Advanced Nuclear Technology

Advanced Reactor Materials Overview

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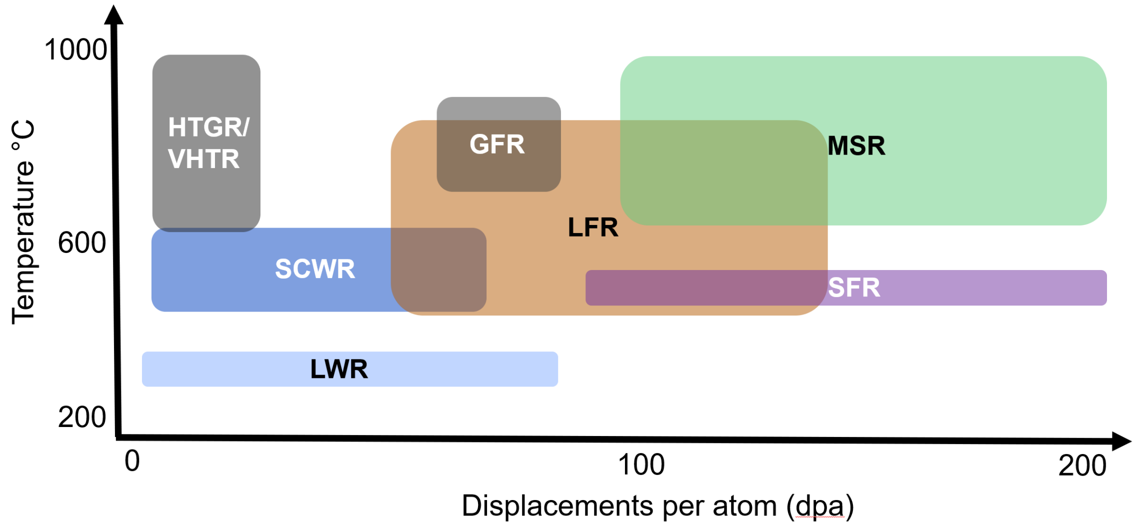
Industry/NRC Materials Technical Exchange
June 2025

Agenda

- Materials Needs for Advanced Reactors
  - Materials Deployment
- EPRI Technical Focus Areas
  - Advanced Manufacturing and Materials Qualification
  - Advanced Reactor Materials Reliability
    - Materials Management - RIM
      - Overview
        - Expert Panels
- Advanced Reactor Materials Technical Advisory Group
- Advanced Reactor Materials Technical Exchange Meeting

New Fuels, Coolants, Conditions = New Material Needs

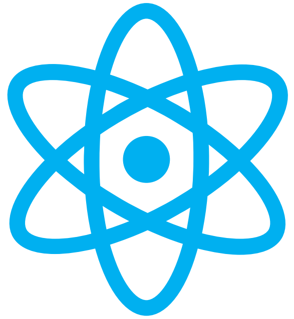


Adapted from Y. Guerin, G. S. Was, and S. J. Zinkle. *Materials Challenges for Advanced Nuclear Energy Systems*. MRS Bulletin V34(1), (2009).

GFR – Gas-cooled Fast Reactor
HTGR – High Temperature Gas Reactor
LFR – Lead-cooled Fast Reactor
LWR – Light Water Reactor
MSR – Molten Salt Reactor
SCWR – Supercritical Water Reactor
SFR – Sodium-cooled Fast Reactor
VHTR – Very High Temperature Reactor

High Temperature Materials Qualification

Materials Compatibility in New Reactor Environments



Materials Management Programs to Ensure Operational Integrity

Materials Deployment for Advanced Reactors

Code Qualification

Limited number of ASME Code Qualified alloys for high temperature service

Can take a DECADE to fully qualify a new alloy

$

Just because the material is **Code Qualified** doesn't mean it is **approved** for Nuclear Service

Environmental Effects

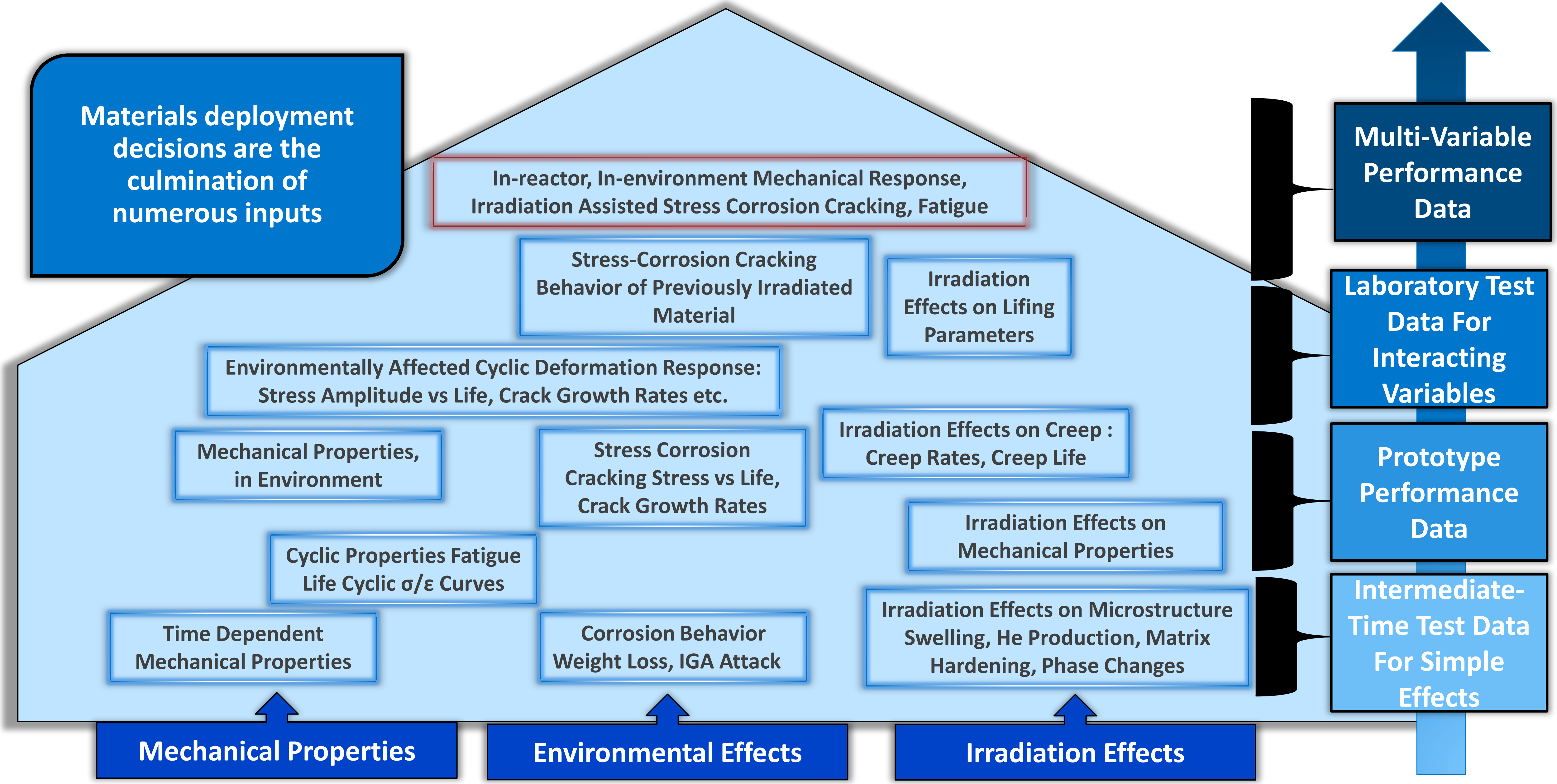
Owner/Operator has the responsibility to demonstrate to regional regulator that the effects on structural failure modes are accounted for in their specific reactor design

- Irradiation Data
- Corrosion Data
- Thermal Performance
- Environmental Testing

Supply Chain

Critical data and understanding required for informed fabrication and design of AR components

Materials Validation and Deployment



Advanced Manufacturing and Materials Qualification

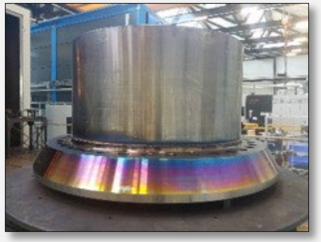
Advanced Manufacturing and Materials Qualification

GOAL & VALUE

Identify, develop, qualify, & implement new materials & manufacturing methods that enable:

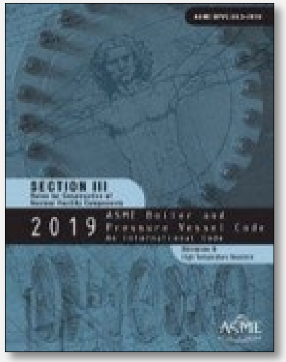
Higher Quality Components | Reduced Lead Times | Alternative Supply Chains | Cost Competitiveness | Enable Deployment

- Evaluate, Qualify, and Demonstrate Advanced Manufacturing Methods
  - Additive Manufacturing
  - PM-HIP
  - Advanced Welding
  - Advanced Cladding
  - Surface stress improvement



Advanced Manufacturing & Fabrication

- AR Materials Development
- Materials Databases
- Qualification in Codes & Standards
- Accelerated Qualification Approaches
- Improved Material Performance



Materials Development & Qualification

- Increase Quality
- Enhanced Specifications & Processes
- Demonstrations at Scale
- Risk Informed Procurement
- Meet growing new build demands

Procurement & Installation

EPRI

Approaches for Accelerated Qualification of Materials

Approaches for Accelerated Qualification of Materials

Roadmap Strategic Gap Addressed:
1) Capture material data and close gaps necessary for deployment of Advanced Reactors

OBJECTIVE

- Qualification of new materials for nuclear applications is time consuming and expensive
  - Particularly for high temp applications (up to 10 years)
- Assess and develop accelerated qualification approaches
- Pilot the framework with codes & standards and regulatory bodies

STATUS

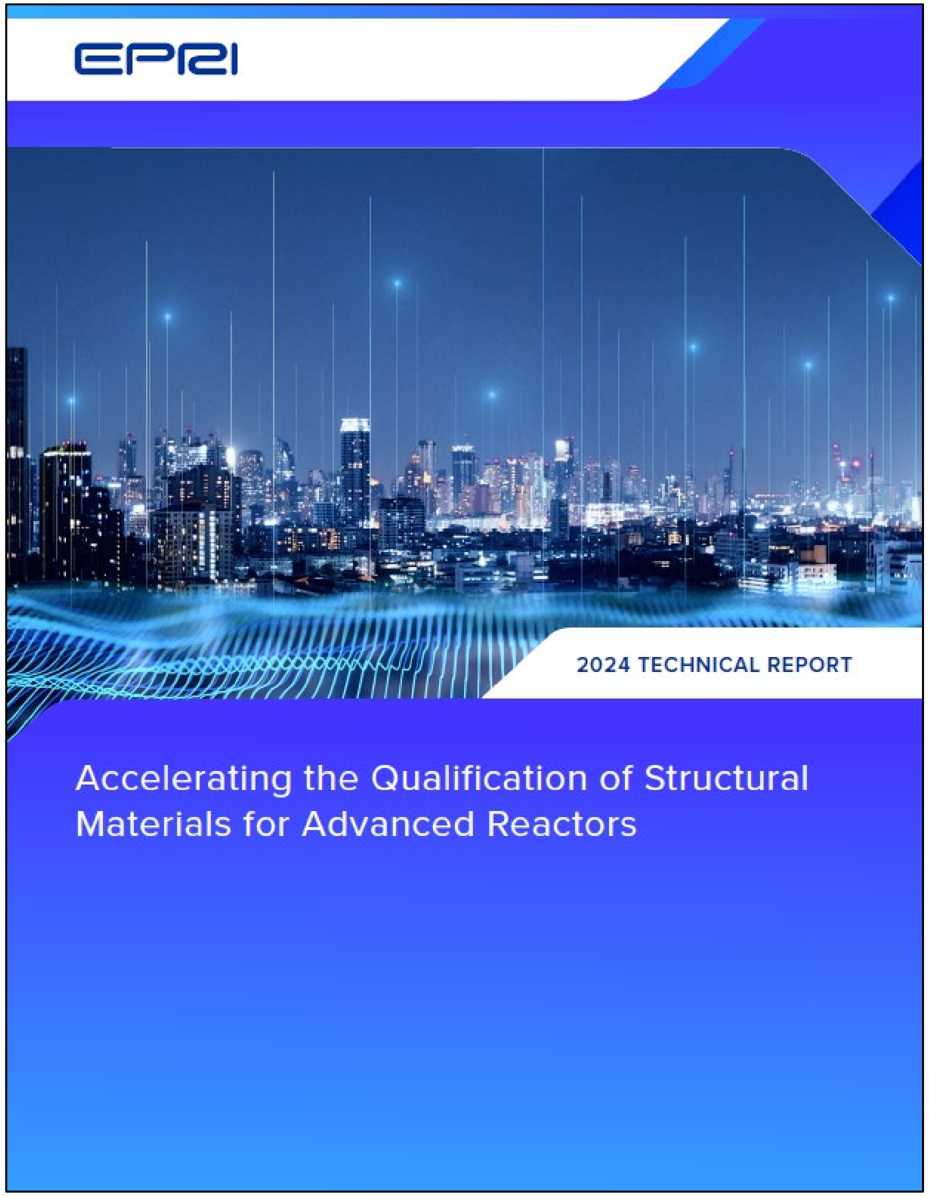
- 3002029265 published November 2024
- Assembled promising and most value-added methods
- Primer document outlining the advantages, disadvantages, and challenges of each approach
- Collaboration with Argonne National Lab

NEXT STEPS

- Integrate numerous approaches into a qualification framework
- Pilot framework with multiple approaches on known material (e.g., 316 variants)
- Continued collaboration with Argonne National Laboratory

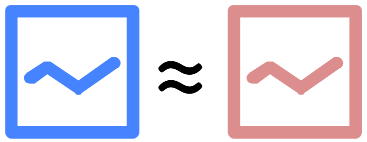
Phase I Activities

- Conducted survey to document methods that could potentially reduce ASME code qualification burden
- Collaboration with Argonne National Lab
- Various methods identified that might allow acceleration of the code process (primarily centered around long-term creep data)
- Report published in late 2024

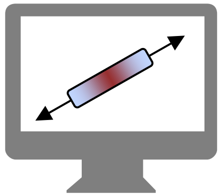


EPRI Report 3002029265, November 2024

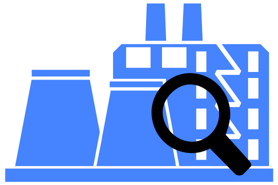
Potential Approaches to Accelerate Material Qualification



Qualification by Analogy



Physics-based Modeling

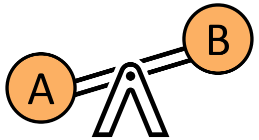


Material Surveillance

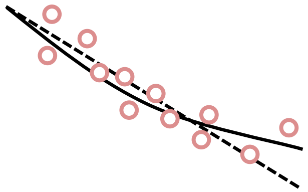
Staggered Qualification

Accelerating qualification: Reduce the time required to conduct testing, analyze data, and secure approval for a new material compared to conventional approaches

Limited Design Scope



Alternate Code Classification



Improved Empirical Models

EPRI

Next Steps – Accelerating Materials Qualification

Published “Primer Document” 3002029265

- Provides a **toolbox of approaches** to accelerating qualification
- Includes advantages, disadvantages, and specific research needed to deploy each given method

- Integrate multiple approaches into a qualification framework
- Continuing the collaboration with ANL

Phase 2 Underway

- Pilot framework with multiple approaches on known material (e.g., 316 variants)
- Looking to leverage pilot towards potential future materials

Advanced Reactor Materials Reliability

Materials Management Programs

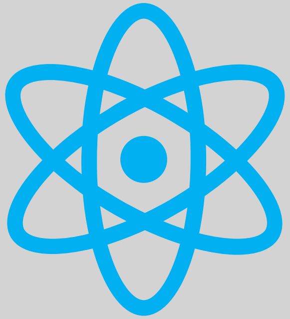
Regulatory Guidance for Advanced Reactor Materials

US Nuclear Regulatory Commission Interim Staff Guidance (DANU-ISG-2023-01)

- …Section III-5, HBB-1110(g) ASME Code rules do not provide methods to evaluate deterioration that may occur in service as a result of corrosion, mass transfer phenomena, radiation effects, or other material instabilities…non-LWR application to **review applicable design requirements including environmental compatibility, qualification and monitoring programs for safety-significant structures, systems, and components** (SSCs)…

High Temperature Materials Qualification

Materials Compatibility in New Reactor Environments



Materials Management Programs to Ensure Operational Integrity

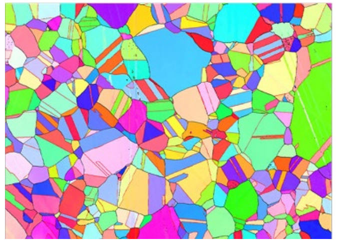
Advanced Reactor Materials Reliability

GOAL & VALUE

Develop foundational building blocks for future materials management programs through:

Understanding Materials Degradation | Identifying Mitigation Opportunities | Enhancing Monitoring and Inspection Capabilities

- Materials Degradation Matrices
- Degradation Mechanism Assessments
- Materials Management Matrices
- Establishing Chemistry Guidelines
- Materials Modelling and Testing

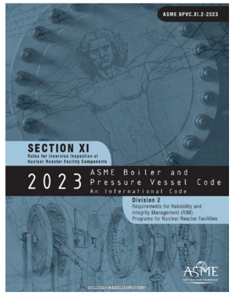


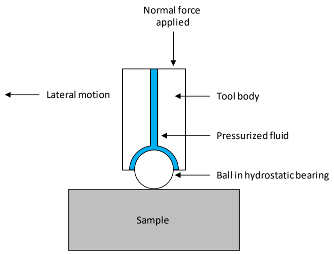
Environmental Compatibility

- Capability Assessments
- Feasibility Assessments
- Technical Justifications
- Performance Demonstration
- Innovative and Novel Techniques

Monitoring and Inspection

- Materials Reliability and Integrity Management
  - Mitigation Techniques
- Codes and Standards
  - Risk-Informed Strategies





Materials Management Programs

Materials Management

Identify applicable materials degradation for an AR environment

- Operating experience available?
- Research data available?
- Can the mechanism be modelled?

Assess impact of degradation

- Time-dependent or time-independent degradation?
- Critical/Detrimental to design integrity?

Can the degradation be designed out?

- Change geometries?
- Change materials?
- Change operating parameters/chemistry controls?
- SSC change, in general?

If not, then mitigate, monitor, or plan for replacement

- Cladding
- Peening
- Overlay
- New/Novel Mitigations
- Continuous monitoring
- Inspections
- Surveillance
- Plan for replacement

Design Phase

Materials TAG
Materials Degradation Matrices
Degradation Mechanism Screening and Assessment

Reactor developer decision making process – reasonable assurance for material deployment

Operational Programs

In-service inspection, monitoring, or surveillance
ASME Section XI, Division 2 - RIM

Reliability and Integrity Management Program

Materials Management Programs

Current Fleet

For the operating, light-water reactor fleet, license holders use **a deterministic approach** to assure as-designed safety margins through a selection of mandated examinations and tests

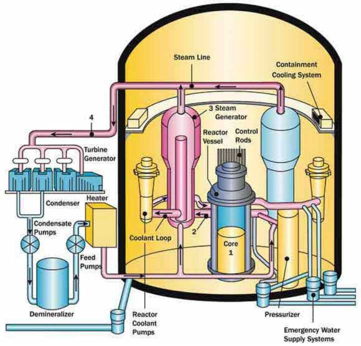
- **ASME Section XI, Division 1**
  - Developed and evolved with over 50 years of operating experience guiding the requirements. However, its requirements are often a poor fit for many new reactor designs.
- **NEI 03-08 Materials Initiative**
  - Industry requirement, endorsed by NRC, to proactively manage aging and degradation of materials

Future Fleet

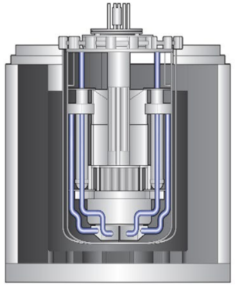
To support a broader range of reactor specifications/designs, a **performance-based alternative** approach to define examinations and tests is now available

- **ASME Section XI, Division 2 (RIM)**
  - A scalable framework designed to accommodate new technologies and evolving plant needs.

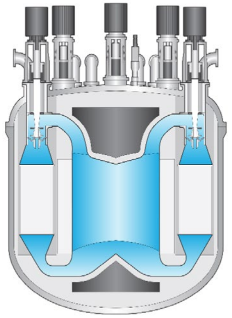
Typical Pressurized Water Reactor



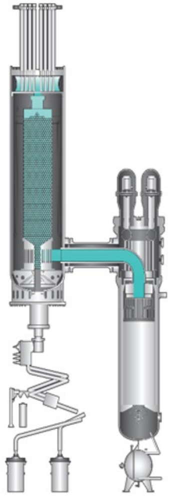
Fast Reactors



Molten Salt Reactors



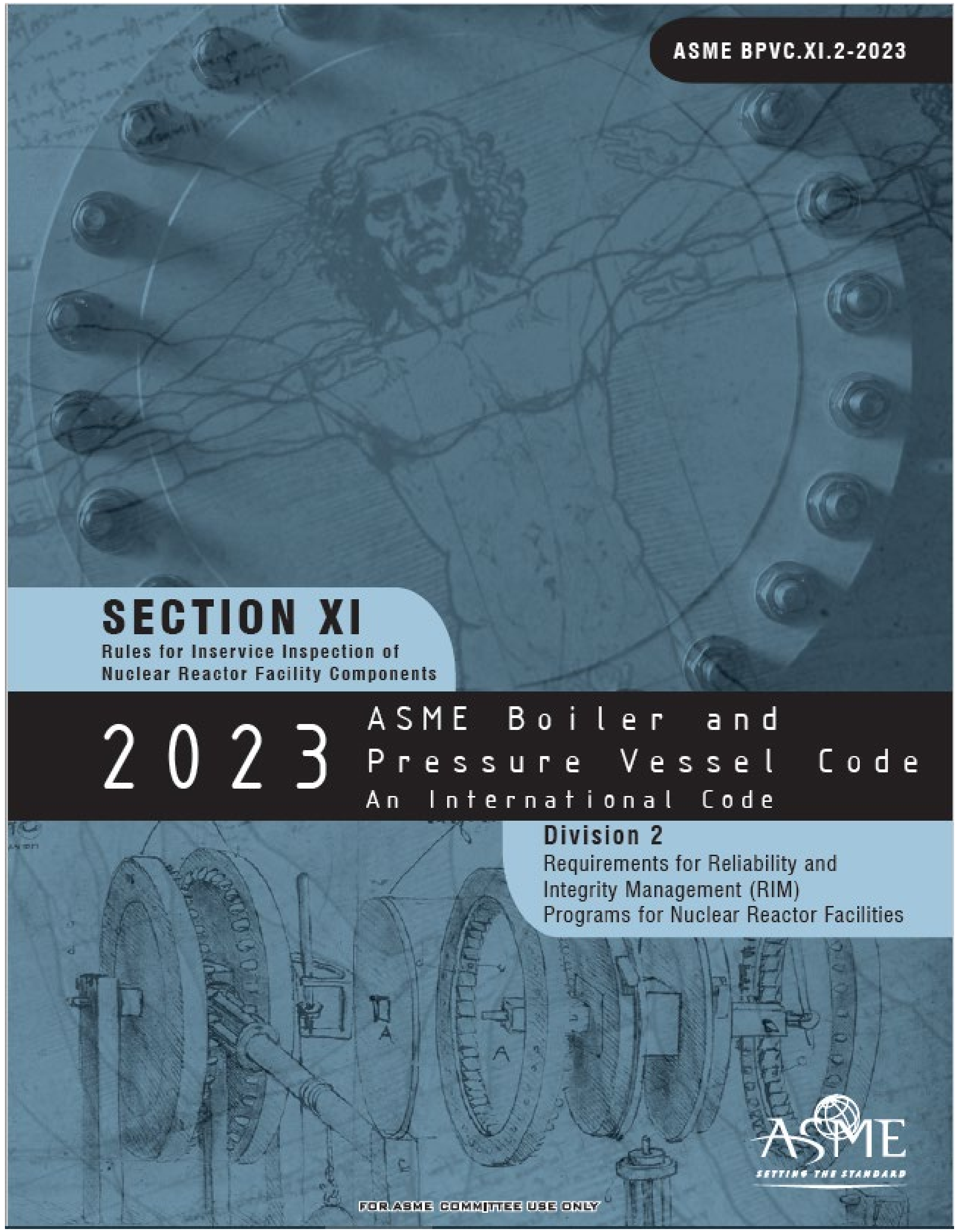
High-temperature Gas-cooled Reactors



Section XI, Division 2 - Reliability and Integrity Management (RIM) Programs

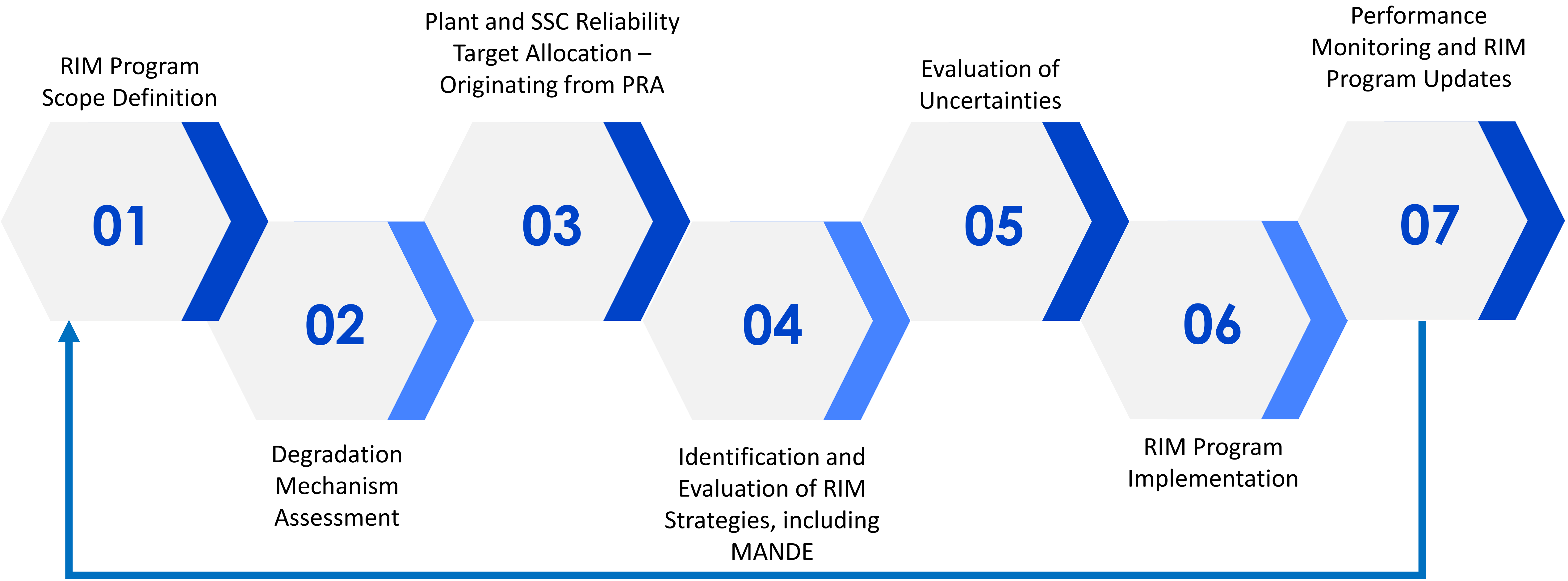
Establishes a flexible, risk-informed, performance-based framework for managing material degradation across all types of nuclear facilities—supporting modern design needs and long-term operational safety. **Not a design Code, but impacts decisions made during the design phase**

- Provides requirements for developing **Risk-Informed Materials Programs** applicable to any nuclear facility
- Offers **flexibility** by allowing implementation without prescriptive inspection tables (unlike Division 1's -2500 tables)
- Supports modern reactor designs by aligning material inspection strategies with safety significance and performance goals



Advanced Reactor Materials Management - The RIM Process

ASME Section XI, Division 2



RIM Process

Materials Degradation

- Degradation Mechanism Assessment

Probabilistic Risk Assessment

- Program Scope Definition
- Plant and SSC Reliability Target Allocation
- Accounting for Uncertainty

RIM Strategies

- Identification and Evaluation of RIM Strategies
- Program Implementation
- Continuous Learning from OE and Research Results

Reliability and Integrity Management Programs

Expert Panels

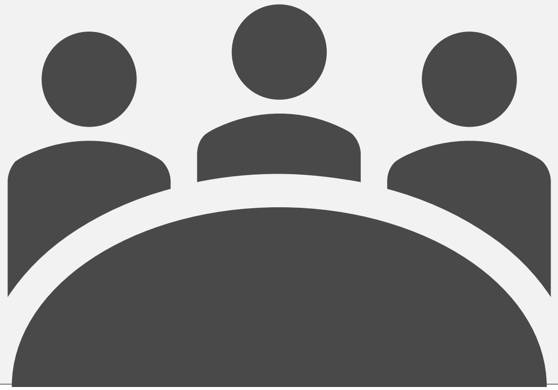
Expert Panels (EP)

The success of the RIM Program is a product of the expert elicitation process

RIM EP

Responsible for overseeing the RIM Program development, documentation, and implementation

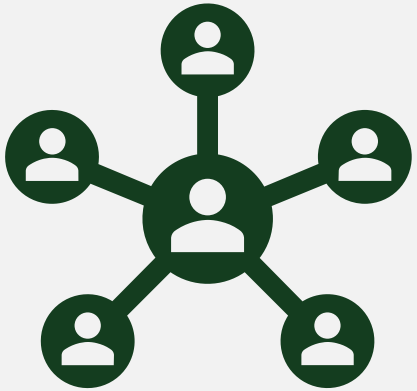
- Identify RIM Program scope, associated Reliability Targets, and RIM Strategies



MANDE EP

Responsible for establishing MANDE specification and overseeing the qualification of MANDE methods and techniques

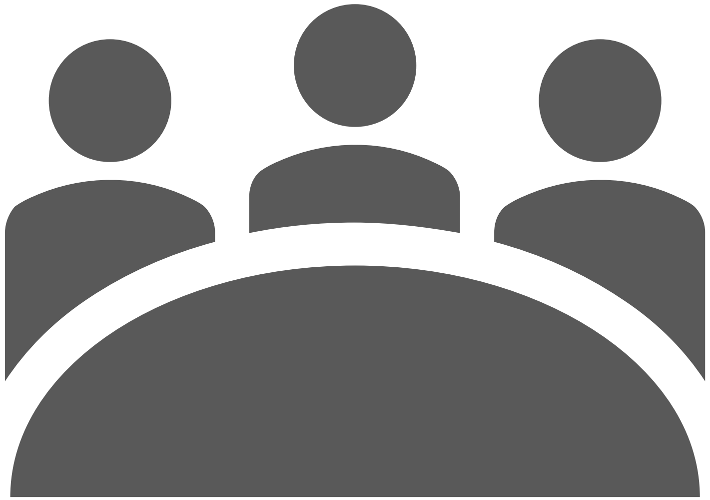
- Specify coverage, frequency, location, and volume for inspection



Expert Panels – RIM EP

This is an overarching panel with the purview of ensuring each of the process steps is completed. There is also a need for this panel to have a broader perspective and understanding of the facility safety case to assist in RIM program scoping, as well as setting the reliability targets for systems, structures, and components. This panel interfaces with the system design departments to understand the system requirements.

Design Expert (Construction Code Analyses)
Design Expert (General Facility Design Requirements)
Materials Degradation Expert(s)
Facility Operations Expert
Probabilistic Risk Assessment Expert(s)
MANDE EP Chair (for coordination)
Licensing Expert (Licensing Modernization Project Expert)



- Determining the SSCs to be included in the RIM Program
- Setting the Reliability Target Values for each SSC
- Coordinating with the MANDE EP to establish what MANDE method(s) should be assigned
- Coordinating with the plant Owner/Designer to assure specific SSC scoped in the program can accommodate selected MANDE
- Validating that uncertainties from initial PRA use or from MANDE selection and performance demonstration actions do not adversely impact required RTVs (reliability target values)

Expert Panels – MANDE EP

This panel oversees more of the technical background to assist in the decision-making process. The inspection type and periodicity requirements will be the product of understanding the materials degradation, flaw growth characteristics, critical flaw sizes, available MANDE techniques/mitigation techniques, and the uncertainties in each of those inputs.
MANDE Chair with extensive background in NDE
Fracture Mechanics expert(s)
Various NDE Technique Experts ○ Acoustic Emissions ○ Eddy Current Testing ○ Leakage Testing (incorporates potential tests for multiple different designs) ○ Liquid Penetrant Testing ○ Magnetic Particle Testing ○ Online Monitoring ○ Ultrasonic Examinations ○ Radiographic Examinations ○ Visual Examinations ○ Surveillance Sampling
Monitoring and Sensors / Instrumentation and Controls Expert
Materials Degradation Expert(s)
Materials Fabrication Experts
Welding Expert
Modelling and Evaluation Expert
Chemistry Expert
Code Expert

- Selecting MANDE methodology(s) to be used for each SSC in the RIM program
- Establishing MANDE periodicity
- Developing MANDE specifications
- Establishing sampling protocol for selected MANDE
- Establishing Performance Demonstration criteria for selected MANDE
- Assisting the RIMEP with establishing acceptance criteria if no industry standard criteria exists
- Providing uncertainty results obtained from the Performance Demonstrations to the RIMEP to assure RTVs will be met

Advanced Reactor Materials Technical Advisory Group

AR Materials Technical Advisory Group (TAG)

Materials Gap Analyses

- **Molten Salt Reactors** 3002010726
- **Sodium Fast Reactors** 3002016949
- **High-Temperature Gas Reactors** 3002015815
- **Lead Fast Reactors** 3002016950

Advanced Reactor Materials Development Roadmap

3002022979

Materials Degradation Matrices

Materials, potential degradation mechanisms, and status of knowledge

- **Molten Salt Reactors MDM**
- **Sodium Fast Reactors MDM**
- **High Temp Gas Reactors MDM**
- **Lead-cooled Reactors MDM**

In Progress | Scoped | Future Project

AR Materials TAG

Key stakeholders to assist in direction setting and prioritization of needs concerning AR materials qualification and testing

Stakeholder engagement and alignment on industry deployment needs

- Code Qualification and Data Gaps
- Environmental Compatibility

Strategic direction setting and prioritization

- Advanced Reactor Materials Deployment Roadmap

Develop & Execute Test Plans

EPRI

Advanced Reactor Materials Technical Exchange

AR Materials Technical Exchange

- The NRC is hosting an NRC / Industry Tech Exchange on Advanced Reactor Materials. The goal of this meeting is to gain insight on expectations for advanced reactor materials needs for deploying advanced reactors.
  - Meeting date and location: October 29-30, 2025, at the NRC headquarters in Rockville, MD (hybrid option available)
  - Register before September 15 at https://forms.office.com/g/5kJe60gHGT
  - POC:
    - EPRI: Chris Wax (cwax@epri.com) and Marc Albert (malbert@epri.com)
    - NRC: Meg Audrain (Margaret.Audrain@nrc.gov) and Ryann Bass (ryann.bass@nrc.gov)

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