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Regulation, Innovation and
Collaboration for a Safer Tomorrow
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Regulatory Considerations for Advanced Enabling Technologies for the Safe Use of Nuclear

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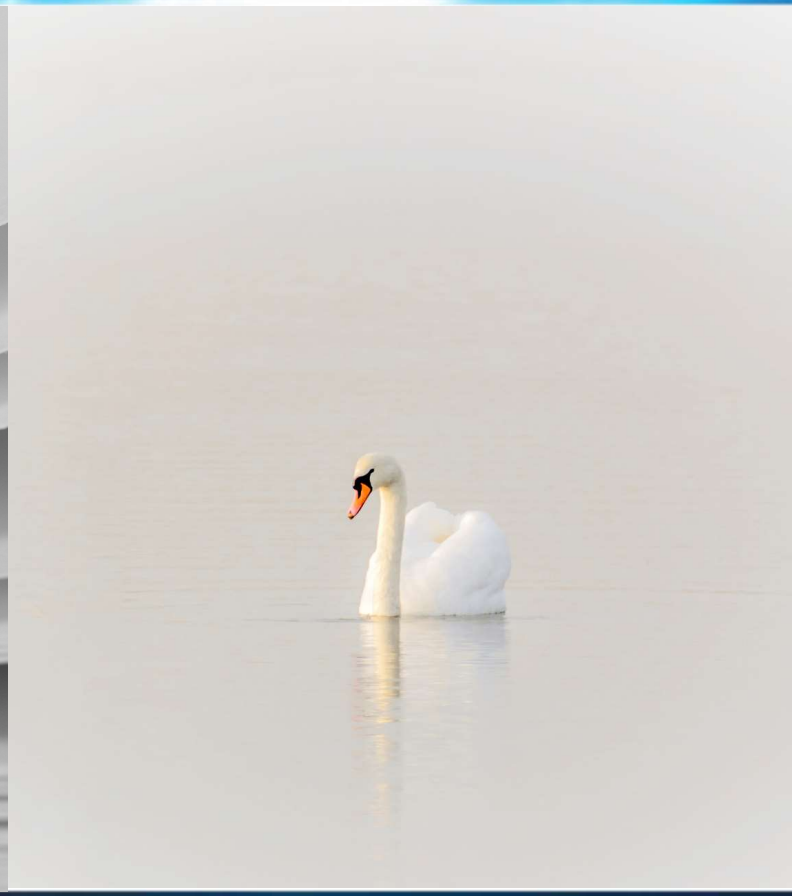


NRC research efforts to enable safe use of advanced technologies for safety-related nuclear applications and efficient licensing reviews

Research Area	Nuclear Reactor/Facility Application
Advanced Materials and Manufacturing	Safety Related Components, Structures, and Systems
M&S: Reactor Safety Codes	Fuel Performance, Severe Accident and Consequence Analyses
M&S: Security	Physical Security Effectiveness and Plans
M&S: Material Control & Accounting	Materials Safeguards and Security
Digital Twins; Condition Monitoring	Live Plant Equipment Status, Operator Assistance
Machine Learning	NDE, IST algorithms
Digital I&C Safety	I&C Upgrades and Modernization
Cybersecurity	Digital and Wireless Security of Plant Operations and Assets

Advanced Materials and Manufacturing Technologies

Fig. 1: Advanced Materials Design

Fig. 2: Nuclear Graphite Components

Fig. 3: Additive Manufacturing

- Actions: Evaluate use of advanced materials, components, and construction rules for advanced reactors; develop computational tools to analyze applications of advanced materials; develop guidelines for advance manufacturing techniques; endorse high-priority codes & standards.
- Outcome: Endorsement of ASME Section III Division 5 (RG 1.87), Section XI Division 2 (RG 1.246); AMT Draft Guidelines; Computational evaluation tools for high-temperature metals and nuclear graphite; numerous technical documents.
- Impact: Enhanced knowledge base; supported several licensing reviews; numerous external requests for NRC-developed tools.

Modeling and Simulation: BlueCRAB Code Framework

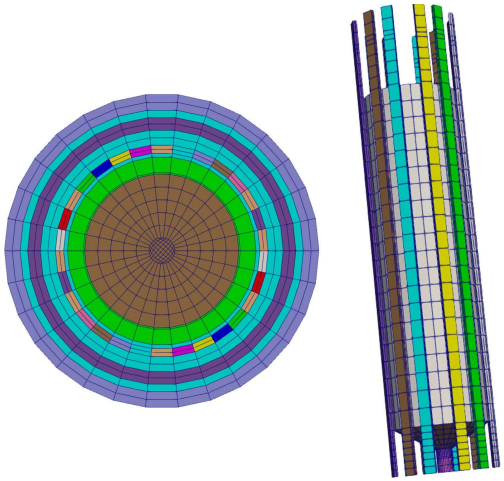


Fig. 1: 3D computational mesh of HTR-PM including control rods (https://www.osti.gov/biblio/2998899)

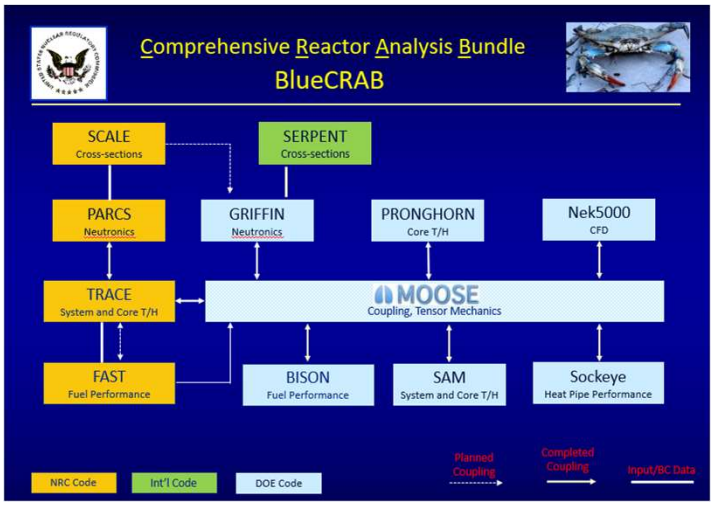


Fig. 2: BlueCRAB coupling structure

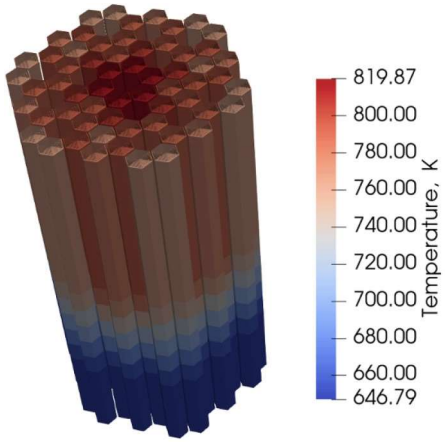


Fig. 3: Steady-state core fluid temperature distribution in ABTR (Griffin/SAM/BISON) (https://www.osti.gov/biblio/2341323)

- Actions: Developed jointly with DOE NEAMS program, BlueCRAB is a modern reactor analysis code system to evaluate design-basis events. The set of tools model advanced reactor technologies through tight coupling of different analysis modules - neutronics, thermal hydraulics, fluid mechanics, and fuel performance. (maintained by INL and ANL)
- Outcome: Provides capability to independently analyze a broad range of advanced non-LWR safety systems.
- Impact: State-of-the-Art tool enabling efficient licensing reviews of advanced designs; External use requests.

Modeling and Simulation: Physical Security

Fig. 1: Pathing analysis of a fictional nuclear power plant

Fig. 2: 3D model of an advanced reactor facility for security analysis

Fig. 3: Video presentation of security M&S

- Actions: NRC reviewed M&S tools to enable more comprehensive assessment of security plans with fewer resources.
- Outcome: Vulnerability assessments enhanced with accredited modeling tools; "Security by design" elements incorporated into advanced reactor plans; training for regional and headquarters staff.
- Impact: Accurate, data-driven approach to security programs and increased effectiveness of security plans; Increased knowledge for informed regulation of "security by design" elements.

Modeling and Simulation: Material Control and Accounting (MC&A) for Advanced Reactors

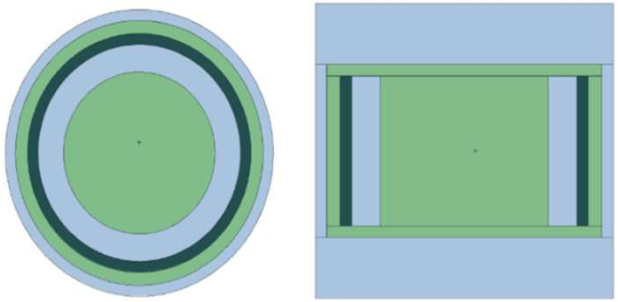


Fig. 1: MCNP Molten Salt Reactor Geometry Cross Section

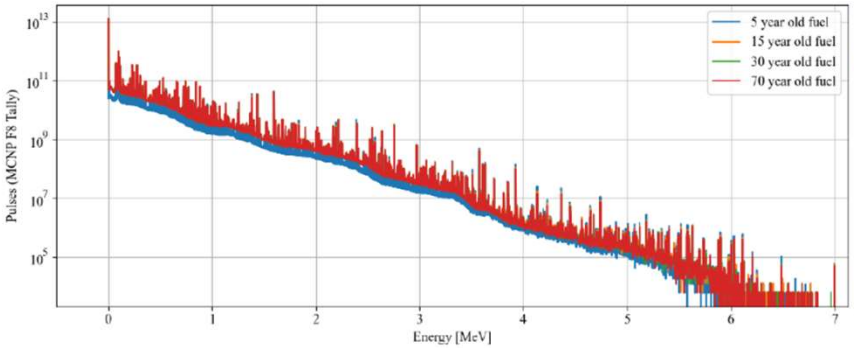


Fig. 2: Simulated Gamma Spectrum for MSR Fuel

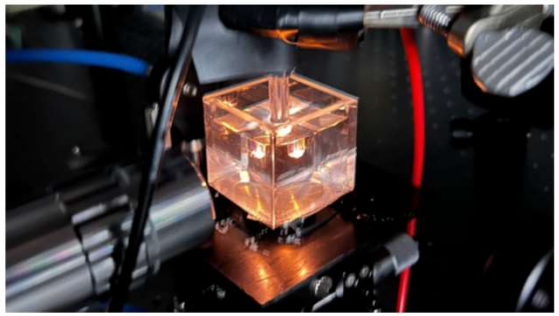
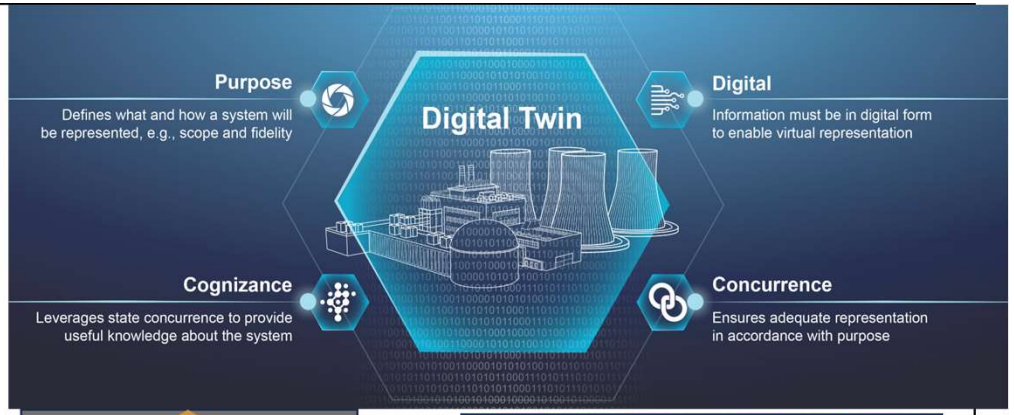


Fig. 3: Plasma Bubble Spectroscopy (Source: Bataller, 2023)

- Actions: NRC reviewed reactor designs with advanced fuel designs, such as liquid fuels and TRISO, with unique MC&A approaches and controls.
- Outcome: SNM information generated from M&S may be used by an applicant for development of a suitable program and assists in development of MC&A best practices.
- Impact: M&S data enables regulatory consideration of novel MC&A program design and tracking elements.

Digital Twins & Condition Monitoring

- **Actions:** Developed technical and regulatory considerations for use of digital monitoring tools through robust operating data representation of plant conditions.
- **Outcome:** 10+ technical reports on state-of-technology and regulatory considerations; Developed a risk-informed graded evaluation framework for condition monitoring to enable efficient regulatory decision-making.
- **Impact:** Allows for better diagnosis and prognosis of the performance of pumps, motors, heat pipes, and valves.



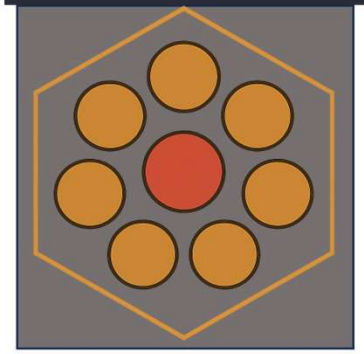


Fig. 2: Heat pipe surrounded by fuel channels

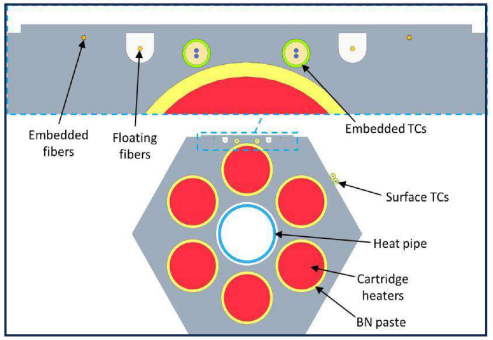


Fig. 3: Heat pipe CM experimental design

Machine Learning for Non-Destructive Evaluation

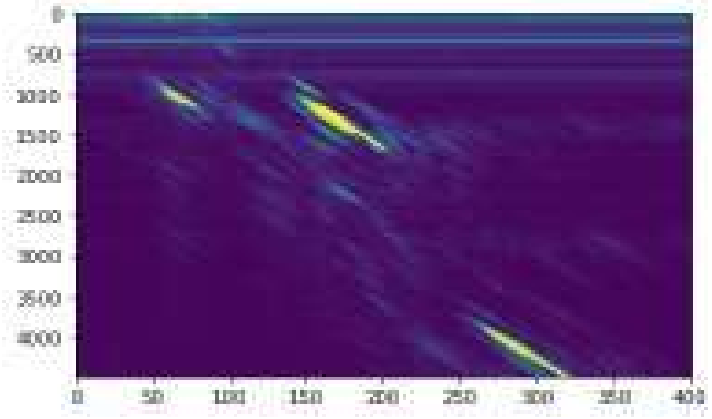


Fig. 1: Ultrasonic Inspection of a Component

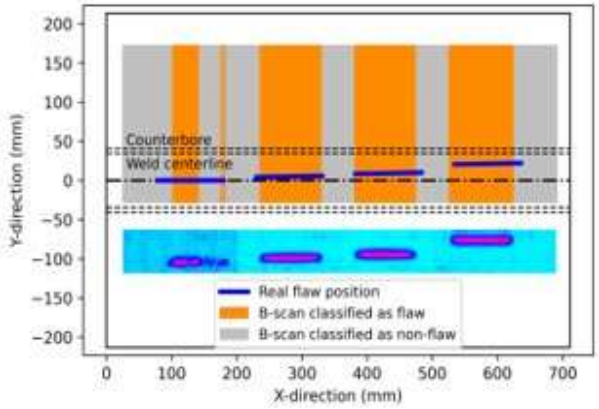


Fig. 2: ML-Assisted Fault Detection in Sample

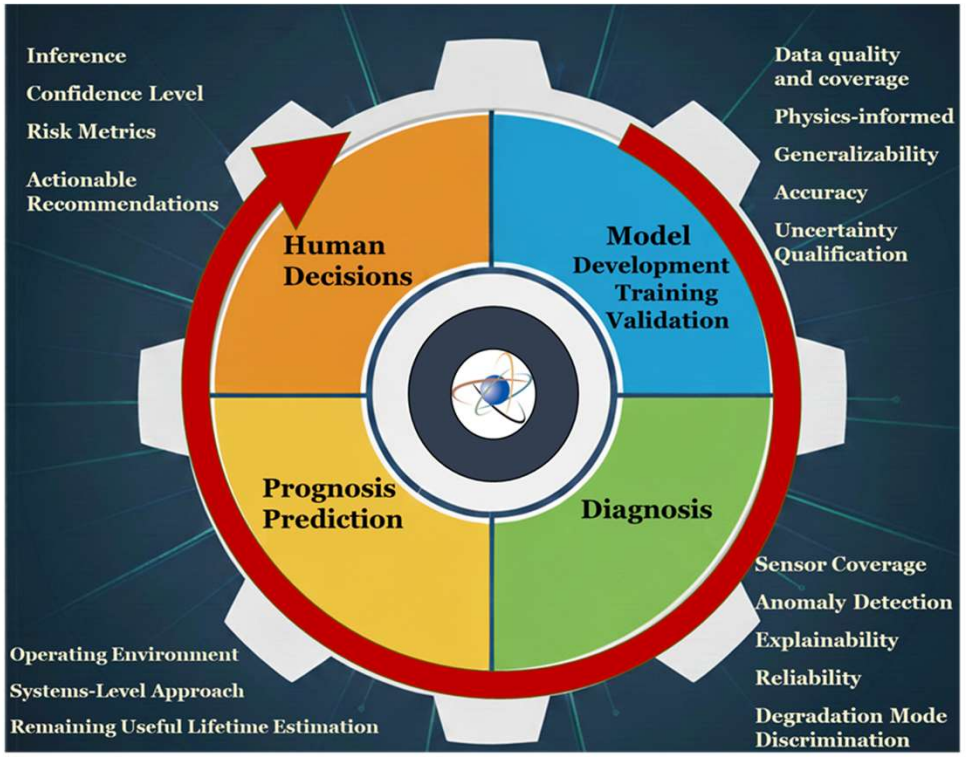
- Actions: Analyses of ultrasonic NDE data to evaluate capability/limitations of ML methods; Develop evaluation metrics and guidelines for assessing ML use in licensing applications related to NDE and inservice inspection (ISI)
- Outcome: Develop basis for regulatory decision-making and potential endorsements of codes and standards for ML use for ISI
- Impact: Enhanced knowledge base; support efficient licensing reviews

Machine Learning for Condition Monitoring

Actions: Evaluate the necessary activities and develop basis to provide reliable and accurate ML condition monitoring of components to support the safe operation of NPPs.

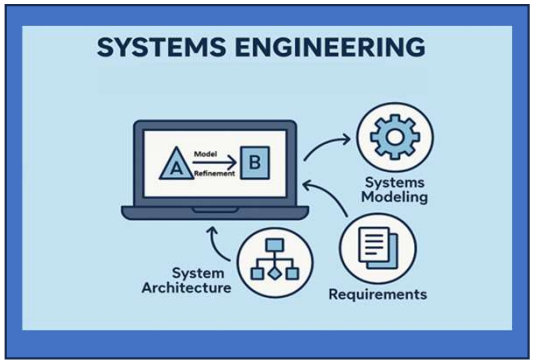
Outcome: Identify guardrails and develop guidelines and framework that provide greater confidence in application of machine learning in condition monitoring.

Impact: Enable safe use of condition monitoring of structure and components for effective operational performance.



Digital I&C Research: Enabling Performance Based Reviews

- Actions: Developed evaluation criteria for safety-outcome focused regulatory reviews using systems engineering principles.
- Outcome: Technical criteria to review Digital I&C submittals.
- Impact: Reduce time, cost, and uncertainty in regulatory reviews.



Cybersecurity Research: Wireless Technologies

- Actions: Analyzing the impact of using wireless technologies for monitoring safety-related (SR)/important-to-safety (ITS) systems.
- Outcome: Gained knowledge on potential cybersecurity vulnerabilities and risks.
- Impact: Reduce cybersecurity risks from introducing wireless technologies to monitor SR/ITS systems at NPPs.

- **Enabling technologies offer important regulatory benefits, including:**
  - **Enhanced risk mitigation**
  - **Reduced technical and operational uncertainty**
  - **Greater overall efficiency in regulatory and licensee operations**
- **The NRC needs to evaluate the safety and risk impact of the enabling technologies and develop guidance, as appropriate and needed.**
- **NRC research is proactively advancing the safe and effective deployment of these advanced enabling technologies across nuclear facilities.**

Acronyms

ASME – American Society of Mechanical Engineers
CM – Condition Monitoring
I&C – Instrumentation and Control
IST – In-Service Testing
ITS – Important-to-safety
ML – Machine Learning
M&S – Modeling and Simulation
MC&A – Material Control and Accounting
NDE – Non-Destructive Examination
NPP – Nuclear Power Plant
RG – Regulatory Guide
SNM – Special Nuclear Material
SR – Safety Related

Advanced Materials and Manufacturing

-NRC Public Site: Advanced Manufacturing Technologies (AMTs) | Nuclear Regulatory Commission

-Additive Manufacturing: ML25204A130, In-Process Monitoring and Non-Destructive Evaluation for Metal Additive Manufacturing Processes

-High Temperature Materials: ML25204A022, Review of Composites for High-Temperature Nuclear Applications

-Regulatory Guide 1.87: ML25176A084, Acceptability of ASME Code Section III, Div. 5, 'High Temperature Reactors'

-Fusion Manufacturing: ML24137A055, Review of Advanced Manufacturing Technologies for Fusion Reactor Materials

-ASME Code Section 8 Assessment: ML25059A010, ML25133A109

Reactor Modeling and Simulation References

-NRC Safety Codes: https://www.nrc.gov/about-nrc/regulatory/research/safetycodes

-NRC Material Safety Codes (FAVPRO, xLPR): Computer Codes | Nuclear Regulatory Commission

-HTGR Reference Plant: https://www.osti.gov/biblio/2998899

-Sodium-Cooled Fast Reactor Reference Plant: https://www.osti.gov/biblio/2341323

-CAMP Thermal-Hydraulic Code Group: https://www.nrc.gov/about-nrc/regulatory/research/camp

Physical Security M&S References

-Vulnerability Assessment: ML25090A245, Assessment of Physical Security Modeling and Simulation in the Vulnerability Assessment Process

-Security By Design: ML25162A019, Hypothetical Nuclear Reactor Facility M&S Data – Scenario Comparison

MC&A M&S References

-Advanced Reactors MC&A: ML25078A020, Modeling and Simulation Supporting Material Control and Accounting for Advanced Reactors

-Fast MSR Depletion Analysis: ML25233A073, Depletion Analysis of a Generic Fast Spectrum Molten Salt Reactor Supporting Material Control and Accounting

Digital Twins & Condition Monitoring References

-NRC Digital Twins: Digital Twins | Nuclear Regulatory Commission

- IST CM: ML24305A162, Assessment of Condition Monitoring Methods and Technologies for Inservice Inspection and Testing of Nuclear Power Plant Components

-IST ACM: ML251951282, Technical Considerations in the Application of Advanced Condition Monitoring for Inservice Testing Programs

-DT CM: ML25135A029, Technical Assessment of the Application of Digital Twin and Prognostic Tools for Condition Monitoring

-Pump CM w/ML: ML2523A274, Investigation of Machine Learning Approaches for Condition Monitoring of Boiling Water Reactor Recirculation Pumps

-RIGA for ACM: ML26056A138, On the Application of a Risk Informed Graded Approach for Advanced Condition Monitoring Programs

Digital I&C Safety and Cybersecurity Research References

-NRC Site on I&C: https://www.nrc.gov/about-nrc/regulatory/research/digital

-NRC Site on Cybersecurity: https://www.nrc.gov/about-nrc/regulatory/research/cybersecurity

-The HARDENS Final Report, Available on GitHub. Video Presentation available on YouTube.

-ML24213A251, A Case Study for Building System-Theoretic Process Analysis Review Capabilities at the U.S. Nuclear Regulatory Commission.

-ML25248A033, Criteria to evaluate a Performance-based Safety Assurance Case for Digital Systems that Protect Operating Reactors.

-ML23264A148, Analyzing the Impact of Using Wireless Technologies for Monitoring Safety-Related Critical Digital Assets