U.S. Nuclear Industry Survey on Artificial Intelligence and Machine Learning in Operating Nuclear Plants

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Project Objectives

- **Explore potential uses and applications of advanced computational tools and techniques, such as artificial intelligence (AI) and machine learning (ML), for operating nuclear plants**
- **Review nuclear DATA sources that could be applied by advanced computational tools and techniques**
  - **Generic-national & international data**
  - **Plant specific operating experience data**
- **Introduce widely used AI/ML algorithms in both supervised and unsupervised learning**
- **Review applications of advanced computational tools and techniques**
  - **reactor system design and analysis**
  - **plant operation and maintenance**
  - **nuclear safety and risk analysis**
- **Present insights on the potential applicability of AI/ML techniques to:**
  - **improve advanced computational capabilities**
  - **contribute to understanding of safety and risk**
  - **help decision-makers make better decisions**

Project Tasks

Task 1: Literature search for advanced computational tools and techniques appropriate for operating nuclear plants

Task 2: Survey to assess the current and potential applications of advanced computational tools in the commercial nuclear industry

Task 3: Explore potential applications of advanced computational tools and techniques to advanced reactors

Nuclear Industry Modernization Is On The Way

- **New approaches will support more efficient compliance with regulatory requirements in 10 CFR 50.65, "Requirements for Monitoring the Effectiveness of Maintenance at Nuclear Power Plants"**
- **NEI 18-10* industry guidance is a departure from the current preventative maintenance assessment paradigm (e.g., establishing structure, system and component performance criteria) and is intended to allow for a more dynamic assessment of maintenance effectiveness based on the use of data and risk trending analytics**
- **NRC resident inspectors will need better understanding of the underlying technologies employed in these new approaches, e.g., AI, ML, and data analytical tools**

***Nuclear Energy Institute, "Monitoring the Effectiveness of Nuclear Power Plant Maintenance," NEI 18-10, 2018**

FRN NRC-2021-0048

- **Issued April 21 2021 (86FR20744)**
- **Posed 11 question to the public at large (ML21104A056)**
- **Designed to elicit industry and public perception regarding the benefits of using AI in nuclear plant operations**
- **12 Responses received (also available on Regulations.com site)**

No.	Participant	Response Accession Number
1	Anonymous	ML21113A083
2	Southern Research Institute (SRI)	ML21126A011
3	Florida Power & Light Company (FPL)	ML21139A103
4	Electric Power Research Institute (EPRI)	ML21141A184
5	Xcel Energy (Xcel)	ML21141A185
6	ForHumanity	ML21145A363
7	Blue Wave AI Labs (Blue Wave)	ML21145A364
8	X-energy	ML21145A366
9	Insight Enterprises, Inc. (IEI)	ML21145A367
10	Nuclear Energy Institute (NEI)	ML21145A369
11	Framatome Inc. (Framatome)	ML21153A056
12	Westinghouse Electric Company LLC (WEC)	ML21211A077

Survey Response Matrix

No.	Participants	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11	Responses Beyond Question Scope
1	Anonymous	N	N	N	N	N	N	N	N	N	N	N	Referenced two publications (Kortelainen et al. 2020, Suman 2020)
2	SRI	N	N	Y	N	Y	N	N	N	N	N	Y	None
3	FPL	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	None
4	EPRI	N	N	N	N	N	N	N	N	N	N	N	Referenced four EPRI-authored publications (EPRI 2020b, EPRI 2020a, EPRI 2021b, EPRI 2021a)
5	Xcel	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	None
6	ForHumanity	Y	Y	Y	Y	N	Y	Y	Y	Y	Y	Y	Included an introduction of AI-related work conducted by the For Humanity
7	Blue Wave	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	None
8	X-energy	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	None
9	IEI	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	None
10	NEI	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	None
11	Framatome	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	None
12	WEC	Y	Y	Y	Y	N	Y	N	N	N	N	Y	None

High-Level Benefits of AI

Design, Operational Automation, Preventive Maintenance Trending, and Staff Productivity

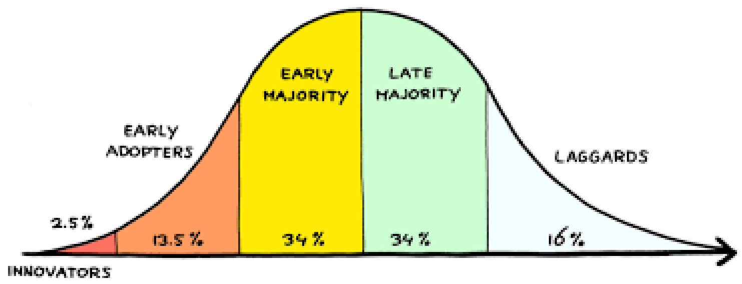
- **Increasing design-process efficiency**
- **Enabling data collection and analysis at a larger scope and faster speed**
- **Identifying patterns unnoticed by humans**
- **Suggesting control strategies not necessarily thought of beforehand**
- **Automating labor-intensive work**
- **Optimizing resource allocation**
- **Streamlining maintenance scheduling**

Common Refrains from Survey

- **Nuclear power may benefit more from AI/ML applications compared to other power generation sources**
  - **Due to the high cost of the workforce and regulatory requirements**
  - **Benefits may be concentrated on high-impact events**
    - **nuclear fuel**
- **But the cost of developing and implementing AI/ML is a challenge**
  - **Costs are usually high and upfront**
  - **Benefits are neither timely nor guaranteed**
- **Survey participants that have completed AI/ML applications said they were able to balance the development costs against expected plant improvements**

Common Refrains (con't)

- Confusion as to whether the nuclear power industry is:
  - Early adopter
  - Majority
  - Laggard



- Licensees foresee using a combination of in-house AI/ML talents and support from external entities such as vendors, national laboratories, and universities
- Most frequently mentioned AI/ML methods:
  - Artificial Neural Network
  - Clustering algorithms
  - Natural Language Processing

Artificial Neural Networks

- **ANNs are the most well-known methods of supervised learning and have the capabilities to be applied in broad areas, including regression analysis, classification, data preprocessing, and robotics**

- **ANN is composed of three types of layers: input, hidden, and output layers. Each layer consists of a set of nodes called neurons. A typical ANN has one input layer, one output layer, and multiple hidden layers**

- **The connections between nodes in different layers are associated with the weights that define the connection strength and are adjusted as learning proceeds**

- **ANN with more than three hidden layers is called a deep NN**

Clustering Algorithms

- **Clustering Analysis is used to identify data subgroups and clusters in such a way that data samples from the same cluster are more similar to each other than to those from different clusters**
- **There are many clustering algorithms because the notion of a ‘cluster’ is not easy to clearly define**
- **The most appropriate algorithm for a particular task needs to be chosen experimentally**
- **It works well for medium size datasets and a small number of clusters**
- **Hierarchical Clustering (HC) builds clusters by recursively partitioning data samples using merging or splitting strategies:**
  - **HC introduces a linkage criterion to decide which cluster pairs should be merged or should be split. The linkage criterion defines the dissimilarity and distance between sets of data samples.**

AI vs Regulatory Efficiency

AI/ML applications can improve NRC regulatory efficiency and effectiveness

Direct Approaches to Improve Regulatory Oversight

- **Use AI/ML to automate NRC staff labors such as reviewing plant documentation**
- **Use NLP to make the NRC ADAMS data more searchable**
- **Use surrogate modeling to verify and run simulation models submitted by the licensees**
- **Adopt advanced oversight methods to streamline regulatory process such as coordinating diagnostics data with risk-informed categorization**

Indirect Approaches to Improve Regulatory Oversight

- **AI/ML applications have potential to lead to safer plants with fewer events and thus a reduction in the number of regulatory activities**
- **Integrating AI/ML into regulatory activities can be a learning process and although decreased efficiency and increased cost might be a side effect initially, it is hoped to be temporary so that costs will eventually stabilize, if not decline**

Data Security

Major Concerns

- **Cyber intrusion**
- **Proprietary information leakage**
- **Loss of export control Several survey participants mentioned that their organizations**

Data Security Defenses

- **Data may have “inherent security” because it may be difficulty to draw significant insights from the stolen data, unless the intruders had access to the original model and software**
- **Some organizations are exploring AI platforms with co-located hardware and inspection systems to process data locally and minimize the need for data transfer**

Applications of AI

<u>Many</u> **applications are under concept exploration or strategic consideration:**

- **System and component monitoring (3 votes)**
- **Predictive maintenance (2 votes)**
- **Digital twins (1 vote)**
- **NDE inspections (1 vote)**
- **Automating human labor (1 vote)**
- **Cybersecurity (1 vote)**
- **Design support (1 vote)**
- **Fuel management (1 vote)**
- **Outage reduction (1 vote)**

Applications of AI (con't)

A *small number* are currently under development

- **Textual report analysis**
- **Predictive maintenance**
- **Work management**
- **Fuel cycle management**
- **Reactor operation and control**
- **Surrogate model development**
- **Focused on:**
    - **Corrective Action Program**
    - **Non-Destructive Examinations**
    - **Root Cause Analysis**

Tools Up & Running

Very few **are already up and running**

- **Customized tools developed for plant improvements:**
  - **Tool to predict moisture carryover in BWRs (MCO.ai developed by the Blue Wave AI Labs)**
  - **Tool to predict the BWR eigenvalue evolution for future fuel cycles (Eigenvalue.ai developed by the Blue Wave AI Labs)**
  - **Tool to determine root causes derived from symptoms (Metroscope developed by the Électricité de France)**
  - **Tool to evaluate multiple regression-based AI/ML algorithms to find trends in the data and select the optimal algorithm-Westinghouse**

Off-the-shelf products:

- **Commercial software tools--IBM Watson**
- **Tools not quite ready for prime time but close:**
  - **Xcel Energy's CAP Intelligence Advisor (targeting late 2021 for the first deployment)**
  - **X-Energy's Xe-100 Digital Twin (targeting 2025-2027 for the first deployment)**

Top Down Mgmt of AI

Both the top-down approach and the case-by-case approach for developing and implementing AI/ML are deemed to have pros and cons

- **No strong preference is demonstrated by the survey participants**

- **Commonly-mentioned advantages of top-down approach:**
    - **Enables a holistic and standardized framework**
    - **Easier to generalize and save repetitive work**
    - **Easier to share knowledge and experience**
    - **Increasing business efficiency**

- **Commonly-mentioned disadvantages of top-down approach include:**
    a. **Difficulty to adapt the framework to a changing technology landscape**
    b. **Challenge in developing a catchall strategy accommodating diverse applications**
    c. **Potential loss of innovative human inputs**
    d. **Uncertainty in oversight from NRC on requirements for top-down guidance**

FRN Questions

- **What is status of the commercial nuclear power industry development or use of AI/ML tools to improve aspects of nuclear plant design, operations or maintenance or decommissioning? What tools are being used or developed? When are the tools currently under development expected to be put into use?**
- **What areas of commercial nuclear reactor operation and management will benefit the most, and the least, from the implementation of AI/ML? Possible examples include, but are not limited to, inspection support, incident response, power generation, cybersecurity, predictive maintenance, safety/risk assessment, system and component performance monitoring, operational/maintenance efficiency and shutdown management.**
- **What are the potential benefits to commercial nuclear power operations of incorporating AI/ML in terms of (a) design or operational automation, (b) preventive maintenance trending, and (c) improved reactor operations staff productivity?**
- **What AI/ML methods are either currently being used or will be in the near future in commercial nuclear plant management and operations? Example of possible AI/ML methods include, but are not limited to, artificial neural networks (ANN), decision trees, random forests, support vector machines, clustering algorithms, dimensionality reduction algorithms, data mining and content analytics tools, gaussian processes, Bayesian methods, natural language processing (NLP), and image digitization.**
- **What are the advantages or disadvantages of a high-level, top-down strategic goal for developing and implementing AI/ML across a wide spectrum of general applications versus an ad-hoc, case-by-case targeted approach?**
- **With respect to AI/ML, what phase of technology adoption is the commercial nuclear power industry currently experiencing and why? The current technology adoption model characterizes phases into categories such as: the innovator phase, the early adopter phase, the early majority phase, the late majority phase, and the laggard phase.**
- **What challenges are involved in balancing the costs associated with the development and application of AI/ML, against plant operational and engineering benefits when integrating AI/ML applications into operational decision-making and workflow management?**
- **What is the general level of AI/ML expertise in the commercial nuclear power industry (e.g. expert, well-versed/skilled, or beginner)?**
- **How will AI/ML effect the commercial nuclear power industry in terms of efficiency, costs, and competitive positioning in comparison to other power generation sources?**
- **Does AI/ML have the potential to improve the efficiency and/or effectiveness of nuclear regulatory oversight or otherwise affect regulatory costs associated with safety oversight? If so, in what ways?**
- **AI/ML typically necessitates the creation, transfer and evaluation of very large amounts of data. What concerns, if any, exist regarding data security in relation to proprietary nuclear plant operating experience and design information that may be stored in remote, offsite networks?**