PROCEEDINGS OF THE WORKSHOP ENABLING TECHNOLOGIES FOR DIGITAL TWIN APPLICATIONS FOR ADVANCED REACTORS AND PLANT MODERNIZATION

Virtual Workshop
September 14-16, 2021

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Prepared by:
J. Carlson
D. Eskins
R. Gascot
R. Iyengar
C. Ulmer

U.S. Nuclear Regulatory Commission
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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**

Patrick 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-energy

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 Y₃Al₅O₁₂ (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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<tr>
<th>First Name</th>
<th>Last Name</th>
<th>Email Address</th>
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<tbody>
<tr>
<td>Mohammad</td>
<td>Abdo</td>
<td><a href="mailto:mohammad.abdo@inl.gov">mohammad.abdo@inl.gov</a></td>
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<tr>
<td>Kamal</td>
<td>Abdulraheem</td>
<td><a href="mailto:kamalabdulraheem@gmail.com">kamalabdulraheem@gmail.com</a></td>
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<td>Chethan</td>
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<tr>
<td>Vivek</td>
<td>Agarwal</td>
<td><a href="mailto:vivek.agarwal@inl.gov">vivek.agarwal@inl.gov</a></td>
</tr>
<tr>
<td>Indarta</td>
<td>Aji</td>
<td><a href="mailto:indartaaji@gmail.com">indartaaji@gmail.com</a></td>
</tr>
<tr>
<td>Ahmed</td>
<td>Alshehhi</td>
<td><a href="mailto:ahmedal565@gmail.com">ahmedal565@gmail.com</a></td>
</tr>
<tr>
<td>Tim</td>
<td>Alvey</td>
<td><a href="mailto:tim.alvey@exeloncorp.com">tim.alvey@exeloncorp.com</a></td>
</tr>
<tr>
<td>Harry</td>
<td>Andreades</td>
<td><a href="mailto:charalampos.andreades@hq.doe.gov">charalampos.andreades@hq.doe.gov</a></td>
</tr>
<tr>
<td>Michela</td>
<td>Angelucci</td>
<td><a href="mailto:michela.angelucci@phd.unipi.it">michela.angelucci@phd.unipi.it</a></td>
</tr>
<tr>
<td>Kwame</td>
<td>Ansh</td>
<td><a href="mailto:ansahkwame466@gmail.com">ansahkwame466@gmail.com</a></td>
</tr>
<tr>
<td>Todd</td>
<td>Anselmi</td>
<td><a href="mailto:todd.anselmi@inl.gov">todd.anselmi@inl.gov</a></td>
</tr>
<tr>
<td>Thompson</td>
<td>Appah</td>
<td><a href="mailto:appahtompson@gmail.com">appahtompson@gmail.com</a></td>
</tr>
<tr>
<td>Jeffrey</td>
<td>Arndt</td>
<td><a href="mailto:arndtjil@westinghouse.com">arndtjil@westinghouse.com</a></td>
</tr>
<tr>
<td>Steven</td>
<td>Arndt</td>
<td><a href="mailto:arndtis@ornl.gov">arndtis@ornl.gov</a></td>
</tr>
<tr>
<td>Dushyant</td>
<td>Arora</td>
<td><a href="mailto:dushyant.arora@siemens.com">dushyant.arora@siemens.com</a></td>
</tr>
<tr>
<td>Oussama</td>
<td>Ashy</td>
<td><a href="mailto:ashyo@ws-corp.com">ashyo@ws-corp.com</a></td>
</tr>
<tr>
<td>Paridhi</td>
<td>Athe</td>
<td><a href="mailto:pathe@ncsu.edu">pathe@ncsu.edu</a></td>
</tr>
<tr>
<td>Md Samdani</td>
<td>Azad</td>
<td><a href="mailto:samdaniazad@konkuk.ac.kr">samdaniazad@konkuk.ac.kr</a></td>
</tr>
<tr>
<td>Vittorio</td>
<td>Badalassi</td>
<td><a href="mailto:badalassiv@ornl.gov">badalassiv@ornl.gov</a></td>
</tr>
<tr>
<td>Jin Whan</td>
<td>Bae</td>
<td><a href="mailto:baej@ornl.gov">baej@ornl.gov</a></td>
</tr>
<tr>
<td>Emilio</td>
<td>Baglietto</td>
<td><a href="mailto:emiliob@mit.edu">emiliob@mit.edu</a></td>
</tr>
<tr>
<td>Nicholas</td>
<td>Baldasaro</td>
<td><a href="mailto:nick@hoplite.ai">nick@hoplite.ai</a></td>
</tr>
<tr>
<td>Han</td>
<td>Bao</td>
<td><a href="mailto:han.bao@inl.gov">han.bao@inl.gov</a></td>
</tr>
<tr>
<td>Sergiu</td>
<td>Basturescu</td>
<td><a href="mailto:Sergiu.Basturescu@ncr.gov">Sergiu.Basturescu@ncr.gov</a></td>
</tr>
<tr>
<td>Melissa</td>
<td>Bates</td>
<td><a href="mailto:melissa.bates@nuclear.energy.gov">melissa.bates@nuclear.energy.gov</a></td>
</tr>
<tr>
<td>Randall</td>
<td>Belles</td>
<td><a href="mailto:bellesrj@ornl.gov">bellesrj@ornl.gov</a></td>
</tr>
<tr>
<td>Eric</td>
<td>Benner</td>
<td><a href="mailto:eric.benner@ncr.gov">eric.benner@ncr.gov</a></td>
</tr>
<tr>
<td>Jacob</td>
<td>Benz</td>
<td><a href="mailto:jacob.benz@pnln.gov">jacob.benz@pnln.gov</a></td>
</tr>
<tr>
<td>Mounia</td>
<td>Berdai</td>
<td><a href="mailto:mounia.berdai@cnsc-ccsn.gc.ca">mounia.berdai@cnsc-ccsn.gc.ca</a></td>
</tr>
<tr>
<td>Satyan</td>
<td>Bhongale</td>
<td><a href="mailto:sbhongale@x-energy.com">sbhongale@x-energy.com</a></td>
</tr>
<tr>
<td>Harry</td>
<td>Bonilla-</td>
<td><a href="mailto:hbonilla@iastate.edu">hbonilla@iastate.edu</a></td>
</tr>
<tr>
<td>Tanner</td>
<td>Boone</td>
<td><a href="mailto:tanner.boone@ncr.gov">tanner.boone@ncr.gov</a></td>
</tr>
<tr>
<td>Katarzyna</td>
<td>Borowiec</td>
<td><a href="mailto:borowieck@ornl.gov">borowieck@ornl.gov</a></td>
</tr>
<tr>
<td>Jyoti</td>
<td>Bose</td>
<td><a href="mailto:jyoti.bose@alithya.com">jyoti.bose@alithya.com</a></td>
</tr>
<tr>
<td>Jeremy</td>
<td>Bowen</td>
<td><a href="mailto:jeremy.bowen@ncr.gov">jeremy.bowen@ncr.gov</a></td>
</tr>
<tr>
<td>Thomas</td>
<td>Braudt</td>
<td><a href="mailto:tbraudt@x-energy.com">tbraudt@x-energy.com</a></td>
</tr>
<tr>
<td>Alexander</td>
<td>Brazalovich</td>
<td><a href="mailto:abrazalovich@x-energy.com">abrazalovich@x-energy.com</a></td>
</tr>
<tr>
<td>Michael</td>
<td>Breach</td>
<td><a href="mailto:michael.breach@ncr.gov">michael.breach@ncr.gov</a></td>
</tr>
<tr>
<td>Jeren</td>
<td>Browning</td>
<td><a href="mailto:jeren.browning@inl.gov">jeren.browning@inl.gov</a></td>
</tr>
<tr>
<td>Logan</td>
<td>Browning</td>
<td><a href="mailto:logan.browning@inl.gov">logan.browning@inl.gov</a></td>
</tr>
<tr>
<td>John</td>
<td>Buchanan</td>
<td><a href="mailto:jbuchanan@deka.batteries.com">jbuchanan@deka.batteries.com</a></td>
</tr>
<tr>
<td>Angela</td>
<td>Buford</td>
<td><a href="mailto:Angela.Buford@ncr.gov">Angela.Buford@ncr.gov</a></td>
</tr>
<tr>
<td>Michael</td>
<td>Buric</td>
<td><a href="mailto:michael.buric@netl.doe.gov">michael.buric@netl.doe.gov</a></td>
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<tr>
<td>Name</td>
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<tr>
<td>Pat Burke</td>
<td><a href="mailto:troy.burnett@inl.gov">troy.burnett@inl.gov</a></td>
<td><a href="mailto:scott.bussey@nrc.gov">scott.bussey@nrc.gov</a></td>
</tr>
<tr>
<td>Troy Burnett</td>
<td><a href="mailto:jdburste@bechtel.com">jdburste@bechtel.com</a></td>
<td><a href="mailto:salvatore.cancemi@phd.unipi.it">salvatore.cancemi@phd.unipi.it</a></td>
</tr>
<tr>
<td>Rob Burns</td>
<td><a href="mailto:rob@arthur.ai">rob@arthur.ai</a></td>
<td><a href="mailto:salvatore.cancemi@phd.unipi.it">salvatore.cancemi@phd.unipi.it</a></td>
</tr>
<tr>
<td>Jonathon Burstein</td>
<td>Troy Burnett</td>
<td><a href="mailto:troy.burnett@inl.gov">troy.burnett@inl.gov</a></td>
</tr>
<tr>
<td>Scott Bussey</td>
<td><a href="mailto:roger@radiantnuclear.com">roger@radiantnuclear.com</a></td>
<td><a href="mailto:christopher.crosby@osisoft.com">christopher.crosby@osisoft.com</a></td>
</tr>
<tr>
<td>Dirk Cairns-Cains</td>
<td><a href="mailto:dirk.cairns-gallmore@nuclear.energy.gov">dirk.cairns-gallmore@nuclear.energy.gov</a></td>
<td><a href="mailto:dirk.cairns-gallmore@nuclear.energy.gov">dirk.cairns-gallmore@nuclear.energy.gov</a></td>
</tr>
<tr>
<td>Pattrick Calderoni</td>
<td><a href="mailto:patrick.calderoni@inl.gov">patrick.calderoni@inl.gov</a></td>
<td><a href="mailto:dirk.cairns-gallmore@nuclear.energy.gov">dirk.cairns-gallmore@nuclear.energy.gov</a></td>
</tr>
<tr>
<td>Clevin Canales</td>
<td><a href="mailto:ccanales@x-energy.com">ccanales@x-energy.com</a></td>
<td><a href="mailto:dirk.cairns-gallmore@nuclear.energy.gov">dirk.cairns-gallmore@nuclear.energy.gov</a></td>
</tr>
<tr>
<td>Salvatore Cancemi</td>
<td><a href="mailto:salvatore.cancemi@phd.unipi.it">salvatore.cancemi@phd.unipi.it</a></td>
<td><a href="mailto:dirk.cairns-gallmore@nuclear.energy.gov">dirk.cairns-gallmore@nuclear.energy.gov</a></td>
</tr>
<tr>
<td>Brent Capell</td>
<td><a href="mailto:bcapell@epri.com">bcapell@epri.com</a></td>
<td><a href="mailto:dirk.cairns-gallmore@nuclear.energy.gov">dirk.cairns-gallmore@nuclear.energy.gov</a></td>
</tr>
<tr>
<td>Jesse Carlson</td>
<td><a href="mailto:jesse.carlson@nr.gov">jesse.carlson@nr.gov</a></td>
<td><a href="mailto:dirk.cairns-gallmore@nuclear.energy.gov">dirk.cairns-gallmore@nuclear.energy.gov</a></td>
</tr>
<tr>
<td>Gene Carpenter</td>
<td><a href="mailto:gene.carpenter@hq.doe.gov">gene.carpenter@hq.doe.gov</a></td>
<td><a href="mailto:dirk.cairns-gallmore@nuclear.energy.gov">dirk.cairns-gallmore@nuclear.energy.gov</a></td>
</tr>
<tr>
<td>Jorge Carvajal</td>
<td><a href="mailto:carvajjv@westinghouse.com">carvajjv@westinghouse.com</a></td>
<td><a href="mailto:dirk.cairns-gallmore@nuclear.energy.gov">dirk.cairns-gallmore@nuclear.energy.gov</a></td>
</tr>
<tr>
<td>Arindam Chakraborty</td>
<td><a href="mailto:achakraborty@viaskorp.com">achakraborty@viaskorp.com</a></td>
<td><a href="mailto:dirk.cairns-gallmore@nuclear.energy.gov">dirk.cairns-gallmore@nuclear.energy.gov</a></td>
</tr>
<tr>
<td>Alvin Chan</td>
<td><a href="mailto:alvin.chan@opg.com">alvin.chan@opg.com</a></td>
<td><a href="mailto:dirk.cairns-gallmore@nuclear.energy.gov">dirk.cairns-gallmore@nuclear.energy.gov</a></td>
</tr>
<tr>
<td>Hasan Charkas</td>
<td><a href="mailto:hcharkas@epri.com">hcharkas@epri.com</a></td>
<td><a href="mailto:dirk.cairns-gallmore@nuclear.energy.gov">dirk.cairns-gallmore@nuclear.energy.gov</a></td>
</tr>
<tr>
<td>Jaydev Chauhan</td>
<td><a href="mailto:jaydev.chauhan@opg.com">jaydev.chauhan@opg.com</a></td>
<td><a href="mailto:dirk.cairns-gallmore@nuclear.energy.gov">dirk.cairns-gallmore@nuclear.energy.gov</a></td>
</tr>
<tr>
<td>Yifeng Che</td>
<td><a href="mailto:yfche@mit.edu">yfche@mit.edu</a></td>
<td><a href="mailto:dirk.cairns-gallmore@nuclear.energy.gov">dirk.cairns-gallmore@nuclear.energy.gov</a></td>
</tr>
<tr>
<td>Danny Chien</td>
<td><a href="mailto:npc1@nrc.gov">npc1@nrc.gov</a></td>
<td><a href="mailto:dirk.cairns-gallmore@nuclear.energy.gov">dirk.cairns-gallmore@nuclear.energy.gov</a></td>
</tr>
<tr>
<td>Roger Chin</td>
<td><a href="mailto:mroizo40@hotmail.com">mroizo40@hotmail.com</a></td>
<td><a href="mailto:dirk.cairns-gallmore@nuclear.energy.gov">dirk.cairns-gallmore@nuclear.energy.gov</a></td>
</tr>
<tr>
<td>Roger Chin</td>
<td><a href="mailto:roger@radiantnuclear.com">roger@radiantnuclear.com</a></td>
<td><a href="mailto:dirk.cairns-gallmore@nuclear.energy.gov">dirk.cairns-gallmore@nuclear.energy.gov</a></td>
</tr>
<tr>
<td>Helene Chini</td>
<td><a href="mailto:chinih@westinghouse.com">chinih@westinghouse.com</a></td>
<td><a href="mailto:dirk.cairns-gallmore@nuclear.energy.gov">dirk.cairns-gallmore@nuclear.energy.gov</a></td>
</tr>
<tr>
<td>Hangbok Choi</td>
<td><a href="mailto:Hangbok.Choi@ga.com">Hangbok.Choi@ga.com</a></td>
<td><a href="mailto:dirk.cairns-gallmore@nuclear.energy.gov">dirk.cairns-gallmore@nuclear.energy.gov</a></td>
</tr>
<tr>
<td>Anthonie Cilliers</td>
<td><a href="mailto:cilliers@kairospower.com">cilliers@kairospower.com</a></td>
<td><a href="mailto:dirk.cairns-gallmore@nuclear.energy.gov">dirk.cairns-gallmore@nuclear.energy.gov</a></td>
</tr>
<tr>
<td>Stephanie Coffin</td>
<td><a href="mailto:stephanie.coffin@nrc.gov">stephanie.coffin@nrc.gov</a></td>
<td><a href="mailto:dirk.cairns-gallmore@nuclear.energy.gov">dirk.cairns-gallmore@nuclear.energy.gov</a></td>
</tr>
<tr>
<td>Christopher Cook</td>
<td><a href="mailto:christopher.cook@nrc.gov">christopher.cook@nrc.gov</a></td>
<td><a href="mailto:dirk.cairns-gallmore@nuclear.energy.gov">dirk.cairns-gallmore@nuclear.energy.gov</a></td>
</tr>
<tr>
<td>Justin Coury</td>
<td><a href="mailto:justin.coury@nrc.gov">justin.coury@nrc.gov</a></td>
<td><a href="mailto:dirk.cairns-gallmore@nuclear.energy.gov">dirk.cairns-gallmore@nuclear.energy.gov</a></td>
</tr>
<tr>
<td>Christopher Crosby</td>
<td><a href="mailto:ccrosby@osisoft.com">ccrosby@osisoft.com</a></td>
<td><a href="mailto:dirk.cairns-gallmore@nuclear.energy.gov">dirk.cairns-gallmore@nuclear.energy.gov</a></td>
</tr>
<tr>
<td>Brad Crotts</td>
<td><a href="mailto:bradley.crotts@orano.group">bradley.crotts@orano.group</a></td>
<td><a href="mailto:dirk.cairns-gallmore@nuclear.energy.gov">dirk.cairns-gallmore@nuclear.energy.gov</a></td>
</tr>
<tr>
<td>Amy Cubbage</td>
<td><a href="mailto:amy.cubbage@nrc.gov">amy.cubbage@nrc.gov</a></td>
<td><a href="mailto:dirk.cairns-gallmore@nuclear.energy.gov">dirk.cairns-gallmore@nuclear.energy.gov</a></td>
</tr>
<tr>
<td>Samir Darbali</td>
<td><a href="mailto:samir.darbali@nrc.gov">samir.darbali@nrc.gov</a></td>
<td><a href="mailto:dirk.cairns-gallmore@nuclear.energy.gov">dirk.cairns-gallmore@nuclear.energy.gov</a></td>
</tr>
<tr>
<td>Ian Davis</td>
<td><a href="mailto:idavis@x-energy.com">idavis@x-energy.com</a></td>
<td><a href="mailto:dirk.cairns-gallmore@nuclear.energy.gov">dirk.cairns-gallmore@nuclear.energy.gov</a></td>
</tr>
<tr>
<td>Niyera Davoodian</td>
<td><a href="mailto:ndavoodian@gmail.com">ndavoodian@gmail.com</a></td>
<td><a href="mailto:dirk.cairns-gallmore@nuclear.energy.gov">dirk.cairns-gallmore@nuclear.energy.gov</a></td>
</tr>
<tr>
<td>Grigorios Delipei</td>
<td><a href="mailto:gkdelipe@ncsu.edu">gkdelipe@ncsu.edu</a></td>
<td><a href="mailto:dirk.cairns-gallmore@nuclear.energy.gov">dirk.cairns-gallmore@nuclear.energy.gov</a></td>
</tr>
<tr>
<td>Matt Dennis</td>
<td><a href="mailto:matthew.dennis@nrc.gov">matthew.dennis@nrc.gov</a></td>
<td><a href="mailto:dirk.cairns-gallmore@nuclear.energy.gov">dirk.cairns-gallmore@nuclear.energy.gov</a></td>
</tr>
<tr>
<td>David Desaulniers</td>
<td><a href="mailto:david.desaulniers@nrc.gov">david.desaulniers@nrc.gov</a></td>
<td><a href="mailto:dirk.cairns-gallmore@nuclear.energy.gov">dirk.cairns-gallmore@nuclear.energy.gov</a></td>
</tr>
<tr>
<td>Hadja Fanta Diakhaby</td>
<td><a href="mailto:nalahadja@gmail.com">nalahadja@gmail.com</a></td>
<td><a href="mailto:dirk.cairns-gallmore@nuclear.energy.gov">dirk.cairns-gallmore@nuclear.energy.gov</a></td>
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<tr>
<td>Xiaoxu Diao</td>
<td><a href="mailto:diao.38@osu.edu">diao.38@osu.edu</a></td>
<td><a href="mailto:dirk.cairns-gallmore@nuclear.energy.gov">dirk.cairns-gallmore@nuclear.energy.gov</a></td>
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<td>Nam Dinh</td>
<td><a href="mailto:ntdinh@ncsu.edu">ntdinh@ncsu.edu</a></td>
<td><a href="mailto:dirk.cairns-gallmore@nuclear.energy.gov">dirk.cairns-gallmore@nuclear.energy.gov</a></td>
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<tr>
<td>Elvis Dominguez</td>
<td><a href="mailto:dominguezoe@ornl.gov">dominguezoe@ornl.gov</a></td>
<td><a href="mailto:dirk.cairns-gallmore@nuclear.energy.gov">dirk.cairns-gallmore@nuclear.energy.gov</a></td>
</tr>
<tr>
<td>Valentin Drouet</td>
<td><a href="mailto:valentin.drouet@metroscope.tech">valentin.drouet@metroscope.tech</a></td>
<td><a href="mailto:dirk.cairns-gallmore@nuclear.energy.gov">dirk.cairns-gallmore@nuclear.energy.gov</a></td>
</tr>
<tr>
<td>Trevor Dudley</td>
<td><a href="mailto:drtdudley@mozweli.com">drtdudley@mozweli.com</a></td>
<td><a href="mailto:dirk.cairns-gallmore@nuclear.energy.gov">dirk.cairns-gallmore@nuclear.energy.gov</a></td>
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<tr>
<td>Christophe Duquennoy</td>
<td><a href="mailto:christophe.duquennoy@edf.fr">christophe.duquennoy@edf.fr</a></td>
<td><a href="mailto:dirk.cairns-gallmore@nuclear.energy.gov">dirk.cairns-gallmore@nuclear.energy.gov</a></td>
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<td>Carmen Dykes</td>
<td><a href="mailto:carmen.dykes@nrc.gov">carmen.dykes@nrc.gov</a></td>
<td><a href="mailto:dirk.cairns-gallmore@nuclear.energy.gov">dirk.cairns-gallmore@nuclear.energy.gov</a></td>
</tr>
<tr>
<td>Derek Ebeling-Koning</td>
<td><a href="mailto:ebelind@westinghouse.com">ebelind@westinghouse.com</a></td>
<td><a href="mailto:dirk.cairns-gallmore@nuclear.energy.gov">dirk.cairns-gallmore@nuclear.energy.gov</a></td>
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<tr>
<td>Shannon Eggers</td>
<td><a href="mailto:shannon.eggers@inl.gov">shannon.eggers@inl.gov</a></td>
<td><a href="mailto:dirk.cairns-gallmore@nuclear.energy.gov">dirk.cairns-gallmore@nuclear.energy.gov</a></td>
</tr>
<tr>
<td>Robert England</td>
<td><a href="mailto:robert.england@inl.gov">robert.england@inl.gov</a></td>
<td><a href="mailto:dirk.cairns-gallmore@nuclear.energy.gov">dirk.cairns-gallmore@nuclear.energy.gov</a></td>
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<tr>
<td>Doug</td>
<td>Eskins</td>
<td><a href="mailto:doug.eskins@nrc.gov">doug.eskins@nrc.gov</a></td>
</tr>
<tr>
<td>Kale</td>
<td>Evans</td>
<td><a href="mailto:kalejevans@gmail.com">kalejevans@gmail.com</a></td>
</tr>
<tr>
<td>Nathan</td>
<td>Faith</td>
<td><a href="mailto:Nathan.Faith@ExelonCorp.com">Nathan.Faith@ExelonCorp.com</a></td>
</tr>
<tr>
<td>Amjad</td>
<td>Farah</td>
<td><a href="mailto:amjad.farah@opg.com">amjad.farah@opg.com</a></td>
</tr>
<tr>
<td>Mario</td>
<td>Fernandez</td>
<td><a href="mailto:mario.fernandez@nrc.gov">mario.fernandez@nrc.gov</a></td>
</tr>
<tr>
<td>William</td>
<td>Ferrell</td>
<td><a href="mailto:will@ams-corp.com">will@ams-corp.com</a></td>
</tr>
<tr>
<td>Matthew</td>
<td>Ferri</td>
<td><a href="mailto:mattferri@gmail.com">mattferri@gmail.com</a></td>
</tr>
<tr>
<td>Leo</td>
<td>Fifield</td>
<td><a href="mailto:leo.fifield@pnnl.gov">leo.fifield@pnnl.gov</a></td>
</tr>
<tr>
<td>Eric</td>
<td>Focht</td>
<td><a href="mailto:eric.focht@nrc.gov">eric.focht@nrc.gov</a></td>
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<tr>
<td>James D</td>
<td>Freels</td>
<td><a href="mailto:freeljsd@gmail.com">freeljsd@gmail.com</a></td>
</tr>
<tr>
<td>Raymond</td>
<td>Furstenau</td>
<td><a href="mailto:raymond.furstenau@nrc.gov">raymond.furstenau@nrc.gov</a></td>
</tr>
<tr>
<td>Pratik</td>
<td>Gandhi</td>
<td><a href="mailto:pratik.gandhi@npxinovation.ca">pratik.gandhi@npxinovation.ca</a></td>
</tr>
<tr>
<td>Alex</td>
<td>Garrison</td>
<td><a href="mailto:alex@radiannuclear.com">alex@radiannuclear.com</a></td>
</tr>
<tr>
<td>Marisol</td>
<td>Garrouste</td>
<td><a href="mailto:mgarrou@umich.edu">mgarrou@umich.edu</a></td>
</tr>
<tr>
<td>Ramon</td>
<td>Gascot</td>
<td><a href="mailto:ramon.gascot@nrc.gov">ramon.gascot@nrc.gov</a></td>
</tr>
<tr>
<td>Lou</td>
<td>Gaussa</td>
<td><a href="mailto:gaussalw@westinghouse.com">gaussalw@westinghouse.com</a></td>
</tr>
<tr>
<td>Debraj</td>
<td>Ghosh</td>
<td><a href="mailto:dghosh@iisc.ac.in">dghosh@iisc.ac.in</a></td>
</tr>
<tr>
<td>Anders</td>
<td>Gilbertson</td>
<td><a href="mailto:anders.gilbertson@nrc.gov">anders.gilbertson@nrc.gov</a></td>
</tr>
<tr>
<td>James</td>
<td>Godwin</td>
<td><a href="mailto:drjamesgodwin30@gmail.com">drjamesgodwin30@gmail.com</a></td>
</tr>
<tr>
<td>Brian</td>
<td>Golchert</td>
<td><a href="mailto:golchebm@westinghouse.com">golchebm@westinghouse.com</a></td>
</tr>
<tr>
<td>Gregory</td>
<td>Golding</td>
<td><a href="mailto:greggolding@moltexenergy.com">greggolding@moltexenergy.com</a></td>
</tr>
<tr>
<td>Carlos</td>
<td>Gonzalez</td>
<td><a href="mailto:Carlos.Gonzalez@nrc.gov">Carlos.Gonzalez@nrc.gov</a></td>
</tr>
<tr>
<td>Nicholas</td>
<td>Goss</td>
<td><a href="mailto:nicholas.goss@westinghouse.com">nicholas.goss@westinghouse.com</a></td>
</tr>
<tr>
<td>Fred</td>
<td>Grant</td>
<td><a href="mailto:ffgrant@sgh.com">ffgrant@sgh.com</a></td>
</tr>
<tr>
<td>Scott</td>
<td>Greenwood</td>
<td><a href="mailto:greenwoodms@ornl.gov">greenwoodms@ornl.gov</a></td>
</tr>
<tr>
<td>Donna</td>
<td>Guillen</td>
<td><a href="mailto:Donna.Guillen@inl.gov">Donna.Guillen@inl.gov</a></td>
</tr>
<tr>
<td>Anil</td>
<td>Gurgen</td>
<td><a href="mailto:agurgen@ncsu.edu">agurgen@ncsu.edu</a></td>
</tr>
<tr>
<td>Alexandria</td>
<td>Haddad</td>
<td><a href="mailto:awhadda@sandia.gov">awhadda@sandia.gov</a></td>
</tr>
<tr>
<td>Andrew</td>
<td>Hahn</td>
<td><a href="mailto:ashahn@sandia.gov">ashahn@sandia.gov</a></td>
</tr>
<tr>
<td>Botros</td>
<td>Hanna</td>
<td><a href="mailto:bn@nmsu.edu">bn@nmsu.edu</a></td>
</tr>
<tr>
<td>Leroy</td>
<td>Hardin</td>
<td><a href="mailto:roy.hardin@gmail.com">roy.hardin@gmail.com</a></td>
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<td>Leroy</td>
<td>Hardin</td>
<td><a href="mailto:roy.hardin@nrc.gov">roy.hardin@nrc.gov</a></td>
</tr>
<tr>
<td>Brennan</td>
<td>Harris</td>
<td><a href="mailto:brennan.harris@inl.gov">brennan.harris@inl.gov</a></td>
</tr>
<tr>
<td>Kurt</td>
<td>Harris</td>
<td><a href="mailto:kurt.harris@flibe-energy.com">kurt.harris@flibe-energy.com</a></td>
</tr>
<tr>
<td>Robert</td>
<td>Harwood</td>
<td><a href="mailto:robert.harwood@slingshotsimulations.co.uk">robert.harwood@slingshotsimulations.co.uk</a></td>
</tr>
<tr>
<td>Alex</td>
<td>Hashemian</td>
<td><a href="mailto:alex@ams-corp.com">alex@ams-corp.com</a></td>
</tr>
<tr>
<td>Hash</td>
<td>Hashemian</td>
<td><a href="mailto:hash@ams-corp.com">hash@ams-corp.com</a></td>
</tr>
<tr>
<td>Trey</td>
<td>Hathaway</td>
<td><a href="mailto:Alfred.Hathaway@nrc.gov">Alfred.Hathaway@nrc.gov</a></td>
</tr>
<tr>
<td>Gale</td>
<td>Hauck</td>
<td><a href="mailto:hauckge@ornl.gov">hauckge@ornl.gov</a></td>
</tr>
<tr>
<td>Jeff</td>
<td>Hawkins</td>
<td><a href="mailto:jeffhawkings@hawkconsulting.com">jeffhawkings@hawkconsulting.com</a></td>
</tr>
<tr>
<td>Robert</td>
<td>Hayes</td>
<td><a href="mailto:rbhayes@ncsu.edu">rbhayes@ncsu.edu</a></td>
</tr>
<tr>
<td>Joe</td>
<td>Heit</td>
<td><a href="mailto:joe.heit@aveva.com">joe.heit@aveva.com</a></td>
</tr>
<tr>
<td>Eric</td>
<td>Helm</td>
<td><a href="mailto:eric.helm@framatome.com">eric.helm@framatome.com</a></td>
</tr>
<tr>
<td>David</td>
<td>Henderson</td>
<td><a href="mailto:david.henderson@nuclear.energy.gov">david.henderson@nuclear.energy.gov</a></td>
</tr>
<tr>
<td>Peter</td>
<td>Henkes</td>
<td><a href="mailto:phenkes@wisc.edu">phenkes@wisc.edu</a></td>
</tr>
<tr>
<td>Richard</td>
<td>Henry</td>
<td><a href="mailto:richard.henry@opg.com">richard.henry@opg.com</a></td>
</tr>
<tr>
<td>Raul</td>
<td>Hernandez</td>
<td><a href="mailto:Raul.hernandez@nrc.gov">Raul.hernandez@nrc.gov</a></td>
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<tr>
<td>Matthew Hertel</td>
<td><a href="mailto:MHeretel@x-energy.com">MHeretel@x-energy.com</a></td>
<td></td>
</tr>
<tr>
<td>Dan Hoang</td>
<td><a href="mailto:dan.hoang@nrc.gov">dan.hoang@nrc.gov</a></td>
<td></td>
</tr>
<tr>
<td>Alec Holla</td>
<td><a href="mailto:alec.holla@npxinnovation.ca">alec.holla@npxinnovation.ca</a></td>
<td></td>
</tr>
<tr>
<td>Brooks Holland</td>
<td><a href="mailto:brooks.holland@inl.gov">brooks.holland@inl.gov</a></td>
<td></td>
</tr>
<tr>
<td>Zachary Hollcraft</td>
<td><a href="mailto:zachary.hollcraft@nrc.gov">zachary.hollcraft@nrc.gov</a></td>
<td></td>
</tr>
<tr>
<td>Philip Honnold</td>
<td><a href="mailto:phonnol@sandia.gov">phonnol@sandia.gov</a></td>
<td></td>
</tr>
<tr>
<td>Loren Howe</td>
<td><a href="mailto:loren.howe@nrc.gov">loren.howe@nrc.gov</a></td>
<td></td>
</tr>
<tr>
<td>Timothy Huddleston</td>
<td><a href="mailto:timothy.huddleston@inl.gov">timothy.huddleston@inl.gov</a></td>
<td></td>
</tr>
<tr>
<td>Nathanael Hudson</td>
<td><a href="mailto:Nathanael.Hudson@nrc.gov">Nathanael.Hudson@nrc.gov</a></td>
<td></td>
</tr>
<tr>
<td>Lauren Hughes</td>
<td><a href="mailto:lhughes@wpainc.com">lhughes@wpainc.com</a></td>
<td></td>
</tr>
<tr>
<td>John Hughey</td>
<td><a href="mailto:john.hughey@nrc.gov">john.hughey@nrc.gov</a></td>
<td></td>
</tr>
<tr>
<td>Clyde Huibregtse</td>
<td><a href="mailto:huibregtse@oklo.com">huibregtse@oklo.com</a></td>
<td></td>
</tr>
<tr>
<td>Amy Hull</td>
<td><a href="mailto:amy.hull@nrc.gov">amy.hull@nrc.gov</a></td>
<td></td>
</tr>
<tr>
<td>Matthew Humberstone</td>
<td><a href="mailto:Matthew.Humberstone@nrc.gov">Matthew.Humberstone@nrc.gov</a></td>
<td></td>
</tr>
<tr>
<td>Eman Ibrahim</td>
<td><a href="mailto:eman.ibrahim@canada.ca">eman.ibrahim@canada.ca</a></td>
<td></td>
</tr>
<tr>
<td>Mesfin Ibrahim</td>
<td><a href="mailto:mesfin.ibrahim@connect.polyu.hk">mesfin.ibrahim@connect.polyu.hk</a></td>
<td></td>
</tr>
<tr>
<td>Dan Isaacs</td>
<td><a href="mailto:dan@omg.org">dan@omg.org</a></td>
<td></td>
</tr>
<tr>
<td>Raj Iyengar</td>
<td><a href="mailto:raj.iyengar@nrc.gov">raj.iyengar@nrc.gov</a></td>
<td></td>
</tr>
<tr>
<td>Prashant Jain</td>
<td><a href="mailto:jainpk@ornl.gov">jainpk@ornl.gov</a></td>
<td></td>
</tr>
<tr>
<td>Nicholas Jameson</td>
<td><a href="mailto:nicholas.jameson@inl.gov">nicholas.jameson@inl.gov</a></td>
<td></td>
</tr>
<tr>
<td>Patty Jehle</td>
<td><a href="mailto:Patricia.Jehle@nrc.gov">Patricia.Jehle@nrc.gov</a></td>
<td></td>
</tr>
<tr>
<td>Mike Jenkinson</td>
<td><a href="mailto:mike.jenkinson@siemens.com">mike.jenkinson@siemens.com</a></td>
<td></td>
</tr>
<tr>
<td>Bob Jewart</td>
<td><a href="mailto:robert.jewart@inl.gov">robert.jewart@inl.gov</a></td>
<td></td>
</tr>
<tr>
<td>Daniel Ju</td>
<td><a href="mailto:daniel.ju@nrc.gov">daniel.ju@nrc.gov</a></td>
<td></td>
</tr>
<tr>
<td>Chul Hwan Jung</td>
<td><a href="mailto:chulhwan.jung@cnscccsn.gc.ca">chulhwan.jung@cnscccsn.gc.ca</a></td>
<td></td>
</tr>
<tr>
<td>Takanori Kajihara</td>
<td><a href="mailto:kajihara@tamu.edu">kajihara@tamu.edu</a></td>
<td></td>
</tr>
<tr>
<td>Aris Kalafatis</td>
<td><a href="mailto:aris.kalafatis@opg.com">aris.kalafatis@opg.com</a></td>
<td></td>
</tr>
<tr>
<td>Min-Tsung Kao</td>
<td><a href="mailto:kaom@ornl.gov">kaom@ornl.gov</a></td>
<td></td>
</tr>
<tr>
<td>Fuad Kassab Junior</td>
<td><a href="mailto:fuad.kassab@usp.br">fuad.kassab@usp.br</a></td>
<td></td>
</tr>
<tr>
<td>Maxine Keeffe</td>
<td><a href="mailto:maxine.keefe@nrc.gov">maxine.keefe@nrc.gov</a></td>
<td></td>
</tr>
<tr>
<td>Paul Keutelian</td>
<td><a href="mailto:paul@radiantnuclear.com">paul@radiantnuclear.com</a></td>
<td></td>
</tr>
<tr>
<td>Genghis Khan</td>
<td><a href="mailto:khan@ge.com">khan@ge.com</a></td>
<td></td>
</tr>
<tr>
<td>Hamed Khodadadi</td>
<td><a href="mailto:hakhodadadi1986@gmail.com">hakhodadadi1986@gmail.com</a></td>
<td></td>
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<tr>
<td>Anya Kim</td>
<td><a href="mailto:anya.kim@nrc.gov">anya.kim@nrc.gov</a></td>
<td></td>
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<tr>
<td>Paul Klein</td>
<td><a href="mailto:paul.klein@nrc.gov">paul.klein@nrc.gov</a></td>
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<tr>
<td>Brendan Kochunas</td>
<td><a href="mailto:bkochuna@umich.edu">bkochuna@umich.edu</a></td>
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<tr>
<td>Andrea Kock</td>
<td><a href="mailto:alk@nrc.gov">alk@nrc.gov</a></td>
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<tr>
<td>Alan Konkal</td>
<td><a href="mailto:alan.konkal@nrc.gov">alan.konkal@nrc.gov</a></td>
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<tr>
<td>Ben Kosbab</td>
<td><a href="mailto:bdkosbab@sgh.com">bdkosbab@sgh.com</a></td>
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<td>Ashish Kotwal</td>
<td><a href="mailto:ashish.kotwal@umd.edu">ashish.kotwal@umd.edu</a></td>
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<tr>
<td>Robert Krawczak</td>
<td><a href="mailto:krawczrk@westinghouse.com">krawczrk@westinghouse.com</a></td>
<td></td>
</tr>
<tr>
<td>Roman Kuchma</td>
<td><a href="mailto:wonderwouker@ukr.net">wonderwouker@ukr.net</a></td>
<td></td>
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<tr>
<td>Vineet Kumar</td>
<td><a href="mailto:kumarv@ornl.gov">kumarv@ornl.gov</a></td>
<td></td>
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<tr>
<td>Jonathan Kyle</td>
<td><a href="mailto:jonathan.kyle@ansys.com">jonathan.kyle@ansys.com</a></td>
<td></td>
</tr>
<tr>
<td>Wilson Lam</td>
<td><a href="mailto:wilsonlam.cns@gmail.com">wilsonlam.cns@gmail.com</a></td>
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</tr>
<tr>
<td>Jeffrey Lane</td>
<td><a href="mailto:lanejw@zachrynuclear.com">lanejw@zachrynuclear.com</a></td>
<td></td>
</tr>
<tr>
<td>John C Lane</td>
<td><a href="mailto:jcl1@nrc.gov">jcl1@nrc.gov</a></td>
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<tr>
<td>Kyoung</td>
<td>Lee</td>
<td><a href="mailto:leeko@ornl.gov">leeko@ornl.gov</a></td>
</tr>
<tr>
<td>David</td>
<td>Lefrancois</td>
<td><a href="mailto:david.lefrancois@alithya.com">david.lefrancois@alithya.com</a></td>
</tr>
<tr>
<td>John</td>
<td>Lehning</td>
<td><a href="mailto:jxl4@nrc.gov">jxl4@nrc.gov</a></td>
</tr>
<tr>
<td>Matthew</td>
<td>Levasseur</td>
<td><a href="mailto:mplevasseur@bwxt.com">mplevasseur@bwxt.com</a></td>
</tr>
<tr>
<td>Binghui</td>
<td>Li</td>
<td><a href="mailto:binghui.li@inl.gov">binghui.li@inl.gov</a></td>
</tr>
<tr>
<td>Jun</td>
<td>Liao</td>
<td><a href="mailto:liao@westinghouse.com">liao@westinghouse.com</a></td>
</tr>
<tr>
<td>Bruce</td>
<td>Lin</td>
<td><a href="mailto:bruce.lin@nrc.gov">bruce.lin@nrc.gov</a></td>
</tr>
<tr>
<td>Linyu</td>
<td>Lin</td>
<td><a href="mailto:linyu.lin@inl.gov">linyu.lin@inl.gov</a></td>
</tr>
<tr>
<td>Yong Chang</td>
<td>Liu</td>
<td><a href="mailto:liuyongchang@gmail.com">liuyongchang@gmail.com</a></td>
</tr>
<tr>
<td>Deleah</td>
<td>Lockridge</td>
<td><a href="mailto:lockridge@gmail.com">lockridge@gmail.com</a></td>
</tr>
<tr>
<td>Christopher</td>
<td>Lohse</td>
<td><a href="mailto:christopher.lohse@inl.gov">christopher.lohse@inl.gov</a></td>
</tr>
<tr>
<td>Chihang</td>
<td>Lu</td>
<td><a href="mailto:cihanglu@gmail.com">cihanglu@gmail.com</a></td>
</tr>
<tr>
<td>Louise</td>
<td>Lund</td>
<td><a href="mailto:Louise.Lund@nrc.gov">Louise.Lund@nrc.gov</a></td>
</tr>
<tr>
<td>Lee</td>
<td>Maccarone</td>
<td><a href="mailto:lmaccar@sandia.gov">lmaccar@sandia.gov</a></td>
</tr>
<tr>
<td>Shah</td>
<td>Malik</td>
<td><a href="mailto:Shah.Malik@nrc.gov">Shah.Malik@nrc.gov</a></td>
</tr>
<tr>
<td>Koushik</td>
<td>Manjunatha</td>
<td><a href="mailto:koushik.manjunatha@inl.gov">koushik.manjunatha@inl.gov</a></td>
</tr>
<tr>
<td>Koushik</td>
<td>Manjunatha</td>
<td><a href="mailto:koush91@gmail.com">koush91@gmail.com</a></td>
</tr>
<tr>
<td>C S</td>
<td>Manohar</td>
<td><a href="mailto:manohar@iisc.ac.in">manohar@iisc.ac.in</a></td>
</tr>
<tr>
<td>Jonathan</td>
<td>Marcano</td>
<td><a href="mailto:Jonathan.Marcano@nrc.gov">Jonathan.Marcano@nrc.gov</a></td>
</tr>
<tr>
<td>Josh</td>
<td>May</td>
<td><a href="mailto:josh@radiantnuclear.com">josh@radiantnuclear.com</a></td>
</tr>
<tr>
<td>Richard</td>
<td>Mcgrath</td>
<td><a href="mailto:RMCGRATH@EPRI.COM">RMCGRATH@EPRI.COM</a></td>
</tr>
<tr>
<td>Noreddine</td>
<td>Mesmous</td>
<td><a href="mailto:noreddine.mesmous@cnscccsn.gc.ca">noreddine.mesmous@cnscccsn.gc.ca</a></td>
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<tr>
<td>Ernest</td>
<td>Mileta</td>
<td><a href="mailto:Ernest.Mileta@opg.com">Ernest.Mileta@opg.com</a></td>
</tr>
<tr>
<td>Jessie</td>
<td>Milligan-Taylor</td>
<td><a href="mailto:Jessica.milligan-taylor@cnscccsn.gc.ca">Jessica.milligan-taylor@cnscccsn.gc.ca</a></td>
</tr>
<tr>
<td>Marwan</td>
<td>Mohamed</td>
<td><a href="mailto:marwan.mohamed@inl.gov">marwan.mohamed@inl.gov</a></td>
</tr>
<tr>
<td>Ricardo</td>
<td>Moreno</td>
<td><a href="mailto:ricardo.morenescudero@ge.com">ricardo.morenescudero@ge.com</a></td>
</tr>
<tr>
<td>Jawad</td>
<td>Moussa</td>
<td><a href="mailto:Jmoussa@unm.edu">Jmoussa@unm.edu</a></td>
</tr>
<tr>
<td>Alewyn</td>
<td>Mouton</td>
<td><a href="mailto:alewyn.mouton@opg.com">alewyn.mouton@opg.com</a></td>
</tr>
<tr>
<td>Raheel</td>
<td>Naqvi</td>
<td><a href="mailto:Raheel.naqvi@opg.com">Raheel.naqvi@opg.com</a></td>
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<tr>
<td>Curt</td>
<td>Nehrkorn</td>
<td><a href="mailto:curt.nehrkorn@hq.doe.gov">curt.nehrkorn@hq.doe.gov</a></td>
</tr>
<tr>
<td>Scott</td>
<td>Nelson</td>
<td><a href="mailto:nelsonsw@ornl.gov">nelsonsw@ornl.gov</a></td>
</tr>
<tr>
<td>Carl</td>
<td>Neuschaefer</td>
<td><a href="mailto:chneusch@aol.com">chneusch@aol.com</a></td>
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<td>Thien</td>
<td>Nguyen</td>
<td><a href="mailto:thien.duy.ng@gmail.com">thien.duy.ng@gmail.com</a></td>
</tr>
<tr>
<td>Daniel</td>
<td>Nichols</td>
<td><a href="mailto:daniel.nichols@nuclear.energy.gov">daniel.nichols@nuclear.energy.gov</a></td>
</tr>
<tr>
<td>Mirela</td>
<td>Nitoi</td>
<td><a href="mailto:mirela.nitoi@nuclear.ro">mirela.nitoi@nuclear.ro</a></td>
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<tr>
<td>Kerstun</td>
<td>Norman</td>
<td><a href="mailto:Kerstun.Norman@nrc.gov">Kerstun.Norman@nrc.gov</a></td>
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<tr>
<td>Alistair</td>
<td>Norris</td>
<td><a href="mailto:alistair.norris@jacobs.com">alistair.norris@jacobs.com</a></td>
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<tr>
<td>Jesus M</td>
<td>Nunez</td>
<td><a href="mailto:jesus@nuclearalternativeproject.org">jesus@nuclearalternativeproject.org</a></td>
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<tr>
<td>Bill</td>
<td>Obaker</td>
<td><a href="mailto:obakerwr@westinghouse.com">obakerwr@westinghouse.com</a></td>
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<td>Joe</td>
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<td><a href="mailto:joseph.oncken@inl.gov">joseph.oncken@inl.gov</a></td>
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<td>One</td>
<td><a href="mailto:yadav.vaibhav@gmail.com">yadav.vaibhav@gmail.com</a></td>
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<tr>
<td>Ekaterina</td>
<td>Paladi</td>
<td><a href="mailto:Ekaterina.paladi@metroscope.tech">Ekaterina.paladi@metroscope.tech</a></td>
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<tr>
<td>Pallavi</td>
<td>Pandey</td>
<td><a href="mailto:pallavi@iisc.ac.in">pallavi@iisc.ac.in</a></td>
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<td>Panicker</td>
<td><a href="mailto:panickerns@ornl.gov">panickerns@ornl.gov</a></td>
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<tr>
<td>Sara</td>
<td>Perez-Martin</td>
<td><a href="mailto:sara.perez@kit.edu">sara.perez@kit.edu</a></td>
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<td><a href="mailto:eternity@ams-corp.com">eternity@ams-corp.com</a></td>
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<td><a href="mailto:angelica.petrovic@inl.gov">angelica.petrovic@inl.gov</a></td>
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<td>Jeffrey Poehler</td>
<td><a href="mailto:jeffrey.poehler@nrc.gov">jeffrey.poehler@nrc.gov</a></td>
<td>Joseph Poisson</td>
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<td>Craig Primer</td>
<td><a href="mailto:craig.primer@inl.gov">craig.primer@inl.gov</a></td>
<td>Anthony Qualantone</td>
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<tr>
<td>Ivan Price</td>
<td><a href="mailto:irprice@sandia.gov">irprice@sandia.gov</a></td>
<td>Majdi Radaideh</td>
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<tr>
<td>Dylan Prevost (Doe)</td>
<td><a href="mailto:dylan.prevost@nuclear.energy.gov">dylan.prevost@nuclear.energy.gov</a></td>
<td>Ravi Raveendra</td>
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<tr>
<td>Florencia Renteria</td>
<td><a href="mailto:florenciareng@gmail.com">florenciareng@gmail.com</a></td>
<td>Gustavo Reyes (Inl)</td>
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<tr>
<td>Will S</td>
<td><a href="mailto:coinbird@gmail.com">coinbird@gmail.com</a></td>
<td>Dagistan Sahin</td>
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<tr>
<td>Suman Saurav</td>
<td><a href="mailto:sumanjiseie@gmail.com">sumanjiseie@gmail.com</a></td>
<td>Abhinac Saxena</td>
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<tr>
<td>Aurelien Schwartz</td>
<td><a href="mailto:aurelien.schwartz@metroscope.tech">aurelien.schwartz@metroscope.tech</a></td>
<td>Ting-Leung Sham</td>
</tr>
<tr>
<td>Paul Sireanni</td>
<td><a href="mailto:sirenpm@westinghouse.com">sirenpm@westinghouse.com</a></td>
<td>Paul Siwy</td>
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<tr>
<td>Sharon Soogrim</td>
<td><a href="mailto:sharon.soogrim@nrc.gov">sharon.soogrim@nrc.gov</a></td>
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<td><a href="mailto:christopher.spirito@inl.gov">christopher.spirito@inl.gov</a></td>
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<td>Antoanela</td>
<td><a href="mailto:antoanela.stoica@cne.ro">antoanela.stoica@cne.ro</a></td>
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<td>Craig</td>
<td><a href="mailto:cstover@epri.com">cstover@epri.com</a></td>
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<tr>
<td>Molly</td>
<td><a href="mailto:Molly.J.Strasser@xcelenergy.com">Molly.J.Strasser@xcelenergy.com</a></td>
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<tr>
<td>Cheng</td>
<td><a href="mailto:cheng.sun@inl.gov">cheng.sun@inl.gov</a></td>
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<td>Xiaodong</td>
<td><a href="mailto:xdsun@umich.edu">xdsun@umich.edu</a></td>
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<tr>
<td>Richard</td>
<td><a href="mailto:richard.szoch@exeloncorp.com">richard.szoch@exeloncorp.com</a></td>
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<td>Emre</td>
<td><a href="mailto:tatlie@westinghouse.com">tatlie@westinghouse.com</a></td>
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<td>James</td>
<td><a href="mailto:james@radiantnuclear.com">james@radiantnuclear.com</a></td>
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<td>Ricardo</td>
<td><a href="mailto:richardo.torres@nrc.gov">richardo.torres@nrc.gov</a></td>
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<td>Robert</td>
<td><a href="mailto:robert.tregoning@nrc.gov">robert.tregoning@nrc.gov</a></td>
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<td>Rizwan</td>
<td><a href="mailto:rizwan@illinois.edu">rizwan@illinois.edu</a></td>
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<td>Christopher</td>
<td><a href="mailto:christopher.ulmer@nrc.gov">christopher.ulmer@nrc.gov</a></td>
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<td>Troy</td>
<td><a href="mailto:troy.unruh@inl.gov">troy.unruh@inl.gov</a></td>
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<tr>
<td>Bob</td>
<td><a href="mailto:bob@radiantnuclear.com">bob@radiantnuclear.com</a></td>
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<tr>
<td>Johannes</td>
<td><a href="mailto:johannes.vanderwatt@und.edu">johannes.vanderwatt@und.edu</a></td>
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<tr>
<td>Stephen</td>
<td><a href="mailto:svaughn@x-energy.com">svaughn@x-energy.com</a></td>
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<tr>
<td>Justin</td>
<td><a href="mailto:Justin.Vazquez@nrc.gov">Justin.Vazquez@nrc.gov</a></td>
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<td>Swetha</td>
<td><a href="mailto:swethav@iisc.ac.in">swethav@iisc.ac.in</a></td>
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<td><a href="mailto:rattehalli.vijay@unnpp.gov">rattehalli.vijay@unnpp.gov</a></td>
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<tr>
<td>Purna</td>
<td><a href="mailto:purnavindhya@iisc.ac.in">purnavindhya@iisc.ac.in</a></td>
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<tr>
<td>Nurali</td>
<td><a href="mailto:nurali.virani@ge.com">nurali.virani@ge.com</a></td>
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<tr>
<td>Ikka</td>
<td><a href="mailto:ikka.virkkunen@aalto.fi">ikka.virkkunen@aalto.fi</a></td>
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<tr>
<td>Cody</td>
<td><a href="mailto:cody.walker@inl.gov">cody.walker@inl.gov</a></td>
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<tr>
<td>William</td>
<td><a href="mailto:william.walsh@nuclear.energy.gov">william.walsh@nuclear.energy.gov</a></td>
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<td><a href="mailto:weijun.wang@nrc.gov">weijun.wang@nrc.gov</a></td>
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<td>Justin</td>
<td><a href="mailto:weinmeister@ornl.gov">weinmeister@ornl.gov</a></td>
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<td>Cindy</td>
<td><a href="mailto:ckwellenbrock@gmail.com">ckwellenbrock@gmail.com</a></td>
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<td>Timothy</td>
<td><a href="mailto:timothy.west@inl.gov">timothy.west@inl.gov</a></td>
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<tr>
<td>Chad</td>
<td><a href="mailto:cmwilhel@bechtel.com">cmwilhel@bechtel.com</a></td>
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<tr>
<td>Katherine</td>
<td><a href="mailto:katherine.wilsdon@inl.gov">katherine.wilsdon@inl.gov</a></td>
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</tr>
<tr>
<td>Paul</td>
<td><a href="mailto:paul.witherell@nist.gov">paul.witherell@nist.gov</a></td>
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<tr>
<td>Brian</td>
<td><a href="mailto:brian.wittick@nrc.gov">brian.wittick@nrc.gov</a></td>
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<tr>
<td>Jennifer</td>
<td><a href="mailto:jennifer.wong@opg.com">jennifer.wong@opg.com</a></td>
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<tr>
<td>Vaibhav</td>
<td><a href="mailto:vaibhav.yadav@inl.gov">vaibhav.yadav@inl.gov</a></td>
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<td>Xingyue</td>
<td><a href="mailto:xingyue.yang@inl.gov">xingyue.yang@inl.gov</a></td>
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<td>Matthew</td>
<td><a href="mailto:Matthew.Yarlett@Westinghouse.com">Matthew.Yarlett@Westinghouse.com</a></td>
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<tr>
<td>Jordan</td>
<td><a href="mailto:jordan.zenenko@opg.com">jordan.zenenko@opg.com</a></td>
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<tr>
<td>Jack</td>
<td><a href="mailto:jack.zhao@nrc.gov">jack.zhao@nrc.gov</a></td>
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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

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<tr>
<th>Day 1</th>
<th>Day 2</th>
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<tr>
<td><strong>Tuesday, September 14th</strong></td>
<td><strong>Wednesday, September 15th</strong></td>
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<td><strong>11:00 - 11:15</strong></td>
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<td>Introduction and Opening Remarks: NRC</td>
<td>Technical Session</td>
<td>Panel Session</td>
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<td>Use Cases of Digital Twin Enabling Technologies in Nuclear Power Plants</td>
<td>Steps Toward Regulatory Realization of Digital Twins</td>
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<td>12:45 Closing Remarks: NRC</td>
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<td>Advanced Sensors &amp; Instrumentations</td>
<td>Digital Twin Enabling Technologies in Advanced Reactor Applications</td>
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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

2019 Results
44% Lower Carbon Emissions

2030 Goal
80% Lower Carbon Emissions

2050 Vision
100% Carbon-Free Electricity

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
Collaboration to Accelerate the Top 4 Innovations

**Machine Learning/Big Data**
EPRI Contact: Thiago Seuaciuc-Osorio
tseuaciuc-osorio@epri.com

**Framework to Share Comparable, Reliable Data**
EPRI Contact: Rob Austin
raustin@epri.com

**Digital Twinning**
EPRI Contact: Hasan Charkas,
hcharkas@epri.com

**Advanced Manufacturing**
EPRI Contact: David Gandy,
dgandy@epri.com
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

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.
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?
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)

- Enabling technologies like AI and ML as well as data analytics are important for ensuring successful DT applications
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The key question: where does it make sense to use DTs? (Technology readiness, cost benefits, and priorities)
SCOTT SIDENER
CONSULTING ENGINEER, DIGITAL INNOVATION

WESTINGHOUSE ELECTRIC COMPANY
Exelon Nuclear Innovation Projects Overview
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**

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

**INNOVATION CAPABILITY & CULTURE**
- Innovation Program with the new Constellation
- Innovation Solution Value Capture and Sustainability

**CONNECTED MOBILE WORKFORCE**
- Expand Use of Smart Procedures
- Future of Work Instructions
Exelon Nuclear Innovation Focus on Value

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

BPM Apps

Potential to achieve significant annual savings

Several dozen projects implemented

Analytics

Large Savings

Significant annual benefit

Wireless sensors and carts

Exelon Smart Procedures

Significant annual savings at full implementation

1000 procedures executed so far

Estimated >40,000 hours saved annually by end of 2022

Thousands per site

Spark Win Transform

Exelon Generation
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

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 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

On track for achieving > $10M in annual savings by the end of 2023

OPS 80% complete with initial implementation

Chem & Maint 50% complete with initial implementation

500+ Procedures issued

1,000+ instances completed in the field

2,000 iPads setup via JAMF and issued
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**

Analytic Characterization

Integration with existing practice
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.
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
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

Program Impact

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

Program Targets

<table>
<thead>
<tr>
<th>Metric</th>
<th>From</th>
<th>To</th>
</tr>
</thead>
<tbody>
<tr>
<td>Automation ↓ labor costs</td>
<td>None</td>
<td>Automated workorders ... ↓ Planning staff Online calibration ... ↓ Tech and admin staff</td>
</tr>
<tr>
<td>Predictive Maintenance ↓ labor &amp; mat’l</td>
<td>Alarms</td>
<td>↓Forced outages &amp; trips ... AI-driven predictive algorithms → ↓ Labor headcount</td>
</tr>
<tr>
<td>Trust</td>
<td>Human</td>
<td>Humble &amp; explainable AI ... quantify uncertainty to establish trust in the models &amp; encourage automation</td>
</tr>
</tbody>
</table>

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
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
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
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. Physical Robot
2. Physical maintenance equipment

**SR 2**
Physical demonstration 1

**AWS**
Component creation, manipulation and “reality - feedback”

**IRTC**
Virtual Construct

**ORNL 3**
Physical demonstration 2

**Virtual**
Physical replicates

**SRI: ML FOR AUTOMATED MAINTENANCE OF FUTURE MSR**

Establish baseline, vendor agnostic methodologies
Look to solve two (2) problem sets
1. Robot positioning
2. Tracking via reinforcement learning (RL)

**DEFT & SR**
Algorithm development

**Physical Robot**

**Physical demonstration 1**

**Virtual replicates**

**ORNL 3**
Physical demonstration 2

**Virtual**
Physical replicates

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

- Reality Capture (drone+laser scanner)
- 4D BIM
- Integrated Project Site Model

CPMS
- Decision Making
- Digital Records Management
- Advances through AI/ML

Manufacturing Site

Quality Control

 reality capture
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.

<table>
<thead>
<tr>
<th>Metric</th>
<th>State of the Art</th>
<th>Proposed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fixed O&amp;M cost</td>
<td>$20/MWh for light-water reactor (LWR) fleet</td>
<td>&lt; $10/MWh for more mature ARs</td>
</tr>
<tr>
<td></td>
<td></td>
<td>&lt; $5/MWh for less mature ARs</td>
</tr>
<tr>
<td>Design life for major</td>
<td>30 – 40 years for PWR steam generator</td>
<td>Major SSCs &lt; 15 years</td>
</tr>
<tr>
<td>plant components</td>
<td>60+ years for RPV</td>
<td>No life limiting SSCs</td>
</tr>
<tr>
<td></td>
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</tbody>
</table>
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.
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
First, we use a model to build live symptoms for the plant

\[ \text{measurements} - \text{expected values} = \text{symptoms} \]

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

\[ \text{diagnostics} = P(\text{failures} | \text{symptoms}) \]

Failures are classified by magnitude, impact and likelihood.
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.
The inferential engine performs a root causes analysis of underlying problems, through the analysis of the symptoms. It solves the following probability: \( P(\text{failure } 1, \text{ failure } 2, \ldots \text{ failure } p \mid \text{ Symptoms}) \)
The software

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

Eric Helm
Principal Investigator

Todd Matthews
TH Modeling and Application Developer

Pascal Brocheny
TH Modeling

Mary Beth Baker
Project Manager

Builds the digital twin and preforms the research work

Provides diagnostics technology and software platform

Provides cyber-digital asset test data and technical consultation
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
Advanced Sensors and Instrumentation for Digital Twin applications

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

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

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

- **Big Data, Machine Learning, Artificial Intelligence**
  - Machine learning and artificial intelligence processes to enable semi-autonomous operation and maintenance by design.

- **Advanced Control Systems**
  - Enable near real-time control of plant or experiments process variables to enhance performance.

IDAHO NATIONAL LABORATORY
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
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

- AUTOMATED CONTROL
  - Supervisory algorithm

- PERFORMANCE MONITORING
  - Physics-based pattern recognition

- OFF-NORMAL DECISION MAKING
  - Reinforcement Learning

- EQUIPMENT HEALTH MONITORING
  - Automated reasoning diagnostics

- MAINTENANCE SHEDULING
  - Markov Process optimization
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

IDAHO NATIONAL LABORATORY
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, AGRS/6/7, ATRC, and MITR (FY22)

Self Power Detectors

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)

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

---

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

<table>
<thead>
<tr>
<th>Performance Parameter</th>
<th>Performance Requirement Stand-Alone Application</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Temperature Range</strong></td>
<td>Room Temperature - 1600°C</td>
</tr>
<tr>
<td>Accuracy</td>
<td>Not Specified</td>
</tr>
<tr>
<td><strong>Drift</strong></td>
<td>3% for 4.5 x 10^{21} nvt (thermal)</td>
</tr>
<tr>
<td><strong>Life</strong></td>
<td>4.5 x 10^{21} nvt (thermal), or 10 thermal shocks (room temperature to 1600°C)</td>
</tr>
<tr>
<td><strong>Mechanical Ruggedness:</strong></td>
<td></td>
</tr>
<tr>
<td>Rugged Junction</td>
<td>Rugged mechanical junction design</td>
</tr>
<tr>
<td>Bend Radius</td>
<td>Minimum of 0.5 inch</td>
</tr>
<tr>
<td>Thermal Shock</td>
<td>5 sudden startups and 5 sudden shutdowns—each causing a thermal shock on the order of room temperature up to 1600°C</td>
</tr>
<tr>
<td><strong>Response Time</strong></td>
<td>&lt;0.5 seconds</td>
</tr>
</tbody>
</table>
**Technology demonstration – acoustic sensors**

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

- Ultrasound based sensors enable distributed temperature measurements up to 2200°C
- 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

- 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)
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

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

Spatially resolved time dependence:
- Black traces are radially closer to fuel
- Excellent symmetry
- Effects of heat sink become more important after 1 min
Technology development

- 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

- 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

Radiation Endurance Ultrasonic Transducer, X-wave Innovation Inc

- 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

Thermoelectric generators (TEGs) for power harvesting

- 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 through NSUF funded project

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

Material removal on inside of elbow

Thermocouples installed on outside diameter

Direct Digital Printing of Passive Wireless Sensors

- Passive wireless sensor technology developed and fabricated at ORNL
- Demonstration included two-antenna relay for communication / sensing through RF-opaque materials

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

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

KEY METRICS

<table>
<thead>
<tr>
<th></th>
<th>Half-Heusler TEG</th>
<th>COMMERCIAL TEG</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power density (W/cm²)</td>
<td>2-3</td>
<td>0.2-0.3</td>
</tr>
<tr>
<td>Max Operating temp</td>
<td>650 °C</td>
<td>250 °C</td>
</tr>
</tbody>
</table>

Courtesy of Uday Singh and Dan Xiang, SBIR grants recipients
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.
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
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)
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 ~3X10²¹ n/cm²
  - 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

---

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
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

Neutron flux = 1e14 n/cm²/sec
Coolant temperature = 300°C
Component max temperature (gamma heating) ~ 500°C

Sensor frequency accurately tracks internal thermocouple and reactor power.
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
Temperature & Gamma Irradiation Test

High temperature oven & data acquisition system

- Minimal to no change in inductance values
- Slight increase in inductor’s series resistance

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

Blue – TC
Purple - Sensor

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
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
VERIFYING COMPLIANCE THROUGH TECHNOLOGY

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

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

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

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

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

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)
Questions?

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

Process Model

Input Model

Plant Model

Initial Design

Start Here

???
I&C Systems Engineering Process Flow + Digital Twin Toolsets

Early Stage
- Large Changes

1. Concept Development
2. Requirements Engineering
3. System Architecture
4. System Design & Development
5. System Integration
6. Test & Evaluation
7. Transition Operation & Maintenance

Late Stage
- Small Changes

- P&ID and Design Specifications
- Transient Analysis
- Physics Simulation

- Early Stage Changes
- Late Stage Changes

- Plant Historian + AI / ML Models
DT Enabled Design by Analysis: IPS Trip Setpoints

1. **Initial Plant Model (Digital Twin)**
2. **Steady State Simulation**
3. **Simulate Open Loop Transient**
4. **Select IPS Sensors & Actuators**
5. **Select Initial IPS Setpoints**

- **No**
- **Adjust IPS Setpoints**

6. **Improved Plant Model (Digital Twin)**
7. **Simulate Protected Transient**
8. **Evaluate Plant Response**
9. **Within Margin?**
   - **Yes**
   - **No**

- **Approve IPS Setpoints**

**External Development Cycle**
## DT Enabled Design by Analysis: Control Trade Study

### Common

<table>
<thead>
<tr>
<th>Controlled Variable</th>
<th>Manipulated Variable</th>
<th>Secondary Variable</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feedwater Valve dP</td>
<td>Feedwater Pump Speed</td>
<td>Feedwater Valve Flow</td>
</tr>
<tr>
<td>Deaerator Level</td>
<td>CIFW Valve Position</td>
<td>CIFW Flow</td>
</tr>
<tr>
<td>Deaerator Pressure</td>
<td>HPT Valve Position</td>
<td>HPT Valve Flow</td>
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<tr>
<td>FWP Recirculation Flow</td>
<td>FWP Recirculation Valve Position</td>
<td>Flow/Speed Ratio</td>
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<tr>
<td>Turbine Header Pressure</td>
<td>Turbine Bypass Valve</td>
<td>N/A</td>
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### Option 1

<table>
<thead>
<tr>
<th>Controlled Variable</th>
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<td>Main Steam Pressure</td>
<td>Feedwater Valve Position</td>
<td>Feedwater Flow</td>
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<td>Reactor Outlet Temperature</td>
<td>Control Rod Depth</td>
<td>Reactor Power</td>
</tr>
<tr>
<td>Main Steam Temperature</td>
<td>Circulator Speed</td>
<td>Helium Mass Flow</td>
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<tr>
<td>Turbine Power</td>
<td>Turbine Throttle Valve Position</td>
<td>Steam Flow</td>
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### Option 2

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<td>Turbine Power</td>
<td>Turbine Throttle Valve Position</td>
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### Option 3

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<td>Feedwater Flow</td>
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<td>Control Rod Depth</td>
<td>Reactor Power</td>
</tr>
<tr>
<td>Turbine Power</td>
<td>Turbine Throttle Valve Position</td>
<td>Steam Flow</td>
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### Option 4 (THTR)

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<td>Circulator Speed</td>
<td>Helium Mass Flow</td>
</tr>
<tr>
<td>Reactor Inlet Temperature</td>
<td>Feedwater Valve Position</td>
<td>Feedwater Flow</td>
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<tr>
<td>Main Steam Temperature</td>
<td>Control Rod Depth</td>
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<tr>
<td>Turbine Power</td>
<td>Turbine Throttle Valve Position</td>
<td>Steam Flow</td>
</tr>
</tbody>
</table>
DT Enabled Design by Analysis: Xe-100 Next Steps
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
Step 1. Determine if calibration is needed
Step 2. Calibrate if needed

OLM
Step 1. Determine if calibration is needed
Step 2. Calibrate if needed
## Typical OLM Results

<table>
<thead>
<tr>
<th>Item</th>
<th>Group Name</th>
<th>Tag Name</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>SG C OUTLET PRESSURE</td>
<td>PT0494</td>
<td>Good</td>
</tr>
<tr>
<td>2</td>
<td>SG C OUTLET PRESSURE</td>
<td>PT0495</td>
<td>Good</td>
</tr>
<tr>
<td>3</td>
<td>SG C OUTLET PRESSURE</td>
<td>PT0496</td>
<td>Good</td>
</tr>
<tr>
<td>4</td>
<td>PRESSURIZER LEVEL</td>
<td>LT0459</td>
<td>Good</td>
</tr>
<tr>
<td>5</td>
<td>PRESSURIZER LEVEL</td>
<td>LT0460</td>
<td>Good</td>
</tr>
<tr>
<td>6</td>
<td>PRESSURIZER LEVEL</td>
<td>LT0461</td>
<td>Good</td>
</tr>
<tr>
<td>7</td>
<td>PRESSURIZER PRESSURE</td>
<td>PT0455</td>
<td>Bad</td>
</tr>
<tr>
<td>8</td>
<td>PRESSURIZER PRESSURE</td>
<td>PT0456</td>
<td>Good</td>
</tr>
<tr>
<td>9</td>
<td>PRESSURIZER PRESSURE</td>
<td>PT0457</td>
<td>Good</td>
</tr>
<tr>
<td>10</td>
<td>PRESSURIZER PRESSURE</td>
<td>PT0444A</td>
<td>Good</td>
</tr>
<tr>
<td>11</td>
<td>PRESSURIZER PRESSURE</td>
<td>PT0445A</td>
<td>Good</td>
</tr>
</tbody>
</table>
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
OLM Checks Calibration Over Much of a Transmitter Operating Range
OLM Analysis at Startup
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
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

<table>
<thead>
<tr>
<th>Cycle</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
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<tbody>
<tr>
<td>Existing</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
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<tr>
<td>Sizewell</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>AMS OLM TR</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
</tbody>
</table>
History of Transmitter Calibration Interval Extension

1990
- EPRI ICMP Millstone (1989)
- NUREG/CR-6343 McGuire

1995
- EPRI TR-104965-R1 NRC SER

2000
- Sizewell B Regulatory Approval

2005
- PWROG PA-SEE-0625 (2019)

2010
- AMS-TR-0720 (2021)

2015

2020
Thank You!

Questions?
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
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.

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

Potential Benefits
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.
Integrated Risk-informed Condition-based Maintenance Capability and Automated Platform

Accomplishments – Wireless Vibration Sensor Installation
Accomplishments – Preventive Maintenance Optimization

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

- 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
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.
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.
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

- Risk Informed Condition Based Maintenance Approach
- Risk Informed Optimized Maintenance Frequency Approach
- Developed Fault Signatures
- Machine Learning Algorithms
- Diagnosis Capability
- Prognosis Capability
- Updated Risk Model
- GOAL 1
- GOAL 2
- GOAL 3
- Data Ingestion & Digital Architecture/Infrastructure
- Additional Sensor Data
- Dataset complete?
- Platform Requirements
- Developed User Interface
- Auto-Generated Work Packages
- Integrated Parts Management
- Risk Model
- Bayesian Regression
- Risk Modeling (Dynamic PRA)
- Risk Informed Maintenance Optimization
- Assets and data determination
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.
QUESTIONS?

Contact Information

Matthew Yarlett - PKMJ Technical Services
Email: Matthew.Yarlett@westinghouse.com

Vivek Agarwal, PhD - Idaho National Laboratory
Email: Vivek.Agarwal@inl.gov

Harry Palas - Public Service Enterprise & Group (PSEG) Nuclear
Email: Harry.Palas@pseg.com
References


Artificial Intelligence (AI) Driven Scalable Condition based Predictive Maintenance Strategy
Vision of Risk-informed Predictive Maintenance (PdM) Strategy

Data Analytics at Scale and Digital Twin

Condition based PdM Flowchart

A schematic representation of a Digital Twin module

Physics based Modeling

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

(a) Top and bottom bearing housings  
(b) Motor shaft and other components  
(c) Motor shaft bearings

Physics Driven model:  
Requires: 1. domain knowledge (material, size etc.)  
2. close interaction with operators

Simplified numerical model for motor, pump, and shaft coupling

Shaft bearings
Simplified motor rotor and stator
Motor shaft
Pump shaft
Shaft coupling
Simplified pump submersible components
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

Scalable Condition based PdM

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

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

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.

Few Challenges to Consider

Lack of good quality data for different fault modes

Lack of synchronization: data and manually entered fault logs, and cloud level synchronization

Data imbalance

Lack of model generalization

Inaccurate model interpretations: Ex. Biased predictions
Team

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

Contact Information:
Koushik A. Manjunatha
koushik.manjunatha@inl.gov
Idaho National Laboratory
THERMAL PERFORMANCE MANAGEMENT FOR NUCLEAR POWER PLANTS WITH DIGITAL TWINS

Use Cases based on EDF experience

09/15/21

Dr Christophe Duquennoy
Nuclear Fleet Thermal Performance Expert
christophe.duquennoy@edf.fr
THERMAL PERFORMANCE MANAGEMENT FOR NUCLEAR POWER PLANTS WITH DIGITAL TWINS

Use Cases based on EDF experience

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
christophe.duquennoy@edf.fr
INTRODUCTION
DIGITAL TWINS FOR THERMAL PERFORMANCE

Thermodynamic Performance Testing and monitoring

- Thermodynamic measurement for NPP
- Performance monitoring, production and maintenance optimization
INTRODUCTION
DIGITAL TWINS FOR THERMAL PERFORMANCE
FIG. 12. Thermal model (with sensors)
INTRODUCTION

DIGITAL TWINS FOR THERMAL PERFORMANCE
INTRODUCTION
DIGITAL TWINS FOR THERMAL PERFORMANCE
INTRODUCTION
DIGITAL TWINS FOR THERMAL PERFORMANCE
INTRODUCTION
DIGITAL TWINS FOR THERMAL PERFORMANCE

2014 Diagnostic methodologies

Δvile
Δsref
Δo2extrac
ΔPpcrf
ΔTif
INTRODUCTION
DIGITAL TWINS FOR THERMAL PERFORMANCE
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
“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
INTRODUCTION
DIGITAL TWINS FOR THERMAL PERFORMANCE
The software combines a Digital Twin of the process and AI to perform a diagnosis in operations

\[ \text{Digital twin} + \text{AI} = \text{Diagnosis} \]

The software uses existing information from sensors to analyze the plant performance and diagnose underlying causes impairing the expected behavior of the process.
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'Energie 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.
METROSCOPE – DEPLOYEMENT ON EDF FLEET

- **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.
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 occurred (2015 December 14th). It was not detected by operators.
- A loss 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

HP Heater 602 leak
MSR tank 101 leak
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

Leak of ACO0027VL valve

Performance

Avoidable loses ~ 8 GWh

First detection by METROSCOPE

Leak Repaired

Partial resolution

Full resolution
• Simultaneous Multiple Diagnostic
• Accurate Quantification of condenser losses due to updated reference Digital Twins

Performance
Avoidable losses 1 mbar = 1MWe
• 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
HEATERS TUBE RUPTURE

- Early detection (2 or 3 weeks)
- Real-time monitoring of 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

---

First Tube rupture

Tubes plugging
LOW HP HEATERS LEVEL

- Situation before METROSCOPE not seen and solved by operators
- Detection of low level situations by METROSCOPE
HP HEATERS LEVEL REGULATION

- Real time detection of low level situations by METROSCOPE
- Optimization plant adjustment by operators
• 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 abnormally closed (GSS009VV)

MSR Ventilation re-openned

METROSCOPE commissionning 06/21/19
MSR VENTILATION LEAK

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

Performance

Avoidable loses  0.4 GWh
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 (Knowledge capitalization)
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
All diagnosis from physical Simulation

Numerical model plugged in the Metroscope for live diagnosis

CONCLUSION
TOMORROW – COOLING TOWER MONITORING WITH METROSCOPE

www.metroscope.tech
CONCLUSION
TOMORROW – COOLING TOWER MONITORING WITH METROSCOPE

Develop Defect models

Use available data to validate
## SYNTHETIC OVERVIEW OF SERVICES PROVIDED BY SPA

<table>
<thead>
<tr>
<th>SERVICE PROVIDED</th>
<th>ESTIMATION OF THE GAIN</th>
<th>LEVEL OF INVOLVEMENT</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>REDUCTION OF PROCESSING TIME OF INCIDENTAL DEFECT</strong></td>
<td>5 GWh/ major defect 20 GWh/other defect 4 major defects/year</td>
<td>trained operator + time required for level 1 support + functional SPA analysis</td>
</tr>
<tr>
<td><strong>OPTIMISATION OF MAINTENANCE CHOICES</strong></td>
<td>20 GWh/maintenance 3 situations /years</td>
<td>competent support engineers + time required for level 2 support</td>
</tr>
<tr>
<td><strong>PRODUCTION FORECAST / OPTIMISATION CHOICES DURING CRISIS</strong></td>
<td>Difficult to quantify</td>
<td>competent engineering unit+ Time required to go further in the analysis</td>
</tr>
<tr>
<td>** FEEDBACKS ON DESIGN CHOICES**</td>
<td>Gain of 0,2°C ↔ 160 GWh over 30 years</td>
<td>competent engineering unit+ + expertise on operation+ design engineering</td>
</tr>
</tbody>
</table>
## Synthetic Overview of Services Provided by SPA + Metroscope

<table>
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<th>Estimation of the Gain</th>
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<tr>
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<td>Difficult to quantify</td>
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</tr>
<tr>
<td>Feedbacks on Design Choices</td>
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<td>competent engineering unit + expertise on operation + design engineering</td>
</tr>
</tbody>
</table>
THANK YOU!

Any questions?
APPENDIX
Asset Management and O&M support through expertise and advanced DATA acquisition diagnosis and prediction

Dr Yves-Laurent BECK
Fleetwide eMonitoring Program Manager
Global Product Manager on Power Block Monitoring
yves-laurent.beck@edf.fr

Dr Christophe Duquennoy
Nuclear Fleet Thermal Performance Expert
christophe.duquennoy@edf.fr
Our mission

- 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

3 MAIN FIELDS:

**MEASUREMENT**
- Measurement engineering, metrology, data bases

**INSPECTION**
- Monitoring on behalf of operators

**EXPERTISE**
- Diagnosis, pronostics & consulting for operators and maintenance teams

FROM DIAGNOSIS TO FORECASTS
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)
THERMODYNAMIC DIAGNOSIS AND PROGNOSIS

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

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

DESIGN & O&M Support Services
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
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
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.
Together...Shaping the Future of Energy™
NDE4.0 and Machine Learning for In-service Inspections
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
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

Aalto University
School of Engineering
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
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

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
Digital Twin Enabling Technologies in Advanced Reactor Applications

Xe-100 Digital Technologies Overview

Ian Davis, Senior Digital Twin Systems Engineer  

September 15, 2021
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).
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
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

1. Concept Development
2. Requirements Engineering
3. System Architecture
4. System Design & Development
5. System Integration
6. Test & Evaluation
7. Transition Operation & Maintenance
Systems Engineering with Xe-100 Digital Twin

(Now) Design

Concept Development → Requirements Engineering → System Architecture → System Design & Development

System Integration → Test & Evaluation → Transition Operation & Maintenance

Operations & Maintenance
Systems Engineering with Digital Twin: Maintenance

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

Ex: What is maintenance burden for Feedwater pumps?

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

Analysis suggests additional instruments be added for better monitoring coverage.

Xe-100 Digital Twin

Outage / Major Maintenance Burden for 4 Xe-100 units
Systems Engineering with Digital Twin: Security

Ex: What does an attempted sabotage event look like?

Security Analysis


Xe-100 Design Docs

Sandia Tool Suite

Xe-100 Digital Twin
Deep Neural Networks (DNNs) to support plant operation

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

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

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)

Convolutional Neural Network (Convnet)

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)
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

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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.

Need Human Help

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


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

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

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

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

<table>
<thead>
<tr>
<th>#</th>
<th>Types of Support</th>
<th>Guard against</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Input anomaly</td>
<td>• Input drift</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Extrapolation</td>
</tr>
<tr>
<td>2</td>
<td>Reconstruction error</td>
<td>• Input drift</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Extrapolation</td>
</tr>
<tr>
<td>3</td>
<td>Geometric neighborhood in embeddings</td>
<td>• Extrapolation</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Ambiguity</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Adversarial manipulations</td>
</tr>
<tr>
<td>4</td>
<td>Output uncertainty anomaly</td>
<td>• Input drift</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• High process uncertainty</td>
</tr>
<tr>
<td>5</td>
<td>Residual error drift</td>
<td>• Concept drift</td>
</tr>
</tbody>
</table>

#### Model Input
- **Neighborhood operator:**
  - (a) by number of neighbors
  - (b) by radius (distance threshold)

#### Model Internal Representation

#### Model Output
- **Expected actual**

---

**Figure:**
- **(1) Input likelihood with density estimation**
- **(2) Reconstruction error-based anomaly**
- **(3) Geometric neighborhood in embeddings (latent spaces)**
- **(4) Output uncertainty anomaly**
- **(5) Residual error drift**
Characterizing region of trust, overlap, and extrapolation for AI to get justification-based reliability

Output = (Belief, j ∈ {IK, IMK, IDK})

Justification from supports

\[ \text{Justification} = \bigcup_{i \in I} \text{support from layer } i; \text{ otherwise} \]

Justified belief is knowledge

Belief = Justification → I know (Region of trust)

Belief ⊂ Justification → I may know (Region of overlap/ambiguity)

Belief ⊄ Justification → I don’t know (Region of extrapolation)


Examples of evaluating competence using internal representations

Dataset:
CIFAR (car and truck class)

Base model:
Residual Network

Layer:
Global average pooling

Support:
$\varepsilon$-ball with $\ell_2$-metric

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

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

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

Support from latent space as exemplars for interpretability

Visualization of Latent Space - Car and Truck Classes – IK, IMK, and IDK
Data to facilitate Health Twin development and validation

*Tennessee Eastman Process (TEP) simulation data*¹

- 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

---


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

1: DATA PREPROCESSING
- Train Data = 400 simulations from training
- CV Data = 100 simulations
- Test Data = 100 simulations from training
- Merge 20 time samples into single sample as additional features

2: BASELINE HEALTH TWIN MODEL
- Train Data 211520 x 1040
- CV Data 535000 x 1040
- Test Data 59600 x 1040

3: HUMBLE HEALTH TWIN
- Prediction + competence IK, IMK, IDK

4: OUTCOME
- Test 59600 x 1040 x 1 label
- Performance validated

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December 7, 2021 120
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)
Thank You!

Building a world that works

Collaborate with us on research programs for a better tomorrow
(nurali.virani@ge.com)
ENABLING TECHNOLOGIES FOR DIGITAL TWIN APPLICATIONS FOR THE KP-FHR

CHRIS POESKY 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

<table>
<thead>
<tr>
<th>KP-FHR</th>
<th>HTGR</th>
<th>Fast Breeder Reactor</th>
<th>PWR SMR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flibe</td>
<td>Helium</td>
<td>Sodium</td>
<td>Water</td>
</tr>
<tr>
<td>280 MW\text{th}</td>
<td>250 MW\text{th}</td>
<td>260 MW\text{th}</td>
<td>200 MW\text{th}</td>
</tr>
<tr>
<td>120 MW\text{e}</td>
<td>100 MW\text{e}</td>
<td>100 MW\text{e}</td>
<td>60 MW\text{e}</td>
</tr>
</tbody>
</table>

* Reactor vessels drawn to notional scale.
KP-FHR Safety Case – Defense in Depth Barriers

- Radionuclide Retention Capabilities
KP-FHR I&C design

Plant protection and control

• KP-Shield: Passive, robust, reliable safety shutdown 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

Control sensor data stream

Optimize control actions

Corrective action

Control Actuation

Optimize control actions

Update Plant Probabilistic Risk Assessment, Structures Systems & Components performance (plant understanding)

Emergency Operating Procedures, Severe Accident Management Guideline, Code of Federal Regulations

Verify Plant Health

Machine Learning

Optimize control policy

Interactive

Selected data

KP-FHR Digital Twin

Operating experience

KP-Sword

KP-Heart

KP-FHR Plant
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.
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

Prof. Emilio Baglietto (PI)
Prof. Koroush Shirvan (co-PI)
Yu-Jou Wang (PhD)
Brandon Aranda (MS)
Genghis Khan (co-PI)

Dr. Panos Tsilifis (co-PI)

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 - JVUQ

- **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 years, 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

<table>
<thead>
<tr>
<th>Civaux (PWR)</th>
<th>Swedish BWRs CR Stems</th>
<th>Superfenix (LMFBR)</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1" alt="Civaux image" /></td>
<td><img src="image2" alt="Swedish image" /></td>
<td><img src="image3" alt="Superfenix image" /></td>
</tr>
</tbody>
</table>
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 \cite{Lenci_2016} (Lenci and Baglietto, 2016)

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

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

 URANS is not applicable to scale overlap.
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

<table>
<thead>
<tr>
<th>Cell size (mm)</th>
<th>Nu. of cells</th>
</tr>
</thead>
<tbody>
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<td>2,500,000</td>
</tr>
<tr>
<td>23.625</td>
<td>801,000</td>
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<tr>
<td>35.437</td>
<td>275,000</td>
</tr>
<tr>
<td>53.156</td>
<td>98,000</td>
</tr>
</tbody>
</table>

Supported by:

- TerraPower
- Mitsubishi Heavy Industries, LTD.
- framatome
- NEAMS
- MISTI
Recap: coherent flow structures drive T variation

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

**URANS (Cubic k-ε)**

- **Mean Temperature**

**STRUCT-ε**

- **Var Temperature**

- **Inst. Temperature**

**Resolved Coherent Temperature Structures**

**URANS (Cubic k-ε)**

URANS Cannot predict Velocity and Temperature Fluctuations responsible for fatigue

**STRUCT-ε**

STRUCT predicts both velocity and Temperature fluctuations with high accuracy

Errors on $T_{rms}$ order of 1%
Application on feedwater system recap

A method for flow feature extraction

Manchester LES

Upper part vortices

Lower part vortices

STRUCT

- The STRUCT model accurately captures the swirl switching features
Swirl-Switching example
Fluid (~3.5 inch downstream)

- 100%
- 50%

Solution Time 0.01 (s)

Solution Time 10.005 (s)
The model outputs will look like this:

- 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:
\[ x = -1.25 \text{ in} \sim 15 \text{ in} \]
\[ \theta = -60 \sim 60 \text{ deg} \]

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

<table>
<thead>
<tr>
<th>Spec.</th>
<th>O.D.</th>
<th>Wall thickness</th>
<th>I.D</th>
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</thead>
<tbody>
<tr>
<td>Main</td>
<td>316L 40S</td>
<td>16(^\circ)</td>
<td>0.375(^\circ)</td>
</tr>
<tr>
<td>Branch</td>
<td>316L 80S</td>
<td>2 1/4(^\circ)</td>
<td>0.276(^\circ)</td>
</tr>
</tbody>
</table>
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

**Rainflow Counting Algorithm**

- Identifying number of cycles in stress histories
- Crack initiation Predictions across all positions and angles
- Uncertainty Quantification in crack initiation

<table>
<thead>
<tr>
<th>Power Level</th>
<th>Cycles</th>
</tr>
</thead>
<tbody>
<tr>
<td>20%</td>
<td>1st Cycle</td>
</tr>
<tr>
<td>100%</td>
<td>nth Cycle</td>
</tr>
</tbody>
</table>

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

Team

- **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


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

Step reactivity insertion (+2\(\beta\))

\[ \Delta \rho = +2\beta \]

Transient response of power, reactivity, and fuel salt temperature changes (1)
Demonstrates the Techno-Economic Value of Continuous Temperature Monitoring

- Temperature distribution in the salt, reflector and vessel walls experience meaningful gradients and local peaks

3D Accident Analysis Completed

Unprotected LOF (Decrease of fuel salt flow rate to 80% exponentially with time constant of 5 sec)
3D Accident Analysis

Unprotected LOF

Temperature [K]

Time [sec]

B1, B2, B3, B4, B5, B6, B7
T1, T2, T3, T4, T5, T6, T7
R1, R2, R3, R4, R5, R6, R7
C1

Massachusetts Institute of Technology
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)
Regrowth LHPG System
Distributed Sensing – Raman OTDR

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


Sapphire fiber attenuation at 532nm, measured by a Raman OTDR system
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 ~750°C
- Molten Chlorides
- Assortment of crystal fiber materials and protection layers
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 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 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
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
Digital Twins - Regulatory Viability
Jeremy Bowen
Digital Twins Project Plan

TECHNICAL PREPAREDNESS

REGULATORY READINESS

ASSESSMENT OF STANDARDS

COMMUNICATION & KNOWLEDGE MANAGEMENT

PREPAREDNESS

$ FFR PROJECT

BL FUNDED
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

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: ML21160A074

Access Link: ML21083A132
Active & Future Tasks

Technical Challenges and Gaps for Digital Twins in Using Data Analytics, ML/AI and Multi-Physics Models

Regulatory Readiness Levels and Gaps Pertaining to Digital Twin Technologies for Nuclear Reactor Applications

Technical Preparedness – Safeguards and Security in Digital Twins

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
Vision | Radiant

Make Nuclear Portable

Maximize speed of iteration to get to a buildable product

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

Regulatory Intents
- Protect Personnel
- Protect Environment
- Protect Hardware
- Prove the Above
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
ANTHONIE CILLIERS
 SENIOR MANAGER
 INSTRUMENTATION, CONTROLS AND ELECTRICAL
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.

Jesse Carlson, NRC - jesse.carlson@nrc.gov
Vaibhav Yadav, INL - vaibhav.yadav@inl.gov
Jenifer Shafer, ARPA-E - jenifer.shafer@hq.doe.gov
Hasan Charkas, EPRI - hcharkas@epri.com
Prashant Jain, ORNL - jainpk@ornl.gov