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# Advanced Materials Program Summary

Advanced Reactor Technologies
GAS-COOLED REACTORS

# DOE Office of Nuclear Energy: Strategic Vision

**Vision**

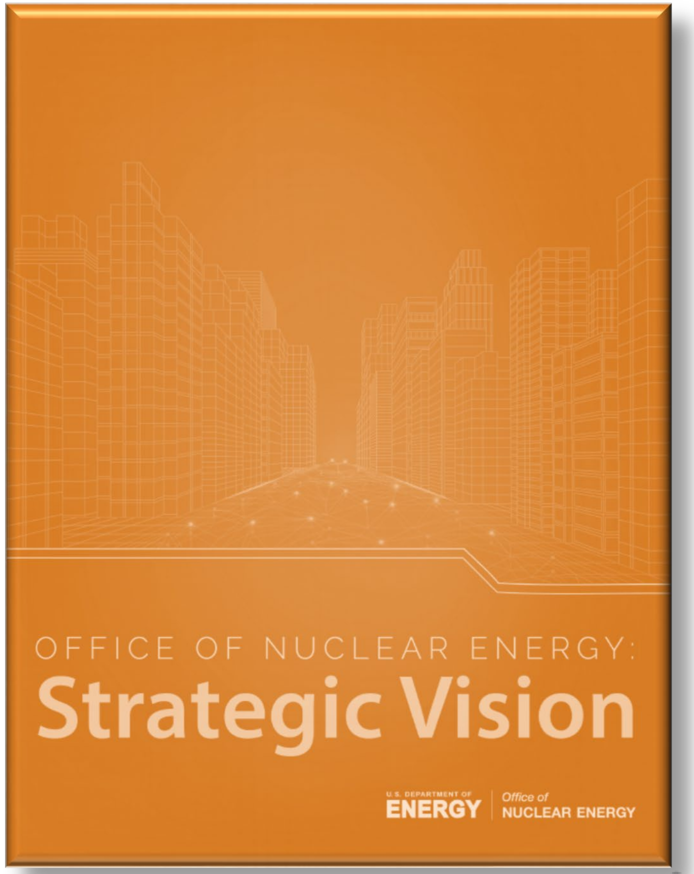
- A thriving U.S. nuclear energy sector delivering clean energy and economic opportunities

**Mission**

- Advance nuclear energy science and technology to meet U.S. energy, environmental, and economic needs

**Goals**

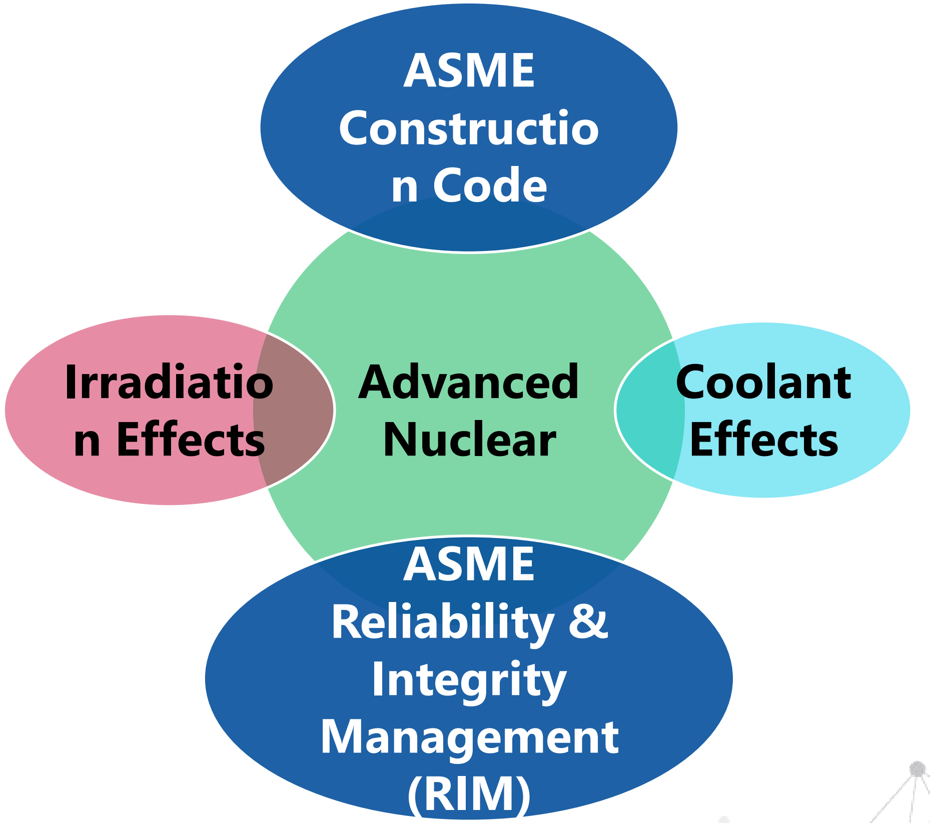
1. Enable continued operation of existing U.S. nuclear reactors
2. Enable deployment of advanced nuclear reactors
3. Develop advanced nuclear fuel cycles
4. Maintain U.S. leadership in nuclear energy technology
5. Enable a high-performing organization




Advanced Materials Activities Support Goals 2 and 4

# Interrelated Design, Construction and Operation Considerations for Structural Materials

- Advanced reactors under development have diverse designs and operational characteristics
  - Inlet/Outlet Temperatures • Thermal Transients • Coolants • Fuel Types (Prismatic, Pebble, Liquid) • Neutron Spectrum and Dose • Design Lifetimes • Safety Characteristics
- Topics directly related to reactor components construction
  - Metallic: High temperature design methodologies • Alloy qualification • Fabrication & examination
  - Graphite and ceramic composites: Qualification and codification
- Additional topics required for advanced reactor license application and plant operations
  - Corrosion effects
    - Gases (He, N, $CO_2$), liquid metals, molten salts
  - Irradiation effects
  - Materials degradation management
  - Flaw evaluations



# ART Advanced Materials

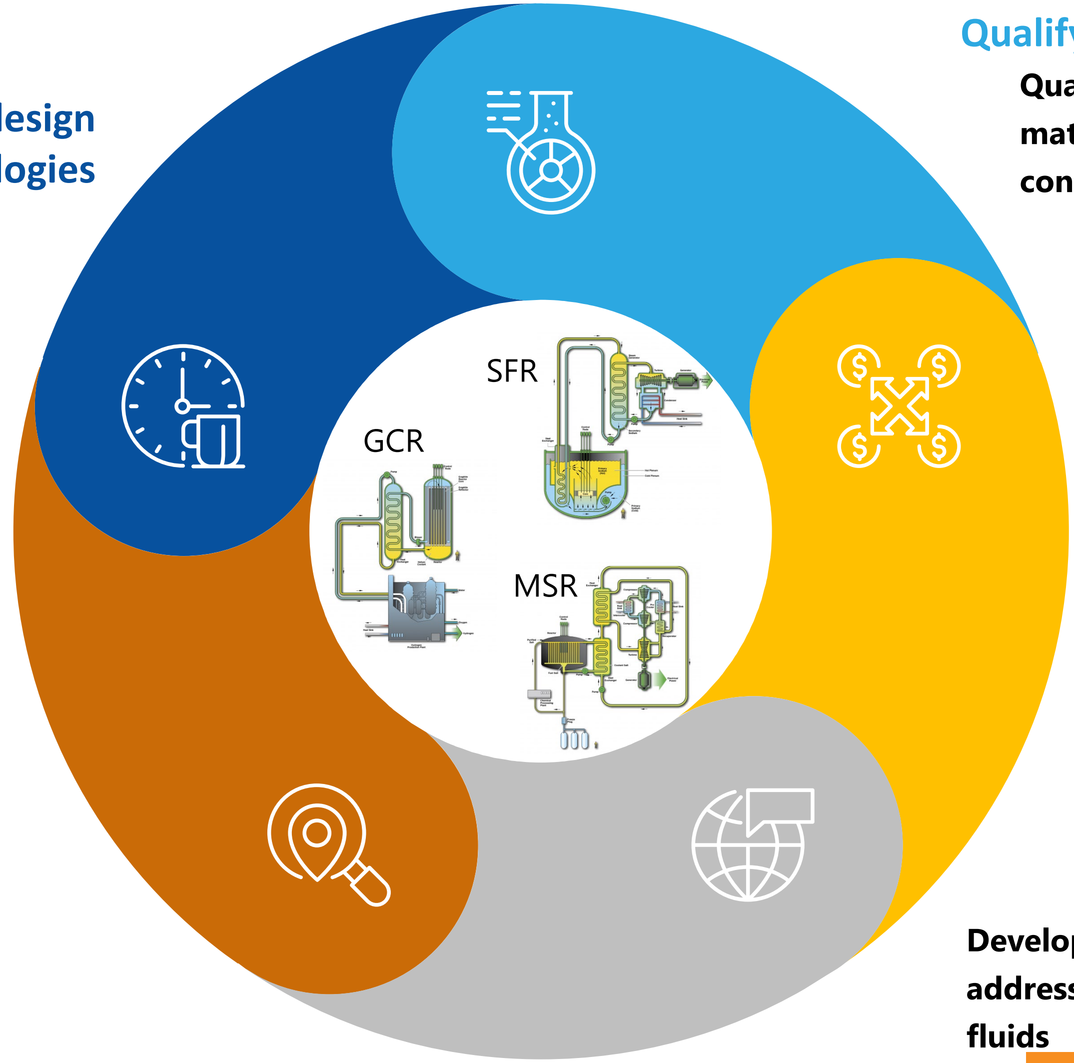
- Focus on materials and design methods to support advanced reactors deployment
- Design, construction, licensing and plant operations

### High temperature design methodologies

**Develop high temperature design methodologies for use of the qualified materials under elevated temperature cyclic service of advanced reactors**

### Existing qualified materials

**Extend qualified lifetimes and usage temperatures of structural materials already approved within the ASME Code for construction of high temperature reactors**




### Qualify new materials

**Qualify additional high performance structural materials for high temperature reactor construction to expand reactor design envelope**

### NRC licensing

- **Understand and predict environmental and irradiation effects relevant to different advanced reactor concepts**
- **Assess & improve methods to evaluate flaw growth and component lifetime predictions to support plant operations**
- **Develop in-reactor high temperature structural materials surveillance technology**

### Innovative materials solutions

**Develop material solutions to address highly corrosive working fluids**

# ART Advanced Materials Portfolio - Metals

## Integration and Coordination

| Funding | Topic | Status | Adv Rx Supported |
|---|---|---|---|
| GCR | Design methods improvement & development | Ongoing | GCR, FR, MSR, MRP |
| GCR | Extension of design lifetime for Class A materials | Ongoing | GCR, FR, MSR, MRP |
| GCR | Qualification of A617 | Completed | GCR, MRP, FR |
| GCR | Qualification of advanced A800H welds | Ongoing | GCR, MRP |
| FR | Qualification of A709 | Ongoing | FR, MSR, MRP, GCR |
| MSR | Surveillance test article development | Ongoing | MSR, FR, GCR |
| MRP | Qualification of PM-HIP components | Ongoing | MRP, MSR, FR, GCR |
| GCR | GIF VHTR Materials PMB | Ongoing | GCR, MRP |
| **Coolant Effects on Metals** | | | |
| GCR | Impure helium effects on A800H and A617 | Completed | GCR, MRP |
| GCR | Crack growth in impure helium – A617 | Ongoing | GCR, MRP |
| GCR | Impure helium effects on A709 | To be initiated | GCR, MRP |
| FR | Sodium effects on G91, A709 | G91 completing; A709 Ongoing | FR, MRP |
| MSR | Effects of molten fluoride and chloride salts on stainless steels and nickel alloys | Ongoing | MSR, MRP |

- GCR – Gas-cooled Reactors Campaign
- FR – Fast Reactors Campaign
- MSR – Molten Salt Reactors Campaign
- MRP – Microreactor Program

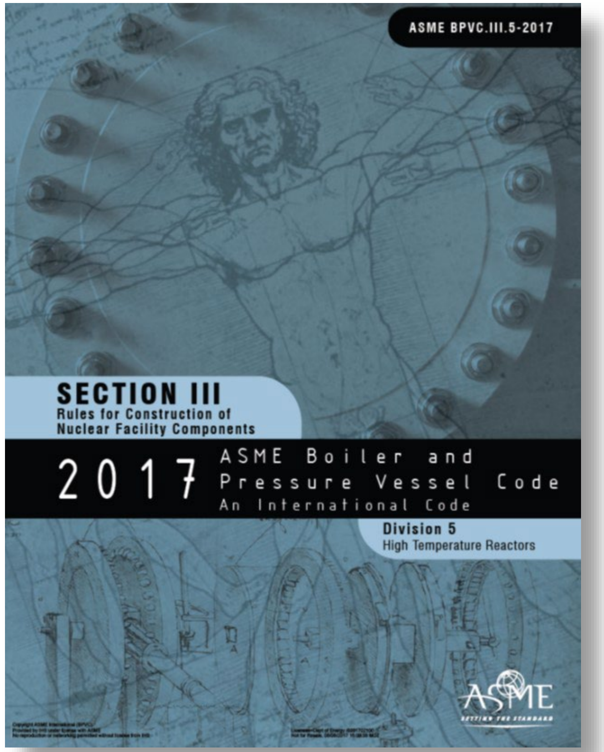

# The Secretary of Energy Achievement Award

- This team effort by the multi-lab staff led to the addition of Alloy 617 to the limited materials for advanced high-temperature Class A reactor component construction that are approved by the ASME Boiler and Pressure Vessel Code, Section III, Division 5
- The success of this multi-year endeavor would not have been possible without the sustained commitment and support from the DOE Office of Nuclear Energy, and the dedication and collaboration of the technical staff across the DOE Lab complex

# NRC Endorsement of ASME Section III, Division 5

## STATUS UPDATE

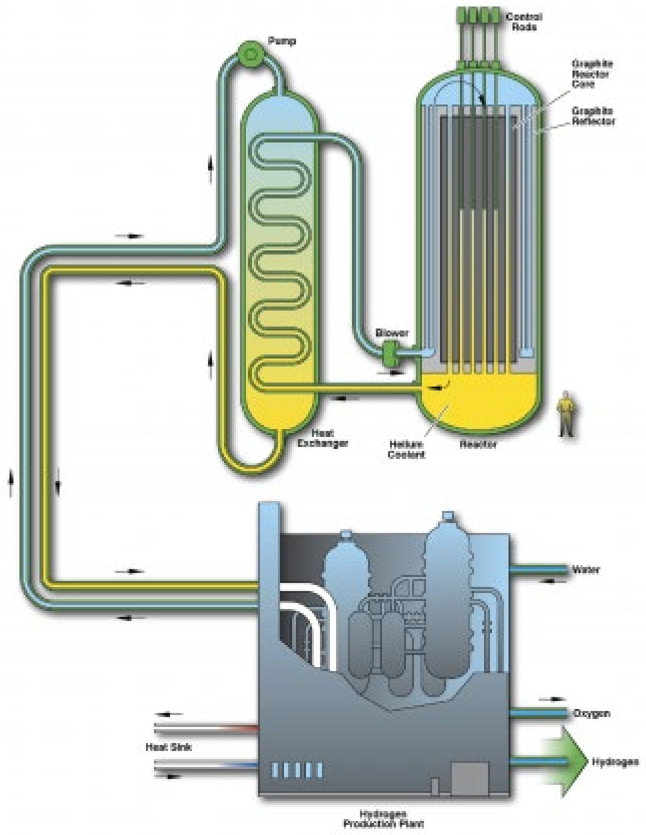
- U.S. Nuclear Regulatory Commission (NRC) is currently assessing ASME Section III, Division 5 and accompanying Code Cases for endorsement
- Endorsement by NRC, with conditions, will be made through the Regulatory Guide 1.87, rev 2, including
  - Section III, Division 5 (2017 Edition)
    - Did not review Nonmandatory Appendix HBB-Y, "Guidelines For Design Data Needs For New Materials," hence no endorsement
  - Code Case N-861, EPP Strain Limits Evaluations
  - Code Case N-862, EPP Creep-Fatigue Damage Evaluations
  - Code Case N-872, Alloy 617 Low Temperature Service Construction
  - Code Case N-898, Alloy 617 Class A Elevated Temperature Service Construction




## ASME issued the first Section III, Division 5, Class A & Class B "N" Certificate of Authorization

- Hayward Tyler, Inc. of Vermont announced on June 2, 2022 that it has been issued the first ASME "N" Certificate of Authorization covering Section III, Division 5 Class A and Class B vessels, pumps, valves and piping systems

# Overview of FY22 Metals Work Funded by Gas-cooled Reactor Campaign




- Contributors
  - Michael McMurtrey, Ryann Bass, Joseph Bass, Heramb Mahajan, Sam Sham (INL)
  - Yanli Wang (ORNL)
  - Mark Messner (ANL)
  - Richard Wright (Structural Alloys, LLC)
  - Bob Jetter (R.I. Jetter Consulting)
  - Peijun Hou (Imtech Corporation)

# Extend Design Parameters to Support 60-Year Design Life

## STATUS UPDATE

<table>
<tr><th>Class A Material</th><th>Time Dependent Allowable Stress</th><th>Minimum Expected Stress-to-Rupture</th><th>Thermal Aging Factors</th><th>Stress Rupture Factor (Weldment)</th><th>Isochronous Stress-Strain Curves</th></tr>
<tr><td rowspan="2">Type 304 and 316 Stainless Steels</td><td colspan="2">• 2023 Code edition<br>  • Update/correct design values up to 300,000 h<br>  • Additional chemistry restrictions</td><td colspan="3">• 2023 Code edition<br>  • Renormalize stress rupture factors with respect to revised base metal rupture stress, up to 300,000 h</td></tr>
<tr><td colspan="5">• Code case to extend all time-dependent design parameters to 500,000 h<br>  • Incorporate Code Case into 2025 Code edition</td></tr>
<tr><td>Alloy 800H</td><td>Ongoing</td><td>Completed</td><td>TBD</td><td>Ongoing</td><td>Ongoing</td></tr>
<tr><td>Grade 91</td><td>Completed</td><td>Completed</td><td>Balloting</td><td>Balloting</td><td>Ongoing</td></tr>
<tr><td>2¼Cr-1Mo</td><td>TBD</td><td>TBD</td><td>TBD</td><td>TBD</td><td>TBD</td></tr>
</table>

# EPP and Inelastic Analysis Methods

## Status Update

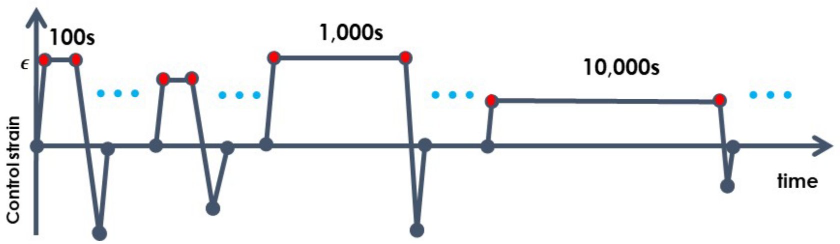
| EPP Code Cases | 304H | 316H | A800H | Grade 91 | 2¼Cr-1Mo | A617 |
|---|---|---|---|---|---|---|
| Primary load | N-924 | | | | | |
| Strain Limits | N-861 | N-861 | Balloting | N-861 | Balloting | N-898 |
| Creep-fatigue | N-862 | N-862 | Balloting | N-862 | Balloting | N-898 |

| EPP Code Cases | 304H | 316H | A800H | Grade 91 | 2¼Cr-1Mo | A617 |
|---|---|---|---|---|---|---|
| General guidelines for development viscoplastic material model | Division 5, Appendix HBB-Z | | | | | |
| Viscoplastic model | TBD | Balloting | Ongoing | Appendix HBB-Z | TBD | Balloting |

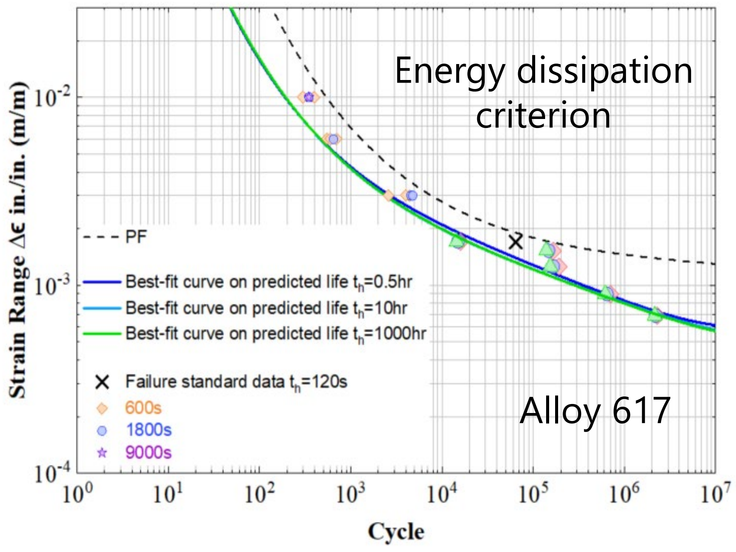
# Alternative Creep-Fatigue Evaluations Using Integrated EPP + SMT Approach

## To Improve Safety Margins and Design Flexibility

- Challenges in developing SMT-based creep-fatigue (CF) design curves
  - Available CF failure data are limited:
    - Most failure data are standard CF
    - Limited to strain ranges at 0.3% and above. No data available at low strain ranges <0.3%.
    - Hold time 0.5 hr and less (very few data with hold time longer than 1 hr)
  - Practical challenges to perform CF to failure with long hold times, e.g., 100-hour hold x 100 cycles at 1% strain range requires a 14-month test
    - At low strain ranges: long test duration and high noise to signal ratio in test data
- Resolution
    - Use physics-based model and experimental data for extrapolation of the design curves to long hold times and low strain ranges
    - Developed block-strain range test protocol to provide critical information needed for hold time and strain range extrapolations



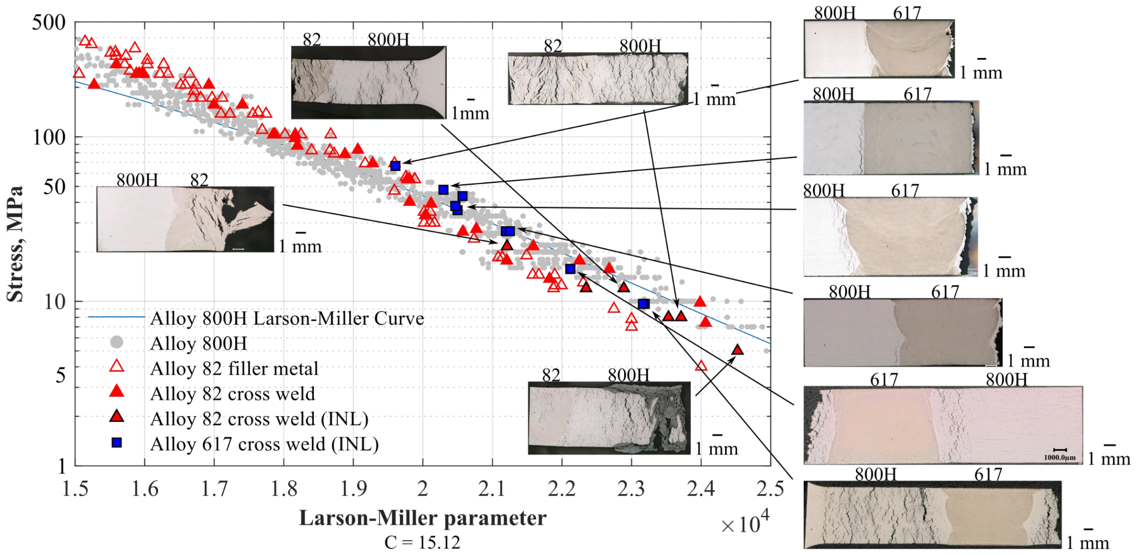

- Status
  - Generated low strain range and long hold time data using block-strain range test protocol
  - Obtained fatigue curves at various hold times using different criteria; time fraction and energy dissipation
  - Conducting tests to generate verification data



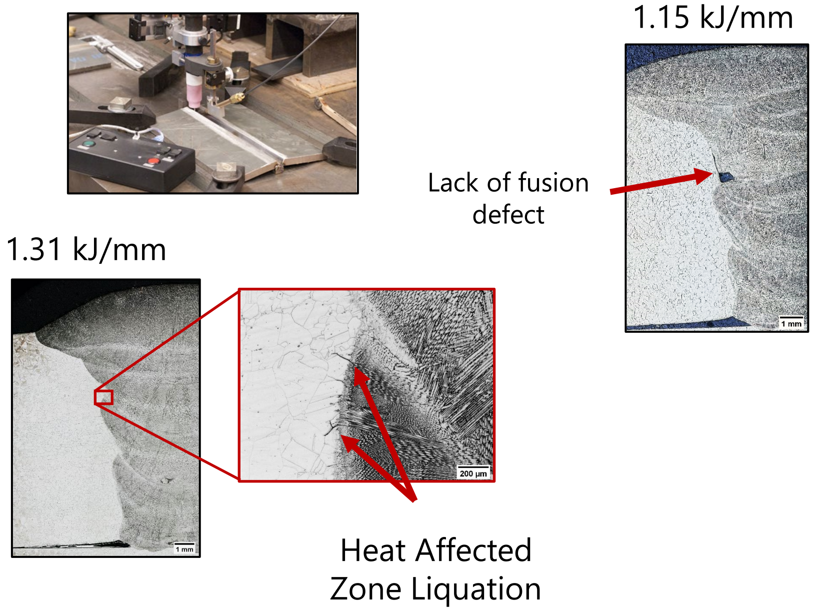
# Improve Alloy 800H Weldment Rupture Strength Using Different Weld Consumables

## Status Update

Alloy 617 weld consumable provided only marginal improvement of Alloy 800H weldment rupture strength




UTP A 2133 Mn Matching Filler Metal

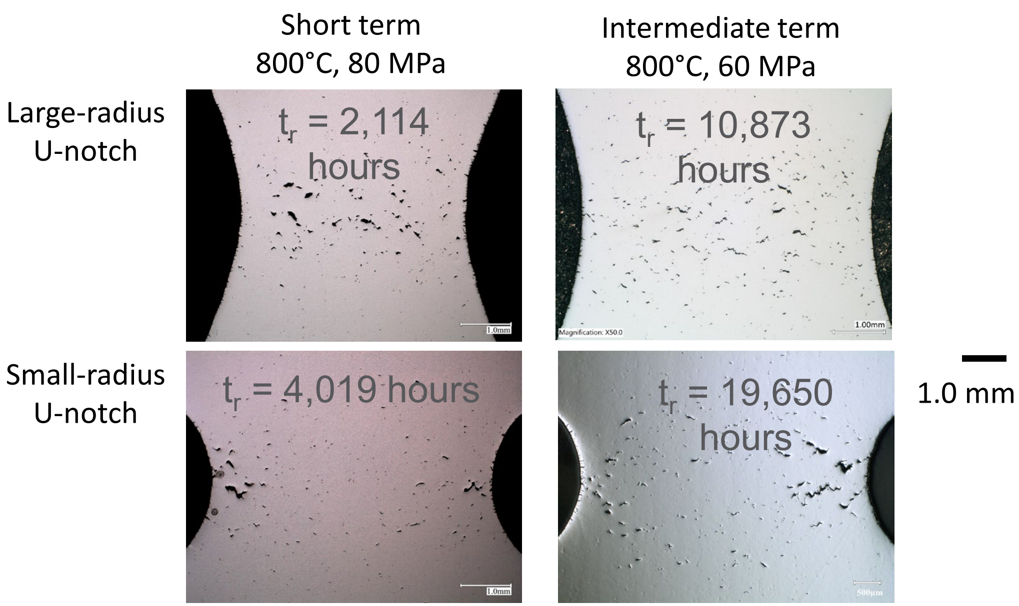



Welding parameters are being optimized

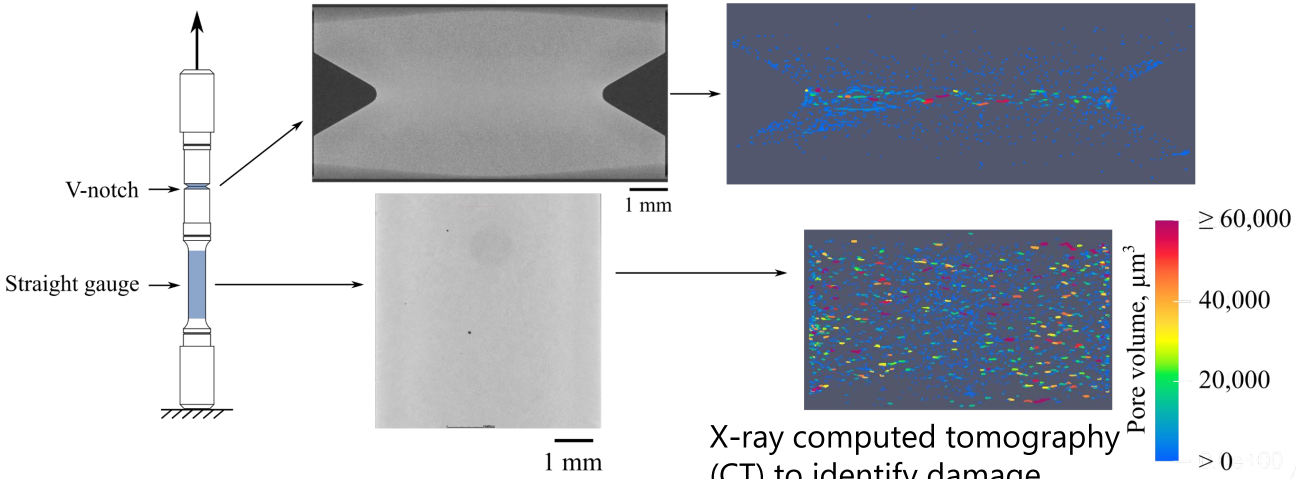
# Effects of Multiaxial Stress State, Material Discontinuity & Notches on Creep Rupture Behavior

## Status Update

- Completed short-term and intermediate-term creep rupture testing of V-notch and U-notch Alloy 617 base metal and weldment specimens
  - Results showed notch strengthening behavior




Long term, 800°C, 35 MPa, targeting 100,000 hours rupture time




X-ray computed tomography (CT) to identify damage

- Status
  - Continuing long-term V-notch creep-rupture tests (1 base metal, 1 weldment) and periodically characterize these specimens with X-ray CT to determine possible notch weakening behavior
  - Continue developing rupture life to damage correlation

# Alloy 617 Crack Growth Testing to Support Licensing and Plant Operations

## Status Update

- Initiated elevated-temperature Alloy 617 crack-growth tests in air and in reactor-grade helium to generate data to establish crack-growth correlations
- In support of Section XI, Division 2 on Reliability and Integrity Management (RIM)
  - Section XI high-temperature flaw evaluation Code Case

# ASME Division 5 Code Classes for Metallic Components

- Selection of appropriate Code Classes for structural components of high temperature reactor systems
  - Starts with the safety classification, or quality group, per safety criteria from applicable standards, and based on a system approach

| Metallic | Quality Group (NRC) | Construction Rules |
|---|---|---|
| Coolant boundary components and supports | Group A - Safety related with safety significance | Section III, Division 5, Class A |
| | Group B - Safety related with low safety significance | Section III, Division 5, Class B |
| | Group C - Non-safety related with safety significance | Section VIII, Division 1 or 2 |
| | Group D - Non-safety related with no special treatment | Owner to establish standards for use |
| Core support structures | Group A - Safety related with safety significance | Section III, Division 5, Class SM |

- Due to different safety characteristics of high temperature reactor designs, more structural components are classified as Class B as compared with LWRs

# Revamp ASME Division 5 Class B Construction Rules

**CURRENT CLASS B RULES**

- Are extension of construction rules of Section III, Division 1, Class 2 vessel, pump, valve and piping designs to elevated temperature service
- Similar to commercial rules (Section I and Section VIII, Division 1)
- Based on the design-by-rule approach
- Allowable stresses based on extrapolated 100,000-hour creep rupture properties
- Cyclic loading in creep regime (i.e., creep-fatigue interaction) not considered
  - Except for piping, but very conservative rules

**ISSUES**

- These rules do not provide the design flexibility and are not adequate to address many design and operational characteristics of new high temperature reactors
  - Different design lifetimes, e.g., 7, 20 or 60 years
  - Thermal cycles
  - Limited permissible Class B materials

**REVAMP CLASS B RULES**

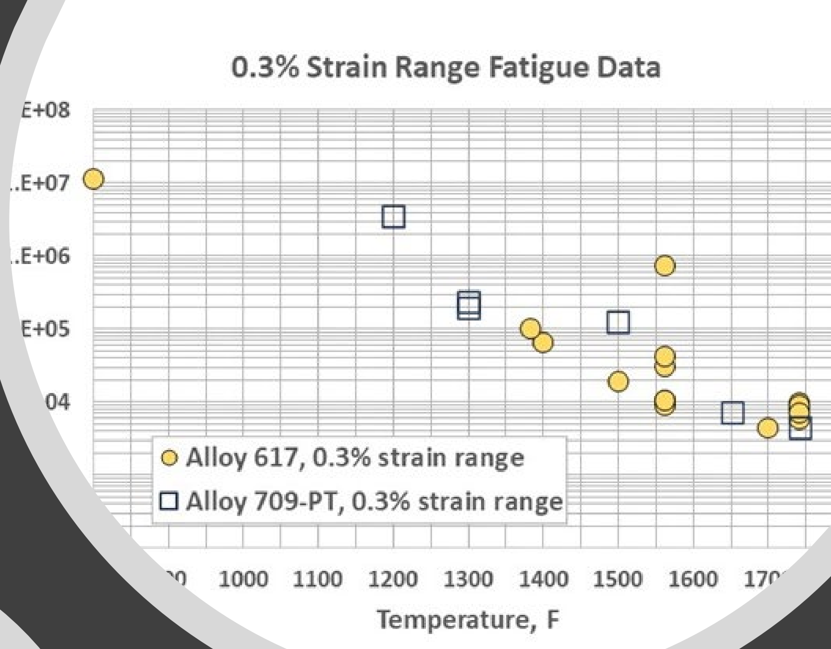
- Incorporate time-dependent allowable stresses and design lifetime concept
- Introduce simplified design-by-analysis approach to address primary load, strain limits and creep-fatigue
- Expand the permissible Class B materials list

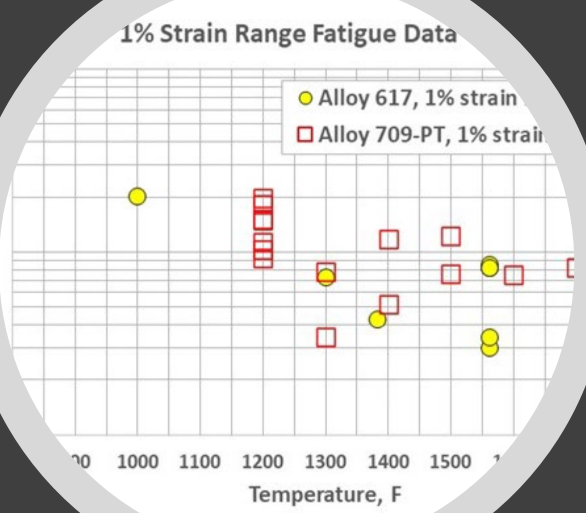
**STATUS**

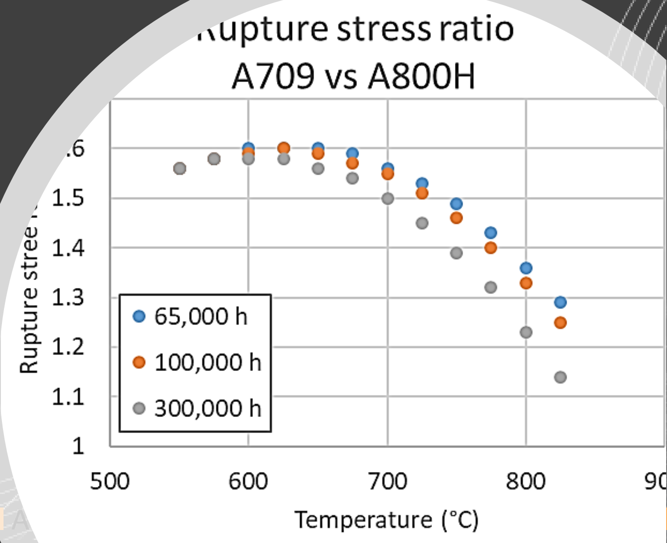
- Established initial rules for primary load, strain limits and creep-fatigue
- Currently performing assessment of the new rules using sample problems

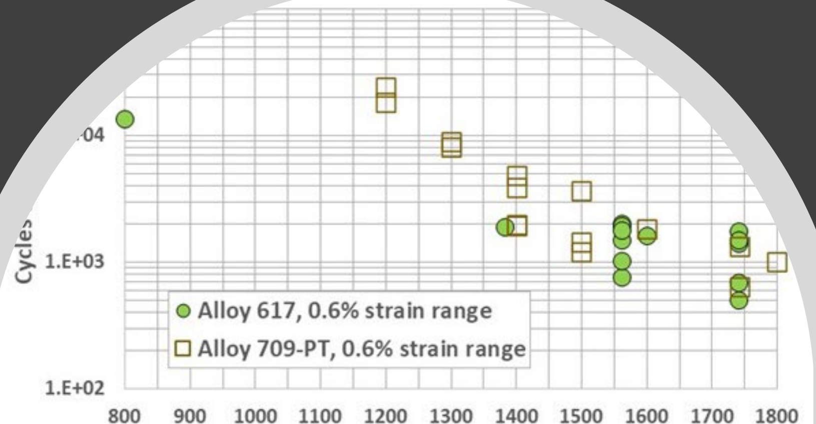
# A709-PT has Enhanced Mechanical Properties

- Fatigue resistance of A709-PT is comparable to A617 at these strain ranges
- Creep strength of A709-PT is higher than A800H
- Data generated to-date show that A709-PT is a good candidate material for gas-cooled reactor applications, leveraging the code qualification effort that is already underway
  - Need to demonstrate that A709-PT is compatible with reactor grade helium
  - Sufficient Cr in A709-PT to form Cr oxide on component surface for corrosion protection
- FY23 to initiate a confirmatory corrosion program, subject to funding availability, to establish A709-PT as a gas-cooled reactor construction material, leveraging the helium corrosion loop from the NGNP Program that is in storage



# Summary

- ART Advanced Materials R&D for metals involves integration and coordination of activities of GCR, FR, MSR, MRP
- Significant accomplishments under GCR funding
- Expected GCR FY23 accomplishments
  - Complete development of full suite of EPP design methods for all Class A materials
  - Approval of 316H and Alloy 617 viscoplastic models by ASME
  - Submit Alloy 800H viscoplastic model for incorporation in Appendix HBB-Z
  - Develop revised time dependent design parameters (allowable stresses, rupture stresses, aging factors, stress rupture factors and isochronous stress-strain curves) for 304H and 316H for extension to 500,000 hours
  - Submit EPP strain limits and creep-fatigue code cases to include Alloy 800H for approval
  - Complete EPP+SMT creep-fatigue development and draft code case
  - Continue notch testing of Alloy 617
  - Continue welding parameters optimization for Alloy 800H/A21.33 Mn weldment and initiate creep rupture testing
  - Continue Alloy 617 creep and cyclic crack growth tests in air and initiate tests in impure helium
  - Continue development of improved Class B design rules to include design-by-analysis and time-dependent allowable stresses
  - Re-establish closed-loop helium system developed under NGNP Program to conduct confirmatory helium compatibility testing to qualify Alloy 709 advanced austenitic stainless steel for HTGR applications (subject to funding availability)