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

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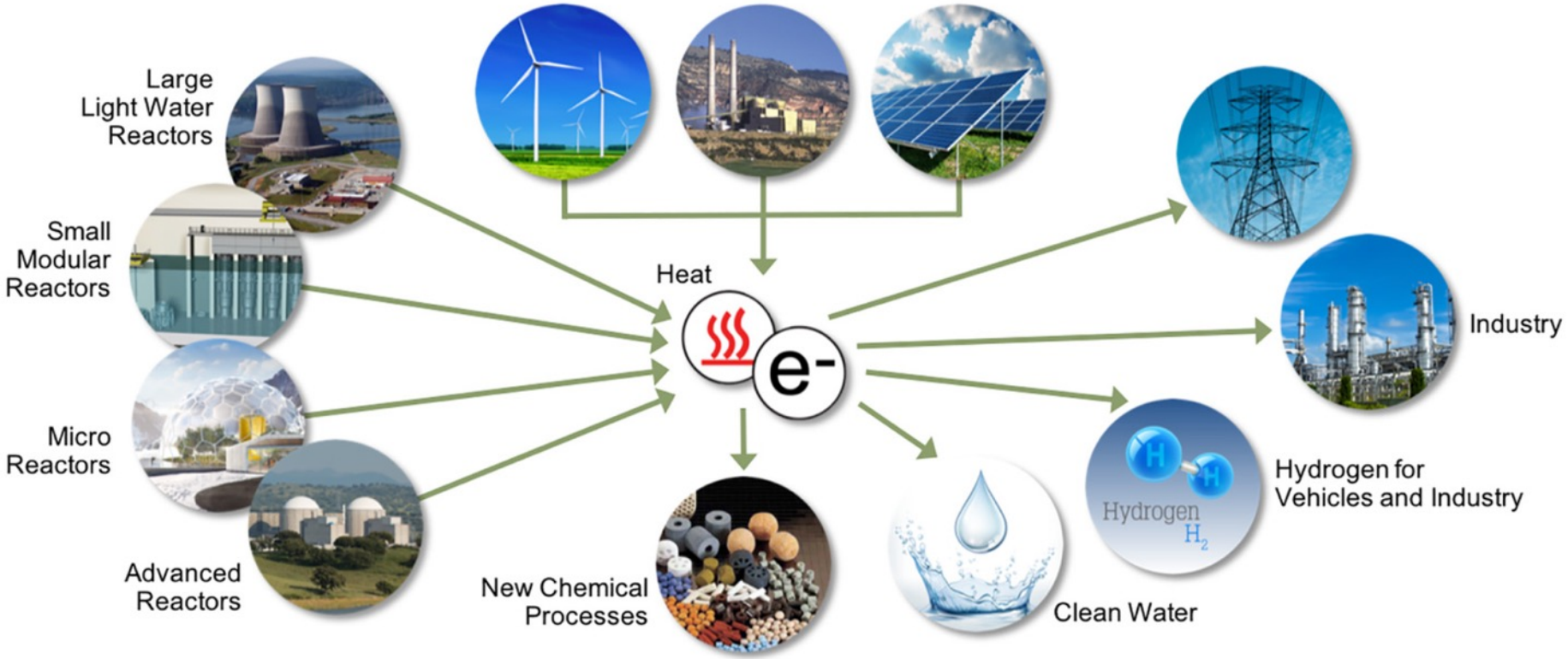
# Introduction

**Today**

Electricity-only focus

**Potential Future Energy System**

Integrated grid system that leverages contributions from nuclear fission beyond electricity sector




- ❖ Flexible Generation
- ❖ Autonomous Operation
- ❖ Low Operating Cost
- ❖ High Reliability

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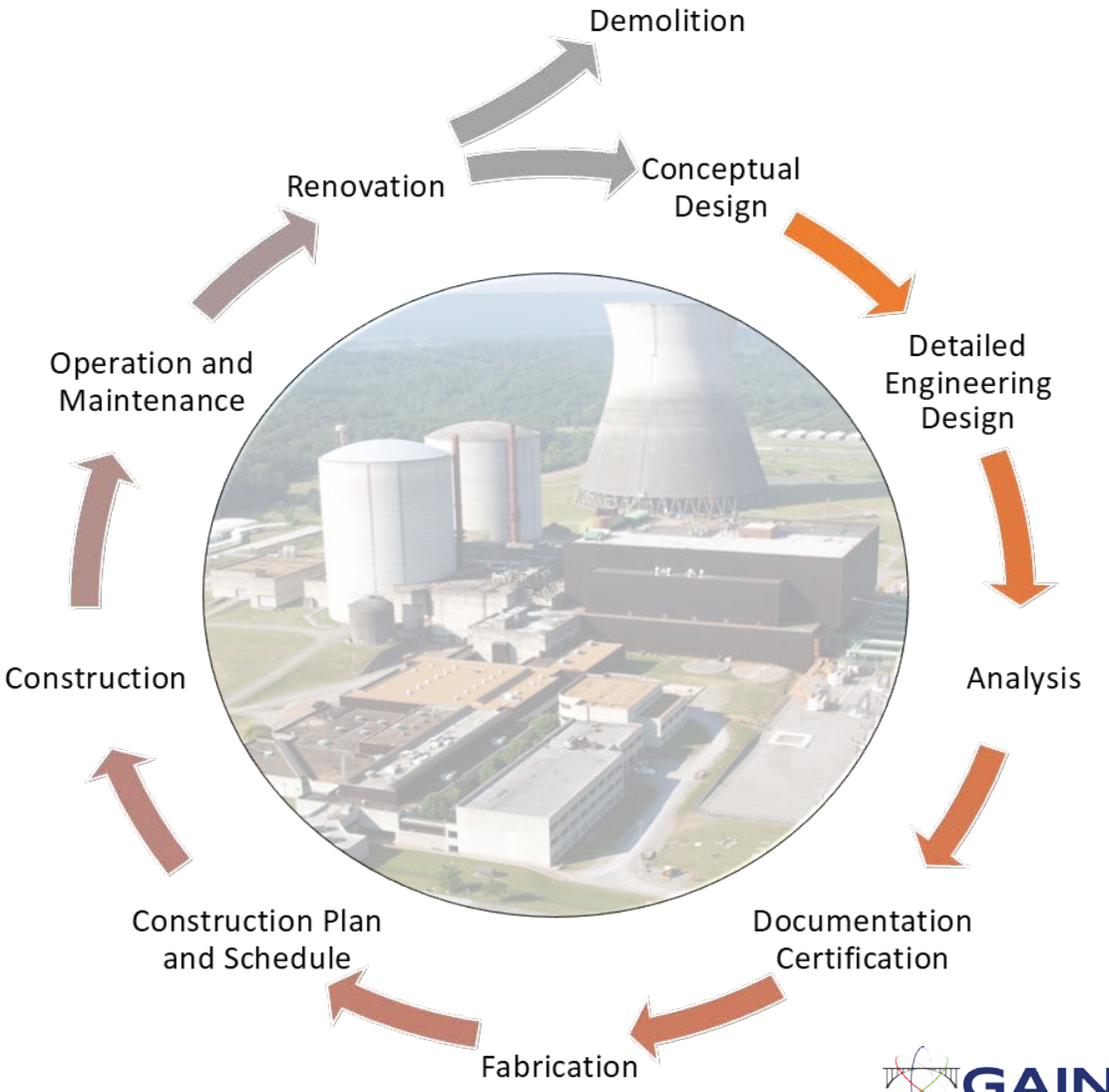
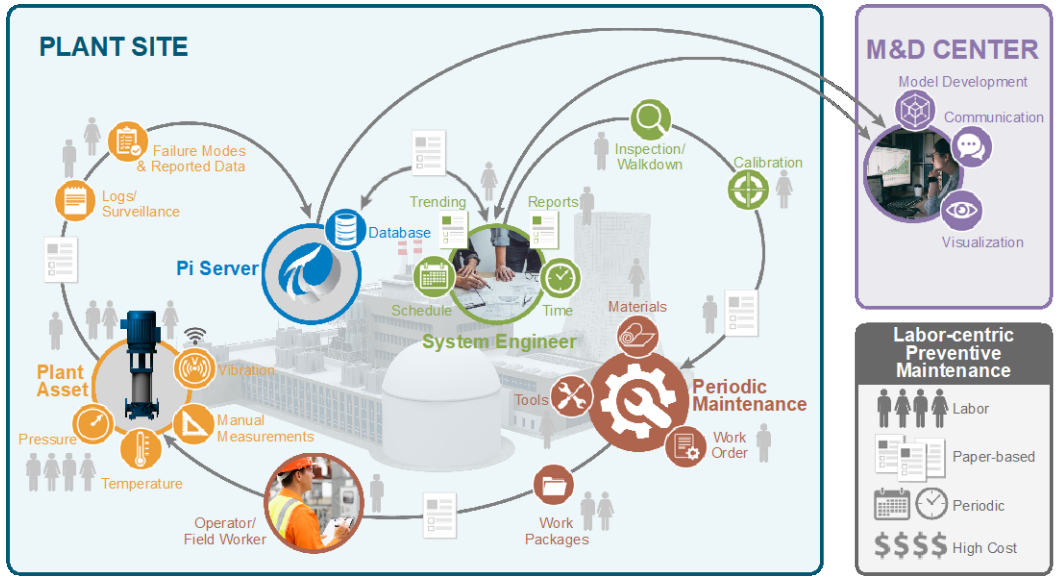
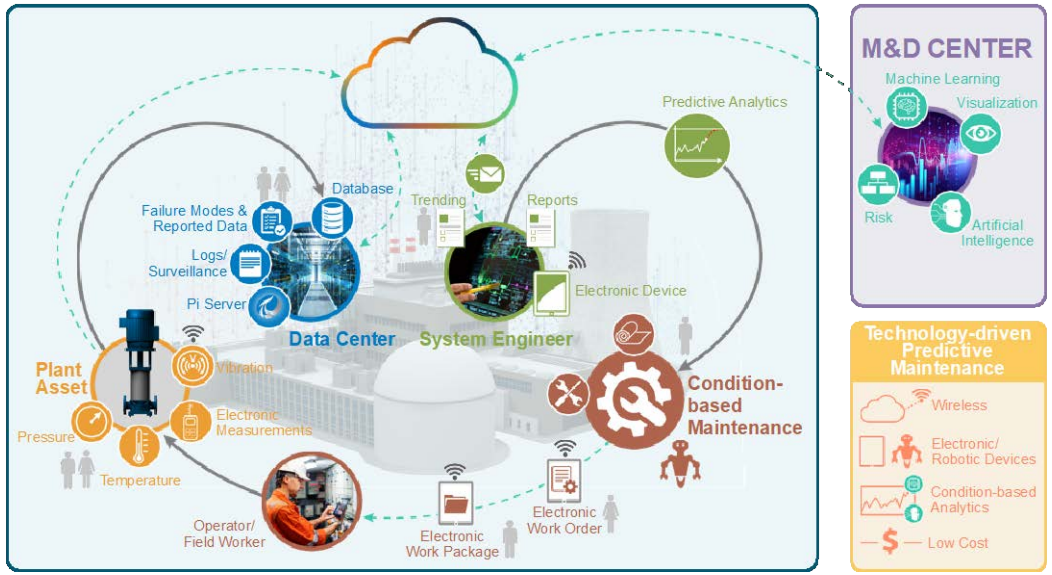
# AI/ML are Part of Holistic Solution to Addressing Deployment Economics of Advanced Reactors




Graphics Credit: Dr. W.D. Pointer

# Scalable Risk-informed Predictive Maintenance Strategy





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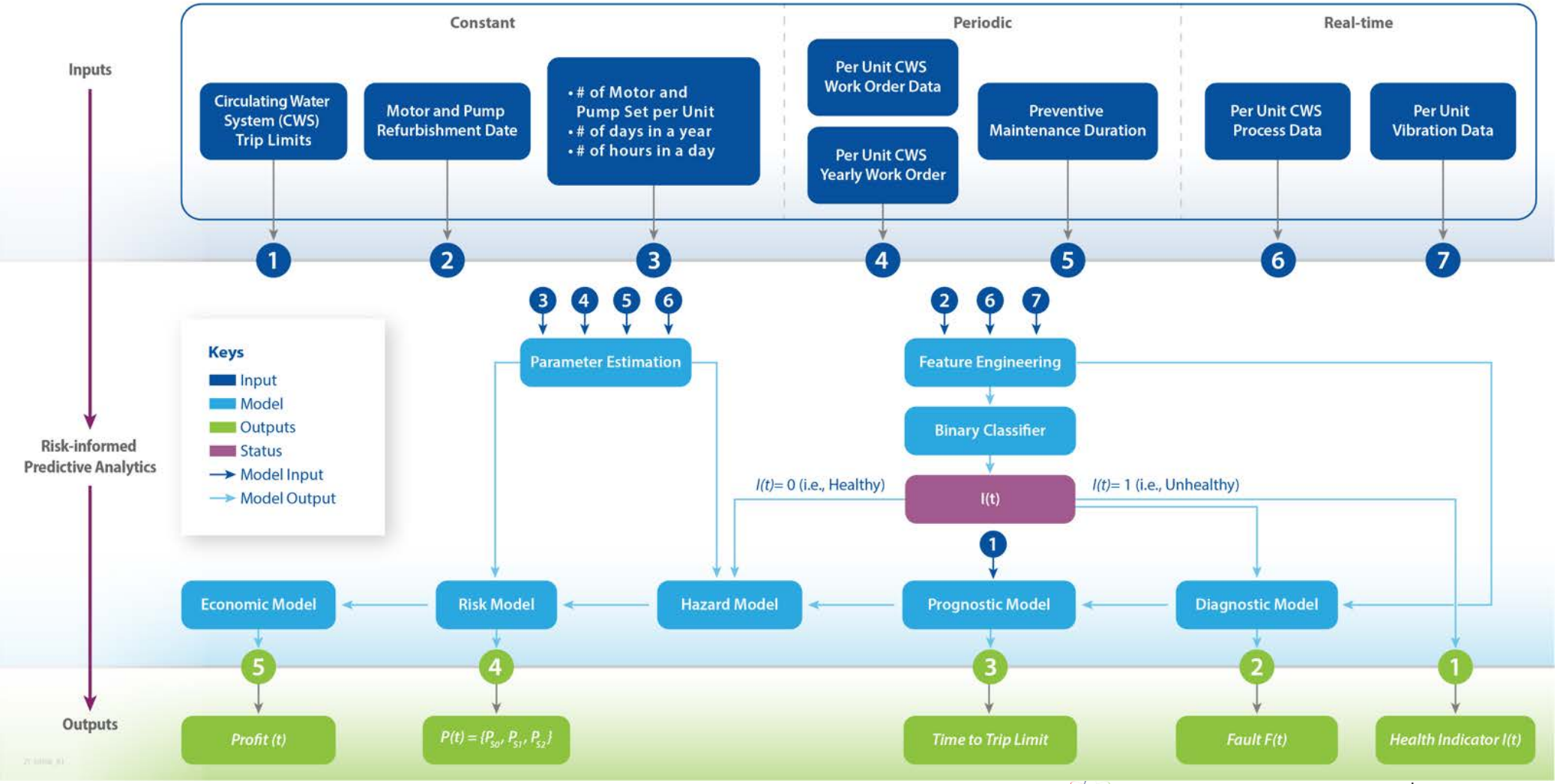
Agarwal et al. *Scalable Technologies Achieving Risk-Informed Condition-Based Predictive Maintenance Enhancing the Economic Performance of Operating Nuclear Power Plants*. Idaho National Laboratory, INL/EXT-21-64168, August 2021.

# Scalable Risk-informed Predictive Maintenance Strategy




Agarwal et al. *Machine Learning and Economic Models to Enable Risk-informed Condition Based Maintenance of a Nuclear Plant Asset*. Idaho National Laboratory, INL/EXT-21-61984, March 2021.

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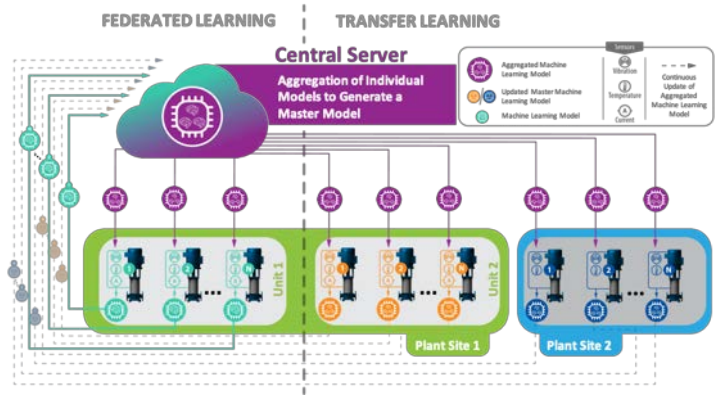
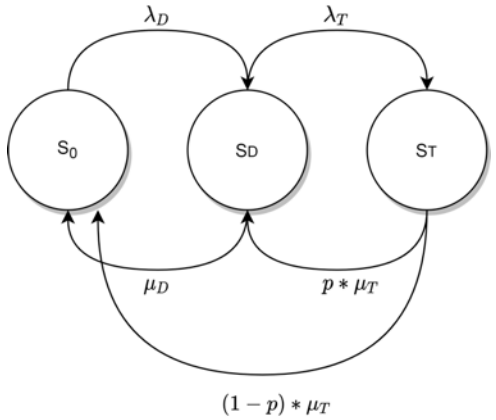
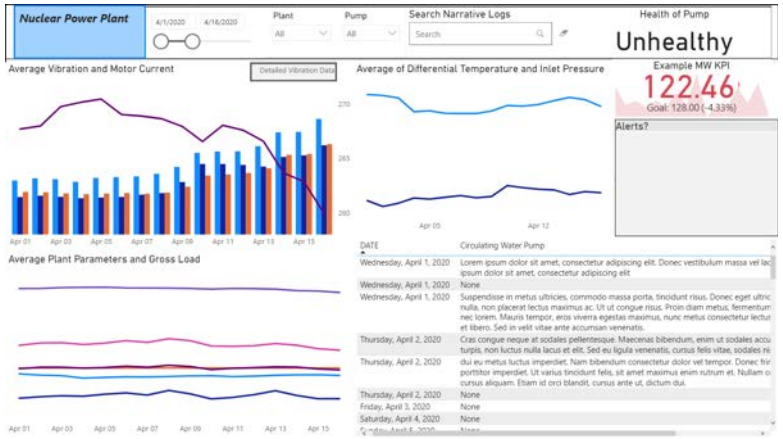
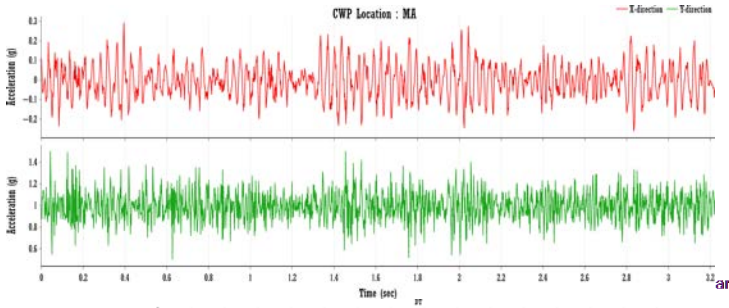
# Scalable Risk-informed Predictive Maintenance Strategy



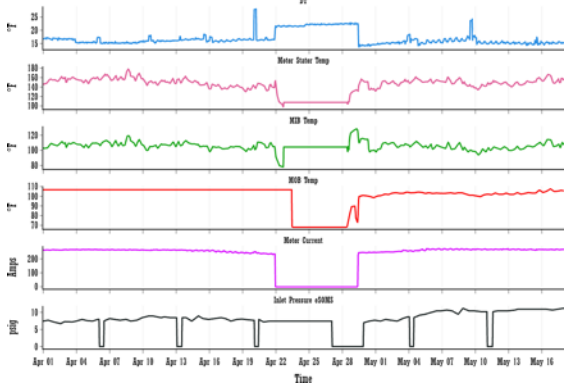



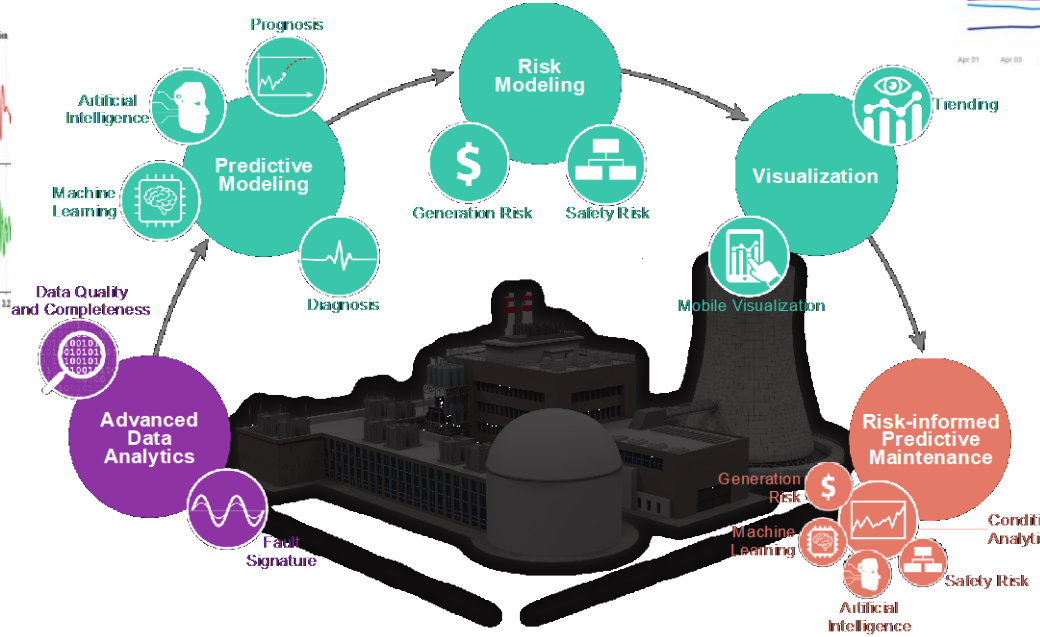



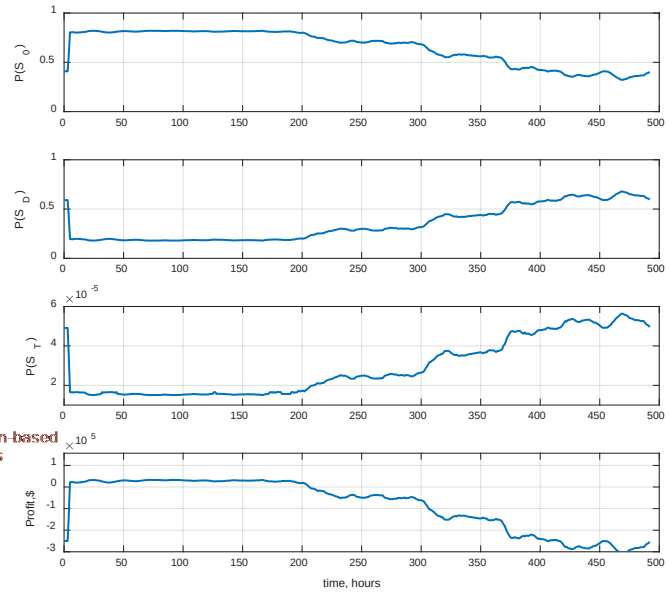

Vibration Data




Process Data

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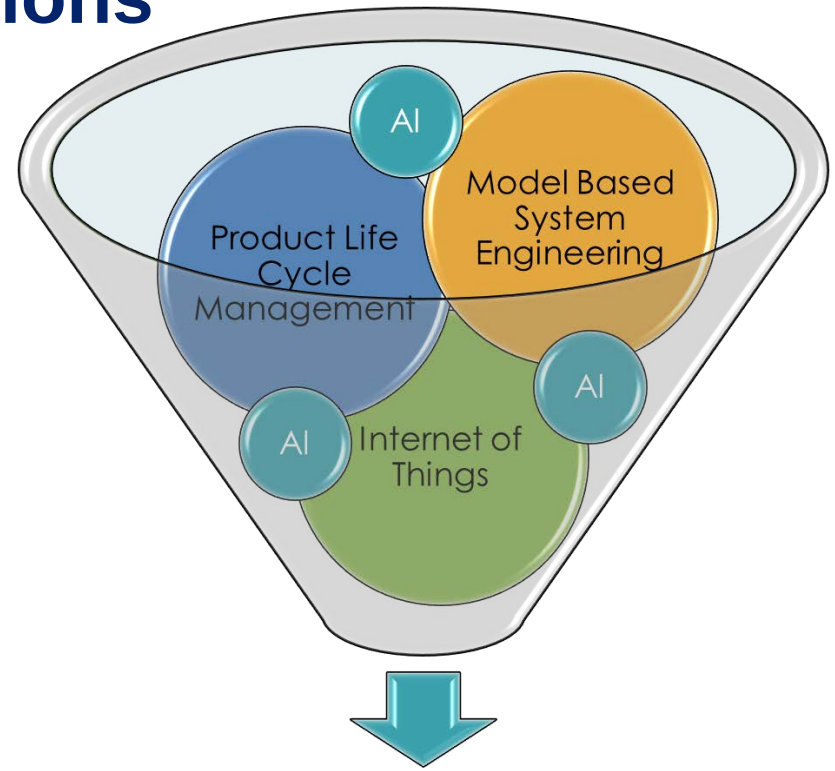
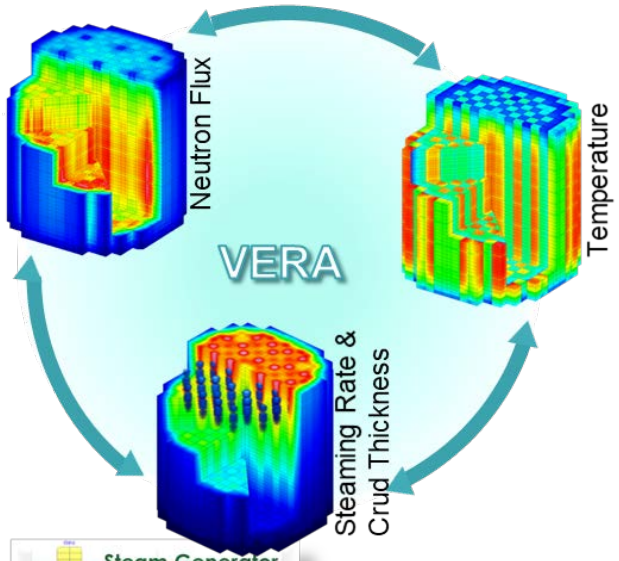
Agarwal et al. *Scalable Technologies Achieving Risk-Informed Condition-Based Predictive Maintenance Enhancing the Economic Performance of Operating Nuclear Power Plants*. Idaho National Laboratory, INL/EXT-21-64168, August 2021.

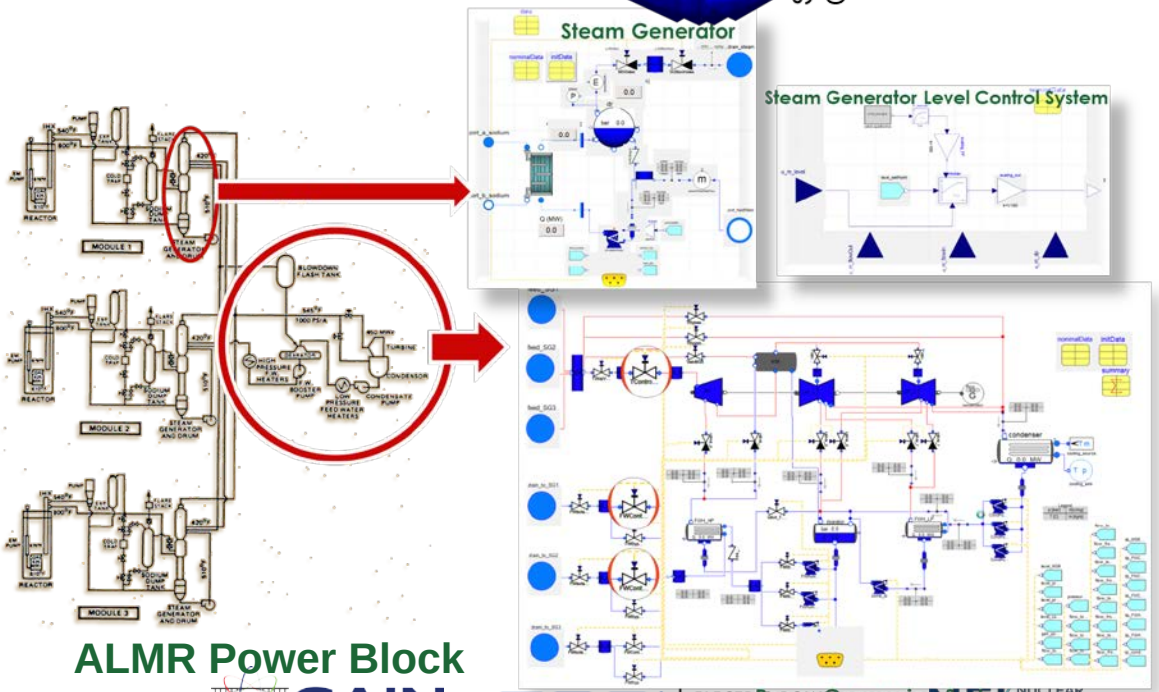
# Machine Learning and AI Enable Digital Twins for Nuclear Power Applications




Digital Twin

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)

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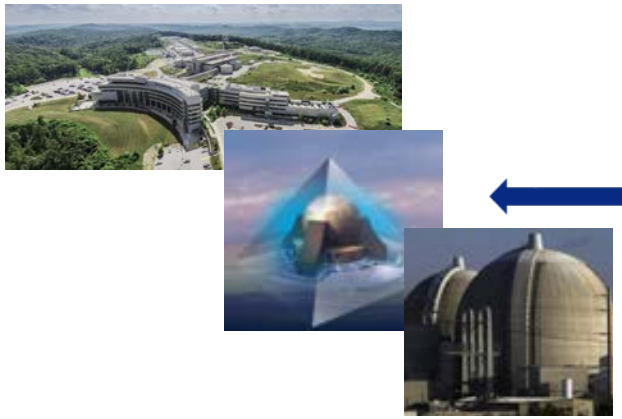
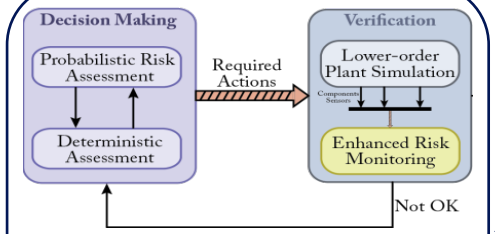
# Digital Twins Enable Scalable Information-Driven O&M

*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)*

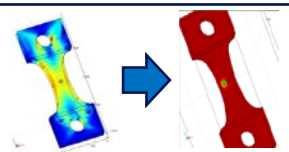


Advanced Nuclear System


Supervisory Control for Autonomous Operation




Autonomous O&M Decision Making



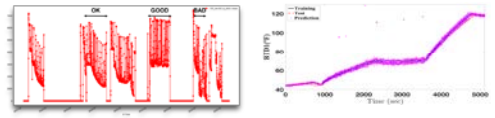
Digital Twins (Physics Informed Dynamic Models)

| Case # | Description | Expected CDF (/yr) | Reduction in Economic Risk Over 40 yrs (Relative to Case A) |
|---|---|---|---|
| A | Expected end-of-life replacement | 6.21E-07 | - |
| B | ERM – safety goal based maintenance | 6.60E-07 | 25.6% |
| C | ERM – safety and economics based maintenance | 5.26E-07 | 28.6% |

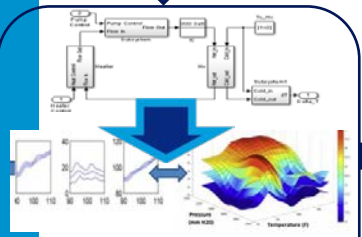
Predictive Risk & Cost Estimates

*Real-time Model Calibration*

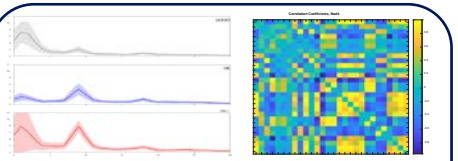
Condition Measurements



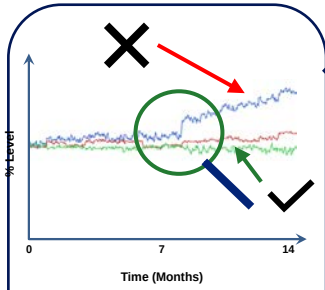
Process Measurements



Sensor Reliability, Uncertainty



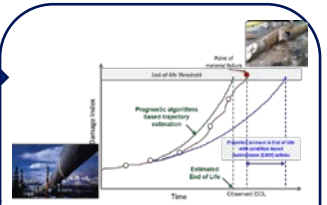
Feature Engineering & Signature Extraction




Diagnostics: Degradation Detection & ID

Uncertainty Quantification

*Causal Analysis*



Equipment Degradation Prognostics & Confidence

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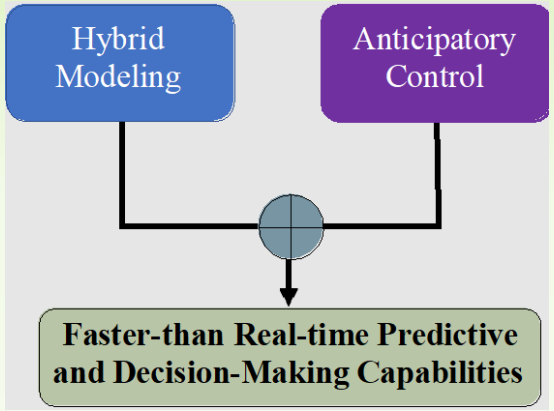
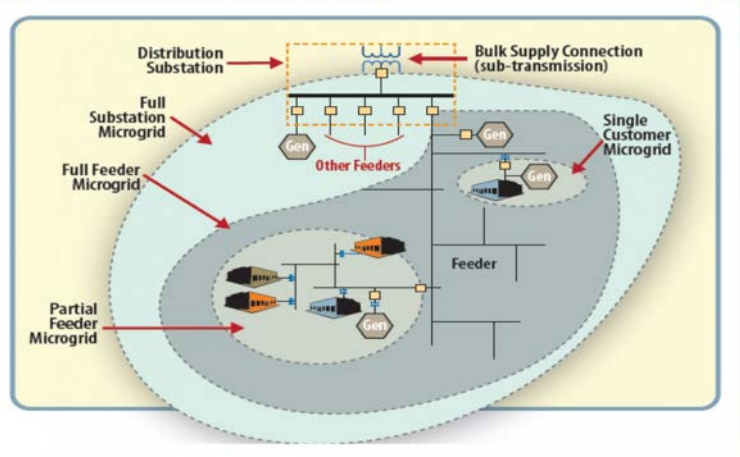
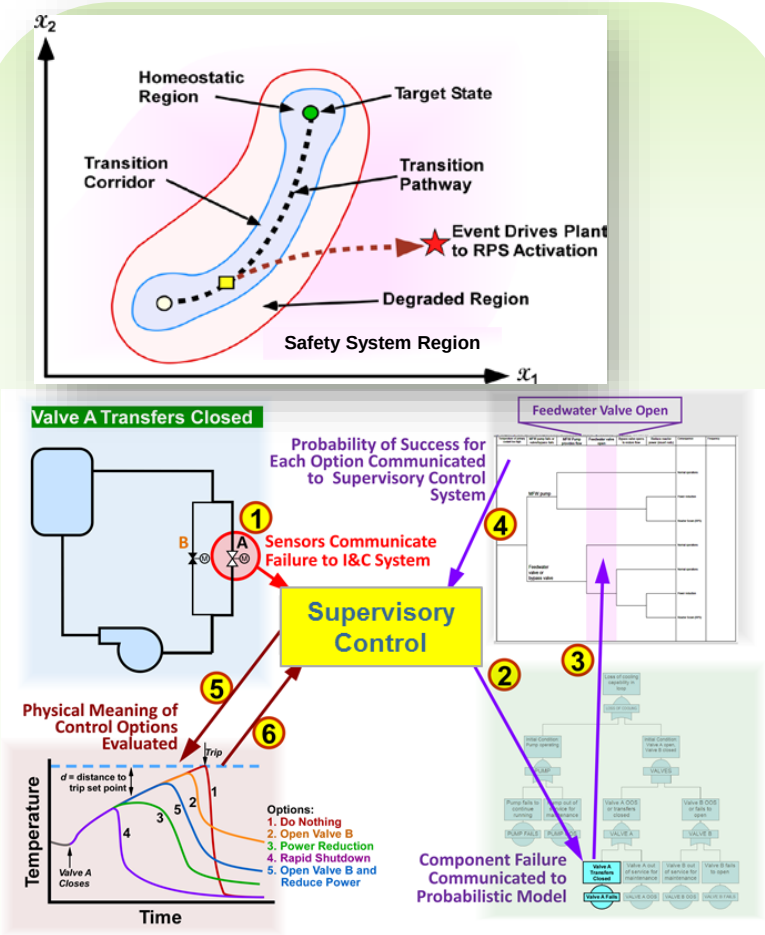
# Digital Twins that Integrate PHM and Control Technologies Enable Anticipatory Control and Autonomous Operation



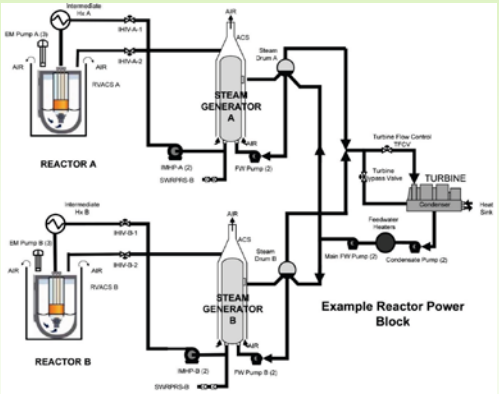

Scalable Framework for Anticipatory Control of Microreactors

*(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)*




Simplified Diagram of Multimodule Reactor

| Case # | Description | Expected CDF (/yr) | Reduction in Economic Risk Over 40 yrs (Relative to Case A) |
|---|---|---|---|
| A | Expected end-of-life (EOL) replacement | 6.21E-07 | - |
| B | Risk-informed + Predicted EOL | 6.60E-07 | 25.6% |
| C | Risk & economics informed + predicted EOL | 5.26E-07 | 28.6% |

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)*

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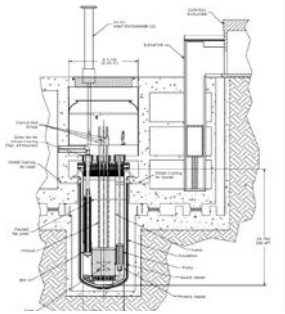
# ML is Also Key to Structural Health Monitoring for Insights into Passive Component Health in Advanced Reactors



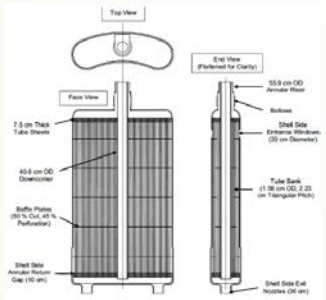
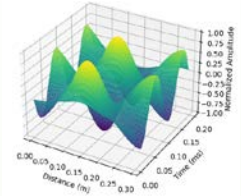


Table III-1. Summary of ISI&M Requirements

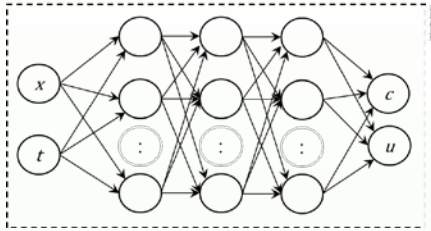
| Major Components | ISI | | Maintenance | | |
|---|---|---|---|---|---|
| | Scheduled Inspection | Access | Preventive | Corrective | Access |
| Control Rod System | | | | | |
| - Control Rod Drive Mechanism | Not Required | N/A | TBD | Replace part | Port [6] |
| - Control Rod Drive Line | Not Required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

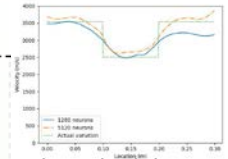
Component Design and Inspection/Monitoring Requirements per Code

Ultrasonic Data (Input)

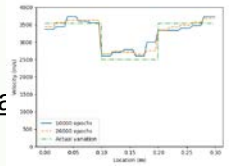


Physics-Informed Neural Network (PI-FNN)

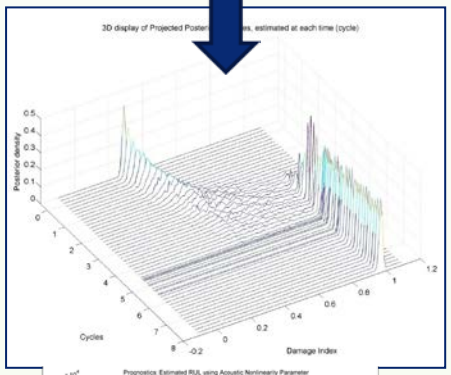


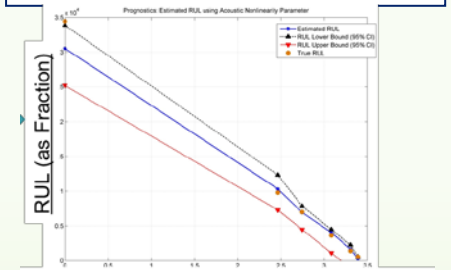


Flaw Size/Shape Estimation



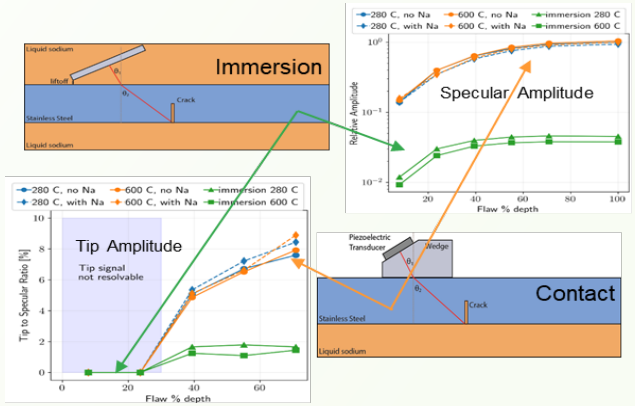
Physics-informed Machine Learning Applied for Structura Component Diagnostics (Rathod, Ramuhalli 2021)

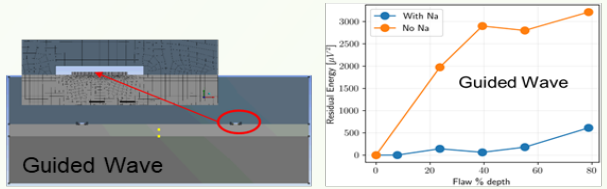





Measurement at Fraction of Remaining Life

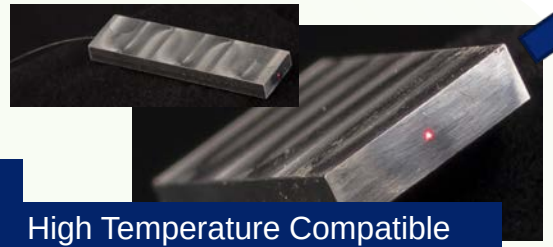
Remaining Life Estimate for Passive Nuclear Structural Components (Ramuhalli et al 2012)



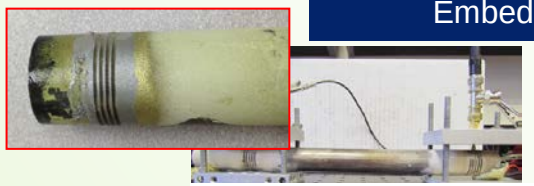




Model based Assessment of SHM in Advanced Reactors (Ramuhalli et al, 2018)

316L sheathed sensor in AM 316L build

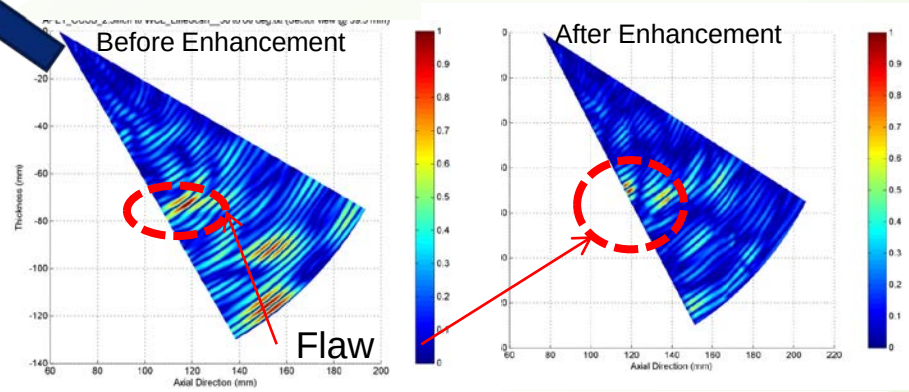


High Temperature Compatible Embedded Sensors



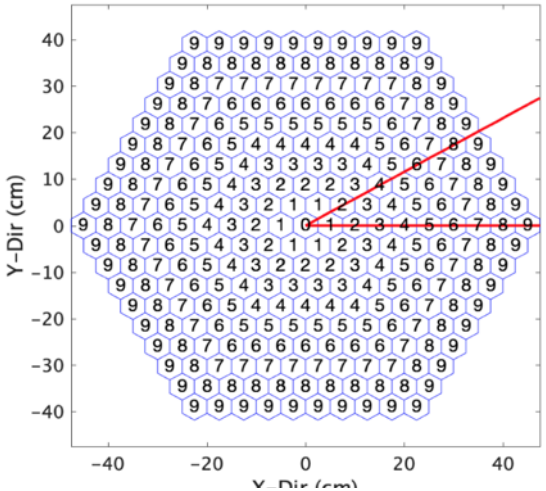
**Integrated Sensors for SHM**

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



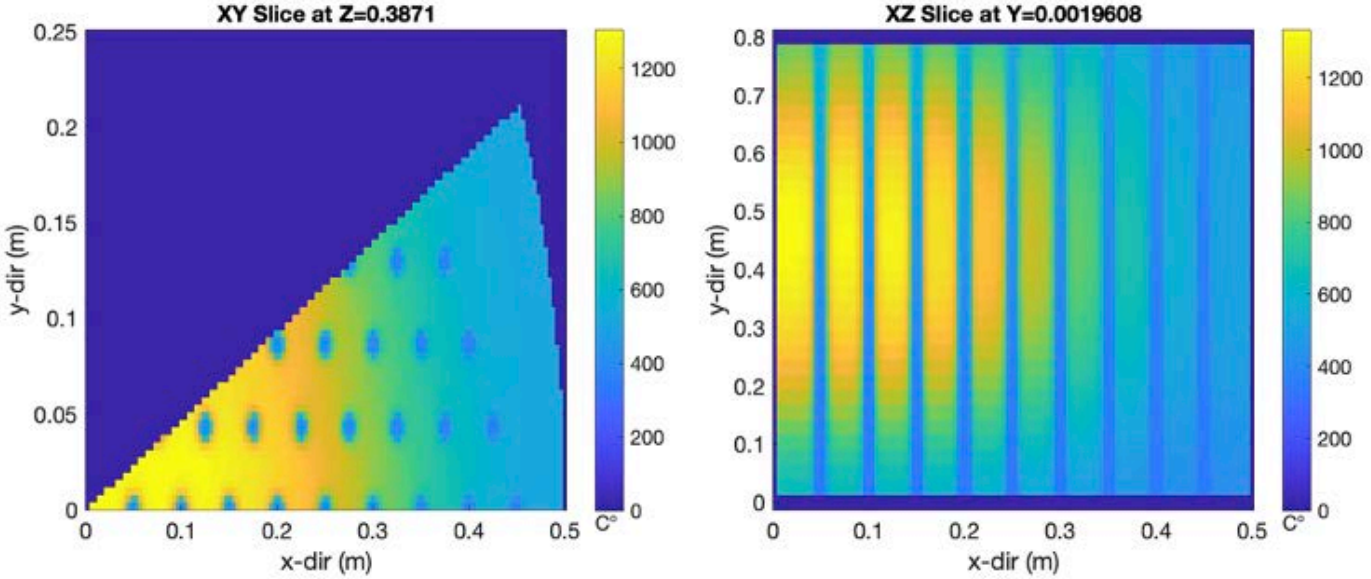

Data Enhancement for Flaw Detection from Ultrasonic Phased Array Measurements (Ramuhalli et al 2010)

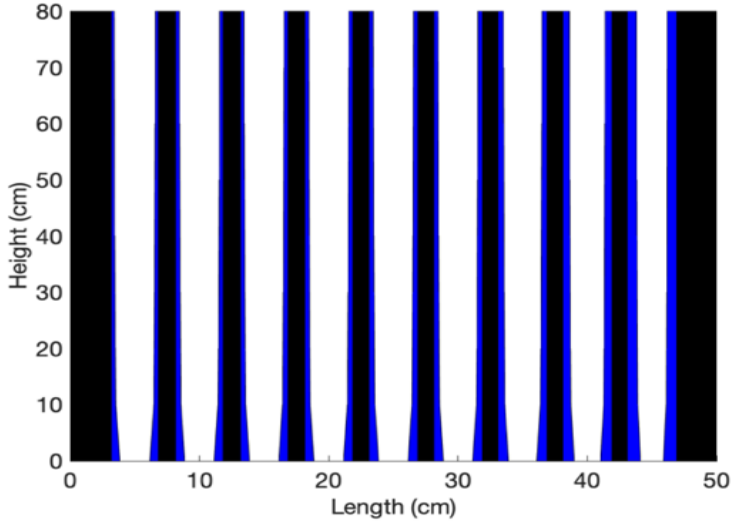
# Use of AI techniques and supercomputers to arrive at non-trivial and highly optimal nuclear designs has been demonstrated



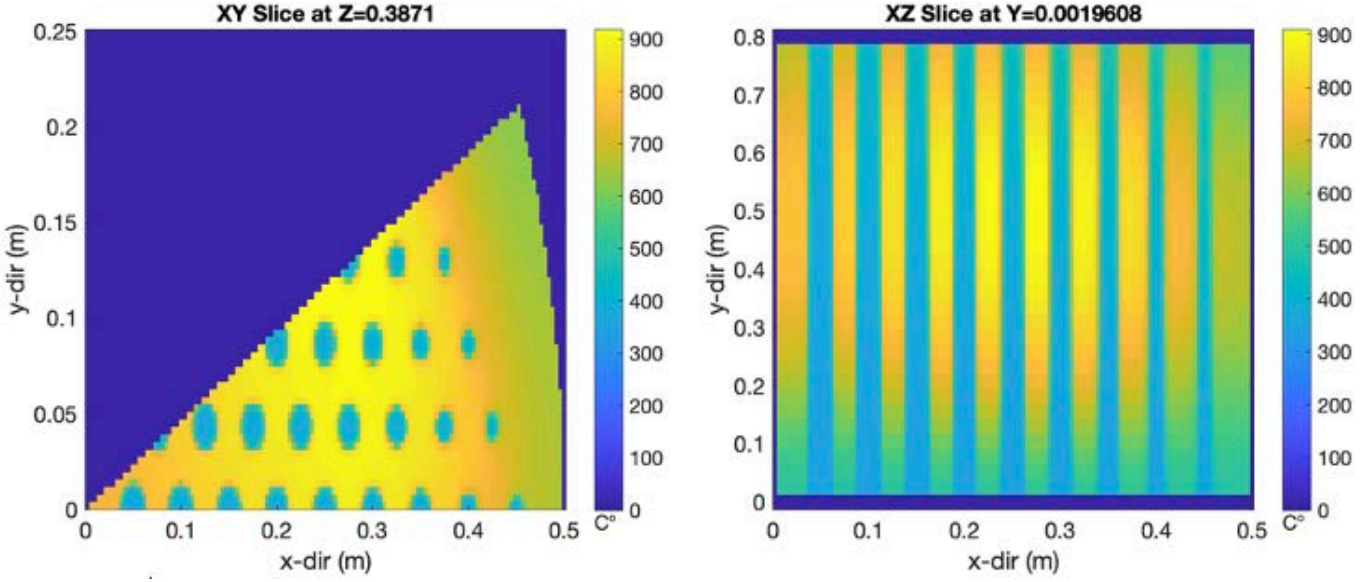

V. Sobes
et al. (2020)

**Temperature gradient across conventional design: ~900°C**



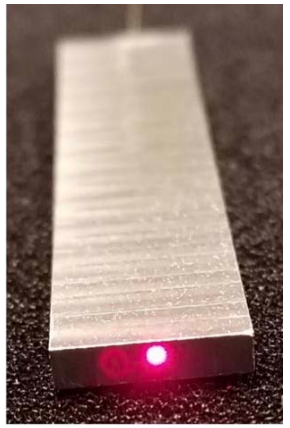

**Temperature gradient across optimal design: ~300°C**

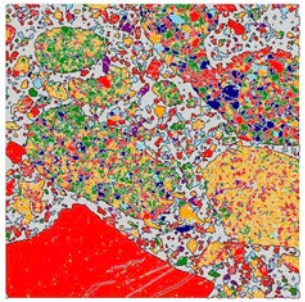


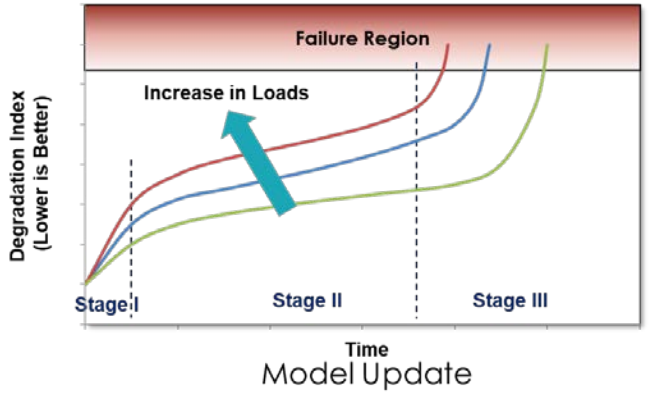

*Graphics and data courtesy Dr. Ben Betzler, ORNL*

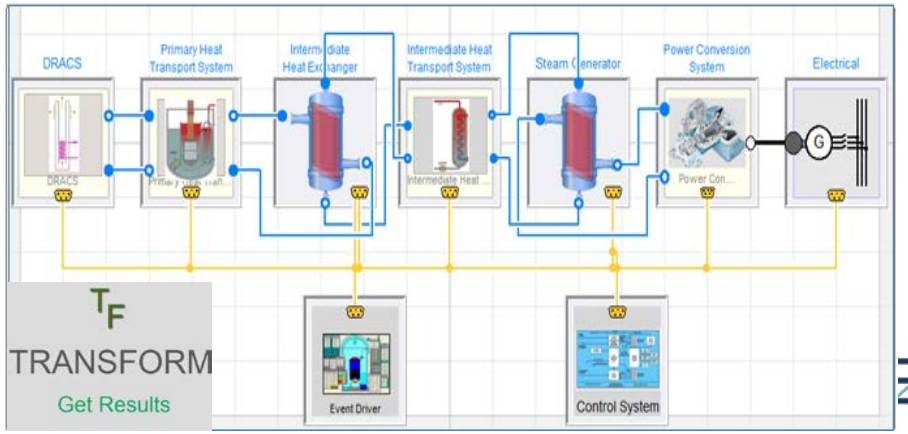
# Looking Forward: Challenges to Leveraging AI/ML to Address Deployment Economics

- 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





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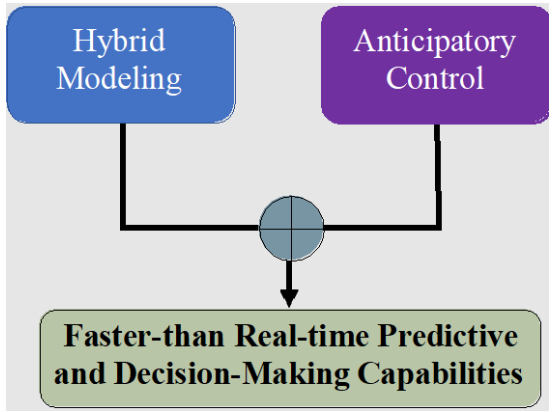
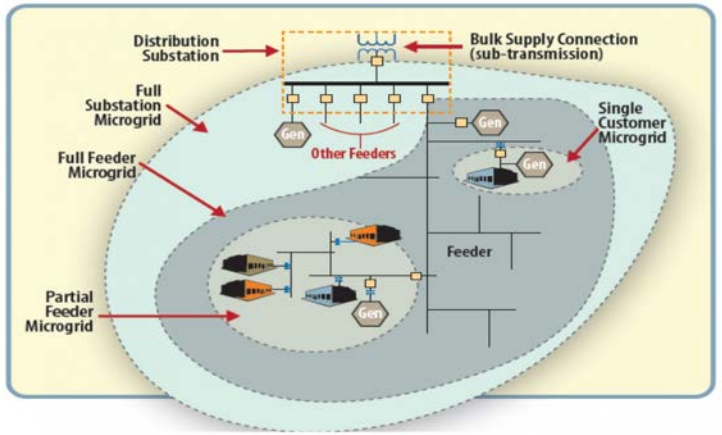
# Extra Slides

# 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)

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