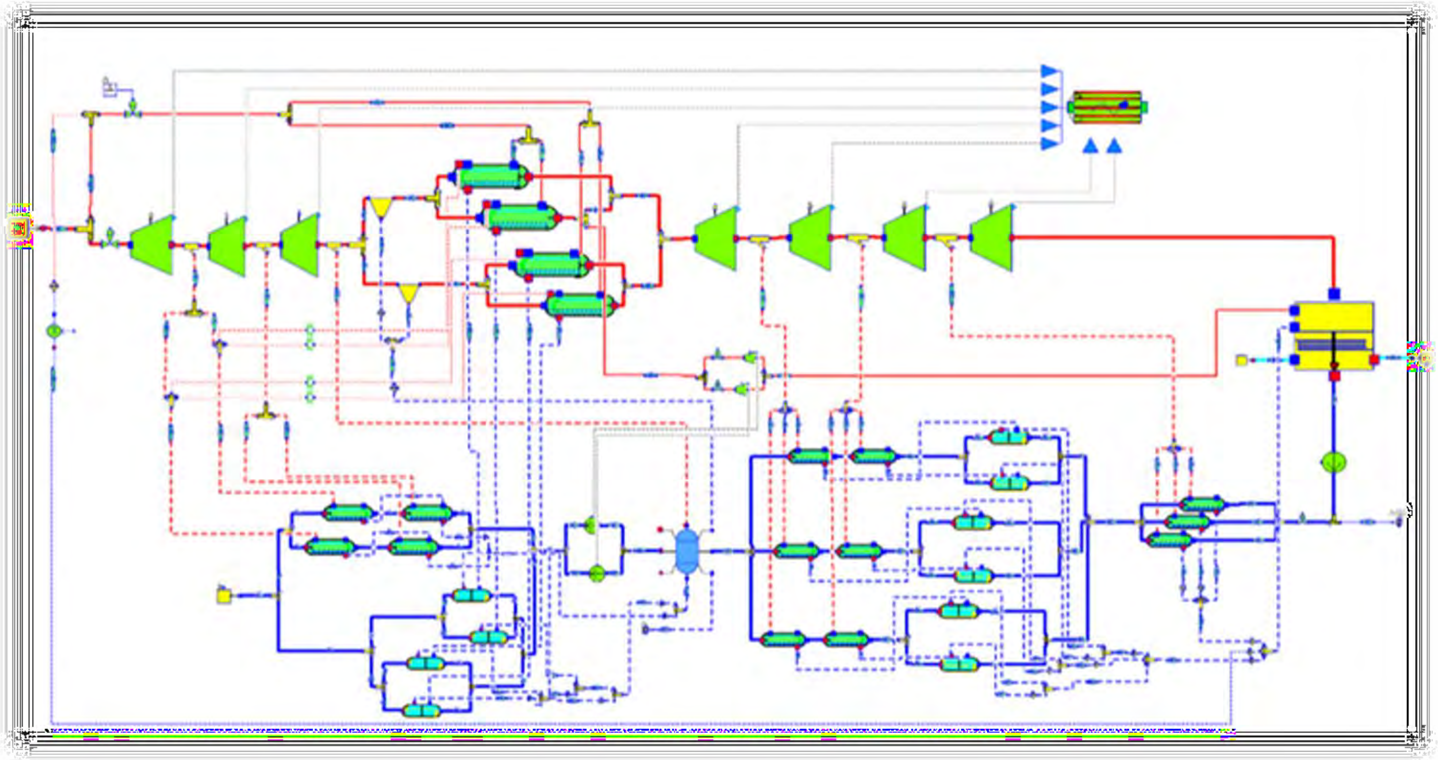
$$diagnostics = P(failures \mid symptoms)$$

Failures are classified by magnitude, impact and likelihood.



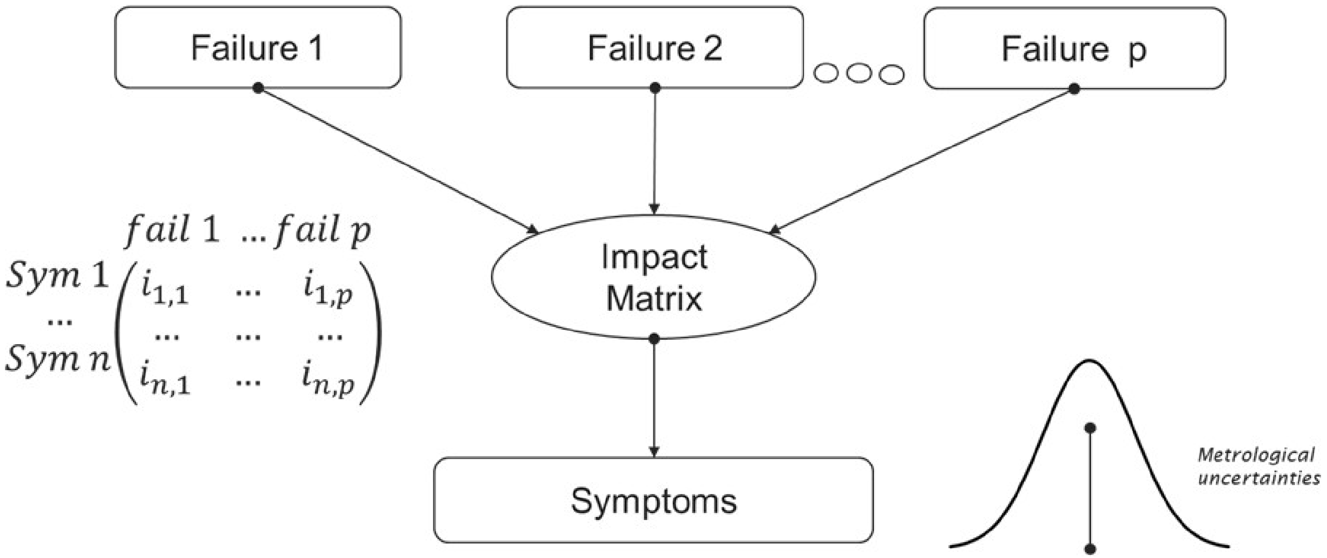
Physical based model

The model of a NPP is composed of around 12 000 equations and variable declarations.
It simulates both the nominal behaviour and failures of the plant



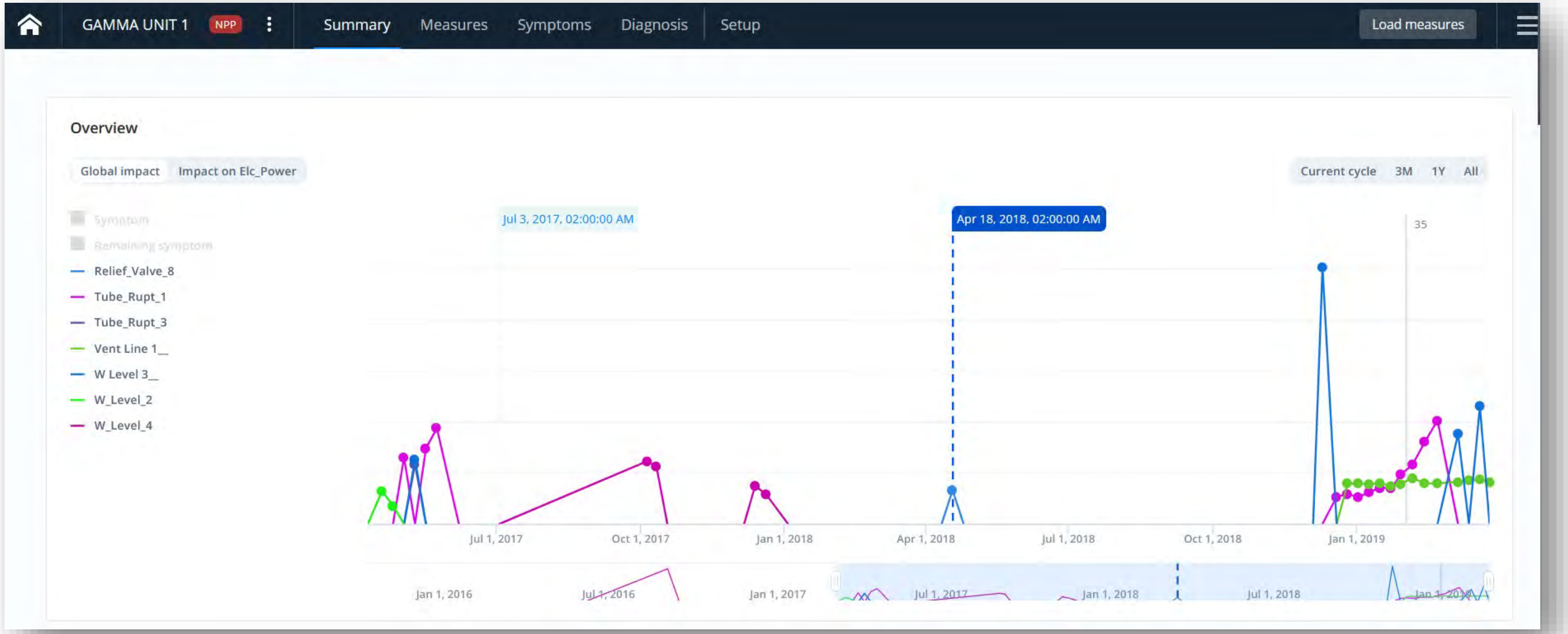
Inferential engine

The inferential engine performs a root causes analysis of underlying problems, through the analysis of the symptoms. It solves the following probability : *P (failure 1, failure 2, … failure p | Symptoms)*



The software

Software UX designed with operating teams
Reliability of 90% observed in 2020 - 2000 GWh energy loss detected - Over 300 users



Technological landscape

Monitoring of power plants aims at understanding any problem the plant during the operations

Soon we think that Physical Models and ML approaches will feed a unique diagnostic engine, making the best out of available process data

Explore	→	Detect	→	Understand
KPIs		Physical models		Root cause identification
Synoptics		Supervised ML		
Statistics		Unsupervised Machine Learning (APR)		
Data viz				

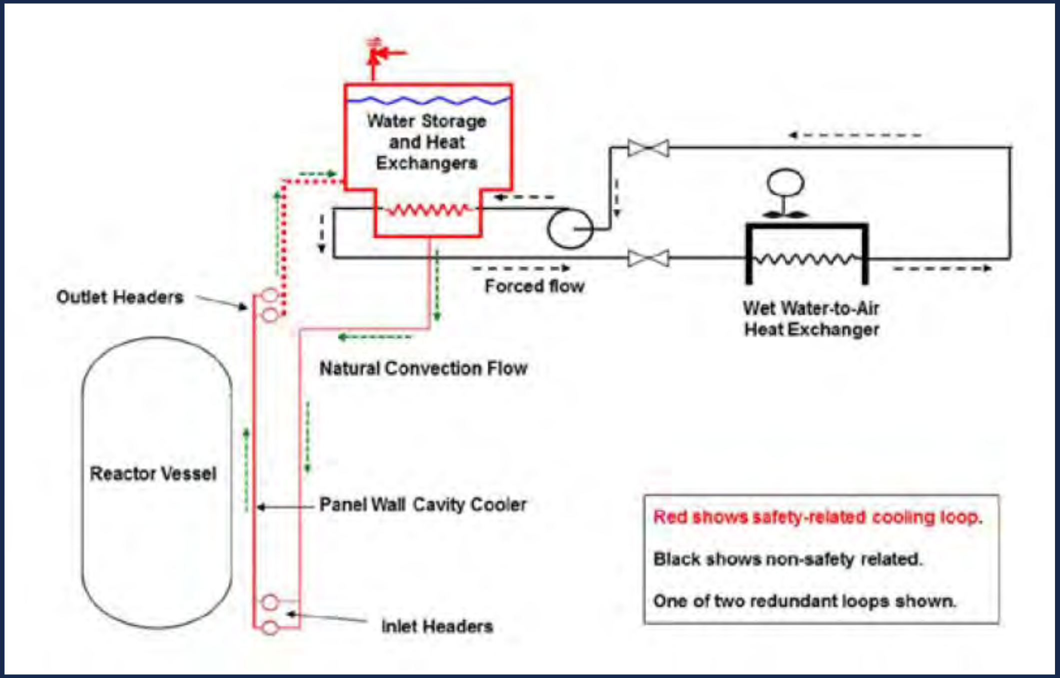
Production ready

Under development

Innovation with ARPA-E

Asset Performance and Reliability for the HTGR Reactor Cavity Cooling System Using Metroscope

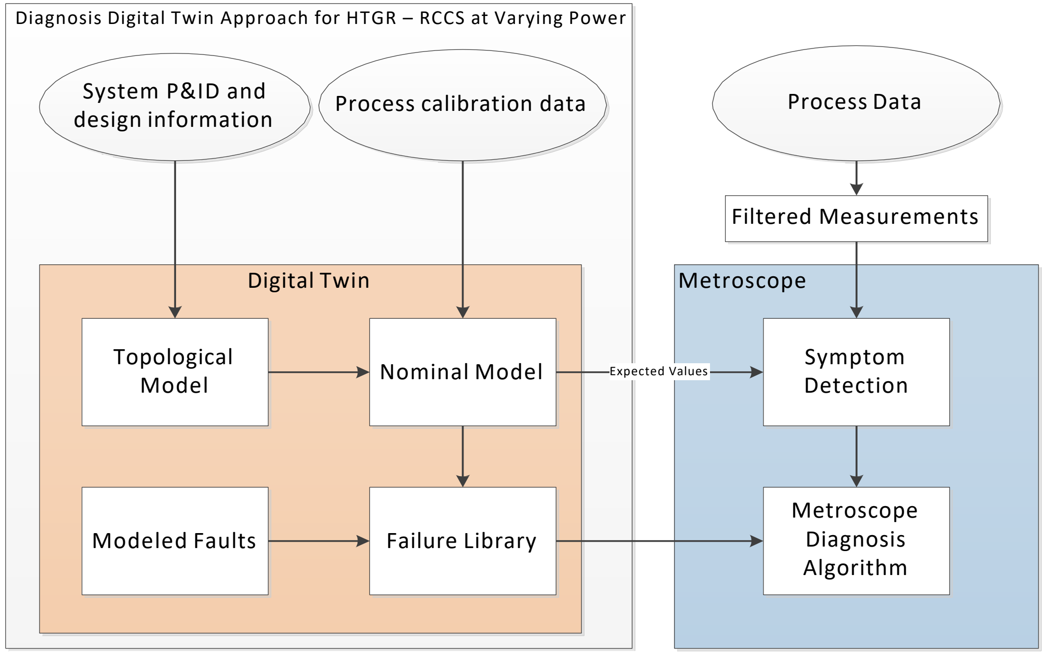
“If we change the digital twin, we change the diagnostics”



In a nutshell

Opportunity: Create trusted, reliable Digital Twin-based diagnoses of equipment problems for all types of plant auxiliary systems – beginning with advanced reactors

Success: Achieve a generalized approach to digital twins that can anticipate new faults over a variety of system modes and can be deployed in a commercial offer with demonstrated ROI



Contributors

framatome

Builds the digital twin and preforms the research work

metroscope

Provides diagnostics technology and software platform

Argonne NATIONAL LABORATORY

Provides cyber-digital asset test data and technical consultation

Eric Helm
Principal Investigator

Mary Beth Baker
Project Manager

Todd Matthews
TH Modeling and Application Developer

Pascal Brocheny
TH Modeling

Other current focus

Tomorrow Christophe Duquennoy will be speaking about diversification on cooling tower and return of experience at EDF

Digital twin are already ready for Gas Plants, Diesels Plants but also common industrial assets such as Data Center cooling processes

Over 50GW and 60 industrial units equipped worldwide

Thank you for your attention

Advanced Sensors and Instrumentations

Technical Session – September 14, 2021

Moderator: Hasan Charkas, EPRI

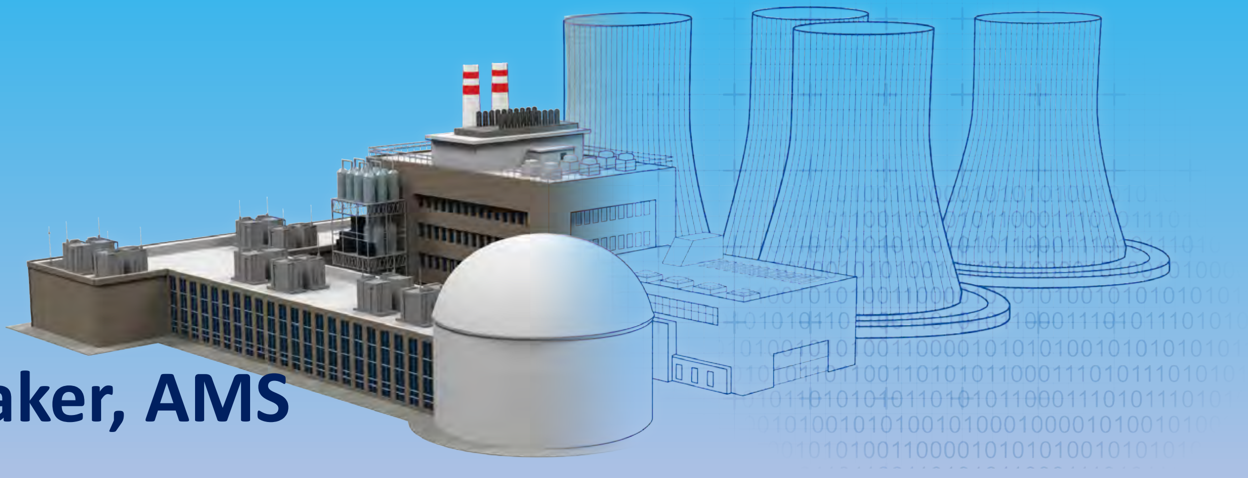
Pattrick Calderoni, INL

Jorge Carvajal, Westinghouse

Molly Strasser, Xcel Energy

Matt Hertel, X-energy

Hash Hashemian & Brent Shumaker, AMS



February 10, 2021

Pattrick Calderoni - INL
National Technical Director, Advanced Sensors and Instrumentation
Manager, Measurement Science Department

Advanced Sensors and Instrumentation for Digital Twin applications

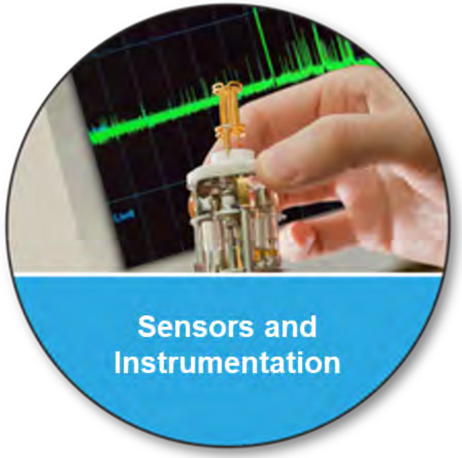
DOE Advanced Sensors and Instrumentation program

Mission

Address **critical technology gaps** for monitoring and controlling existing and advanced **reactors** and supporting **fuel cycle** development

Vision

ASI research results in advanced sensors and I&C technologies that are **qualified, validated, and ready to be adopted by the nuclear industry**



Reliable, cost-effective, real-time, accurate, and high-resolution measurement of the performance of existing and advanced reactors core and plant systems

Resilient, real-time transmission of sufficient amount of data for online monitoring and advanced data analytics

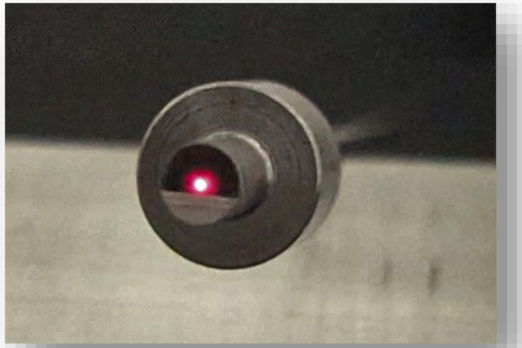
Machine learning and artificial intelligence processes to enable semi-autonomous operation and maintenance by design

Enable near real-time control of plant or experiments process variables to enhance performance

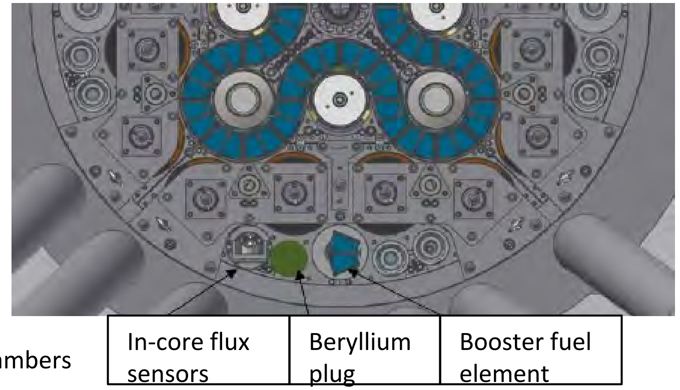
Program objectives FY22-25

- **Sensors** for advanced reactors
  - Develop advanced sensors (multi-mode; multi-point/distributed; miniature size and limited or no penetrations) and supporting technology (rad-hard electronics, wireless communication, power harvesting) for nuclear instrumentation
  - Demonstrate nuclear instrumentation performance in conditions relevant to advanced reactors (including irradiation)
  - Establish a supply chain for advanced reactor instrumentation (fabrication and services)

- **Instrumentation** for irradiation experiments
  - Provide real time instrumentation and passive monitors to measure local operational parameters (neutron flux, temperature, pressure, mechanical solicitations) in TREAT, ATR, HFIR and MITR experiments
  - Develop methods to characterize nuclear fuel and material properties (thermal conductivity, microstructure, mechanical behavior) during irradiation



Instrumented capsule for LWR fuel safety test in TREAT

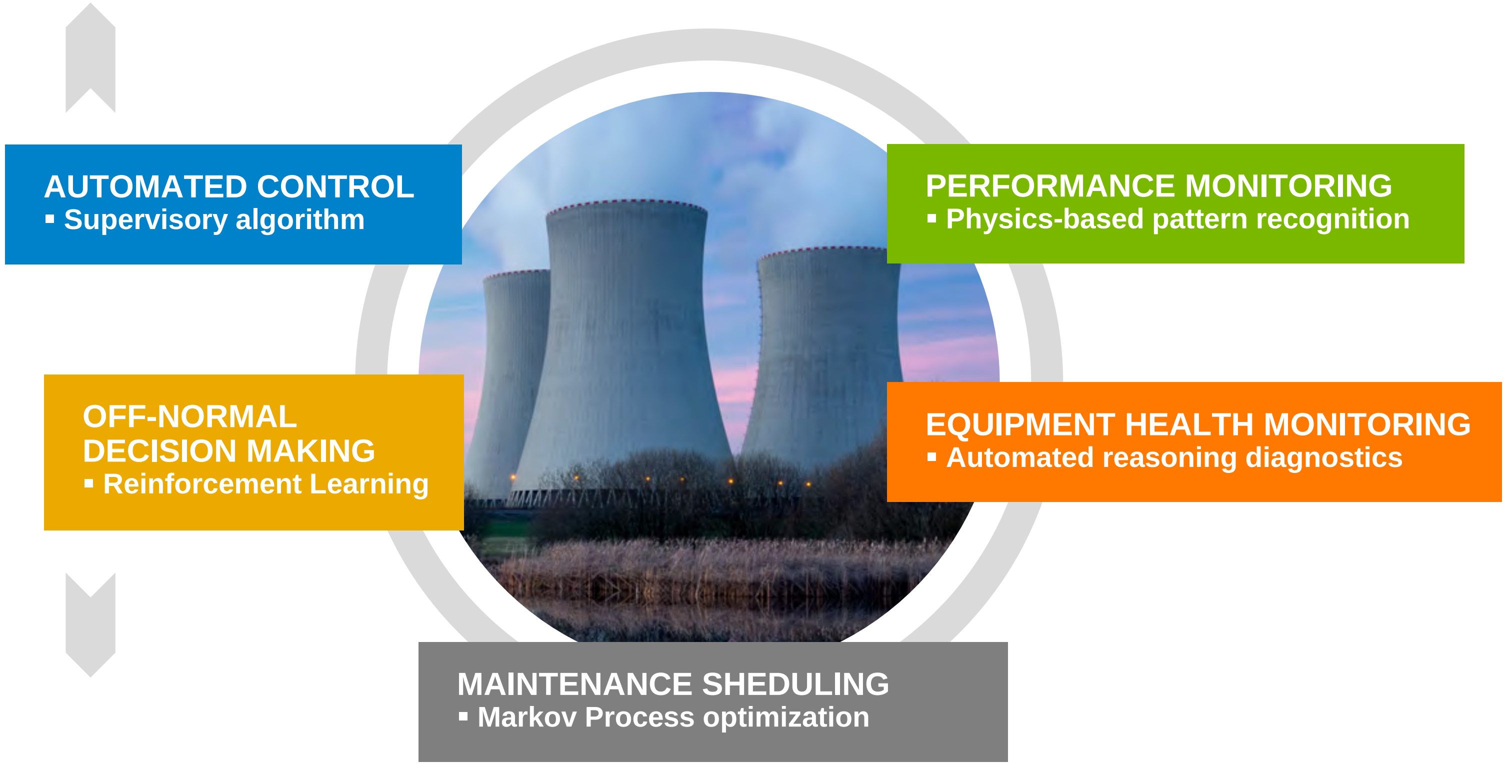


Neutron flux sensors (SPND, fission chambers and dosimetry) deployed in ATRC to characterize the I-loop booster performance

Program objectives FY22-25

- **Digital Technology for advanced reactors**
  - Integrate advanced sensors and instrumentation in Nuclear Digital Twins (NDT) with Hardware in the Loop simulation for the phased demonstration of performance-based control algorithms to enable autonomous operation
  - Develop condition monitoring technologies for anomaly detection, diagnostics, prognostics, and decision making that can operate on streaming data
  - Develop modeling and simulation tools for communication technologies to support integration with control systems

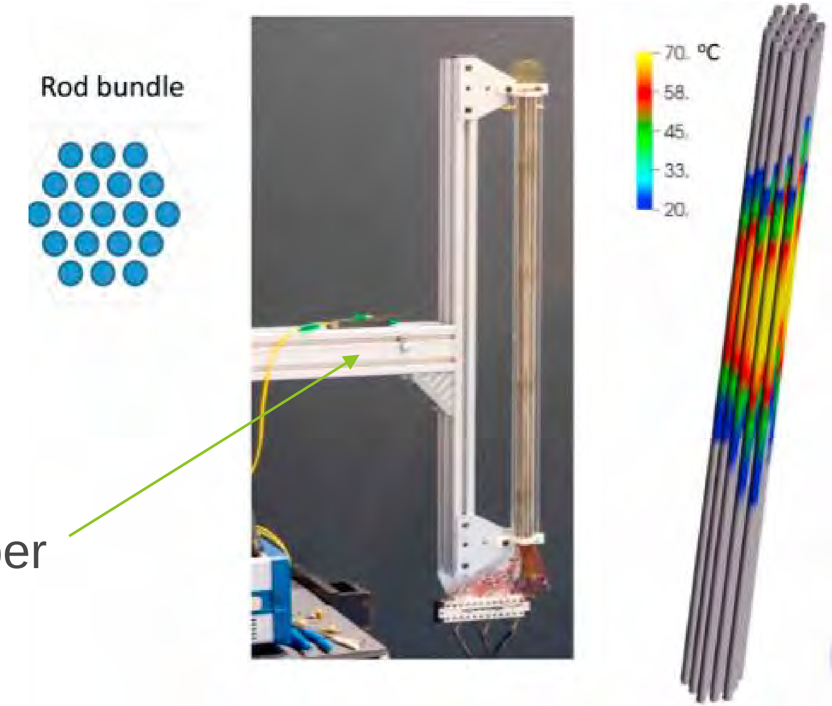
A logical progression towards sensor-based autonomous operation of advanced reactors



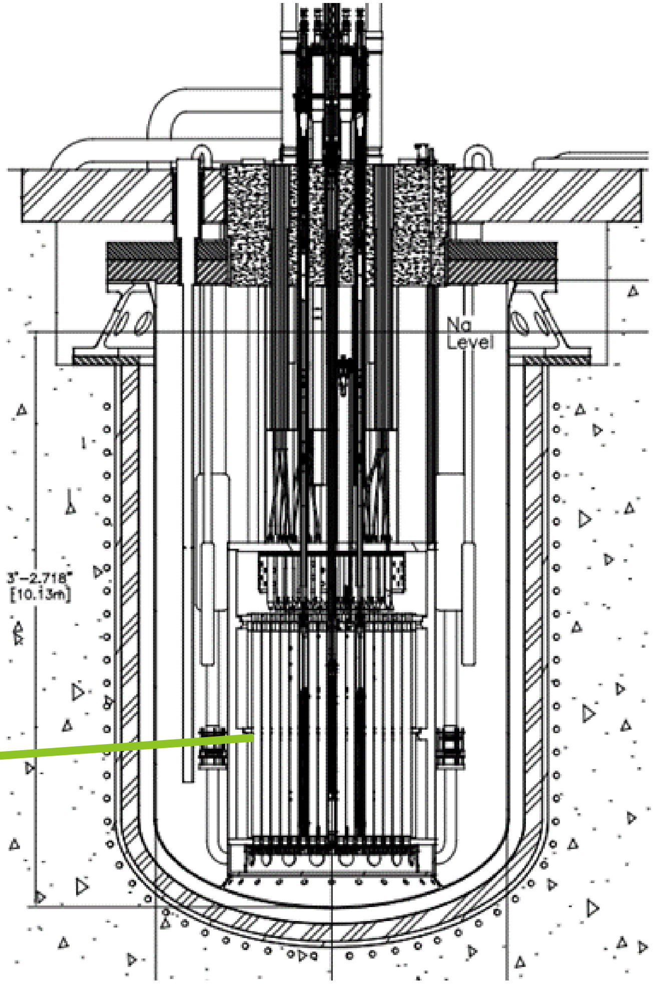
Sensing modalities

In-core

- Multi-point and distributed measurements of process variable fields
  - Core-wide estimation of temperature, power, approach to safety limits etc.



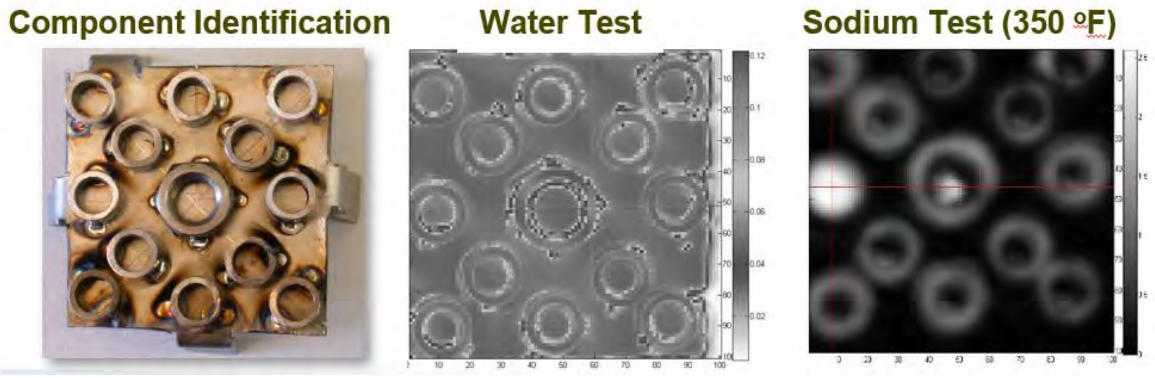
Optical fiber

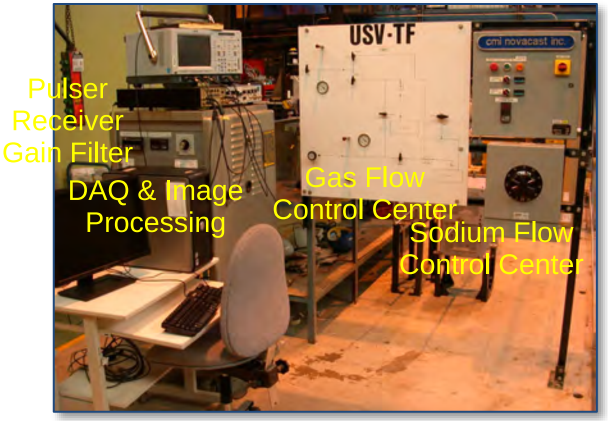


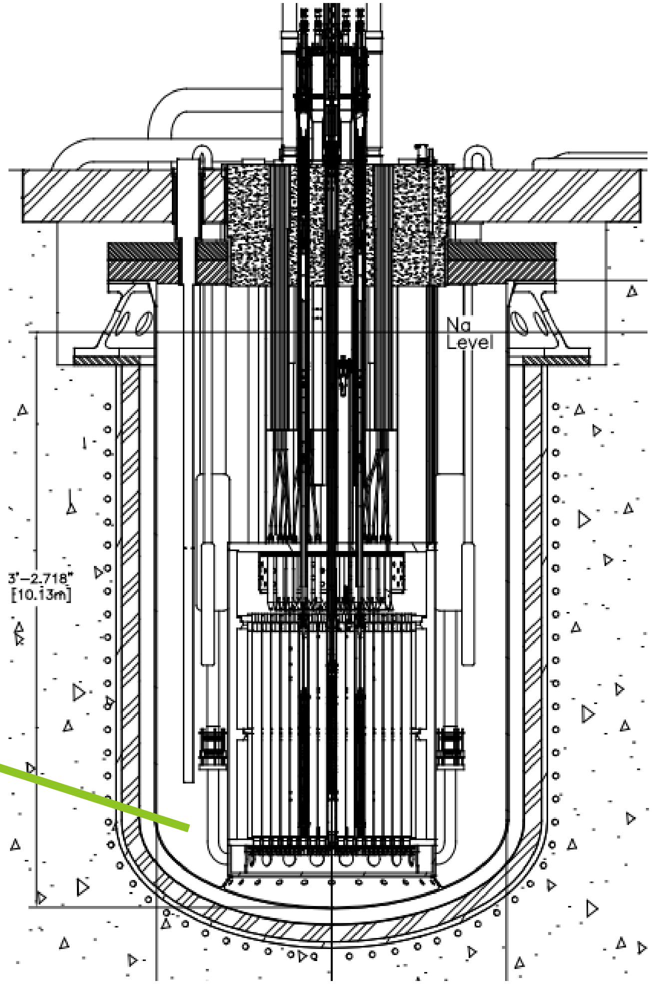
Sensing modalities

In-vessel

- Imaging opaque environments for in-service inspection



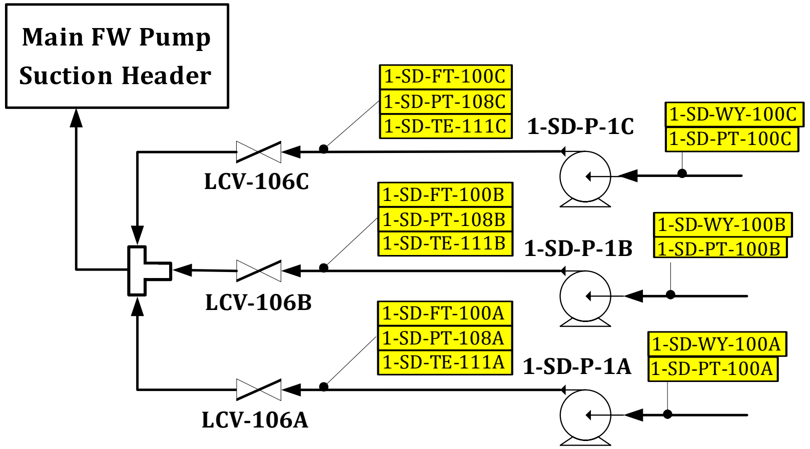


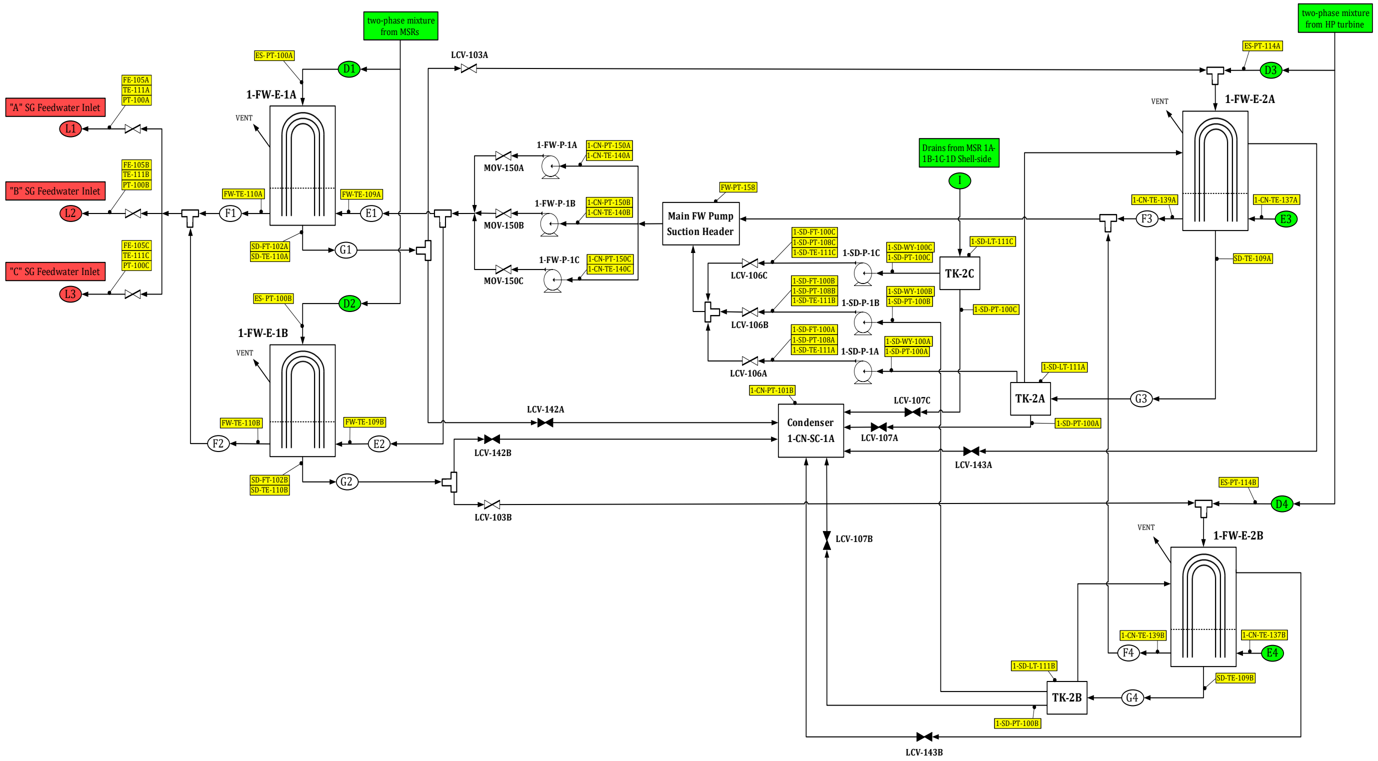


Sensing modalities

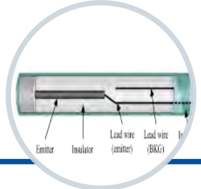
Ex-vessel

- Plant-wide sensing combined with process models for full state awareness



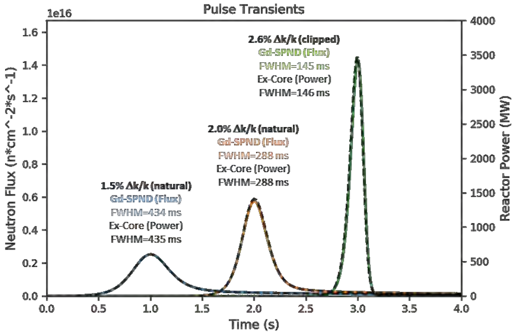


Technology demonstration – in-core neutron flux sensors

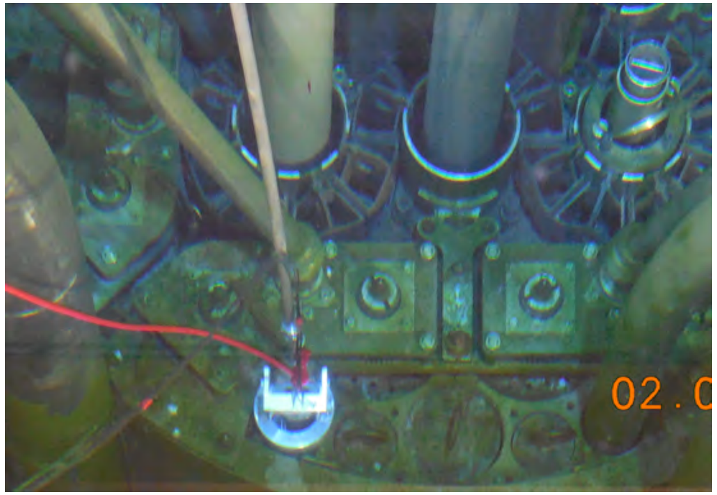


- Neutron and gamma detection
- Fast (Hf, Gd) and slow (Rh, Vd) time response
- Established design and fabrication process at INL
- Calibration and temperature compensation development in NRAD (summer 2021)
- Performance demonstration in TREAT, AGR5/6/7, ATRC, and MITR (FY22)

Self Power Detectors



TREAT pulse transient with Gd- and Hf-SPNDs compared to an ex-core detector.

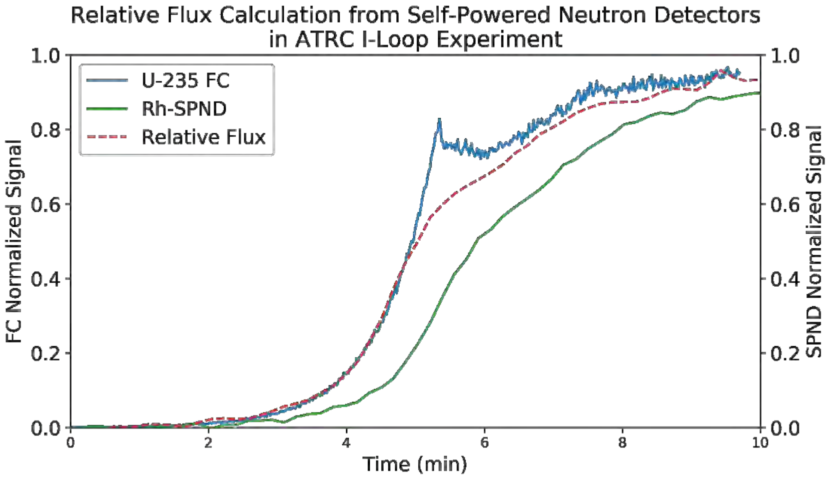


Test rig was installed in ATRC I-13 position on 2/11/2021 and irradiated for six hours.

- VTR project on fast spectrum SPND – design optimization using ORNL Geant4 code for Ta emitter
- NRAD test include fission chambers from CEA (Loic Barbot 2 months visit) and Photonis

ATR-C test objectives:

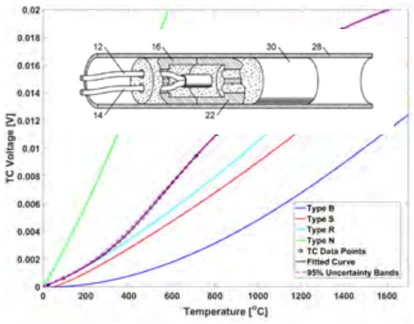
- **Testing instruments in representative environments (SPND, FC, dosimeters),**
- **Developing key domestic expertise for in-core instrumentation,**
- **Supporting characterization of test positions (Iloop booster)**



Technology demonstration – TCs for fuel and cladding materials

- Mo-Nb junction for high temperature applications (1600 C) and low drift under neutron irradiation
- Performance demonstration in AGR5/6/7 – highest temperature ever recorded in pile without drift (1482 C)
- Design optimization: corrosive environments, multi-point detection
- Commercialization: TCF with Idaho Labs Corp, ASTM standard and industrial qualification at AMS

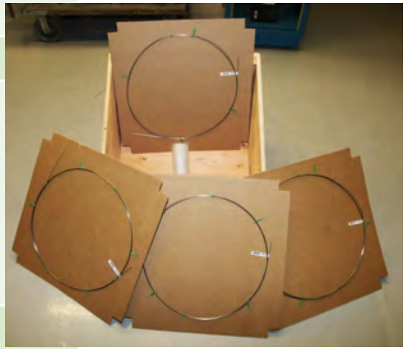
High Temperature Irradiation Resistant (HTIR) thermocouple



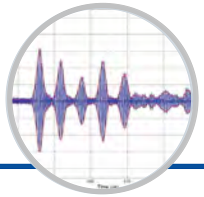
HTIR response compared with standard types

Table 1: Summary of performance parameters for the HTIR-TC

Performance Parameter	Performance Requirement Fuel Test Application	Performance Requirement Stand-Alone Application
Temperature Range	**Room Temperature - 1600°C**	**Room Temperature - 1600°C**
Accuracy	Not Specified	±1%
Drift	**3% for 4.5 x 10^{21} nvt (thermal)**	**3% for 4.5 x 10^{21} nvt (thermal)**
Life	**4.5 x 10^{21} nvt (thermal), or 10 thermal shocks (room temperature to 1600°C)**	**18 months or 4.5 x 10^{21} nvt (thermal)**
Mechanical Ruggedness:		
Rugged Junction	Rugged mechanical junction design	Rugged mechanical junction design
Bend Radius	Minimum of 0.5 inch	Minimum of 0.5 inch
Thermal Shock	5 sudden startups and 5 sudden shutdowns—each causing a thermal shock on the order of room temperature up to 1600°C	100°C/hr
Response Time	<0.5 seconds	<0.5 seconds

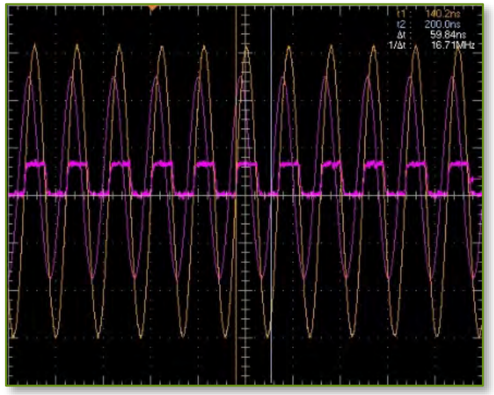


Technology demonstration – acoustic sensors



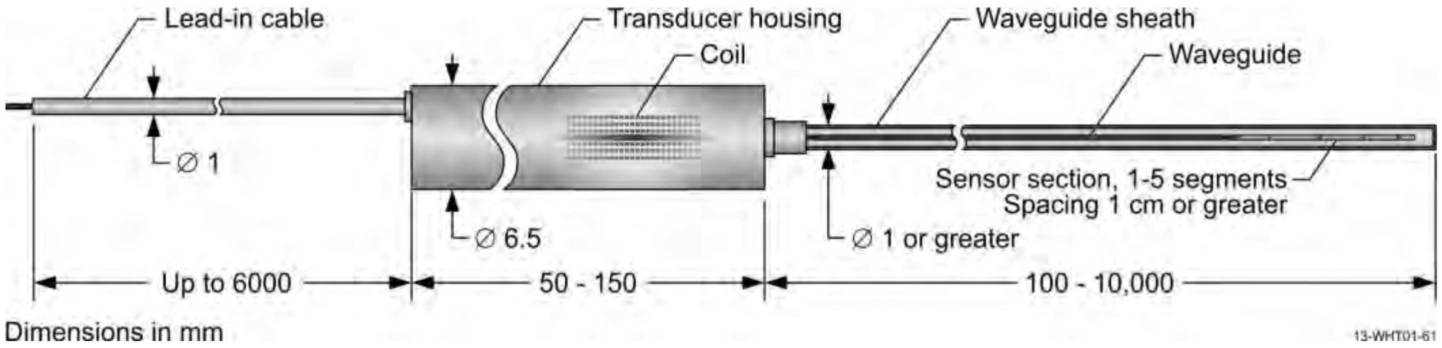
- Ultrasound based sensors enable distributed temperature measurements up to 2200ºC
- INL had demonstrated the reliability of magnetostrictive material transducers under irradiation
- Current research focuses on waveguide design optimization and unfolding signal response of distributed measurements

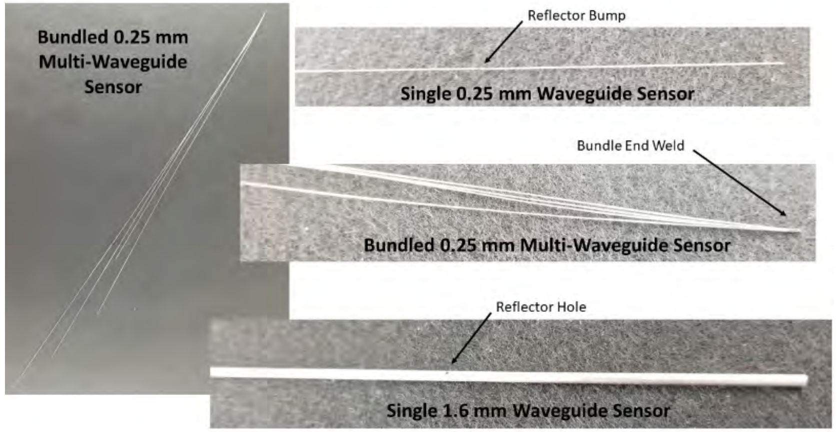
Ultrasonic Thermometers



UT operational window defined in high temperature furnace (up to 2200 C):

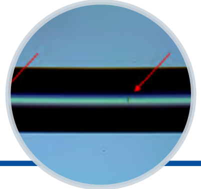
- Sheathed multi-waveguide materials: 316-stainless steel, lanthanated molybdenum, and zircaloy-4
- Non sheathed single waveguide materials: 316-stainless steel, molybdenum and tungsten





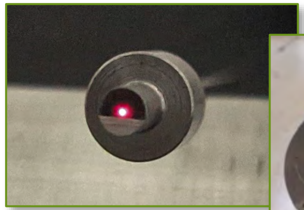
- UT performance modeling and design optimization is ongoing
- UT demonstration continues in irradiation experiments (DISECT in BR2, TREAT, MITR)
- Consolidating work on Surface Acoustic Wave sensors development based on radiation resistance materials (AlN, LiNbO)

Technology demonstration – optical fiber sensors



- Advanced sensor configuration and interrogation techniques to measure:
    - Distributed temperature, strain and vibration
    - Fission gas pressure and composition
- Engineering solutions for sensor packaging, pressure feeds
- Active compensation techniques for OF sensors operating in radiation environments

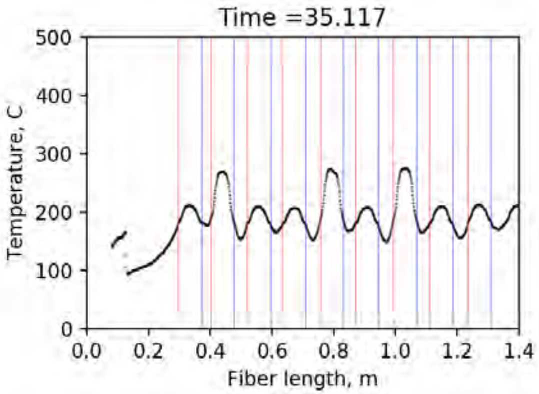
Optical Fibers

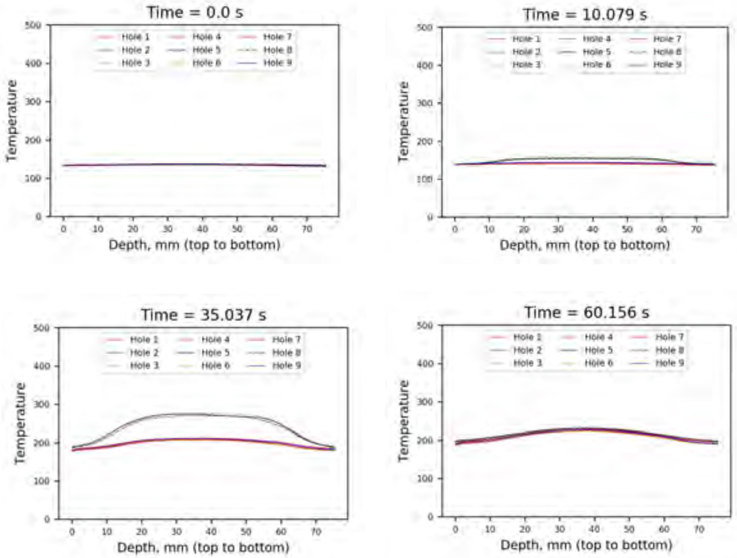


Prototype optical fiber pressure sensor based on Fabry-Perot interferometry

Optical Frequency Domain Reflectometry (OFDR) for temperature mapping of TREAT heat sink

Distributed Temperature Sensing (DTS) for DRIFT experiment in TREAT: temperature profile along the length of a **single** fiber

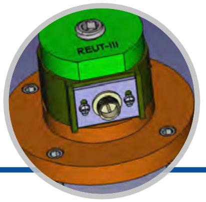




Spatially resolved time dependance:

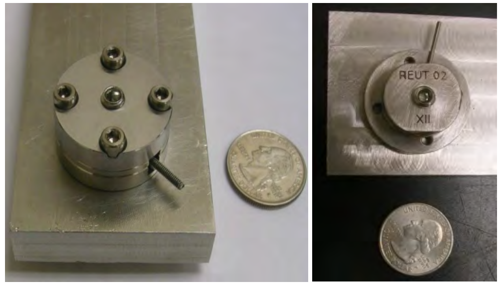
- Black traces are radially closer to fuel
- Excellent symmetry
- Effects of heat sink become more important after 1 min

Technology development



- Ultrasonic transducers and sensor systems operating in extreme conditions with long operational life
- The use of Z-cut LiNbO3 piezoelements coated with Cr/Au thin film allows high temperature operation (800 C) and rad tolerant
- Broadband transducer (bandwidth up to 30 MHz) now being coupled with temperature, pressure, flow and SHM acoustic emission sensors

Radiation Endurance Ultrasonic Transducer, X-wave Innovation Inc



REUT prototype, (left) Version 1, (right) Version 2, and (up) CAD model of Version 3

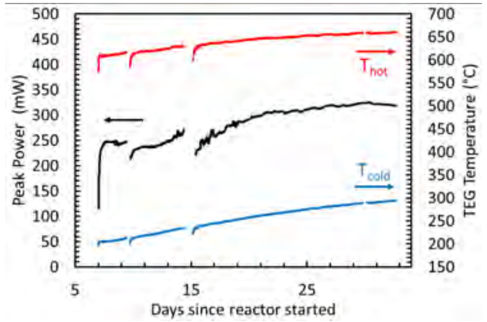
Courtesy of Uday Singh and Dan Xiang, SBIR grants recipients

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

- High-temperature & high-power-density capability for in-core or in-vessel power harvesting
- Technology development through ASI funded project at the University of Notre Dame (Yanliang Zhang)
- Performance demonstration in MITR though NSUF funded project

Thermoelectric generators (TEGs) for power harvesting

KEY METRICS	Half-Heusler TEG	COMMERCIAL TEG
Power density (W/cm^2)	2-3	0.2-0.3
Max Operating temp	650 °C	250 °C



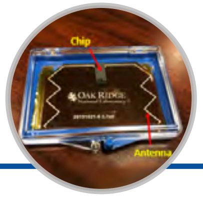
- Automated technology coupled with advanced data analytics for assessing the health of pipes in nuclear power plants as the pipe material degrades due to corrosion
- Combines innovations in materials for sensing both chemical and mechanical degradation with statistical algorithms based on Bayesian modeling.

Diagnostics and Prognostics of Corrosion Processes in Pipes

Material removal on inside of elbow

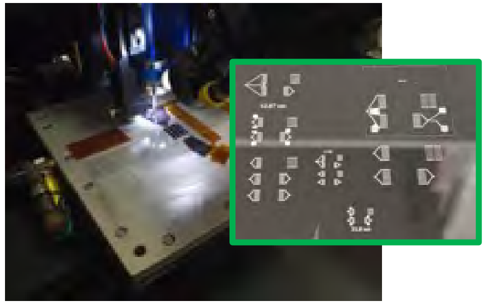
Thermocouples installed on outside diameter

D. Adams, Vanderbilt University
Y. Zhang, University of Notre Dame
V. Agarwal, Idaho National Laboratory



- Passive wireless sensor technology based on a network of digitally printed radio frequency (RF) surface acoustic wave (SAW) sensors
- Enable multi-point and multi-mode sensing (temperature, hydrogen gas, voltage, and current)
- Demonstration included two-antenna relay for communication / sensing through RF-opaque materials

Direct Digital Printing of Passive Wireless Sensors



Printed SAWs developed and fabricated at ORNL – courtesy of Tim McIntyre

Idaho National Laboratory

Non-Intrusive Temperature and Pressure Wireless Sensor and Transceiver System for Extreme Environment Applications

Jorge Carvajal, Fellow Engineer

September 2021

Presented at “Enabling Technologies for Digital Twin Applications for Advanced Reactors and Plant Modernization” workshop

Sensor Applications and Benefits

In-Rod Instrumentation

- Non-intrusive real-time data
- Accelerates new fuel development
- Accelerates new fuel licensing
- Increase operating margins at plants
- Enhances instrumentation for DOE test reactors

Spent Fuel Storage

- Both Commercial & DOE canisters
- Accelerates licensing of casks
- Improved efficiency of interim storage
- Develop basis for dry storage of new fuels
- Utility fuel handling no longer reliant on conservative models:
  - Fuel can be removed from pool earlier
  - Reduced drying cycles
  - Increased heat load margins in storage
- Enables canister surveillance monitoring

Other Applications

- Applications requiring wireless real- time surveillance in extreme conditions
- Nuclear safeguards
- Nuclear defense
- Gas pipelines
- Gas storage
- Etc.

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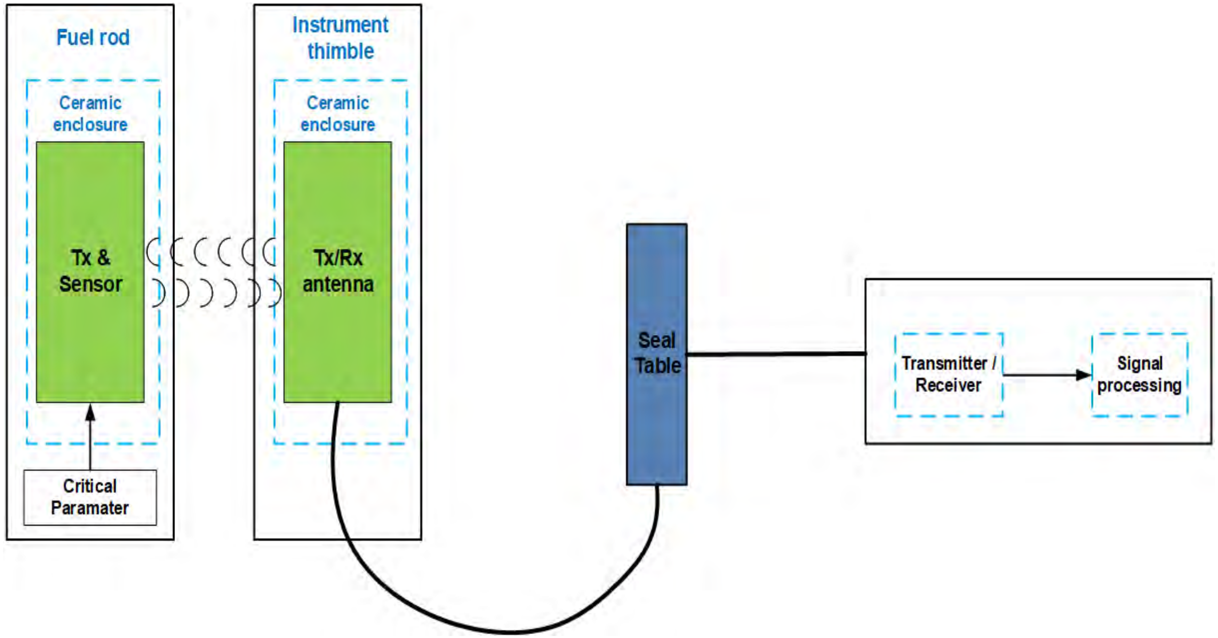
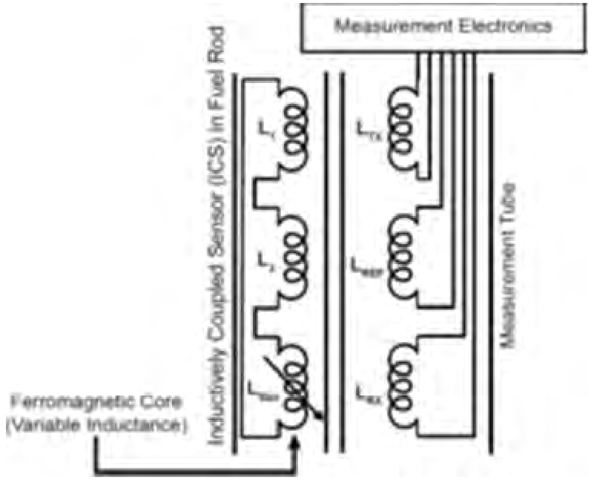
In-Rod Sensor System Introduction

- Wireless sensor located in a fuel rod provides real-time data
  - centerline fuel pellet temperature
  - pellet elongation
  - rod internal pressure
- Facilitates licensing of new fuel products
- Enhances plant operation through improved utilization of margins
- Similar to in-rod data collection techniques used in test reactors such as Halden but with wireless data transmission
- Delta in the coupling amplitude is proportional to measurement of interest
- U.S. patent application serial No. 16/214445 and 16/564150





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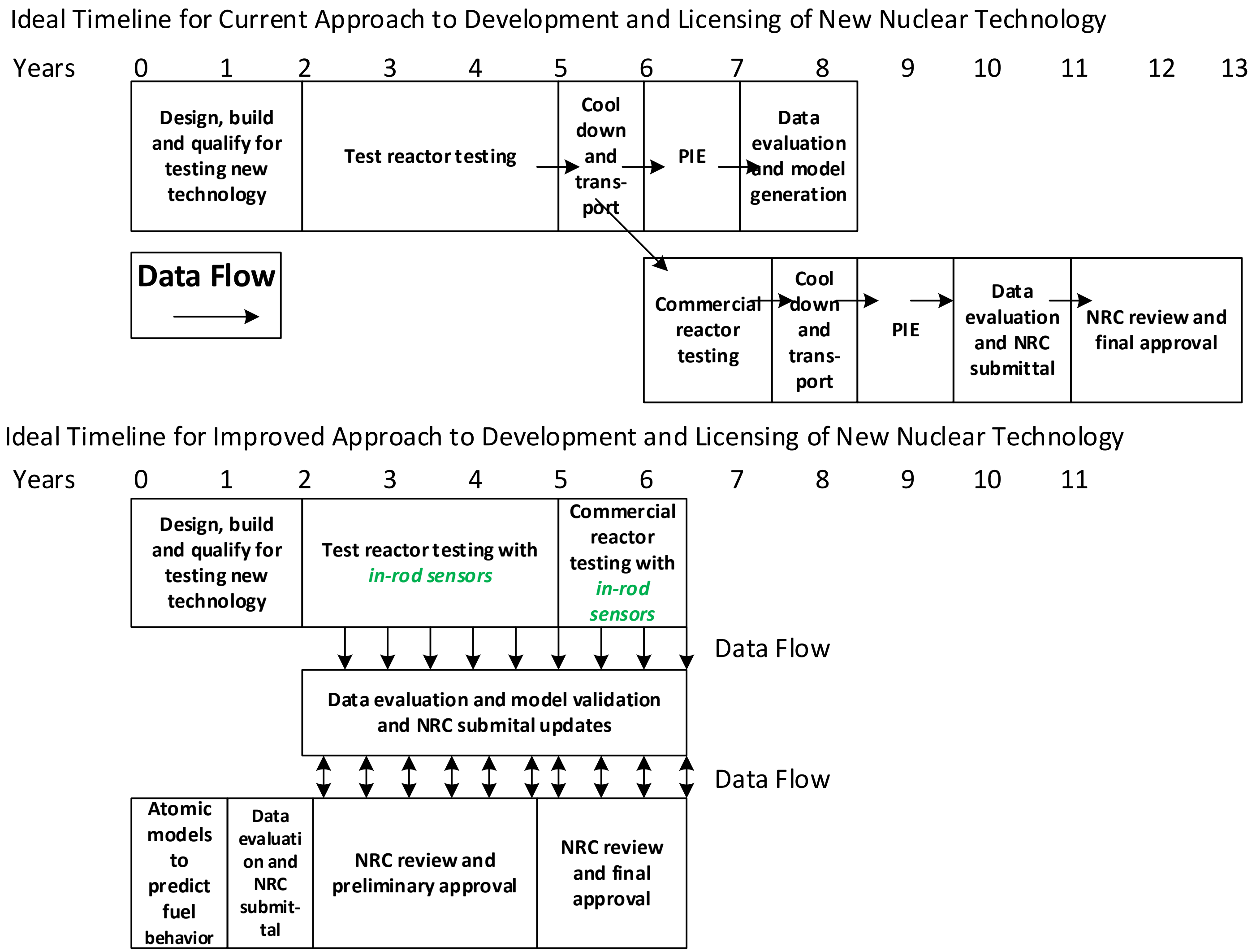
Benefits

- Non-intrusive real-time data instead of the typical “cook and look” significantly accelerates development
- New approach significantly reduces time for licensing, increases reliability of models and therefore licensing decisions
- Significant enhancement to in-core instrumentation for test reactors, especially National Laboratory Reactors (e.g. INL ATR and ORNL HFIR)



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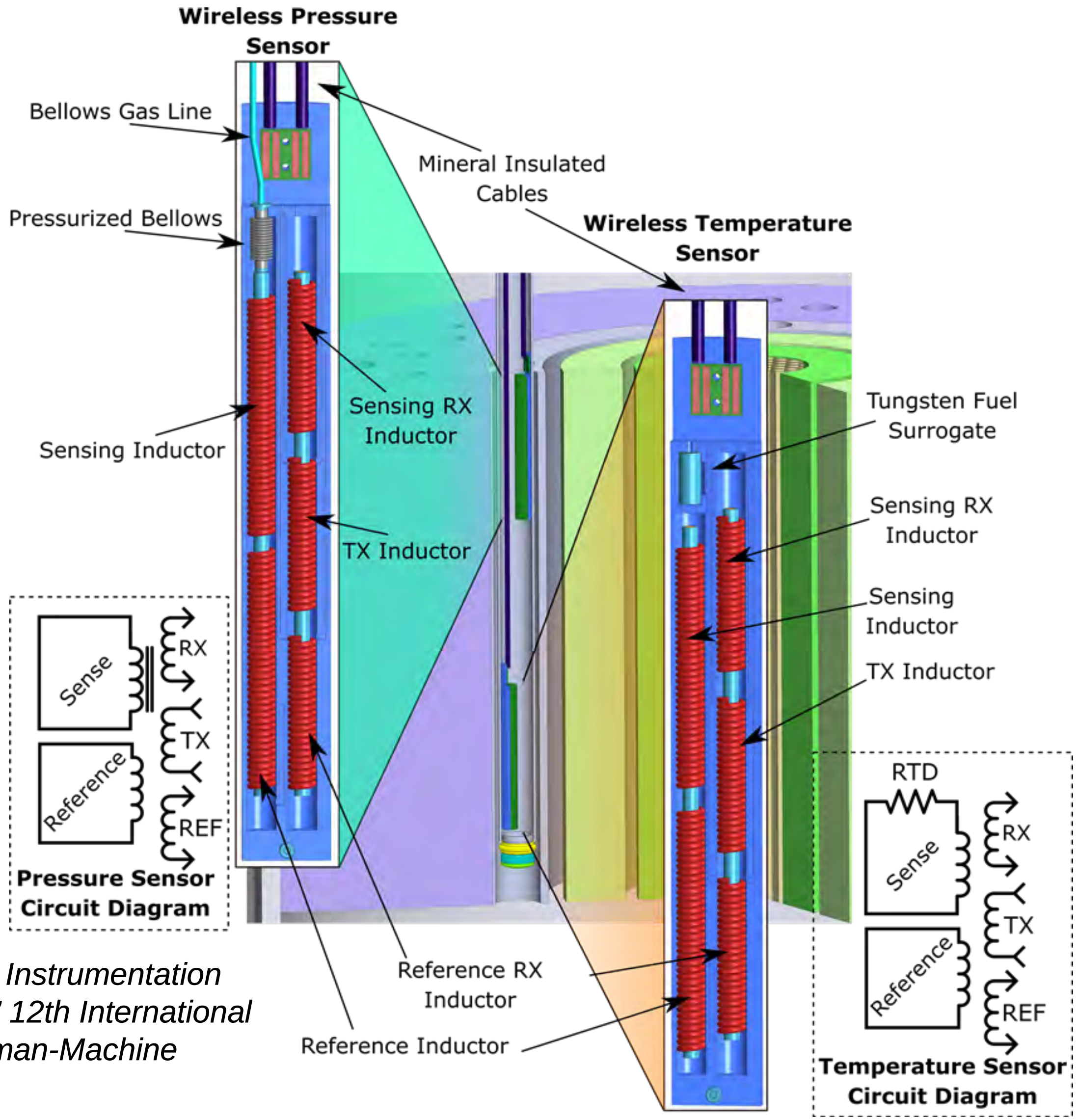
In-Rod Sensor System Next Step

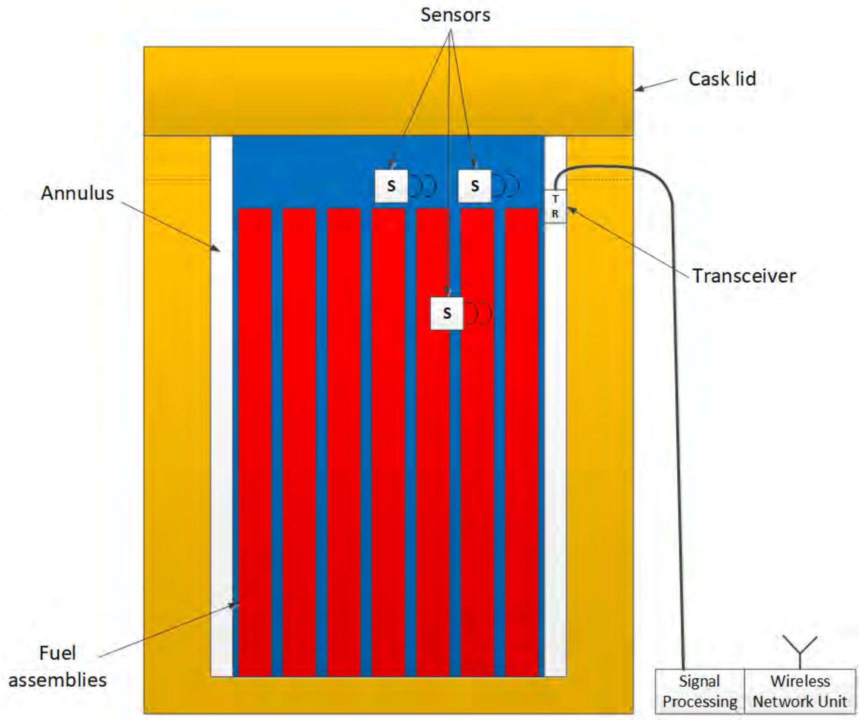
- ORNL HFIR Irradiation & PIE (NSUF project)
  - Temperature & Pressure sensor to be installed in HFIR late 2021
  - Expected temperature range 300°C - 500°C
  - 5 cycles, total dose ~$3X10^{21}$ n/cm^2
  - Fuel surrogate simulates temp source
  - External gas injection simulates rod internal pressure
  - Continuous data collection
- WEC Long Term Temperature test
  - Two sensors to be installed in autoclave at prototypical fuel rod pressures
  - Held at ~400°C for 6 – 12 months
  - Continuous data collection



P. Mulligan, "In-Core Neutron Flux, Temperature, And Pressure Instrumentation For The Wire-21 Experiment In The High Flux Isotope Reactor," 12th International Conference On Nuclear Plant Instrumentation, Control, and Human-Machine Interface Technologies (NPIC & HMIT), June 2021.

Dry-Cask Sensor System Introduction

- Technology derived from the Westinghouse Accident Tolerant Fuel (ATF) In-rod sensor development
- Wireless sensor located inside dry cask steel canister provides real time data such as temperature and pressure
- Sensor does not require penetrations to the canister
- Multiple sensors can be interrogated simultaneously
- Sensor lifetime > 40 years (based on dry cask 3.5 Grad 40-year TID estimate).
- Long term maximum operating temperature 425˚C
- U.S. patent application serial No. 16/448706



"S" represents the sensors and "TR" represents the transceiver

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For more information on our **SENTRY™ spent fuel management system**, visit us at https://www.westinghouse**nuclear**.com/d-d/spent-fuel-services

Customer Value – Utilities, NRC, DOE

- Online data potentially enables the reduction in time and cost of spent fuel management. Utilities are no longer reliant on overly conservative peak clad temperature (PCT) models, which prescribe:
  - **When** fuel is removed from spent fuel pool
  - **Heat load margins** in dry storage canisters
  - Drying cycle **duration**
  - Canister **susceptibility to degradation** (e.g. chloride induced stress corrosion cracking, etc.)

- Accelerates **dry storage** and **transportation** of advanced fuels
  - NRC will require data to develop technical basis of dry storage of new materials
  - Synergy with high enrichment, high burnup, and ATF

- Dry cask inventory at utility is **growing** given the lack of a permanent repository location

Dry-Cask Sensor System Next Step

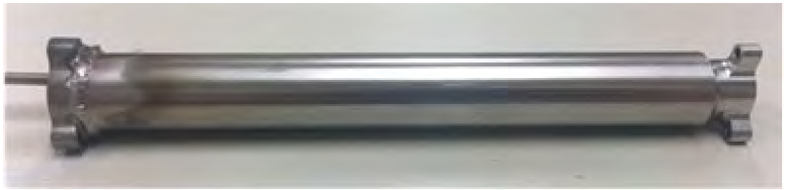
WEC/EPRI Joint Sensor Demonstration Project Objectives:

Accelerate development and qualification of remote wireless sensors for use in extreme environments, e.g. high radiation fields and temperatures

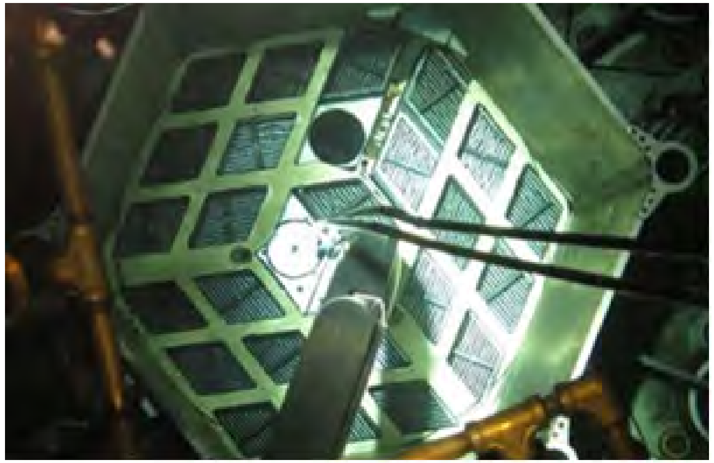
- Phase I: Establish Design Criteria
  - Develop Sensors Performance Requirements Document
  - Identify Key Objectives, Functional Criteria, Survivability Needs, etc.
    - Separate Dry Storage, Transportation, and Disposal Considerations
- Phase II: Laboratory Scale Testing and Qualifications
- Phase III:Full Scale Testing and Validation
  - Canister Mockups and Loaded Canister Demonstrations

MITR Test (April 2019)
Power cycling & temperature measurement results

Ceramic enclosure housing sensor components

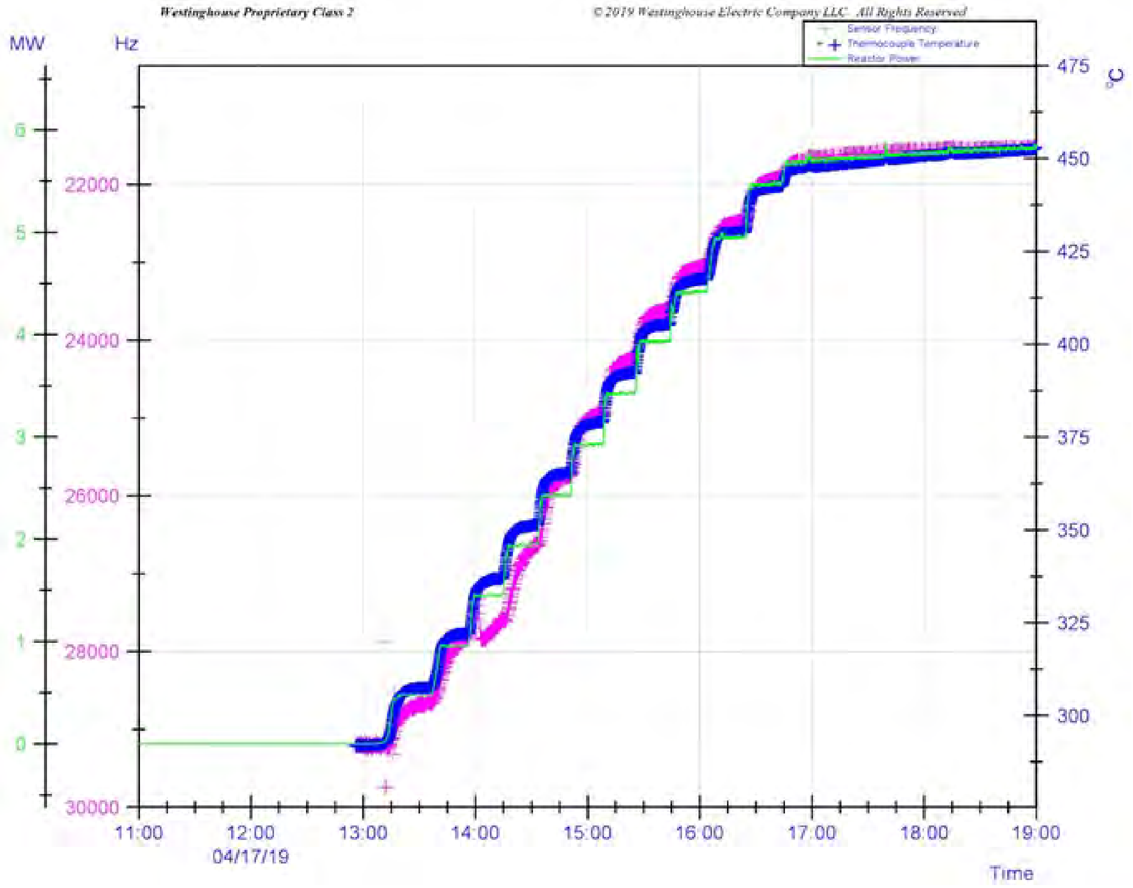


SS enclosure holds ceramic enclosure within autoclave PWR loop



MITR Core with water loop position open

Neutron flux = 1e14 n/cm^2/sec
Coolant temperature = 300°C
Component max temperature (gamma heating) ~ 500°C



Sensor frequency accurately tracks internal thermocouple and reactor power

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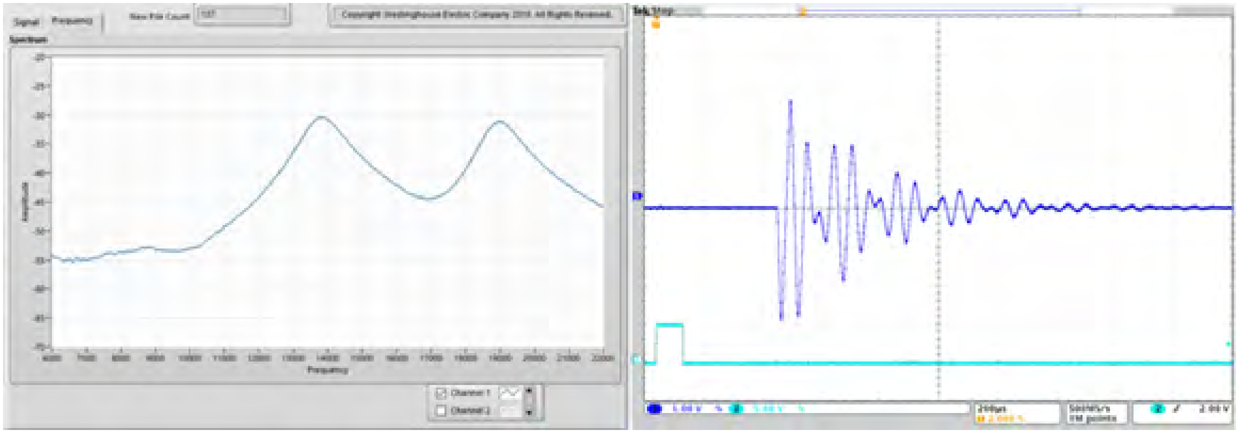
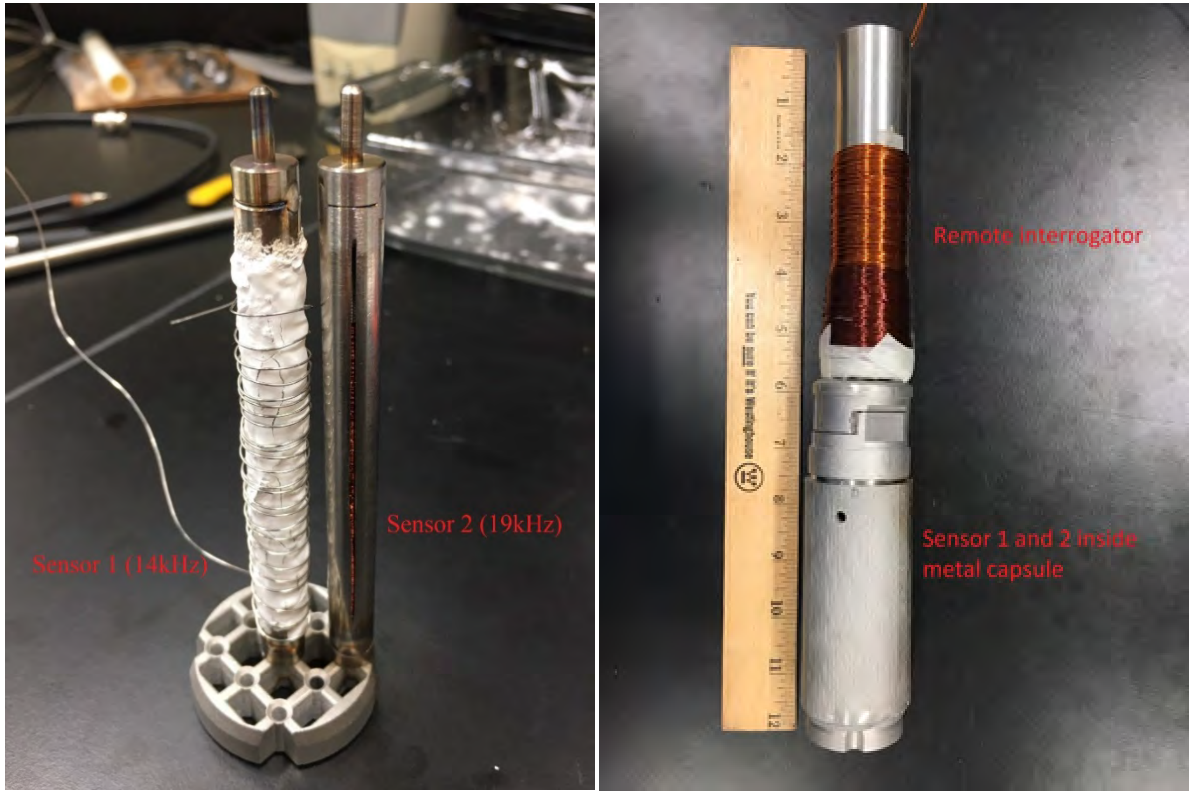
Functional Test – Multiple Sensors

- Two resonant sensor circuits assembled in a metallic enclosures and remotely interrogated
- Received signal cannot be resolved in time domain. FFT necessary to resolve signal



Multiple sensors in the frequency (left) and time (right) domain



Sensors at two unique frequencies with remote interrogator

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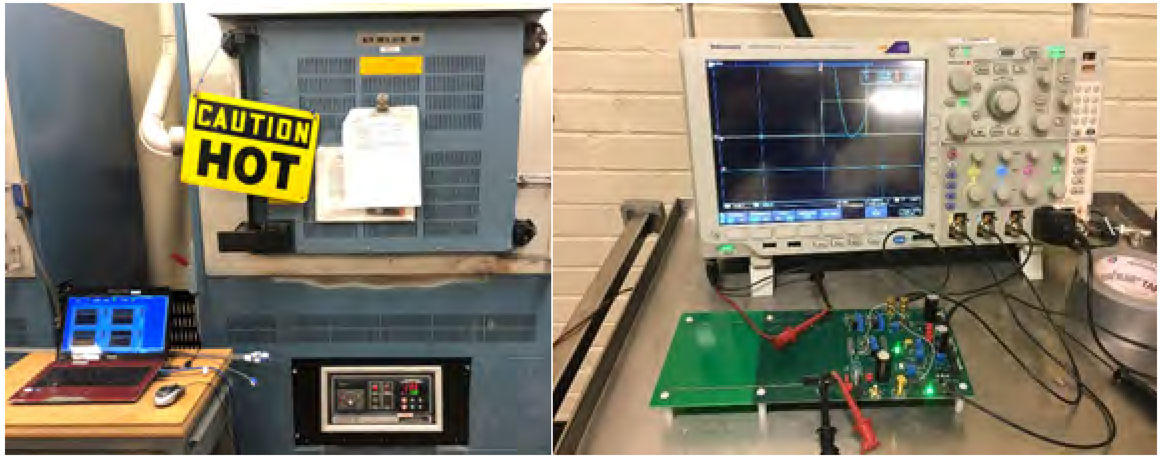
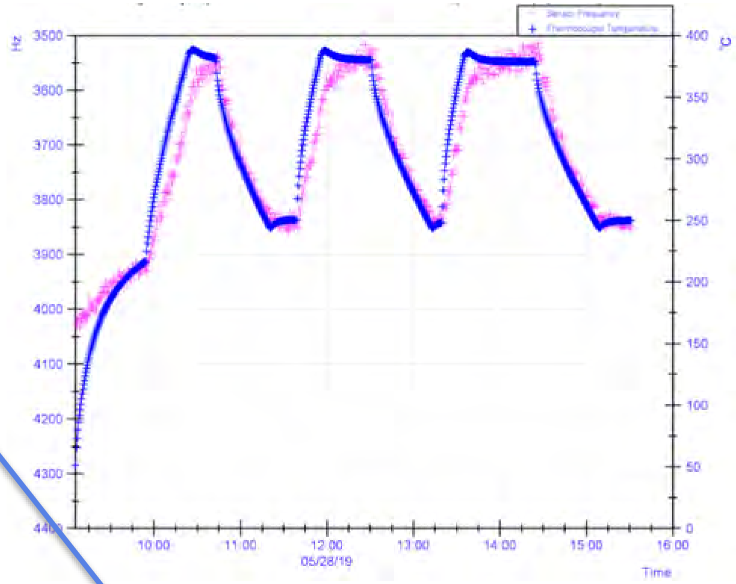
Temperature & Gamma Irradiation Test

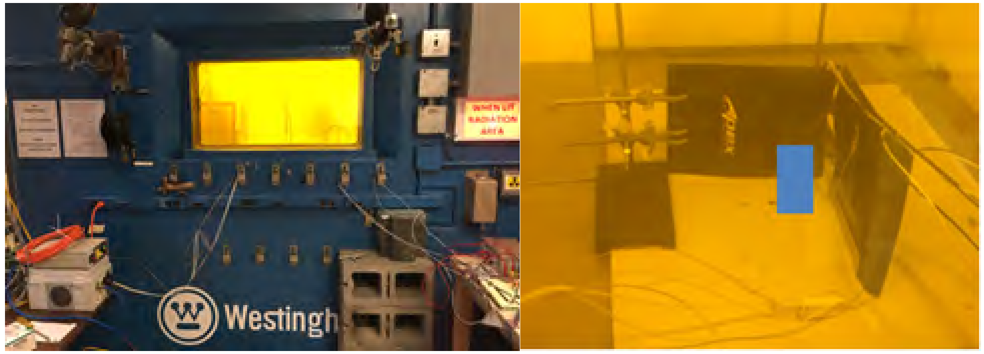


High temperature oven & data acquisition system



Blue – TC

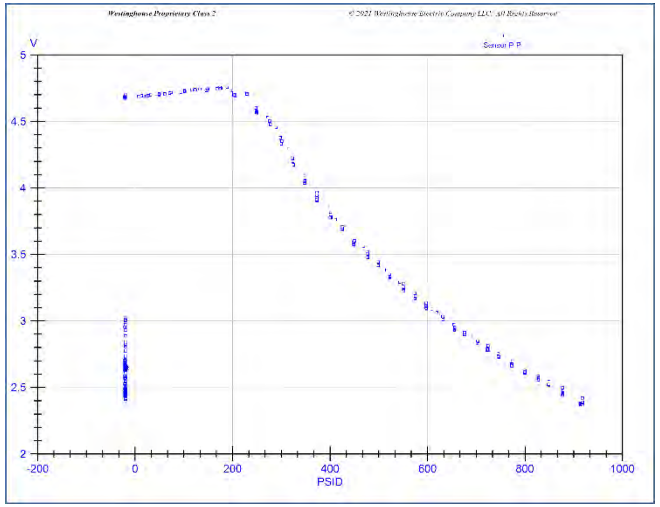
Purple - Sensor



Gamma testing: Clean Hot Cell exterior (left) and interior (right)

-Minimal to no change in inductance values

-Slight increase in inductor's series resistance



Sensor signal vs. pressure

Thank you!

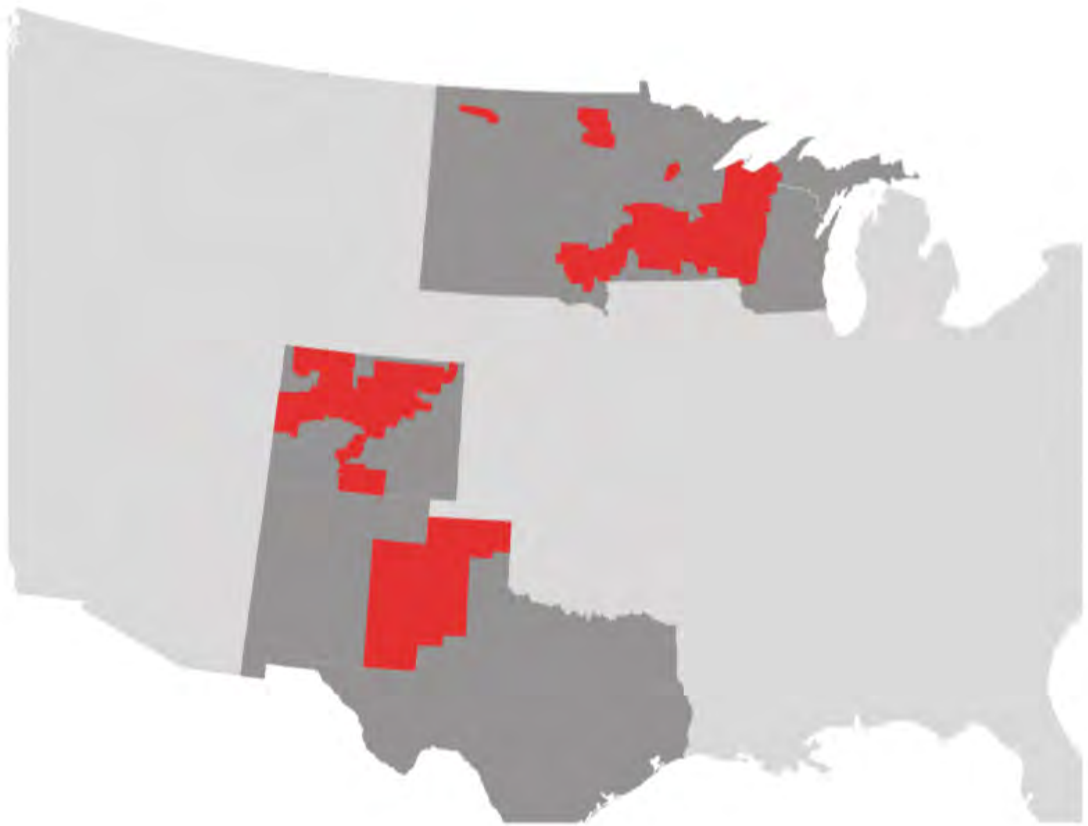
Jorge Carvajal, carvajjv@westinghouse.com

Data Analytics and Remote Monitoring Integration

Molly Straser

Xcel Energy Company Overview

- **3.7 million** electric customers
- **2.1 million** natural gas customers



Xcel Energy®

Monitoring & Diagnostics (M&D)

Utilizing advanced analytics to proactively identify equipment risk, leading to reduced maintenance expense and unplanned outage impact, while enabling condition-based maintenance practices and operational excellence.

Advanced Pattern Recognition (APR) predictive analytics identify statistical deviations of modeled operating parameters.

Xcel Energy Monitoring & Diagnostics (M&D)

2014: Inception - 7 plant pilot program

2016: Major thermal units included:14 plants, 35 units

2017: Expansion to wind, 3 nuclear units

2020: 13,135 MW thermal generation

- 846 MW Wind generation, 2000 MW Wind EOY 2020

Predictive Analytics - Mechanical condition monitoring

- Failure modes limited by plant instrumentation

$29M avoided and hard savings through Q1 2020

- >4000 actionable advisories

M&D Success & Results

Operational Excellence

- Excessive desuperheat spray leading to HRSG tube damage
- Feedwater regulator closed resulting in low fuel gas temp – damage prevented
- Excessive feedwater heater draining – low levels, erratic levels
- Poor condenser performance, efficiency impact

Avoided Cost Examples

- Wind turbine gearbox – numerous early gear defects avoiding gearbox replacement ~ $350k per event
- Air heater guide bearing temperature increase, lube oil supply problem corrected
- Steam turbine vibration changes, balancing prior to forced event
- Fan bearing temperature increase, cooler operation corrected preventing failure
- Boiler acoustic leak indication, operation mitigation until scheduled outage

Direct Savings Examples

- Major maintenance deferrals, known good condition and performance, i.e., BFP overhaul elimination ~ $250k
- Capital budget reduction for wind turbine gearbox replacements, early fault identification and known condition
- Condition based maintenance – known good condition allows for delay or elimination of scheduled or calendar-based maintenance – expansion priority

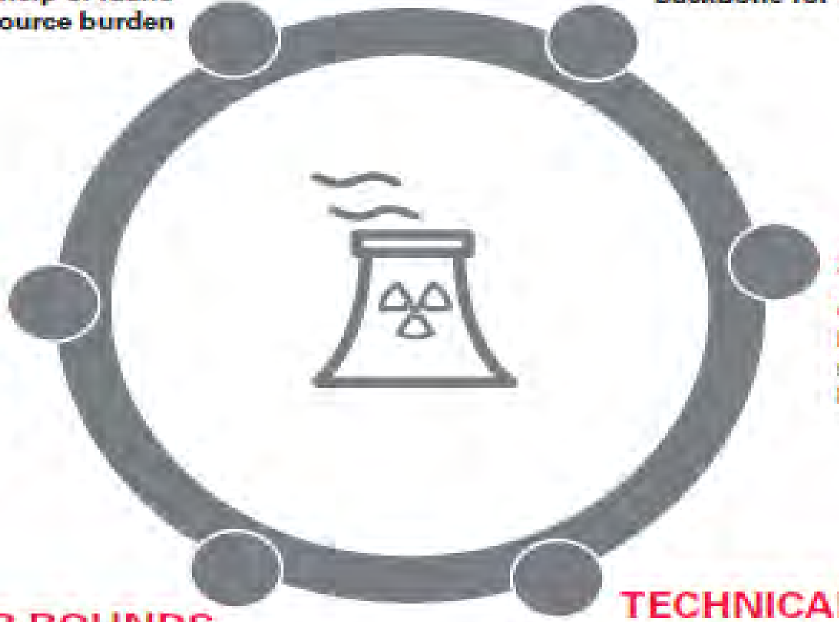
Xcel Energy®

Nuclear Focus

VERIFYING COMPLIANCE THROUGH TECHNOLOGY

CORRECTIVE ACTION PROGRAM
Improved CAP screening tools with the help of Idaho National Laboratory reduces the resource burden

INFRASTRUCTURE
Permanent Wi-Fi in plants serves as backbone for technological improvements



PREVENTIVE MAINTENANCE
Maintain equipment at the optimal time using data trends from new wireless sensors and advances in machine learning

STAKEHOLDER AUDITS & INSPECTIONS
New process for automated data sharing supports inspections and key performance indicators

OPERATOR ROUNDS
Critical data for trending plant performance with wireless sensors and machine learning application developed with USA

TECHNICAL SPECIFICATION SURVEILLANCES
Increased public safety by monitoring plant equipment with wireless sensors ensures continual compliance with technical specifications

Xcel Energy

Xcel Energy Nuclear Innovation: Sensor Infrastructure

Mechanical Sensors

- Vibration Sensors
- Wireless Gauge Readers
- Void Monitoring
- Remote Radiation Mapping
- Valve Position Indication

Electrical Sensors

- EPRI Acoustic Monitors for Transformers
- EPRI Disconnect Switch Monitor
- Continuous Thermal Imaging

Wi-Fi Devices

- AR Headsets / iPhones / Tablets

Xcel Energy Nuclear Innovation: USA Advanced Remote Monitoring

- Xcel is working with INL to begin development of a method to streamline current pain points in the M&D architecture
- Part of a larger initiative with collaboration with USA plants, as well as Idaho National Lab
  - Standardized Monitoring and Diagnostics (M&D) Software Platform
  - Automatic thermal performance and fire detection using image/video recognition tied into cyber compliant systems
  - Beginning to automate operator round data collection
  - Transformer and cycle isolation monitoring
  - Begins to apply machine learning to monitoring limits (Xcel collaboratively with INL)

Xcel Energy®

Questions?

Molly Strasser
Nuclear Innovation Manager
Molly.J.Strasser@xcelenergy.com

2021 Workshop on Enabling Technologies
for Digital Twin Applications
for Advanced Reactors and Plant Modernization

X energy

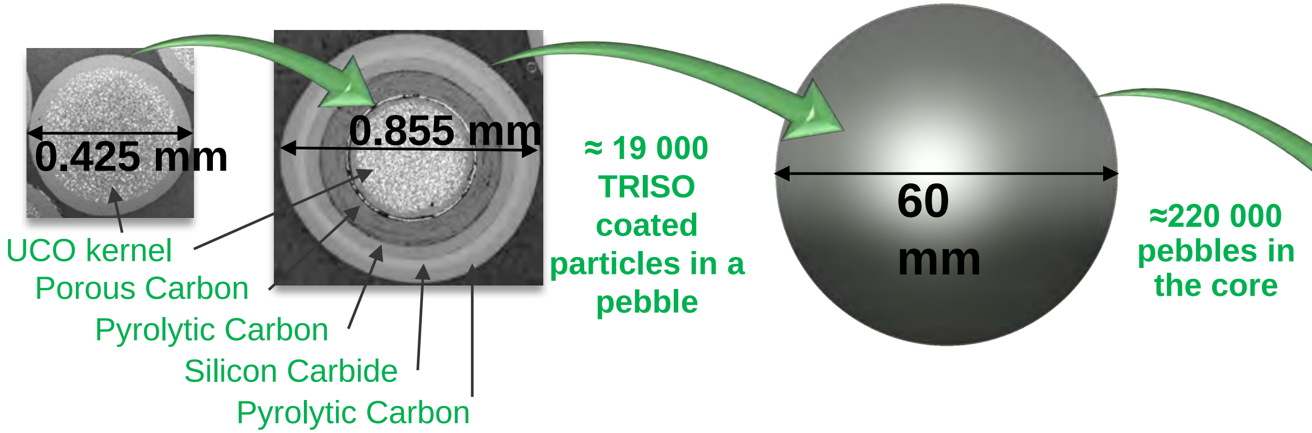
Advanced Sensors and Instrumentation

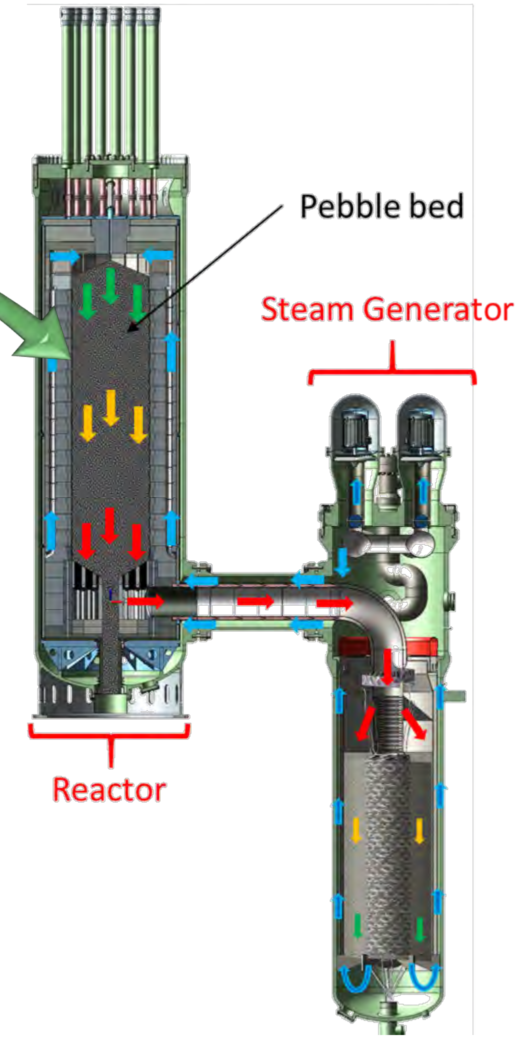
Digital Twin Impact on I&C Systems Development for Xe-100

Matthew Hertel, *Senior Nuclear I&C Engineer*

September 14th, 2021

UCO TRISO Particle – Primary Fission Product Barrier



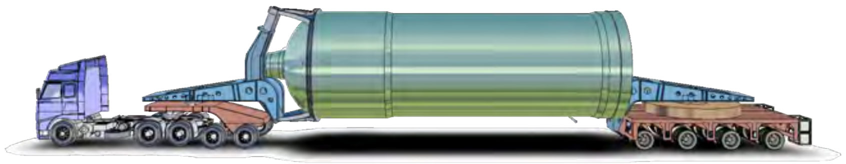


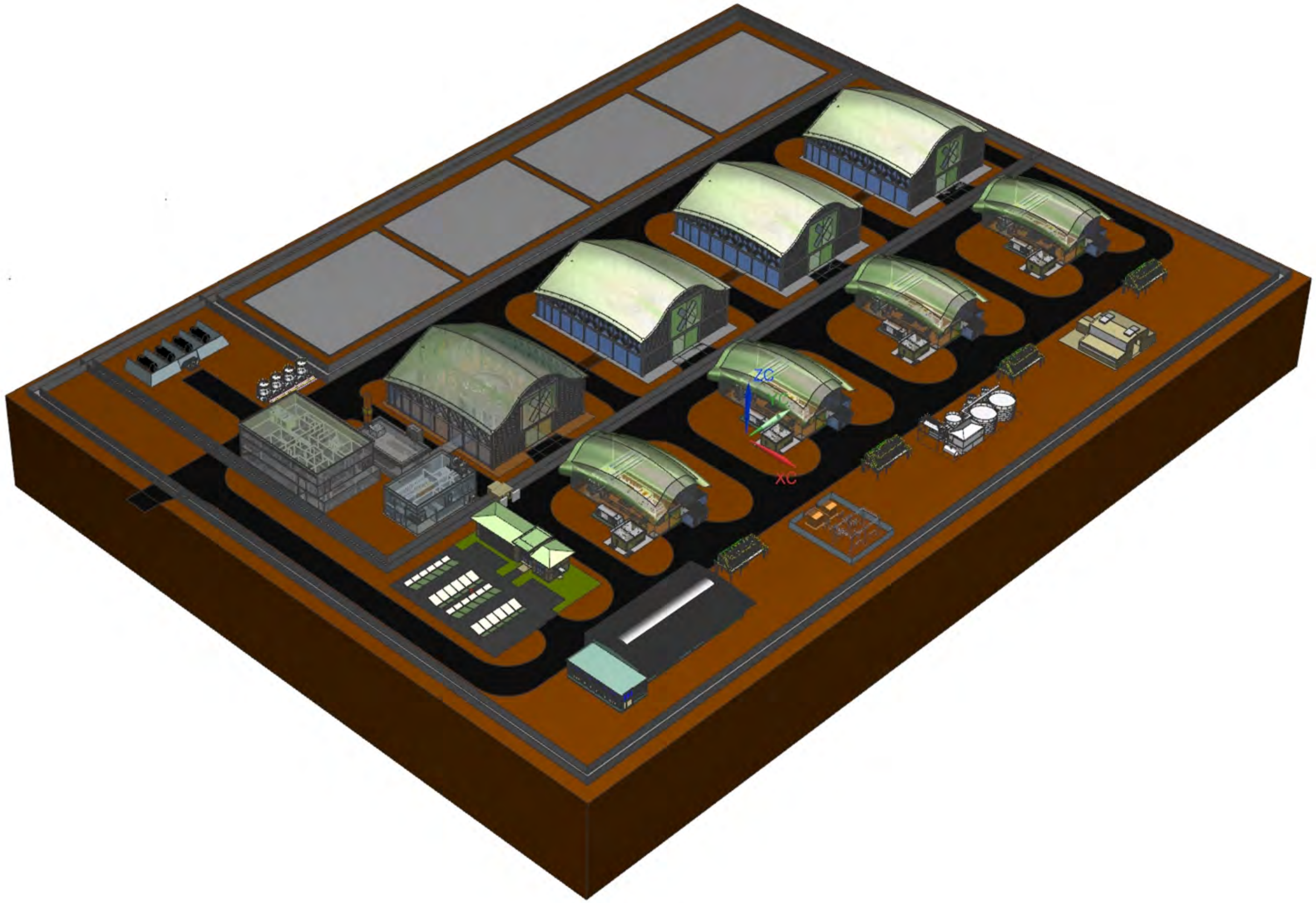
- Primary safety goal is to ensure that fission products are retained within the TRISO coated fuel particles to the maximum extent possible
- This is achieved through production of high quality TRISO fuel and ensuring that temperatures in the core never exceed the temperatures for which the fuel has been tested (AGR Experiments)

Background: Xe-100 Plant Overview

Standard X-energy plant have 4 Reactors - 4 Turbines producing 320 MWe, attributes include:

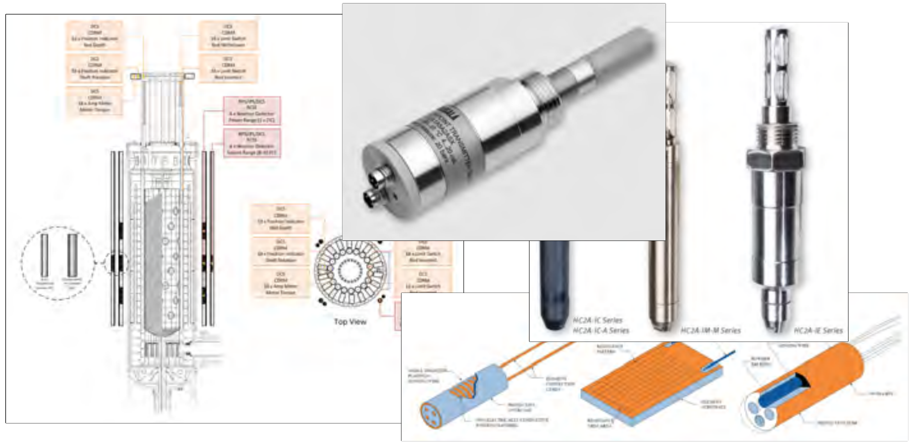
- 200MWth/80MWe Per Module
- Process heat applications
- Proven intrinsically safe
- Meltdown proof
- Walk-away safe
- Modular construction
- Requires less time to construct (2.5-4 years)
- Road transportable for diverse geographic areas
- Uses factory-produced components
- Load-following to 40% power within 15 minutes
- Continuous fueling; resilient on-site fuel storage





Digital Twin I&C Development Cycle

I&C Systems Design

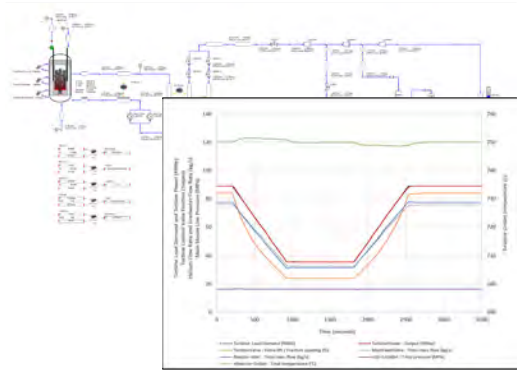


Initial Design

Start Here

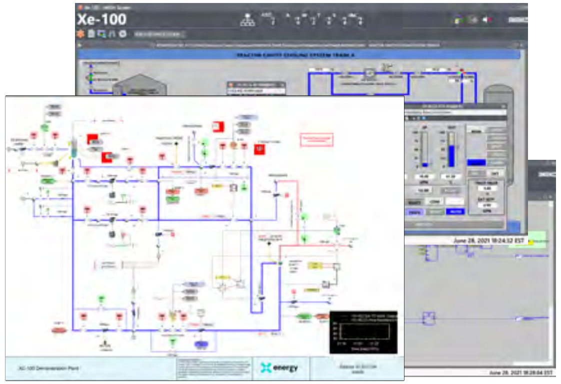
Input Model

FLOWNEX SIMULATION ENVIRONMENT

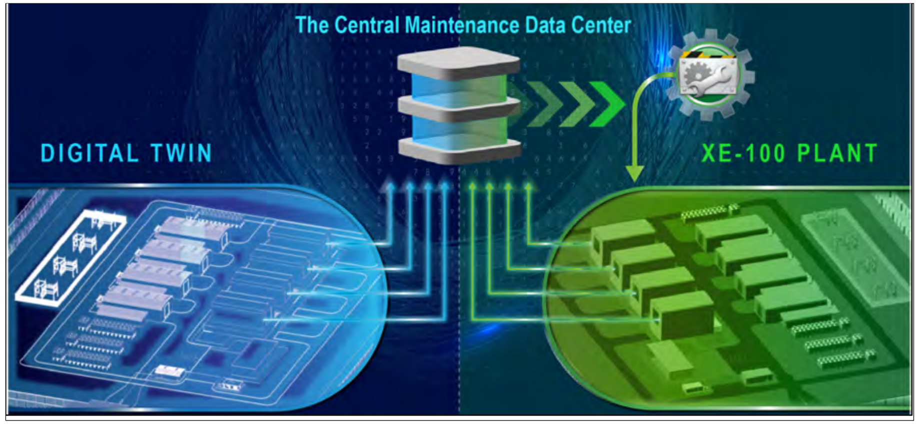


Process Model

SimGenics



Plant Model



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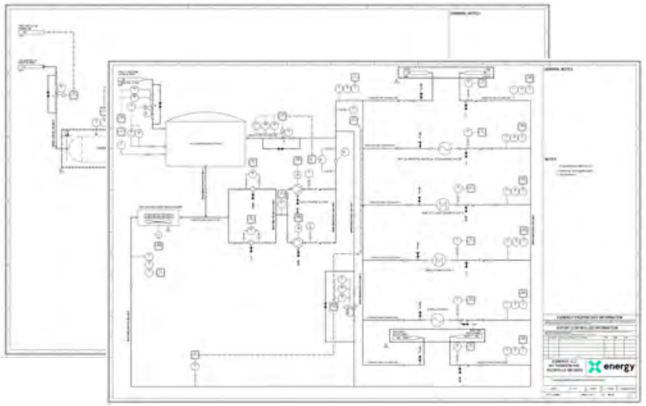
I&C Systems Engineering Process Flow + Digital Twin Toolsets

Early Stage
Large Changes



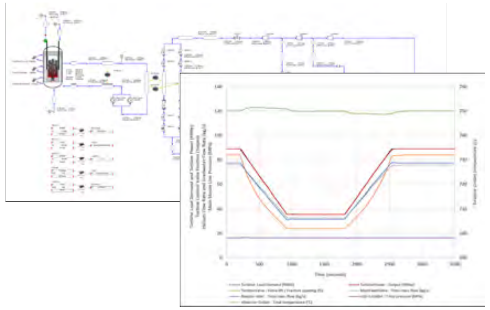
P&ID and Design Specifications

+

Transient Analysis

+

FLOWNEX®
SIMULATION ENVIRONMENT



Physics Simulation

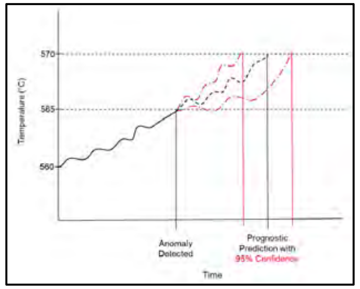
Concept Development → Requirements Engineering → System Architecture → System Design & Development → System Integration → Test & Evaluation → Transition Operation & Maintenance

Late Stage
Small Changes

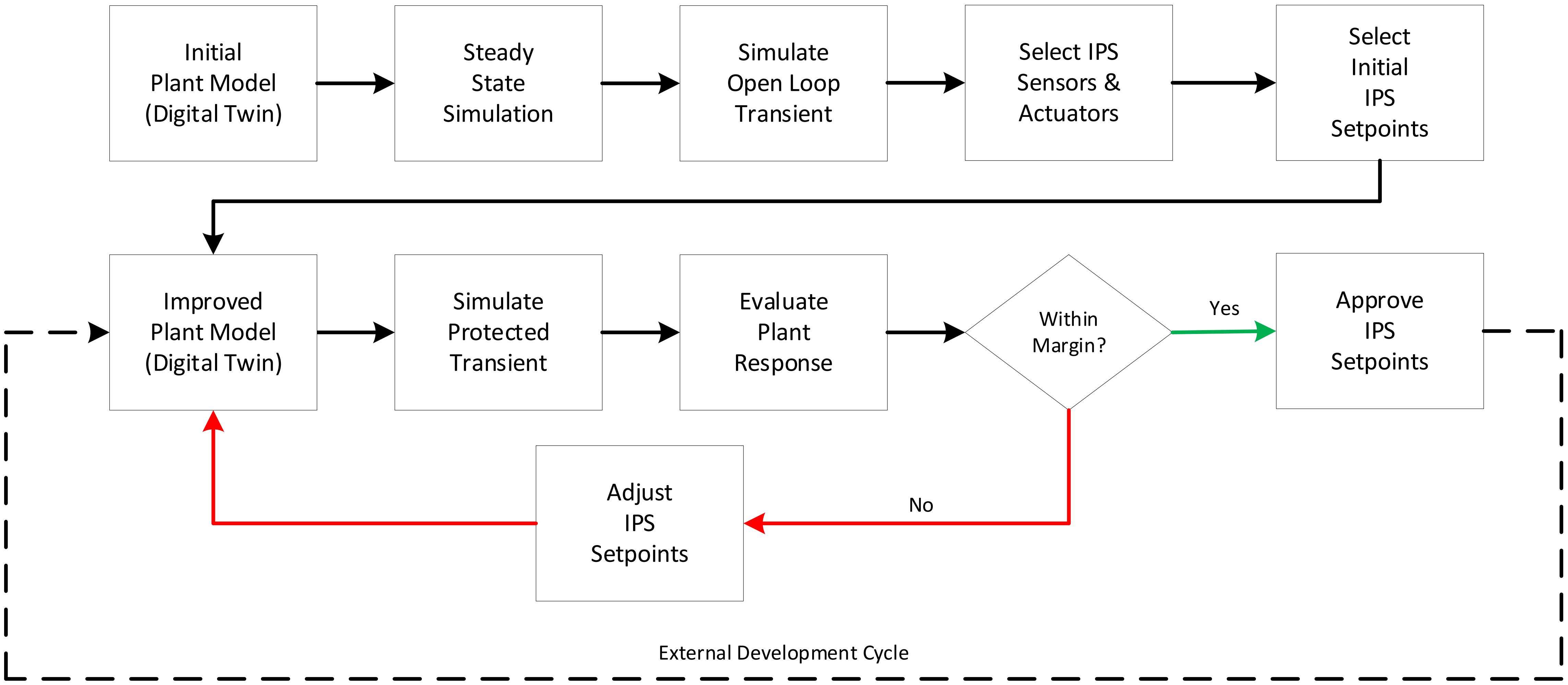
Plant Historian

+

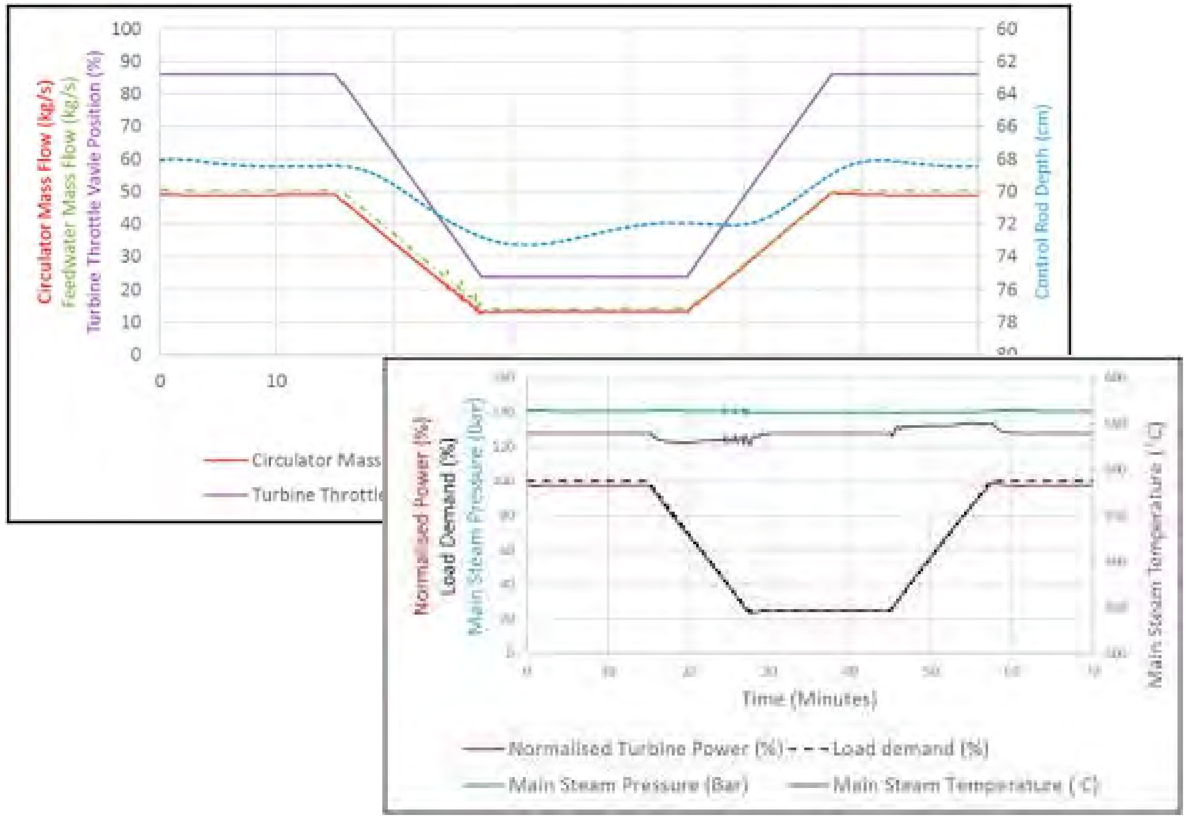
AI / ML Models



DT Enabled Design by Analysis: IPS Trip Setpoints



DT Enabled Design by Analysis: Control Trade Study



Common		
Controlled Variable	**Manipulated Variable**	**Secondary Variable**
Feedwater Valve dP	Feedwater Pump Speed	Feedwater Valve Flow
Deaerator Level	CIFW Valve Position	CIFW Flow
Deaerator Pressure	HPT Valve Position	HPT Valve Flow
FWP Recirculation Flow	FWP Recirculation Valve Position	Flow/Speed Ratio
Turbine Header Pressure	Turbine Bypass Valve	N/A

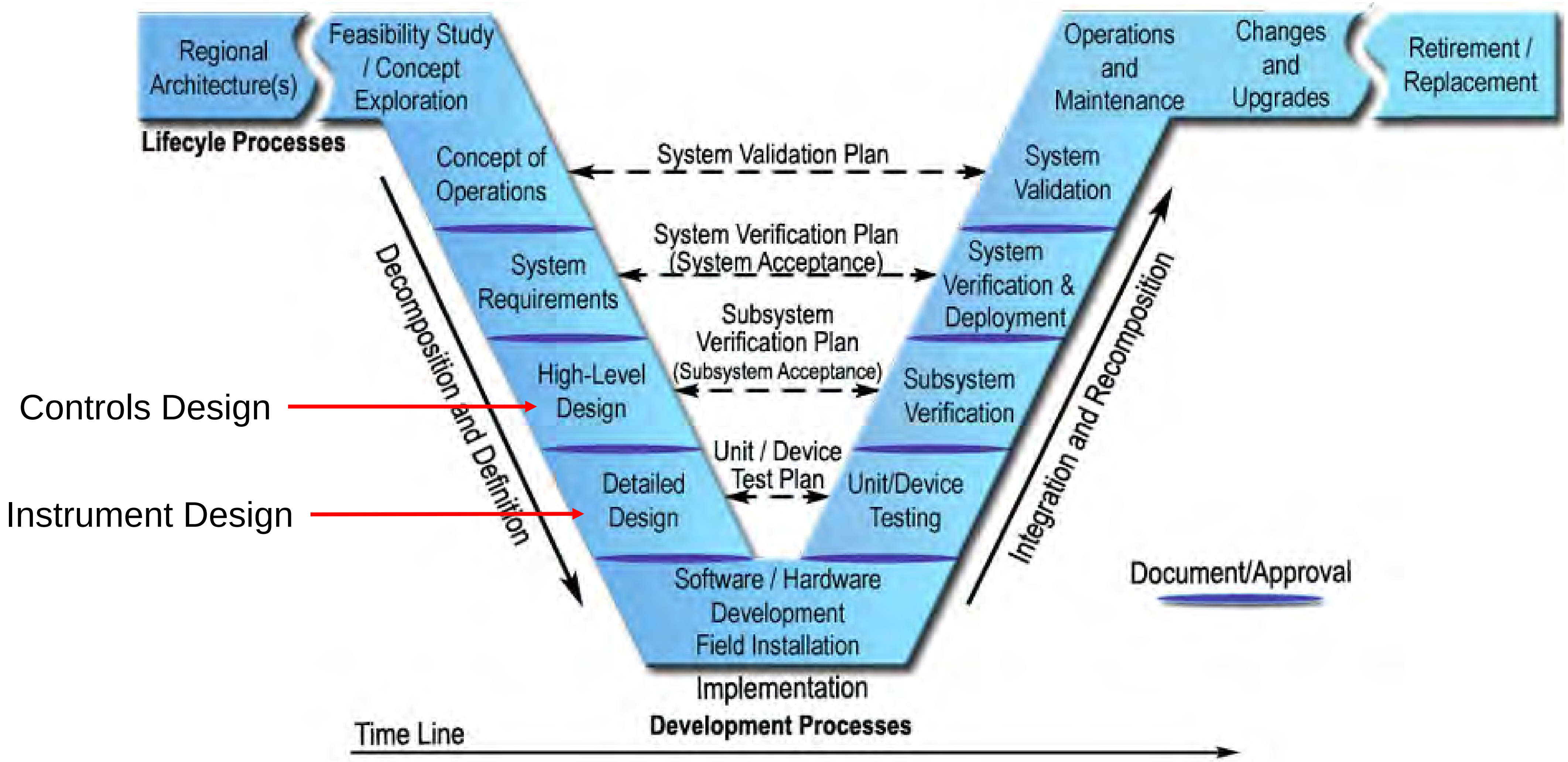
Option 1		
Controlled Variable	**Manipulated Variable**	**Secondary Variable**
Main Steam Pressure	Feedwater Valve Position	Feedwater Flow
Reactor Outlet Temperature	Control Rod Depth	Reactor Power
Main Steam Temperature	Circulator Speed	Helium Mass Flow
Turbine Power	Turbine Throttle Valve Position	Steam Flow

Option 2		
Controlled Variable	**Manipulated Variable**	**Secondary Variable**
Main Steam Pressure	Circulator Speed	Helium Mass Flow
Reactor Outlet Temperature	Control Rod Depth	Reactor Power
Main Steam Temperature	Feedwater Valve Position	Feedwater Flow
Turbine Power	Turbine Throttle Valve Position	Steam Flow

Option 3		
Controlled Variable	**Manipulated Variable**	**Secondary Variable**
Main Steam Pressure	Feedwater Valve Position	Feedwater Flow
Reactor Inlet Temperature	Circulator Speed	Helium Mass Flow
Main Steam Temperature	Control Rod Depth	Reactor Power
Turbine Power	Turbine Throttle Valve Position	Steam Flow

Option 4 (THTR)		
Controlled Variable	**Manipulated Variable**	**Secondary Variable**
Main Steam Pressure	Circulator Speed	Helium Mass Flow
Reactor Inlet Temperature	Feedwater Valve Position	Feedwater Flow
Main Steam Temperature	Control Rod Depth	Reactor Power
Turbine Power	Turbine Throttle Valve Position	Steam Flow

DT Enabled Design by Analysis: Xe-100 Next Steps



INNOVATING NUCLEAR TECHNOLOGY

Online Monitoring (OLM) Implementation to Extend Transmitter Calibration Intervals in Nuclear Facilities

Presented by:

Brent Shumaker and H.M. Hashemian

AMS Corporation

Presented for:

2021 Workshop on Enabling Technologies for Digital Twin Applications for Advanced Reactors and Plant Modernization

September 2021

All Plants Calibrate Transmitters Every Cycle

Procedure

Prepare M&TE

Dress out for containment entry

Remove channel from service

Valve-off sensing lines

Inject test signal to transmitter

Calibrate (if needed)

Return everything to service

Drawbacks

Radiation exposure

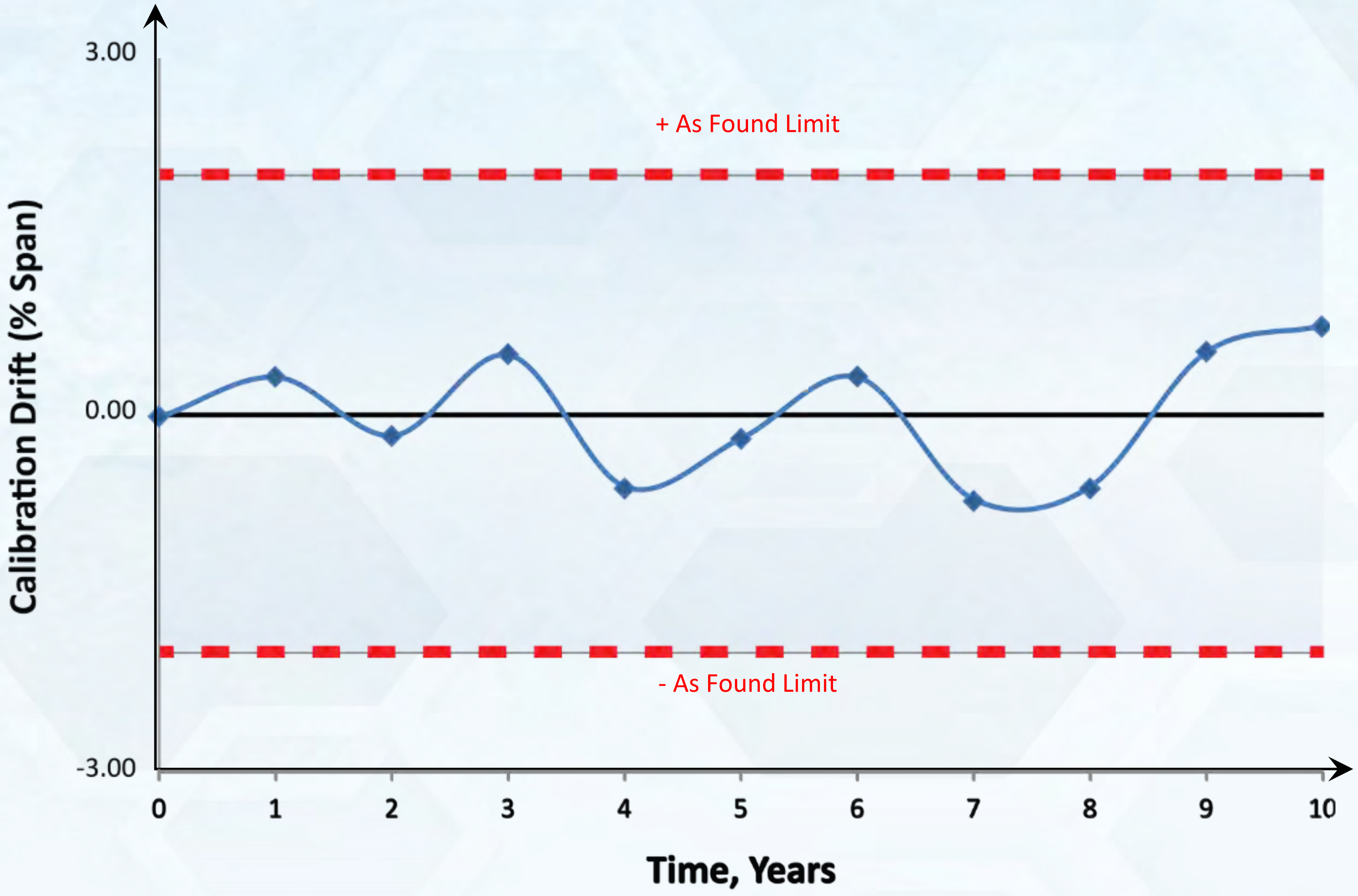
Potential to damage transmitters

Up to 5% experience maintenance-induced errors

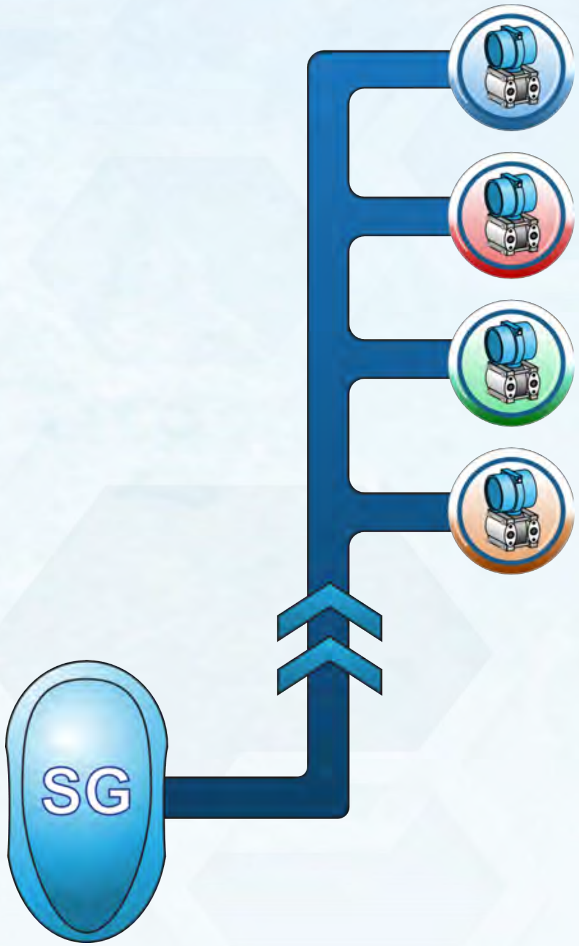
Farley recently replaced numerous manifold valves due to wear and tear

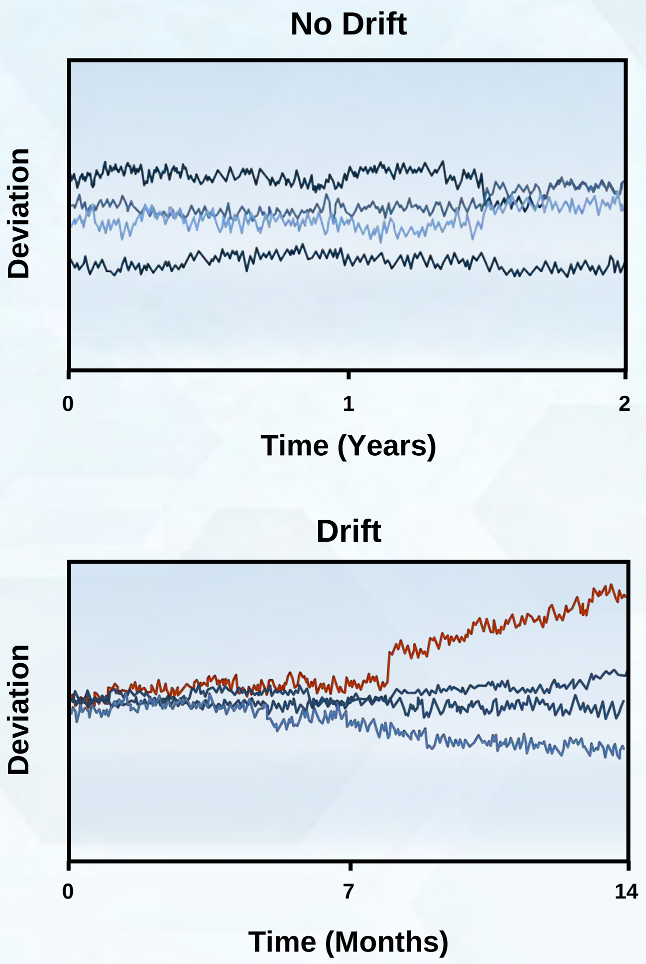
Increased outage maintenance and critical path time

Why Do We Say Transmitters Drift Very Little?
(10-year calibration history of a typical nuclear grade transmitter)



Online Monitoring (OLM) Identifies Drifting Transmitters (Actual PWR Plant Data)





Traditional Calibration vs. OLM

Traditional Calibration	OLM
Step 1. Determine if calibration is needed	Step 1. Determine if calibration is needed
Step 2. Calibrate if needed	Step 2. Calibrate if needed

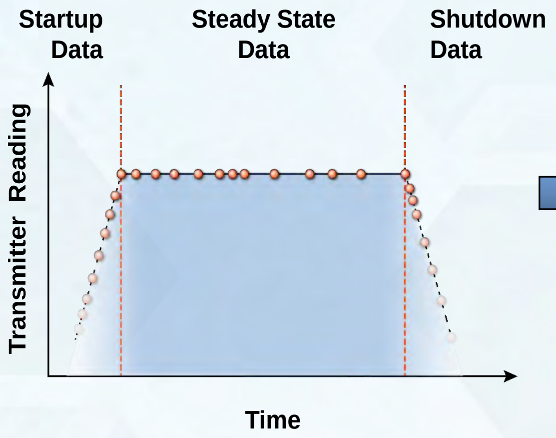
Typical OLM Results

Item	Group Name	Tag Name	Result
1	SG C OUTLET PRESSURE	PT0494	Good
2	SG C OUTLET PRESSURE	PT0495	Good
3	SG C OUTLET PRESSURE	PT0496	Good
4	PRESSURIZER LEVEL	LT0459	Good
5	PRESSURIZER LEVEL	LT0460	Good
6	PRESSURIZER LEVEL	LT0461	Good
7	PRESSURIZER PRESSURE	PT0455	Bad
8	PRESSURIZER PRESSURE	PT0456	Good
9	PRESSURIZER PRESSURE	PT0457	Good
10	PRESSURIZER PRESSURE	PT0444A	Good
11	PRESSURIZER PRESSURE	PT0445A	Good
⋮	⋮	⋮	⋮

OLM Process for Pressure Transmitter Calibration Extension

- Retrieve data from plant computer
- **Analyze data to identify transmitters that have drifted out of tolerance**
- Provide a list of transmitters to be calibrated

Data Historian



Item	Group Name	Tag Name	Result
1	SG A OUTLET PRESSURE	PT0474	Good
2	SG A OUTLET PRESSURE	PT0475	Good
3	SG A OUTLET PRESSURE	PT0476	Good
4	SG A NARROW RANGE LEVEL	LT0474	Good
5	SG A NARROW RANGE LEVEL	LT0475	Good
6	SG A NARROW RANGE LEVEL	LT0476	Good
7	PRESSURIZER LEVEL	LT0459	Good
8	PRESSURIZER LEVEL	LT0460	Bad
9	PRESSURIZER LEVEL	LT0461	Good

•
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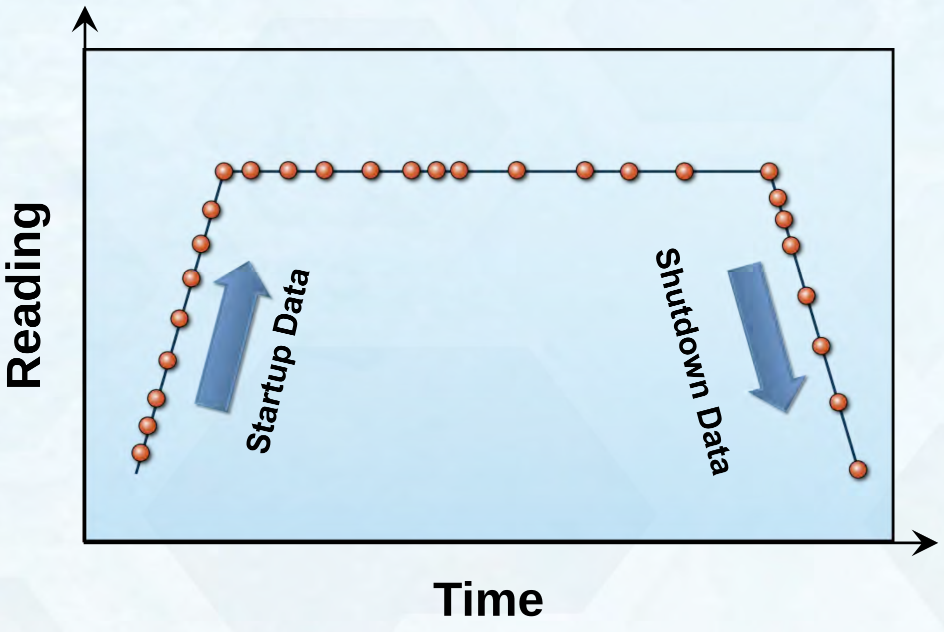
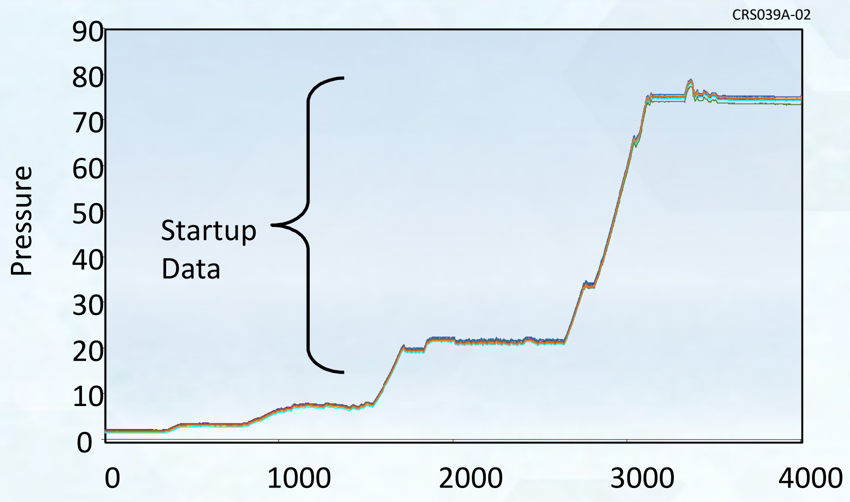
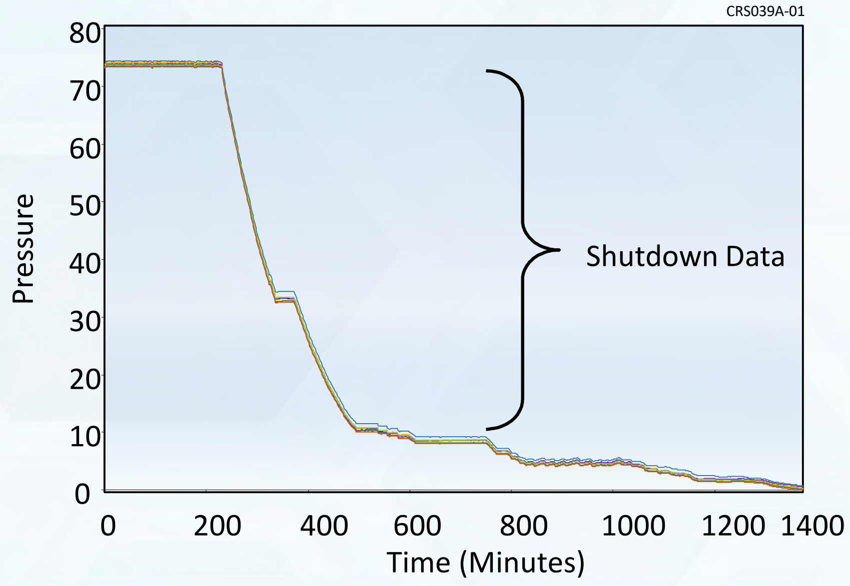
•

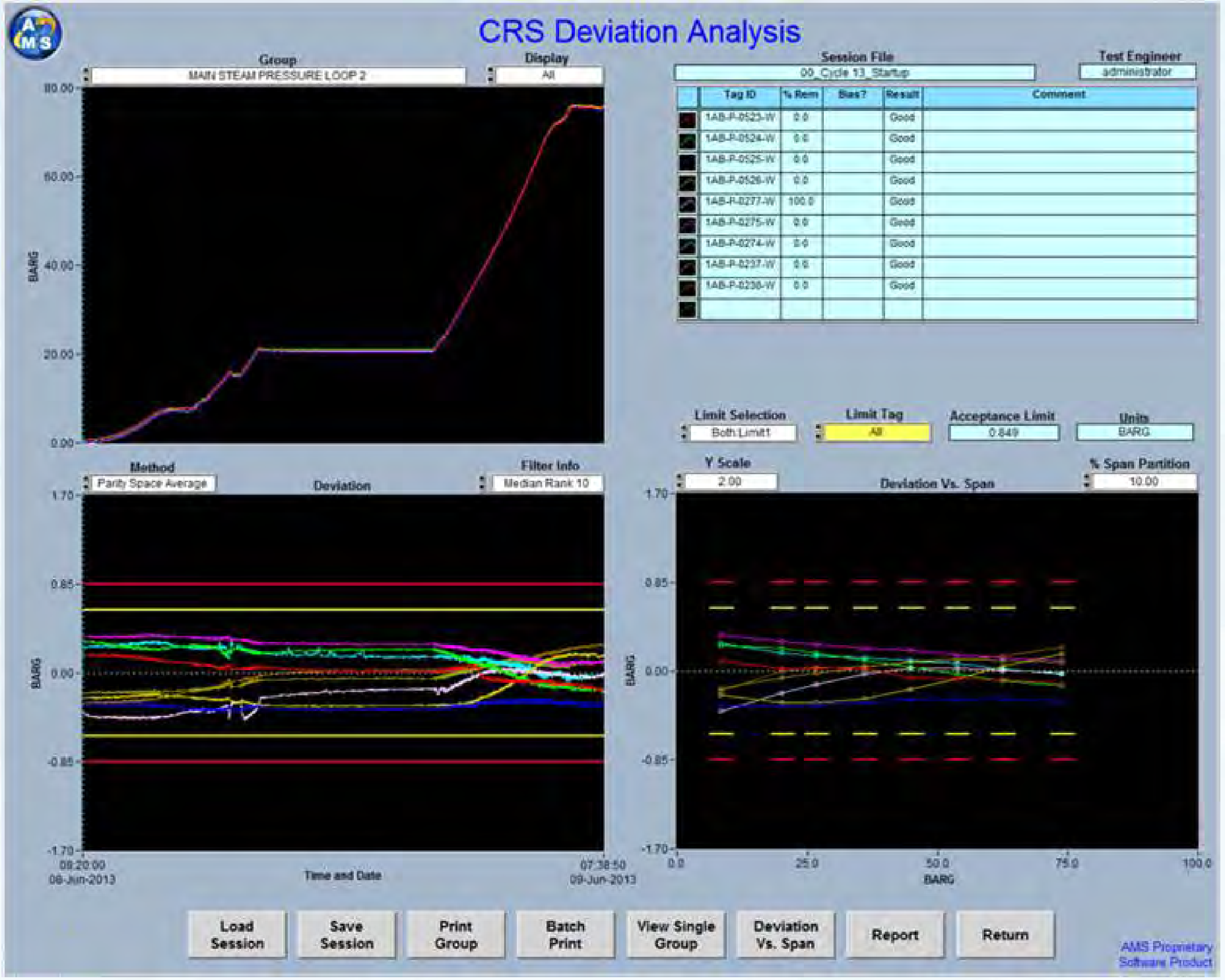
OLM Checks Calibration Over Much of a Transmitter Operating Range







OLM Analysis at Startup



Tag ID	% Rem	Bias?	Result	Comment
1AB-P-0523-W	0.0		Good	
1AB-P-0524-W	0.0		Good	
1AB-P-0525-W	0.0		Good	
1AB-P-0526-W	0.0		Good	
1AB-P-0277-W	100.0		Good	
1AB-P-0275-W	0.0		Good	
1AB-P-0274-W	0.0		Good	
1AB-P-0237-W	0.0		Good	
1AB-P-0238-W	0.0		Good	

Commercial OLM Implementations in Nuclear Facilities

Sizewell B : 2005 - present

- Approved by UK's Nuclear Installations Inspectorate - 2005
- Calibration induced human error problems minimized

Vogtle Units 1 and 2 : 2018 - present

Advanced Test Reactor : 2015 - present

Sizewell B

Vogtle

Advanced Test Reactor

AMS OLM Topical Report

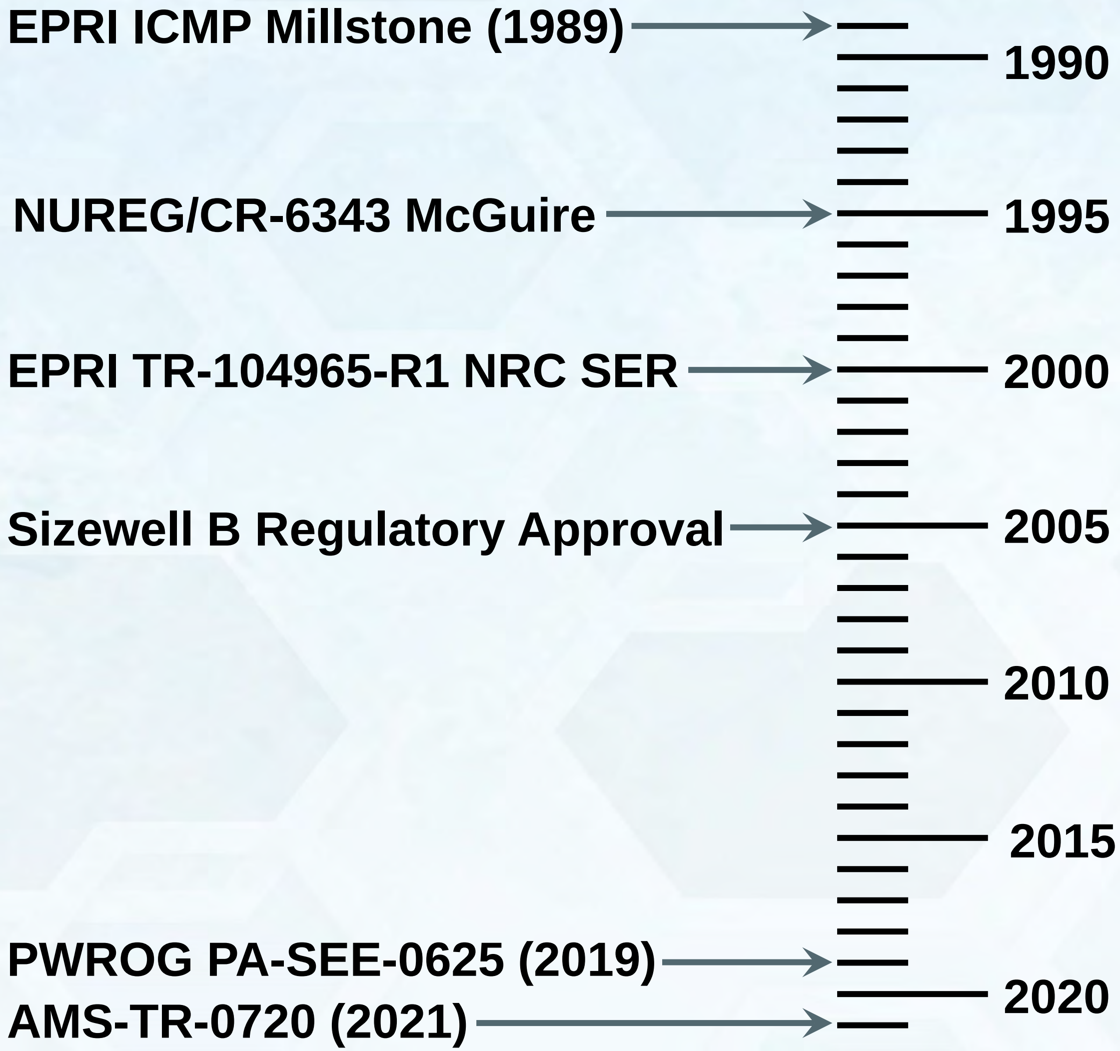
- **Step-by-Step OLM Implementation Methodology**
  - Determine Calibration Intervals
  - Establish OLM Limits
  - Perform Drift Analysis
  - Perform Dynamic Failure Mode Assessment
- **Example Changes to Existing Tech. Specs.**
  - Description of OLM Program
  - Changes to SR Frequency Column
  - Changes to Bases Section of Each SR

Example Calibration Schedules for a Group of 4 Redundant Transmitters

Cycle

	1	2	3	4	5	6	7	8	9	10	11	12
Existing	1, 2, 3, 4	1, 2, 3, 4	1, 2, 3, 4	1, 2, 3, 4	1, 2, 3, 4	1, 2, 3, 4	1, 2, 3, 4	1, 2, 3, 4	1, 2, 3, 4	1, 2, 3, 4	1, 2, 3, 4	1, 2, 3, 4
Sizewell	1	2	3	4	1	2	3	4	1	2	3	4
AMS OLM TR												1

History of Transmitter Calibration Interval Extension



Thank You!

Questions?

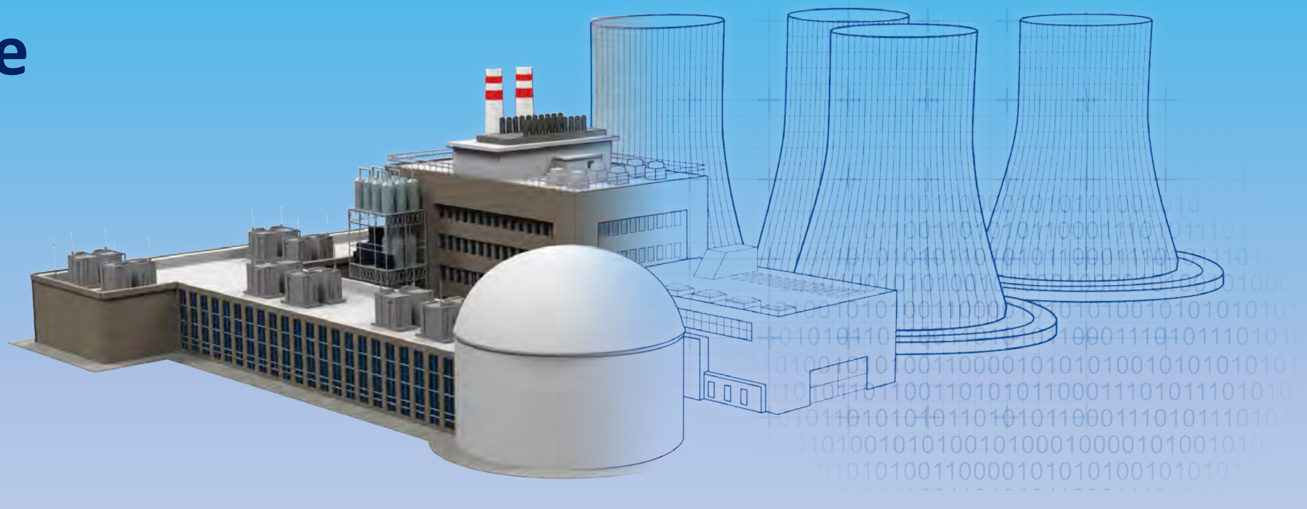
Oak Ridge National Laboratory
Idaho National Laboratory
U.S.NRC United States Nuclear Regulatory Commission *Protecting People and the Environment*
arpa·e CHANGING WHAT'S POSSIBLE
EPRI ELECTRIC POWER RESEARCH INSTITUTE

Use Cases of Digital Twin Enabling Technologies in Nuclear Power Plants

Technical Session – September 15, 2021

Moderator: Gene Carpenter, DOE

Matthew Yarlett, Westinghouse
Koushik A Manjunatha, INL
Christophe Duquennoy, EDF
Richard McGrath, EPRI
Iikka Virkkunen, AALTO



Integrated Risk-informed Condition-based Maintenance Capability and Automated Platform

Matthew Yarlett – PKMJ Technical Services, LLC

2021 Workshop on Enabling Technologies for Digital Twin Applications for Advanced Reactors and Plant Modernization

September 15, 2021

PKMJ Technical Services
Engineering and Software Solutions

Integrated Risk-informed Condition-based Maintenance Capability and Automated Platform

In November 2018, the U.S Department of Energy selected PKMJ Technical Services, Idaho National Laboratory, and Public Services Enterprise & Group (PSEG) Nuclear, LLC for an Advanced Nuclear Technology Project.

https://www.energy.gov/ne/articles/us-advanced-nuclear-technology-projects-receive-18-million-us-department-energy

PKMJ Technical Services Engineering and Software Solutions

Project Objective

Integrate advancements in online monitoring and data analytic techniques with advanced risk assessment methodologies

Goals

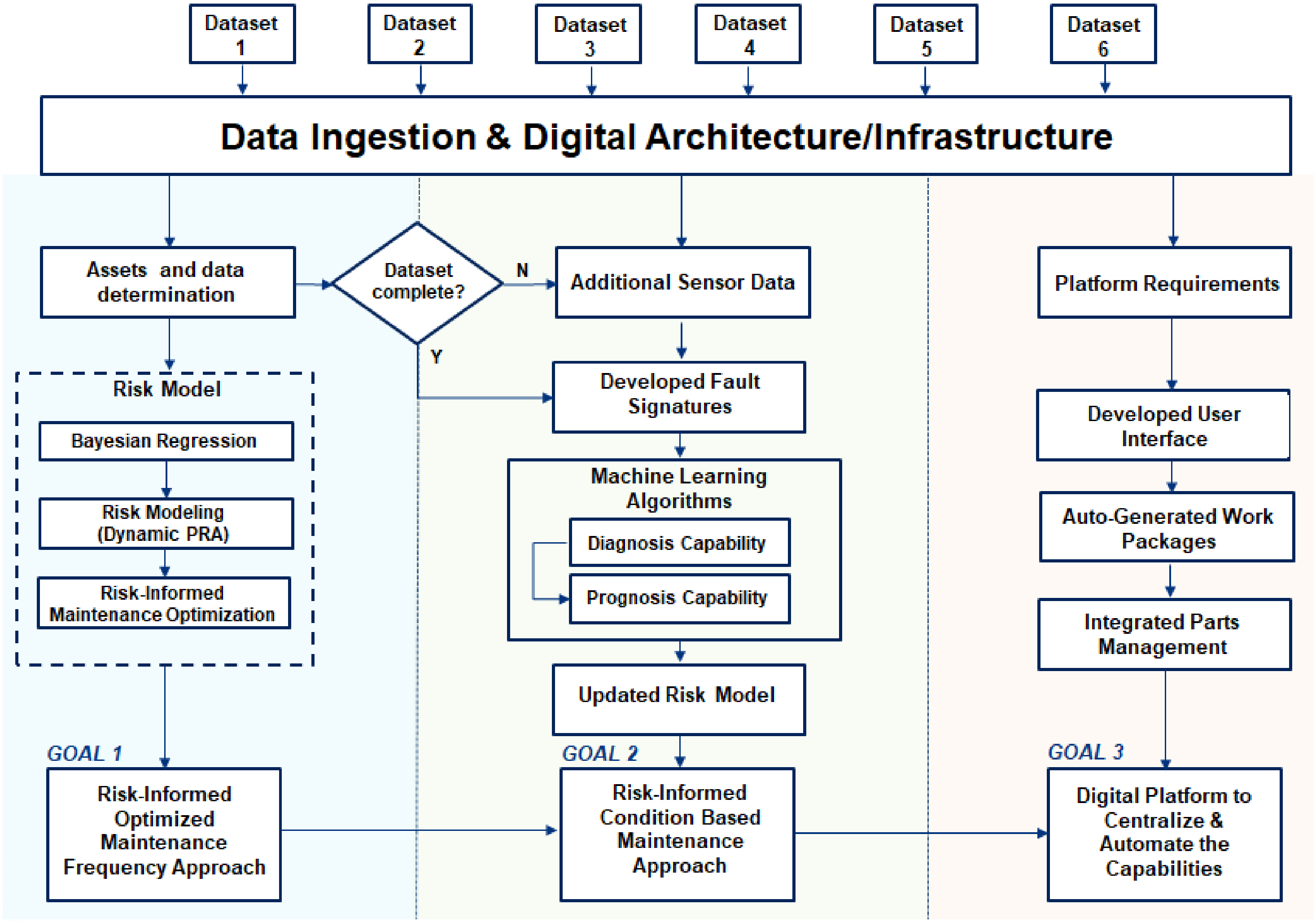
1. Risk-informed approach to optimize equipment maintenance frequency
2. Risk-informed approach to condition-based maintenance
3. Develop and demonstrate a digital, automated platform

Duration

August 2019 – July 2021

Integrated Risk-informed Condition-based Maintenance Capability and Automated Platform

Scope



Technical Services
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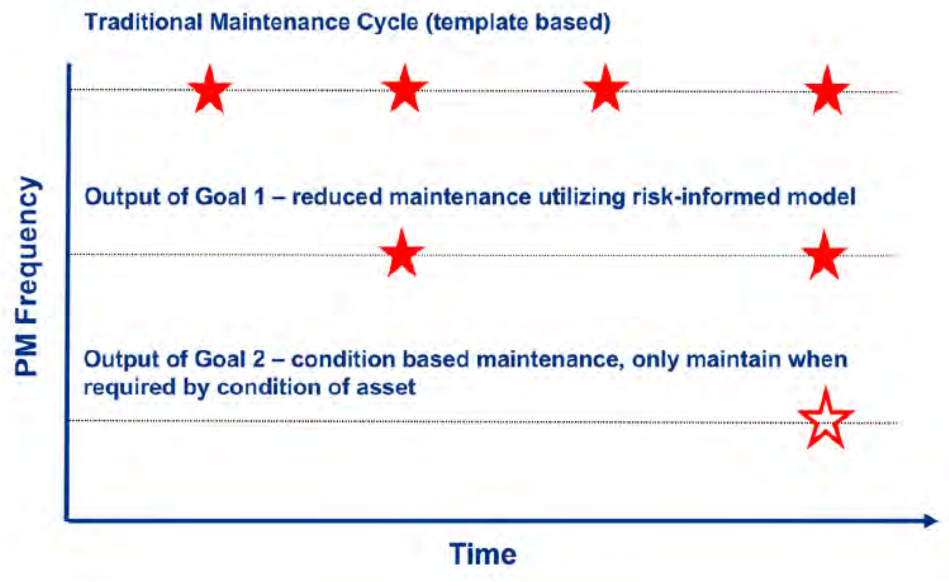
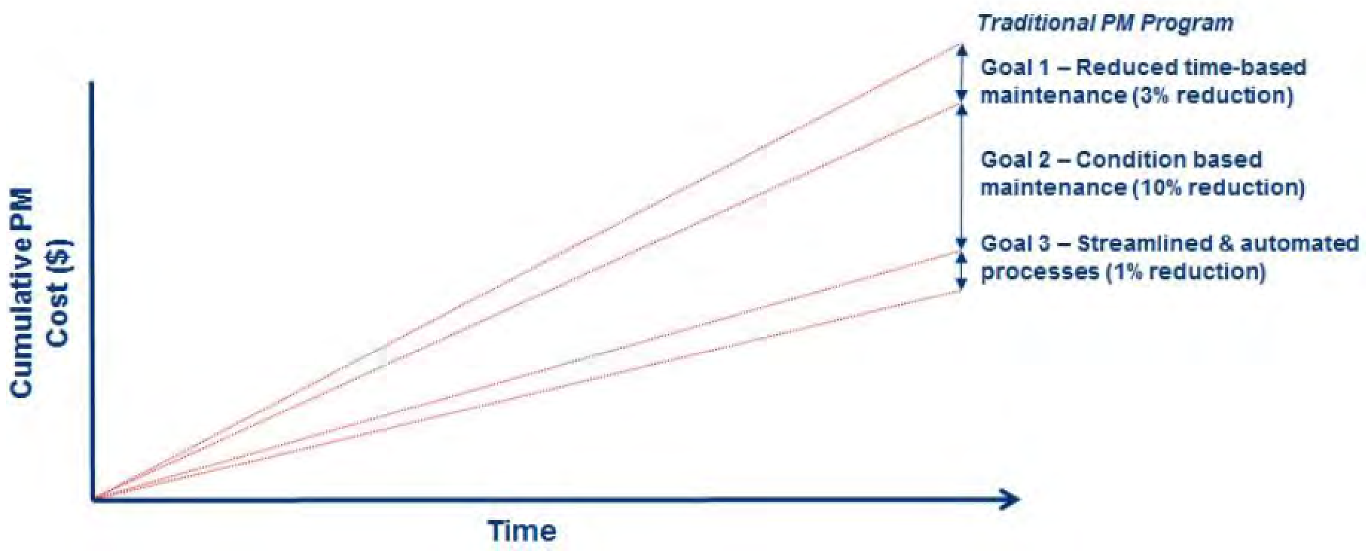
Integrated Risk-informed Condition-based Maintenance Capability and Automated Platform

Potential Benefits





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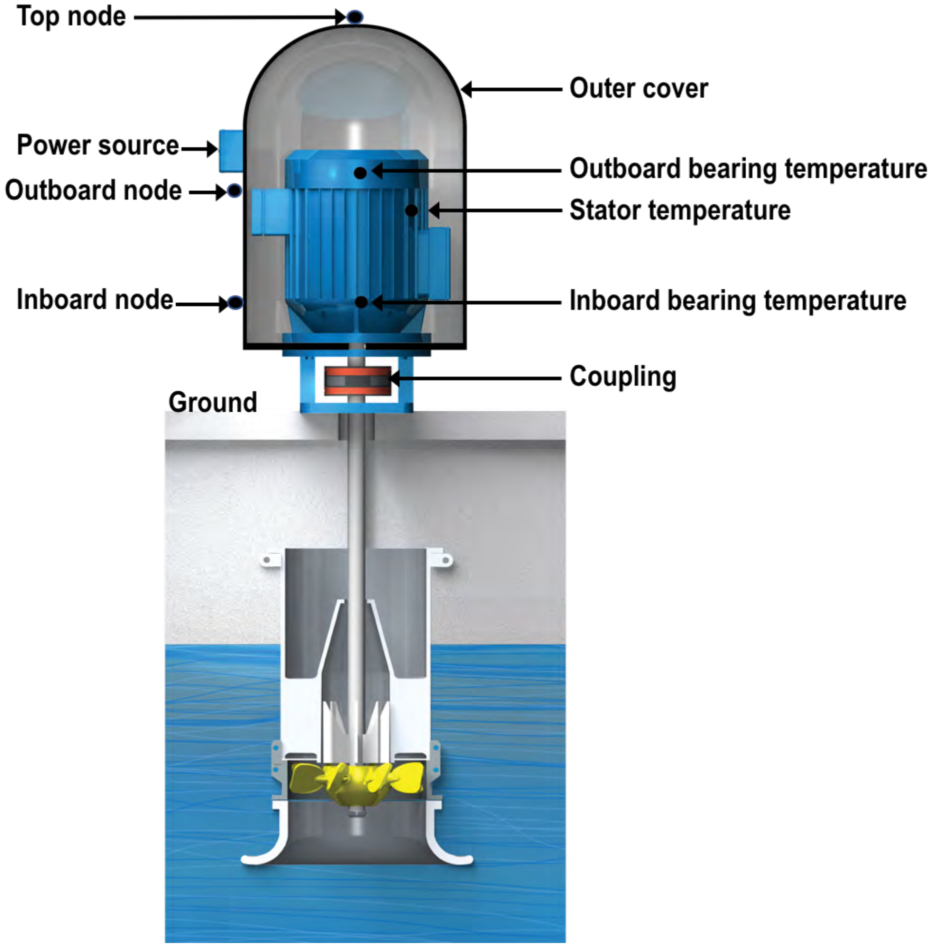
Integrated Risk-informed Condition-based Maintenance Capability and Automated Platform

Accomplishments – Target Equipment Selected

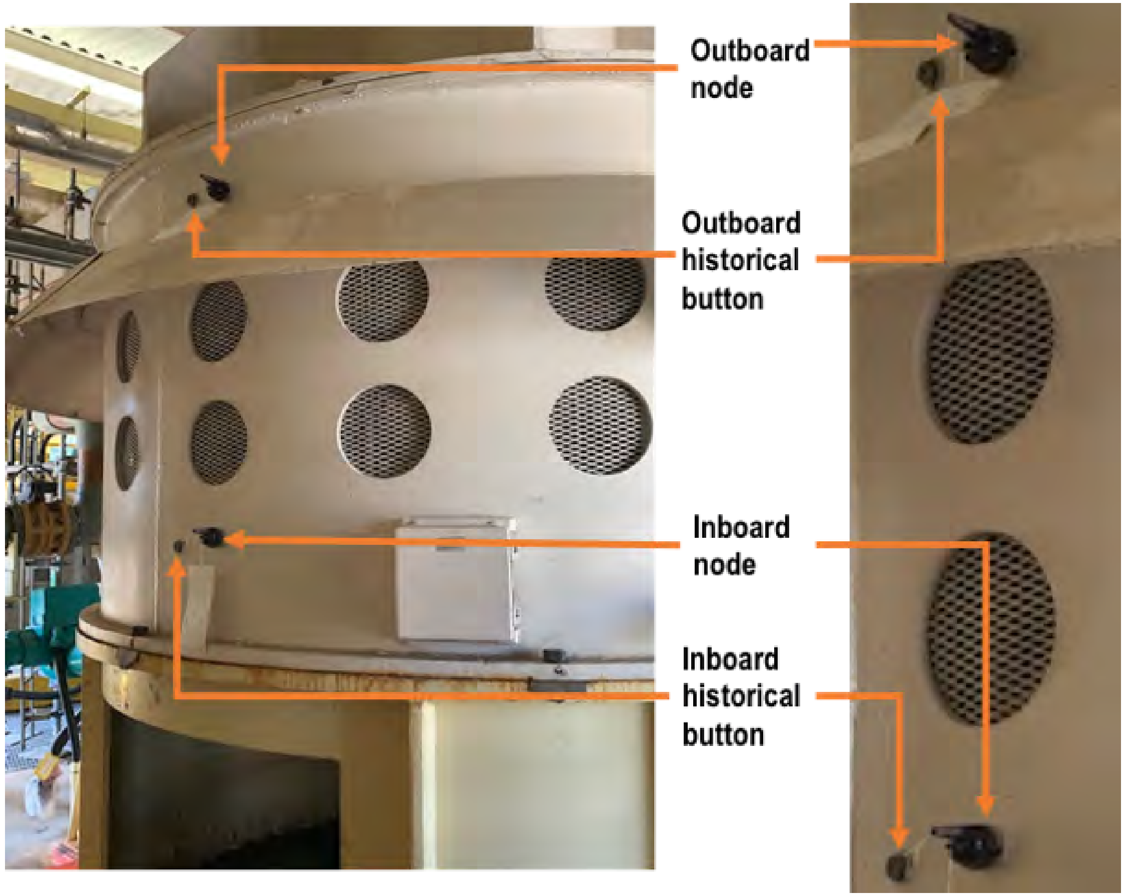


60 Vibration Sensor Nodes have been installed across Salem's 12 Circulating Water System pumps, motors and associated bypass valves. Each sensor node consists of two accelerometers sensitive to orthogonal in-plane motion and a temperature sensor.

PKMJ Technical Services Engineering and Software Solutions

Integrated Risk-informed Condition-based Maintenance Capability and Automated Platform

Accomplishments – Wireless Vibration Sensor Installation



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Integrated Risk-informed Condition-based Maintenance Capability and Automated Platform

Accomplishments – Preventive Maintenance Optimization

Equipment	Task Title	Current Frequency	Industry Average	Recommendation	Recommended Frequency
Pump	**Refurbishment**	**6 years**	**14 years**	**Less Frequent**	**9 years**
	External Visual Inspection	18/24 months	2.8 years	Keep	18 months
Motor	**Vibration Analysis**	**3 months**	**5.5 months**	**Less Frequent**	**6 months**
	Oil Analysis	6 months	8 months	Keep	6 months
	Inspect/Electrical Testing	3 years	3 years	Keep	3 years
	Replace Motor	**6 years**	**10.7 years**	**Less Frequent**	**9 years**
Motor Cable	VLF TAN-Delta Testing	6 years	7 years	Keep	6 years
Protective Relays	Inspect/Calibrate	6 years	4 years	Keep	6 years
Pressure Switch	Calibration	4 years	4.2 years	Keep	4 years

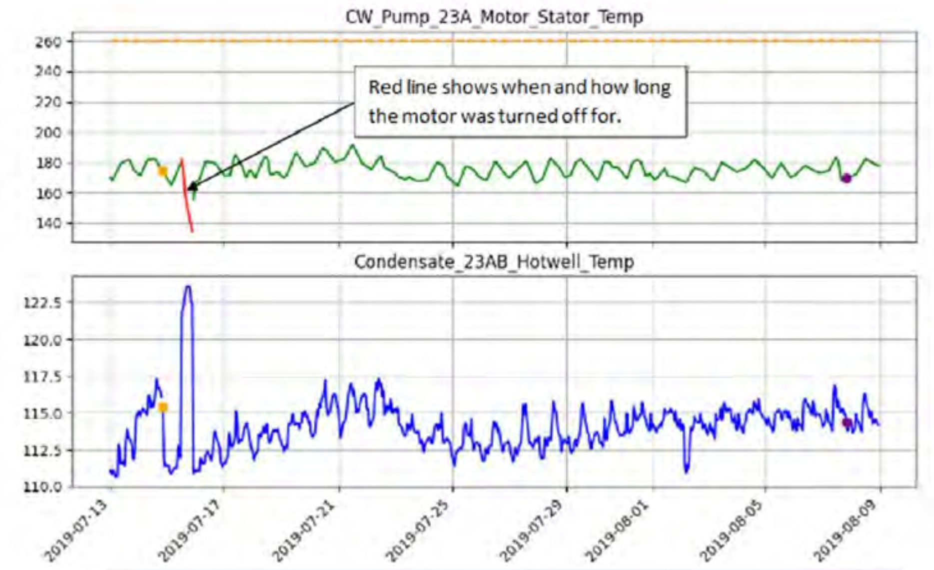
- Risk models developed by INL support the pump refurbishment and motor replacement frequency recommendations
- **$4.37M -** Net savings over next six years if implemented at the site

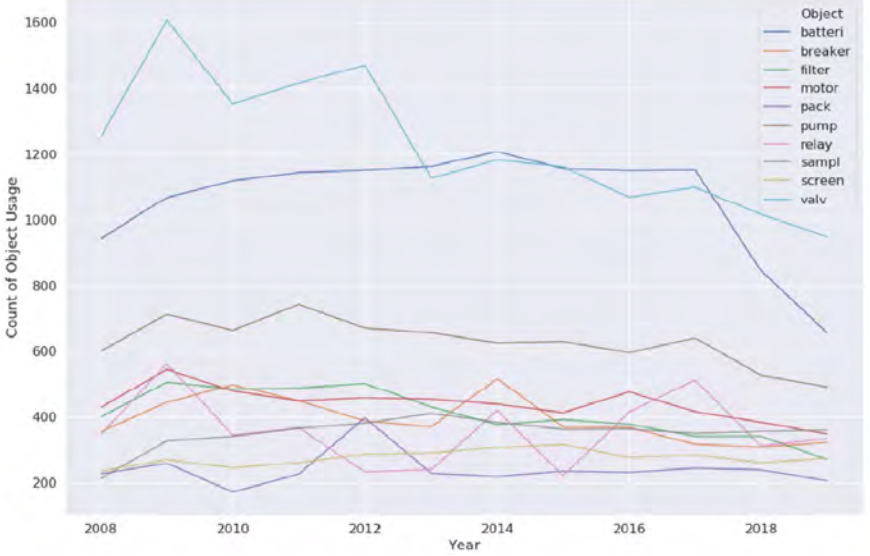
PKMJ Technical Services Engineering and Software Solutions

Integrated Risk-informed Condition-based Maintenance Capability and Automated Platform

Accomplishments – Work Order Data Analysis

- WO Failure Classification was performed using Natural Language Processing (NLP) techniques to classify work orders associated with equipment degradation, failure, and other. NLP was also utilized to evaluate the primary object types (component types), conditions identified, and actions performed for work orders at Salem (see bottom figure).
- Created a plant process data and work order dashboard in PowerBI (see top figure). This was used for engineering review of events and work orders to better understand the impacts to plant process parameters when faults occurred.
- Developed WO work type classifier to determine when work requires part usage, improves health, includes inspection (check-up), identifies potential issues, restores condition to As Good As New, or others.
- Developed parts clustering technique to identify common parts used for work orders of a given type. This method allows for the identification of required and contingent parts, which can be used to enhance supply chain decision making based on future planned work.



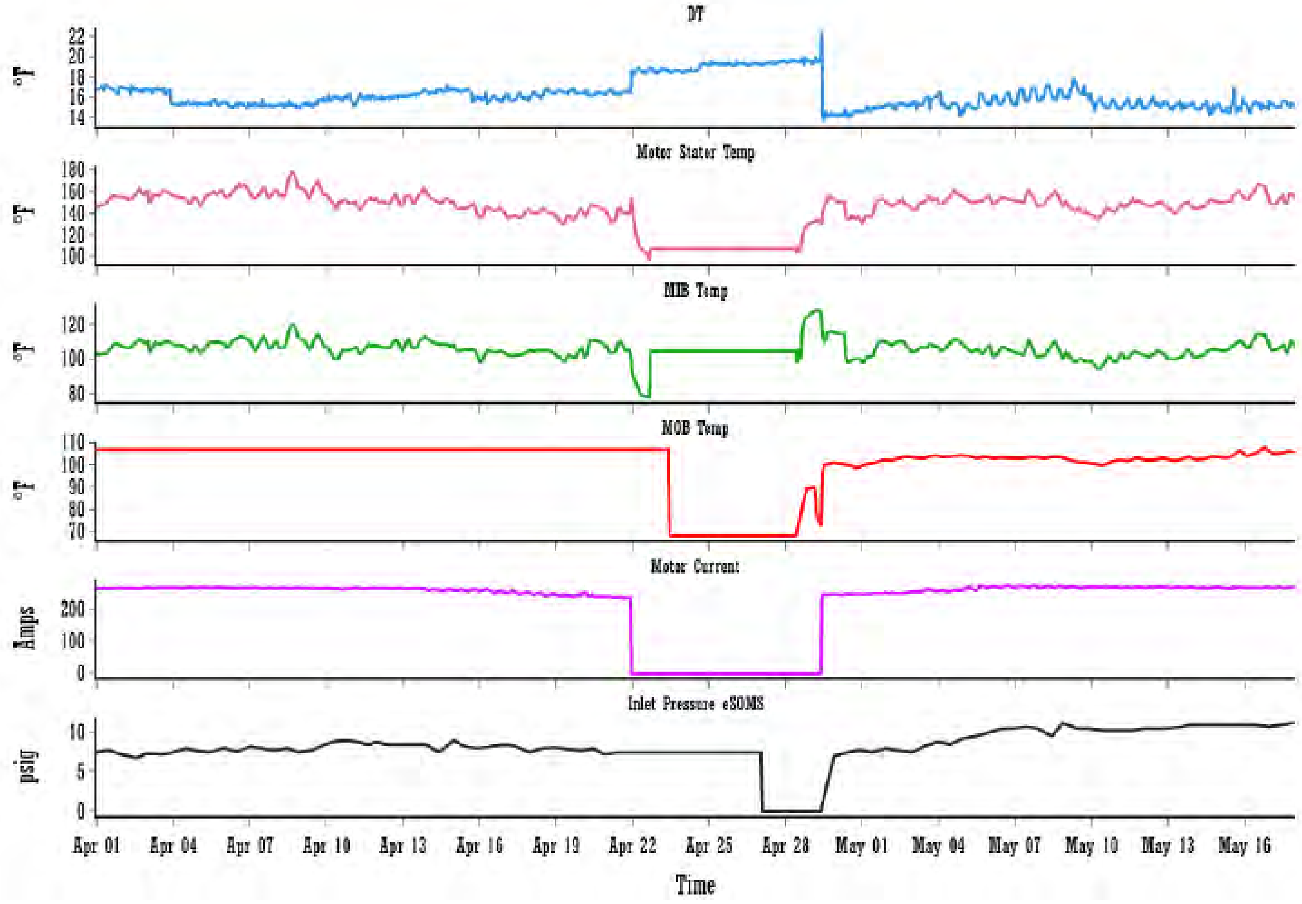


P K M J
Technical Services
Engineering and Software Solutions

Integrated Risk-informed Condition-based Maintenance Capability and Automated Platform

Accomplishments – Identification of Fault Signatures

- PSEG Plant Process data was used to identify characteristics of specific faults that occurred with the Salem Circulating Water System equipment
- Time-domain and frequency-domain features were examined where possible to associate plant conditions with engineering characteristics
- Fault Signatures were used as the foundation for developing diagnostic models
- The development of fault signatures considered various scenarios based on the amount of indication available (i.e., without motor current, without vibration data, etc.) to provide insight into the flexibility of a fault signature solution

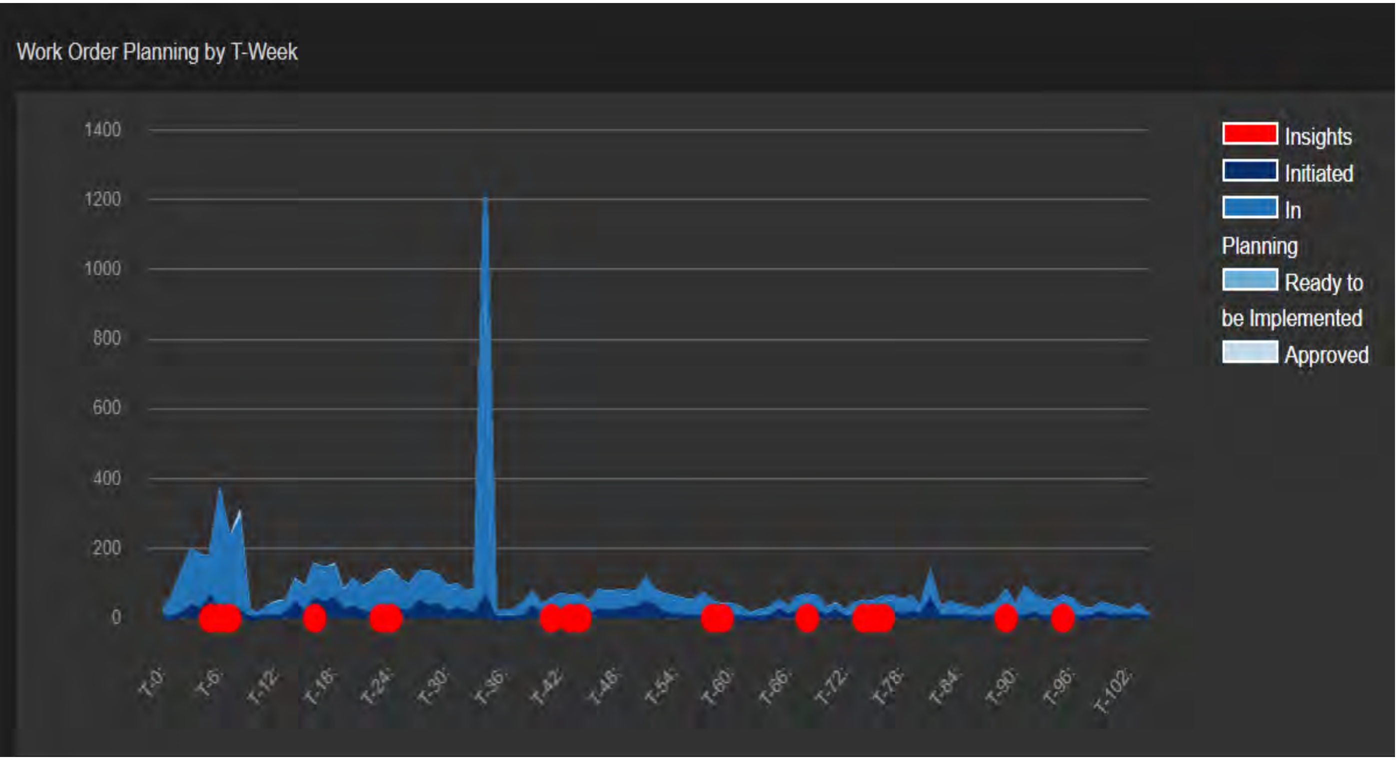


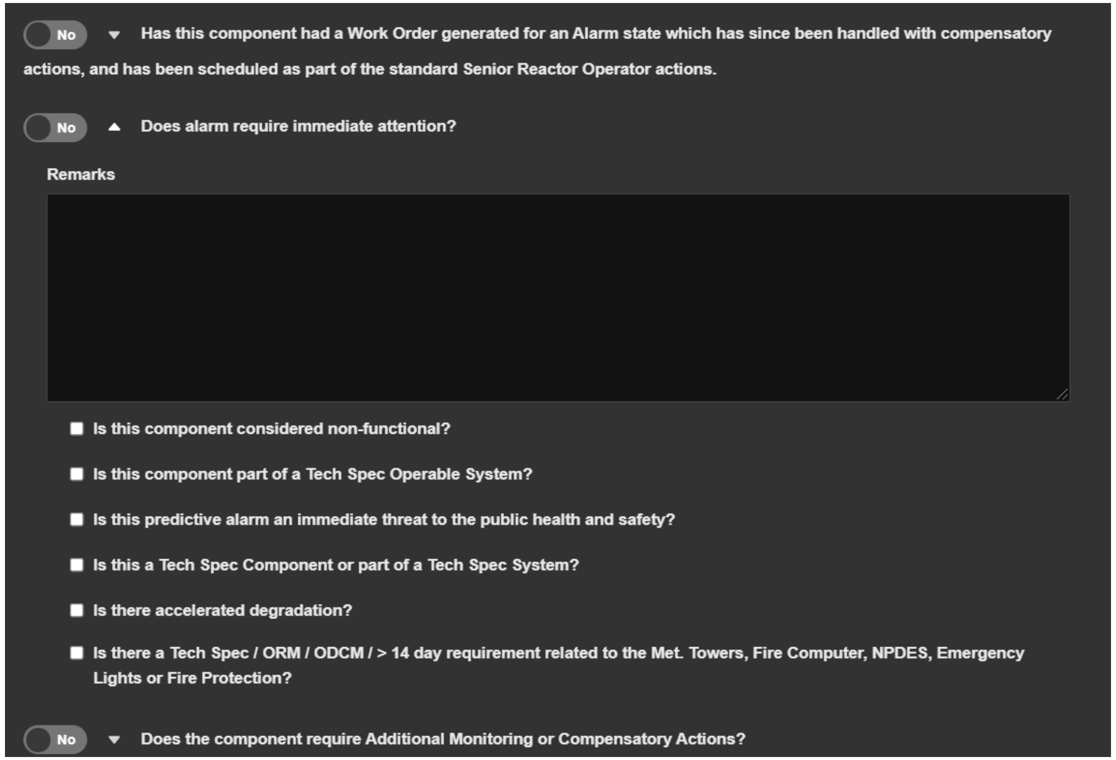
PKMJ Technical Services Engineering and Software Solutions

Integrated Risk-informed Condition-based Maintenance Capability and Automated Platform

Accomplishments – Development of an Automated Digital Platform

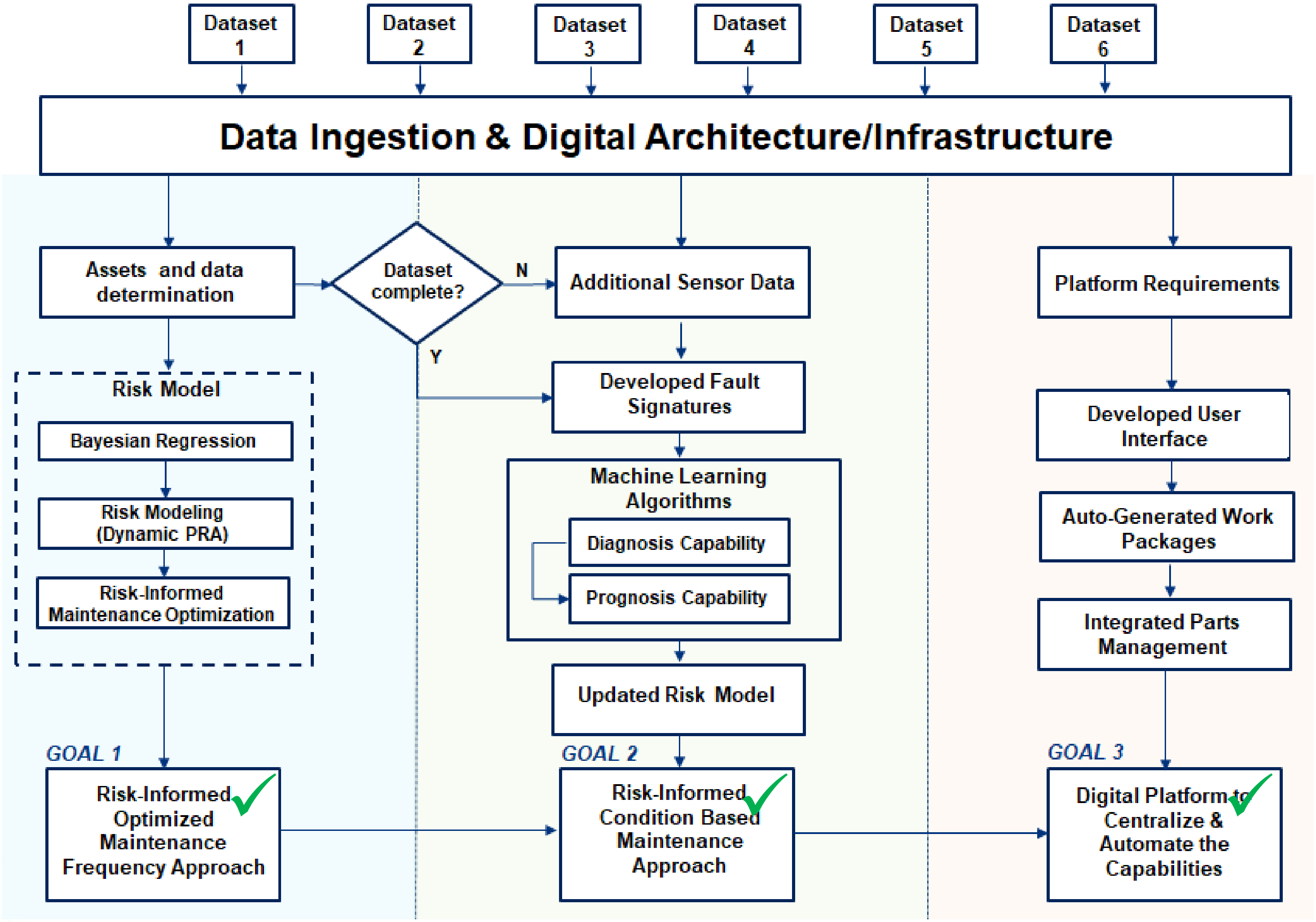
- PKMJ developed a cloud-hosted application using Microsoft Azure to enhance industry decision-making and data visualization
- Tools and services such as Azure Active Directory, Azure API Manager, Azure Function/Logic Apps, Azure DataLake Storage, DataFactory etc. were used to provide the structure, security, and data for the application
- The digital platform developed under the project supports maintenance strategy optimization, responding to fault signature alarms, and generation of automated work orders.





Integrated Risk-informed Condition-based Maintenance Capability and Automated Platform

Summary



Technical Services
Engineering and Software Solutions

Integrated Risk-informed Condition-based Maintenance Capability and Automated Platform

Future Development

- PKMJ is in discussion with INL to continue the research, development, and commercialization of the digital platform solution. Areas of interest include:
    - Enhancements to Fault Signature Models
    - Integration of the Platform to Utility Systems
    - Improved Economic Modeling

- PKMJ is also working with its parent company, Westinghouse, to incorporate other Condition Monitoring solutions into the digital platform

PKMJ Technical Services
Engineering and Software Solutions

QUESTIONS?

Contact Information

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PKMJ Technical Services
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References

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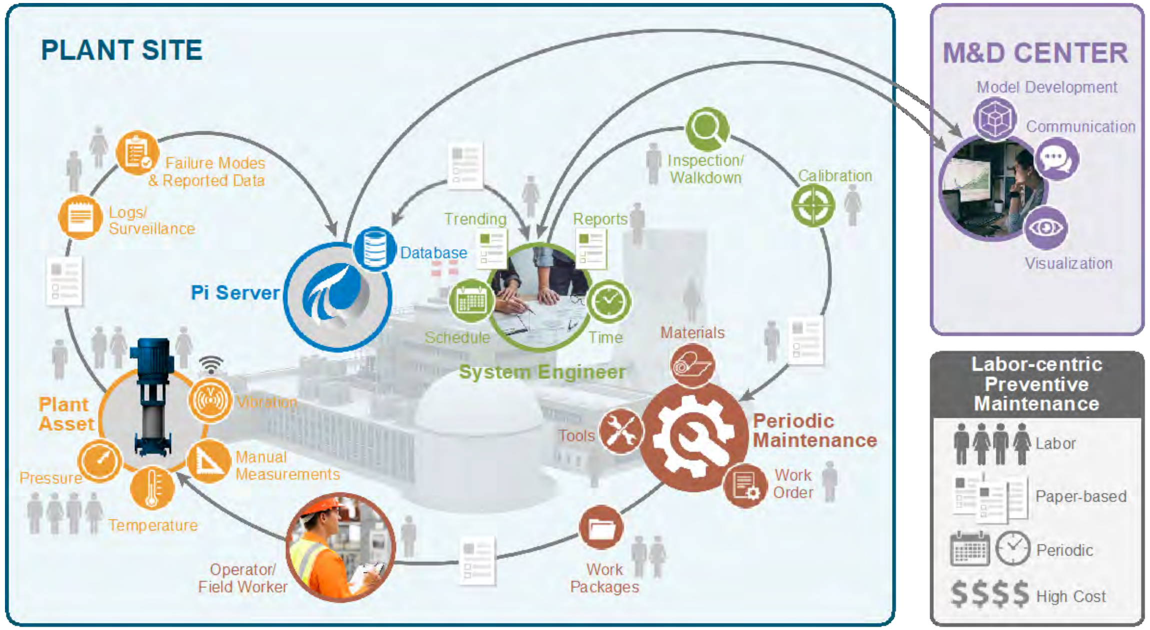
September 15, 2021

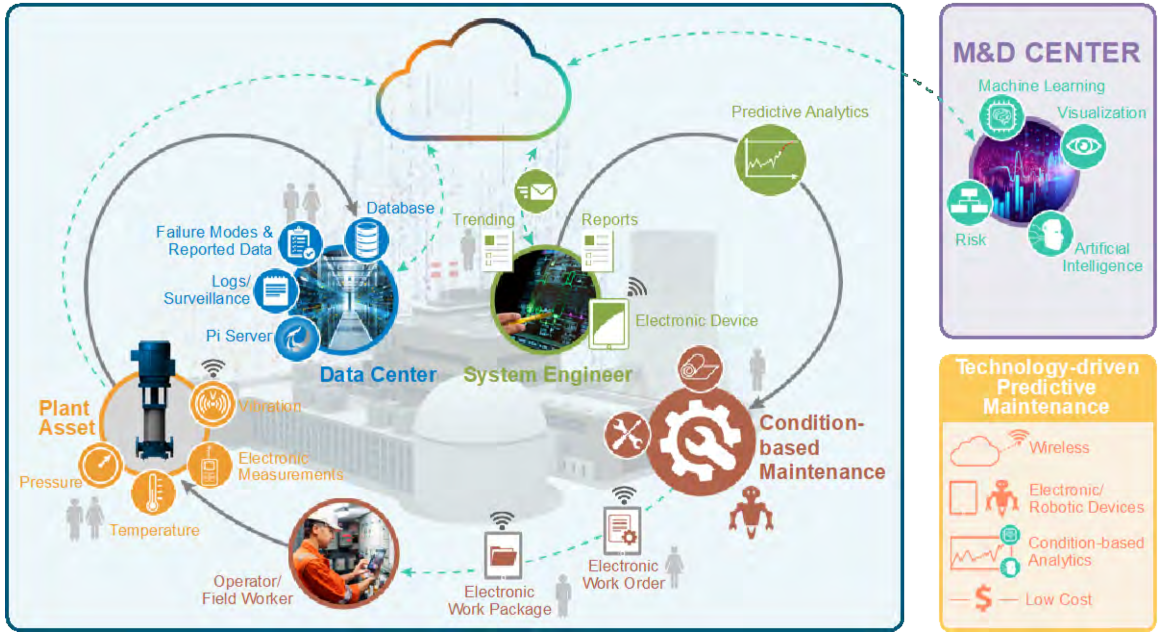
Koushik A. Manjunatha
Staff Research Scientist, INL

Artificial Intelligence (AI) Driven Scalable Condition based Predictive Maintenance Strategy

Idaho National Laboratory

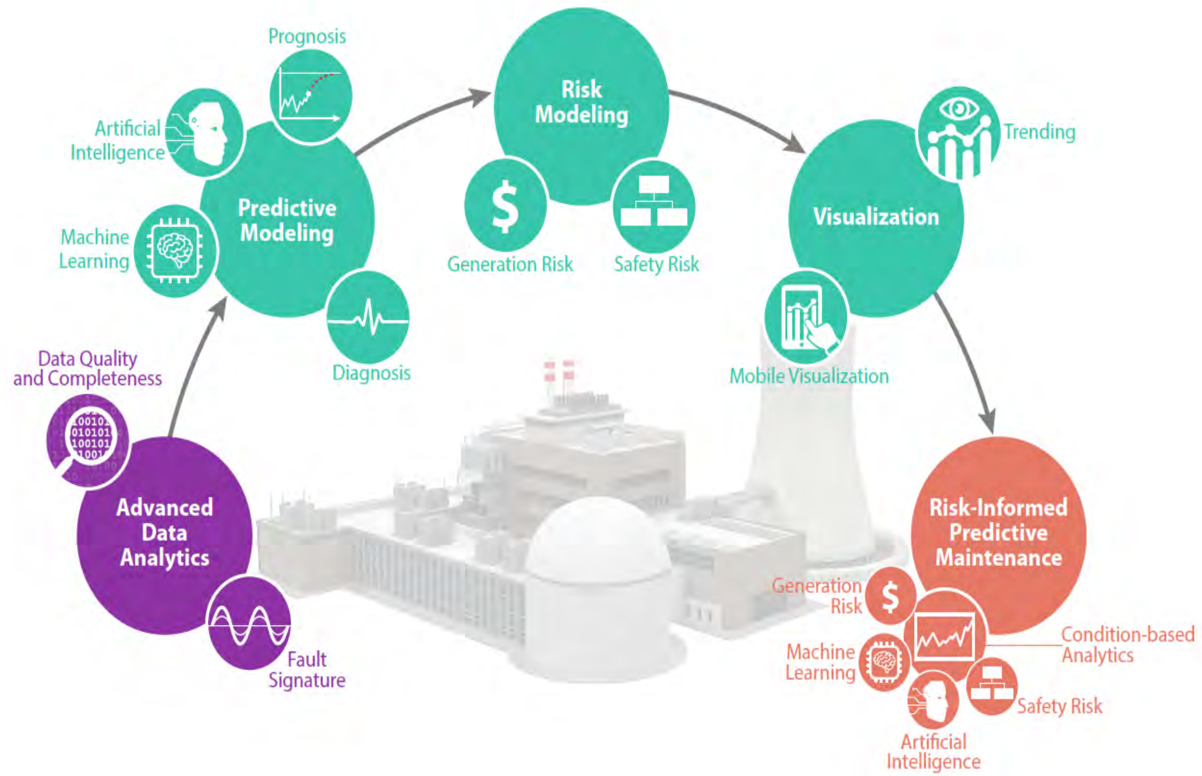
Vision of Risk-informed Predictive Maintenance (PdM) Strategy



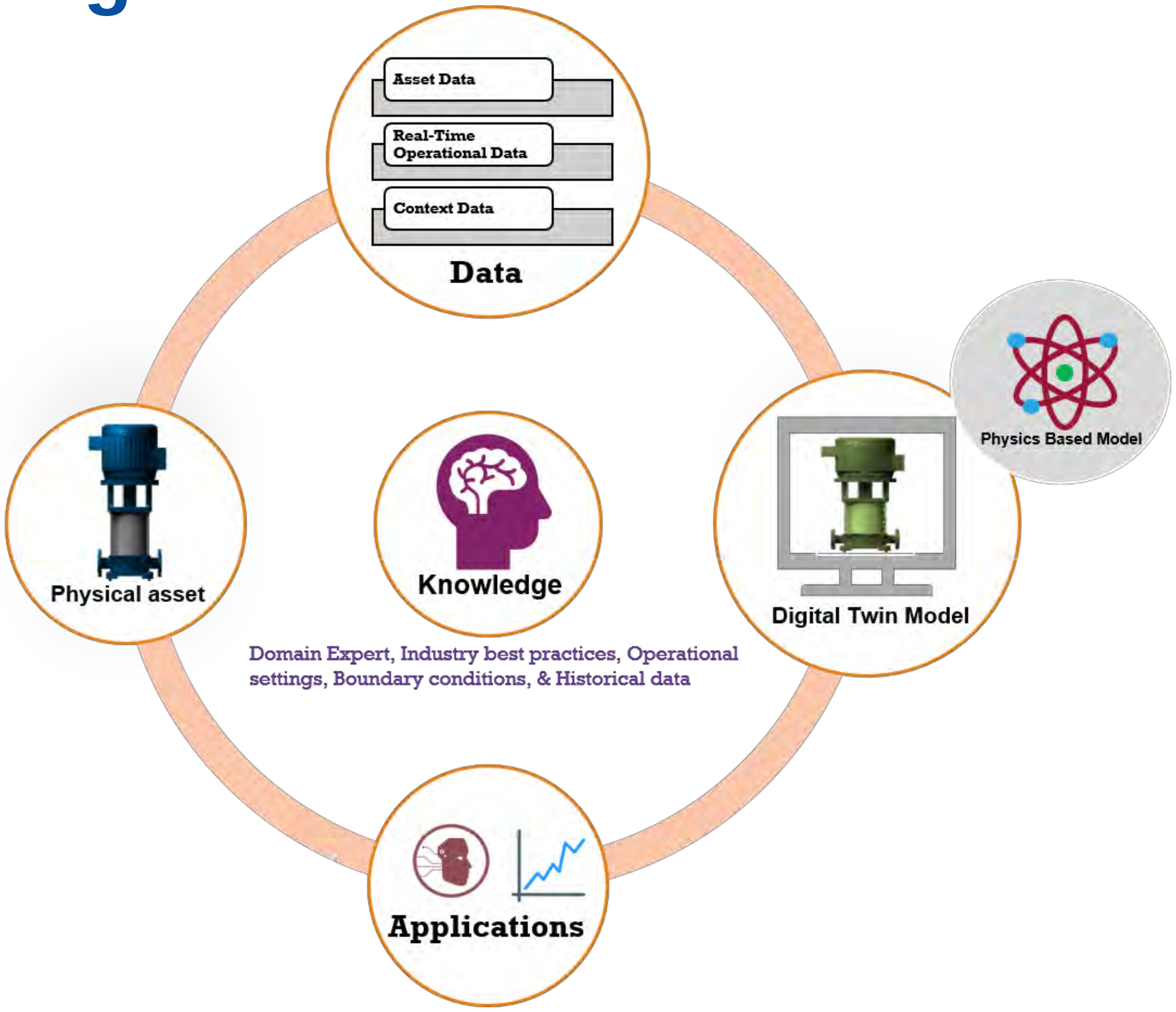


Agarwal, V., A Manjunatha, K et al. (2019, September). Deployable Predictive Maintenance Strategy based on Models Developed to Monitor Circulating Water System at the Salem Nuclear Power Plant (INL/LTD-19-55637). Idaho National Laboratory.

Data Analytics at Scale and Digital Twin



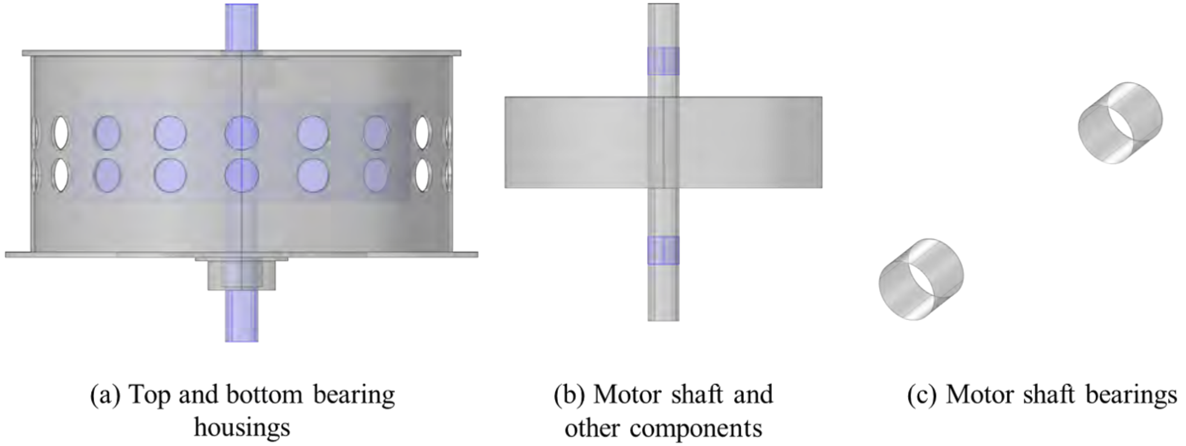
Condition based PdM Flowchart



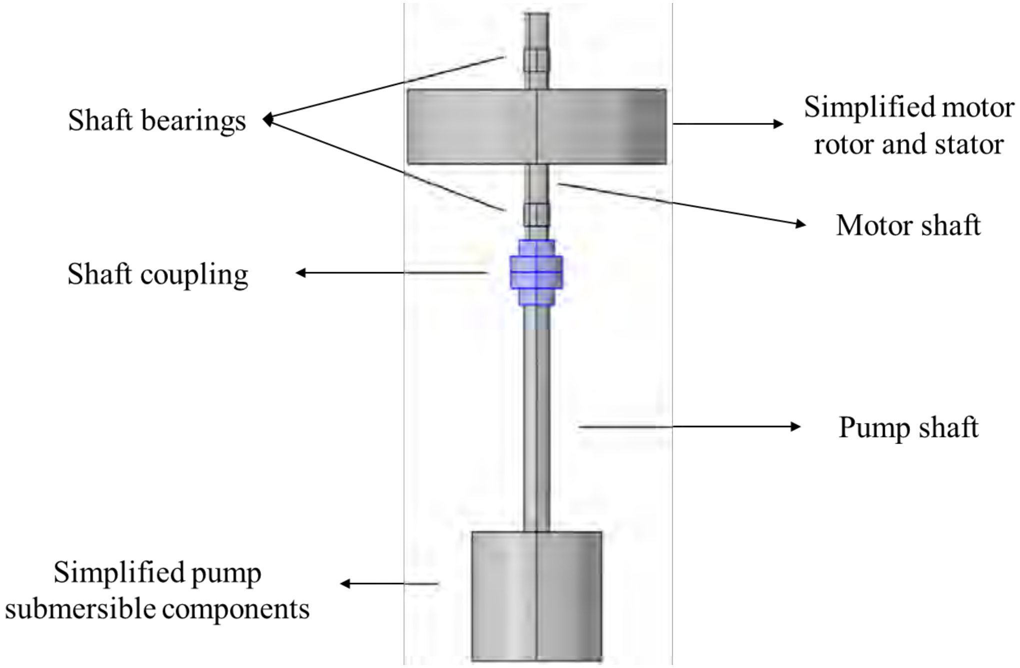
A schematic representation of a Digital Twin module

Agarwal, V., A Manjunatha, K., et al. (2021, August). Scalable Technologies to Achieve Condition-Based Predictive Maintenance Enhancing the Economic Performance of Operating Nuclear Power Plants (INL/EXT-21-01418). Idaho National Laboratory.

Physics based Modeling



Numerical model representation of the top and bottom bearing housings, where mechanical loads are introduced



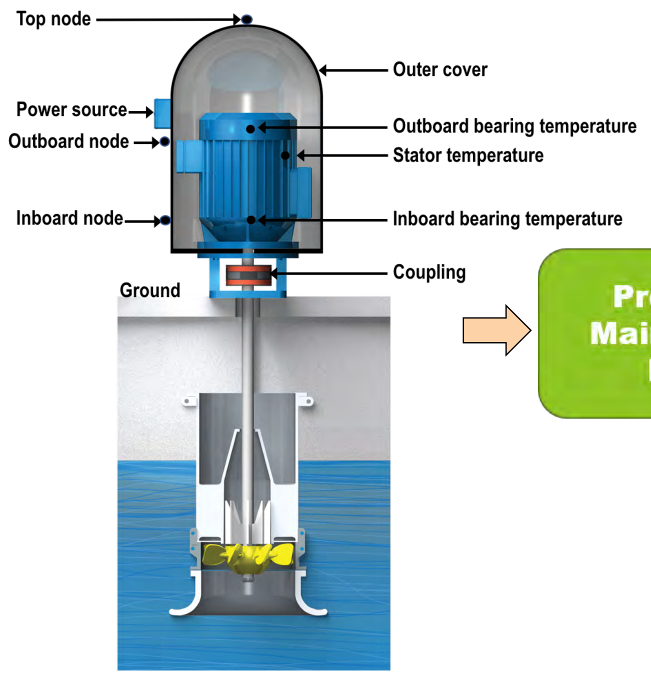
Simplified numerical model for motor, pump, and shaft coupling

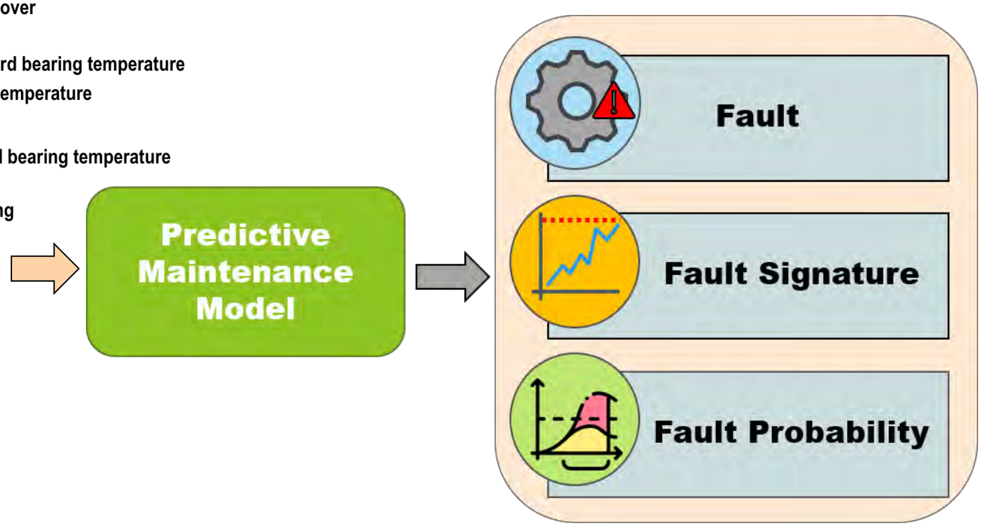
Physics Driven model:

Requires: 1. domain knowledge (material, size etc.)

2. close interaction with operators

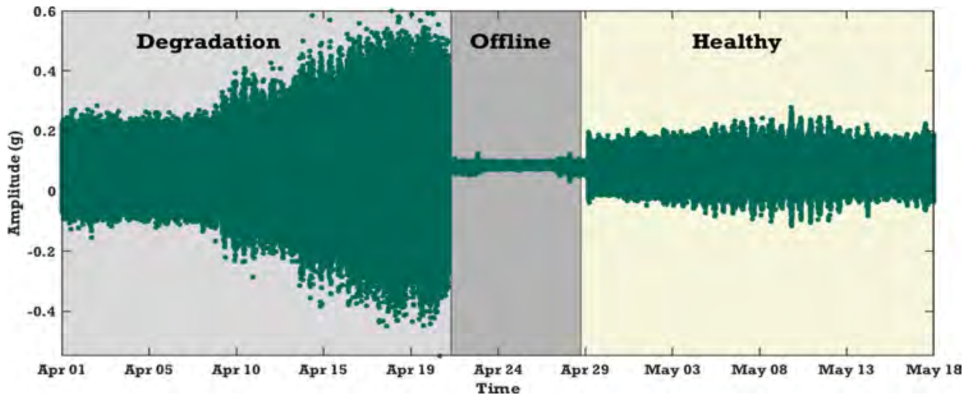
Condition based PdM Model and Outputs



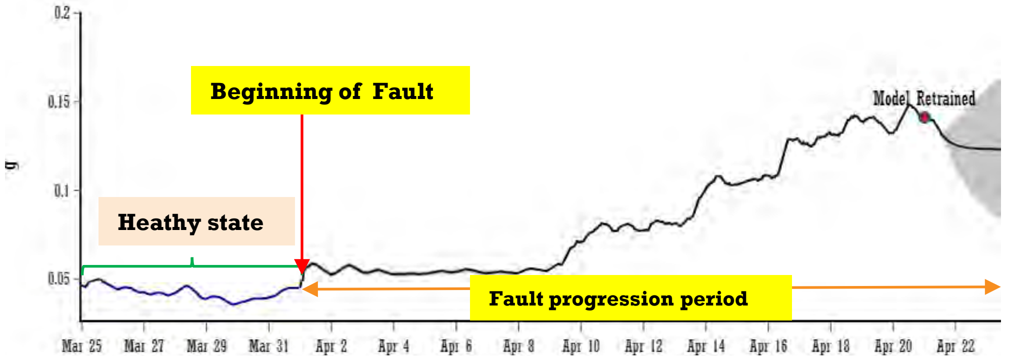


A schematic representation of a motor and pump with temperature measurement locations

Vibration Data



A representative figure of a particular fault captured in vibration signal



Forecasting dominant fault signature after prediction of a fault

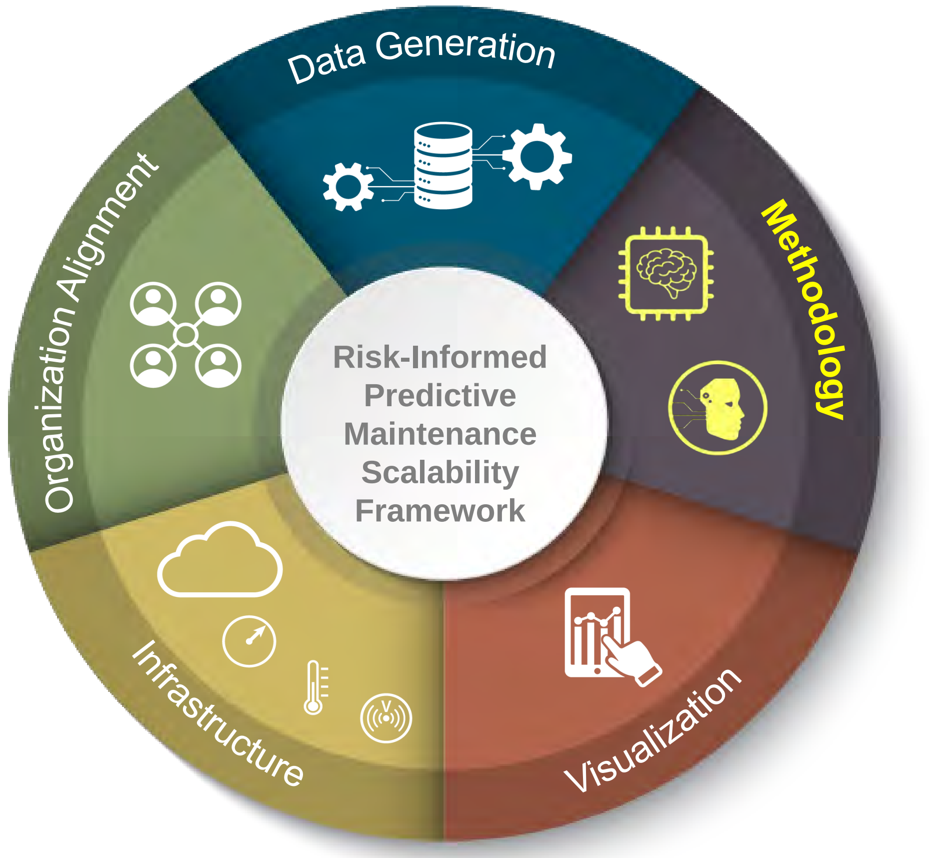
Agarwal, V., A Manjunatha, K., et al. (2021, August). Scalable Technologies to Achieve Condition-Based Predictive Maintenance Enhancing the Economic Performance of Operating Nuclear Power Plants (INL/EXT-21-01418). Idaho National Laboratory.

Scalable Condition based PdM

Scalability is defined as expanding capabilities of a target entity to meet current and future application-specific requirements

For NPPs, building a comprehensive AI model is challenging because

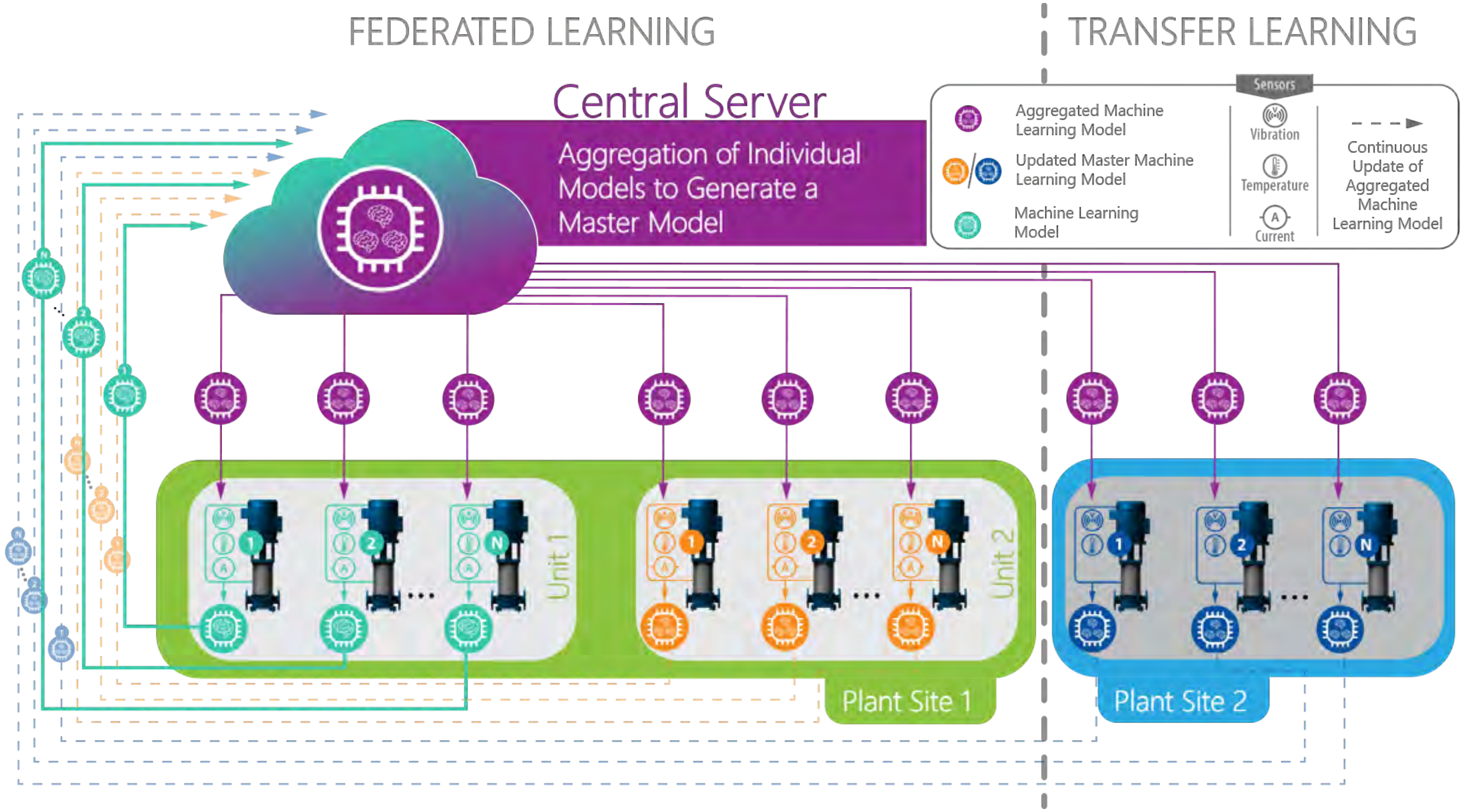
- Faults are rare events, and it is highly unlikely for all the faults to occur in each component;
- For a newly installed component/system or plant unit, it is infeasible to build AI models from scratch;
- Collecting data at a centralized location is limited by
  - High bandwidth costs
  - Real-time decision
  - Privacy, security, and commercial concerns



Agarwal, V., A Manjunatha, K., et al. (2021, August). Scalable Technologies to Achieve Condition-Based Predictive Maintenance Enhancing the Economic Performance of Operating Nuclear Power Plants (INL/EXT-21-01418). Idaho National Laboratory.

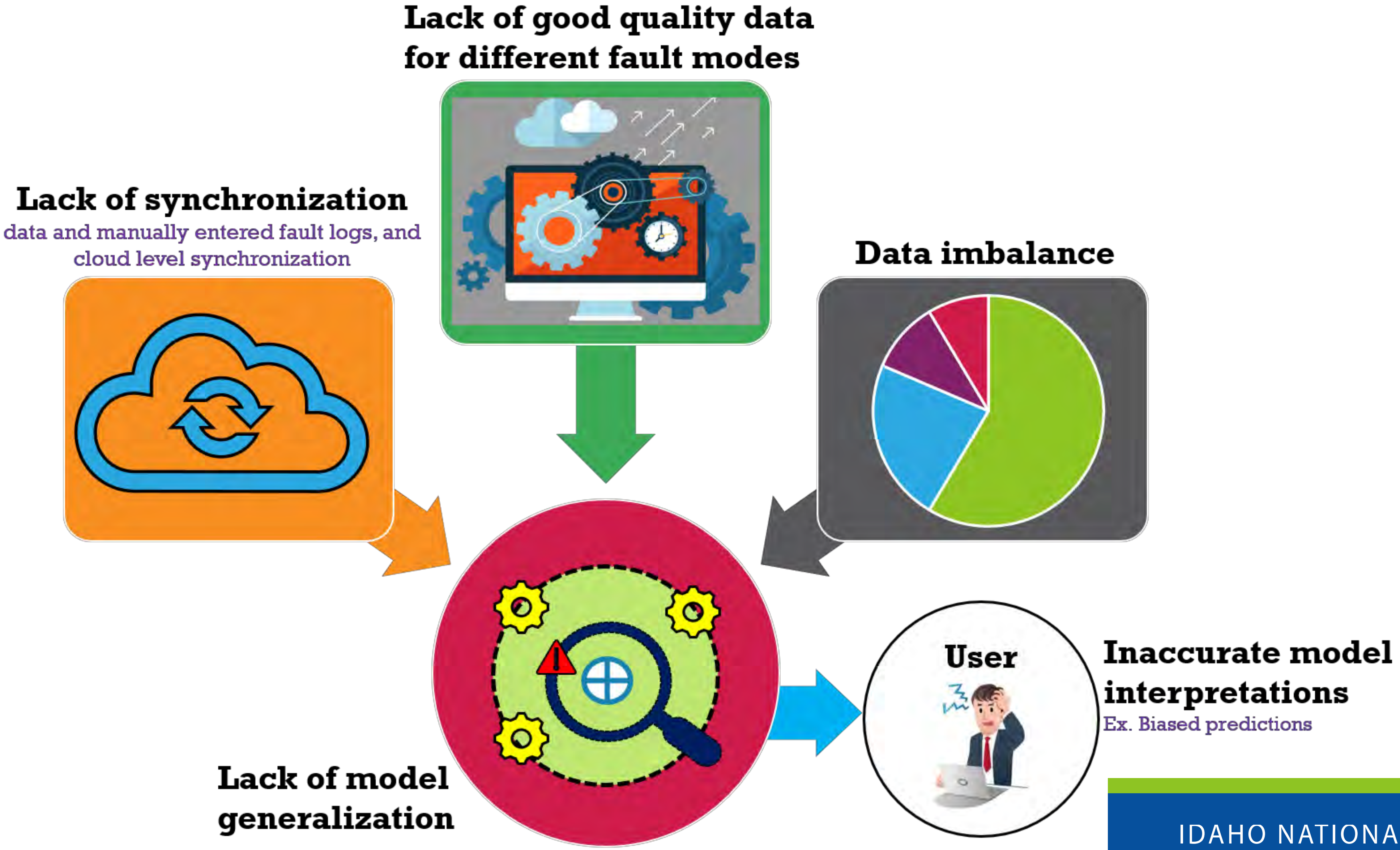
Federated Transfer Learning

- Individual component-level model using component-specific available data sources
- Consolidating the knowledge gained from individual component models into a master model,
- Using the master model to make diagnostic and prognostic estimations of the entire system,
- Applying (i.e., transferring) the master model to similar plant systems, either at the same plant site or at different plants.



Agarwal, V., A Manjunatha, K., et al. (2021, August). Scalable Technologies to Achieve Condition-Based Predictive Maintenance Enhancing the Economic Performance of Operating Nuclear Power Plants (INL/EXT-21-01418). Idaho National Laboratory.

Few Challenges to Consider



Team

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- Public Service Enterprise Group, Nuclear LLC Team
- PKMJ Technical Services Team

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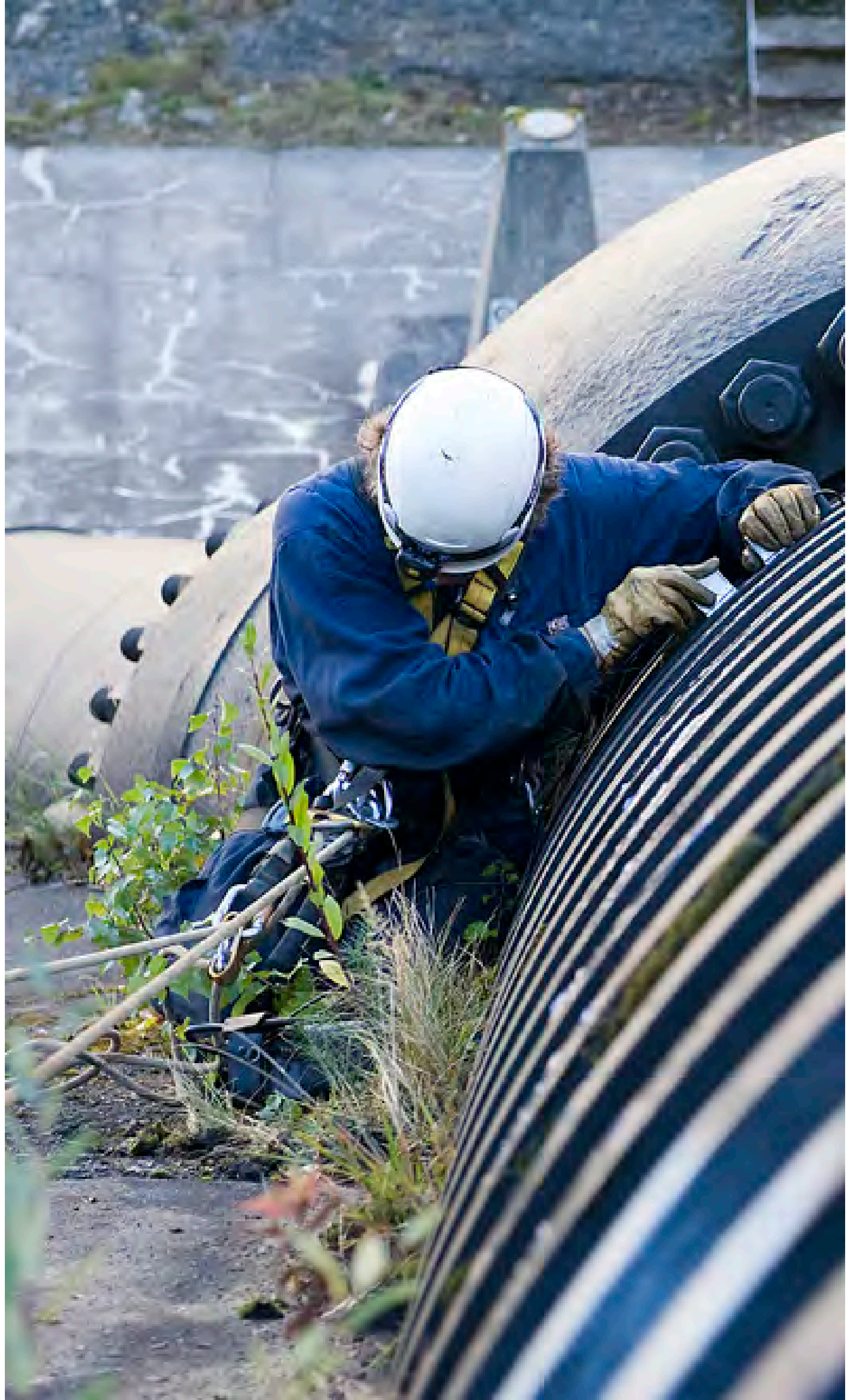
LWRS
LIGHT WATER REACTOR SUSTAINABILITY

THERMAL PERFORMANCE MANAGEMENT FOR NUCLEAR POWER PLANTS WITH DIGITAL TWINS

Use Cases based on EDF experience

09/15/21



Dr Christophe Duquennoy
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THERMAL PERFORMANCE MANAGEMENT FOR NUCLEAR POWER PLANTS WITH DIGITAL TWINS

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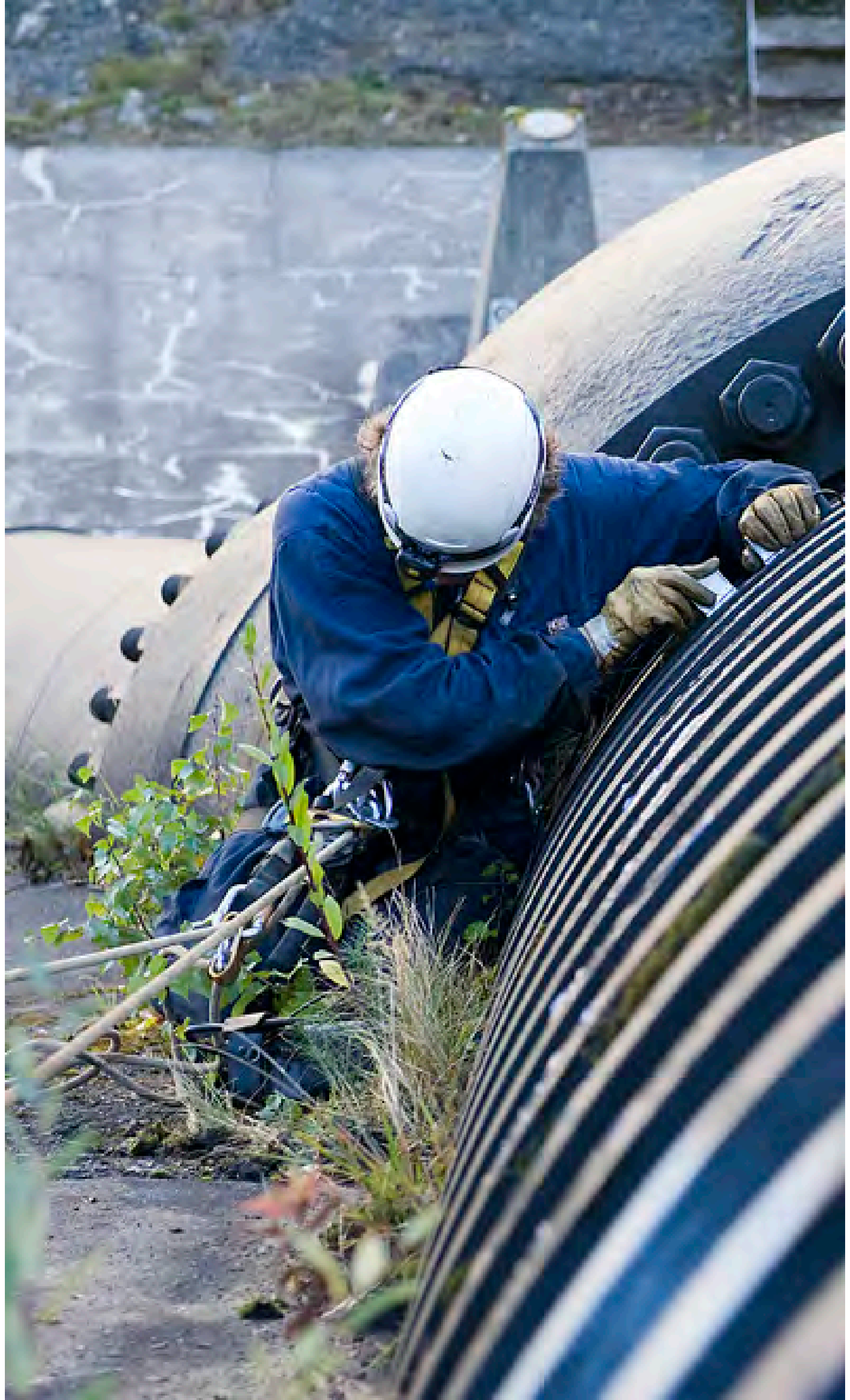
09/15/21



AGENDA

1. INTRODUCTION
2. DIGITAL TWINS FOR THERMAL PERFORMANCE
3. METROSCOPE SOFTWARE
4. USE CASES

DTG, from sensor to added value

Asset Management and O&M support

through

expertise and advanced DATA acquisition diagnosis and prediction

Dr Christophe Duquennoy
Nuclear Fleet Thermal Performance Expert
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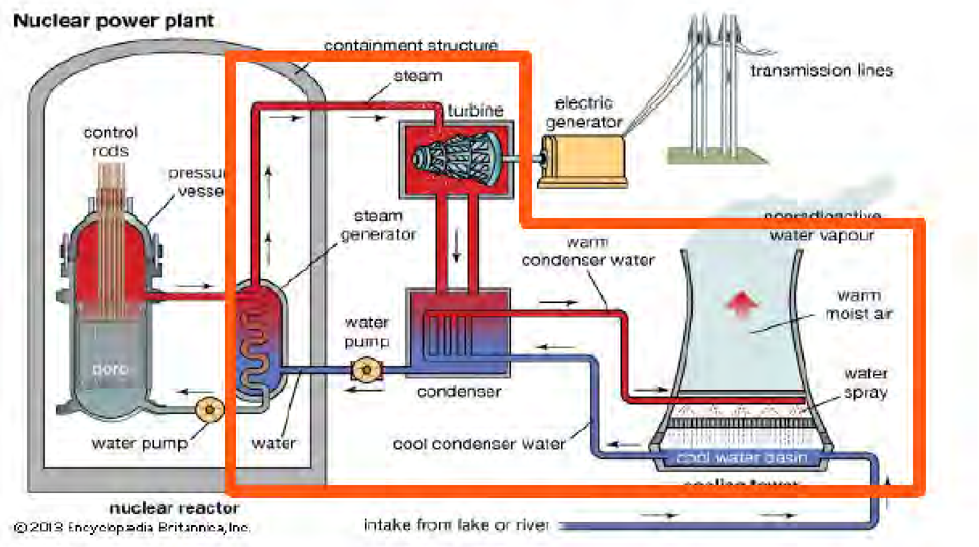
Thermodynamic Performance Testing and monitoring

- Thermodynamic measurement for NPP
- Performance monitoring, production and maintenance optimization




Before 2000

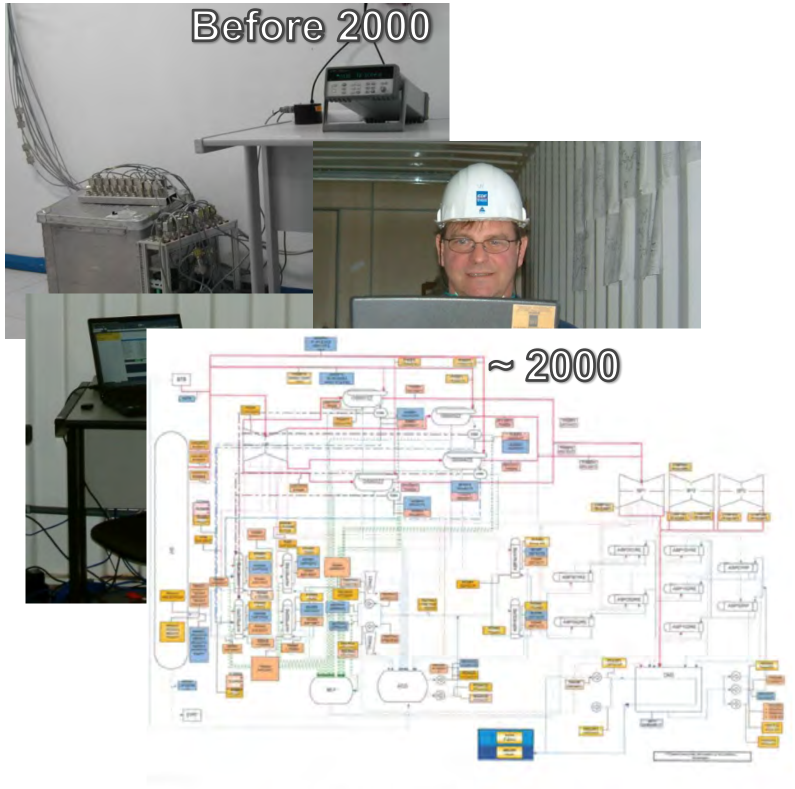


FIG. 12. Thermal model (with sensors)

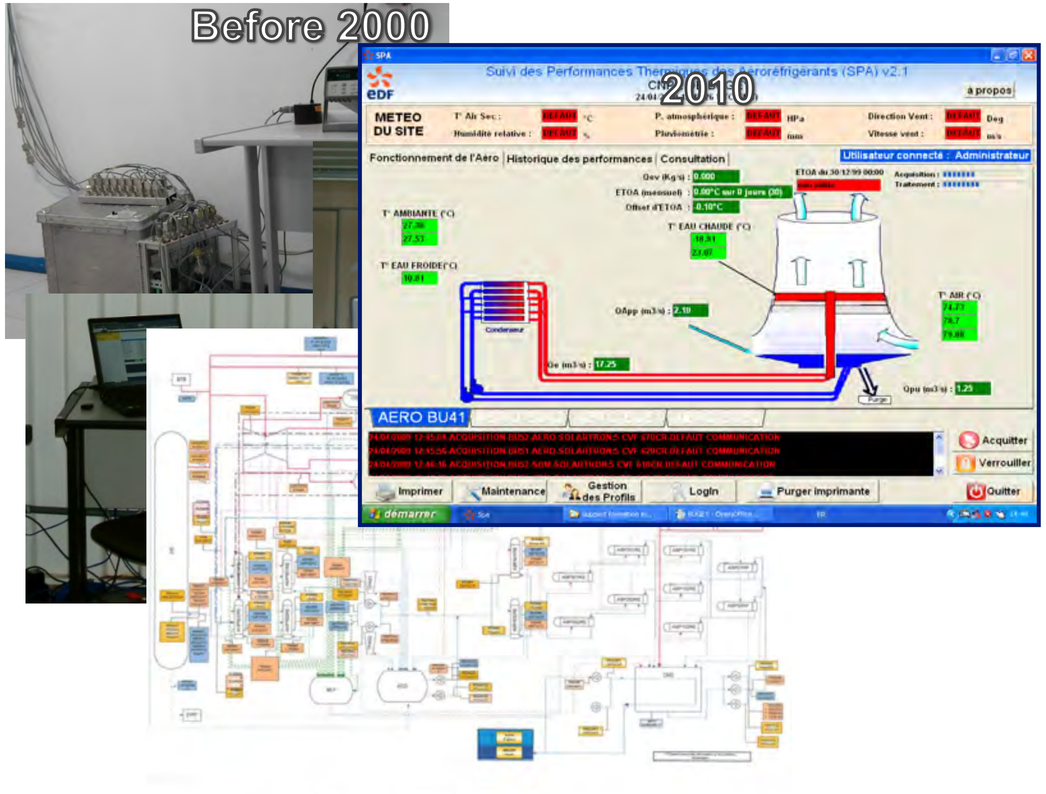
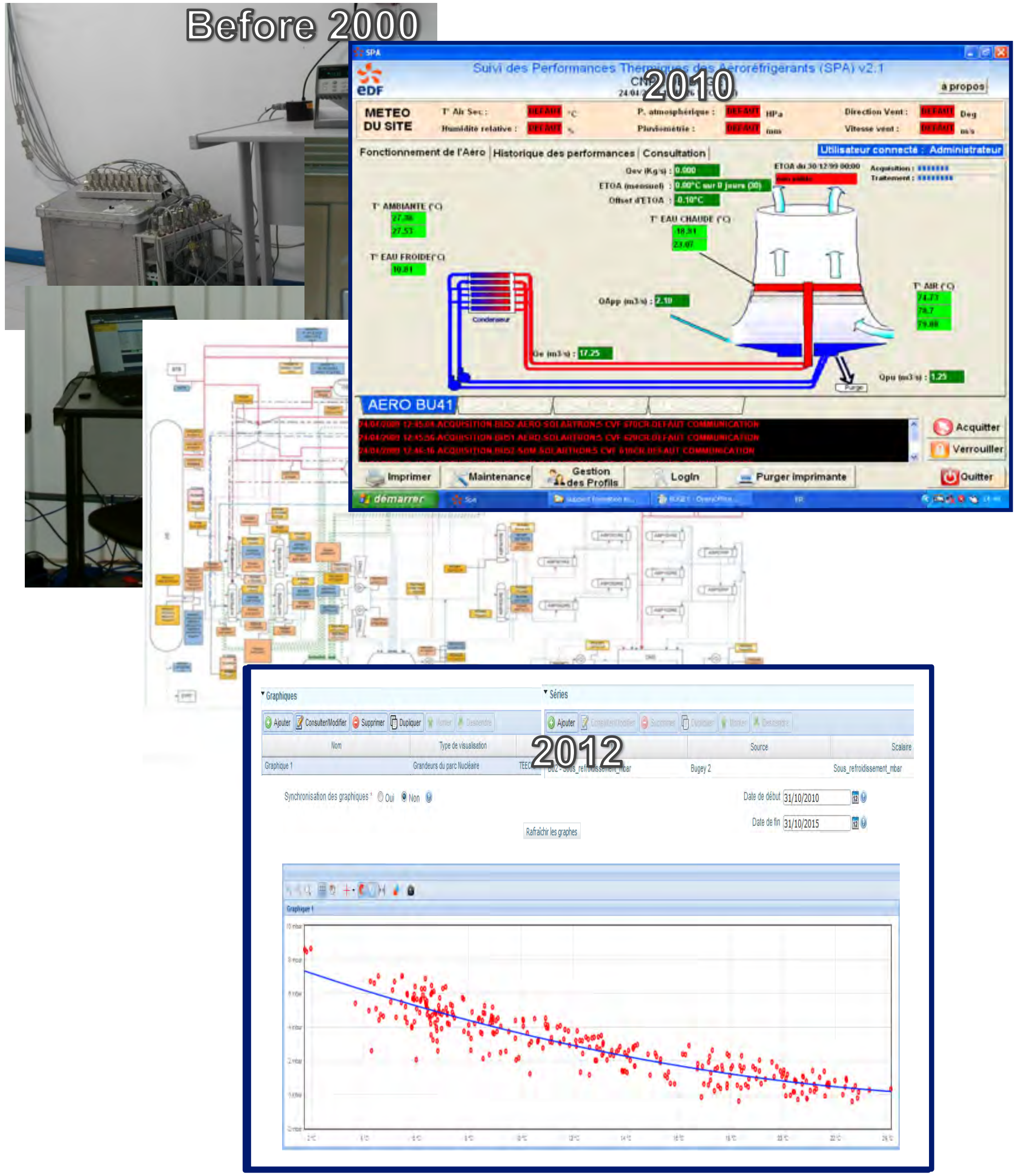


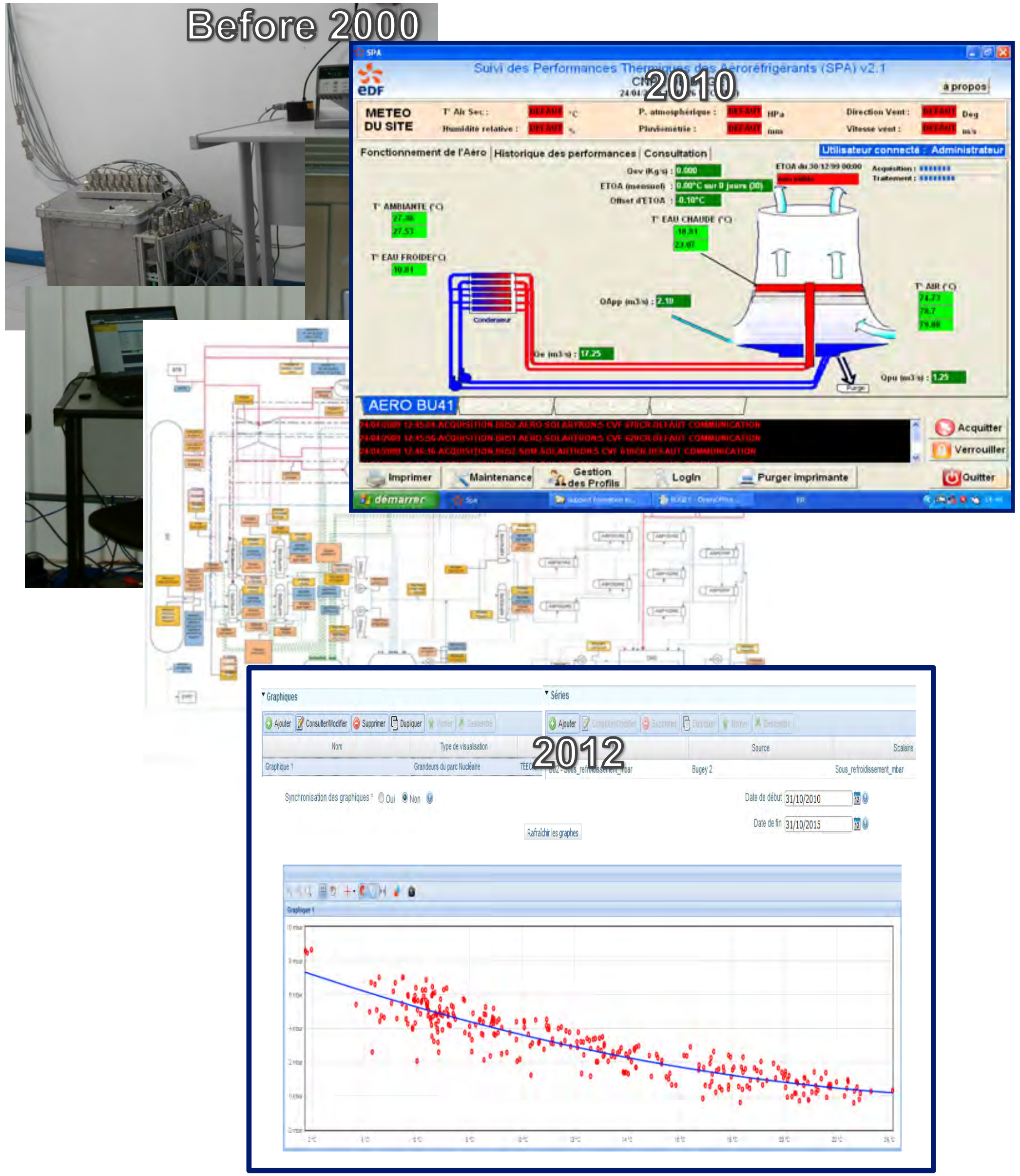
FIG. 12. Thermal model (with sensors)

INTRODUCTION

DIGITAL TWINS FOR THERMAL PERFORMANCE

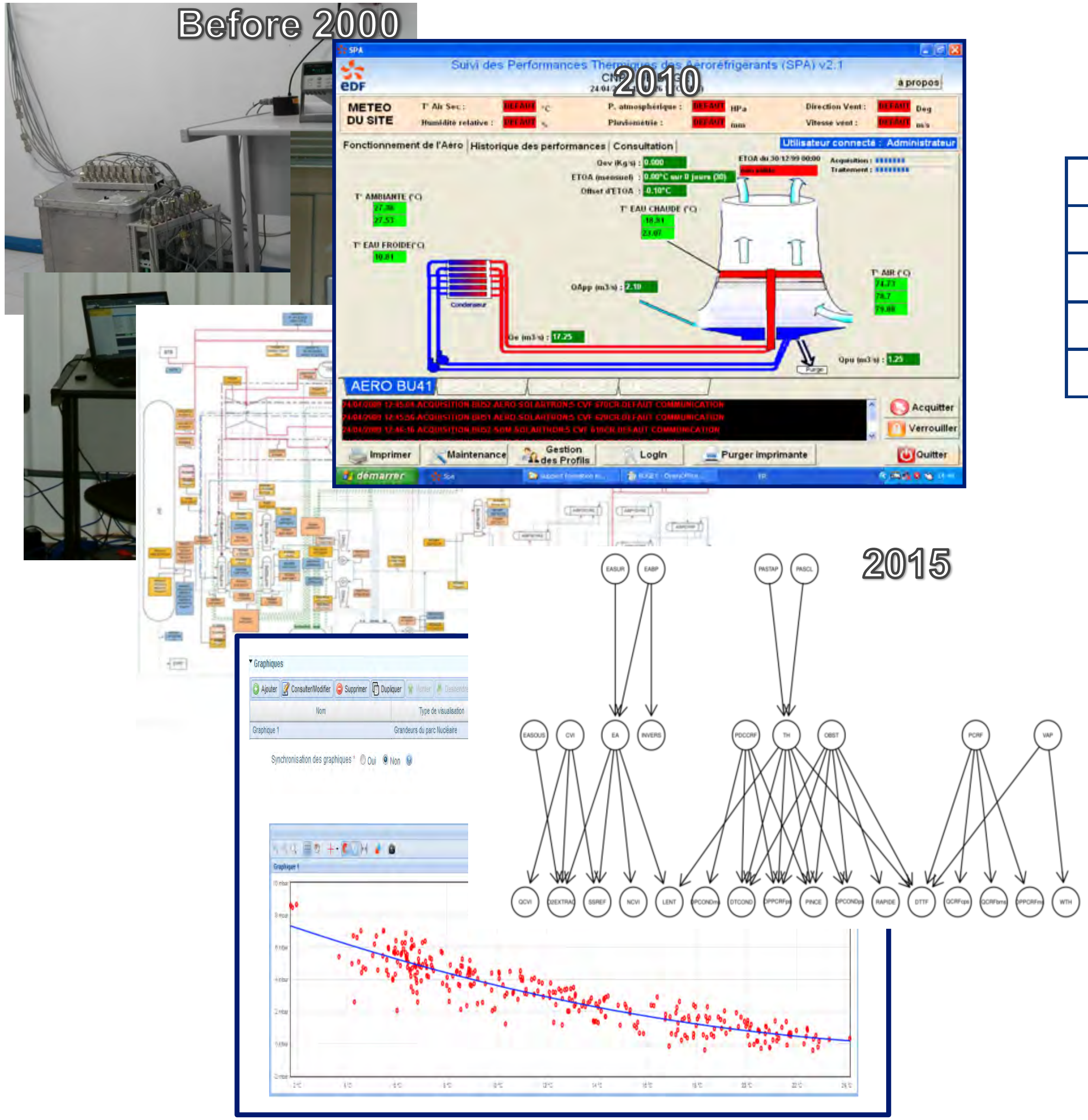


DTG



2014
Diagnostic methodologies

Δvide	↗
Ssref	↗
O_2extrac	↗
ΔPpcrf	→
ΔTtf	→



2014
Diagnostic methodologies

Δvide	↗
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O_2extrac	↗
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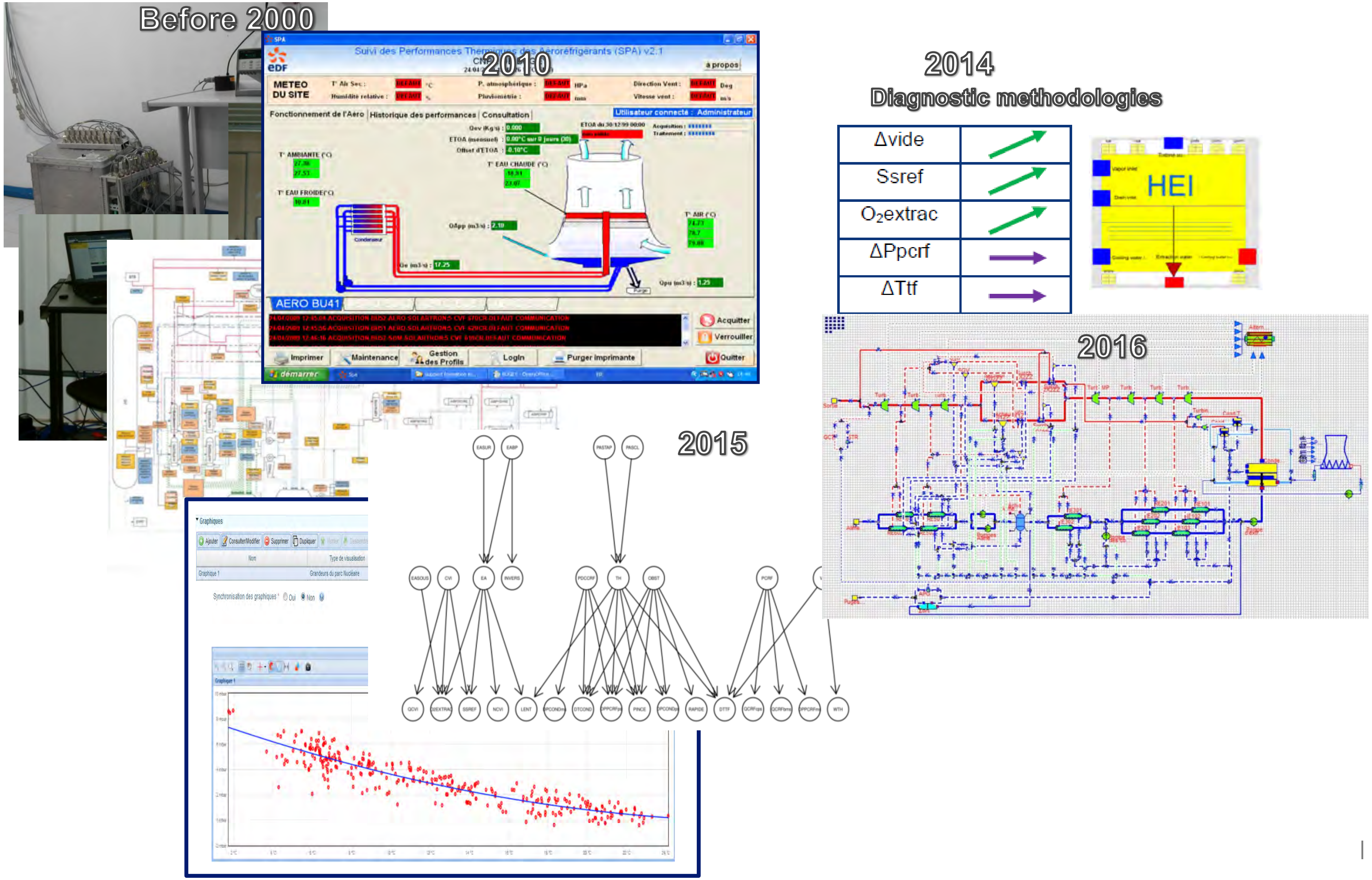
ΔTtf	→

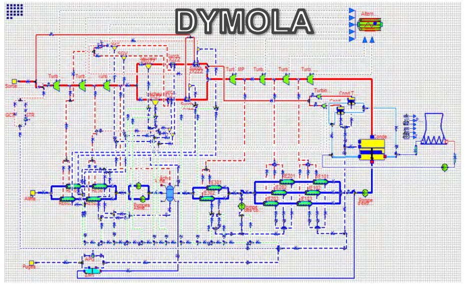
DTG

INTRODUCTION

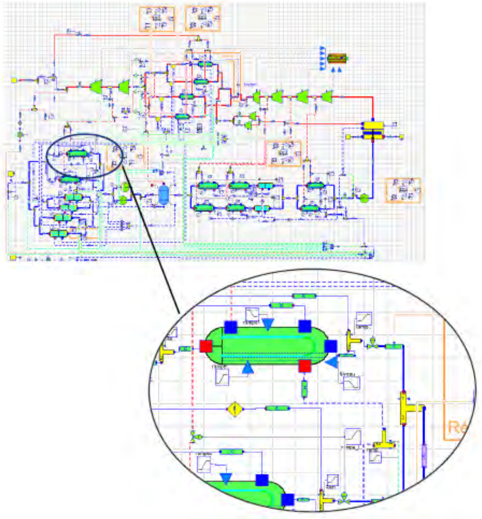
DIGITAL TWINS FOR THERMAL PERFORMANCE

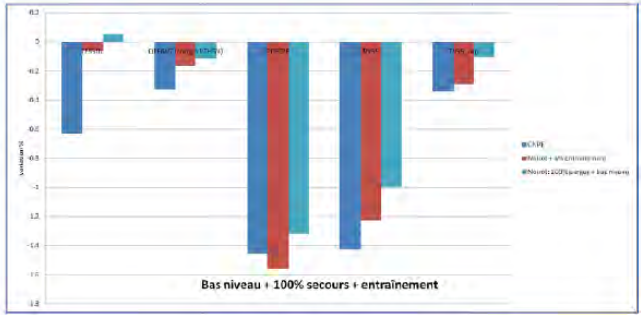


- **Saint Laurent NPP: Bypass leak on cooling tower vs Row Water leak in condenser**
  - We provided the maximum affordable power to allow to repair Row Water leak within operation. ➔ Avoided Plant Shut down



- **Cruas : Diagnostic for 14 Mwe lost in R501 HP Heater**
  - Medialization of simultaneous defects : Low level in heater + condensates leak + vapor entrainment

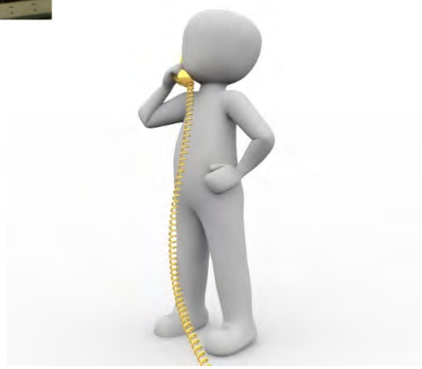




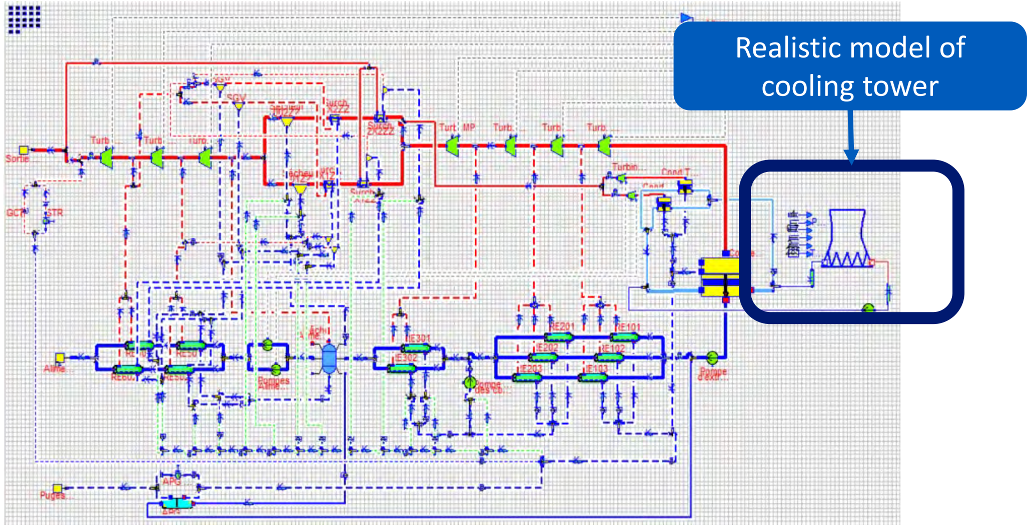
DTG

INTRODUCTION
DIGITAL TWINS FOR THERMAL PERFORMANCE

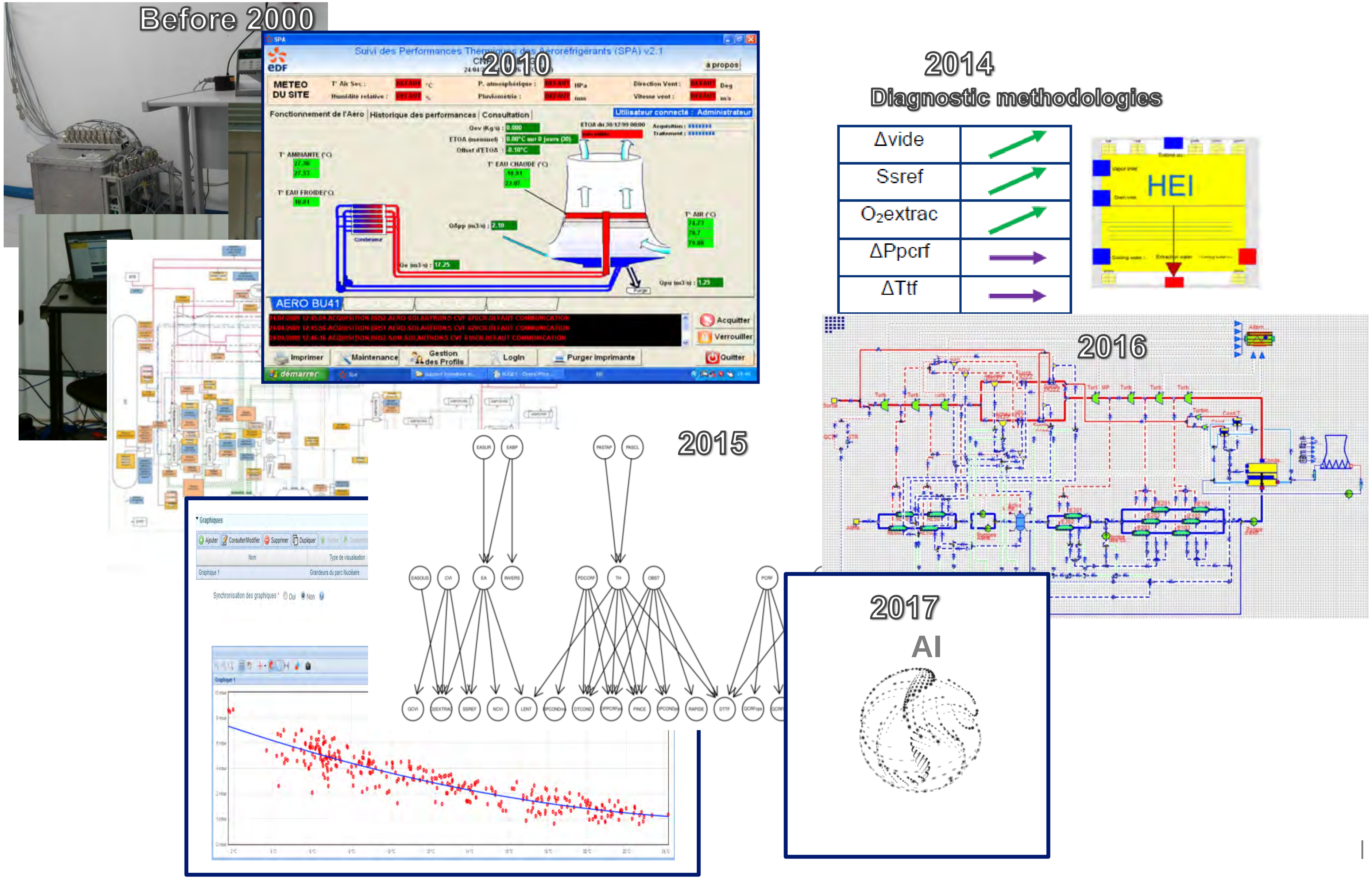
“We’ve got a drain piping under our water collectors which is about to break. Should we repair it before we turn on the plant ?”



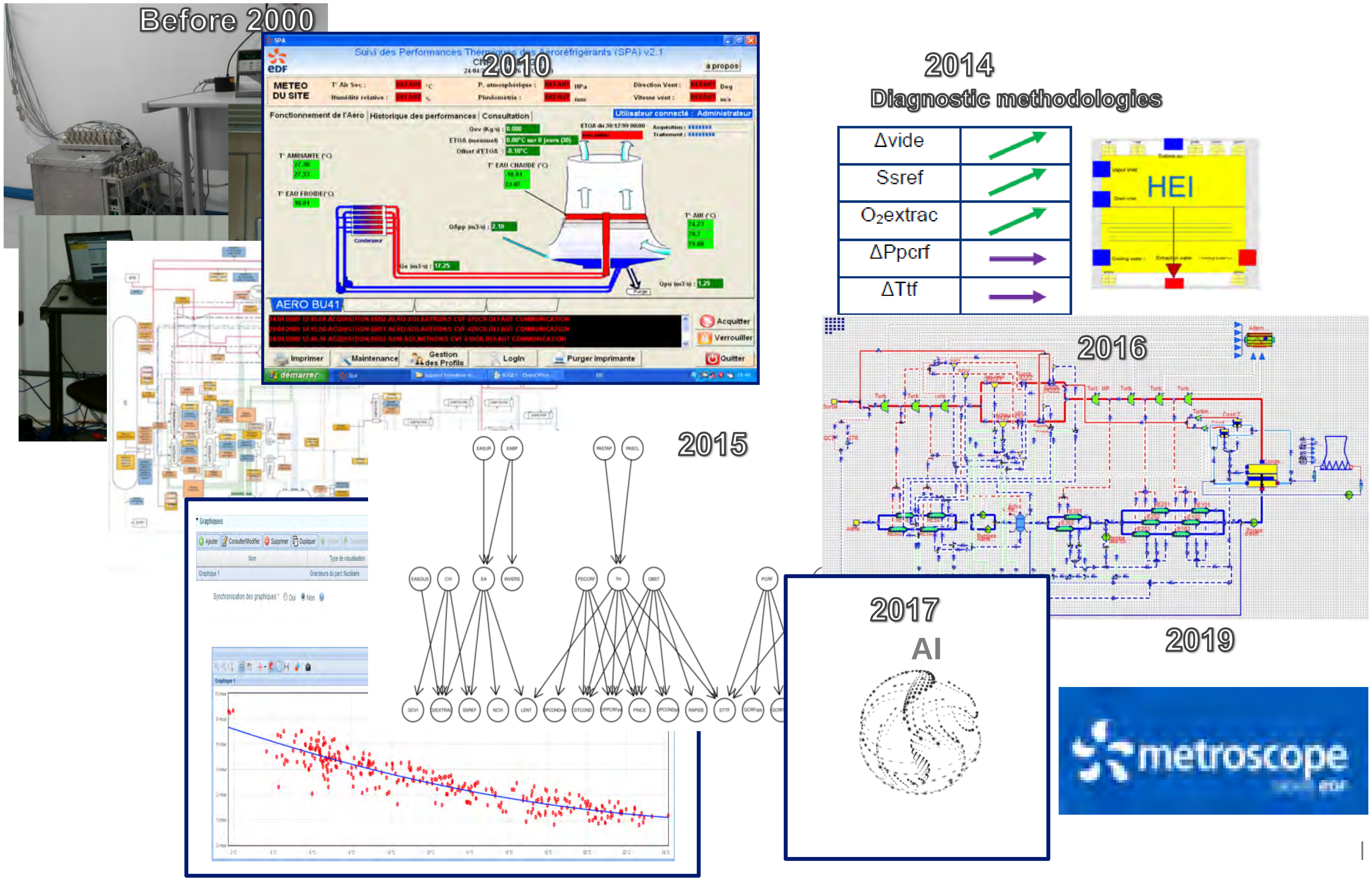
- **Nogent NPP draining pump rupture:**
  - Our analysis lead to maintenance and avoided ~600 k€ of loss.



INTRODUCTION
DIGITAL TWINS FOR THERMAL PERFORMANCE



DTG



Before 2000
2010
Suivi des Performances Thermiques des Aéroréfrigérants (SPA) v2.1
METEO DU SITE
AERO BU41
2014
Diagnostic methodologies
Δvide
Ssref
O2extrac
ΔPpcrf
ΔTtf
HEI
2015
2016
2017
AI
2019
metroscope

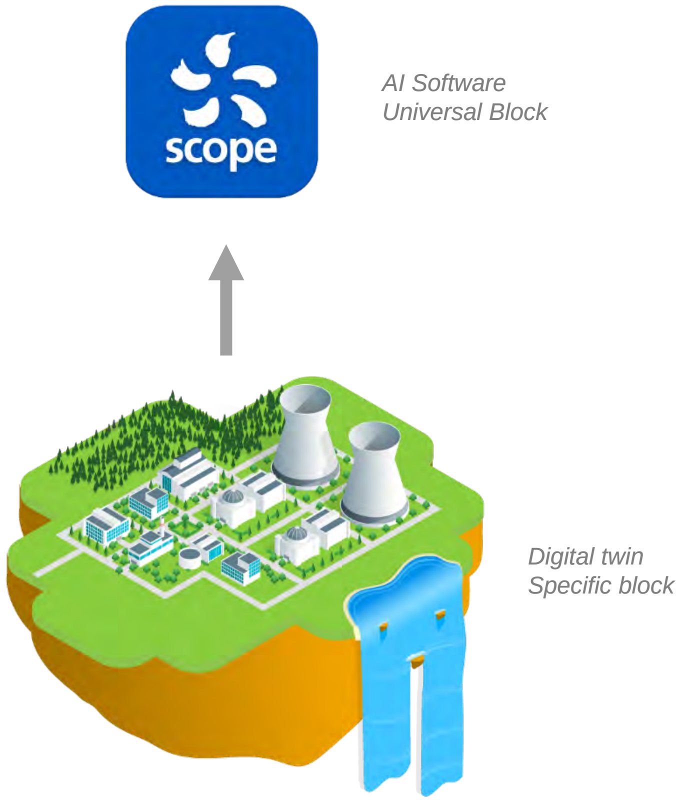
DTG

METROSCOPE SOFTWARE – GENERAL PRINCIPLE

The software combines a Digital Twin of the process and AI to perform a diagnosis in operations

$$Digital\ twin + AI = Diagnosis$$

The software uses existing information from sensors to analyze the plant performance and diagnose underlying causes impairing the expected behavior of the process



METROSCOPE SOFTWARE – GENERAL PRINCIPLE

Three steps to perform a Diagnosis

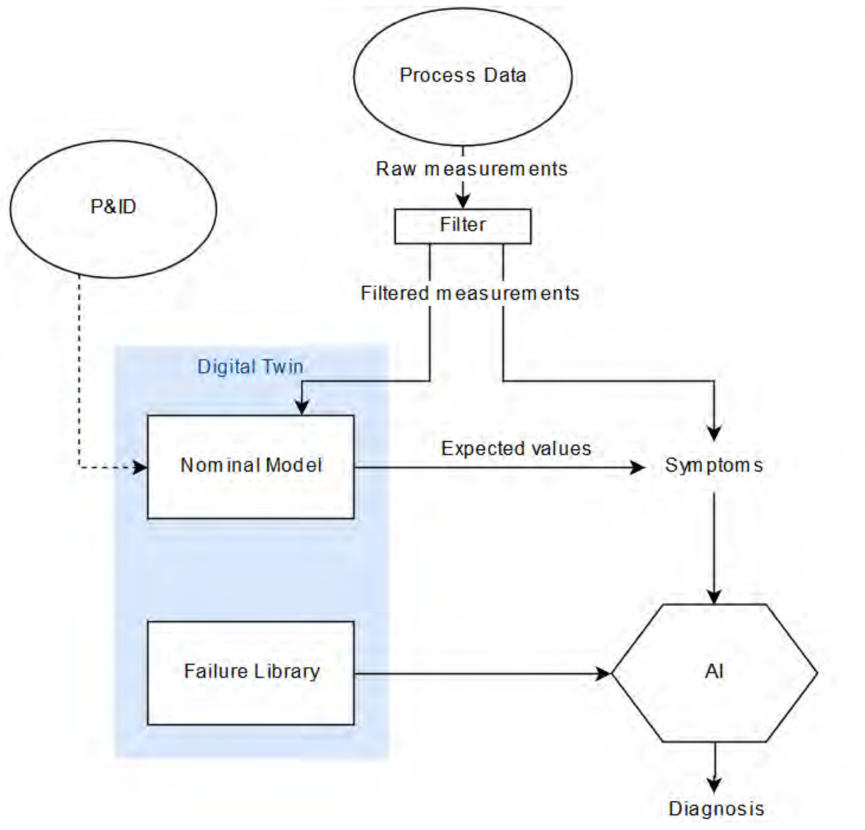
1 Metrological analysis of the raw data

2 The symptoms are generated using the Digital Twin.

3 The diagnosis is produced thanks to AI

Two bricks to make a Digital Twin

- **the nominal model** represents the nominal behavior in operation of the process, calibrated on historical data
- **the failure library** is a mathematical description of the failure modes of the process and their impact on the measurements



METROSCOPE AI belong to the domain of Symbolic AI (in opposition to Statistical AI)

It is meant to address Small Data problematics where decision relies on both Knowledge and Data.

METROSCOPE AI has been inspired by Medical Diagnosis

Most knowledge-based systems have two distinguishing features: a knowledge base (here the digital twin) and an inference engine (here the Bayesian network)

Awarded Best Innovation in Nuclear in 2019 by the Société Française de l'Enérgie Nucléaire

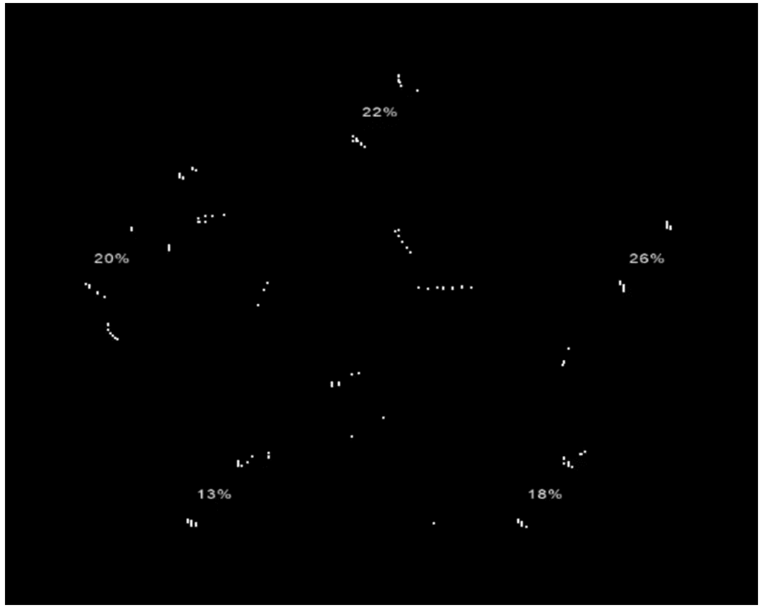


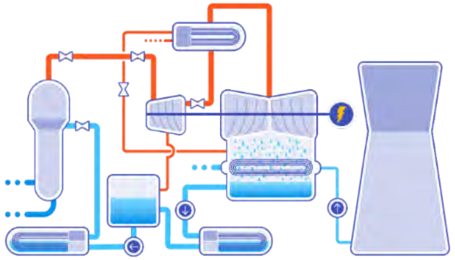
Illustration des chaînes de Markov

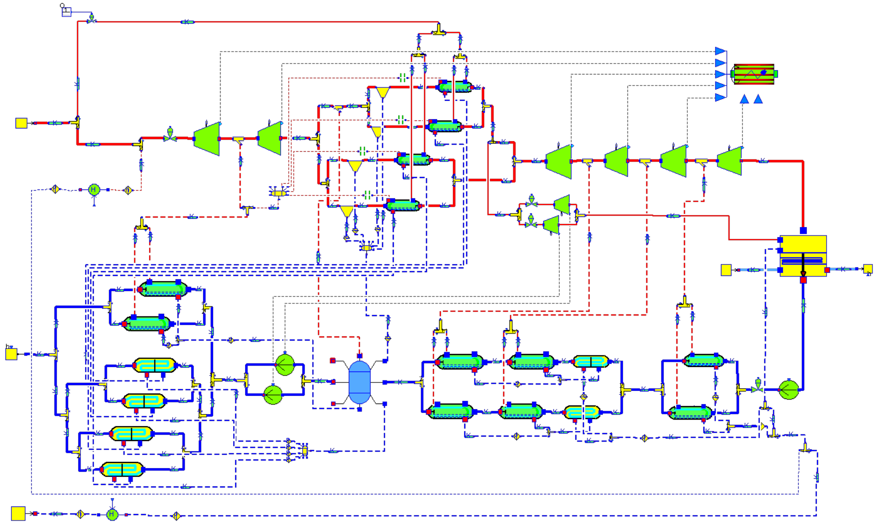
The Digital Twin (DT) is a numerical representation of the secondary side, able to simulate both nominal and impaired behaviors of the process.

DT is built from the P&ID of the plant and calibrated on historical data.

DT of a NPP is composed of around 10 000 equations and variable declarations.

Perimeter and Accuracy of the DT are meant to evolve overtime

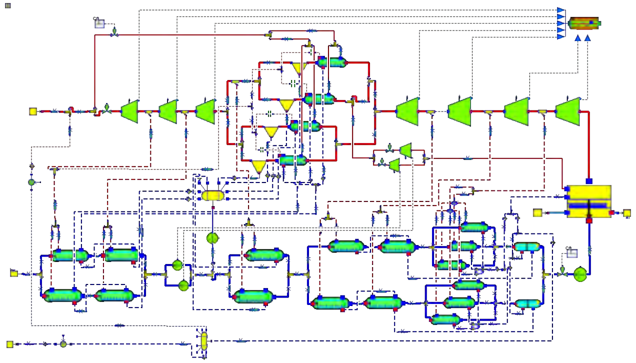




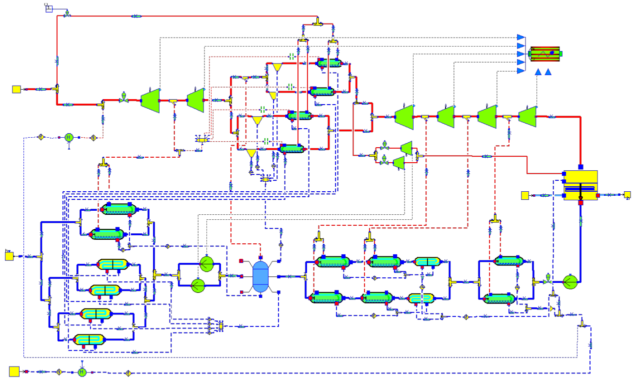
Jumeau numérique du circuit secondaire

METROSCOPE – DEPLOYEMENT ON EDF FLEET

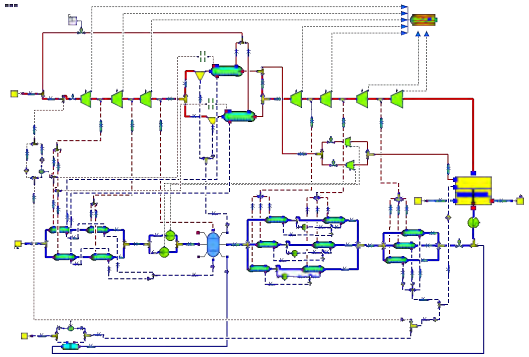
CP1



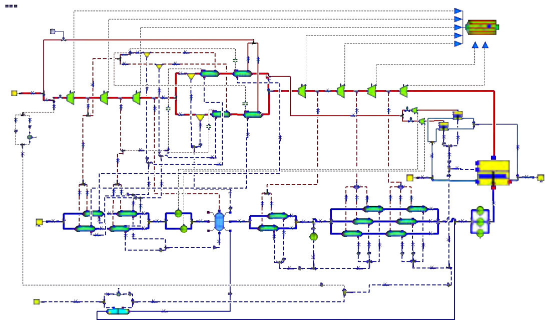
CP2



H4 – P'4

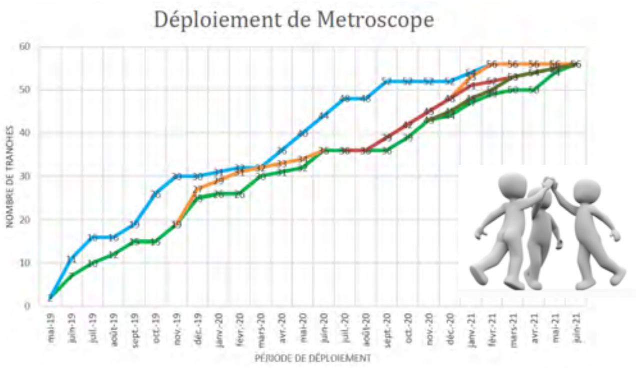


N4



- **Fleet References:**
  - 58 condensers digital twins encapsulating the best ever seen performance based on historian data.
  - 32 cooling towers digital twins tuned encapsulating the best ever seen performance based on historian data
  - Métroscope compatible Digital Twins

- Production of all the reference models for French Nuclear Fleet's METROSCOPE : 56 units in 3 years
- Production of all defect libraries based on EDF operation feedback.
- In particular: Expertise on key components in terms of thermodynamic performance: Condensers, Cooling Towers, Heaters.



DTG

HIGH PRESSURE HEATER LEAK

Detection of simultaneous leaks on both MSR and HP Heaters :

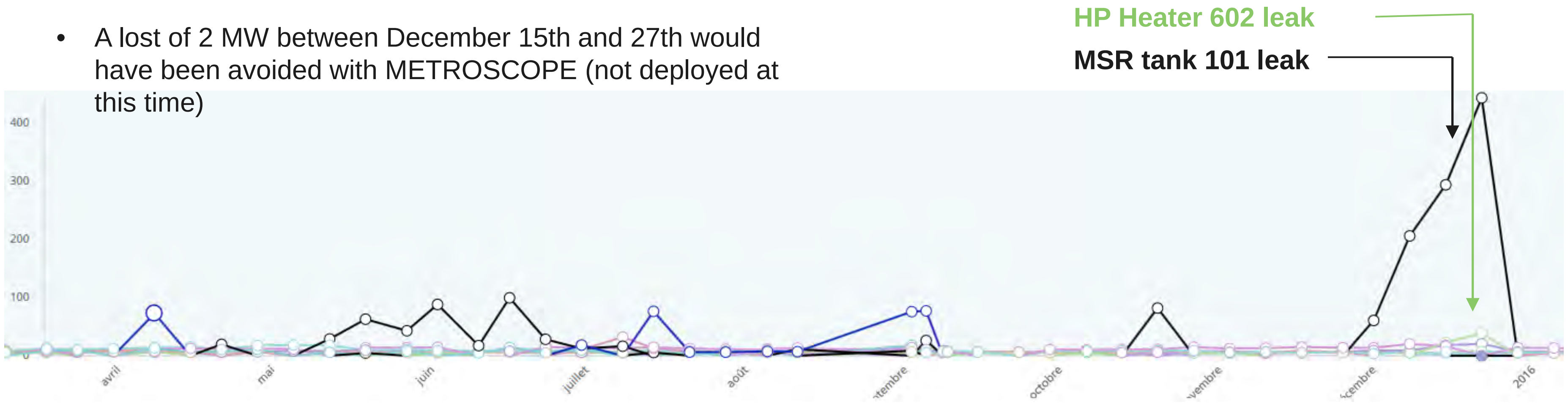
- MSR condensate regulation fault was **detected by the operator** (since 2015 November 30th)

- Meanwhile heater’s leak on condensates occured (2015 December 14th). It was **not detected by operators**.

- A lost of 2 MW between December 15th and 27th would have been avoided with METROSCOPE (not deployed at this time)

Performance Gain

Avoidable loses 0,5 GWh

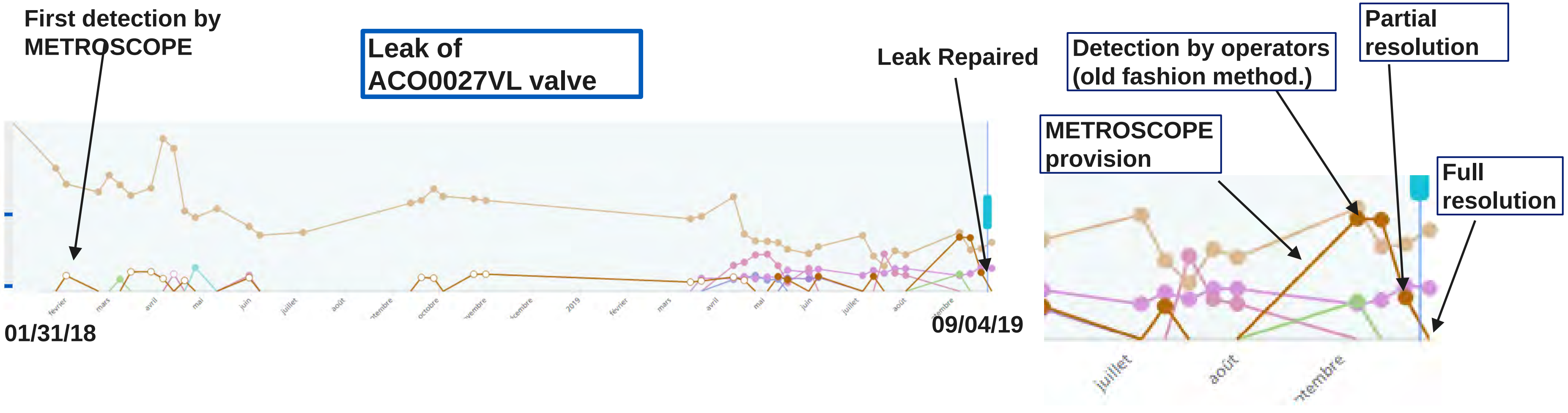


CONDENSATE COLLECTOR TANK LEAK

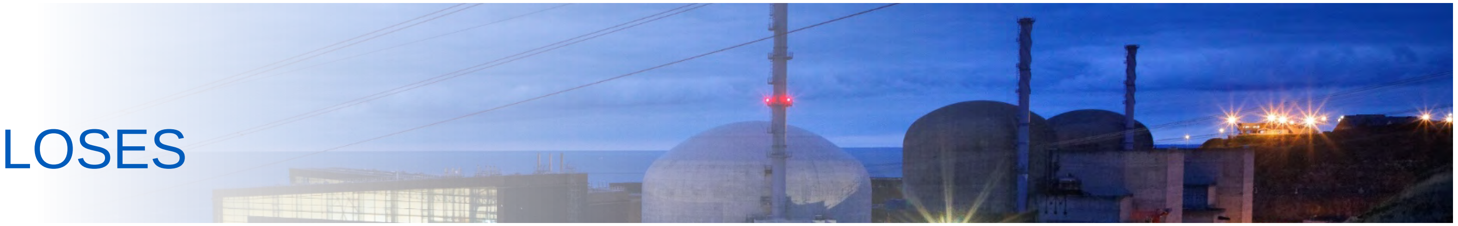
- Early detection of small magnitude leak (~2% of the nominal flow)
- Reliable quantification of the impact (1.5 MWe)
- Diagnostic of multiple simultaneous defects

Performance

Avoidable loses ~ 8 GWh



CONDENSER LOSES



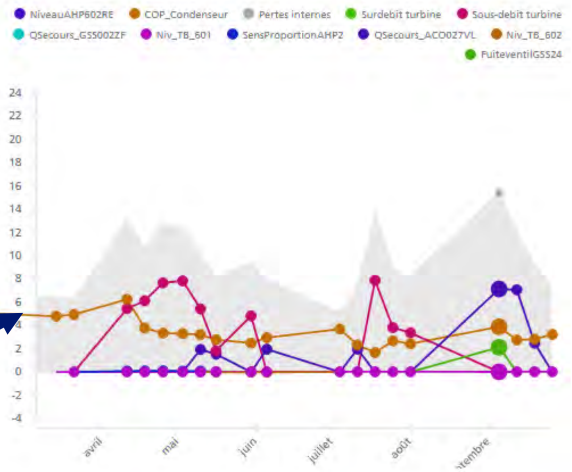
- Simultaneous Multiple Diagnostic
- Accurate Quantification of condenser losses due to updated reference Digital Twins

Performance

Avoidable losses 1 mbar = 1MWe

Le 04/09/2019 à 12:08:18
Cycle 36 - Essai 047

PMD repère		971 MW
Puissance brute corrigée		957,4 MW
Puissance mesurée		938,5 MW
Pertes internes		15,4 MW
QSecours_ACO027VL	59,2 kg/s	7,1 MW
Niv_TB_601	0 so	0 MW
FuiteventilGSS24	2,3 kg/s	2,1 MW
COP_Condenseur	3,7 mbar	3,9 MW
Inexpliqué		2,2 MW

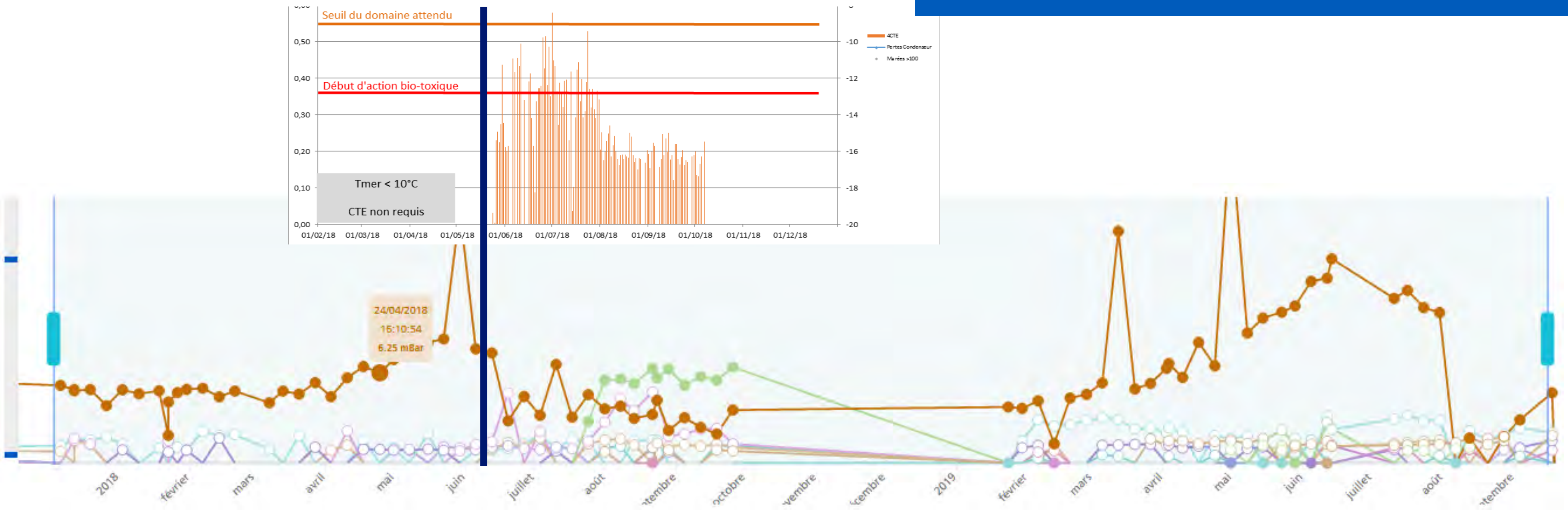


CONDENSER LOSES

- Real time reliable monitoring of condenser thermal performances
- Possibility to optimize biocidal injection during crises
- Accurate Quantification of condenser losses due to updated reference Digital Twins

Performance / Maintenance

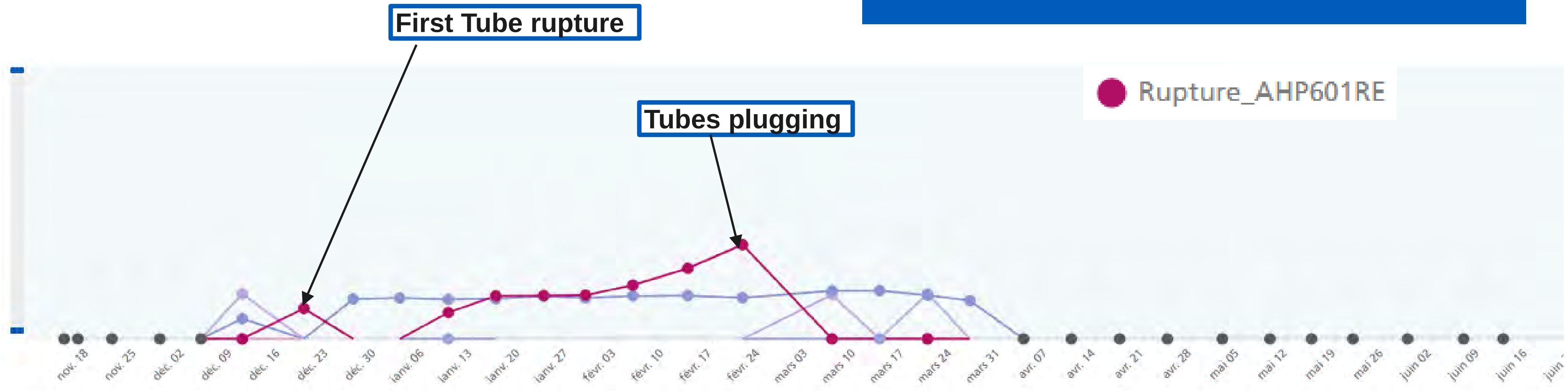
Avoidable losses 1 mbar = 1MWe
Optimization of operating solutions :
Biocidal injection, Taproges CTA, reboiling.



HEATERS TUBE RUPTURE

- Early detection (2 or 3 weeks)
- Real time monitoring of number broken tubes
- **Maintenance schedule optimization**
- Limit the duration of maintenance intervention (better prepared)
- Capitalization of feedback of evolution signatures.

	Maintenance
Gain	Optimization of maintenance scheduling and duration

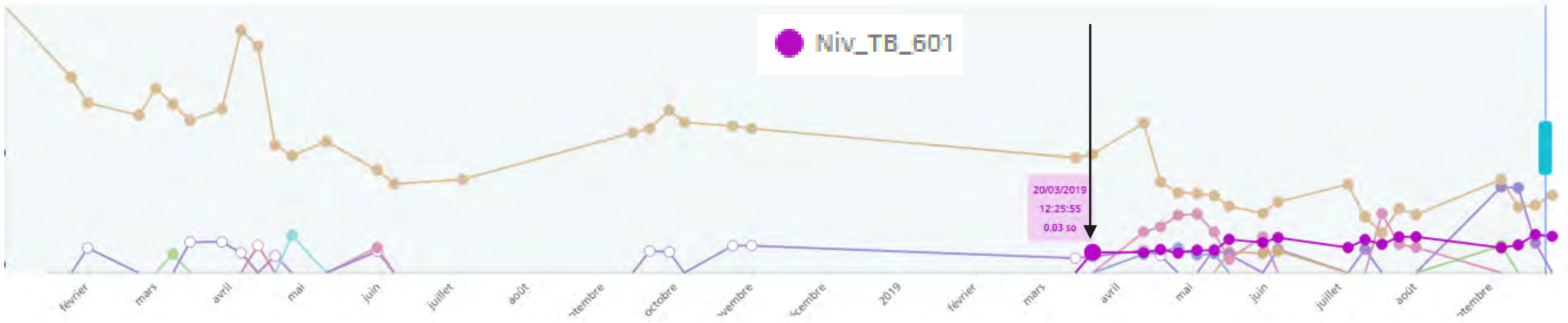


LOW HP HEATERS LEVEL

- Situation before METROSCOPE not seen and solved by operators
- Detection of low level situations by METROSCOPE

Maintenance	
Gain	Plant adjustment

Low Heater Level detection



HP HEATERS LEVEL REGULATION

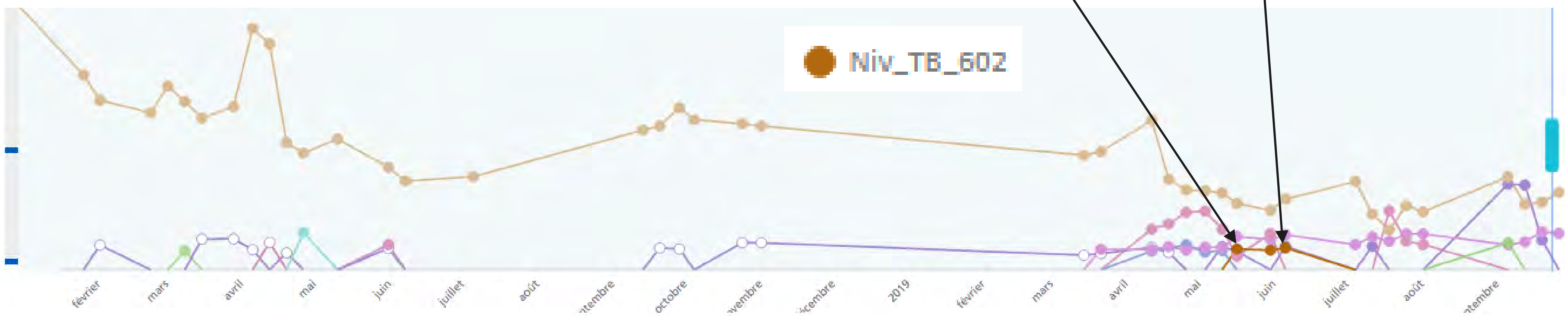
- Real time detection of low level situations by METROSCOPE
- Optimization plant adjustment by operators

Maintenance

Gain | Plant adjustment

Disturbed Heaters level regulation niveau

Adjustment of HP Heaters level regulation

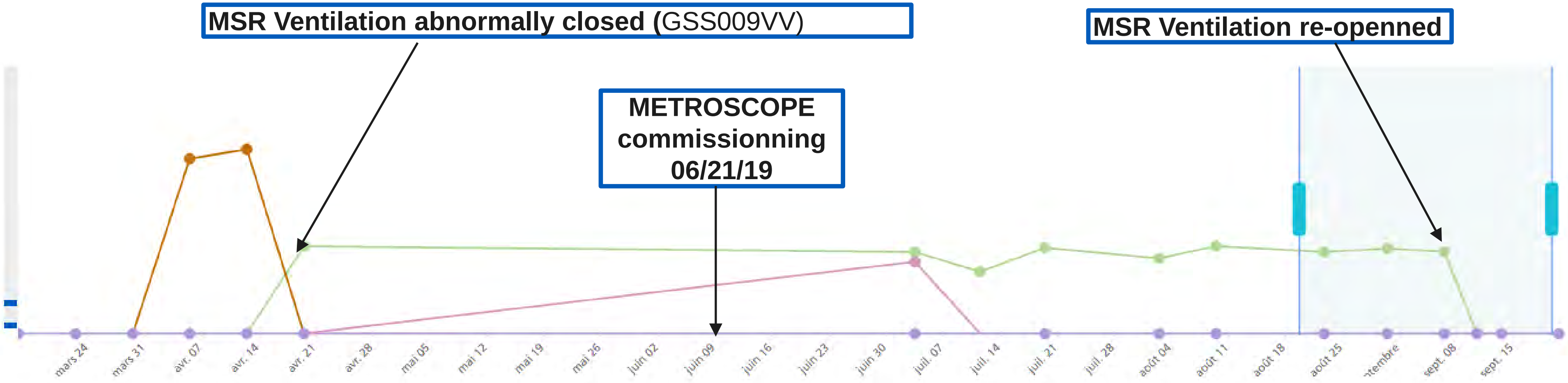


MSR VENTILATION OBSTRUCTION

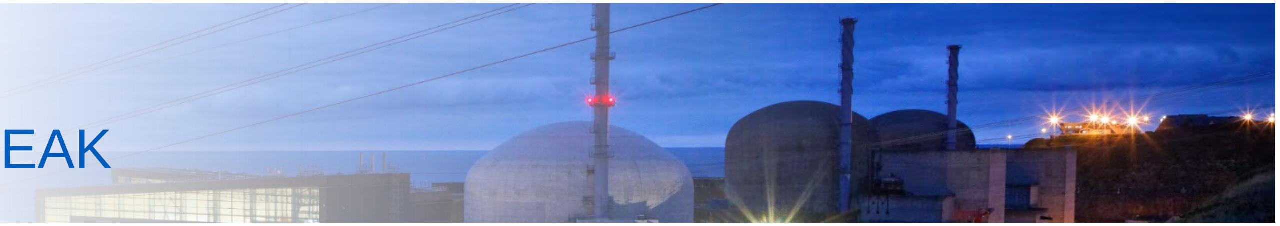
- Based on low signal detection (variation under 4% = 2 kg/s)
- After operator intervention, the defect is solved

Maintenance

Gain: Incondensable gas management



MSR VENTILATION LEAK



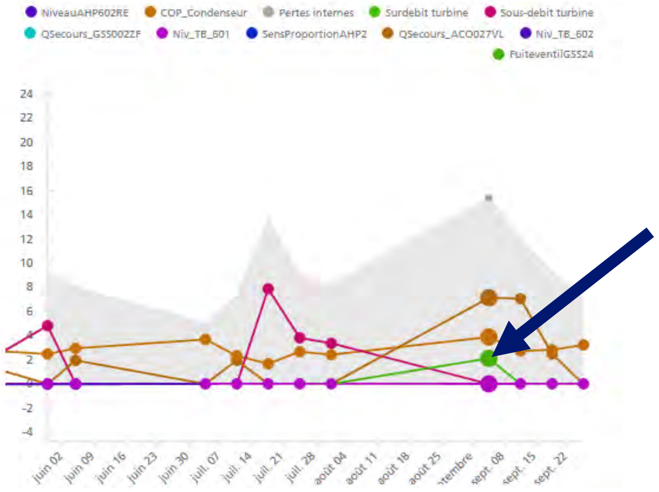
- Simultaneous Multiple Diagnostic
- Almost MWe Losses are explained (~ 2 MW of residual losses)

Performance

Avoidable loses 0.4 GWh

Le 04/09/2019 à 12:08:18
Cycle 36 - Essai 047

PMD repère		971 MW
Puissance brute corrigée		957,4 MW
Puissance mesurée		938,5 MW
Pertes internes		15,4 MW
QSecours_ACO027VL	59,2 kg/s	7,1 MW
Niv_TB_601	0 so	0 MW
FuiteventilGSS24	2,3 kg/s	2,1 MW
COP_Condenseur	3,7 mbar	3,9 MW
Inexpliqué		2,2 MW



CONCLUSION

SYNTHETIS OF MAIN GAINS

A large variety of situations are well catch

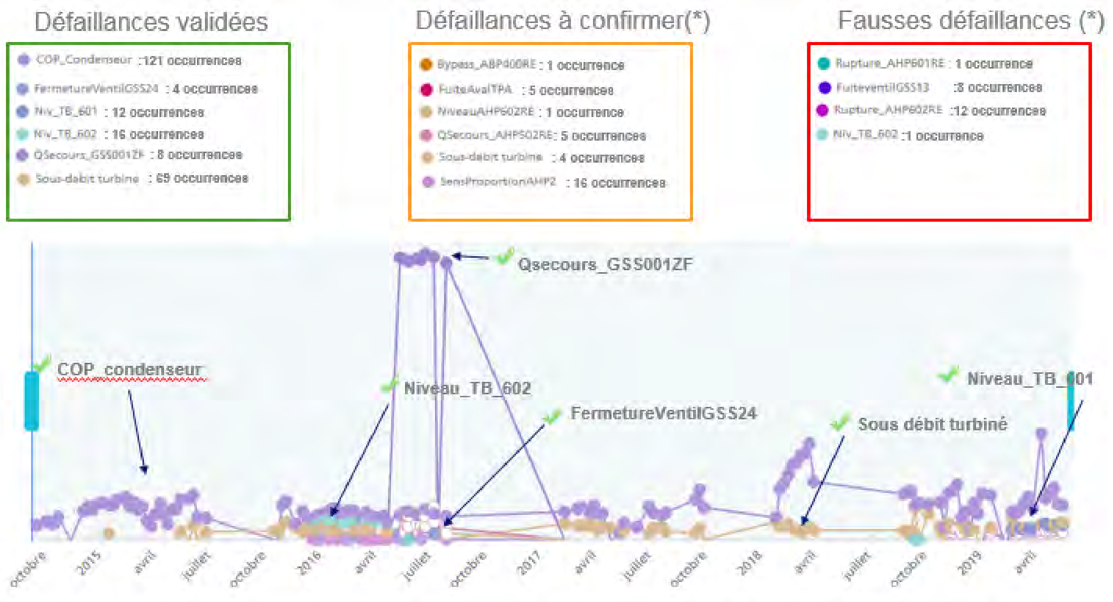
- Condenser Performance drift
- Steam flow decrease in the turbine
- Feed Water Heater unoptimal level regulation
- Feed water tank leak
- ….

→ METROSCOPE automated diagnosis strongly simplifies operators life

→ METROSCOPE is online, and provide a fleet wide supervision of the plants (enhance the production national reports for LTO)

Real life situations leads to

- Validation of DT (**Reliable reference of best historical performance**)
- Validation of Failure Libraries (**Know ledge capitalization**)



CONCLUSION

SYNTHETIS OF MAIN GAINS

Performance Monitoring

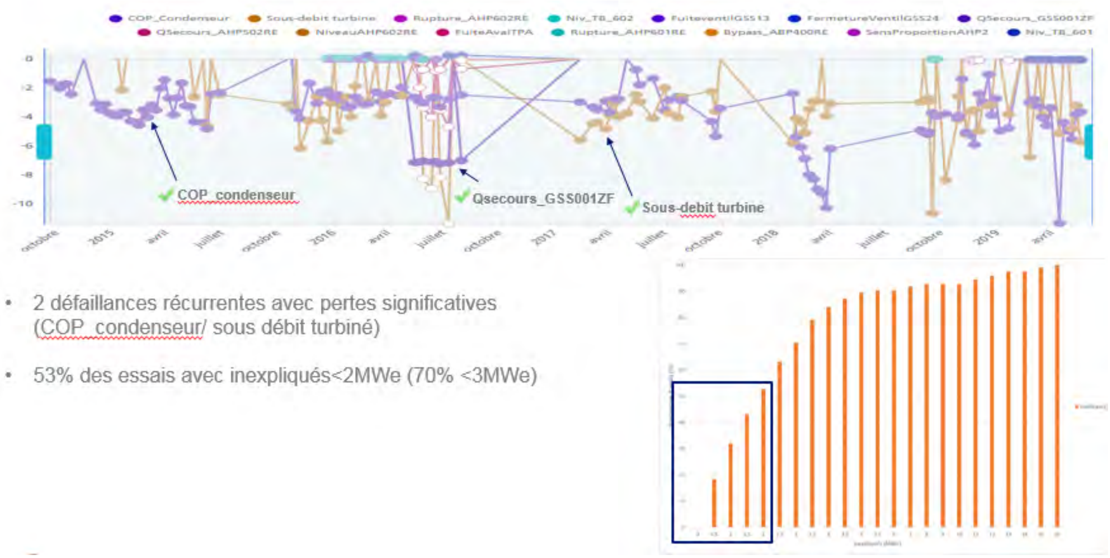
- Identification of major failures in terms of losses
- Smaller MW losses are catch
- Some failures impact maintenance only

With METROSCOPE unexplained MW losses are

- Under 2 MW 53% of the time
- Under 3 Mw 70% of the time

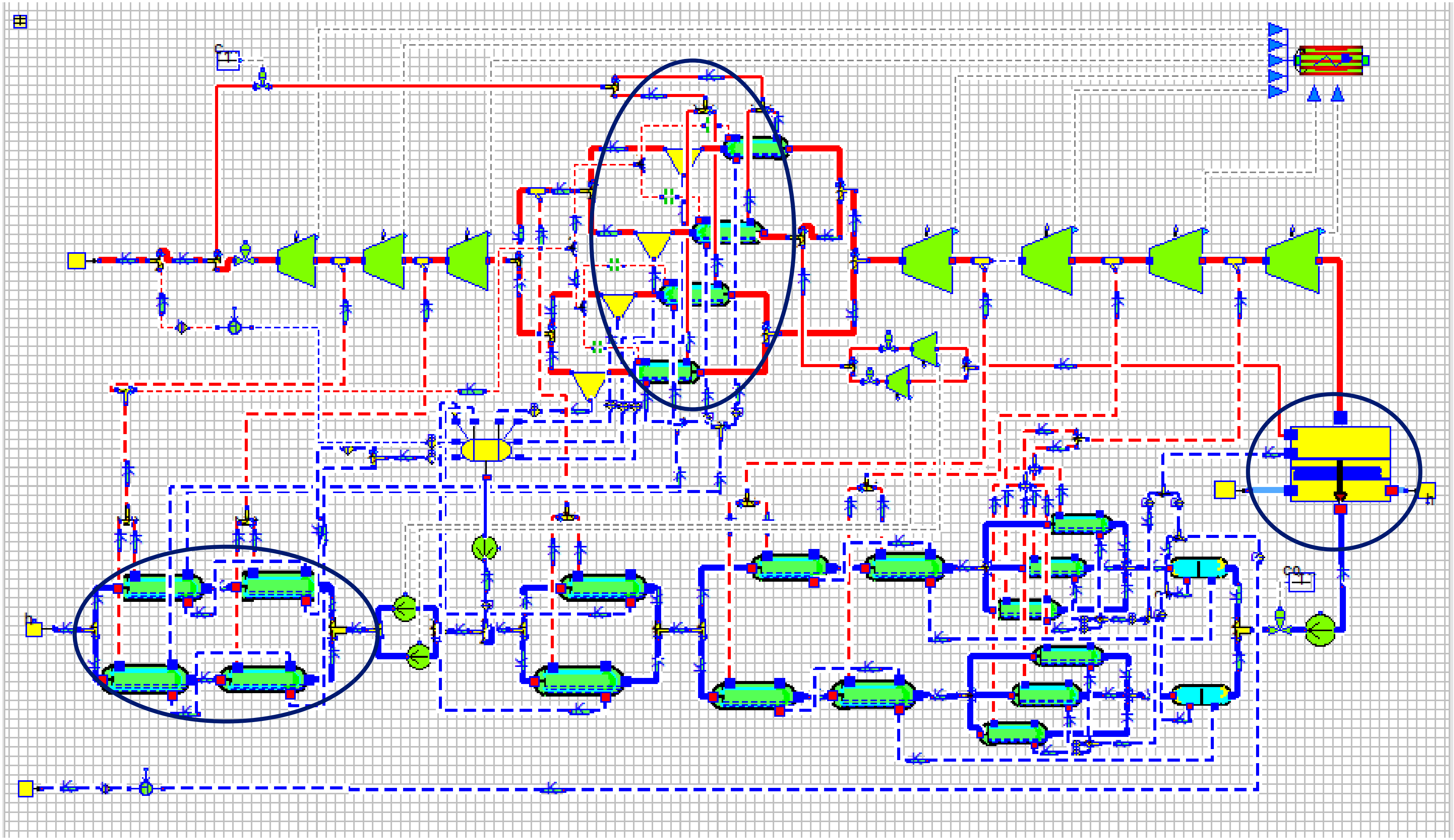
→ Here METROSCOPE has been calibrated to detect just a little bit more than what's really happening

METROSCOPE interface is very useful to analyze unexpected behaviors of the tool



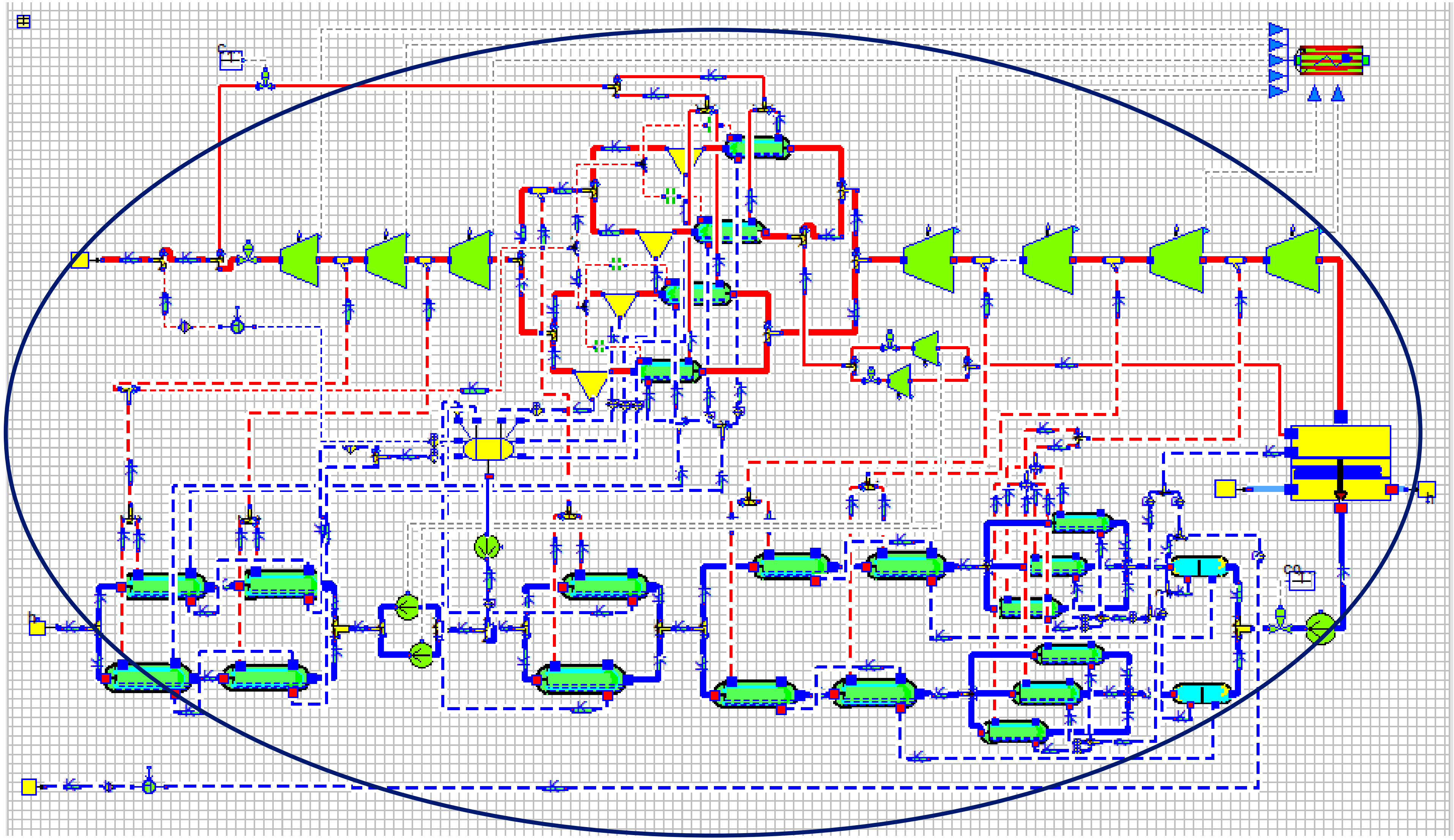
CONCLUSION

EXTENSION OF AUTOMATIQUE DIAGNOSTIC



CONCLUSION

EXTENSION OF AUTOMATIQUE DIAGNOSTIC

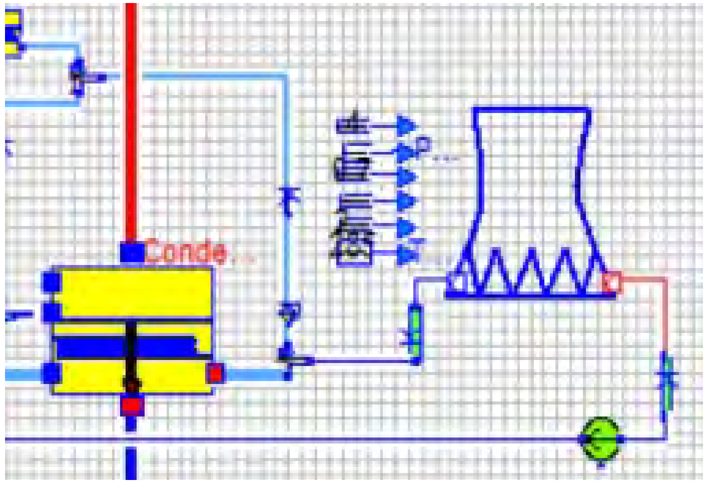


metroscope GROUPE EDF

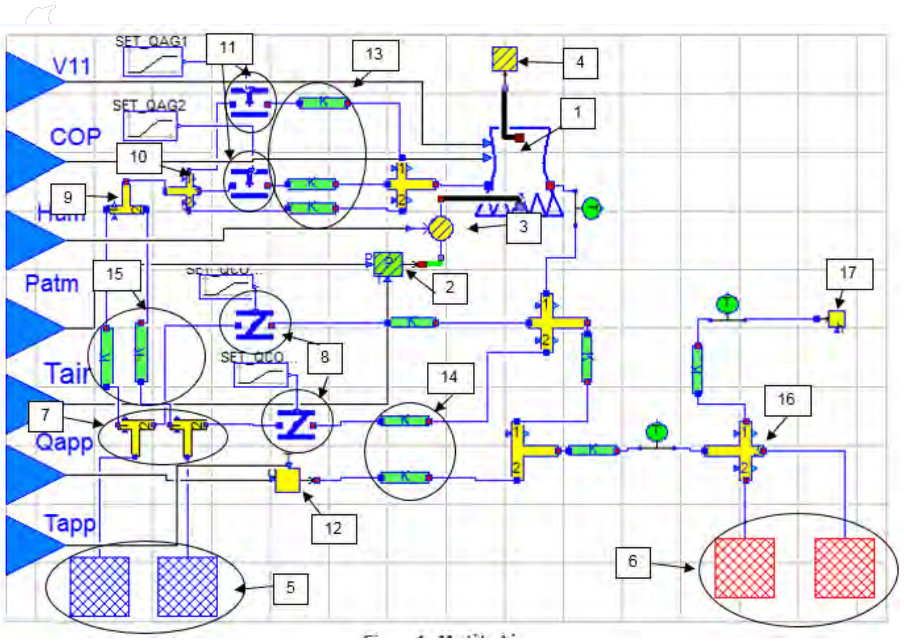
All diagnosis
from physical Simulation

www.metroscope.tech

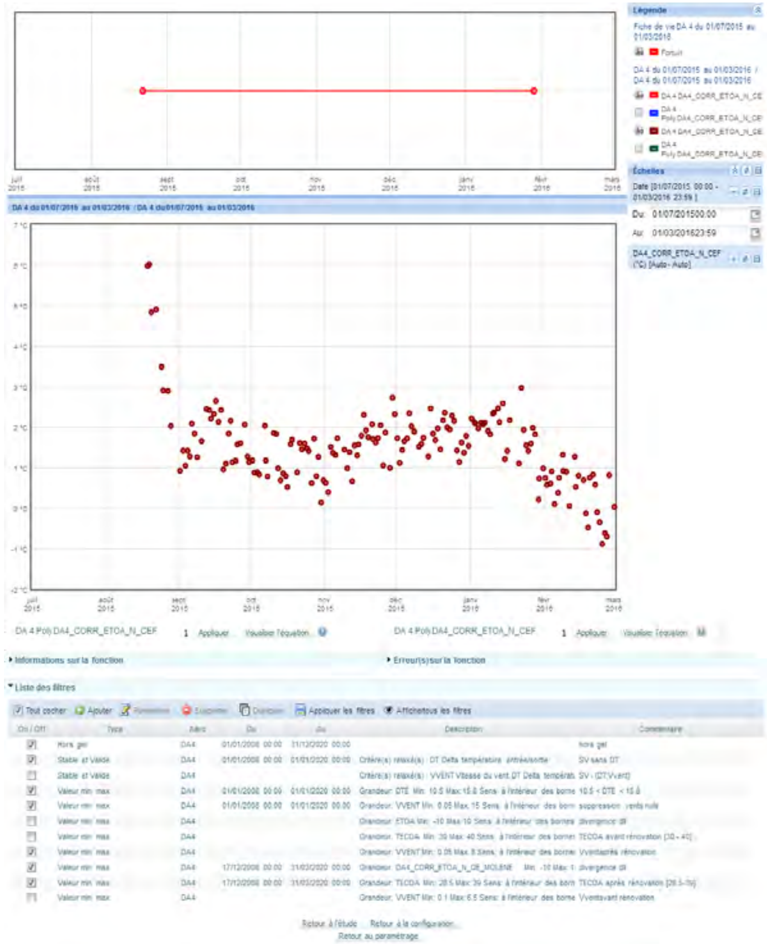
Numerical model plugged in the Metroscope for live diagnosis



TOMORROW – COOLING TOWER MONITORING WITH METROSCOPE



Develop Defect models



Use available data to validate

CONCLUSION

TOMORROW – COOLING TOWER MONITORING WITH METROSCOPE

SYNTHETIC OVERVIEW OF SERVICES PROVIDED BY SPA

SERVICE PROVIDED	ESTIMATION OF THE GAIN	LEVEL OF INVOLVEMENT	
REDUCTION OF PROCESSING TIME OF INCIDENTAL DEFECT	5 GWh/ major defect 20 GWh/other defect 4 major defects/year	trained operator + time required for level 1 support + functional SPA analysis	
OPTIMISATION OF MAINTENANCE CHOICES	20 GWh/maintenance 3 situations /years	competent support engineers + time required for level 2 support	
PRODUCTION FORECAST / OPTIMISATION CHOICES DURING CRISIS	Difficult to quantify	competent engineering unit+ Time required to go further in the analysis	
FEEDBACKS ON DESIGN CHOICES	Gain of 0,2°C ⇔ 160 GWh over 30 years	competent engineering unit+ + expertise on operation+ design engineering	

CONCLUSION

TOMORROW – COOLING TOWER MONITORING WITH METROSCOPE

SYNTHETIC OVERVIEW OF SERVICES PROVIDED BY SPA + METROSCOPE

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THANK YOU!

Any questions?

APPENDIX

DTG, from sensor to added value

Asset Management and O&M support
through
expertise and advanced DATA acquisition diagnosis and prediction

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Global Product Manager on Power Block Monitoring
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Dr Christophe Duquennoy
Nuclear Fleet Thermal Performance Expert
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EDF-DTG Our mission

3 MAIN FIELDS :

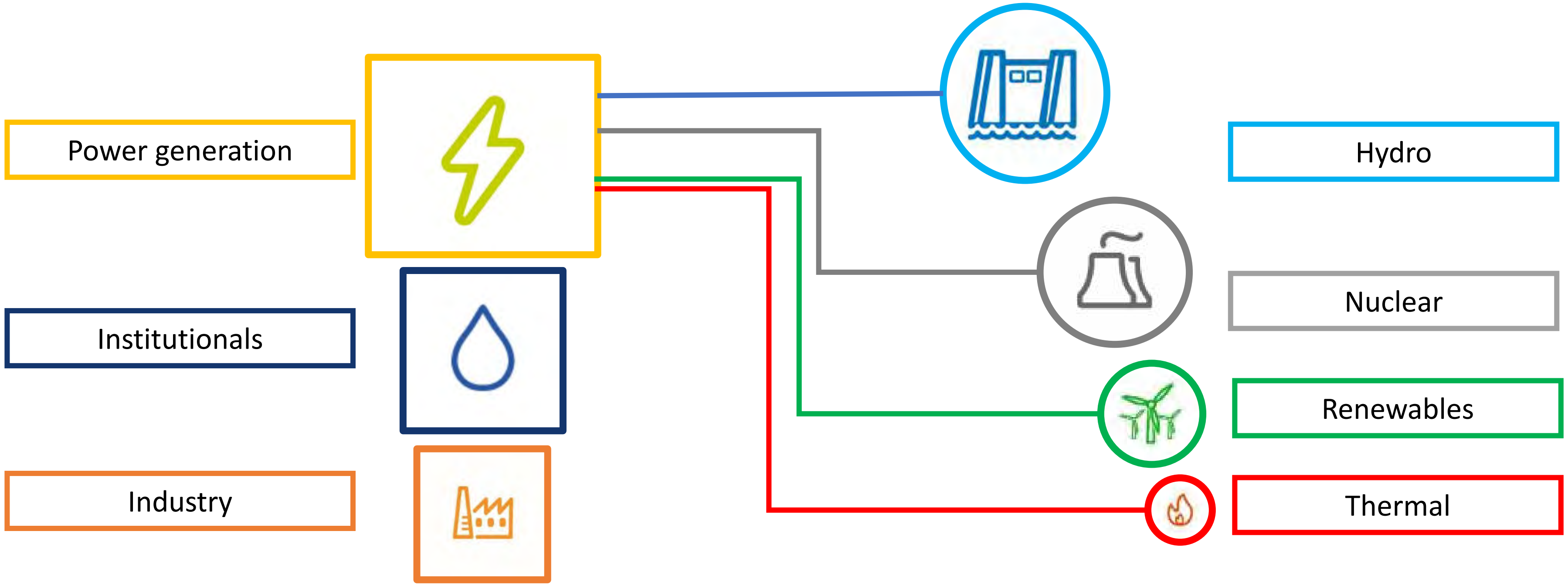
MEASUREMENT
> Measurement engineering, metrology, data bases

INSPECTION
> Monitoring on behalf of operators

EXPERTISE
> Diagnosis, pronostics & consulting for operators and maintenance teams

- Monitoring, diagnosis and forecasts for EDF Group power plants (nuclear, hydro, fossil-fired and wind energy) to **assist operators** in making effective safety decisions and in managing performance
- **Develop technical skills and expertise** required to operate energy production facilities, to find solutions about energy development and environmental issues
- **Integrate and make reliable** new R&D monitoring solutions

EDF-DTG   Our customers



EDF-DTG Our strength

Accurate and independant diagnosis & prognosis

DATA historian based on **50 years** of experience

Know-how to convert **DATA into value**

An unique **expertise in O&M**

Innovative solutions

DESIGN & O&M Support Services

MECHANICAL INSPECTION AND DIAGNOSIS

- Inspection during production
- Assessment of key static components for power plants (penstock, secondary circuit…): non destructive testing, corrosion-erosion modeling, damage analysis and repair tracking

SYSTEMS AND VIBRATING ENGINEERING

- Monitoring mechanical behaviour of power plants, pipe systems and rotating machinery
- Acoustic testing of primary circuit for nuclear fleet
- Condition-based maintenance of nuclear valves

ELECTRICAL EQUIPMENT

- Diagnosis of main electrical equipment needed for power plants operation, based on tests carried out on site and in the lab
- Diagnosis using infrared thermography (electrical trouble spots)

DESIGN & O&M Support Services

SETTINGS, PROTECTION, OPTIMISATION PROCESSES, ANCILLARY SERVICES

- Testing the safety protection of power-generating facilities
- Testing the network reconstitution and voltage recovery following an incident
- System services monitoring and optimisation: contribution to system voltage and frequency stability

ACOUSTICS

- Noise control for all EDF Group facilities : acoustic impact studies and modeling, sound power measurements in situ, ...
- Optimising the soundproofing of installations and to ensure compliance with regulations

THERMODYNAMIC DIAGNOSIS AND PROGNOSIS

- Measuring thermodynamic performances of thermal power plants (fossil-fired and nuclear)
- Monitoring energy performances, looking for productivity gains

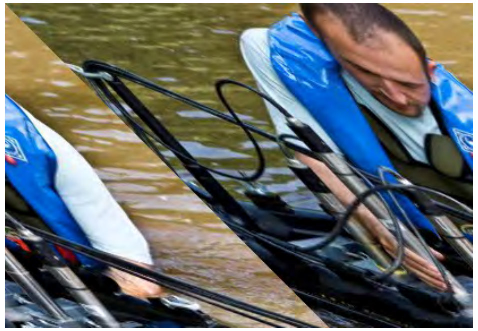
DESIGN & O&M Support Services

METROLOGY, IT & DATA technologies

- Development of appropriate IT solutions for the various business activities
- Data collection, management, processing and archiving
- Certified by Cofrac, the DTG laboratory is a reference for the calibration of temperature, pressure and humidity variables

MONITORING NUCLEAR FACILITIES

- Continuous monitoring of mechanical behaviour of equipment and civil engineering structures
- Containment tightness : monitoring and control during pressure tests



WATER RESOURCE FORECAST & MANAGEMENT

- Evaluation and management of the impacts of electricity generating activities on atmospheric, acoustic and aquatic environments
- Impact of aquatic environment on electricity generation

Digital Twin of a Real-time Radiation Monitoring Network

An EPRI NextGen RP Project

Rich McGrath
Principal Technical Leader
rmcgrath@epri.com

2021 Workshop on Enabling Technologies for Digital Twin Applications for Advanced Reactors and Plant Modernization

September 14-16, 2021

Discussion Topics

- Background of Need for Digital Twins
- Results of Scoping Study of Available Technologies
- In Progress Project Tasks
- Future Work

Background of Need for Digital Twins

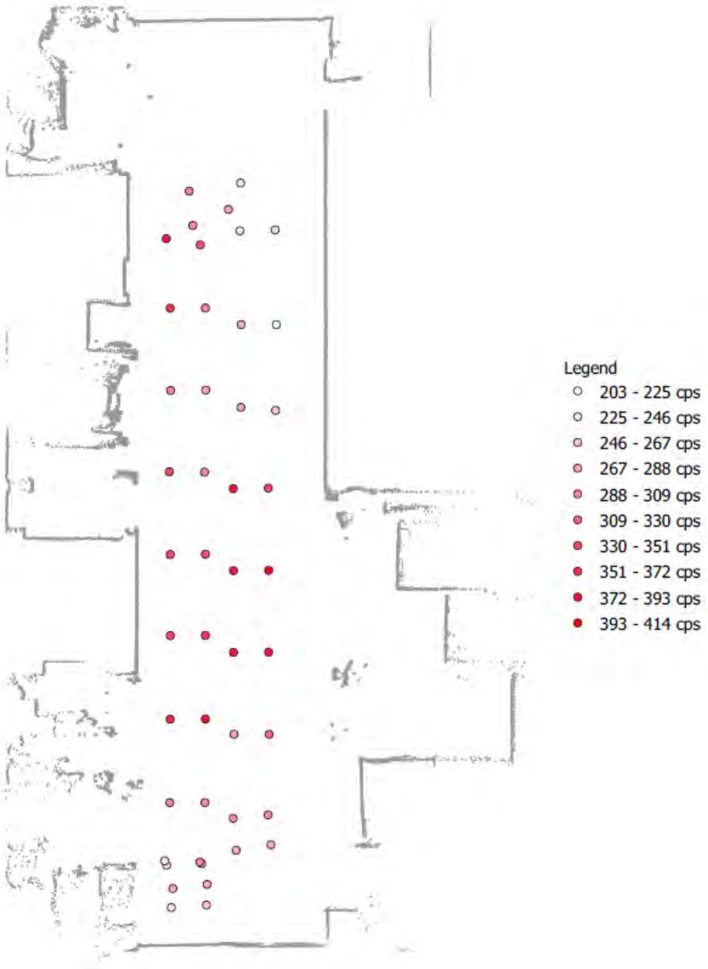
- Utility RP Organizations need to seek additional measures for cost reduction while still maintaining excellent performance and safety while faced with the following challenges:
  - Shrinking contract RP technician resources,
  - Reductions in site RP staffing,
  - Cost efficiency,
  - Knowledge retention and transfer, and
  - Maintaining and/or enhancing worker safety.
- Currently, most radiation protection (RP) tasks for the collection of radiation field data are conducted manually at nuclear power plants. For example:
  - Most radiation field measurement and characterization activities (i.e., surveys) are conducted
  - Data from radiation surveys are manually entered into the plant database and subsequent data analyses to inform radiation protection, and/or source term management, and/or ALARA planning are conducted manually.
- The EPRI Digital Twin Project is evaluating:
  - Technologies that provide remote/automated radiological measurements that accurately reflect the radiological environment in the plant
  - If technologies are available, then creation of a Digital Twin of the radiological environ can be used to optimize work in the radiological areas of the plant.

Digital Twin of a Real-time Radiation Monitoring Network

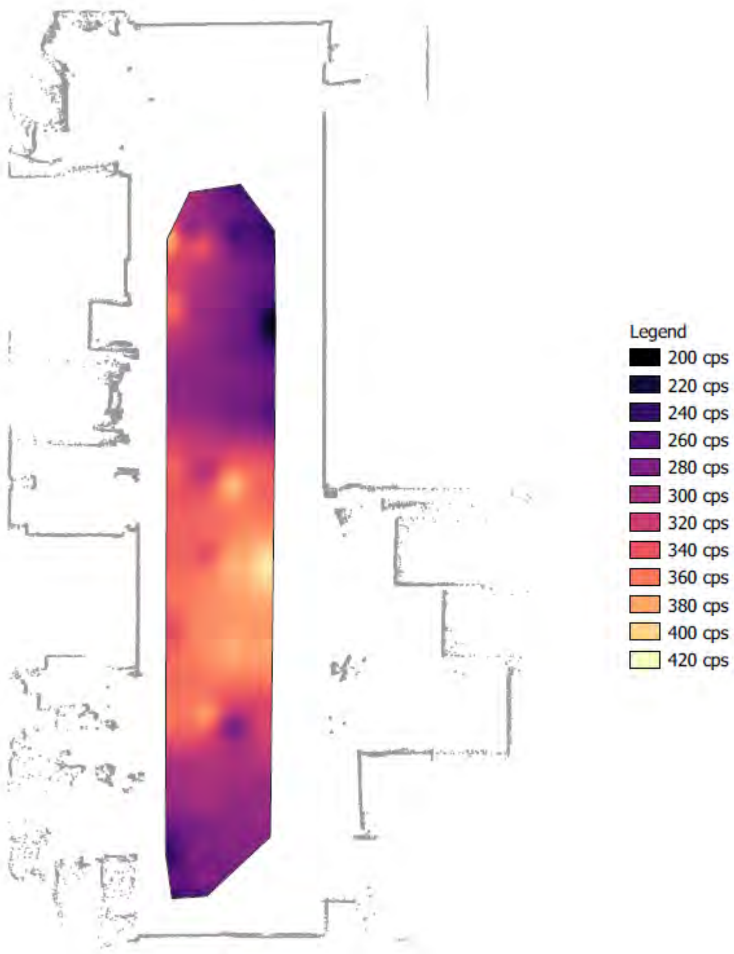
Phase 1 - Demonstrate a Geophysical Application for Analyzing Radiological Survey Data

- Increased use of remote radiation monitoring technology is providing real-time radiological data.
- Measurement points are shown as single point sources with no values in between measurements.
- Geospatial technologies are available that can interpolate available remote detector readings to model the radiological conditions between measurement points.
- Applications could be applied in reverse to determine where remote monitoring devices should be placed to adequately monitor dose rates
- This EPRI project will in 2021:
  - Evaluate available software applications
  - Test geostatistical software tool(s) to see if tool accurately interpolates actual survey data

Example of Actual Interpolation of Survey Data



Survey Measurements

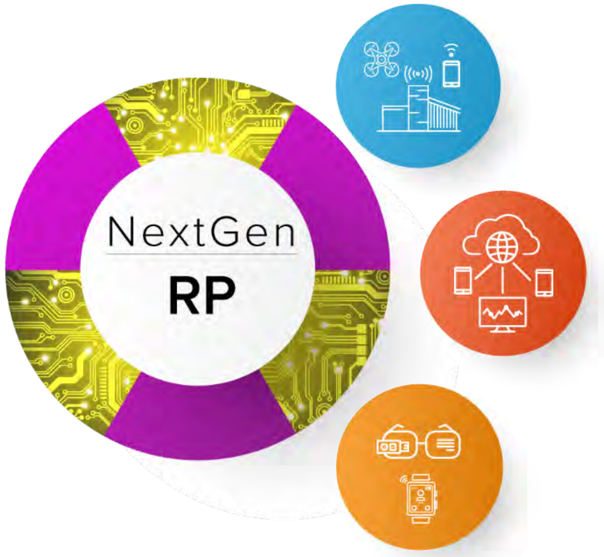


Interpolation of Survey Data

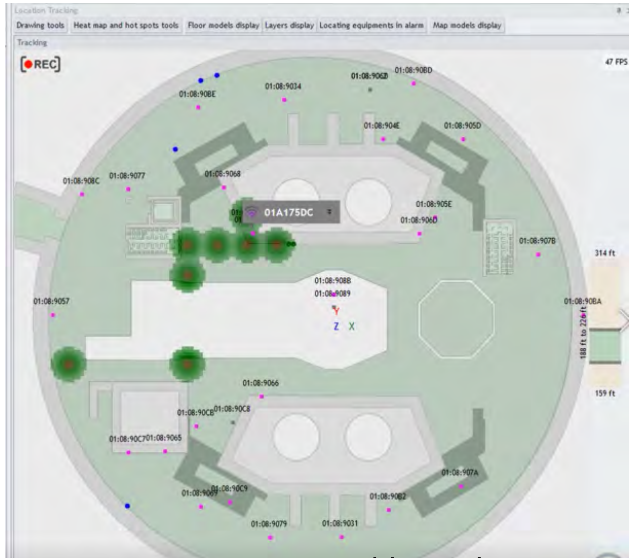
Initial Tasks of EPRI Project

- EPRI Team has completed an initial scoping study to determine what software tools and associated technologies are currently available or planned that can create a digital twin of the radiation fields at a nuclear power plant.
- For each candidate software/technology supplier, the technology search attempted to determine the following:
  - The current state of development and/or planned future enhancements as it relates to this project.
  - Current state of deployment - where it has been used or is being used at a nuclear power plant site
  - Willingness of the supplier to participate in a tabletop demonstration of the software tool

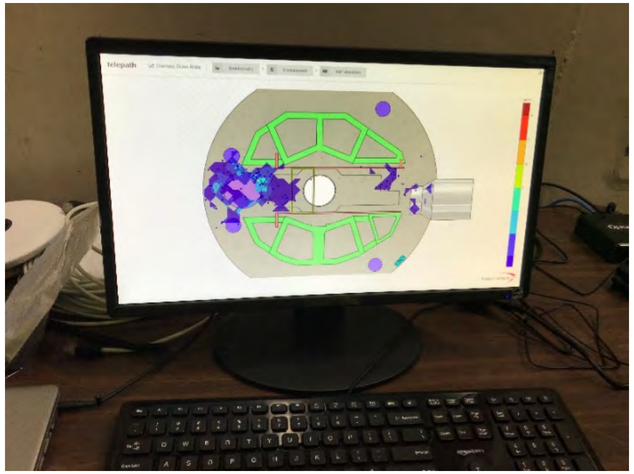
Examples of Supplier Capabilities for Tabletop Demos



- EPRI Indoor Positioning System (IPS) system demonstrations showed functionality applicable to digital twin technology such as:
  - Track tags to ~1-2 meter accuracy
  - Collect dose rate data continuously
  - Generate live dose rate maps
- EPRI Demonstrations Performed at nuclear power plants:
  - Bluetooth Low Energy (BLE) based Quuppa
  - Ultra Wide Band (UWB) based Mirion Orion Real Time Locating System (RTLS)
- EPRI Technical Report for the IPS project to be published in 2021



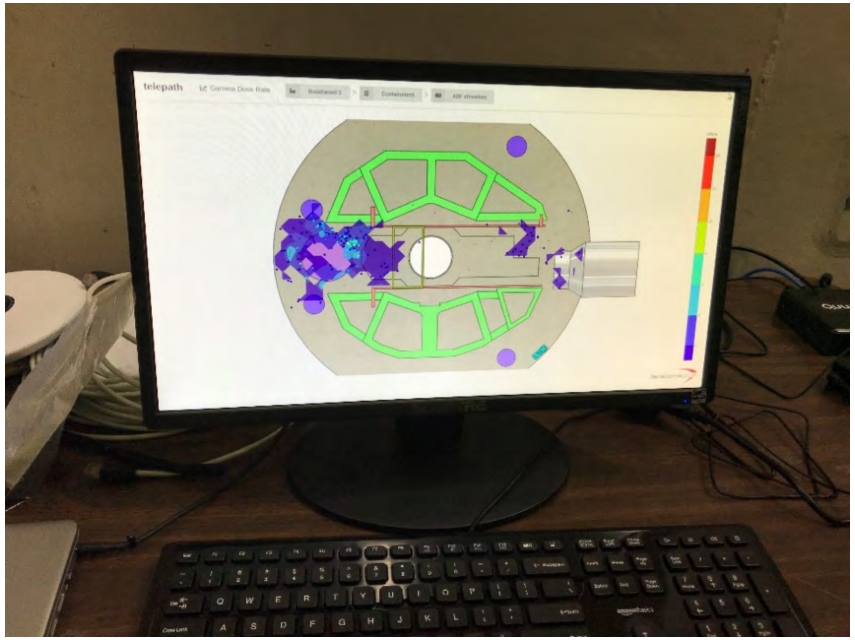
Mirion Orion RTLS

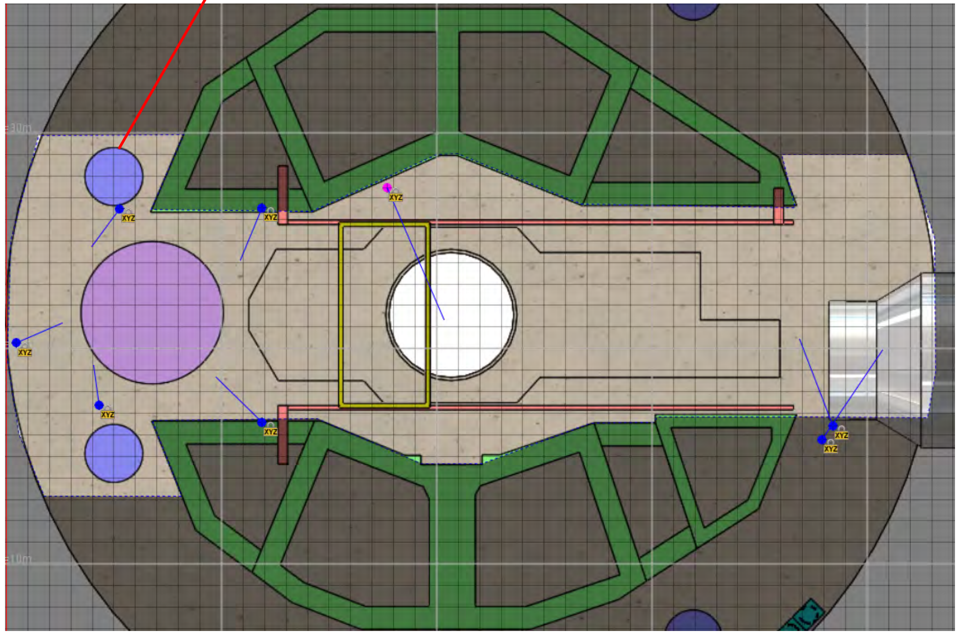


DEI Telepath™ Live Map Display

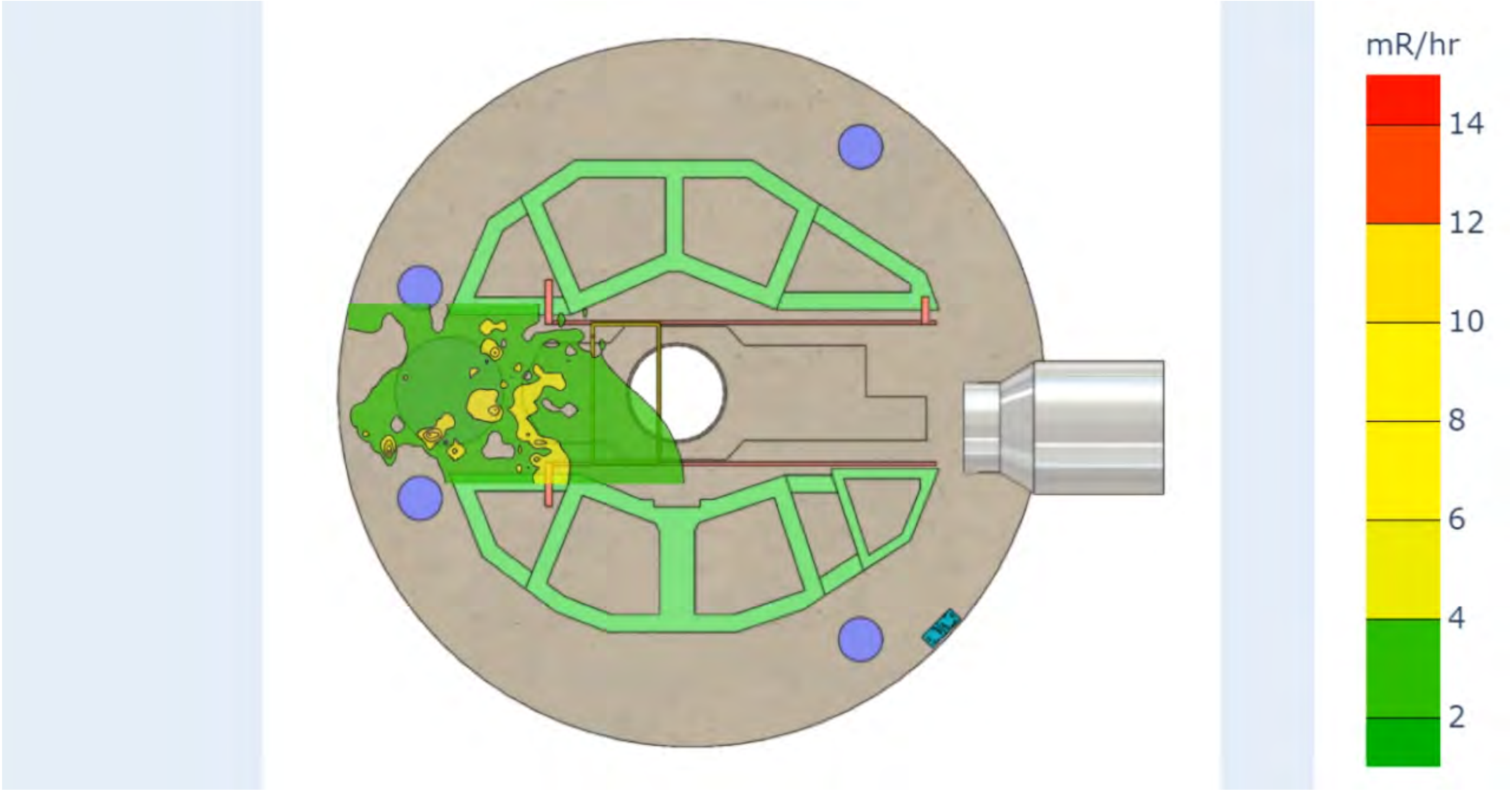
Quuppa Demonstration

- Workers provided with positioning tags and teledosimeter
- Anchors with magnet mounts for receiving signals from dosimeters installed as shown in images
- Dose rate data from teledosimeter and positioning data from tags are merged together to create dose maps





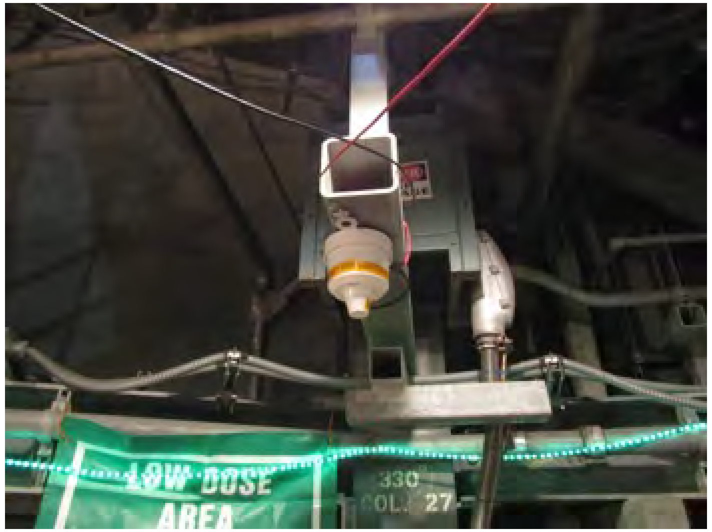
Quuppa Demonstration - Live Dose Rate Map

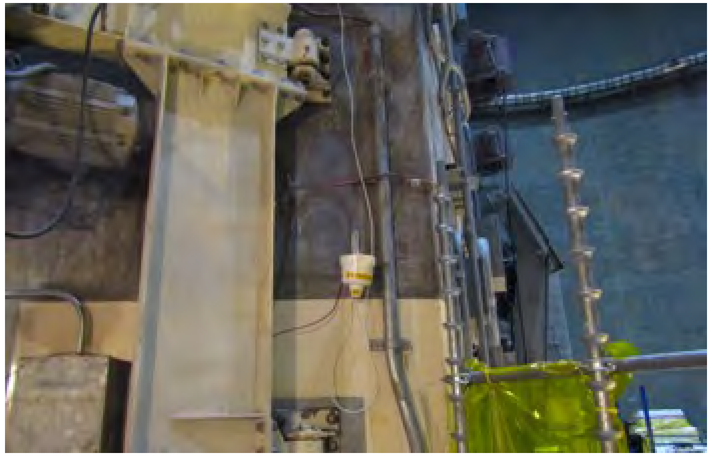


Rad Mapping from DEI Telepath™ Software

Anchor Placement

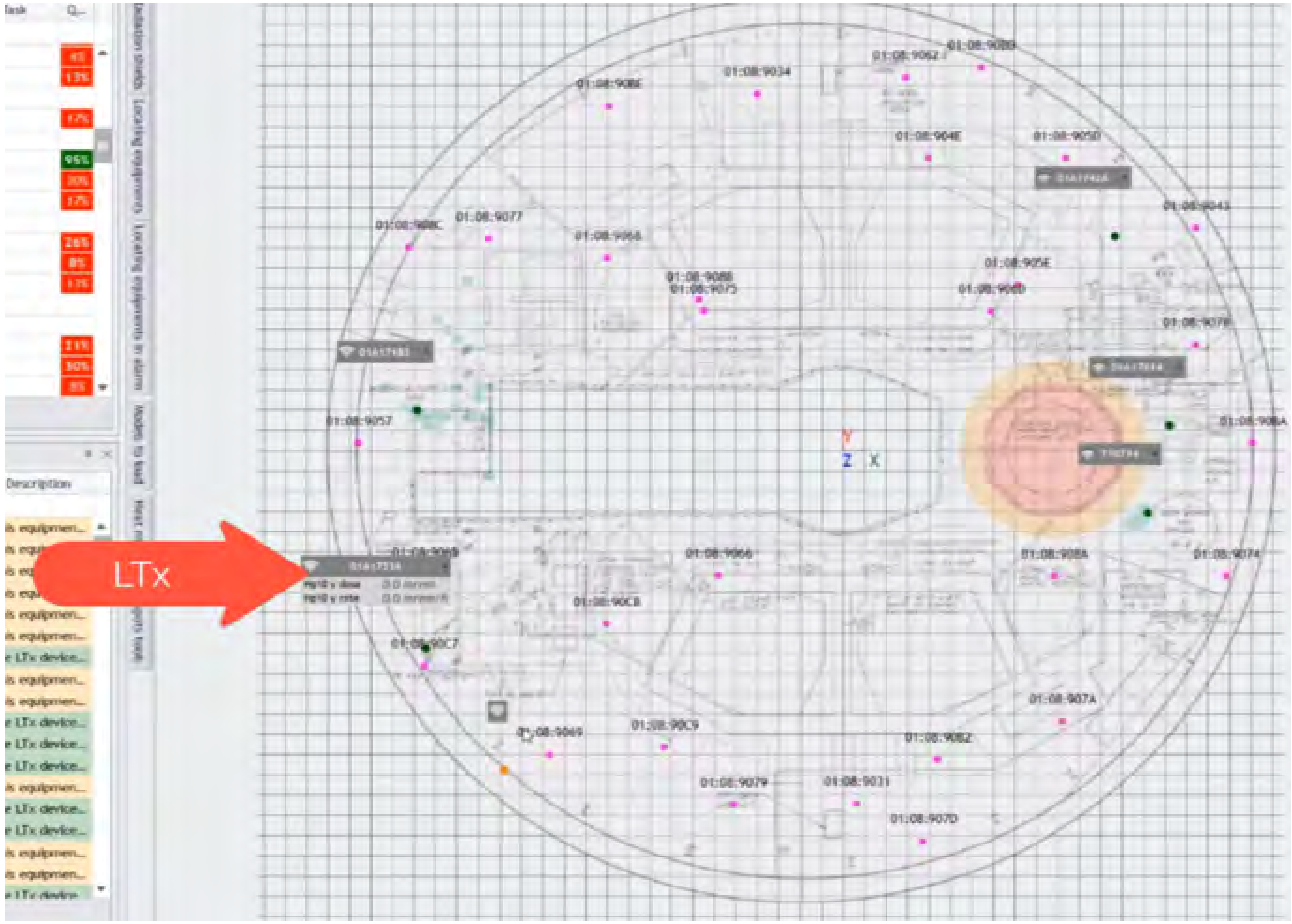
- Similar approach but different anchor design for Mirion system





Accuracy

- Accuracy was observed to be 1-2 m
- For some isolated locations, the position was erratic due to structural interference
- Accuracy increases with number of anchors and transmit frequency
- Dose rate data displayed on the maps



Other Technology Available

- Capabilities offered by other vendors:
  - Creation of 3D maps of the plant using LIDAR system incorporated into the portable radiation detector
    - Readings from detector automatically recorded onto the 3D map as the survey is conducted
- Upload new or existing 3D CAD generated maps of the plant into the software:
  - Radiation readings automatically loaded onto maps from:
    - Handheld survey meters as survey progresses
    - Electronic dosimetry as workers transit area
    - Fixed area monitors

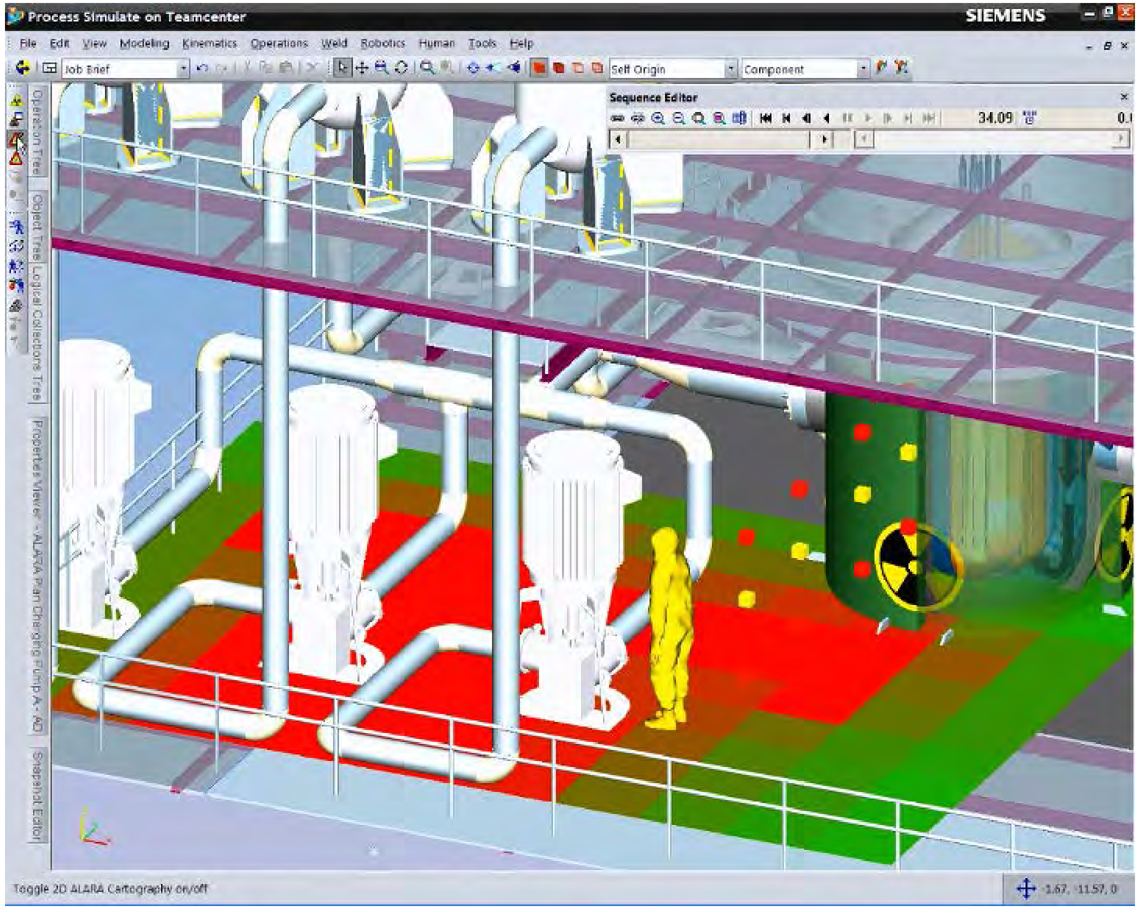
EPRI Digital Twin Project Status – Phase 1

- Multiple vendors have:
  - At least one technology that appears to be capable of supporting development of a digital twin of a radiation monitoring network, or have much of that development in place.
  - Appear to have products that are fairly mature with variations on aspects of their product relative to each other (e.g., location tracking, radiation field heat map, use of fixed radiation monitors, etc.).
  - Have products that were able to utilize 3D scanning technology that would subsequently support area mapping, heat map generation and location tracking.
  - Expressed a willingness to participate in a tabletop demonstration
- Selection of supplier(s) for the Tabletop Demo this month
- Demos to be conducted in 2021

Digital Twin of a Real-time Radiation Monitoring Network

Phase 2 - Apply Machine Learning to Geophysical Radiological Survey Application

- Machine learning can be coupled with the geospatial algorithm to refine the radiation field estimates as measurements are updated
- The digital twin could be used to provide ongoing monitoring, trending, and alerts and allow for alternative maintenance and dose optimization scenarios to be investigated in cyberspace before the work is performed
- Simulation results could be visualized by the worker during job preparations, job briefings, and in the work environment using augmented reality techniques.
- Simulations would enable development of efficient maintenance practices to save time, reduce worker exposure, and reduce cost
- Could be used for event recreation and emergency plan exercises
- The proposed added scope for 2022-2023 includes:
  - Evaluate software tool(s) for use in machine learning of survey data
  - Test application to see if tool accurately predicts future radiation dose rate trends from survey data analyzed

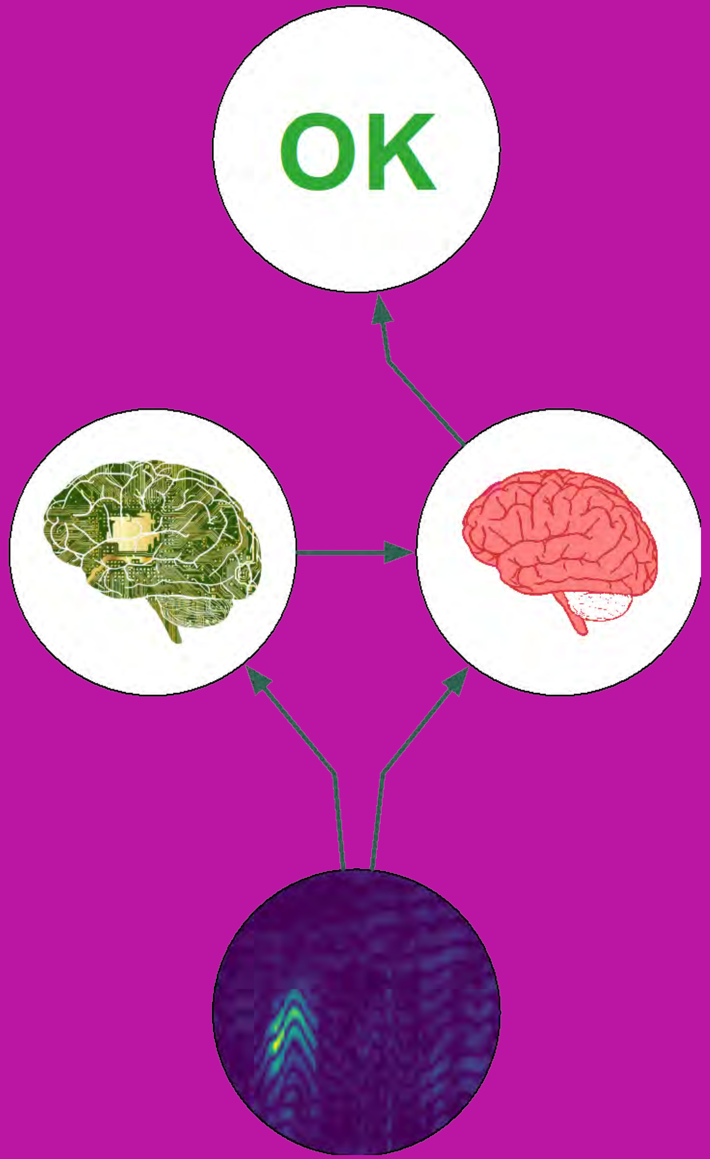


Example of ALARA Planning Tool for Potential Further Development

Together…Shaping the Future of Energy™

Iikka Virkkunen
Prof. (Adjunct) at Aalto University,
Managing Director or Trueflaw, Ltd.

NDE4.0 and Machine Learning for In-service Inspections



Aalto University
School of Engineering

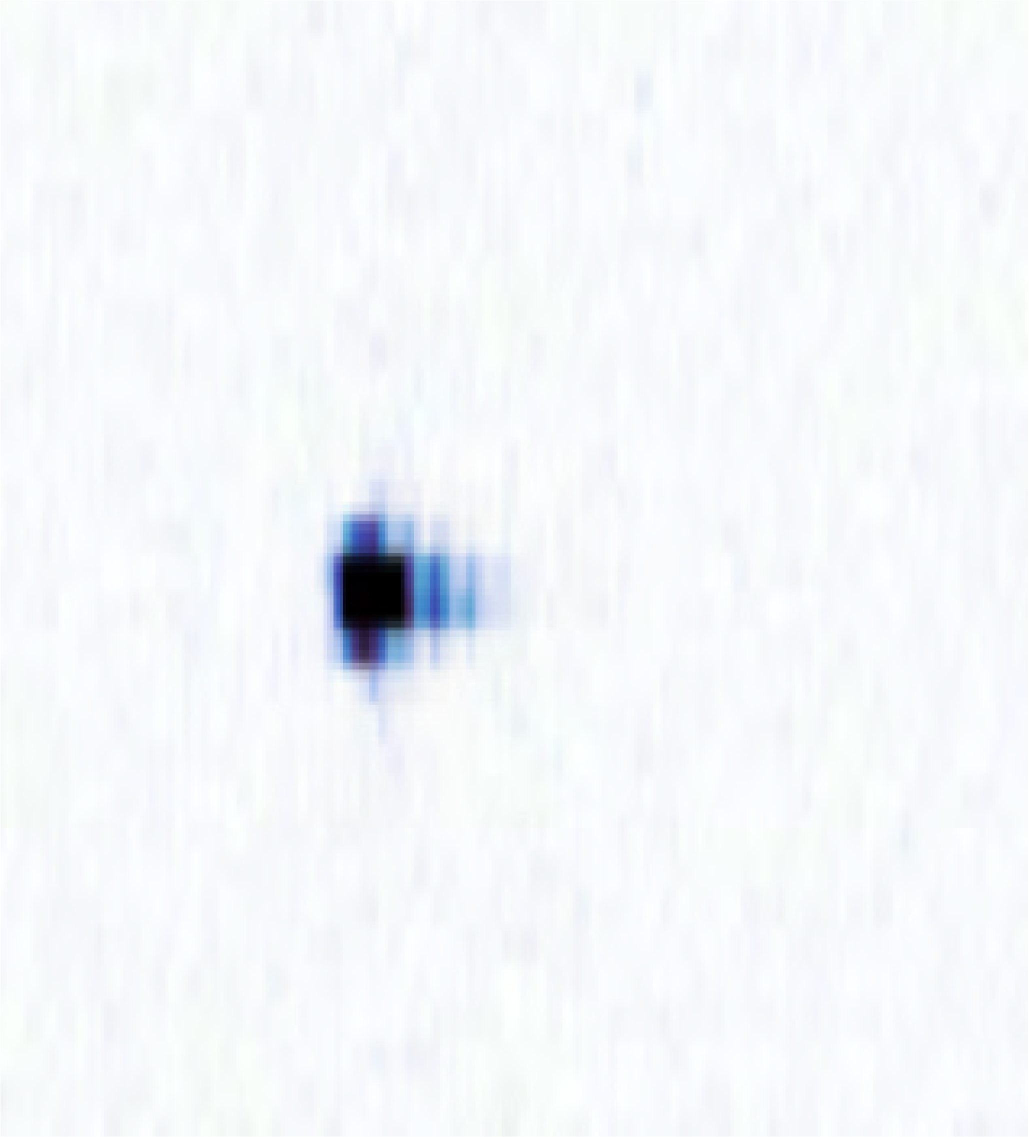
NDE increases reliability

Today's NDE3.0

- *Qualified and reliable*
- *Rich digital data*
- *Important contribution to reliable and safe operation*

But

- *Time consuming*
- *Potential for human errors*
- *Limited information extracted*
- *More is less*



Aalto University
School of Engineering

Machine learning enables human-level automated evaluation

Human-level performance in automated defect recognition

Applicable to various inspections:

- *Ultrasonics*
- *Digital radiography*

Already in field use in non-nuclear inspection

Case: GKN digital X-ray of aerospace welds

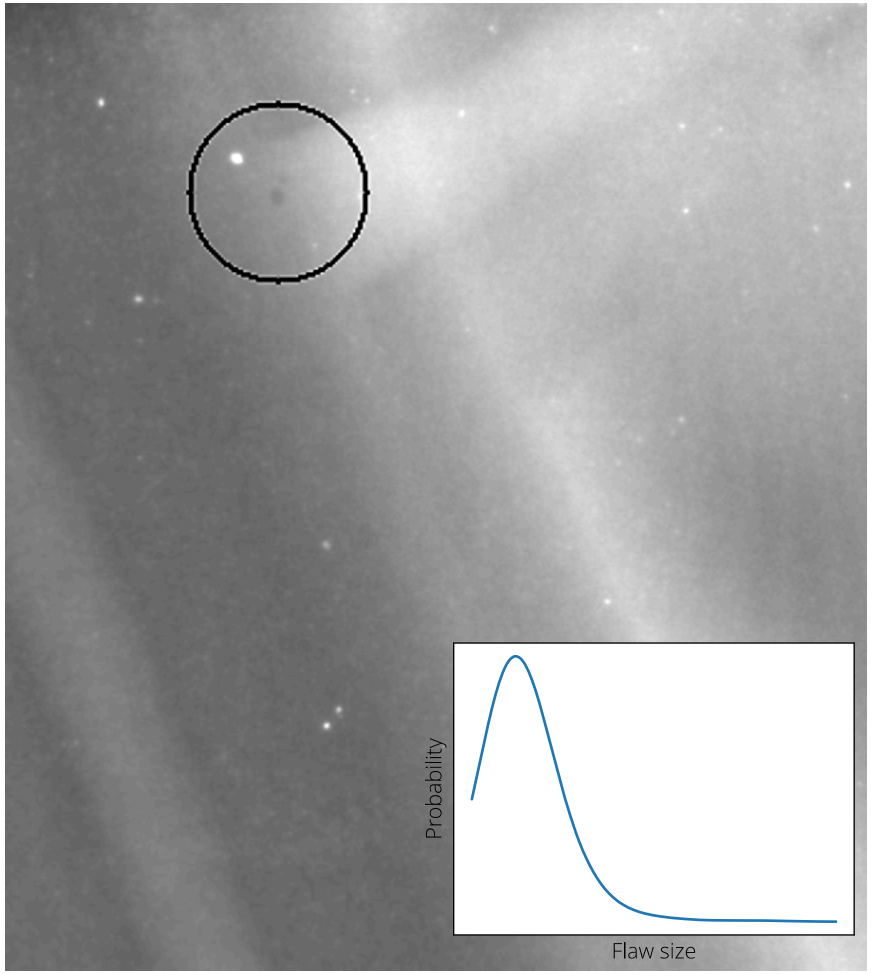
High quality automated welds

Small flaws, difficult to detect

Current status:

- *Human level detection*
- *Accurate sizing*
- *Criteria comparison*

Additional data on small flaws



Case: CRDM TOFD inspection

EPRI – Trueflaw collaboration

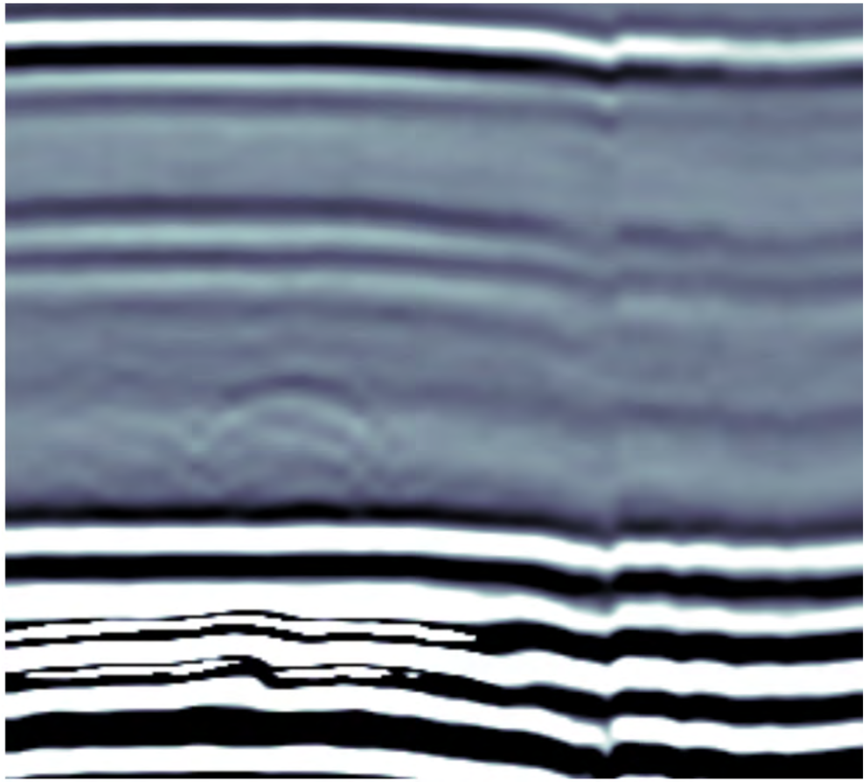
Very difficult data

Limited real data available

Limited real flaws available

Human level performance

Next: field test planned



NDE3.0 + ML = NDE3.5

- *Automated analysis can manage large data*
- *Inspector work elevated to focus on the important parts*
- *More is more again*

Additional benefits

- *More sensitivity*
- *Predictive capability*
- *Added value from NDE*

NDE4.0 Integrated NDE data

- *Connected systems can aggregate data*
- *Digital twin etc.*
- *Elevated to focus on the important parts for the system*
- *More is exponentially more due to network effects*

Additional benefits

- *Situation awareness*
- *Predictive capability*
- *Added value from NDE*

How do we get there, safely?

- Compatibility with existing qualification
- Compatibility with current practices
- Data security

Qualification

2020 ENIQ published a position paper:

- *Qualifying (certain) ML systems filled within framework*

ENIQ RP13:

Recommended practice for
Qualification of Non-Destructive Testing Systems that
Make Use of Machine Learning

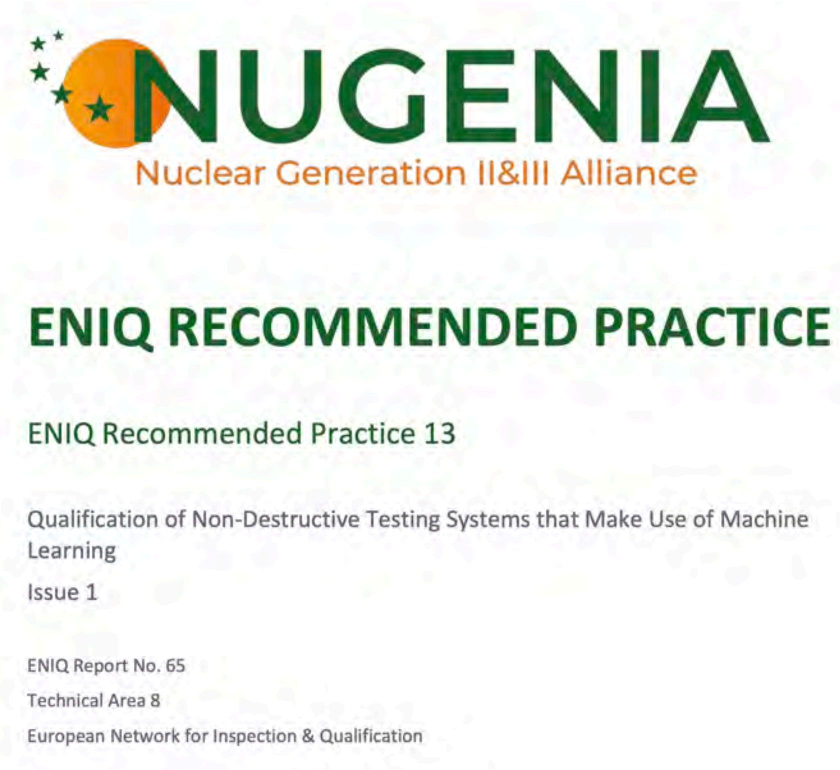
We now know how to qualify ML

Repeatability of ML systems is good for qualification

Main changes are with test data

- *ML systems may require more test data*
- *Combining open and blind trials may reduce test block needs*

Qualifications must be done using frozen software


NUGENIA
Nuclear Generation II&III Alliance

ENIQ RECOMMENDED PRACTICE

ENIQ Recommended Practice 13

Qualification of Non-Destructive Testing Systems that Make Use of Machine Learning

Issue 1

ENIQ Report No. 65

Technical Area 8

European Network for Inspection & Qualification

Edge devices can secure data

- *Stand-alone unit*
- *Easy to use*
- *Works with existing data files*
- *Multiple options for reports*
- *Can provide traditional reports*
- *Can integrate to digital twins*

Conclusions

For digital twins, NDE ⇒ 4.0

The tools are ready:

- *Machine learning*
- *Edge computing*

The transition is clear

- *Qualification RP13*
- *Adoption with stand-alone units*

Digital Twin Enabling Technologies in Advanced Reactor Applications

Technical Session – September 15, 2021

Moderator: Angela Buford, NRC

Ian Davis, X-energy

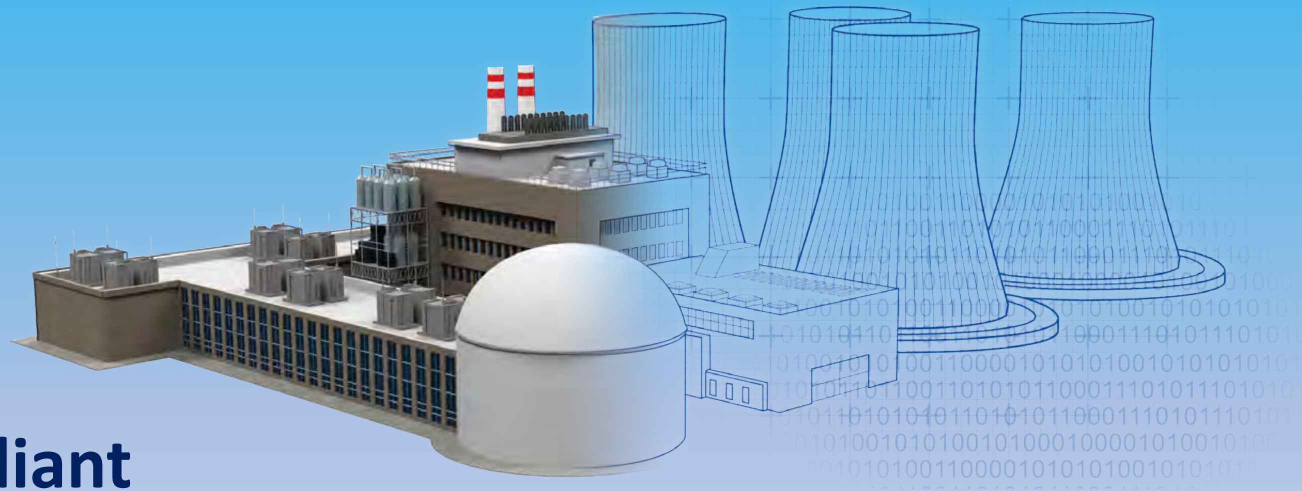
Nurali Virani, GE

Anthonie Cilliers, Kairos Power

Emilio Baglietto, MIT

Michael Buric, DOE

Bob Urberger & Roger Chin, Radiant



X energy

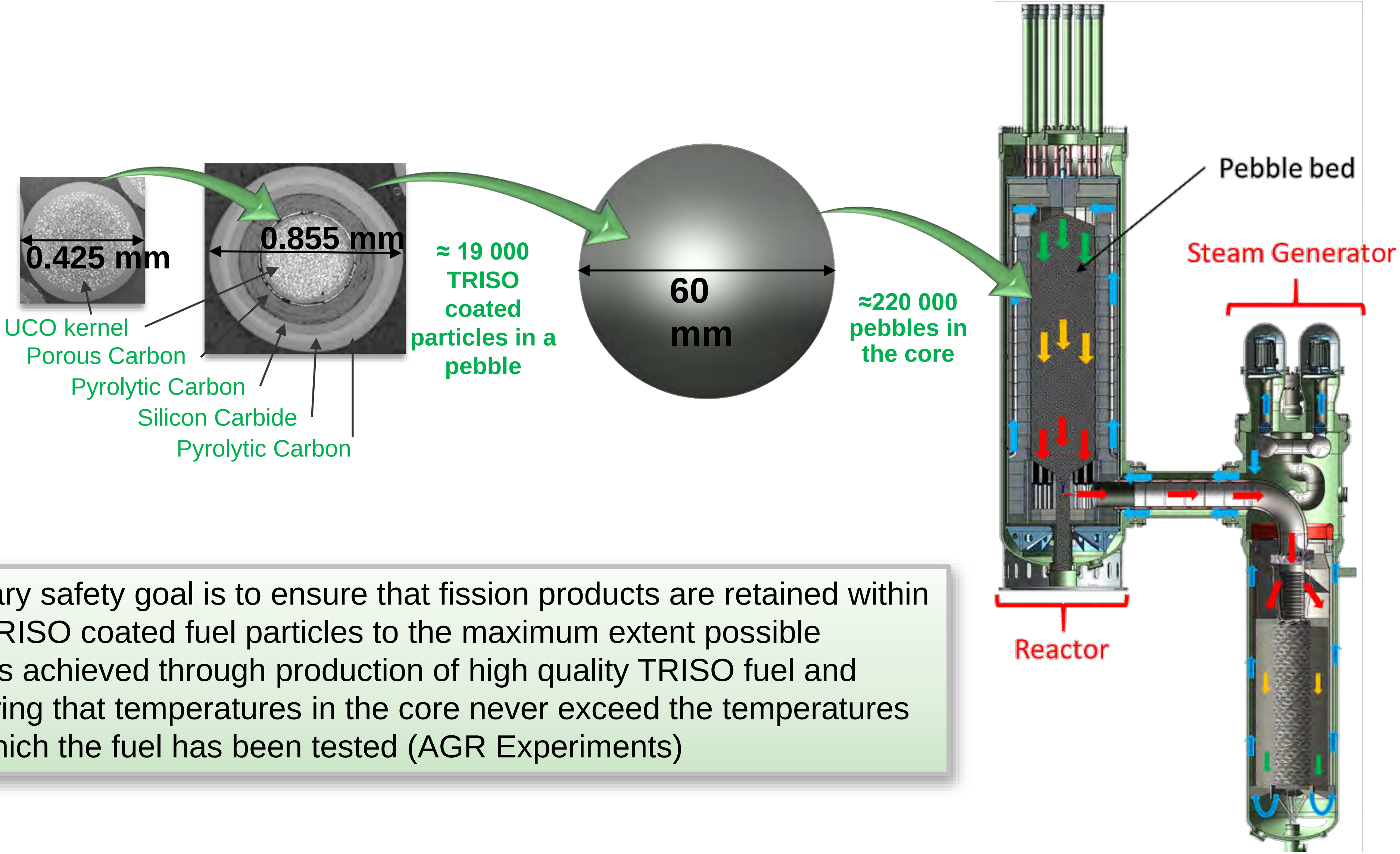
Digital Twin Enabling Technologies in Advanced Reactor Applications

Xe-100 Digital Technologies Overview

Ian Davis, *Senior Digital Twin Systems Engineer*

September 15, 2021

UCO TRISO Particle – Primary Fission Product Barrier

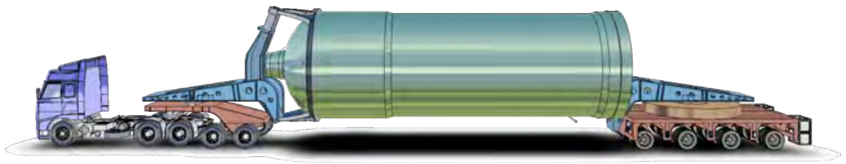


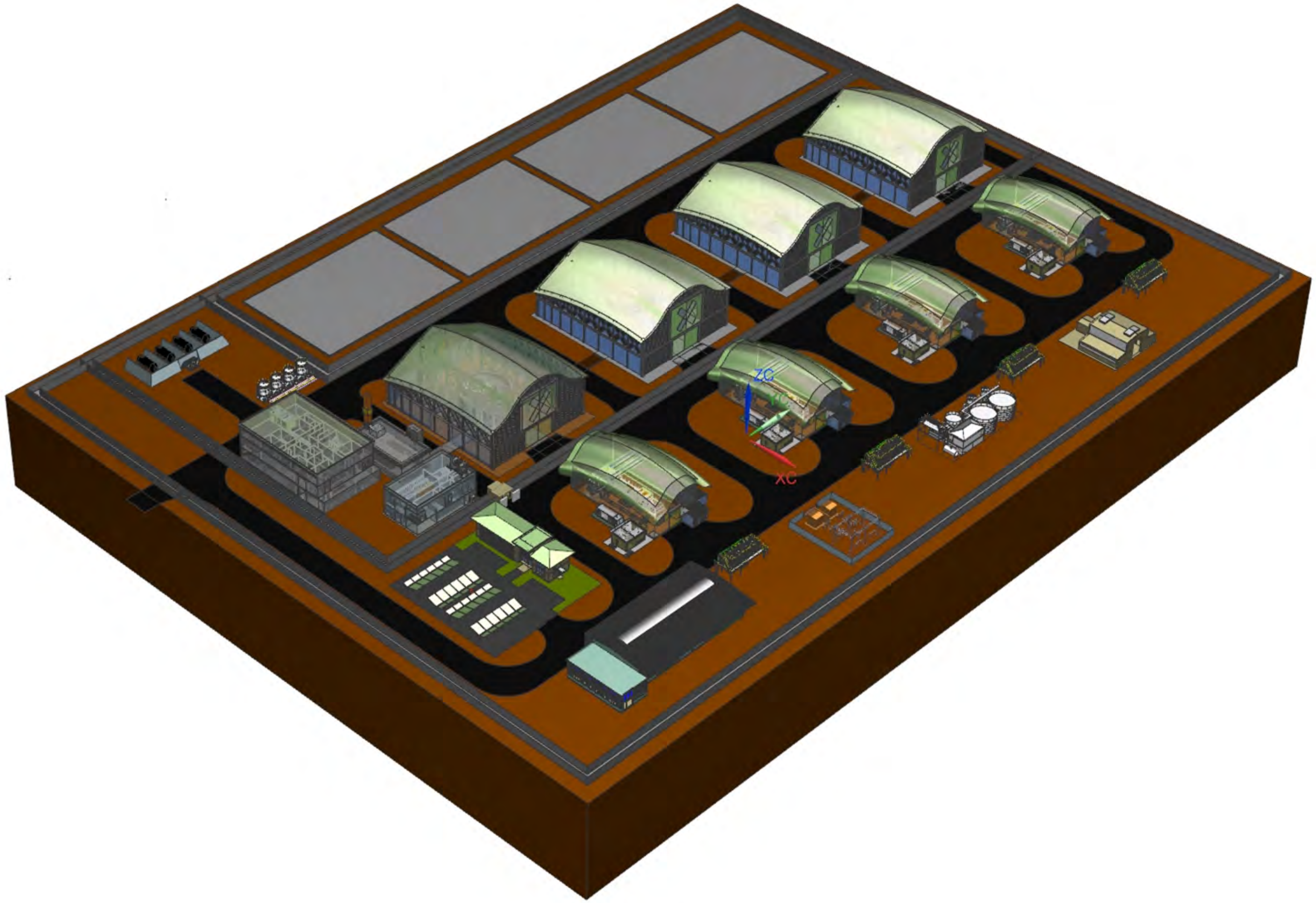
- Primary safety goal is to ensure that fission products are retained within the TRISO coated fuel particles to the maximum extent possible
- This is achieved through production of high quality TRISO fuel and ensuring that temperatures in the core never exceed the temperatures for which the fuel has been tested (AGR Experiments)

Background: Xe-100 Plant Overview

Standard X-energy plant have 4 Reactors - 4 Turbines producing 320 MWe, attributes include:

- 200MWth/80MWe Per Module
- Process heat applications
- Proven intrinsically safe
- Meltdown proof
- Walk-away safe
- Modular construction
- Requires less time to construct (2.5-4 years)
- Road transportable for diverse geographic areas
- Uses factory-produced components
- Load-following to 40% power within 15 minutes
- Continuous fueling; resilient on-site fuel storage



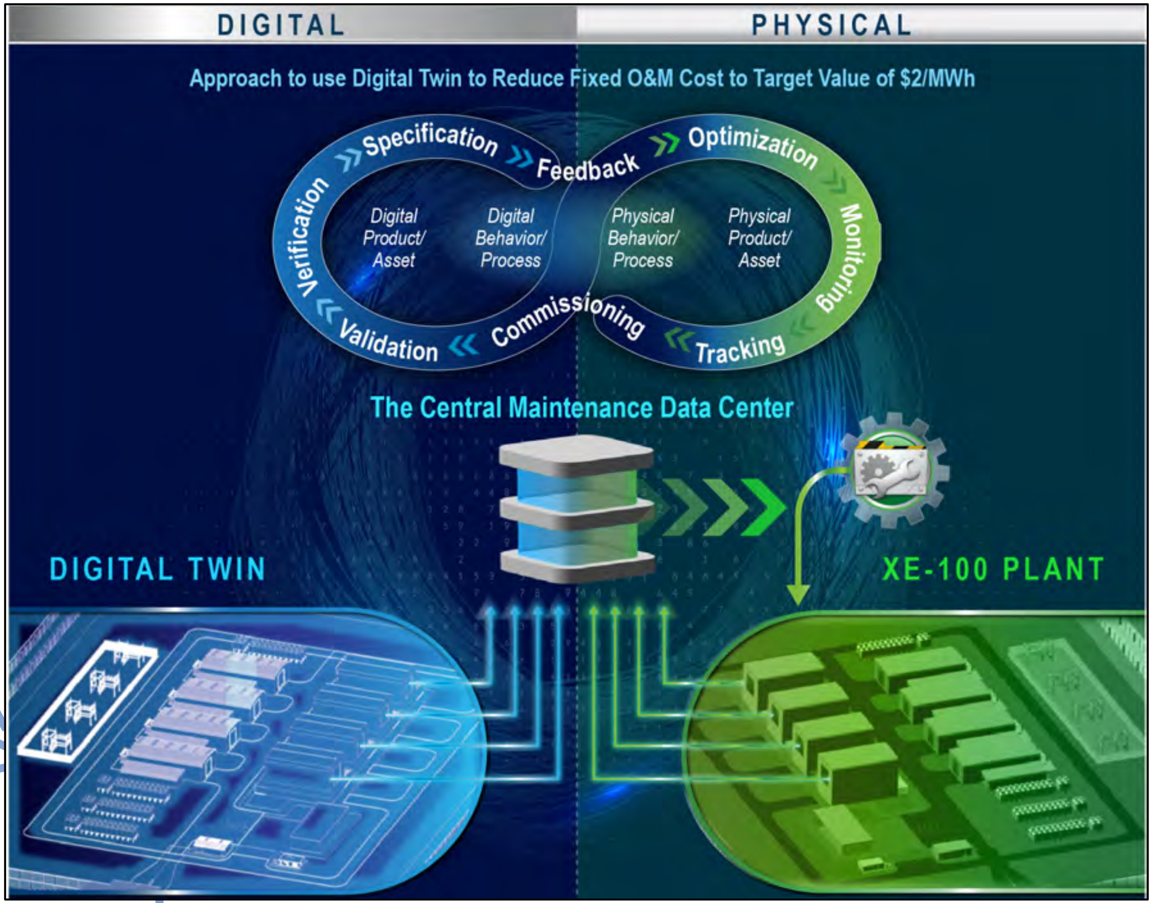


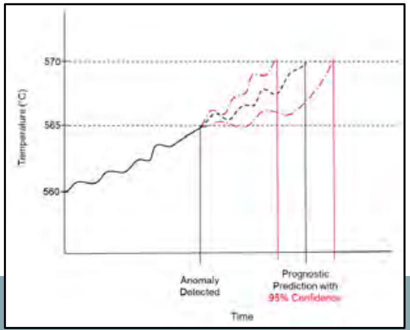
Xe-100 Digital Twin Tools

3D Models with AR / VR

Operator Training Simulator

Plant Historian

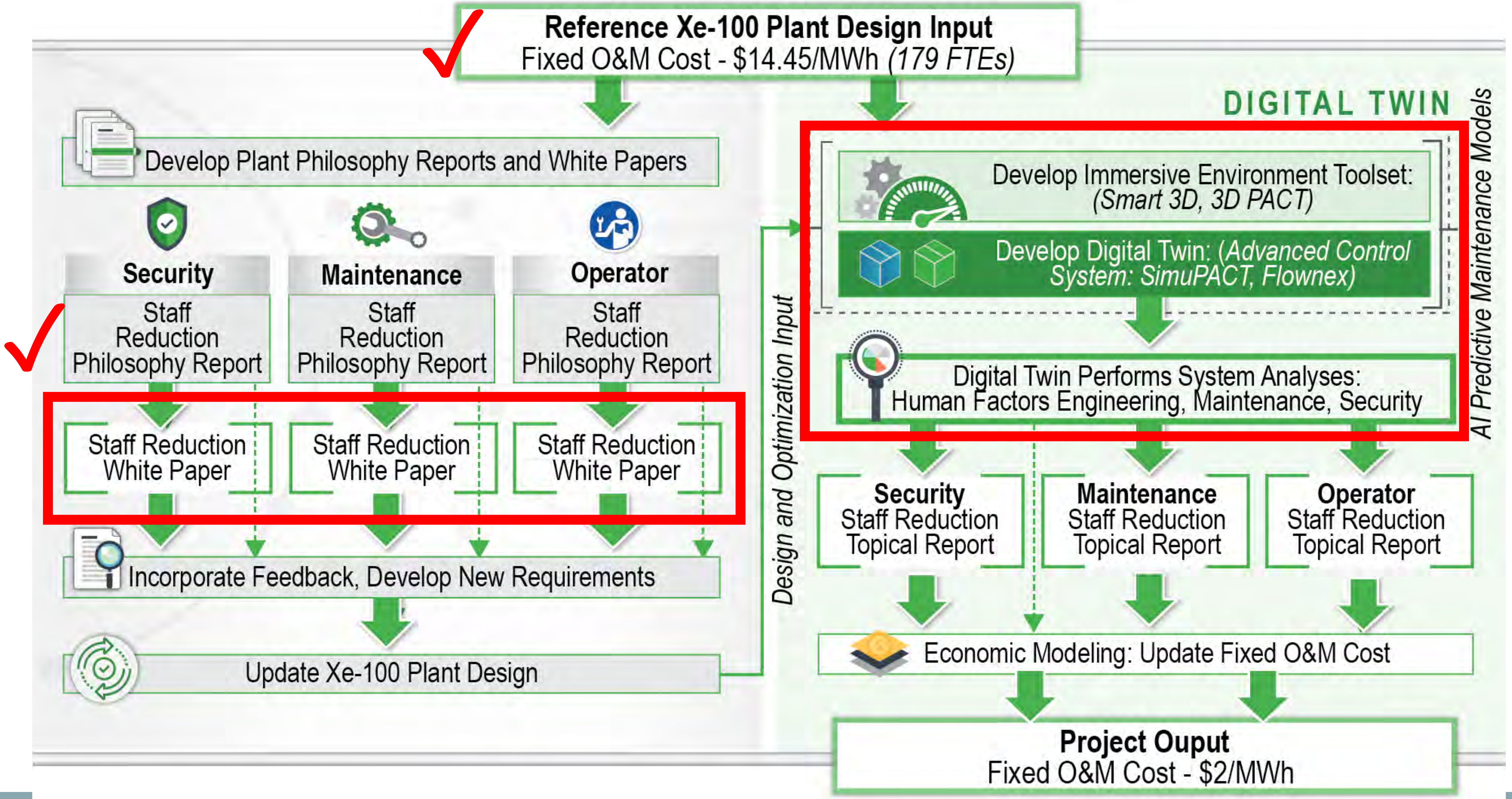




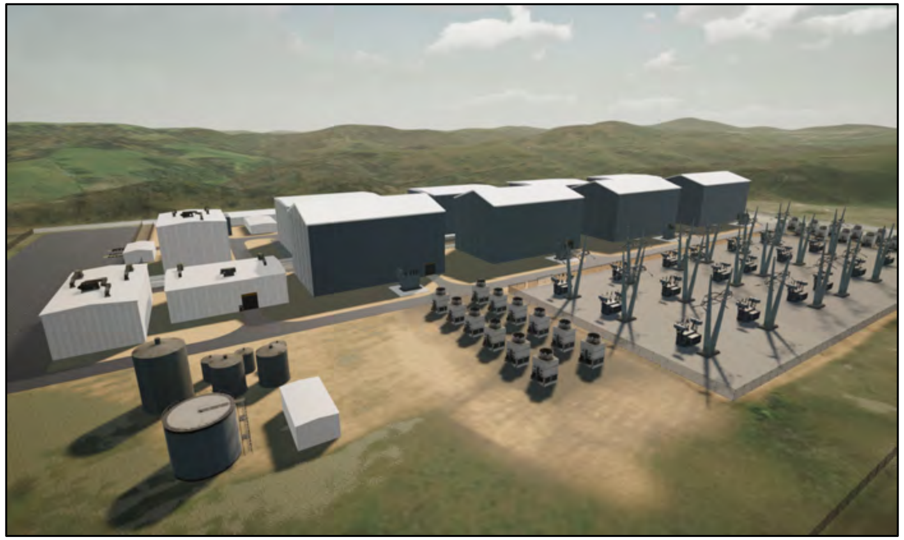
AI / ML Models

ARPA-E GEMINA Project Progress Summary

- Project Title: *Advanced Operation & Maintenance Techniques Implemented in the Xe-100 Plant Digital Twin to Reduce Fixed O&M Cost*
- $7.5 Million award from DOE for Digital Twin (DT) and Central Maintenance Model (CMM) concepts

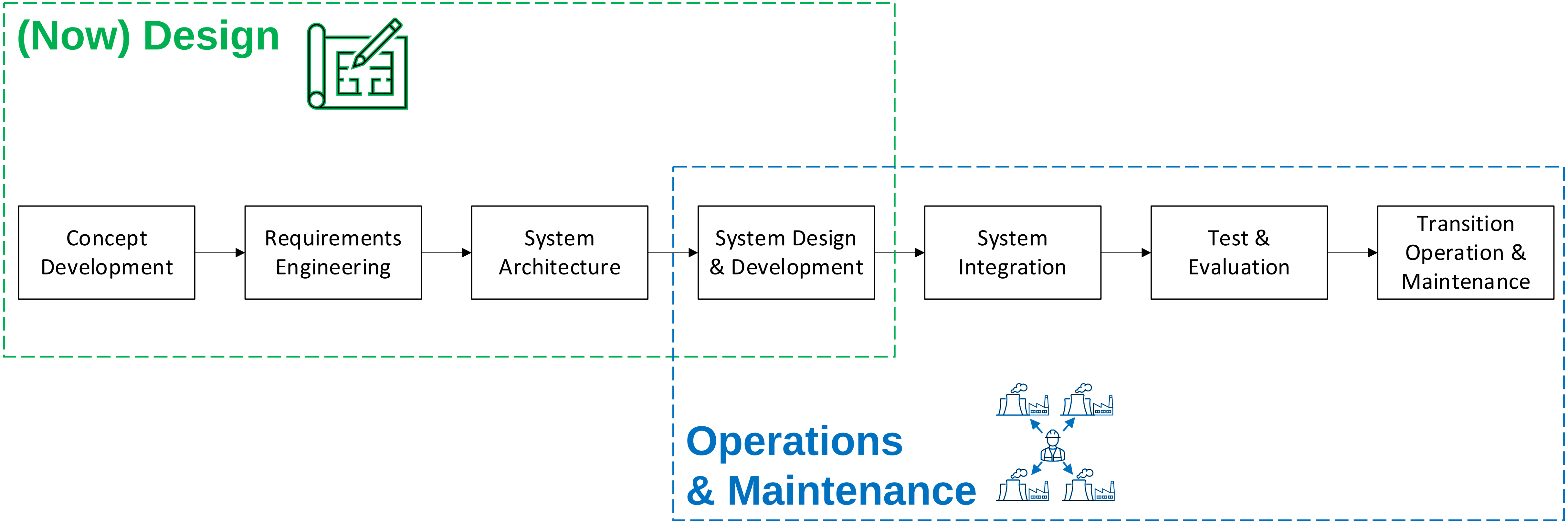


Simulator and 3D Models



Systems Engineering

Systems Engineering with Xe-100 Digital Twin



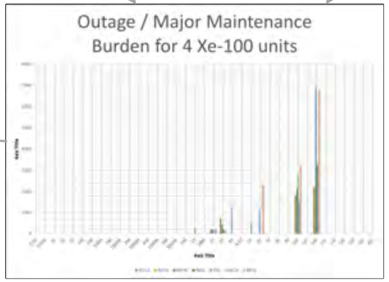
Systems Engineering with Digital Twin: Maintenance

Concept Development → Requirements Engineering → System Architecture → System Design & Development → System Integration → Test & Evaluation → Transition Operation & Maintenance

Maintenance Analysis

Ex: What is maintenance burden for Feedwater pumps?

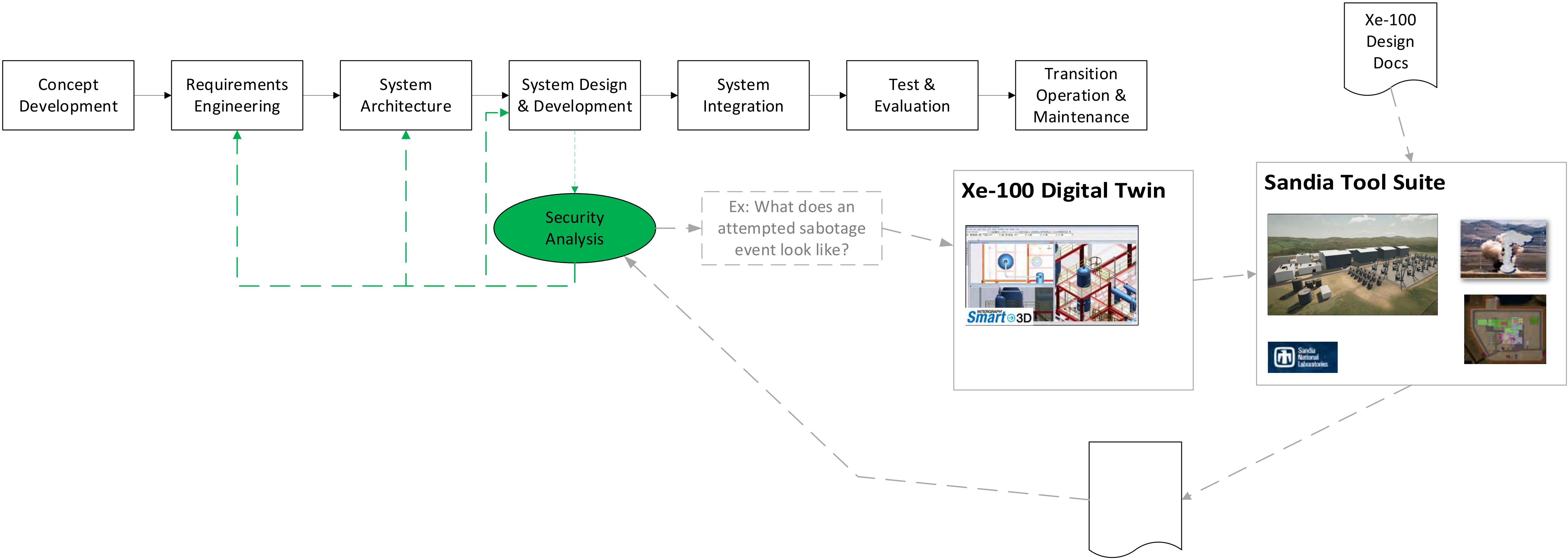
Xe-100 Digital Twin



Ex: Analysis suggests additional Feedwater train be added for redundancy.

Analysis suggests additional instruments be added for better monitoring coverage.

Systems Engineering with Digital Twin: Security

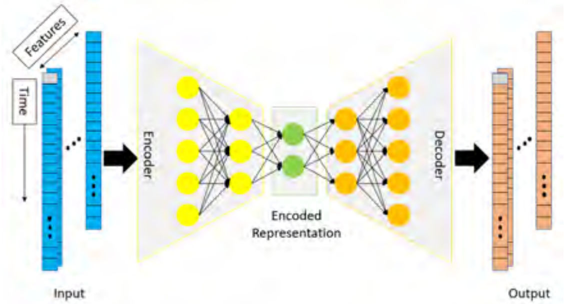


Anomaly Detection with Machine Learning

Deep Neural Networks (DNNs) to support plant operation

Q: Is the system on normal operation (steady-state)?
Goal: detect anomalies with minimal delays

Long Short Term Memory Autoencoder (LSTM-AE)



Q: How soon will any setpoint be exceeded?
Goal: predict time-to-threshold

Setpoints: helium T & P, power, steam T & P, mass flow rate …

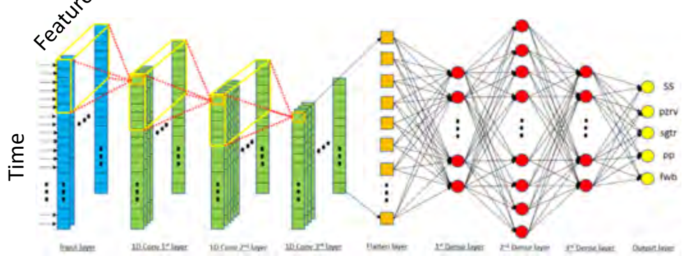
Long Short Term Memory Dense (LSTM-D) (not shown)

Transient events → Anomaly detection → Transient characterization → Progression prediction → **Corrective operations**

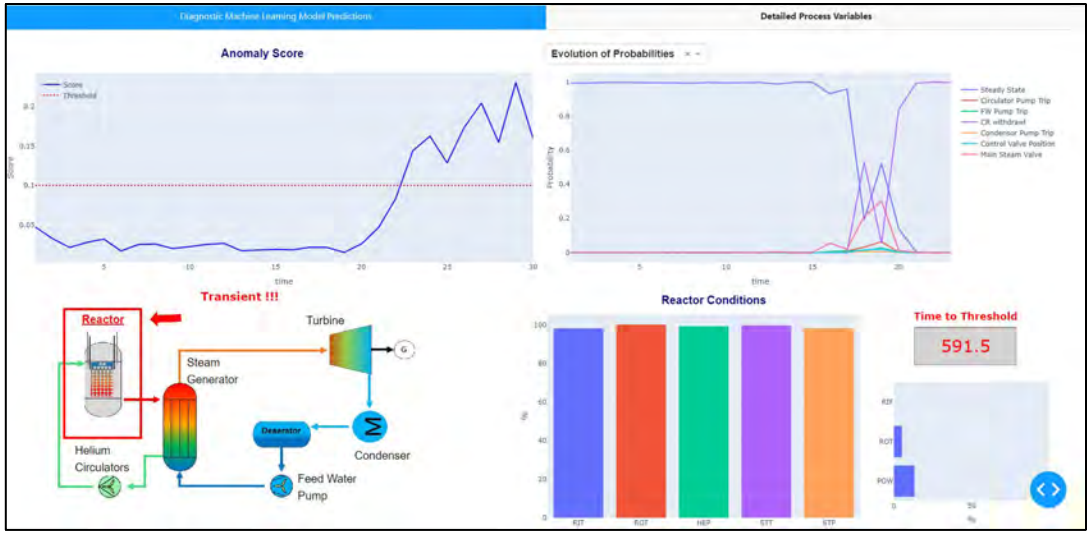
Q: What is the ongoing transient?
Goal: categorize the transient

Major events
- Circulator pump trip
- Condenser pump trip
- Control valve position
- Clogging of MSV in turbine
- Control rod withdrawal
- Feedwater pump trip
- Unknown

Convolutional Neural Network (Convnet)



Human Machine Interface (HMI)



Wednesday, September 15th
Digital Twin Enabling Technologies in Advanced Reactor Applications

Humble AI for Reliable Machine Learning-based Health Twins

Dr. Nurali Virani
Lead Scientist – Machine Learning, GE Research

December 7, 2021

What are Machine Learning-based Health Twins?

Digital twins for fault detection, diagnosis, and health estimation of physical systems and components

Detection

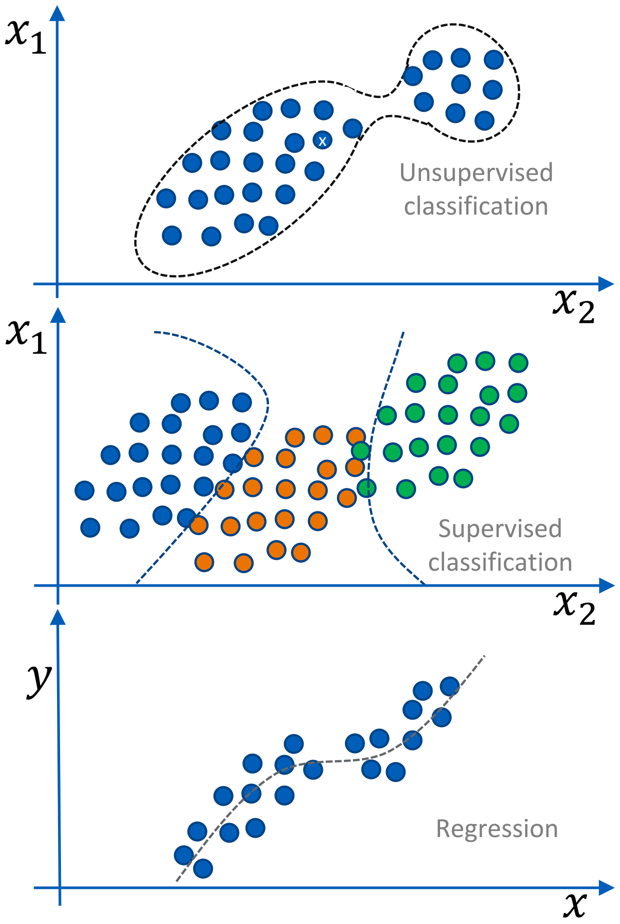
- Fault or anomaly detection with early warning is formulated as an unsupervised learning problem
- Needs data of nominal behavior from modeled system

Diagnosis

- Fault classification is formulated as a supervised learning problem
- Needs labeled data for multiple fault classes

Health estimation & Forecasting

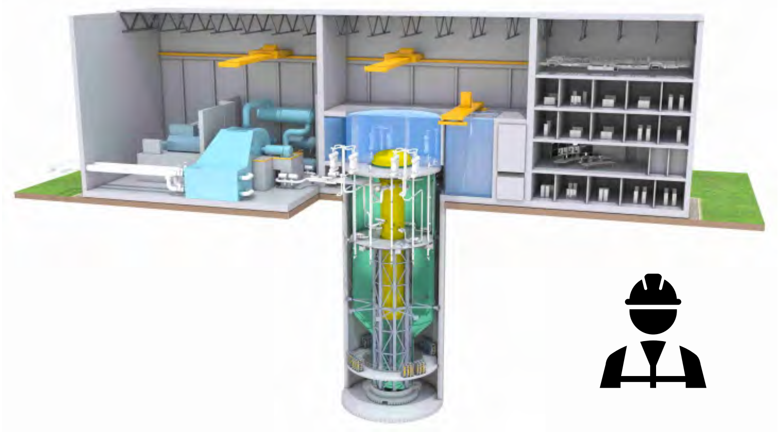
- Health estimation and performance prediction of continuous-valued variable is formulated as supervised learning regression problem
- Needs input-output data pairs for training the model



Key gap in using health twins-based automation for critical industrial infrastructure is in *characterization of reliability* and *trust* as safety and performance are paramount

Understanding prediction reliability can help improve outcomes and build trust in AI

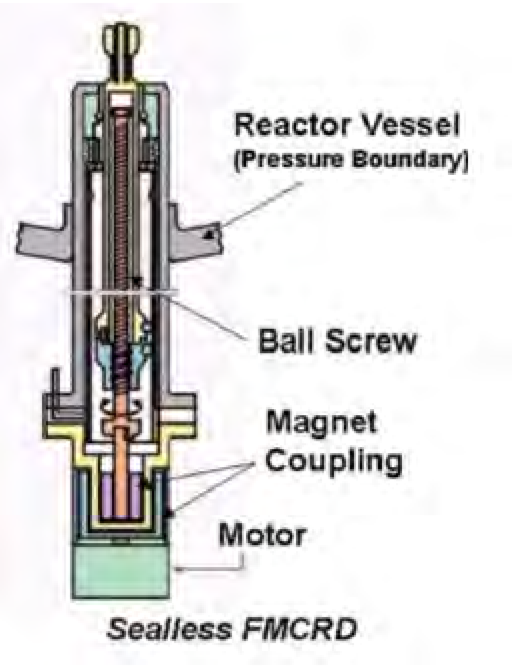
Automated Fault Classification



- I know this is fault class 1, here is my evidence, please authorize to take appropriate actions.
- The *feedwater pump* might have fault 1 or 3, but not 2, send technicians who can address type 1 and 3 faults

Reduce O&M cost via automation, minimize repeated crew trips and avoidable shutdown events

Need Human Help

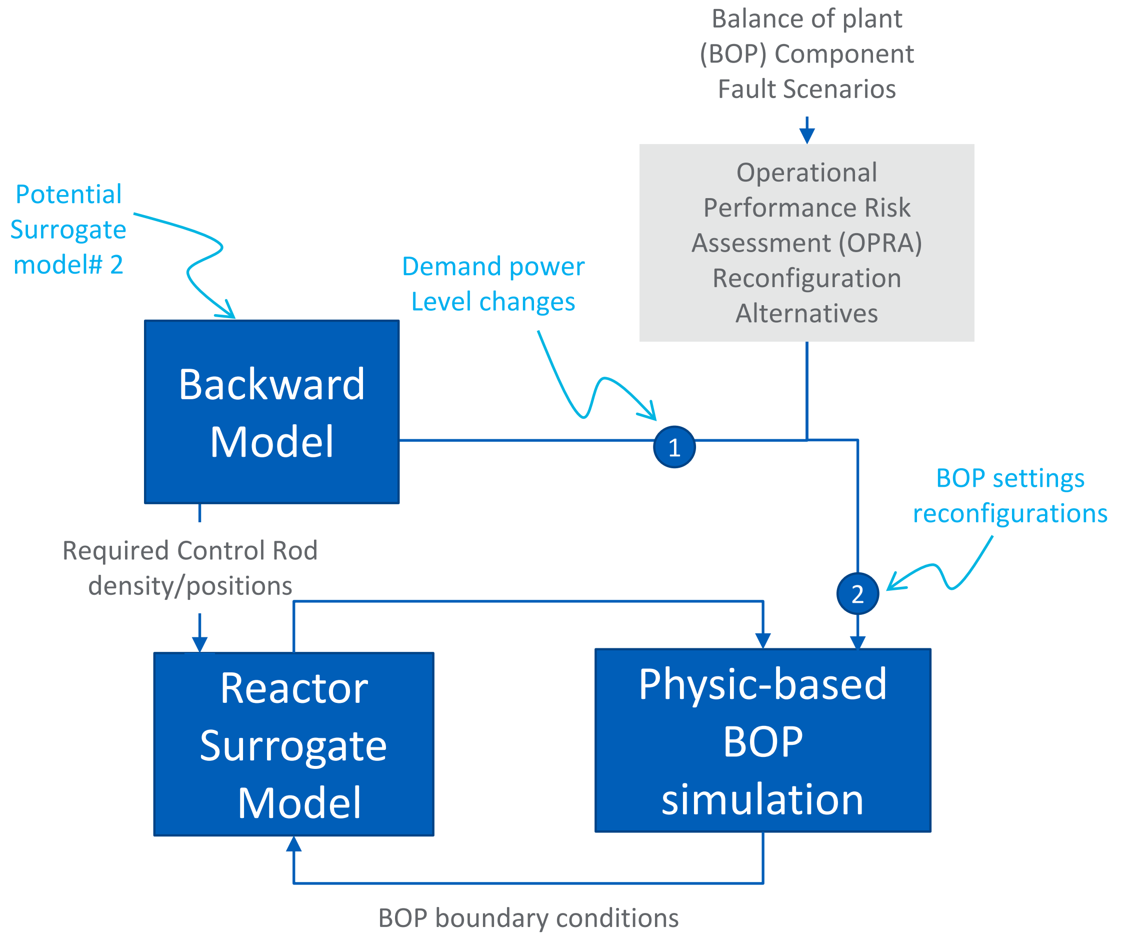


The *FMCRD* behavior is anomalous. I don't know if *FMRCD* has a known fault, partner can you investigate it and trigger safe mode operation.

Image source: FIG. 2.2 in https://aris.iaea.org/PDF/ABWR(Hitachi-GE)_2020.pdf

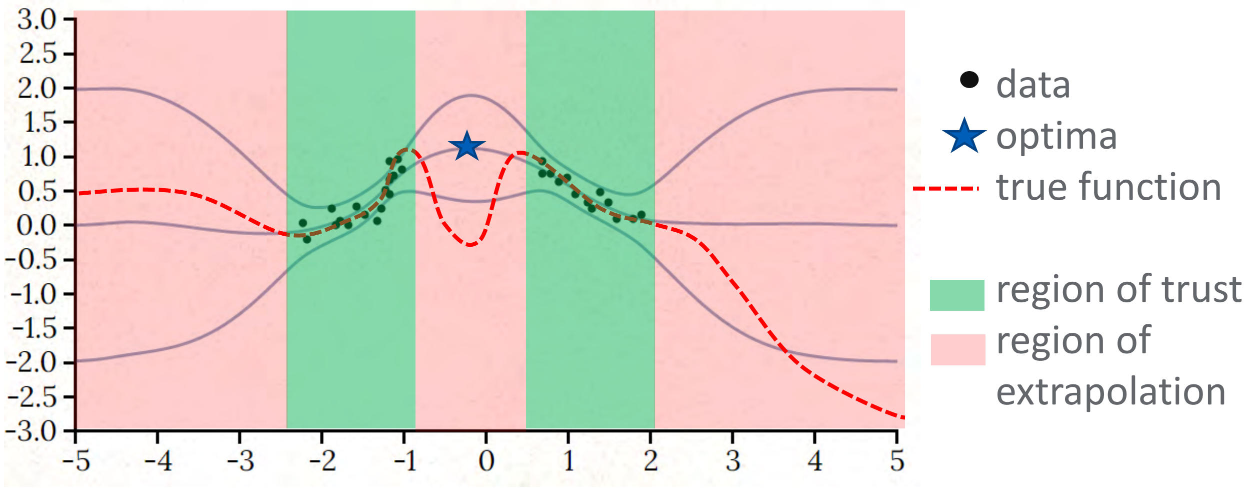
Better collaborative outcomes and ability to deal with novel scenarios

Surrogate model-based optimization and control needs better assessment of prediction reliability



From ARPA-E GEMINA Predictive Maintenance with Digital Twin program (GE Research, ORNL, UTK, GE Hitachi, Exelon)

Script: https://github.com/to-mi/gp-demo-js
GP from live version at: http://www.tmpl.fi/gp/

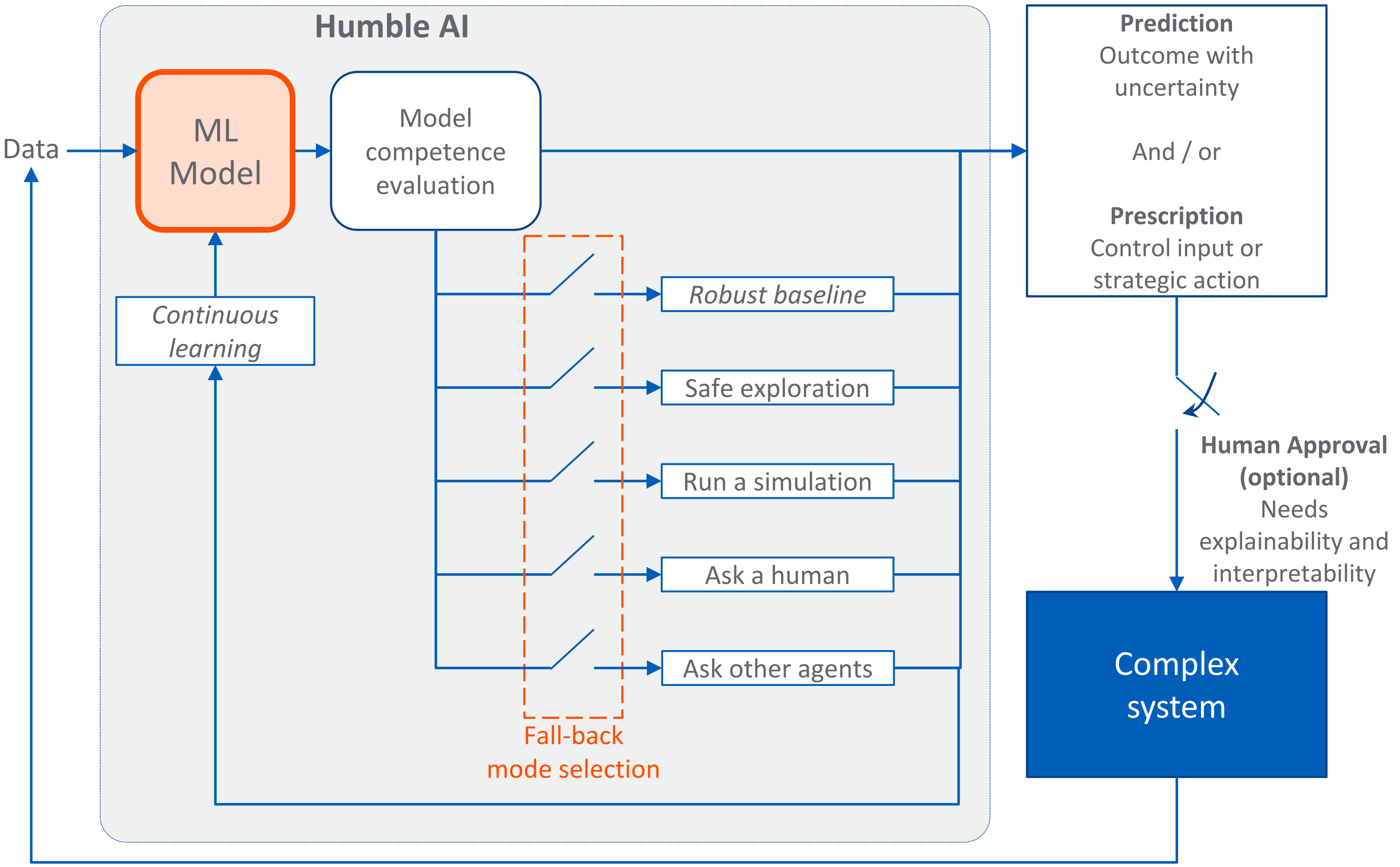


Lack of coverage: Complete variability that we expect during deployment is not available in training data

Can I trust the surrogate model prediction for the suggested BOP boundary conditions and control rod density values?

Humble AI for Digital Twin

An AI that is aware of its own competence and improves its competence via learning



Defining capabilities

- understand region of trust
- quantify uncertainty
- ask for help when incompetent
- continual learning from 1 or more sources

✓ Humble AI will reduce Time to Value

✓ Humble AI will maintain safety

Key Gap and Research Question

- Key Gap: Machine learning provides statistically impressive results which might be individually unreliable.
  - ✘ "My validation accuracy was high, so trust my belief"
  - ✘ "Soft-max value for predicted class is high, so trust my belief" (distance from hyperplane)
- In many situation, randomized inspection of samples is inadequate to verify reliable outcomes and complete inspection defeats the purpose of using AI

Can we characterize individual prediction reliability to understand the limitations of ML due to:

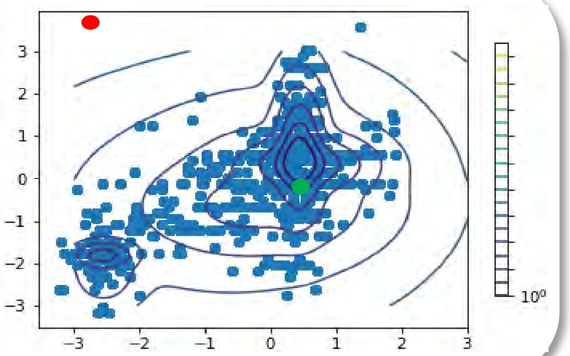
- ❖ Observability (or separability)?
- ❖ Brittle extrapolation?

Support types to create justification for model competence

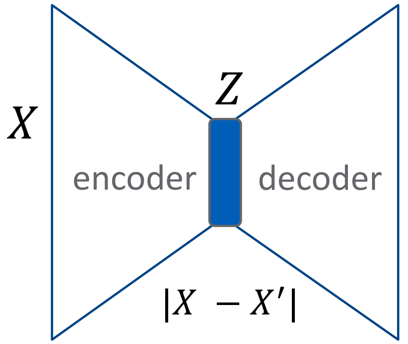
Using model input, model internal representation, and model outputs for support

#	Types of Support	Guard against
1	Input anomaly	• Input drift • Extrapolation
2	Reconstruction error	• Input drift • Extrapolation
3	Geometric neighborhood in embeddings	• Extrapolation • Ambiguity • Adversarial manipulations
4	Output uncertainty anomaly	• Input drift • High process uncertainty
5	Residual error drift	• Concept drift

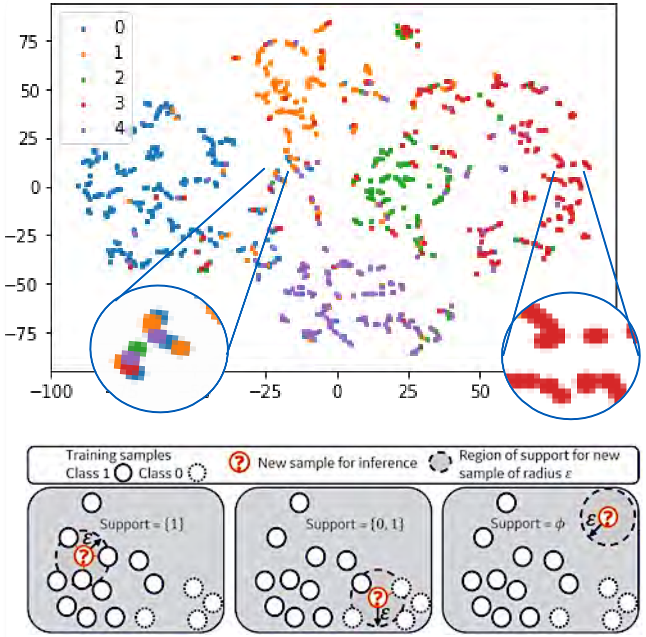
(1) Input likelihood with density estimation



(2) Reconstruction error-based anomaly



(3) Geometric neighborhood in embeddings (latent spaces)

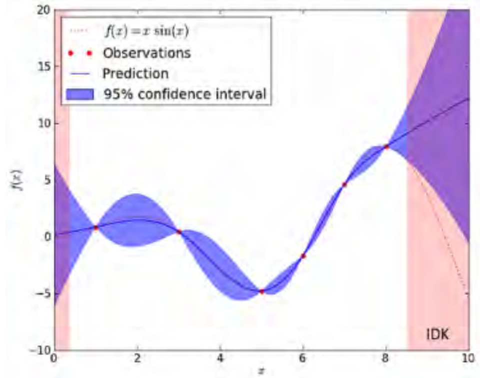


Neighborhood operator:

(a) by number of neighbors

(b) by radius (distance threshold)

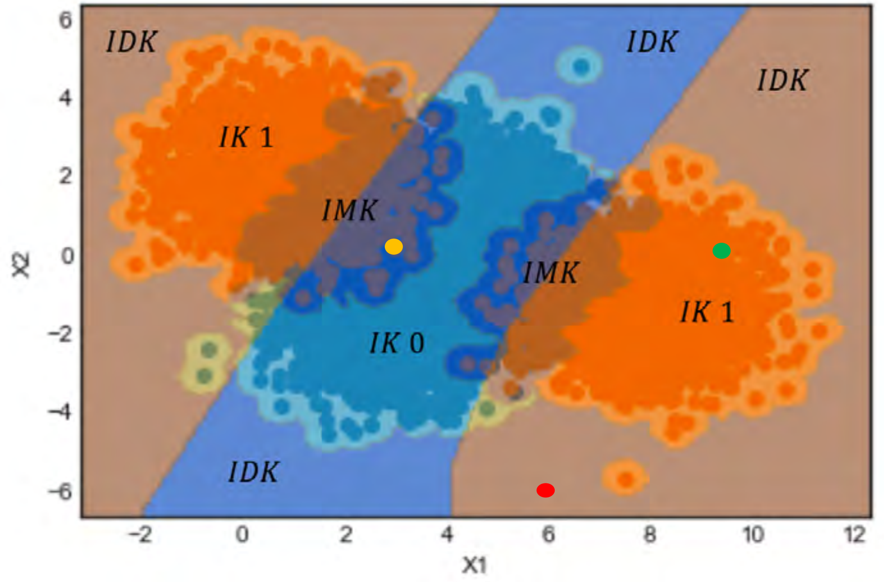
(4) Output uncertainty anomaly

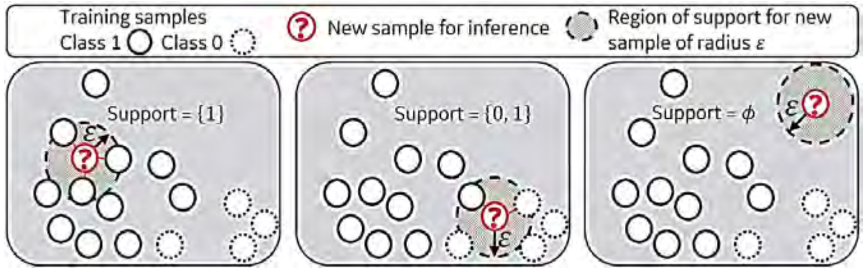


(5) Residual error drift

Model Input — Model Internal Representation — Model Output

Characterizing region of trust, overlap, and extrapolation for AI to get justification-based reliability





Output = $(Belief,\ j \in \{IK, IMK, IDK\})$

Justification from supports

$$Justification = \left\{ \begin{array}{c} \phi;\ \ if\ support\ is\ \phi \\ \bigcup_{i \in I} support\ from\ layer\ i\ ;otherwise \end{array} \right\}$$

Justified belief is knowledge

$Belief = Justification$ → I know (Region of trust)

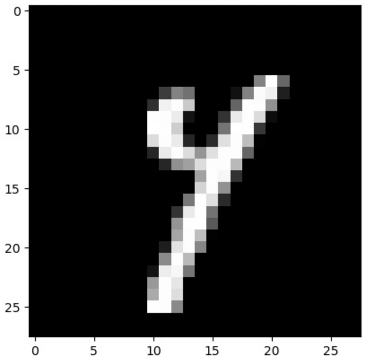
$Belief \subset Justification$ → I may know (Region of overlap/ambiguity)

$Belief \not\subset Justification$ → I don't know (Region of extrapolation)

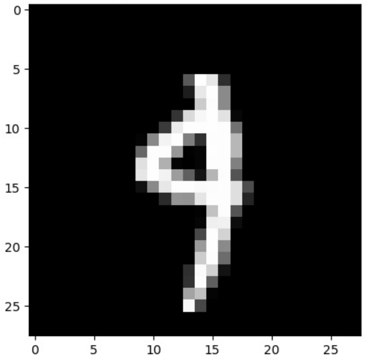
1. Virani, N., Iyer, N. and Yang, Z. Justification-Based Reliability in Machine Learning. in AAAI 2020

2. Bhushan, C., Yang, Z., Virani, N. and Iyer, N., 2020. Variational encoder-based reliable classification. arXiv preprint arXiv:2002.08289. (IEEE ICIP 2020)

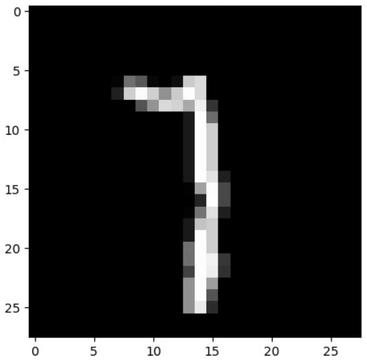
Examples of evaluating competence using internal representations



Belief : 9
IMK [4, 9]
Truth: 4

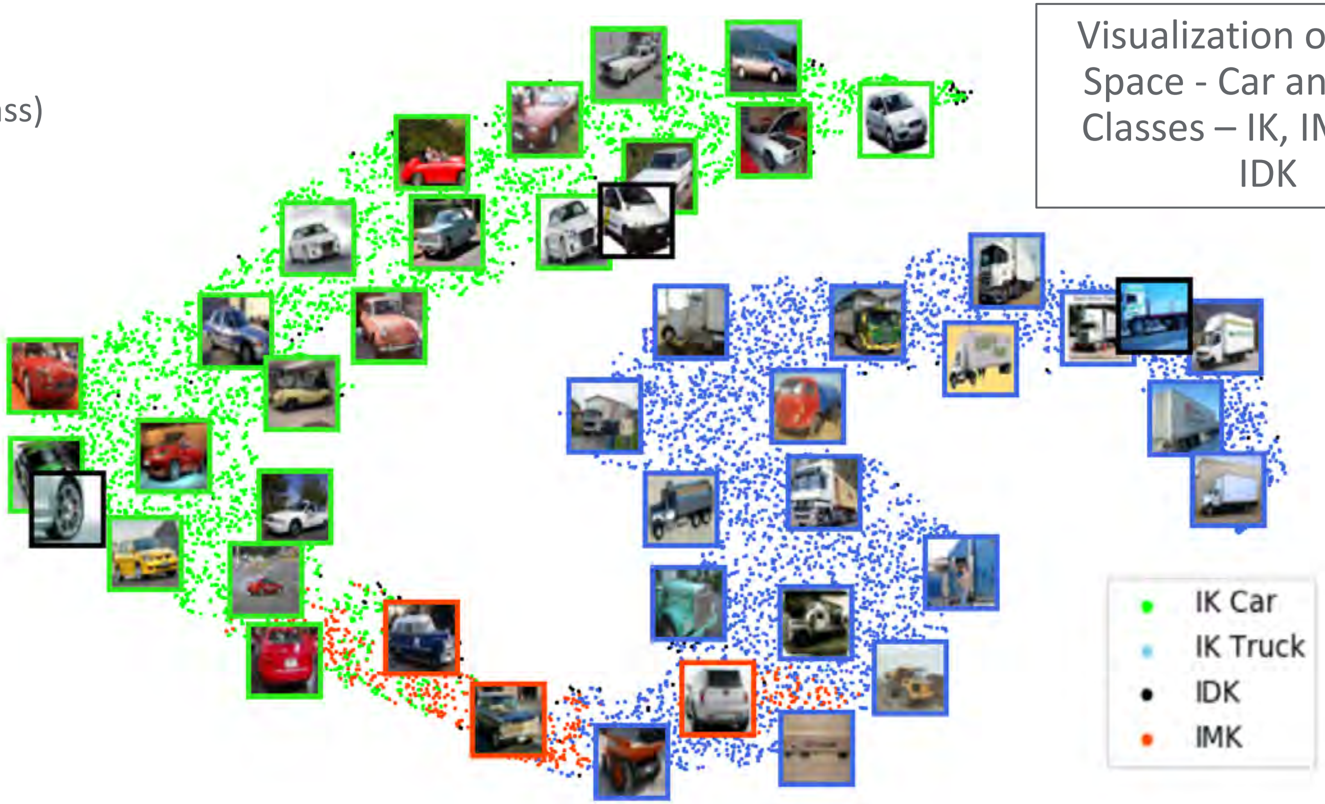


Belief : 4
IMK [4, 9]
Truth: 4

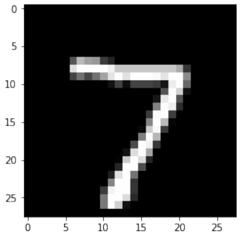


Belief : 1
IMK [1, 7]
Truth: 7

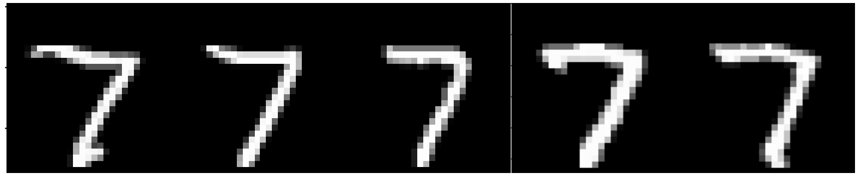
Dataset:
CIFAR (car and truck class)
Base model:
Residual Network
Layer:
Global average pooling
Support:
ε-ball with
ℓ_2-metric



Visualization of Latent Space - Car and Truck Classes – IK, IMK, and IDK



IK [7]

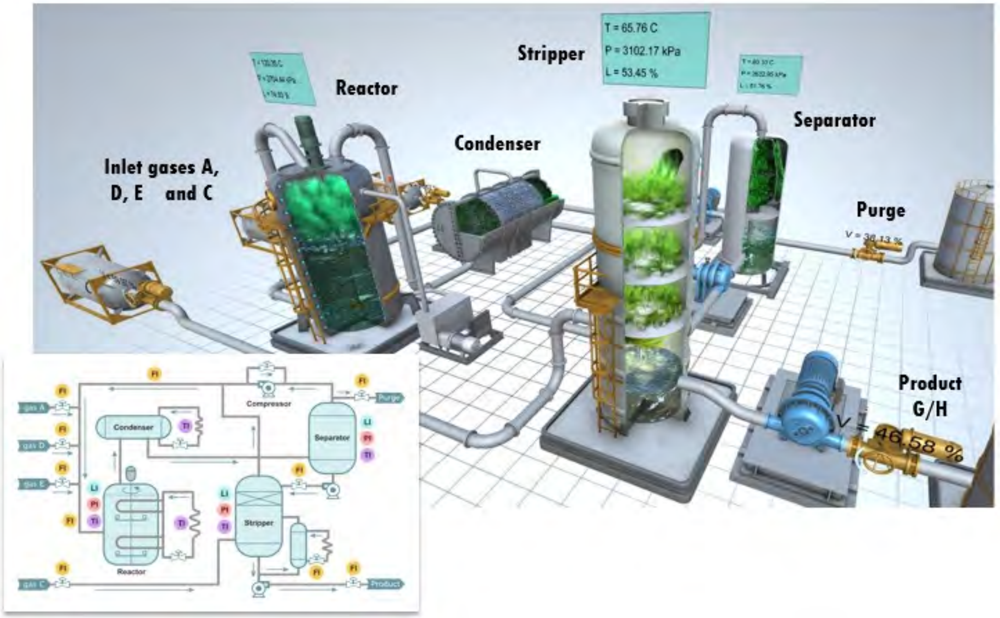


Support from latent space as exemplars for interpretability

Data to facilitate Health Twin development and validation

Tennessee Eastman Process (TEP) simulation data[a]

- Open-source benchmarking data of industrial chemical process for the purpose of developing, studying and evaluating process control and fault detection
- Process has 12 valves available for manipulation and 41 measurements available for monitoring or control.
- Time series sensor data, with faults injected using simulation
- Variables sampled every 3 minutes for a total of 25 hours (training data) and 48 hours (test data)
- Overall Data size: 15M rows x 52 variables x 1-label
- Labels: 20 fault-types + Normal

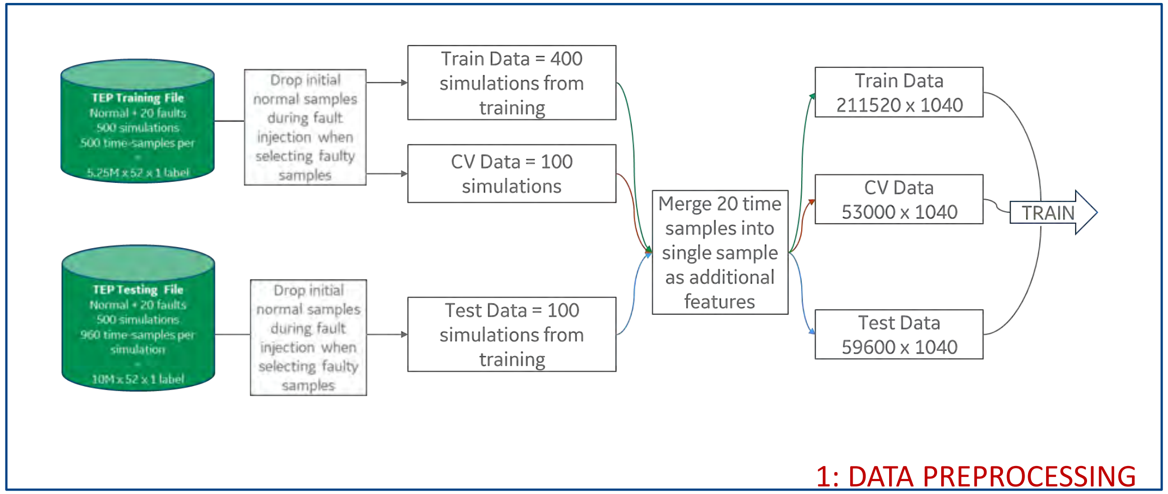


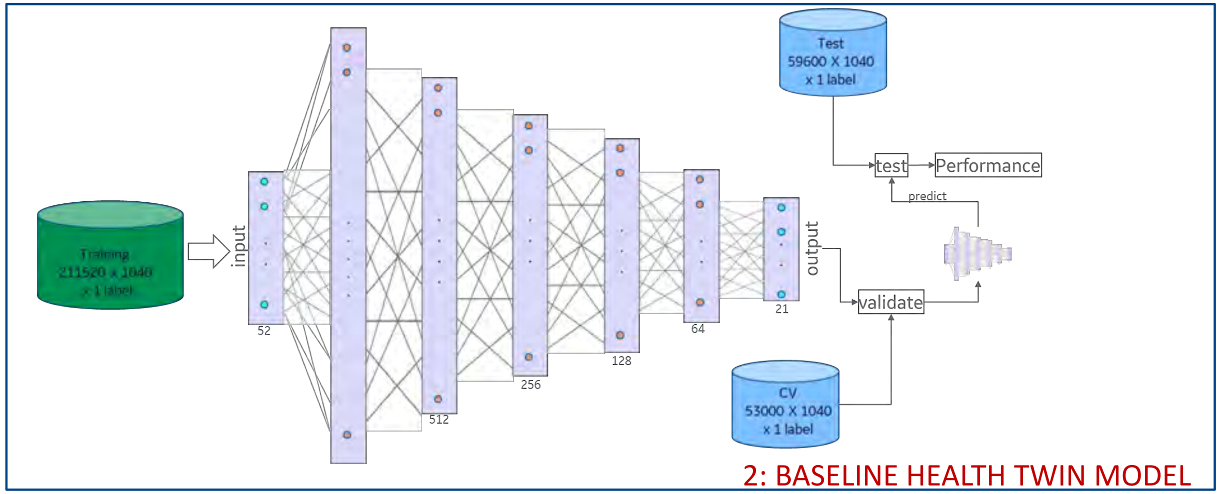
a:
1> Downs, J.J. and Vogel, E.F., 1993. A plant-wide industrial process control problem. *Computers & chemical engineering*, *17*(3), pp.245-255

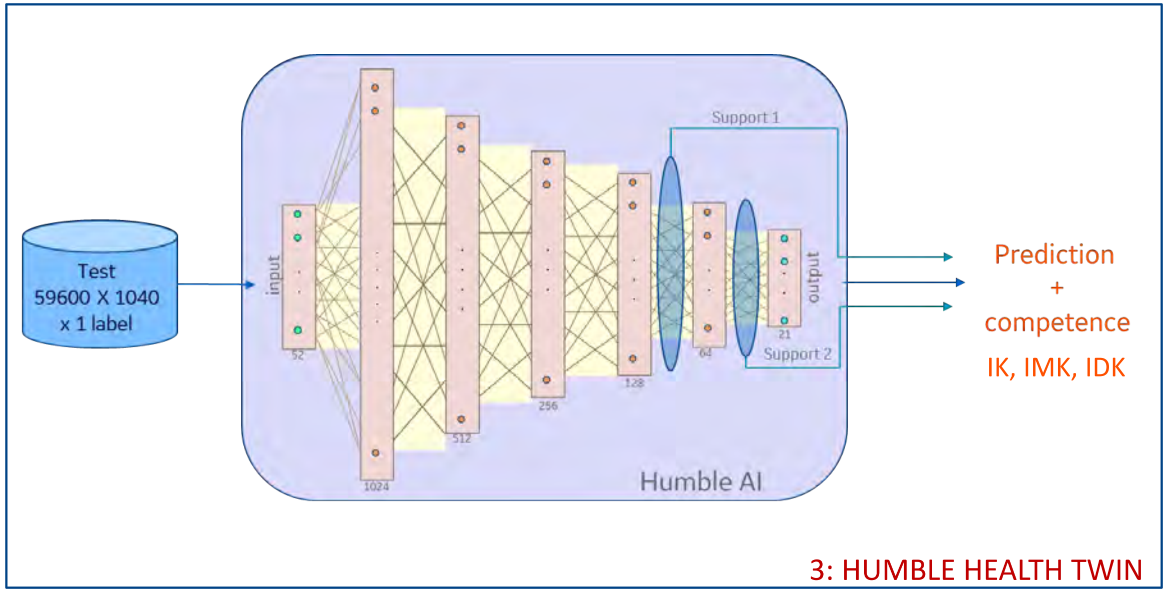
2> Rieth, Cory A.; Amsel, Ben D.; Tran, Randy; Cook, Maia B., 2017, "Additional Tennessee Eastman Process Simulation Data for Anomaly Detection Evaluation"

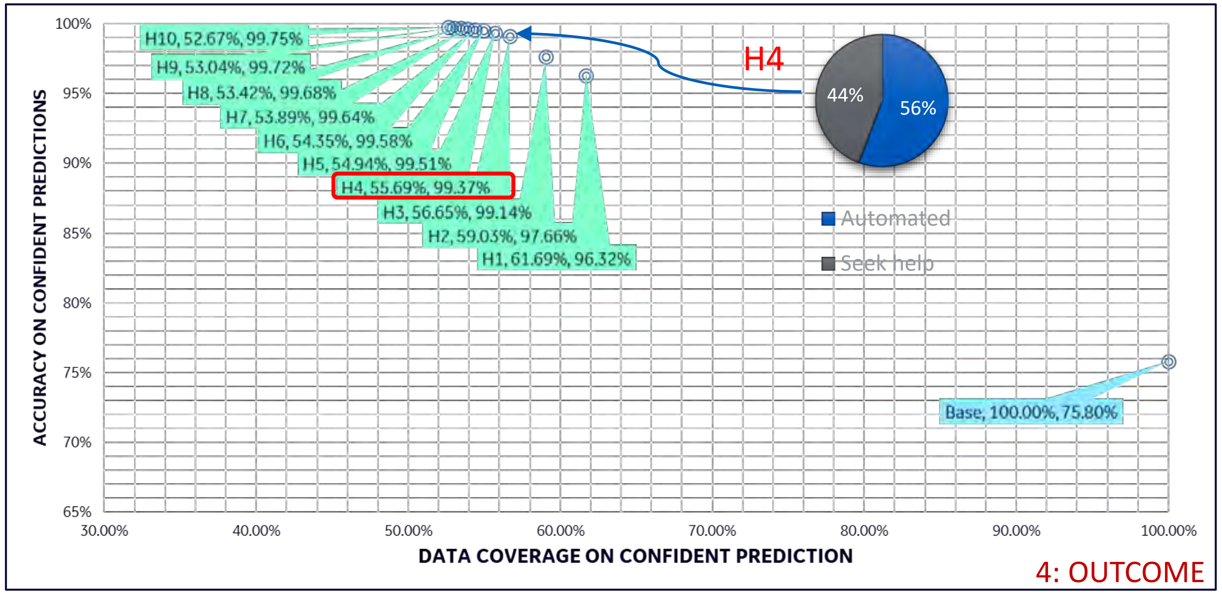
Humble Health Twins for Fault Classification

Approach & Outcomes



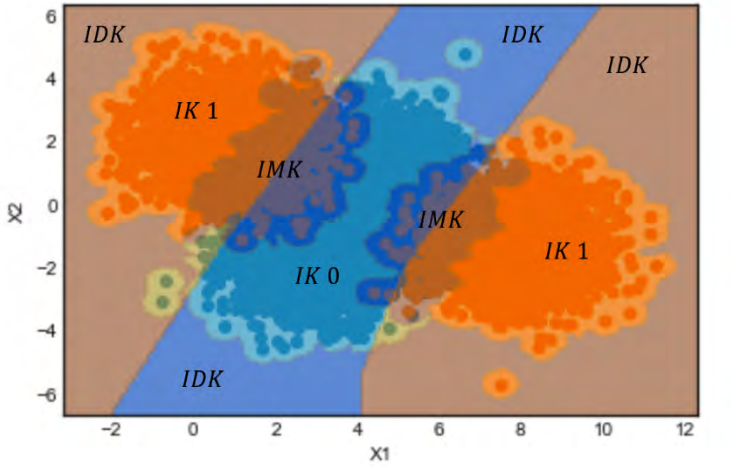


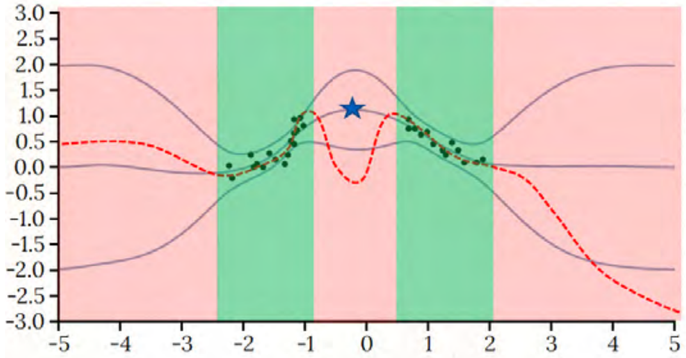




Summary

- ✓Humble AI is an AI that is aware of its own competence and improves its competence via learning
- ✓Current focus of Humble AI is on ML-based digital twins (specifically health twins)
- ✓Humble AI enables to characterize region of trust for health twins to get justification-based reliability where automation can be enabled
- ✓Extend to use model input, model internal representation, and model outputs for support (beyond NN models)






GRCTHINK
Thank You!
Building a world that works
Collaborate with us on research programs for a better tomorrow
(nurali.virani@ge.com)

Kairos Power

ENABLING TECHNOLOGIES FOR DIGITAL TWIN APPLICATIONS FOR THE KP-FHR

CHRIS PORESKY AND ANTHONIE CILLIERS

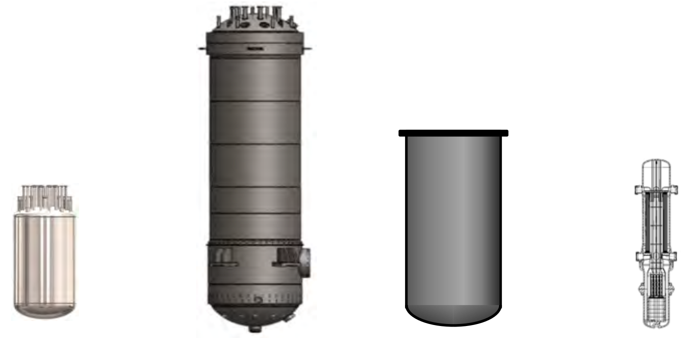
Kairos Power's mission is to enable the world's transition to clean energy, with the ultimate goal of dramatically improving people's quality of life while protecting the environment.

Advanced reactors – challenges and opportunities

- Industry experience in plant simulators is entirely focused on light water reactors
- Challenging environments, more difficult component and structure qualification
- Limited historical data on performance and documentation of material and chemical properties
- Parallel engineering – developing capabilities while developing application space simultaneously
- Advanced reactor priority phenomena may occur at different (i.e. slower) timescales
- Modern instrumentation and control may more easily lend itself to data communication
- Two-phase phenomena may be deprioritized for non-water coolants
- Passive safety may reduce the dependency on active control

Overview of Kairos Power

- **KP-FHR Inherent Safety and Economic Potential are Unique:**
- **Robust Inherent Safety**
  - Large ***fuel temperature margins***
  - fission products retained by fuel and primary coolant
  - Low-pressure system
  - Passive decay heat removal
- **Lower Capital Costs**
  - Reduced reliance on high-cost, nuclear-grade ***components and structures*** through FHR intrinsic safety and plant architecture
  - Leverage conventional materials, existing industrial equipment, and conventional fabrication and construction methods
- **Improved Operating Economics**
  - High efficiency
  - Flexible deployment of low-cost nuclear heat

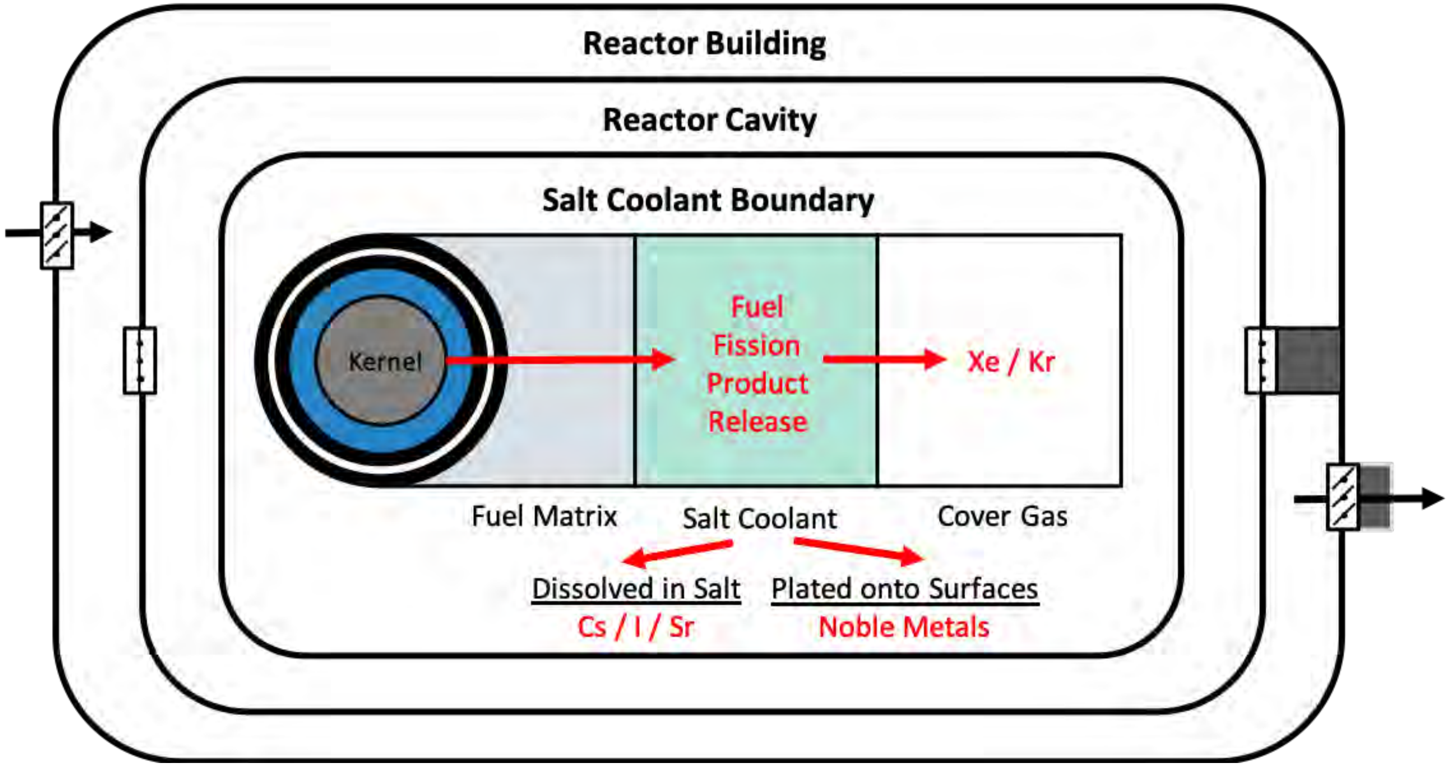


KP-FHR	HTGR	Fast Breeder Reactor	PWR SMR
Flibe	Helium	Sodium	Water
280 MW_{th}	250 MW_{th}	260 MW_{th}	200 MW_{th}
120 MW_e	100 MW_e	100 MW_e	60 MW_e

** Reactor vessels drawn to notional scale.*

KP-FHR Safety Case – Defense in Depth Barriers

- Radionuclide Retention Capabilities



KP-FHR I&C design

Robust Inherent Safety

- Low operating pressure
- Large fuel temperature margins
- Effective passive decay heat removal
- Uniquely large heat capacity
- Strong negative temperature coefficient
- Slow transient response

Plant protection and control

- KP-Shield: Passive, robust, reliable safety shut-down system

Safety Hazard Intervention and Event Limiting Defense (Shield)

- KP-Sword: Active plant control

System with Operational Reliability and Diagnostics (Sword)

- KP-Heart: Intelligent Health Monitoring

Health Evaluation and Analysis in Real-Time (Heart)

- KP-Sight: Semi-autonomous control room

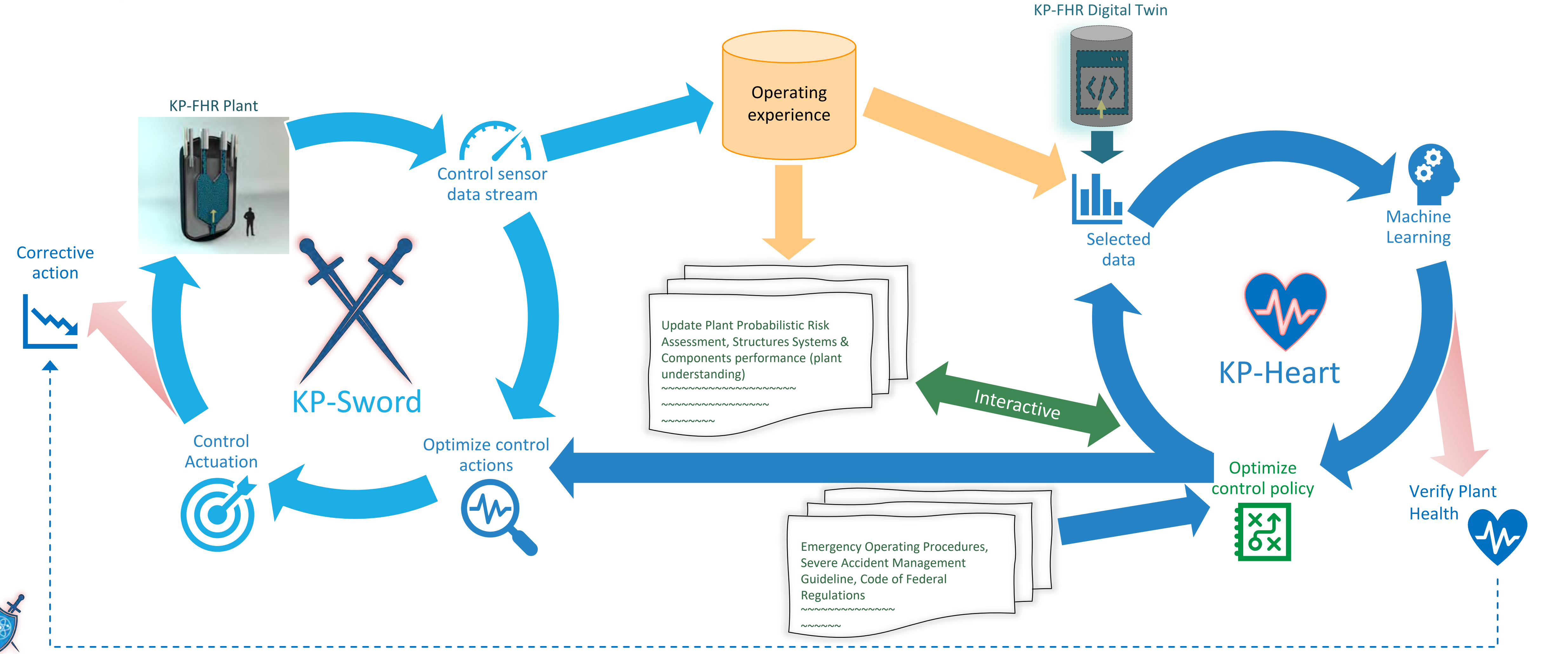
Semi-autonomous Industrial Grade HMI Technology

- KP-Bolt: Electrical supply

Basic Ohm Law Triangle (V = I.R)

Active plant Control & Health Monitoring: KP-Sword & KP-Heart

Normal Operations and Anticipated Operational Occurrences

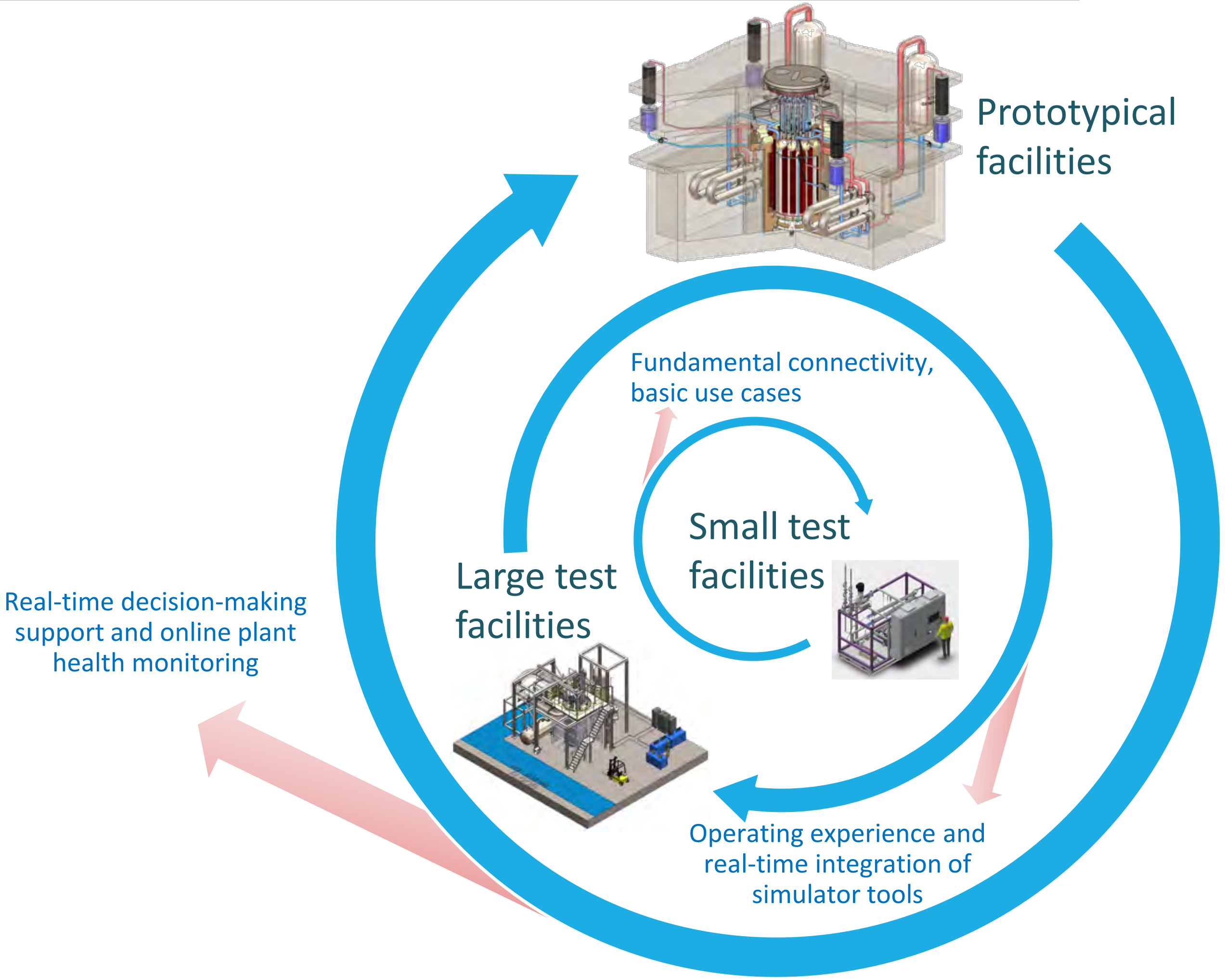


KP-FHR digital twin working definition

- Collects, compiles, and contextualizes plant information from a variety of sources and makes it accessible to aid plant operation
  - Visualization
  - Database
  - Physics simulation
  - Real-time communications and feedback
  - Data analytics
    - Plant health monitoring
    - Operations optimization
    - Operator decision support

KP-FHR digital twin development process

- Small test facilities
  - Demonstrate ability to connect facilities using different hardware and software
  - Validate simulation tools against representative physical systems
- Large test facilities
  - Deploy digital twins alongside tests to gather operating experience and train models
  - Integrate simulation into operation to improve understanding of system
- Prototypical facilities
  - Support decision-making in real time
  - Passively and continuously monitor plant health and flag unexpected behavior



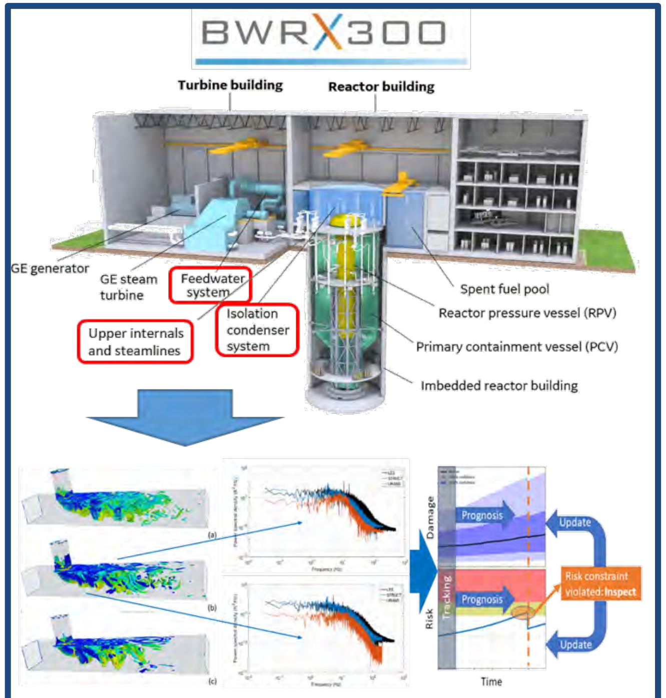
Desired capabilities and enabling technology

- Desired capabilities
  - Run continuously alongside plant operation
  - Provide lookahead and optimization capabilities to operators and support staff
  - Flag unexpected behavior and prompt important operations and maintenance activities

- Enabling technology
  - *Communications infrastructure*: talk to engineering tools, plant hardware, controls and simulation software
  - *Physical processes*: develop and specify all plant components and prototypical information
  - i: develop faster-than-real time physics simulation and data analysis capabilities

A note on cybersecurity and plant design

- If the plant design precludes consequence, the risk for all failures is lower
- If instrumentation and controls architecture precludes consequence, the reactor protection functions are not at risk
- If reactor protection functions are not at risk, the value of added capabilities becomes much more attractive despite potential risks
- Digital twins can **bolster** cybersecurity by improving the ability not only to detect but also to mitigate cyber threats
  - Mitigation of cyber threats and approach to cybersecurity should be baked into plant design the same as it is for mitigation of insider threat, access control, intellectual property management, etc.



Virtual models (left) are adopted to generate high resolution data for thermal induced thermal fatigue (center) and DT development (right)

HIGH FIDELITY DIGITAL TWINS FOR BWRX-300 CRITICAL SYSTEMS

Focus on “enabling” technology

Emilio Baglietto
Massachusetts Institute of Technology
Department of Nuclear Science and Engineering

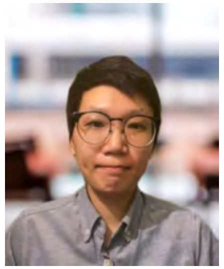
High Fidelity Digital Twins for BWRX-300

The Team

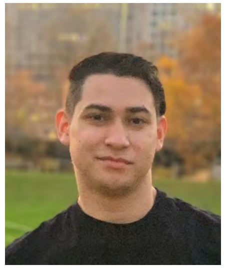
MIT

Prof. Emilio Baglietto (PI)

Prof. Koroush Shirvan (co-PI)



Yu-Jou Wang (PhD)



Brandon Aranda (MS)

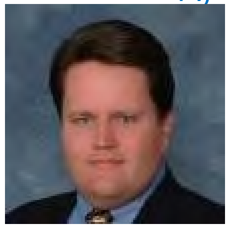
GE Global Research

Dr. Panos Tsilifis (co-PI)

Genghis Khan (co-PI)

HITACHI

Dr. Christer Dahlgren(co-PI)



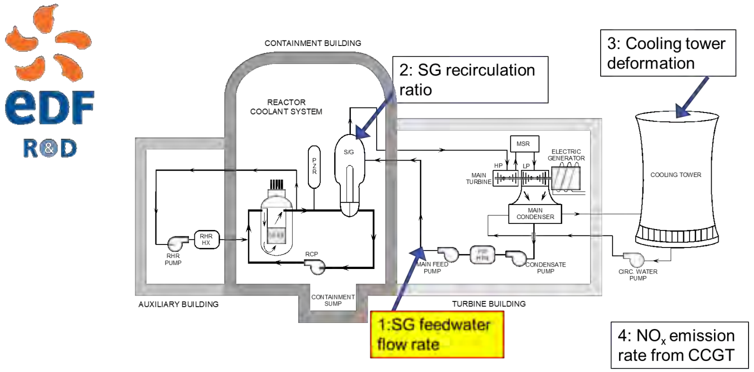
Douglas McDonald

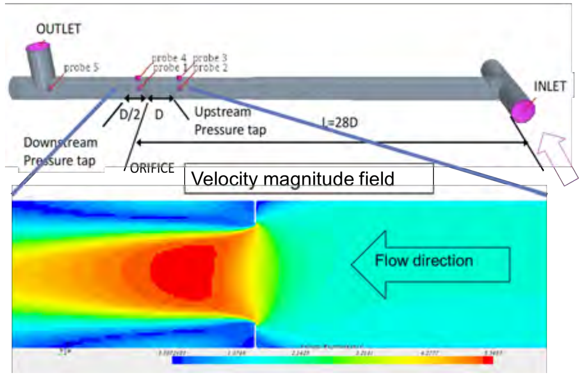
David Hinds

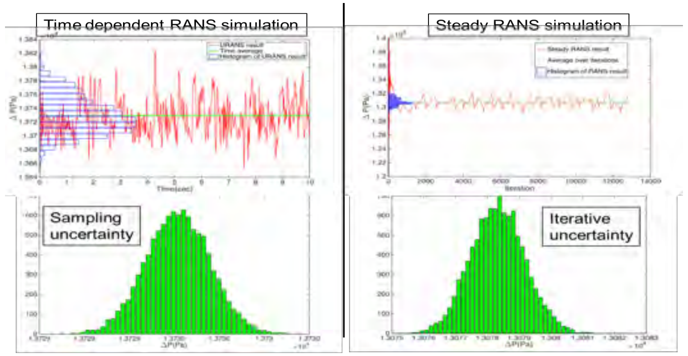
Charles Heck

The Backbone

- **MIT**: e.g. demonstrated reduction of operating uncertainty through high fidelity simulations

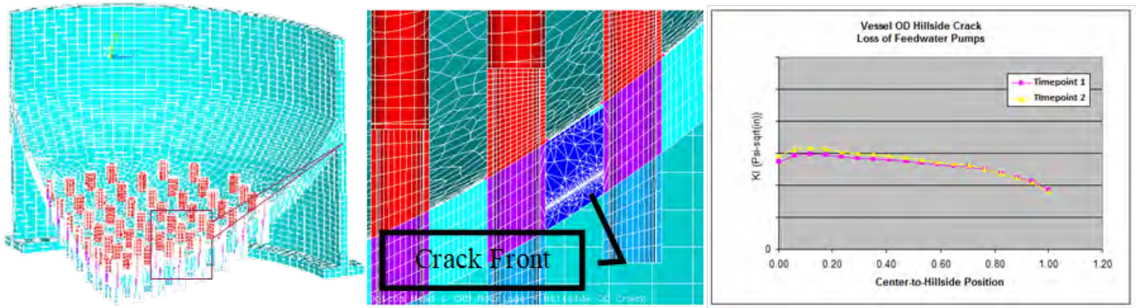




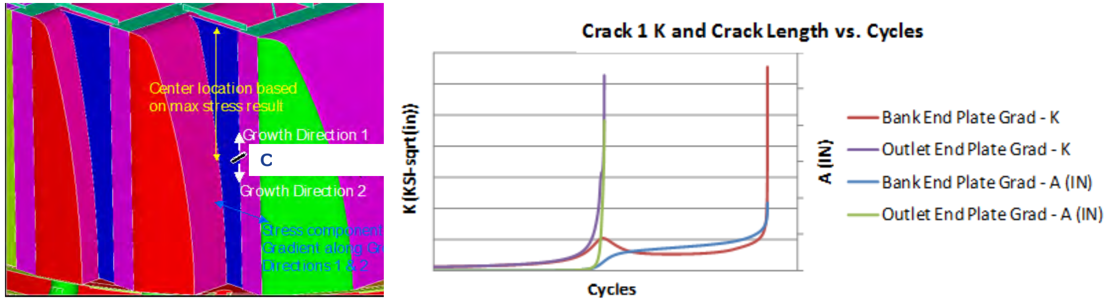


U.Otgonbaatar, E.Baglietto, Y.Caffari , N.E.Todreas and G.Lenci - A METHODOLOGY FOR CHARACTERIZING REPRESENTATIVENESS UNCERTAINTY IN PERFORMANCE INDICATOR MEASUREMENTS OF POWER GENERATING SYSTEMS - JVVUQ

- **GE**: e.g. digital twin deployed in Nuclear and Aerospace Industries



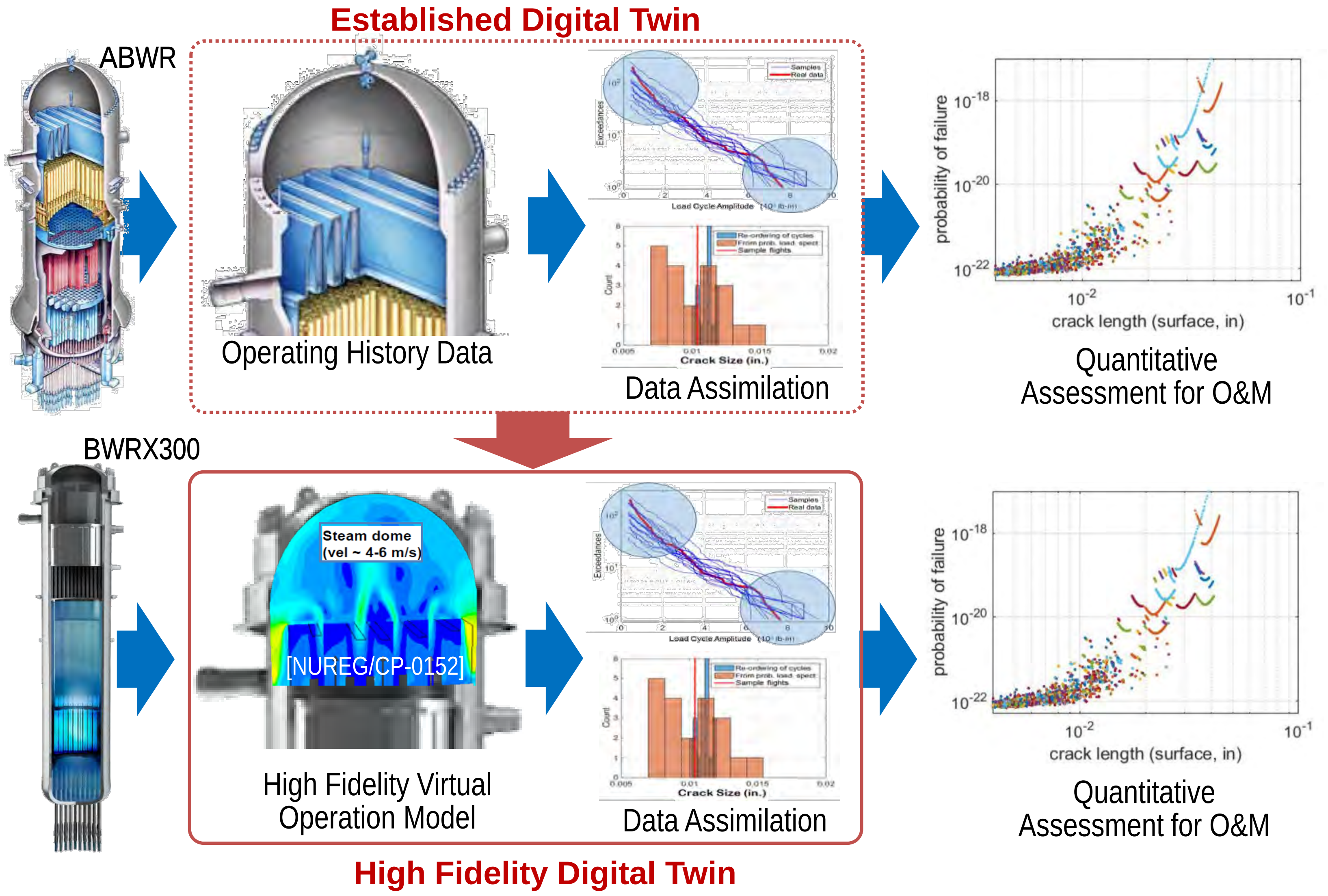
Digital Twin of BWR Stress Intensity Factor after simulated loss of feedwater pumps



Digital Twin of Steam Dryer Stress Intensity Factors and Crack Lengths due to Vibration

Why high-fidelity and why now …

- Advancement and demonstration of **high-fidelity simulations based** maintenance approaches and model based fault system detection techniques.
- Address mechanical and thermal fatigue failure modes which drive O&M activities of BWRX-300



Why high-fidelity and why now …

- Advancement and demonstration of **high-fidelity simulations based** maintenance approaches and model based fault system detection techniques.
- Address mechanical and thermal fatigue failure modes which drive O&M activities of BWRX-300, and are **extendable to all advanced reactors (ARs)** where a flowing fluid is present.

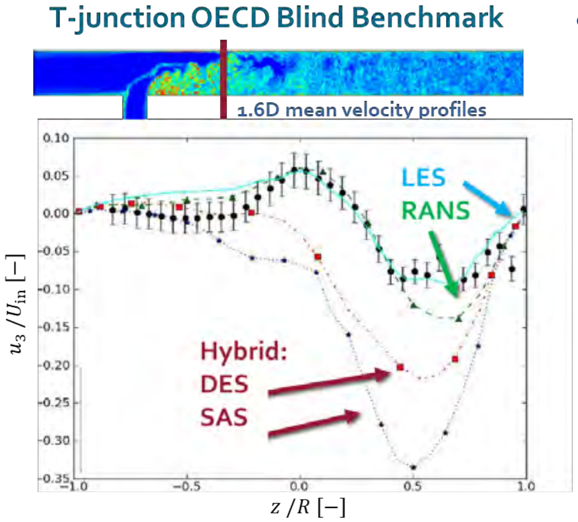
… why now …

- Computational Fluid Dynamics is an old tool, it has been leveraged by various industries for many years, and it has provided great support to design and safety of nuclear reactors as a complement to experimental and experience based approaches
- CFD has a much greater potential: " to provide high-fidelity data to support efficient operation" of NPPs… bootstrapping the lack of operational data
- The incomplete maturity of the simulation methods (and teams) and the excessive computational costs has hindered this last major jump.

- Leveraging the last 10 years of DOE and industry sponsored effort we are in position to demonstrate this jump

... why now ...

- Computational Fluid Dynamics is an old tool, it has been leveraged by various industries for many year, and it has provided great support to design and safety of nuclear reactors as a complement to experimental and experience based approaches
- But CFD has a much greater potential: " to provide high-fidelity data to support efficient operation" of NPPs… bootstrapping the lack of operational data
- The incomplete maturity of the simulation methods (and teams) and the excessive computational costs has hindered this last major jump.



- *T-junction blind international benchmark 2013 had good and bad news*
  - LES works very well, but its too slow to drive Operational DTs
  - Many acceleration ideas proposed for external aero, some successful, but not for Nuclear Applications

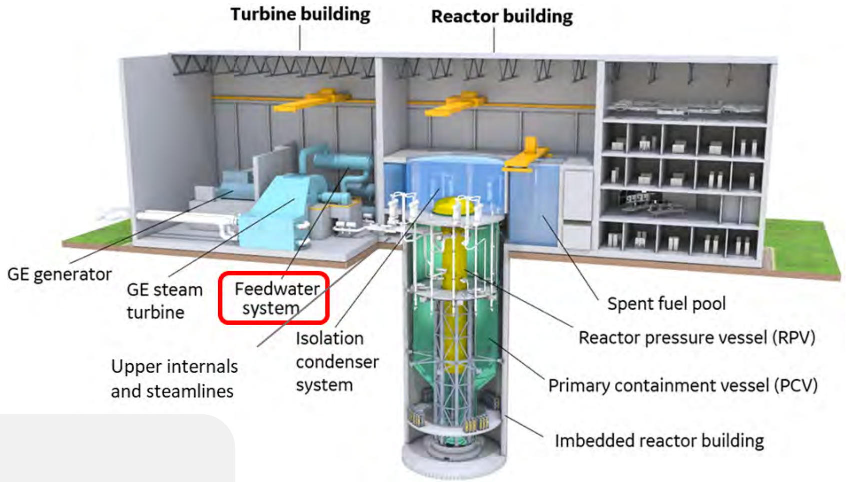
For Nuclear Applications we need robust reliability:

- *We are looking for local hybridization in presence of turbulent structures*
- *Independence from grid resolution*
- *Independence from time stepping and spatial interpolation methods*

- Leveraging the last 10 years of DOE and industry sponsored effort we are in position to deliver this capability

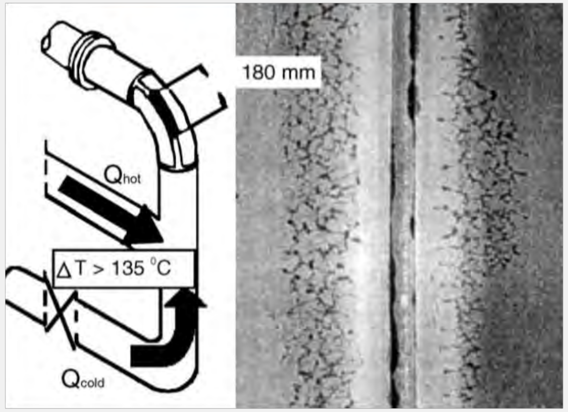
Thermal striping driven fatigue prediction

- Thermal striping fatigue has largest applicability to all AR concepts, beyond BWRX-300 – **FIRST OBJECTIVE**



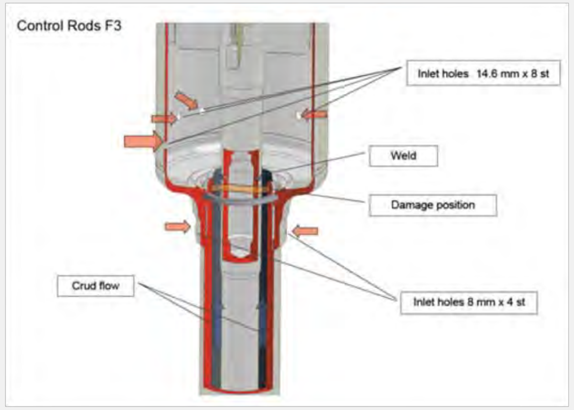
A few notorious examples

Civaux (PWR)



Civaux, EDF, crack in an elbow weld [K.-J. Metzner, U. Wilke /Nuclear Eng. and Design 235 (2005) 473–484 481]

Swedish BWRs CR Stems



Fatigue Inside Control Rod Guide Tubes [Eric Lillberg, ICONE21-16632]

Superfenix (LMFBR)

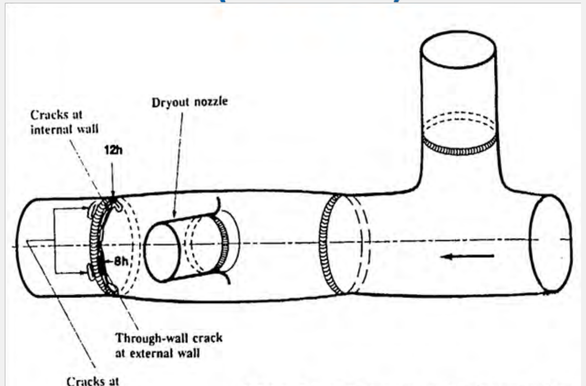
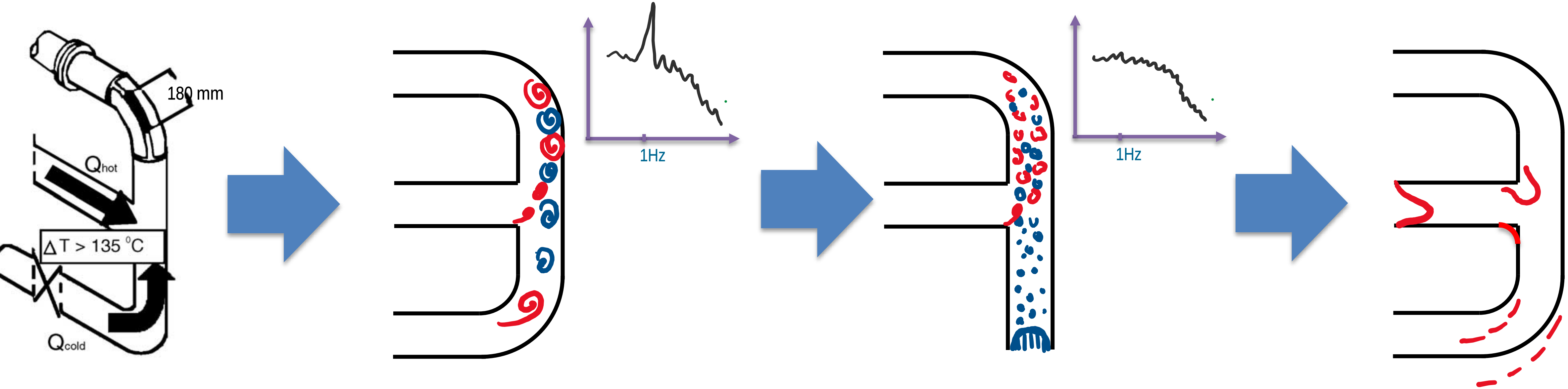


FIGURE 7 : cracks detected on the SPX tee-junction

Auxiliary pipe in secondary circuit [O. Gelineau, M. Sperandio/IAEA-IWGFR/90 (1994)]

The challenge in a (hand drawn) nutshell

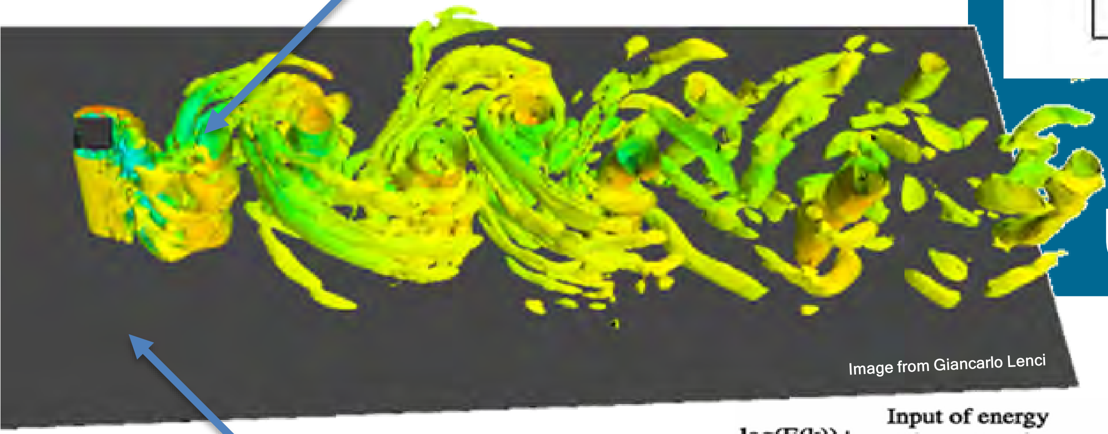
- We can leverage the Civaux failure for discussion

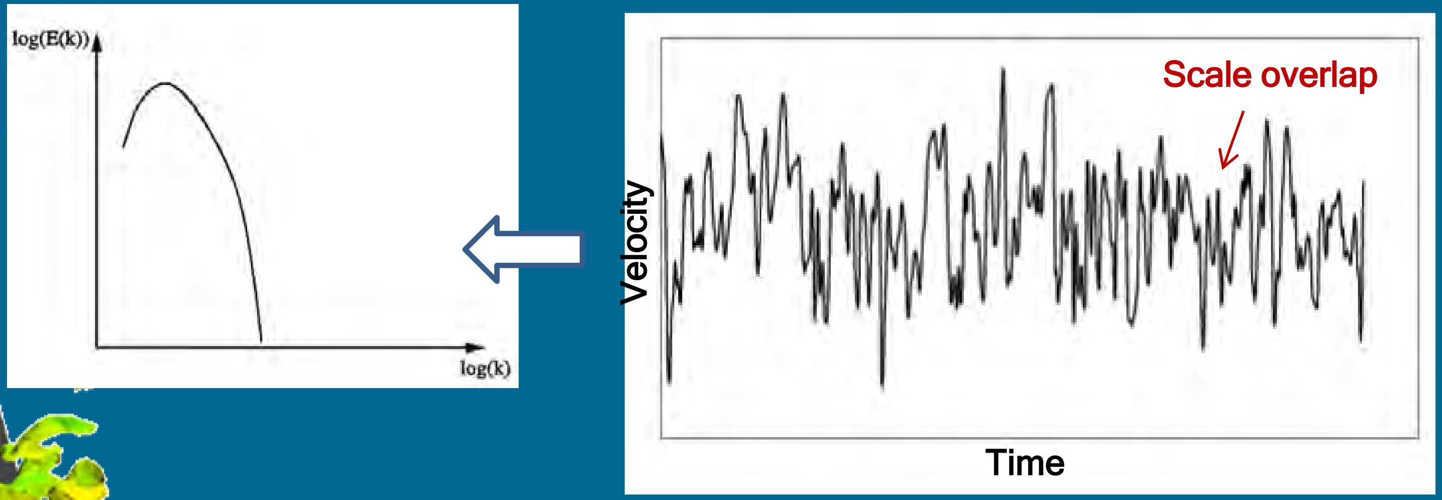


- The turbulent structures generated at the 90° elbow interact at the T and lead to low frequency (1-3 Hz) large temperature oscillation that lead to accelerated fatigue failure
- The same T connection without the elbow does not suffer of these oscillations (but small flow / geometry variations could lead to the opposite results)
- Phenomenon is driven by formation and interaction of large turbulent structures and is strongly non-linear, not prone to "lumping" and generalization

The STRUCT idea *(Lenci and Baglietto, 2016)*

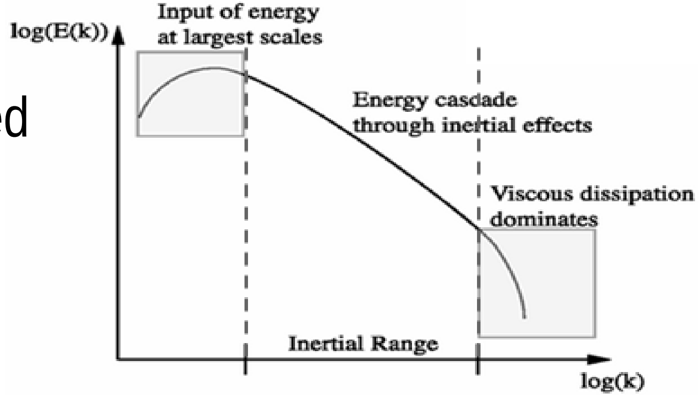
In regions with separation, jets, swirls, and strong mixing, flow deviates from equilibrium

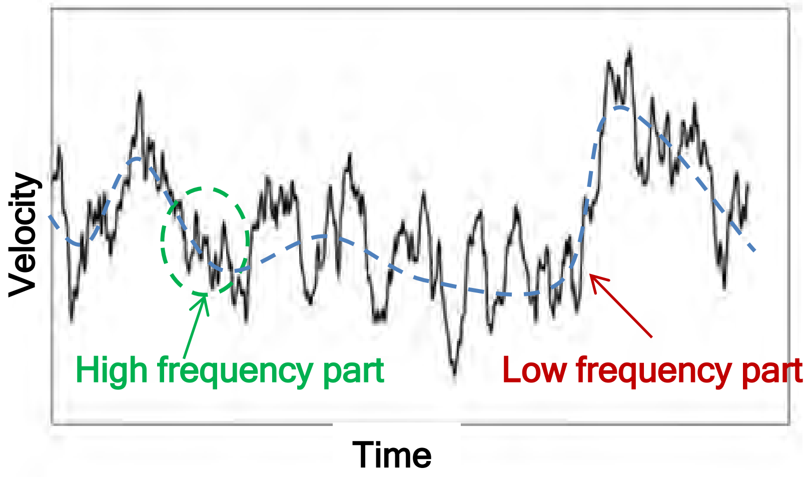




URANS is not applicable to scale overlap

(U)RANS models are based on the assumption of an "equilibrium spectrum"

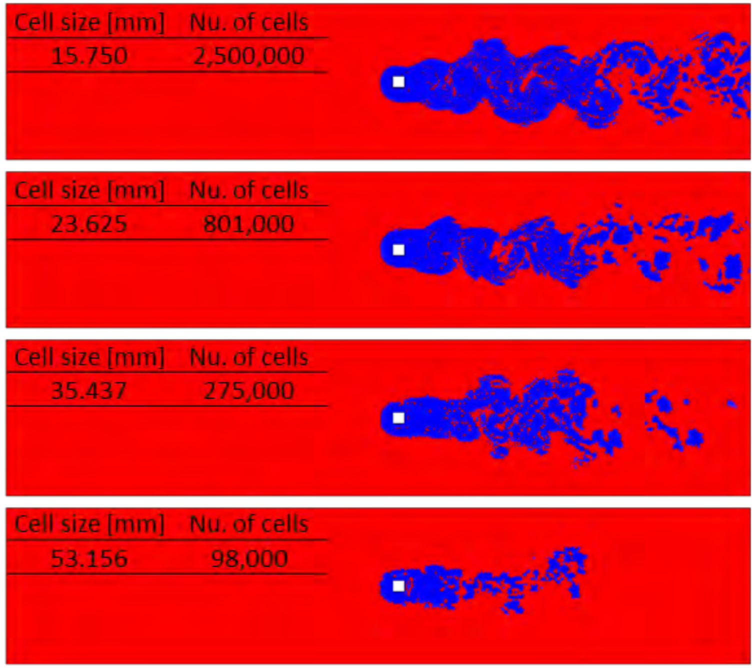


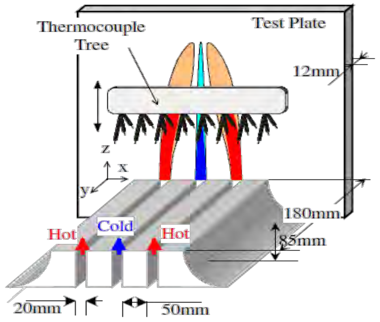


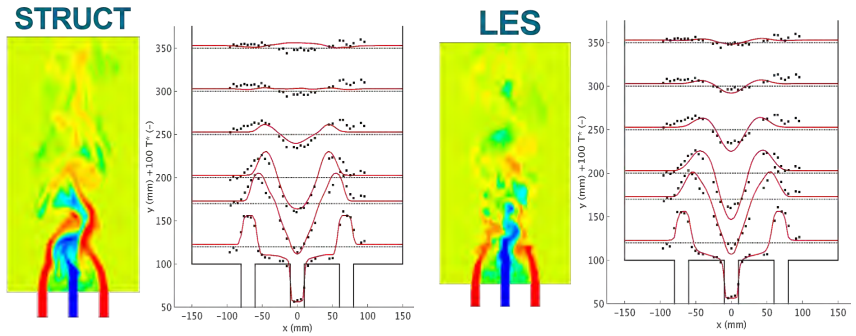
http://ffden-2.phys.uaf.edu/647fall2013_web.dir/j_stroh/tec.html

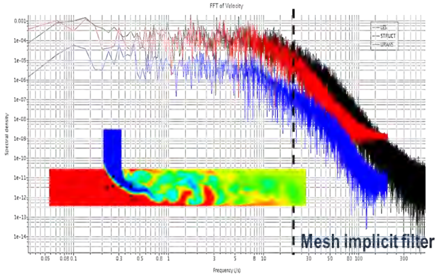
The STRUCT idea *(Lenci and Baglietto, 2016)*

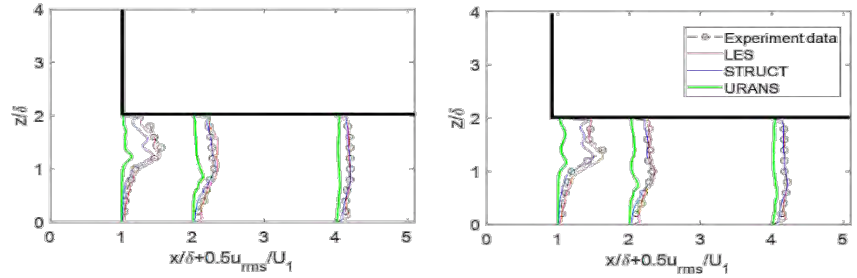
- STRUCT has demonstrated consistent grid convergence and accelerations between 50-100x on a number of validations
- Thanks to DOE and Industrial sponsorship

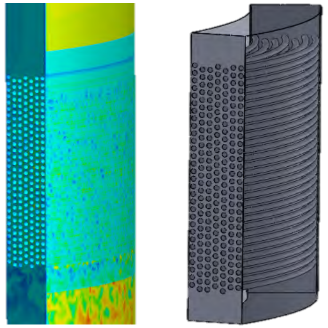


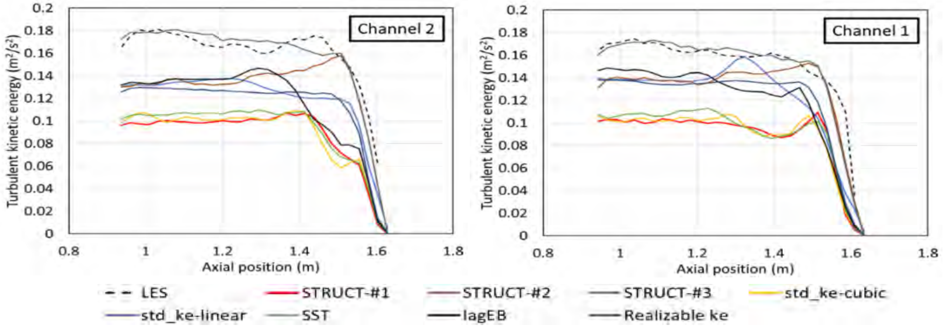












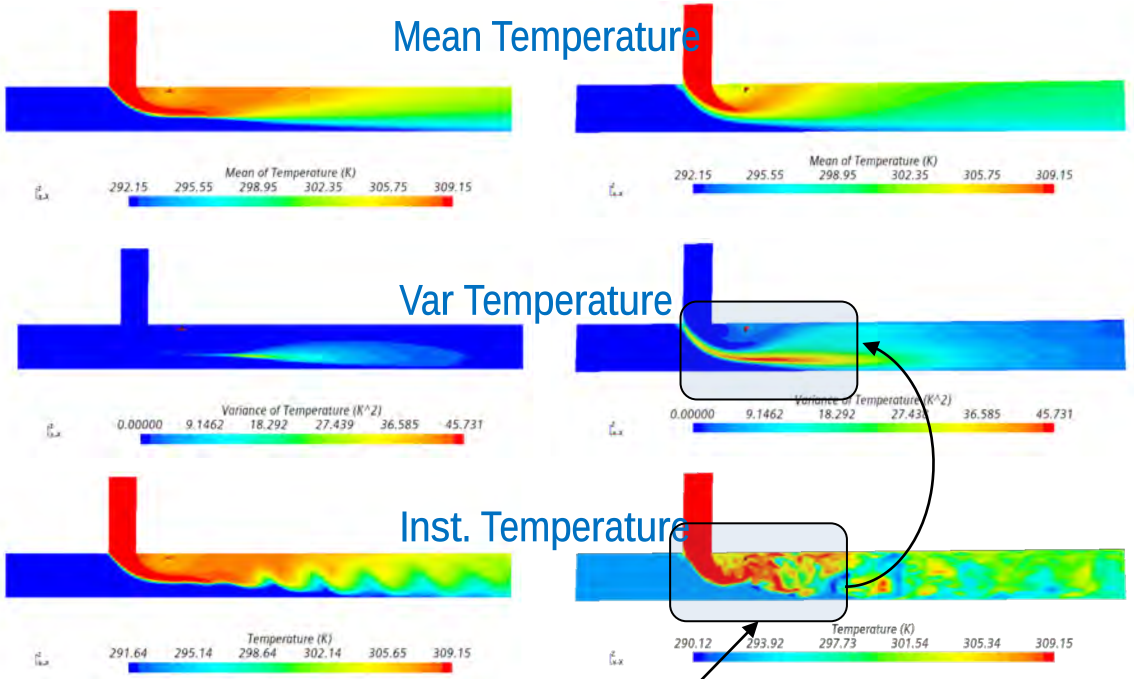
Supported by:

TerraPower MITSUBISHI HEAVY INDUSTRIES, LTD. framatome NEAMS NUCLEAR ENERGY ADVANCED MODELING & SIMULATION PROGRAM MISTI

Recap: coherent flow structures drive T variation

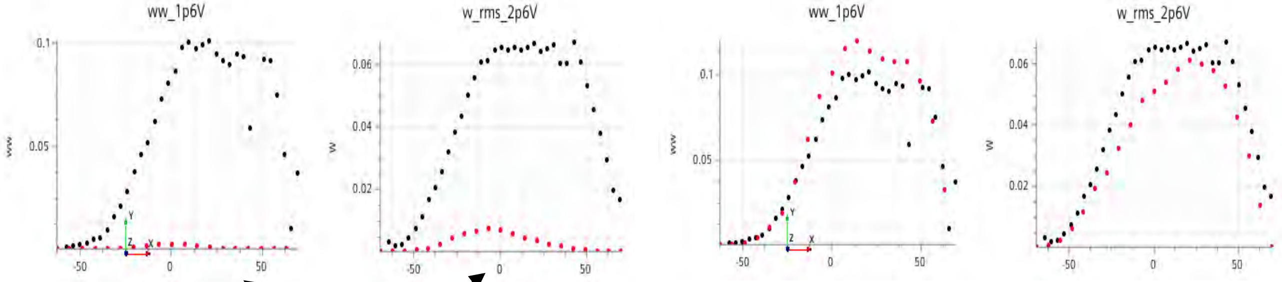
- Maturity of models and application experience, at reduced computational cost

URANS (Cubic k-ε) STRUCT-ε



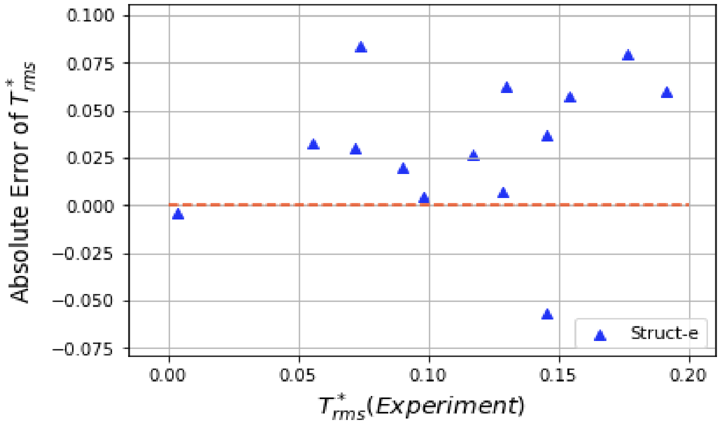
Resolved Coherent Temperature Structures

URANS (Cubic k-ε) STRUCT-ε



URANS Cannot predict Velocity and Temperature Fluctuations responsible for fatigue

STRUCT predicts both velocity and Temperature fluctuations with high accuracy



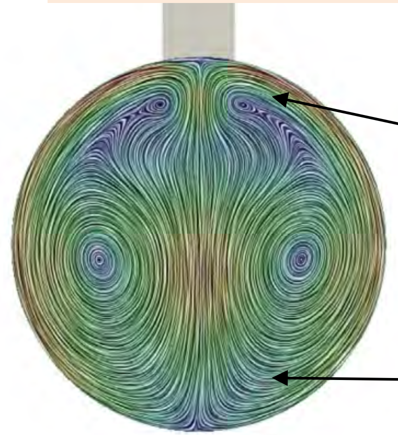
Errors on T_{rms} order of 1%

Application on feedwater system recap

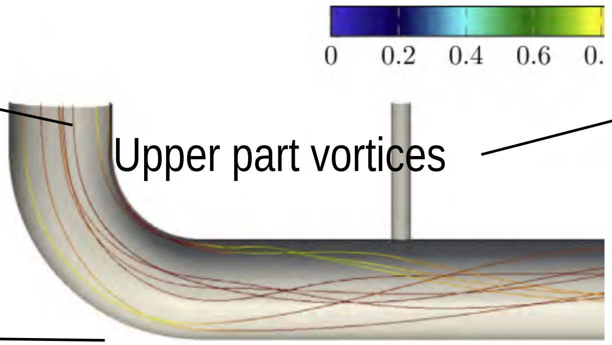
Manchester LES

STRUCT

Velocity Vector

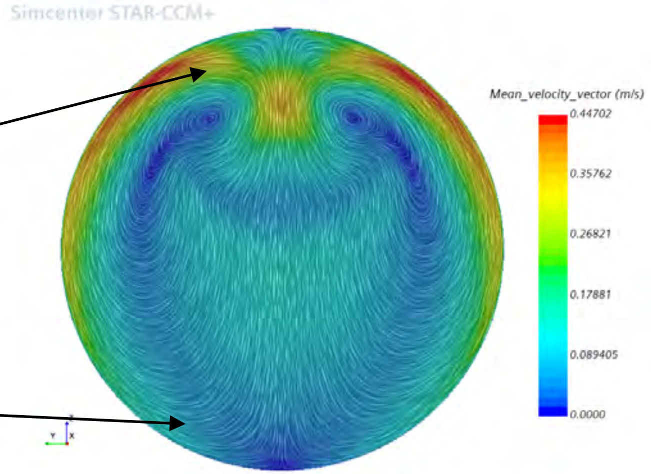


(a) $7D_b$ upstream



Upper part vortices

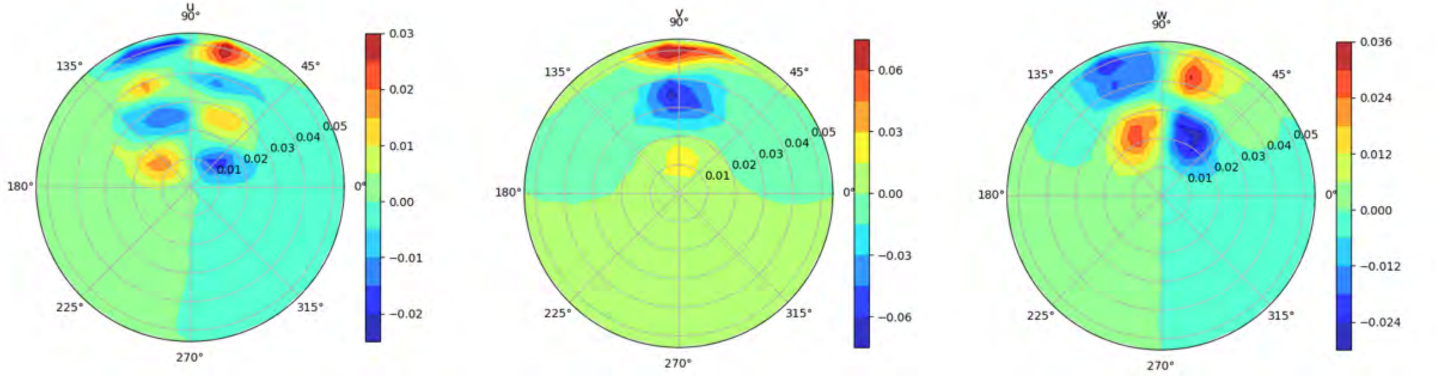
Lower part vortices



A method for flow feature extraction

POD Mode 1

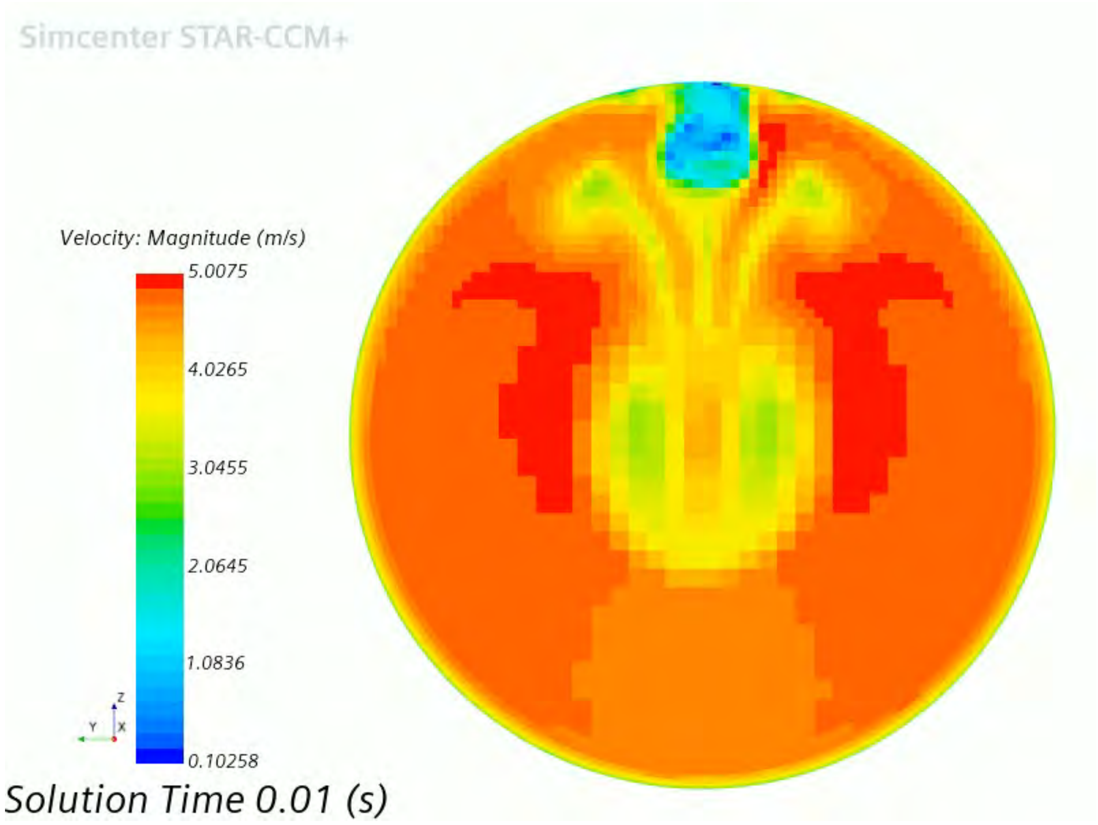
(a) $7D_b$ upstream



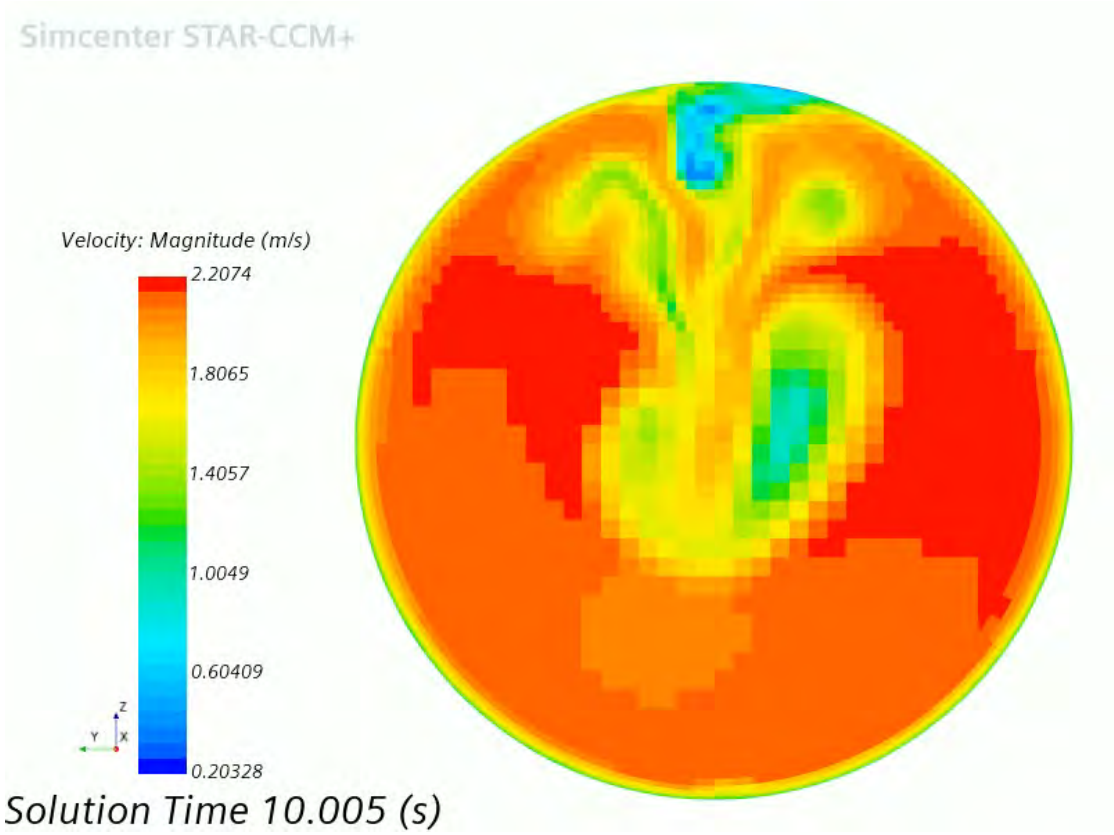
– The STRUCT model accurately captures the swirl switching features

Swirl-Switching example
Fluid (~3.5 inch downstream)

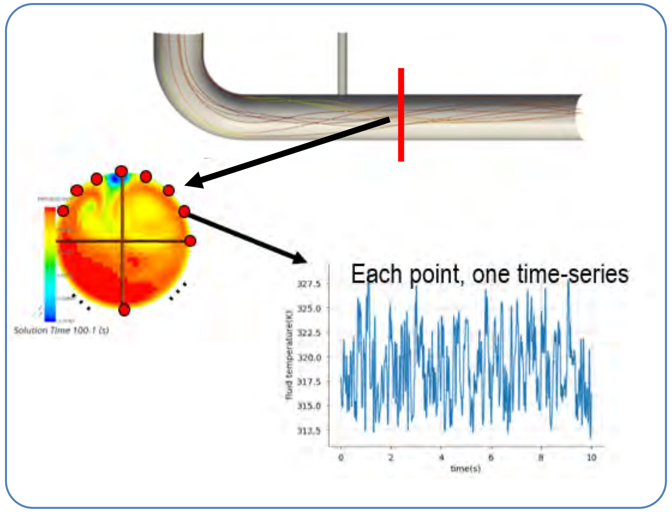
- 100%



- 50%



High-fidelity simulation based DT generation

Inputs → Model → Temperature & Stress → 

→ Damage or Fatigue lifetime

The model outputs will look like this:

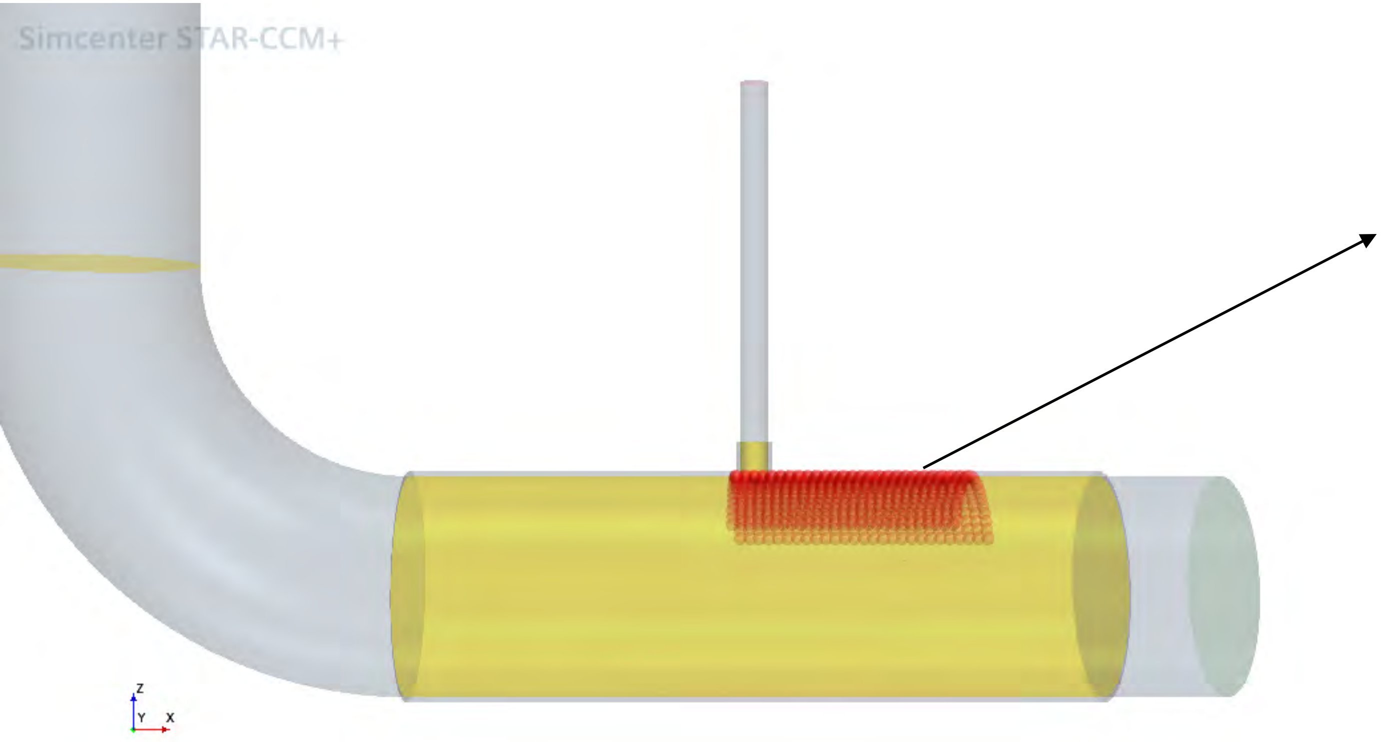
Labels (BC) | Point 1's stress time-series | Point 2's stress time-series | Point n's stress time-series

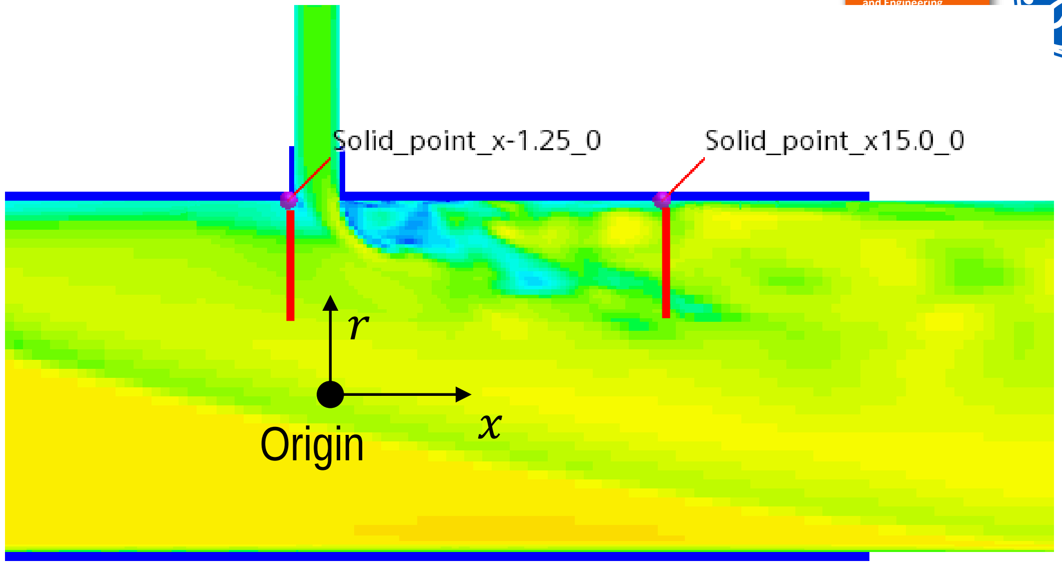
1st operation conditions →
2nd operation conditions →
⋮

$$\begin{bmatrix} \dot{m}_{C1}\ \dot{m}_{H1}\ T_{C1}\ T_{H1} & S_{1,p1}(t_1)\dots S_{1,p1}(t_n) & S_{1,p2}(t_1)\dots S_{1,p2}(t_n) & & S_{1,pn}(t_1)\dots S_{1,pn}(t_n) \\ \dot{m}_{C2}\ \dot{m}_{H2}\ T_{C2}\ T_{H2} & S_{2,p1}(t_1)\dots S_{2,p1}(t_n) & S_{2,p2}(t_1)\dots S_{2,p2}(t_n) & \cdots & S_{2,pn}(t_1)\dots S_{2,pn}(t_n) \\ \vdots\ \ \vdots\ \ \vdots\ \ \vdots & \vdots & \vdots & & \vdots \end{bmatrix}$$

- The high-fidelity data provide a uniquely rich database for DT generation
- Capability of including sensitivity to many parameter variations

High fidelity Data Collection

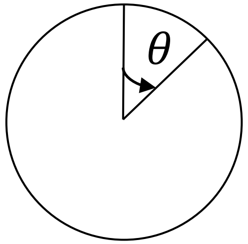




Probes:

$\boldsymbol{x = -1.25\ in \sim 15\ in}$

$\boldsymbol{\theta = -60 \sim 60\ \mathrm{deg}}$

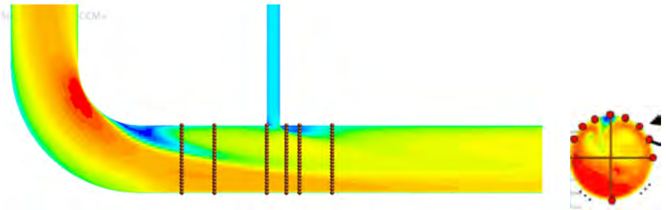


	Spec.	O.D.	Wall thickness	I.D
Main	316L 40S	16"	0.375"	15.25"
Branch	316L 80S	2 ½"	0.276"	1.948"

- 675 points at the inner wall ($r = 7.625\ in$)
- 675 points at the outer wall ($r = 8\ in$)

Digital Twin Prototype

Feedwater subsystem



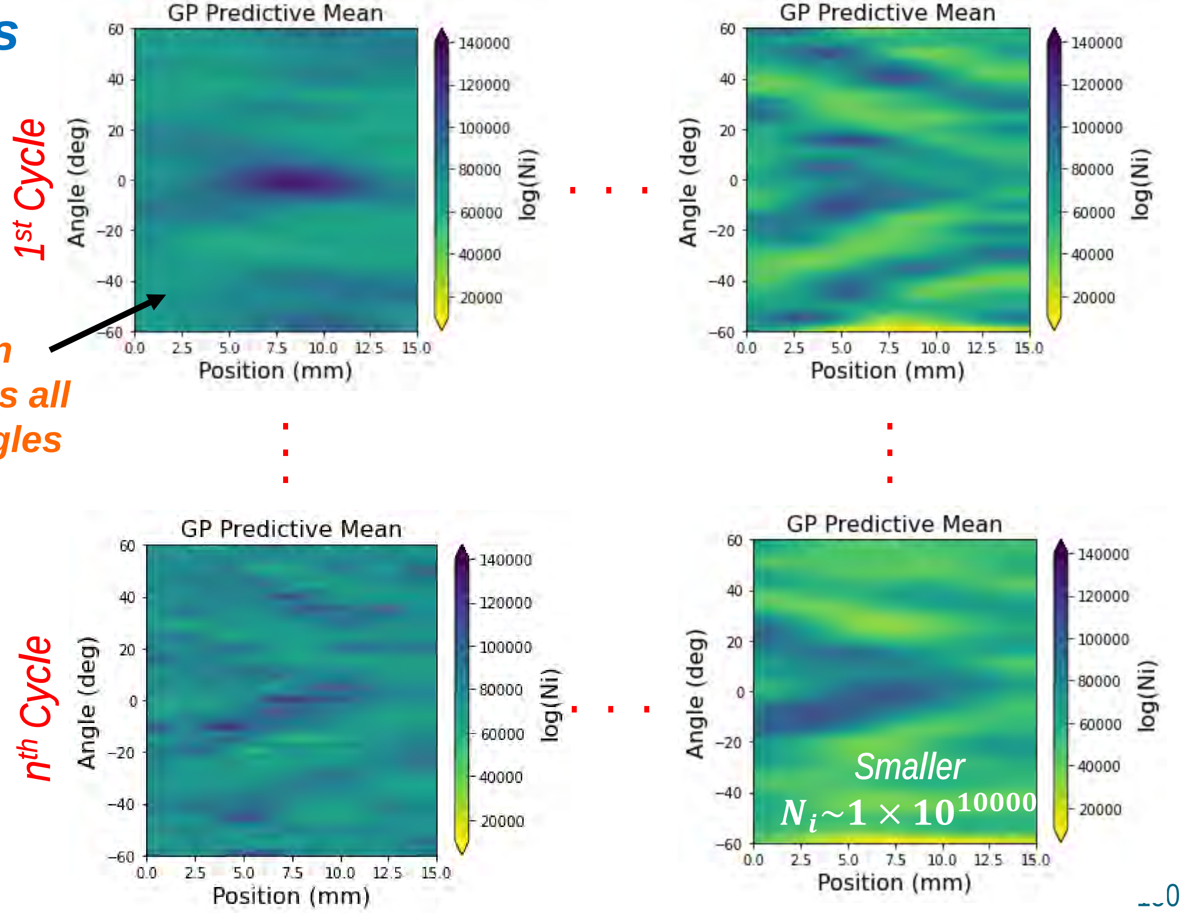
Analysis of number of cycles to damage initiation (N_i) using simulated data at each power level:

1. *Selection of power level (user input)*
2. *Running Rainflow Counting on the available simulated stress histories*
3. *Calculating N_i values*
4. *Modeling N_i across all angles and positions in the data for each cycle using Gaussian Process models*

Uncertainty Quantification in Crack Initiation

Power Level →

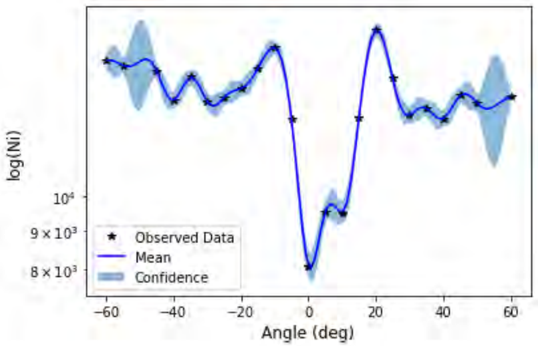
Cycles ↓



Crack initiation Predictions across all positions and angles

Rainflow Counting Algorithm

Uncertainty Quantification in crack initiation



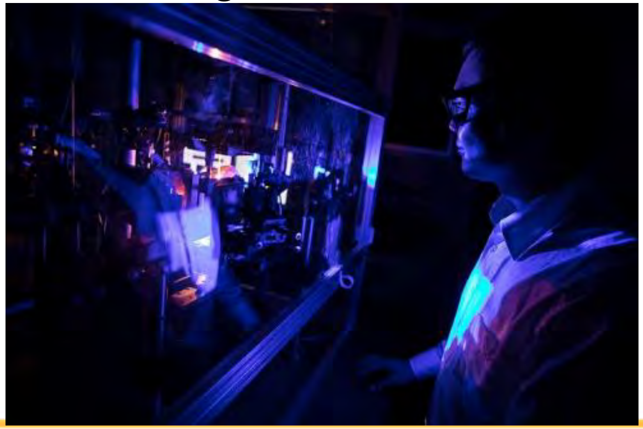
Molten salt-loop development acceleration with distributed single-crystal harsh-environment optical fiber-sensors

Presented by: Michael Buric, Staff Scientist NETL

2019-2022 ARPA-e TINA, 2021 update

Crystal fiber distributed sensing Project Objectives

- Introducing fully-distributed sensing to Molten-Salt Reactors
- Growing new cladded single-crystal optical fibers for molten-salt environments
- Gathering thousands of data-points to map reactor coolant-path temperatures or other parameters
- Mapping in-core temperature distributions
- Next-gen sensing replaces single-point sensors like thermocouples
- Providing data to guide reactor design and improvement through thermal efficiency
- Support LFMSR Licensing Basis



Crystal fiber distributed sensing

- National Energy Technology Lab (fiber growth, sensor design, interrogator design)
  - Michael Buric (PI, fiber optics and systems)
  - Guensik Lim (LHPG)
  - Juddha Thapa (LHPG, materials)
  - Jeff Wuenschell (DTS, testing)
- Idaho National Lab (reactor expertise, system implementation and testing)
  - Pattrick Calderoni
    (in-pile instrumentation director, co-PI)
  - Joshua Daw (nuclear instrumentation)
  - Ruchi Gakhar (nuclear materials)
- MIT (material compatibility, efficacy simulations)
  - David Carpenter (Irradiation Engineering Director)
  - Koroush Shirvan (reactor design and simulation, co-PI)
  - Tony Zheng, Yeongshin Jeong

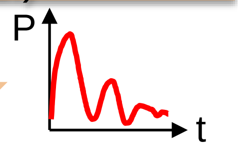
GOAL: MSR Thermal Response Analysis for sensor specification and placement

- Providing information on the transient responses under possible transients of molten salt reactor for monitoring system with fiber optic sensor

Neutronics
(SERPENT)

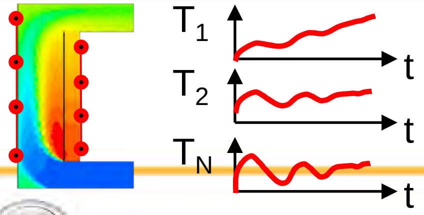
- ✓ Generation of neutronics parameters
- ✓ 0-D/3-D, Steady state
  - ➢ Neutronics: static fuel at constant temperature

Coupled neutronics/T-H
(Simplified MSR Kinetics Model)



- ✓ Transient response of state variables (power, salt and structure temperature, reactivity, etc.)
- ✓ Lumped model, transient
  - ➢ Neutronics: effects of precursor transport due to flow
    T/H: energy balance only, constant flow rate

Thermal-Hydraulics
(Star-CCM+)

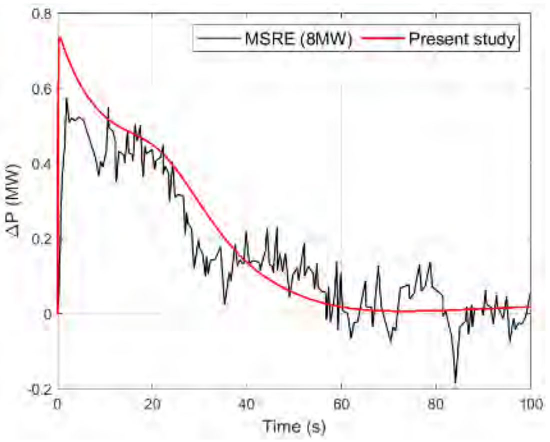


- ✓ Thermal response of MSR in time and space
- ✓ 2-D (or 3-D), transient
  - ➢ Neutronics: power changes imported from simulator
  - ➢ T/H: momentum/energy balance incl. convective and radiative heat transfer of salt

Simple System Transient Model Completed

Validation

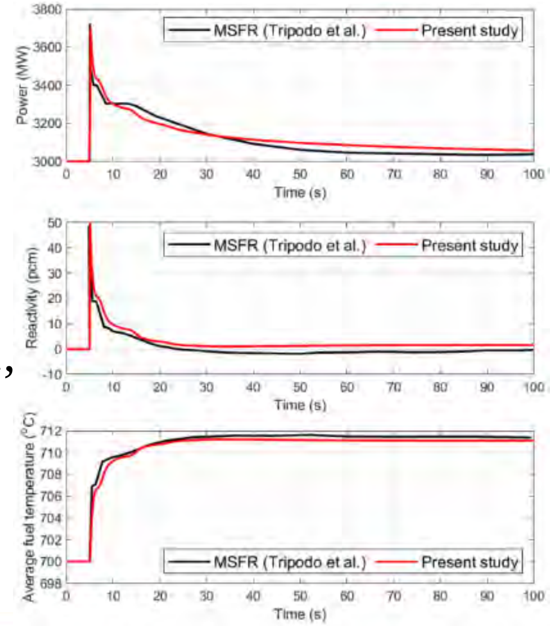
ORNL MSRE Data



Verification

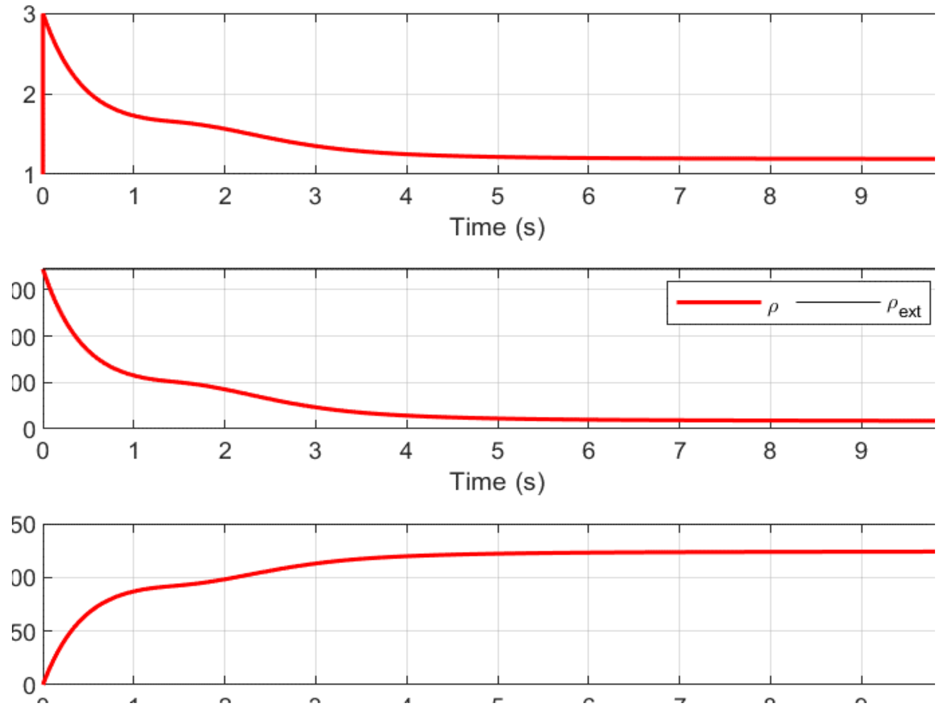
European MSR Simulator

C. TRIPODO et al., "*EPJ Nuclear. Sci. Technol.*, **5**, 13 (2019).



MCFR Application
(Based on Available Literature on TerraPower MCFR Design)

Step reactivity insertion (+2β)

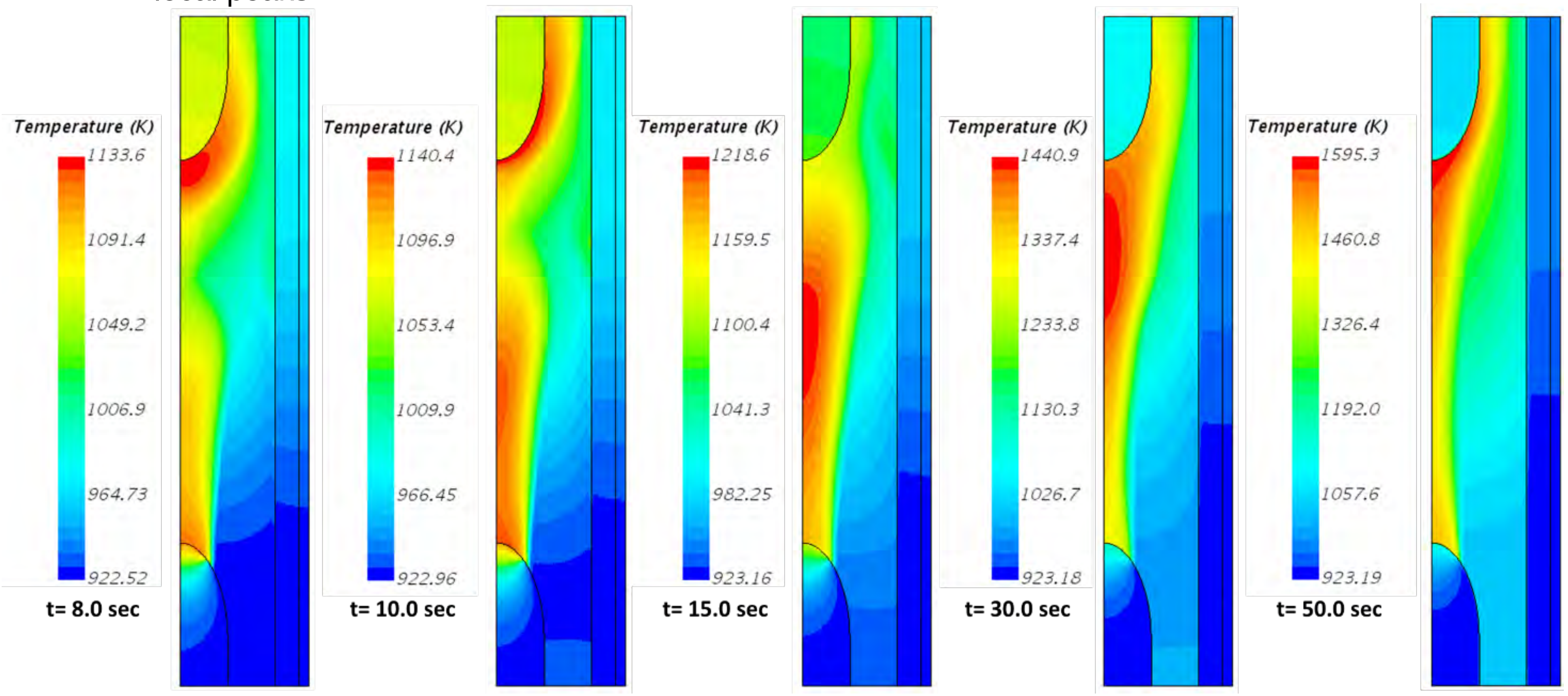


Δρ=+2β

Transient response of power, reactivity, and fuel salt temperature changes (1)

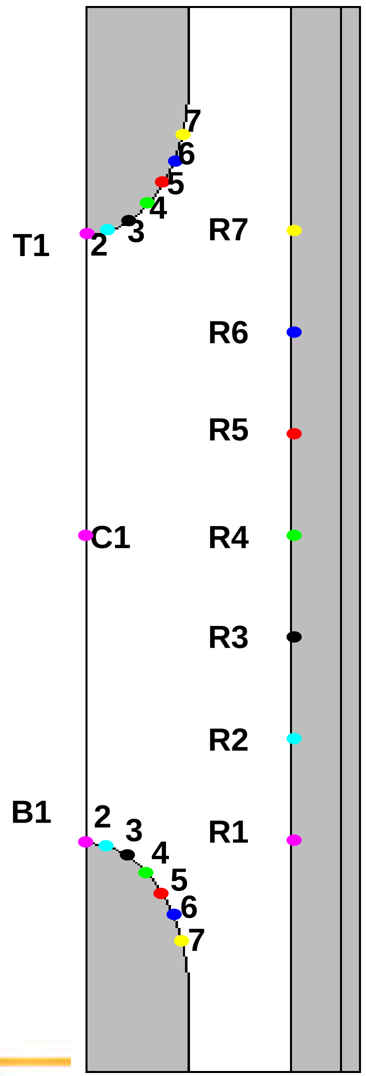
3D Accident Analysis Completed

- Demonstrates the Techno-Economic Value of Continuous Temperature Monitoring
  - ✓ Temperature distribution in the salt, reflector and vessel walls experience meaningful gradients and local peaks

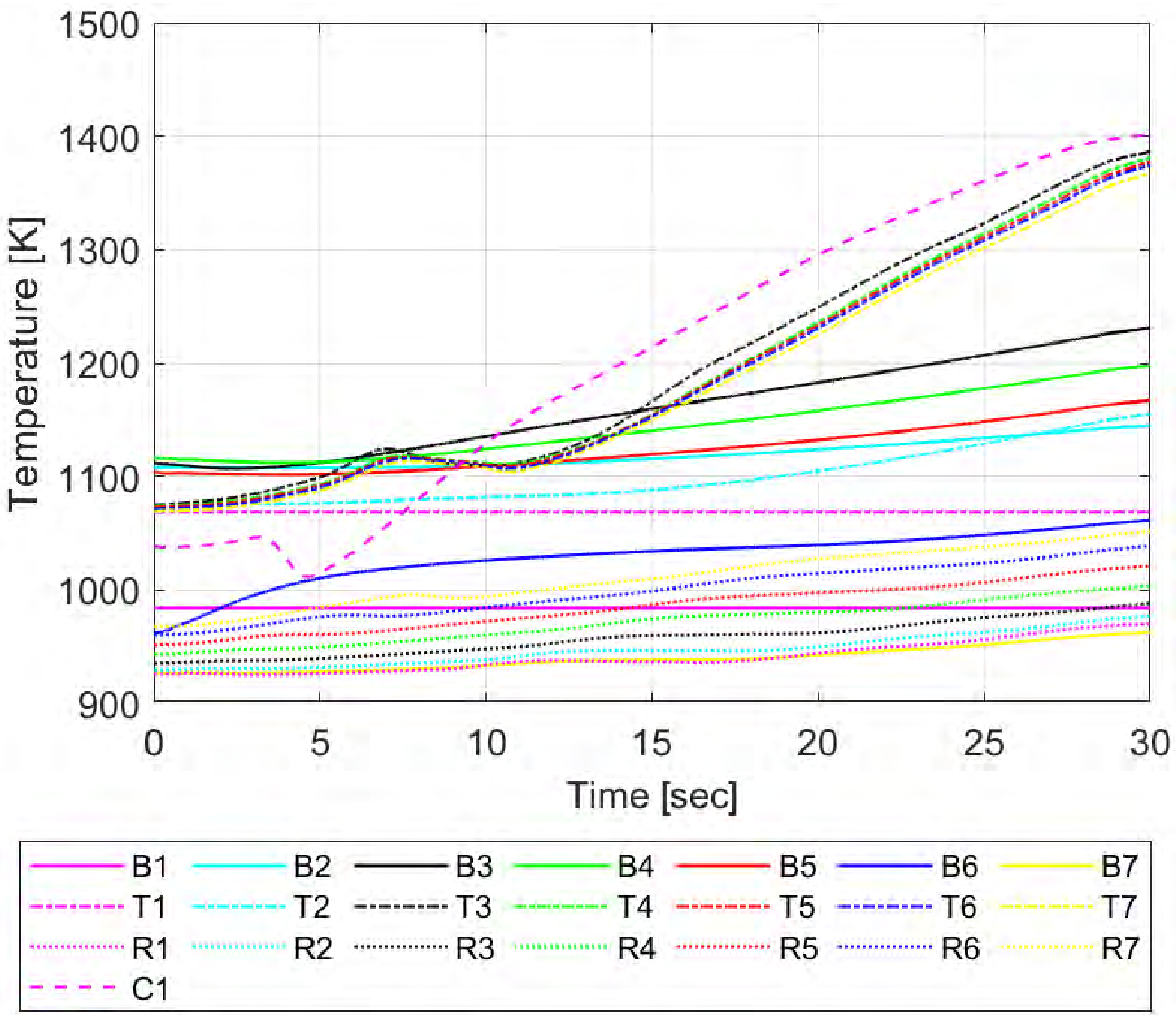


Unprotected LOF (Decrease of fuel salt flow rate to 80 % exponentially with time constant of 5 sec)

3D Accident Analysis



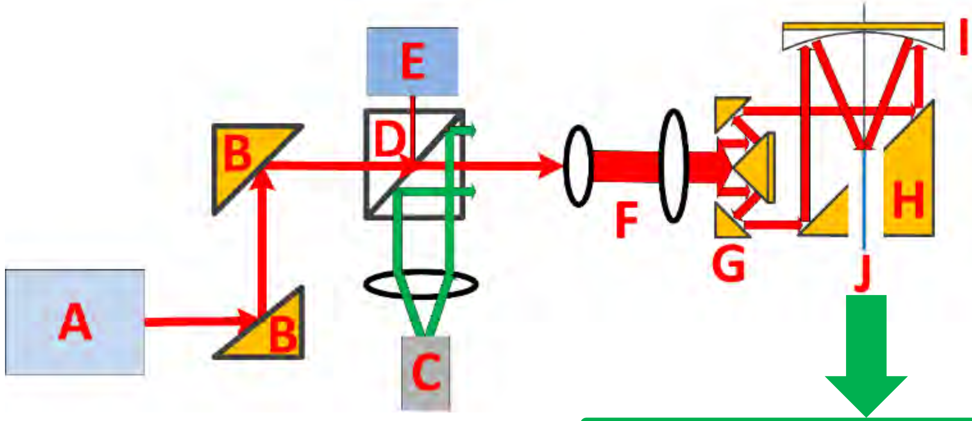
Unprotected LOF

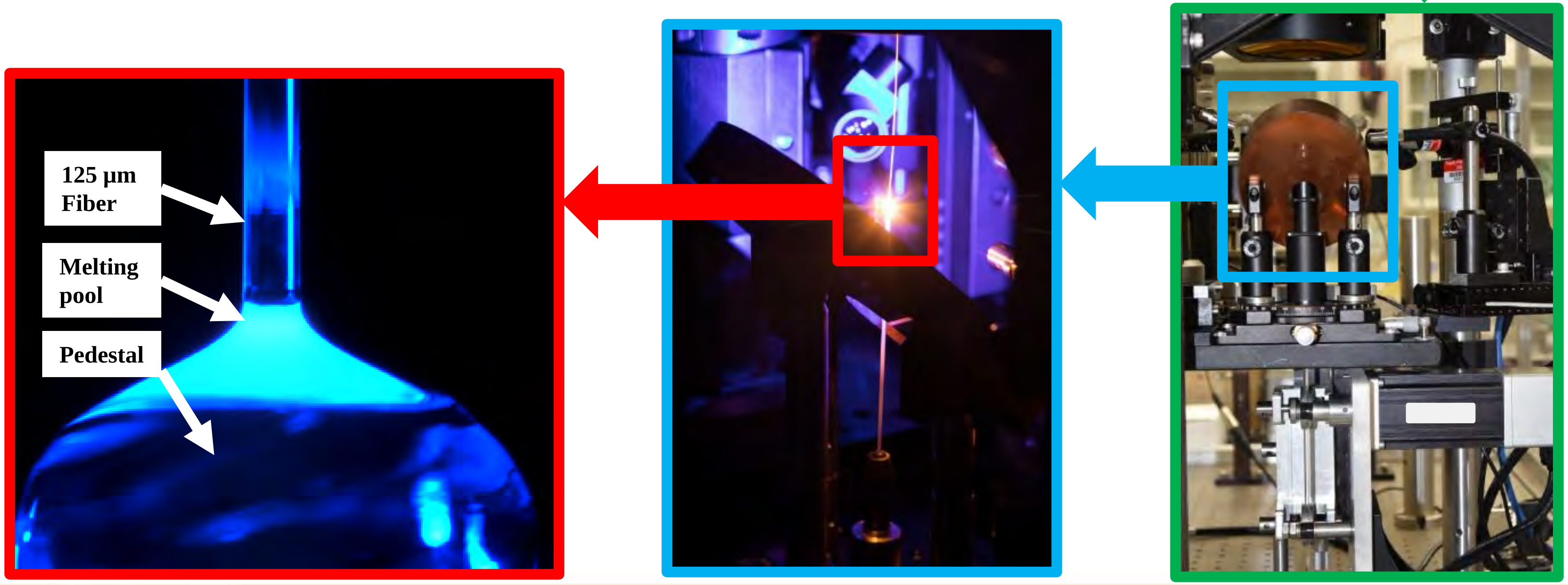


Crystal fiber distributed sensing - LHPG

How LHPG works:

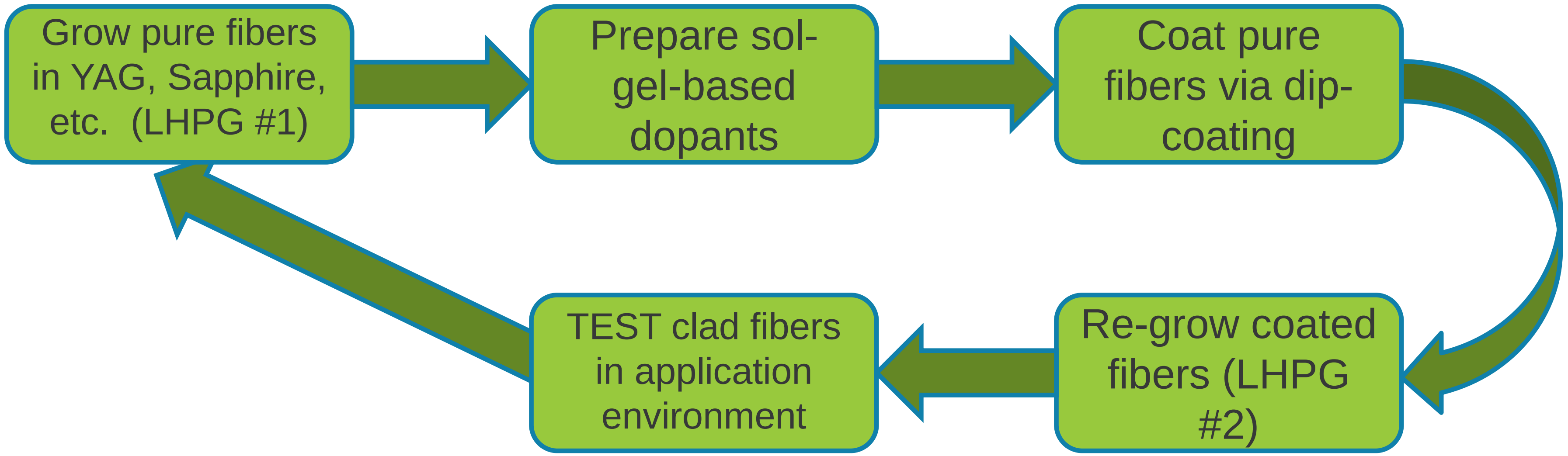
- CO2 laser melts oxide feedstock
- Seed crystal lowered into melt
- Controlled motion of seed and feedstock upward
- Fiber is grown from the melt



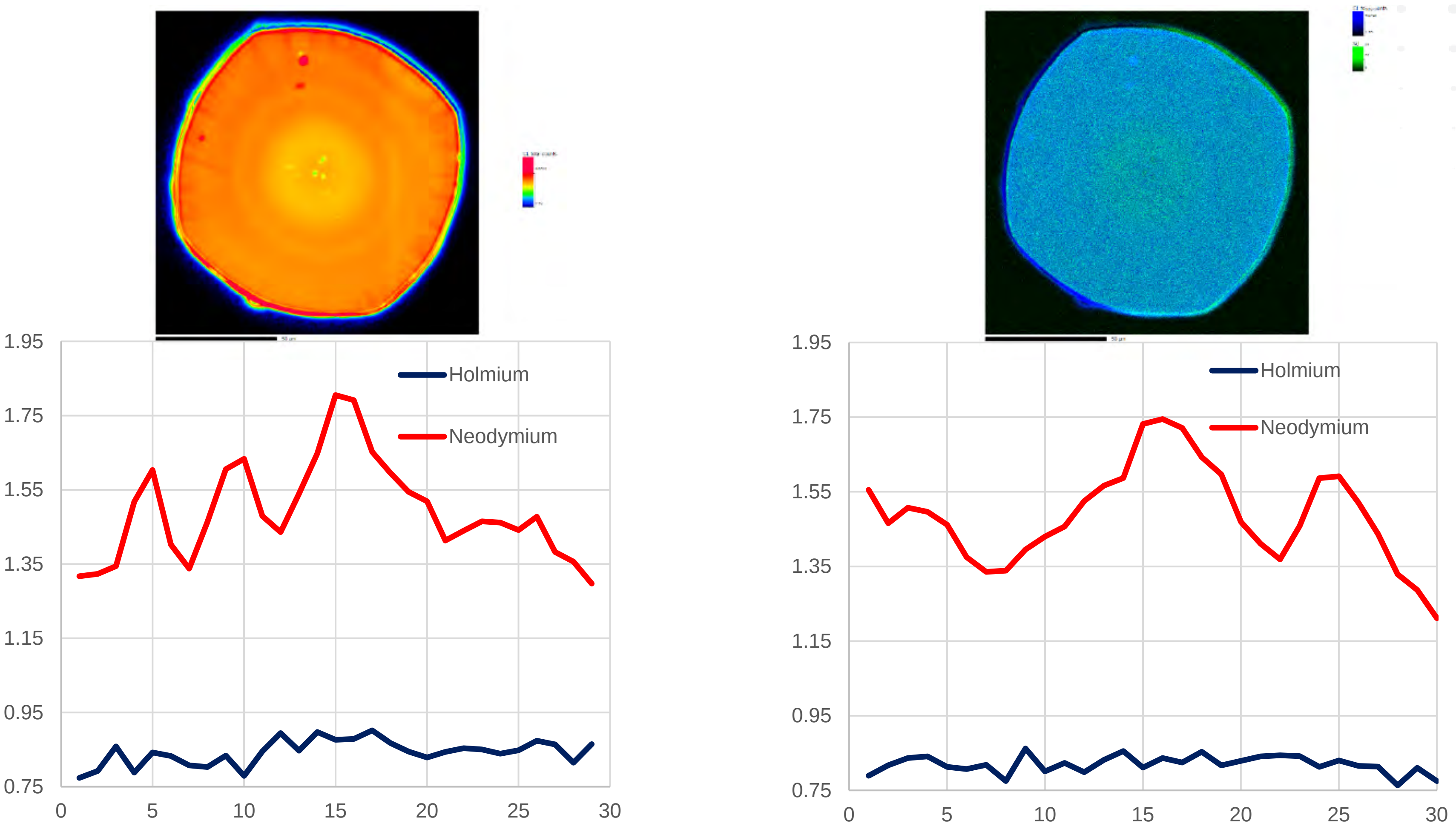


Crystal fiber distributed sensing

- Grow cladded fibers with 2-stage LHPG
  - Sapphire or YAG
  - Sol-gel (or other) dopant additions
- Evaluate materials compatibility in fluoride and chloride salts (bench tests)
- Evaluate radiation durability (gamma source, research reactor)



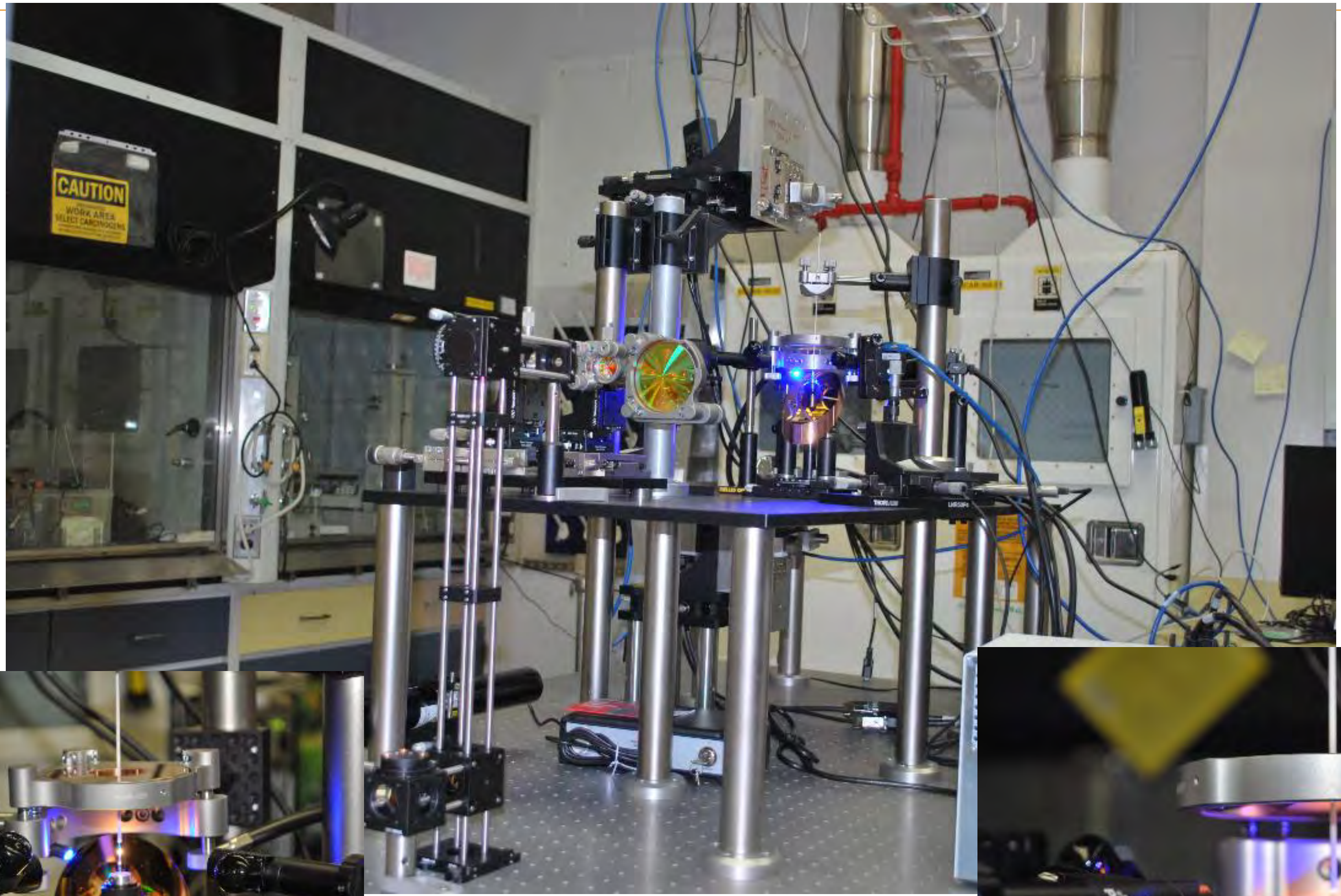
Crystal fiber distributed sensing - Claddings

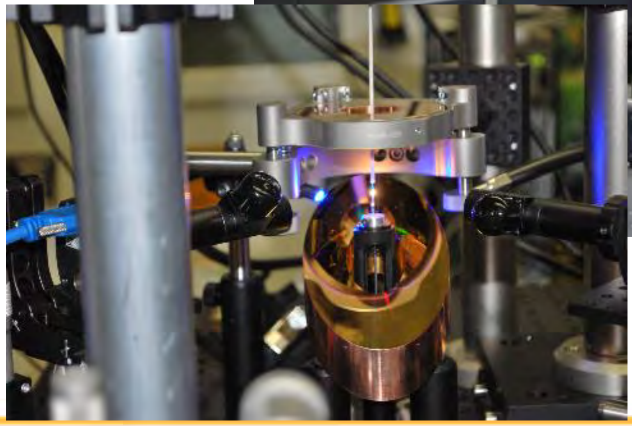


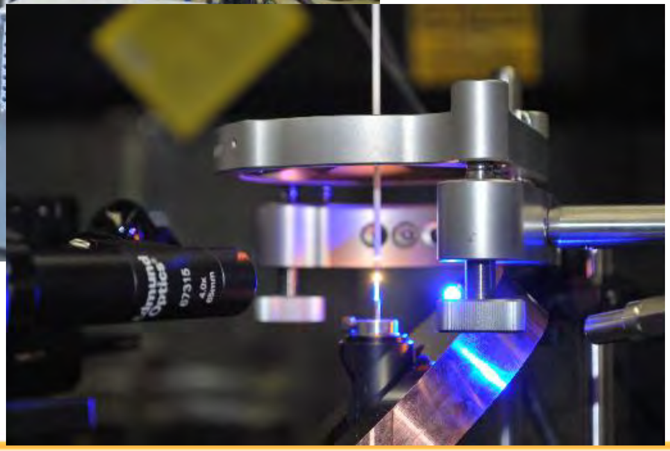
Automatic Dopant Segregation through LHPG: Top left: Visible light guiding in GRIN YAG fiber, Top right: EMPA map of Nd concentration in a GRIN YAG fiber, Bottom plots: Co-doped Nd and Ho: YAG fiber dopant concentrations in X (left) and Y (right)

arpa·e
CHANGING WHAT'S POSSIBLE

Regrowth LHPG System



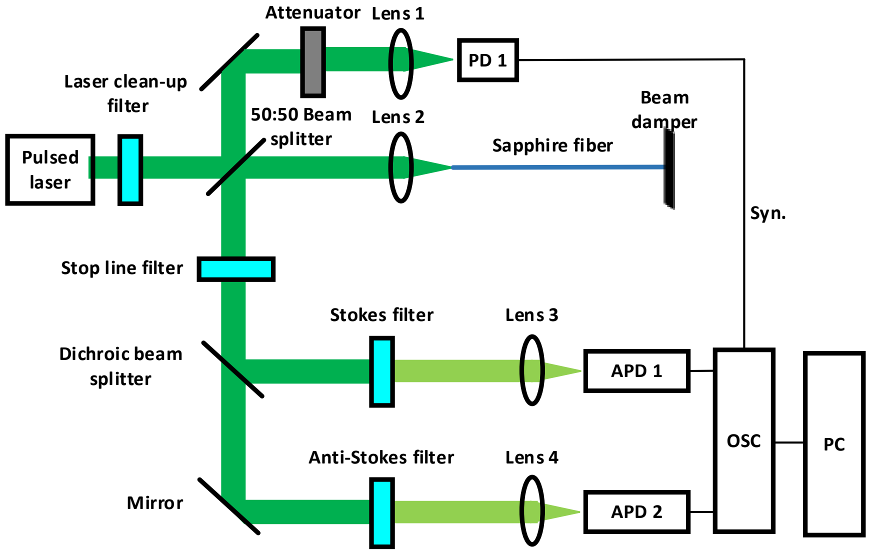




Distributed Sensing – Raman OTDR

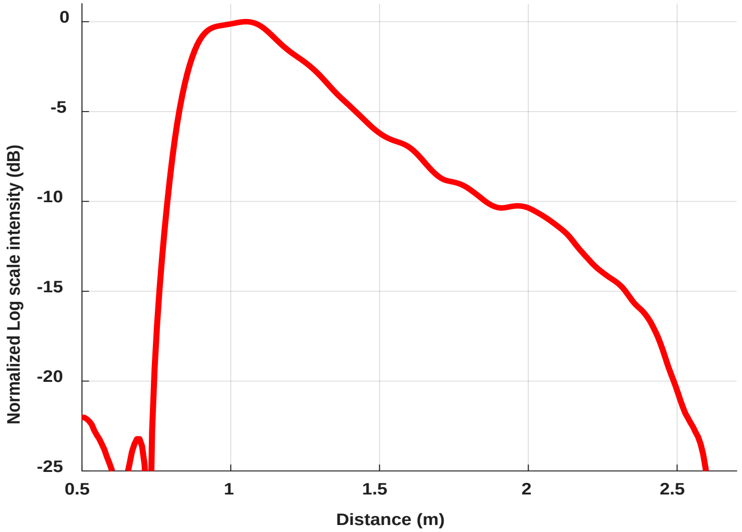
- OTDR with Single Crystal fiber
- Useful for high-rad/ high-T
- ~5cm, ~1C resolution

Raman OTDR, Liu et al Opt. Lett., 2016

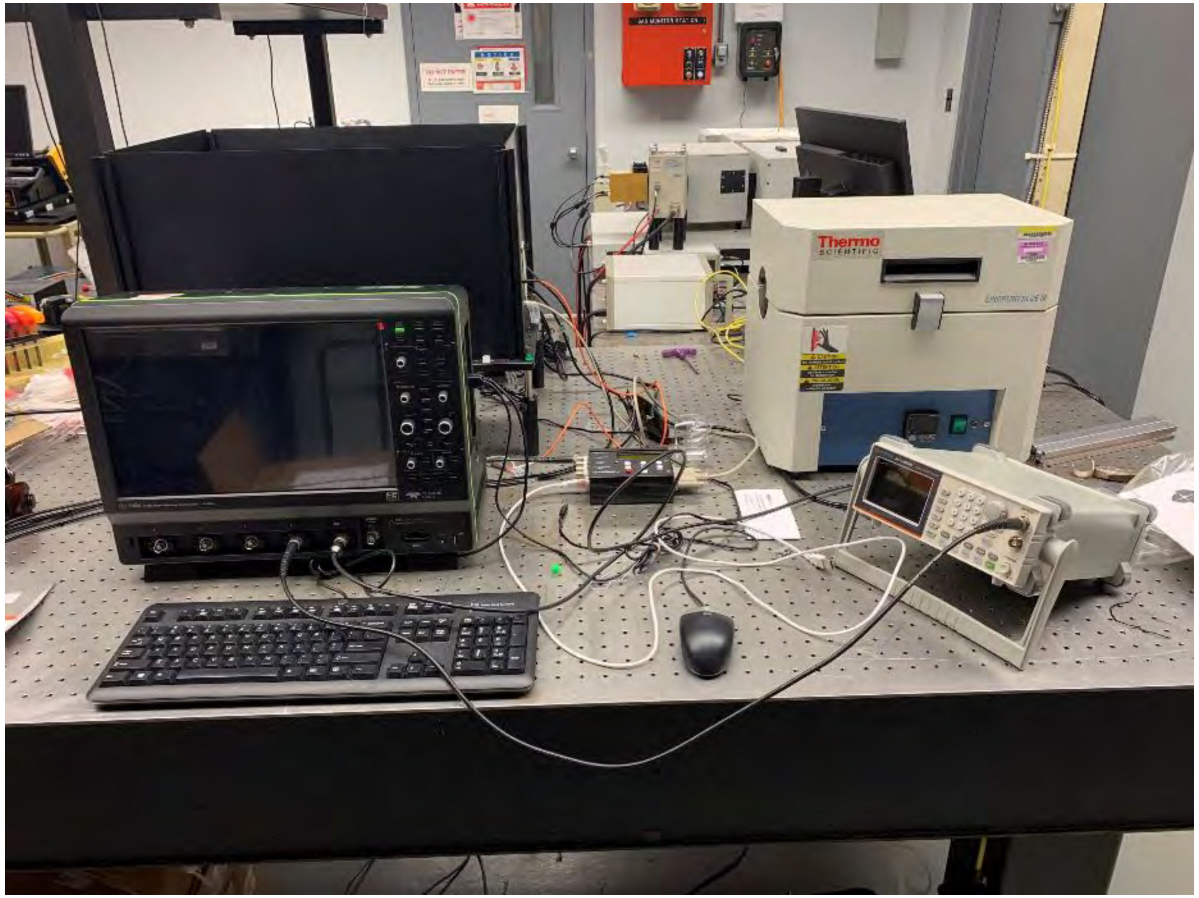


Sapphire fiber attenuation at 532nm, measured by a Raman OTDR system

Virginia Tech 1872



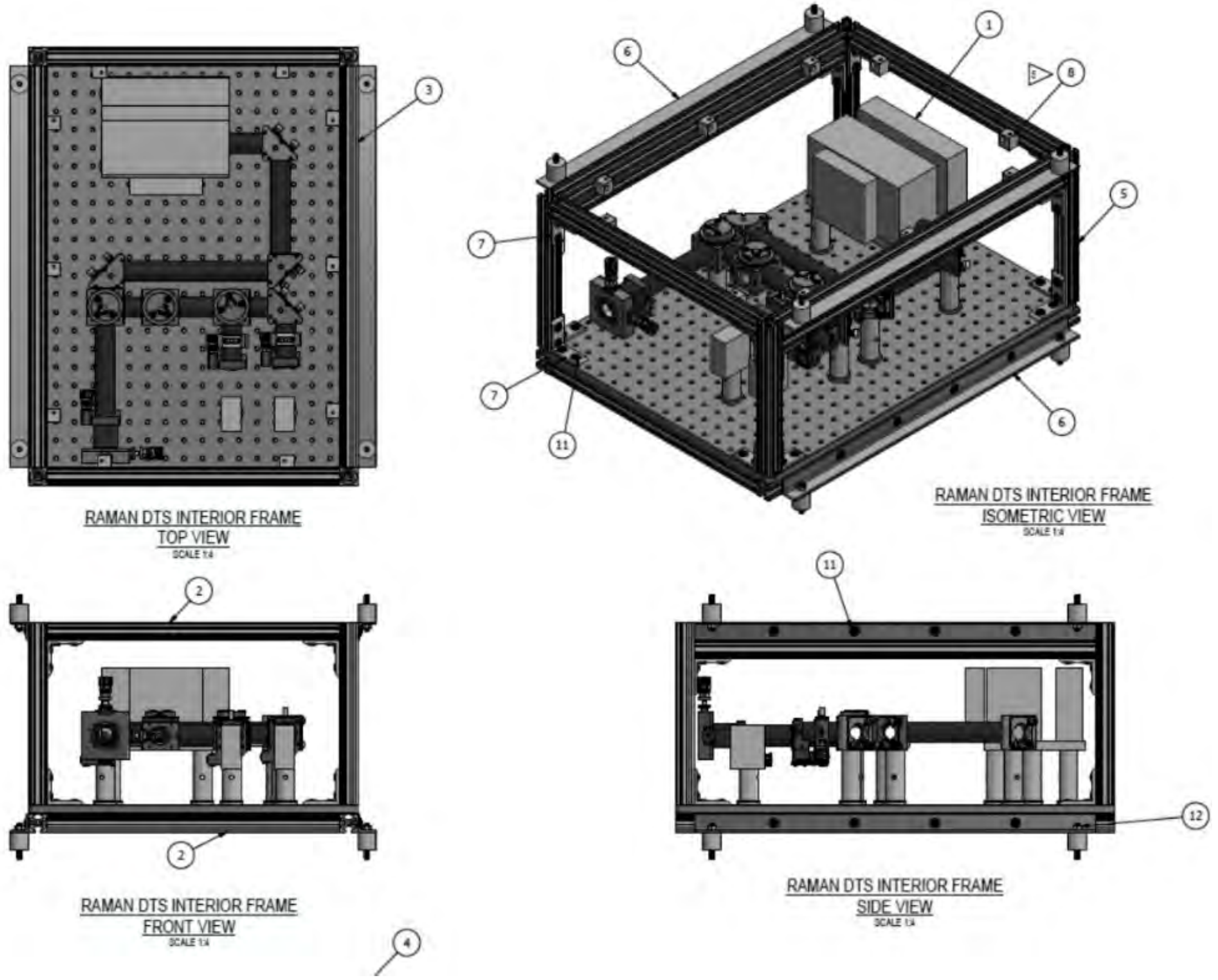
Raman DTS design and operations



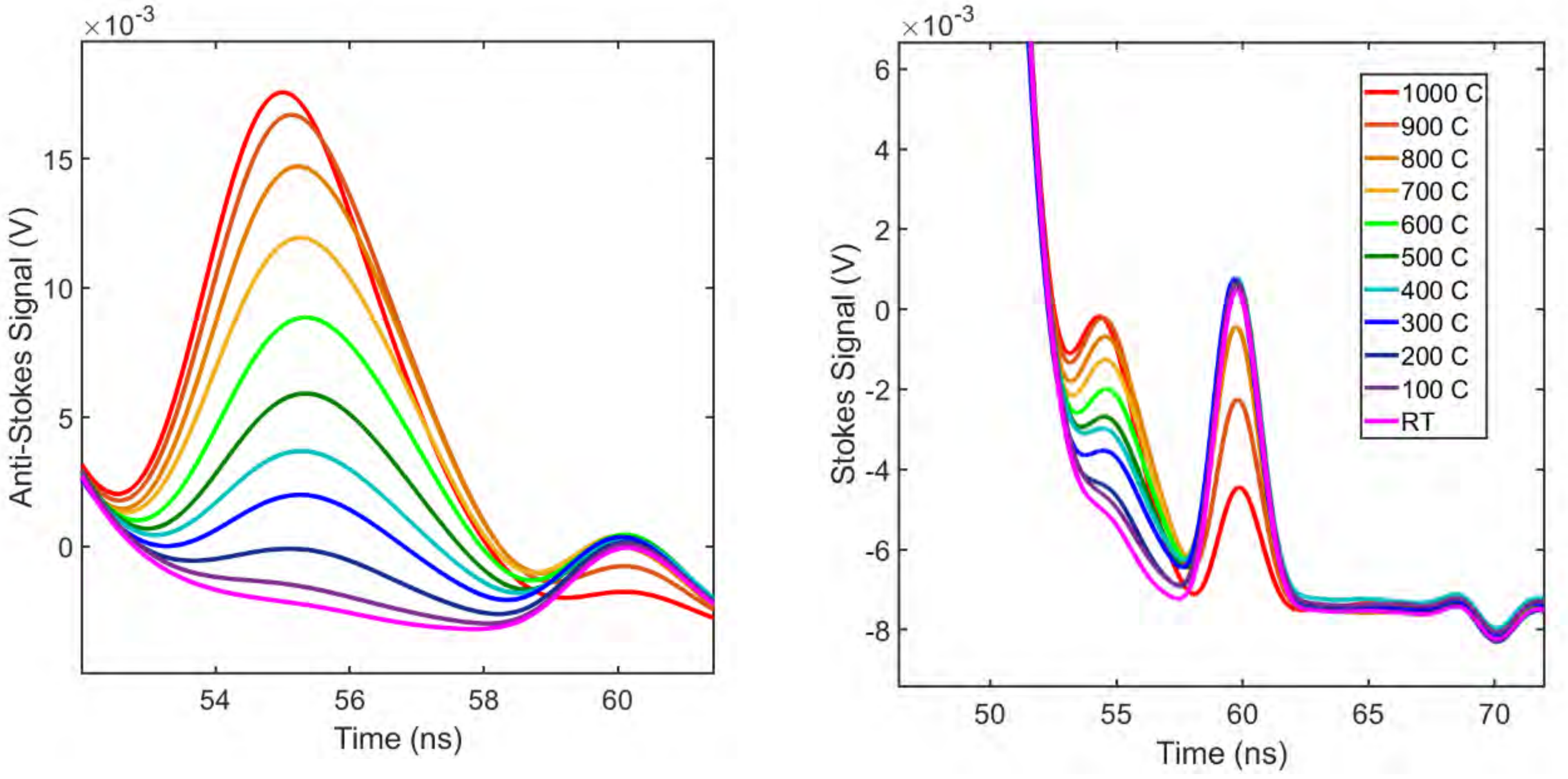
Current view of Raman DTS in the lab
with external test systems

DTS design for portability / finished product prototype

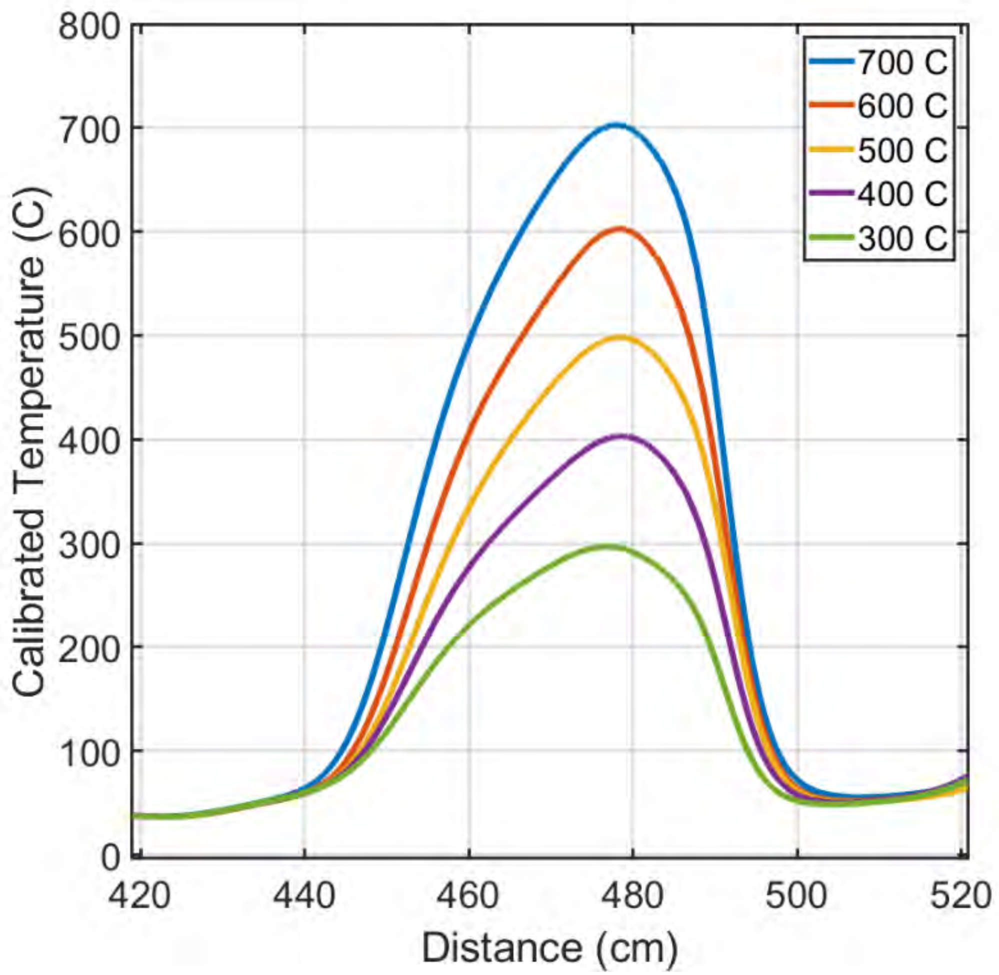
- Flight case design
- Laser safety – electrical interlocks
- Software for lead-in fiber
- Field tests in July at INL
- (even more important) field test in October at MITRR



Furnace calibration with 50' standoff



New data processing for long-standoff



- With 50-ft. lead fiber
- Apply small delay in Stokes vs. Anti-Stokes based on reflection peak delay (one light-ns is 300mm)
- Calibrating only on range where temperature-based losses are minimal (300-700 C).
- Lower loss fiber leads to higher Temp capability
- Smaller fiber leads to higher temp capability

INL Molten salt field tests

- Testing up to ~750C
- Molten Chlorides
- Assortment of crystal fiber materials and protection layers

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MITR test planning

- Encapsulation tubing (pressure boundary) for fiber
- “dummy” fuel element insertion
- DTS standoff at ~60 feet
- October 11th installation

Conclusions

- Distributed sensing is coming to numerous industries
- Single-crystal Optical fiber technology can extend into nuclear harsh-environments
- Raman DTS is a good distributed platform for SC-fiber
- Temperature mapping needed for LFMSR transient response
- Amazing new levels of visibility and automation are here!

Digital Twins to Production Reactors

The Simulation Continuum

Bob Urberger, Roger Chin

09/15/2021

RADIANT

Who Are We? | Radiant

- Radiant was founded by former SpaceX engineers in 2019 to make nuclear power portable.
- Currently designing and building Kaleidos, a 1 MW electrical reactor that fits in an ISO shipping container.
- We believe our experience from the aerospace and software industries will allow us to bring a safe, reliable product to market quickly.

Digital Twins as a Tool

Digital Twin

Regulator

- Parameters and Documentation Source
- Verification and Validation
- High Fidelity Modeling & Simulation

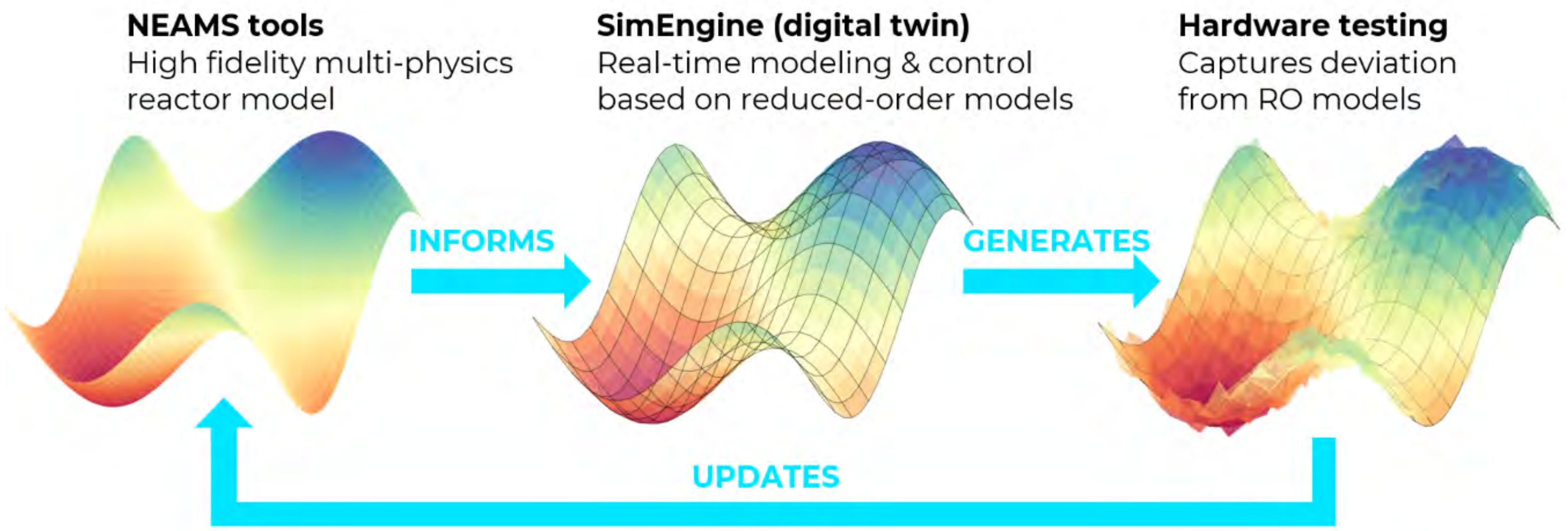
Developer

- Control Systems/Realtime Modeling & Simulation
- Anomaly Response Modeling
- Performance Assessment
- Real-Time Modeling & Simulation
- Machine Learning Applications

Digital Twins are a common tool between regulators and developers to ensure common sources of information for aspects relevant to them.

Why Do We Simulate?

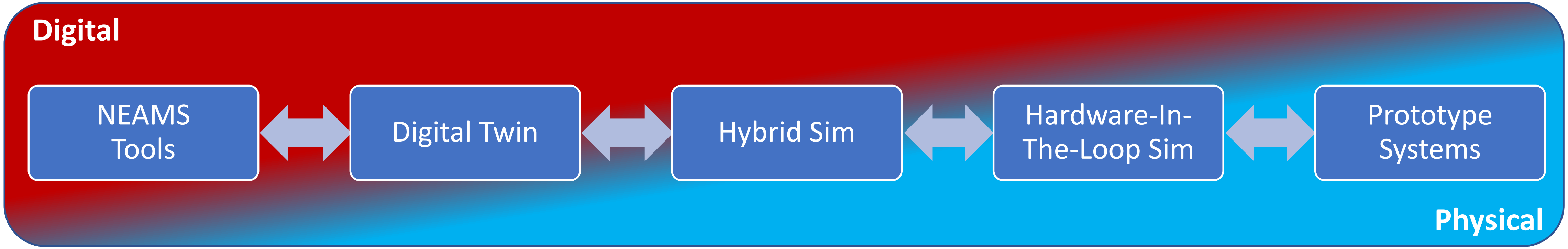
- Inform Design Aspects
- Test Operational Procedures
- Iterate Quickly and Inexpensively
  - Real systems are always correct and used for validation
  - Simulation purpose must be explicitly defined and designed for



Simulations accelerate design and build confidence in a real system by informing decisions.

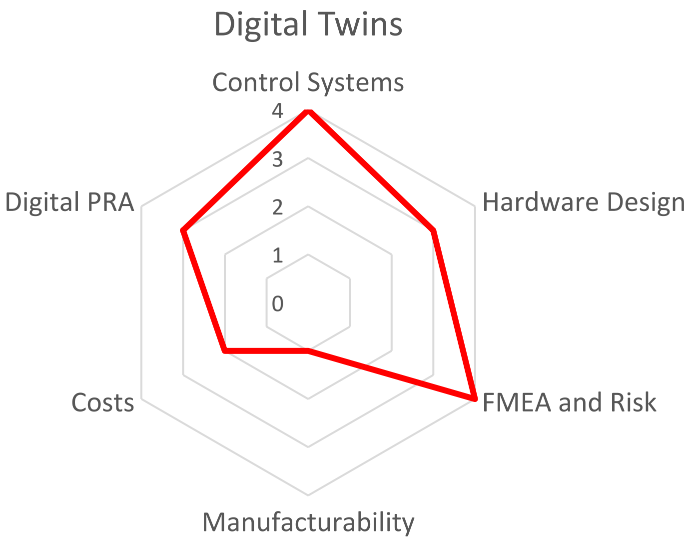
The Radiant Simulation Continuum

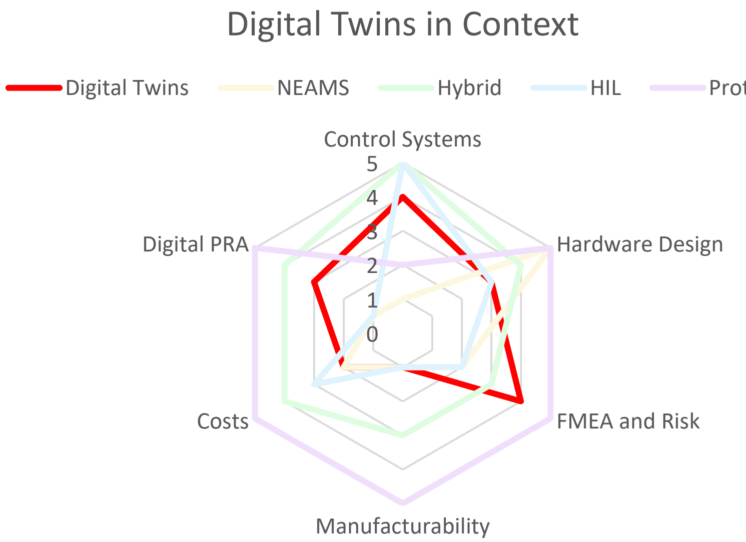
- Our digital twin is low fidelity. How do we bridge the gaps?
- Exploit the strengths of other simulation technologies.
- The scope of each simulation must be carefully defined.
  - What does this sim model?
  - How accurate is it?
  - What can it NOT model?

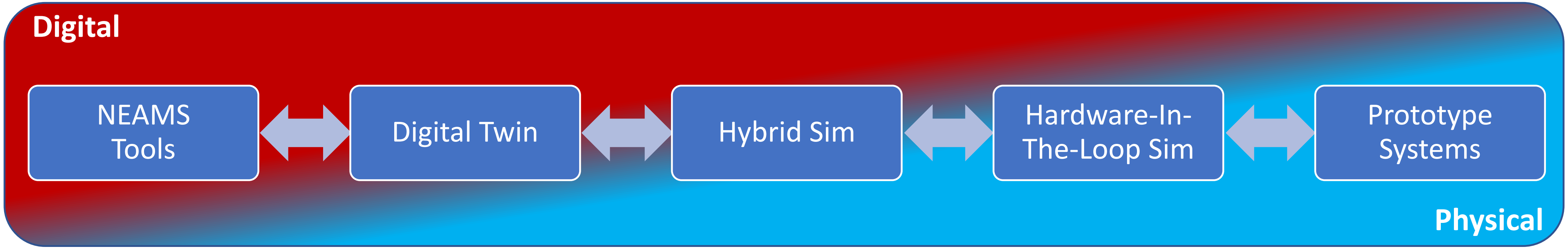


Digital Twins fill a missing role in between high fidelity simulations and physical hardware

Digital Twins Strengths



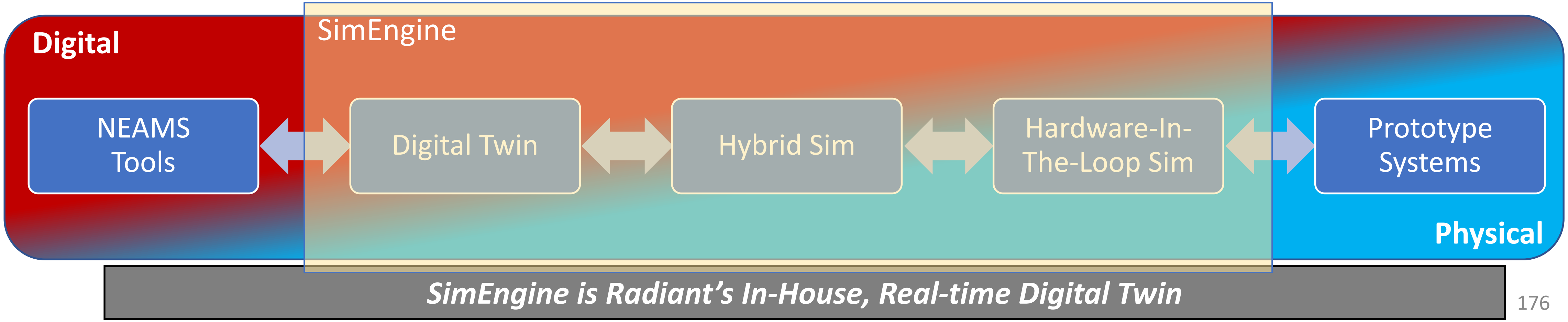




Digital Twins are complementary to existing technologies for a development cycle.

The Radiant Simulation Continuum

- SimEngine is Radiant's in-house simulation tool.
  - It can run in real time.
  - It can run with any mix of real and simulated hardware
  - Each model can be anchored to either a higher fidelity digital model or a higher fidelity physical model
    - Real hardware is used as the source of truth when possible.
    - NEAMS tool solutions used as source of truth elsewhere.



Summary

- Reality is the ultimate truth. Digital twins have limitations.
- Simulations must have a defined scope.
  - What can/can't they predict? How accurate are they?
- Simulations must be anchored.
  - How do we know the simulation is correct? We need to know the source of truth and the simulation's relationship to it.
- A single high-fidelity digital sim isn't practical for Radiant's use. Instead, we cover a larger simulation space with multiple narrowly focused simulations.

Thank you for your attention

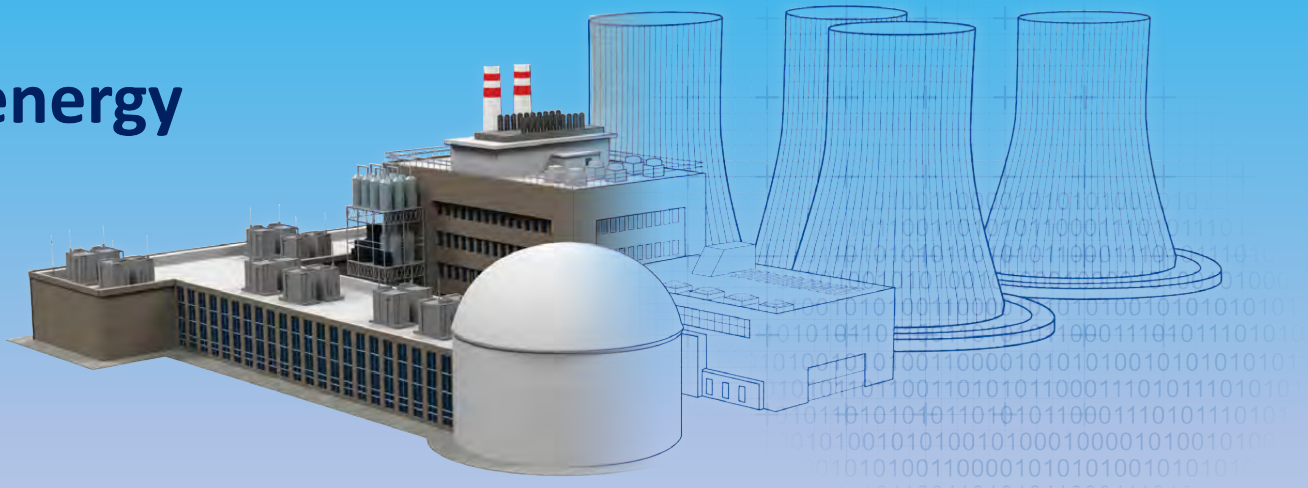
Oak Ridge National Laboratory | Idaho National Laboratory | U.S.NRC United States Nuclear Regulatory Commission *Protecting People and the Environment* | arpa·e CHANGING WHAT'S POSSIBLE | EPRI ELECTRIC POWER RESEARCH INSTITUTE

Steps Toward Regulatory Realization of Digital Twins

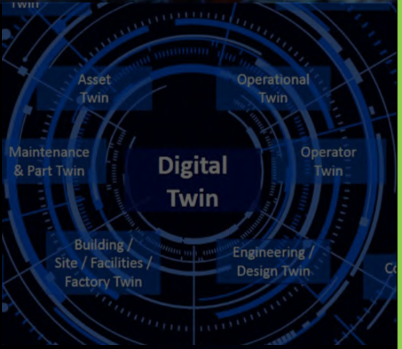
Closing Panel Session – September 16, 2021

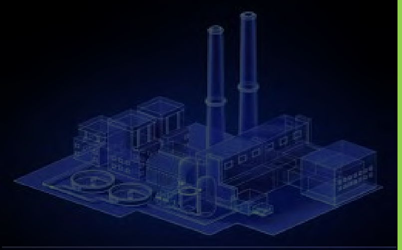
Moderator: Eric Benner, NRC

Jeremy Bowen, NRC
Tom Braudt & Steve Vaughn, X-energy
Paul Keutelian, Radiant
James Slider, NEI
Anthonie Cilliers, Kairos Power
Brian Golchert, Westinghouse





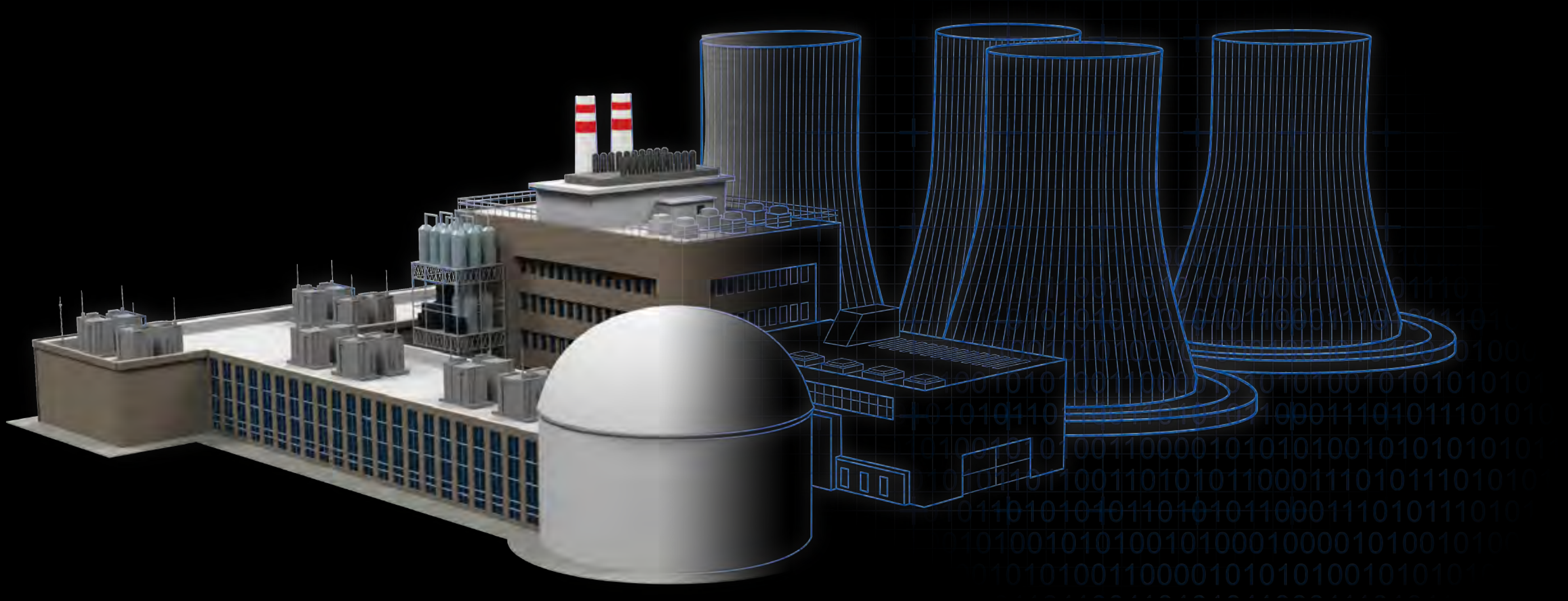





U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment

Digital Twins - Regulatory Viability

Jeremy Bowen



The 2021 Workshop on Enabling Technologies for Digital Twin Applications for Advanced Reactors and Plant Modernization
September 14 – 16, 2021

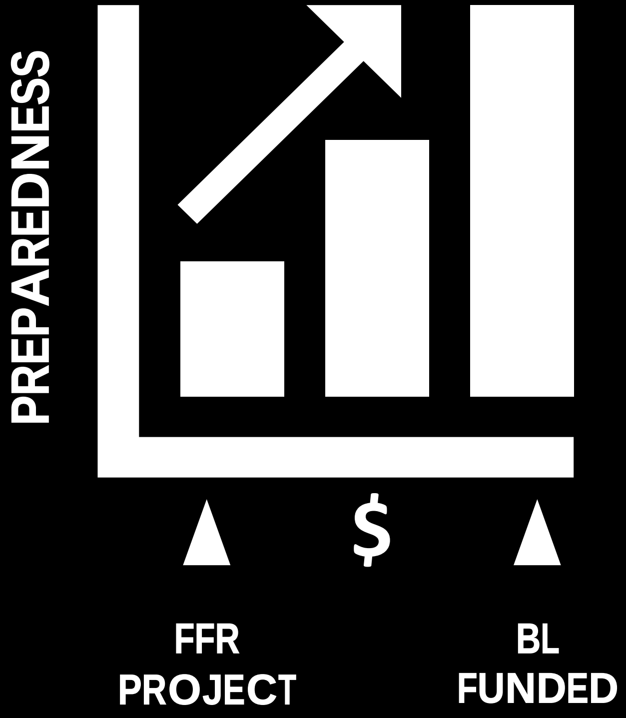
Digital Twins Project Plan

TECHNICAL PREPAREDNESS

REGULATORY READINESS

ASSESSMENT OF STANDARDS

COMMUNICATION & KNOWLEDGE MANAGEMENT



Takeaways Thus Far

The State of Technology of Application of Digital Twins

- Assessment of the state of DT technology in nuclear reactor applications
- Proven benefits
- Development of a common understanding

Access Link: ML21160A074

Public Workshop #1

- Widespread interest with >400 participants across the globe
- Technique is increasing and developing rapidly
- Need for community of practice to collaborate

Access Link: ML21083A132

Active & Future Tasks

- Technical Challenges and Gaps for Digital Twins in Using Data Analytics, ML/AI and Multi-Physics Models
- Technical Preparedness – Safeguards and Security in Digital Twins
- Regulatory Readiness Levels and Gaps Pertaining to Digital Twin Technologies for Nuclear Reactor Applications
- Online Monitoring for Enhanced Diagnostics and Prognostics

Steps Toward Regulatory Realization of Digital Twins
Xe-100 Licensing Perspectives

Tom Braudt and Steve Vaughn, X-energy Licensing

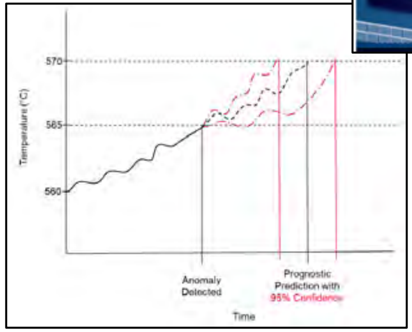
September 16, 2021

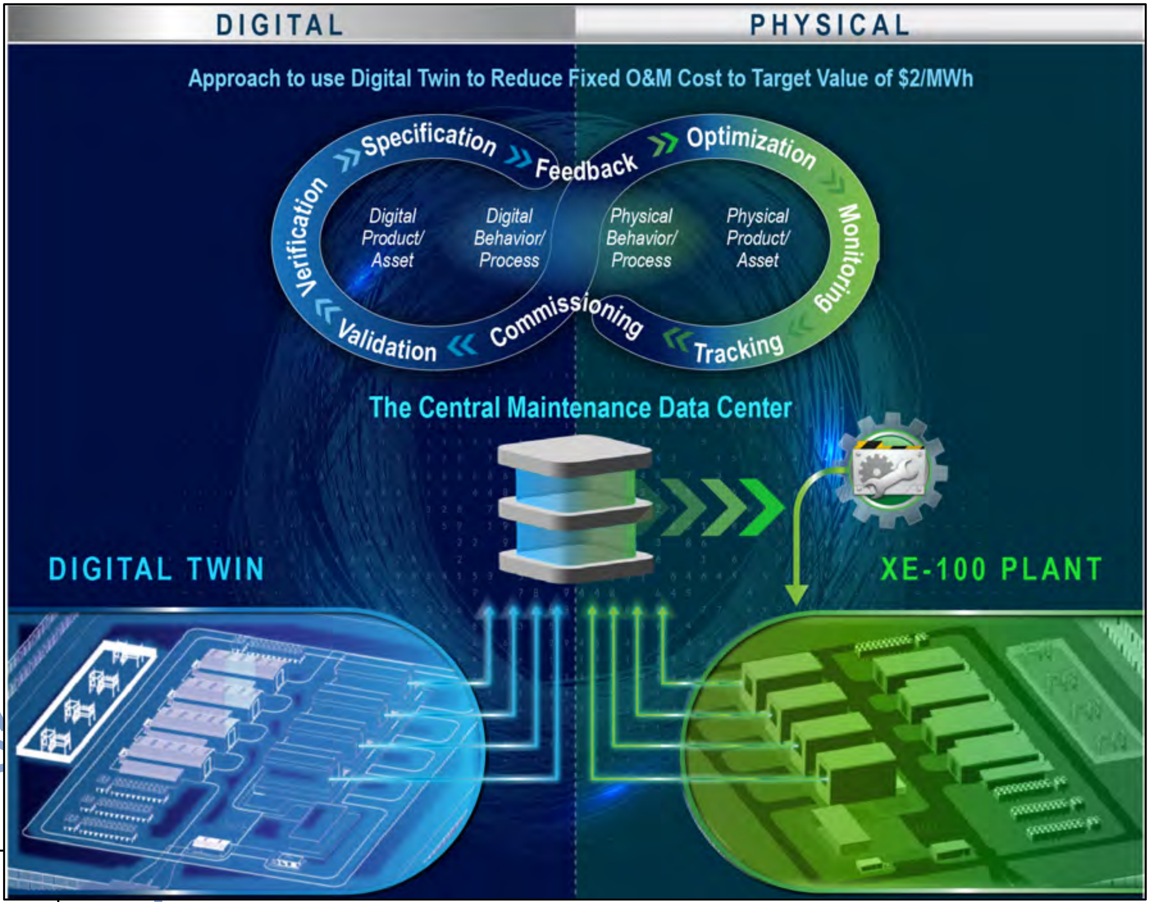
Xe-100 Digital Twin Tools

3D Models with AR / VR

Operator Training Simulator

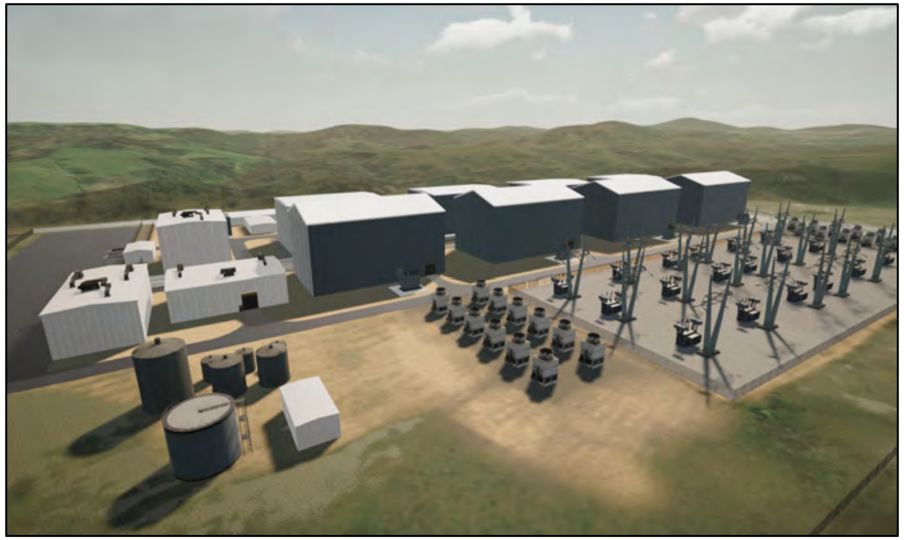
Plant Historian





AI / ML Models

Hi-Fidelity Simulator and 3D Models



Simulator Certification
Simulator HFE Validation

Regulatory Intersections with the Xe-100 Digital Twin

Digital Twin Primary Purpose is Plant Economics – Not Regulated

Some Intersectionality with:

- Xe-100: extensive use of digital control and monitoring systems
- Maintenance Rule – predictive maintenance
- Simulator fidelity and configuration management
- Human Factors Engineering – predictive trending and intelligent alarms reduce operator workload
- NLO/Maintenance/I&C/RP Training – multi-role approach
- ALARA dose reduction
- Security analytics and what-if scenarios
- Fire Detection – intelligent dispatch and response
- Support load-follow, industrial heat, hydrogen production

Strong NRC Staff Interest in Understanding Xe-100 Digital Twin Capabilities and Usage

- Control Room - staffing methodology
- Operator Training - methodology and workload

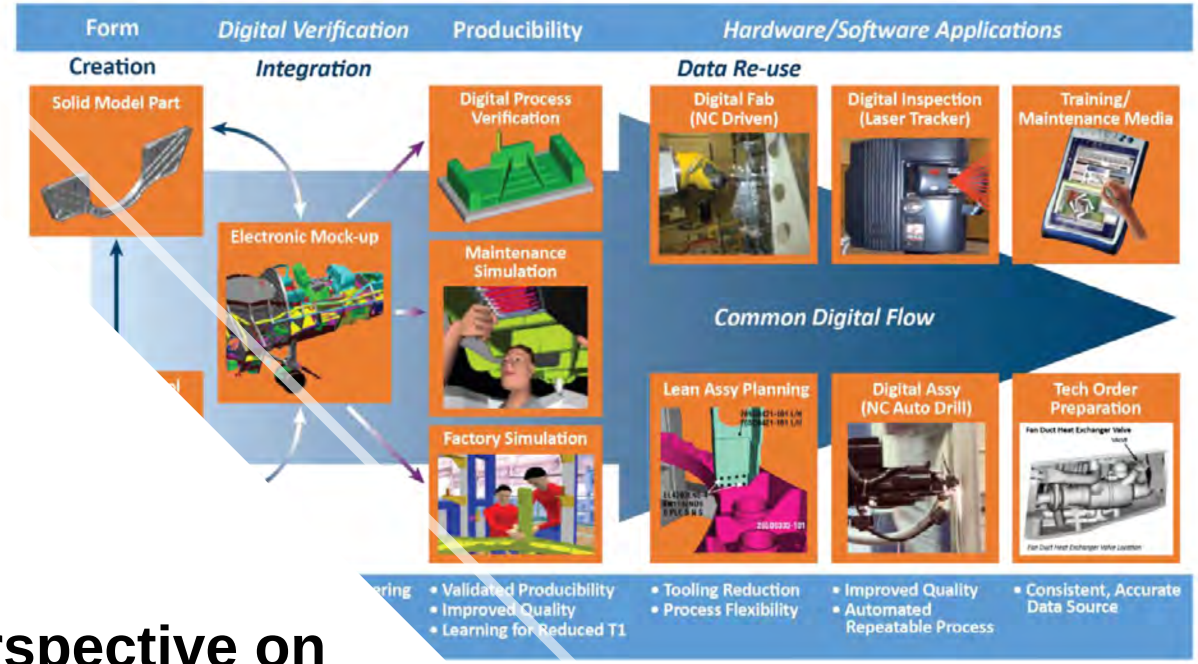
Digital Twin Regulator Pathway – Future Considerations

Use of AI / ML for Control Functions

- Ensuring regulatory framework positioned to support
- Leverage lessons-learned from safety-related digital retrofits (cyber)
- NUREG/CR-7273 starting point

Dynamic PRA Usage - initiating event prediction via AI
Pre-emptive utilization of "Remaining Useful Life" (RUL) for equipment
Sensor Drift Detection
Cyber Security Requirements for Control Functions – DoD Lessons Learned
Encourage Research at NR/ INL/ORNL to Support Control Functions

Making 'digital twins' to monitor and control tomorrow's reactor designs - INL



A Personal Perspective on Digital Twin Capabilities: no 2-seat F-35s

Using Digital Twins to Support Regulations

Paul Keutelian

September 16, 2021

RADIANT

RADIANT

Vision | Radiant

Make Nuclear Portable

Maximize speed of iteration to get to a buildable product

Provide streamlined regulatory analysis

Novel Challenges

Regulatory Intents

Digital Twins → **?** →

- **Protect Personnel**
- **Protect Environment**
- **Protect Hardware**
- **Prove the Above**

Digital Twins are a powerful potential to answer these core questions, the challenge comes from understanding where is it appropriate to use this tool, and how do we work with regulators to build confidence?

Digital Twins as a Tool

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- Verification and Validation
- High Fidelity Modeling & Simulation

Developer

- Control Systems/Realtime Modeling & Simulation
- Anomaly Response Modeling
- Performance Assessment
- Real-Time Modeling & Simulation
- Machine Learning Applications

Digital Twins are a common tool between regulators and developers to ensure common sources of information for aspects relevant to them.

Contributions

- Internal analysis documentation standardization
- Visualizations for eased introduction to analysis
- Automation of explicit analysis flows
- Common interface with Regulators

JAMES SLIDER

TECHNICAL ADVISOR

Kairos Power

ANTHONIE CILLIERS

SENIOR MANAGER

INSTRUMENTATION, CONTROLS AND ELECTRICAL

Westinghouse

BRIAN GOLCHERT

PRINCIPAL ENGINEER

Enabling Technologies for Digital Twin Applications for Advanced Reactors and Plant Modernization

September 14-16, 2021

Thank you for your participation in this workshop. The proceedings for the workshop will be publicly available in the next few months. Please provide any comments or feedback to one of these workshop sponsors.

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