Artificial Intelligence and Machine Learning Technologies: Enabling Advanced Reactor Deployment Economics

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Introduction

- Flexible Generation
- Autonomous Operation
- Low Operating Cost
- High Reliability
AI/ML are Part of Holistic Solution to Addressing Deployment Economics of Advanced Reactors

Graphics Credit: Dr. W.D. Pointer
Scalable Risk-informed Predictive Maintenance Strategy

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Machine Learning and AI Enable Digital Twins for Nuclear Power Applications

A software design pattern that represents a physical object with the objective of understanding the asset’s state, responding to changes, improving business operations and adding value (Gartner)
Digital Twins Enable Scalable Information-Driven O&M

Advanced Nuclear System

Supervisory Control for Autonomous Operation

Condition Measurements

Process Measurements

Sensor Reliability, Uncertainty

Feature Engineering & Signature Extraction

Real-time Model Calibration

Digital Twins (Physics Informed Dynamic Models)

Decision Making

Probabilistic Risk Assessment

Deterministic Assessment

Required Actions

Veriﬁcation

Lower-order (Phase Simulation)

Enhanced Risk Monitoring

Not OK

Autonomous O&M Decision Making

Diagnostics: Degradation Detection & ID

Uncertainty Quantification

Causal Analysis

Equipment Degradation Prognostics & Conﬁdence

Predictive Risk & Cost Estimates

Adapted from:
• Ramuhalli, Veeramany et al, ICONE25, 2016
• Cetiner, Muhlheim et al, Nuclear News 2015
• Roy, Ramuhalli et al, ANS NPICHMIT 2015
• Dib, Roy, et al, ANS NPICHMIT 2017
• Tipireddy, Ramuhalli et al, ANS NPICHMIT 2017
• Ramuhalli et al, 2016 (Advanced Reactor R&D Program Technical Report)
Digital Twins that Integrate PHM and Control Technologies Enable Anticipatory Control and Autonomous Operation

Hybrid Modeling

Faster-than Real-time Predictive and Decision-Making Capabilities

Anticipatory Control

Scalable Framework for Anticipatory Control of Microreactors

(Agarwal et al., Laboratory Directed Research and Development Project. (FY21 – FY23))

Autonomous Selection of Supervisory Control Options for Hypothetical Advanced Reactor Minimizes Unnecessary Trips

(Cetiner, Muhlheim et al, Nuclear News 2015)

Safety System Region

Scalable Framework for Anticipatory Control of Microreactors

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Potential for Improvement in O&M Cost Due to PHM and Autonomous Operation in a Hypothetical Advanced Reactor

(Adapted from Ramuhalli, Veeramany et al, ICONE25, 2016)

Simplified Diagram of Multimodule Reactor
ML is Also Key to Structural Health Monitoring for Insights into Passive Component Health in Advanced Reactors

Model based Assessment of SHM in Advanced Reactors (Ramuhalli et al, 2018)

Physics-informed Machine Learning Applied for Structural Component Diagnostics (Rathod, Ramuhalli 2021)

remaining Life Estimate for Passive Nuclear Structural Components (Ramuhalli et al 2012)

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

Extended Wave

Contact

Specular Amplitude

Immersion

Ultrasonic Data

Physics informed Neural Network (PINN)

Flaw Size/Shape Estimation

Component Design and Inspection/Monitoring Requirements per Code

316L sheathed sensor in AM 316L build

High Temperature Compatible Embedded Sensors

Integrated Sensors for SHM

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

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Use of AI techniques and supercomputers to arrive at non-trivial and highly optimal nuclear designs has been demonstrated.

V. Sobes et al. (2020)

Temperature gradient across conventional design: \(~900^\circ\)C

Temperature gradient across optimal design: \(~300^\circ\)C

Graphics and data courtesy Dr. Ben Betzler, ORNL
Looking Forward: Challenges to Leveraging AI/ML to Address Deployment Economics

• Data (normal and off-normal under steady state and transient conditions)
  - Availability
  - Access and quality
  - Optimal sensing, sensor placement and number

• Machine learning models
  - Computationally light, scalable
  - Model updating
  - Uncertainty quantification, robustness
  - Cybersecurity and cyber-resilience

• Verification and validation approaches and testbeds
Scalable Framework for Anticipatory Control of Microreactors

- Development of an Anticipatory Hybrid Model
  - Development of a High-Fidelity Hybrid Reactor Model
  - Development of an Anticipatory Control System
- Validation and Scalability of the Anticipatory Hybrid Model
- Establish Decision Support
- Perform Cost-Benefit Analysis

Significance
- Lay the foundation for a standard architecture that would interest all advanced reactor stakeholders
- Architecture will allow us to address some of the regulatory questions (concerns) around automation, application of machine learning, and human factors engineering
- Add or subtract features from a microreactor design to make it easier to autonomously control

Agarwal et al. Scalable Framework of Hybrid Modeling with Anticipatory Control Strategy for Autonomous Operation of Modular and Microreactors. Laboratory Directed Research and Development Project. (Funding Period FY21 – FY23)