INL/MIS-24-76440-Revision-0

# Fast Reactor Materials R&D Update

February 2024

Changing the World's Energy Future

Ting-Leung Sham

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**Ting-Leung Sham**

**February 2024**

**Idaho National Laboratory**
**Idaho Falls, Idaho 83415**

**http://www.inl.gov**

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FAST REACTOR PROGRAM

# Fast Reactor Materials R&D Update


Ting-Leung (Sam) Sham
Idaho National Laboratory



DOE-NE ART Fast Reactor Program Review Meeting
February 6-8, 2024
Argonne National Laboratory, Lemont, IL

# Fast Reactor Materials R&D

**Major focus: Deployment of A709 for fast reactor structural applications**

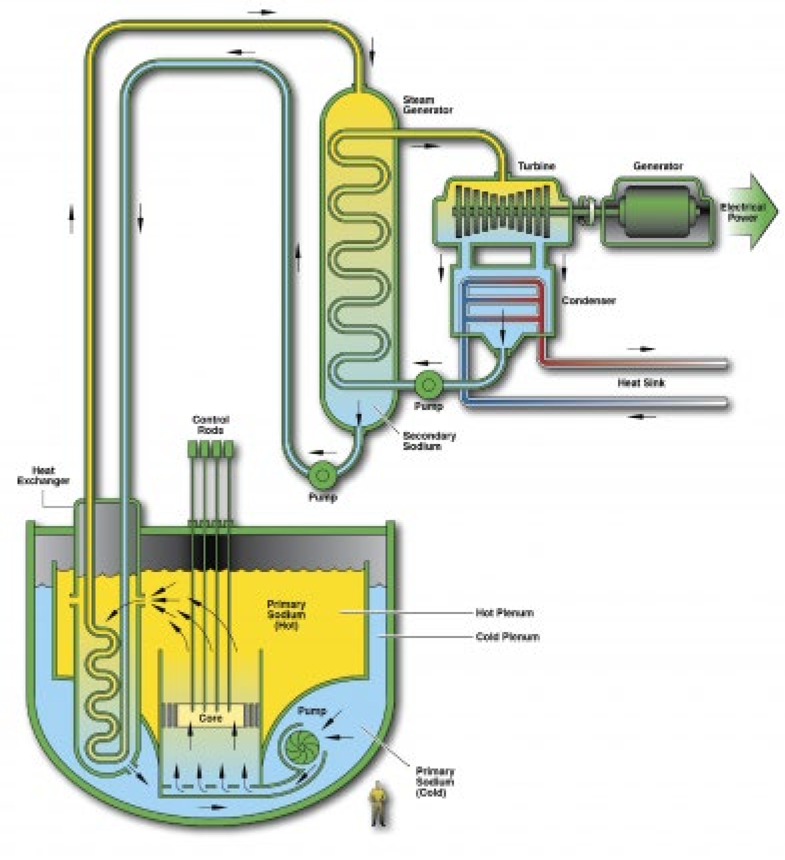



Image Credit: Idaho National Laboratory

# Deployment of New Materials for Adv Rx Components

| Design | Fabrication | Supply Chain | Adx Rx Operation |
|---|---|---|---|
| • Design rules<br>• End-of-life Design parameters<br>    • Air data (ASME material code case)<br>    • Irradiation data (if needed)<br>    • Corrosion data | • Melt practice<br>• Thermomechanical processing parameters (forging, rolling, etc.)<br>• Heat treatment (solution anneal, precipitation treatment, etc.)<br>• Product acceptance<br>• Welding processes<br>    • Weld inspection | • Materials suppliers and fabricators need higher volume of production<br>    • Materials deployable for multiple advanced reactor concepts could increase vendor sales volume | • Materials degradation management<br>    • Surrogate materials surveillance<br>• Health monitoring<br>• Reliability integrity management (RIM)<br>• Stress corrosion cracking, Stress relaxation cracking, subcritical crack growth |

# FY24 Work Packages for Fast Reactor Materials

## FY24 Work Packages

- AT-24AN050401, A709 Near Term Code Case - ANL
- AT-24IN050402, A709 Near Term Code Case - INL
- AT-24OR050403, A709 Near Term Code Case – ORNL
- AT-24OR050501, A709 Long-term Creep and Thermal Aging Testing - ORNL
- AT-24IN050502, A709 fabrication process optimization – INL
- RD-24AN040501, A709 sodium compatibility – ANL

## Fast Reactor Materials Technical Staff

- Xuan Zhang, Yiren Chen, Mark Messner (ANL)
- Heramb Mahajan, Tate Patterson, Grace Burke, Sam Sham (INL)
- Yanli Wang, Zhili Feng (ORNL)
- Richard Wright, John Grubb, Walter Sperko (Subject Matter Experts)

# NRC Endorsed ASME Section III, Division 5

- Section III, Division 5, 2017 Edition was endorsed by the U.S. Nuclear Regulatory Commission (NRC), with exceptions and limitations, via Regulatory Guide 1.87 Revision 2, January 2023
- This is a significant milestone in the reduction of regulatory risk for reactor developers towards the licensing of their advanced reactors

U.S. NUCLEAR REGULATORY COMMISSION

REGULATORY GUIDE 1.87, REVISION 2

Issue Date: January 2023
Technical Lead: Jeffrey Poehler

ACCEPTABILITY OF ASME CODE, SECTION III, DIVISION 5, "HIGH TEMPERATURE REACTORS"

A. INTRODUCTION

**Purpose**

This regulatory guide (RG) describes an approach that is acceptable to the staff of the U.S. Nuclear Regulatory Commission (NRC) to assure the mechanical/structural integrity of components that operate in elevated temperature environments and that are subject to time-dependent material properties and failure modes. It endorses, with exceptions and limitations, the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel (BPV) Code (ASME Code) Section III, "Rules for Construction of Nuclear Facility Components," Division 5, "High Temperature Reactors" (Ref. 1), and several related code cases.

**Applicability**

This RG applies to non-light-water reactor (non-LWR) licensees and applicants subject to Title 10 of the Code of Federal Regulations (10 CFR) Part 50, "Domestic Licensing of Production and Utilization Facilities" (Ref. 2), and 10 CFR Part 52, "Licenses, Certifications, and Approvals for Nuclear Power Plants" (Ref. 3).

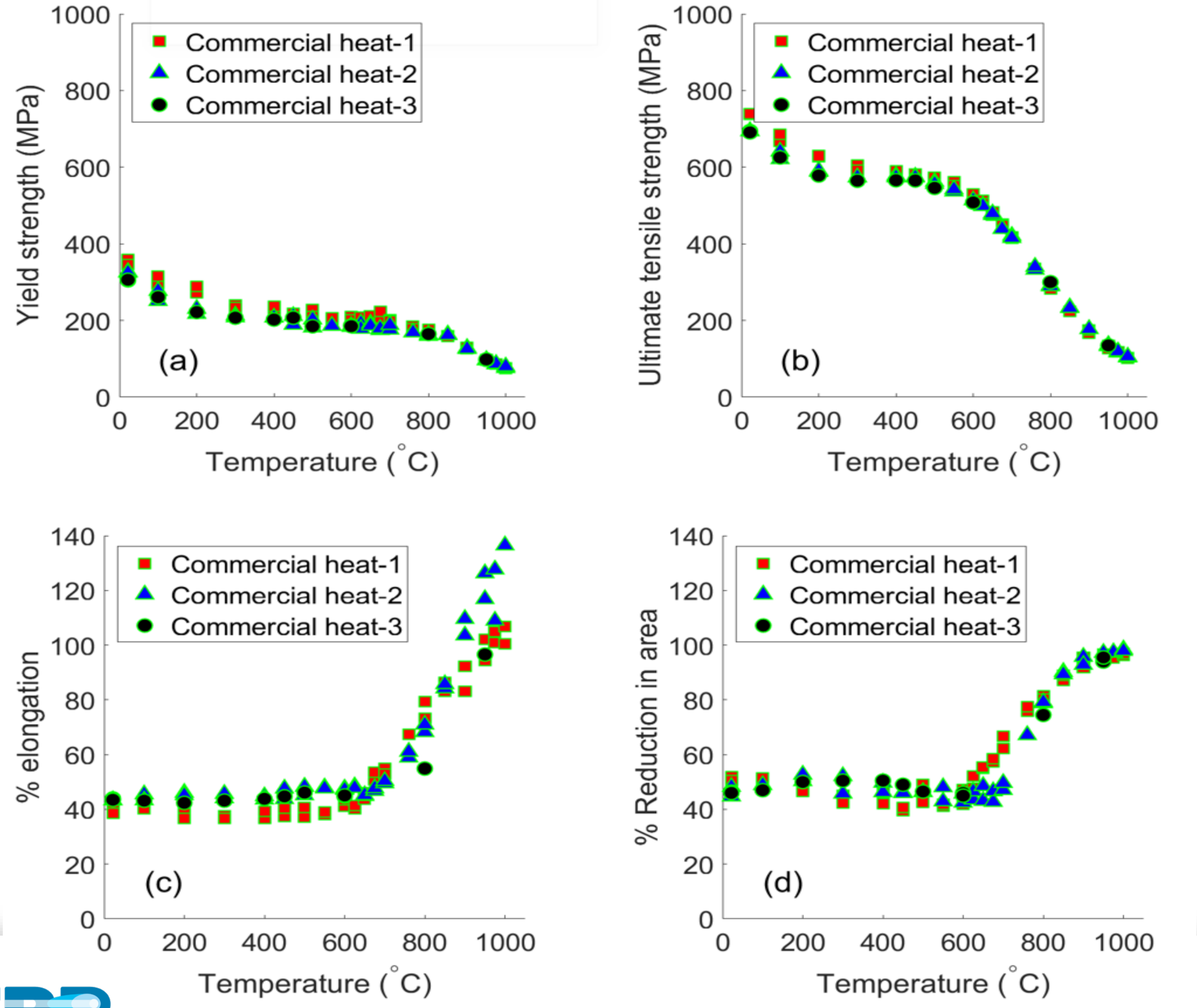
# ASTM Standards Specification for A709 Base Metal - Status

- ASME Division 5 requires new material to have a specification in Section II, Part A or Part B, which incorporates the specification from the ASTM Standards
- ASTM Standards define specific characteristics the alloy must meet, these definitions are the basis for receiving inspection for material from a vendor as part of a NQA-1 quality program
- A709 (UNS S31025, Grade TP310MoCbN) has been approved under standard ASTM A213/213M-21b and ASME SA213/213M-21b "Standard Specification for Seamless Ferritic and Austenitic Alloy-Steel Boiler, Superheater, and Heat-Exchanger Tubes"
- Recent progress on adding A709 base metal plates standard specifications:
  - It has been approved and incorporated into ASTM A240/A240M REV A, (11/1/2023) "Standard Specification for Chromium and Chromium-Nickel Stainless Steel Plate, Sheet, and Strip for Pressure Vessels and for General Applications"
  - Heat treatment requirements belong in ASTM A480/A480M "*Standard Specification for General Requirements for Flat-Rolled Stainless and Heat- Resisting Steel Plate, Sheet, and Strip". It has been balloted and approved to be included in this specification.* It has been incorporated in ASTM A0480/A0480M-23 REV B (11/1/2023)

# ASTM Standards Specification for A709 Weld Wire - Status

- With A709 (UNS S31025) now in published standards, it will be straightforward to have it assigned a P-number in ASME Section IX.
  - That proposal has been submitted for the February 2024, Section IX committee meeting
- A709 has been used as filler metal in test coupons and been demonstrated as weldable. The data will be submitted to the American Welding Society (AWS) A5 committee for inclusion in AWS A5.9. That committee will assign it an AWS classification. Once that specification has been published, it will be assigned an A-number and an F-number in Section IX.
  - This request has been submitted to AWS in January 2024
- Since AWS A5.9 is on a 5-year publication cycle, and it was last published in 2022, bringing A709 wire into AWS A5.9 will take a while
  - This will not prevent its use as a filler metal since Section IX allows one to qualify any filler metal by defining its chemical composition and mechanical properties, so those using A709 can weld using 709 composition filler metal simply by qualifying a Welding Procedure Specification (WPS) using that filler metal

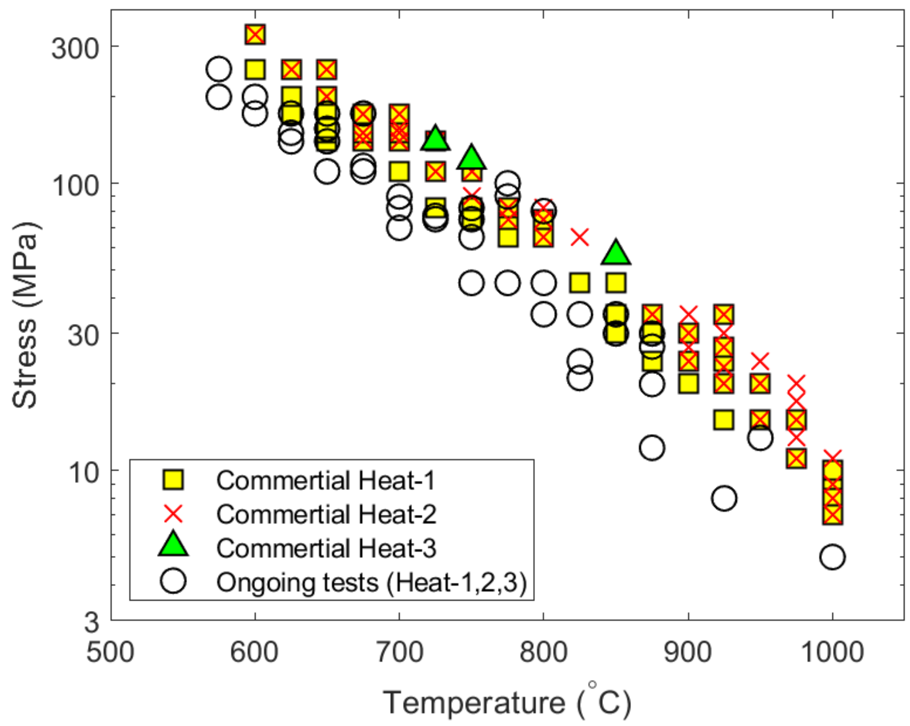
# A709 Code Case Testing Status - Tensile

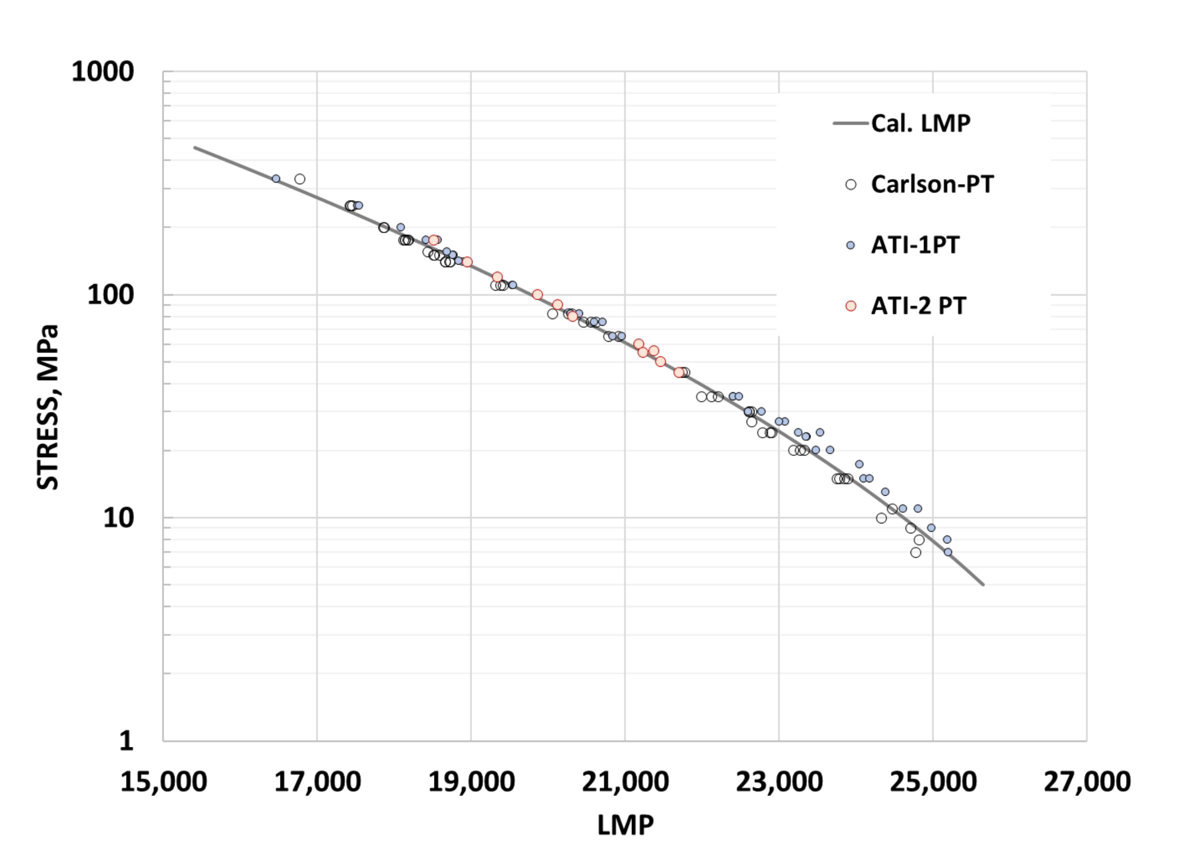



- Tensile code case testing on the three heats of A709 is approaching completion (with a few tests remaining to complete at 50$^{o}$C interval)
- Tensile data were generated from RT to 1000$^{o}$C with 2 repeats each condition.

# A709 Code Case Testing Status – Creep Rupture

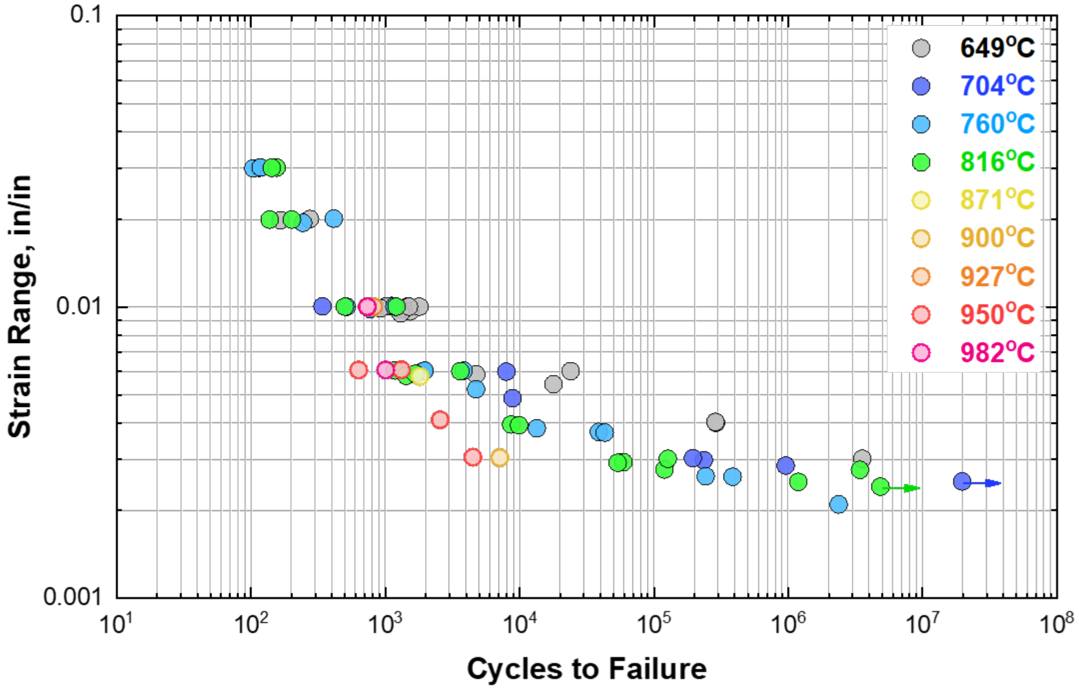
Finished and ongoing creep tests



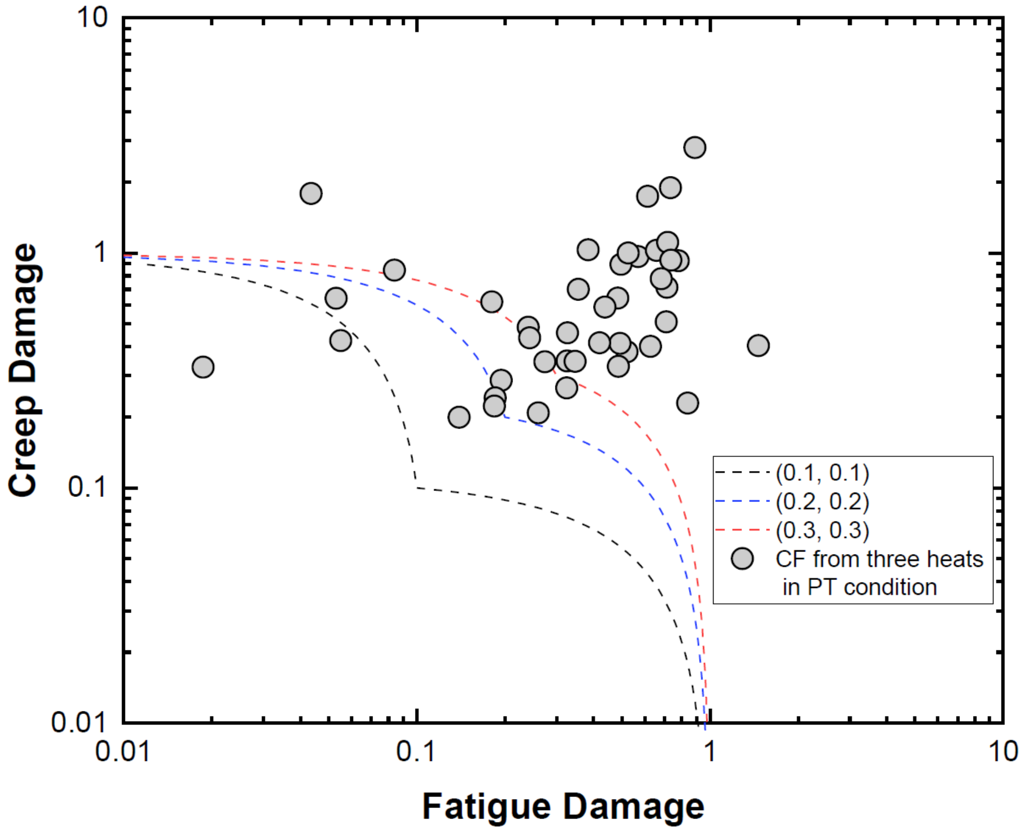

Creep-rupture data collected to date

# Development of A709 Fatigue Design Curves




- Data plotted are strain-controlled fatigue tests for the A709-PT materials from the first and second commercial heat
- Ongoing fatigue testing includes duplicates for the first two commercial heats (Carlson, ATI-1), and the full matrix for the 3rd commercial heat (ATI-2)

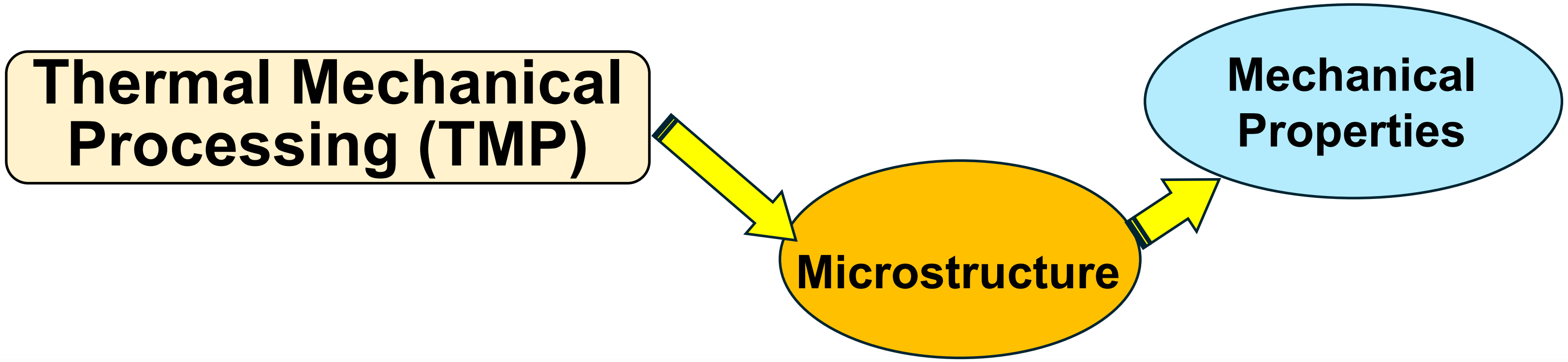
# Preliminary A709 Creep-Fatigue Interaction Diagram




(0.1,0.1) or (0.2,0.2) are both reasonable intersection points

# Establish Processing – Microstructure - Mechanical Properties Relationships for A709

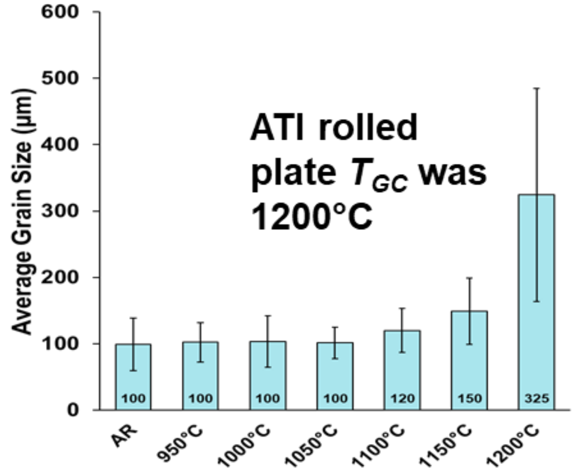
- Work led by Grace Burke (INL)
- Experiments performed at the University of Pittsburgh
- Objectives of this A709 development work
  - To establish thermomechanical processing – microstructure – mechanical properties relationships
  - To develop fabrication parameters that can be employed for product forms such as bars, pipes, and forgings in addition to plates



# Grain Coarsening and Continuous Cooling Precipitation (CCP) Behavior of A709

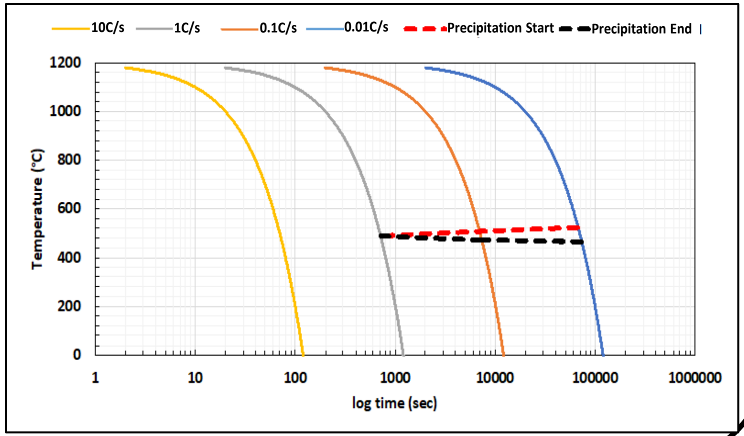
## Experimentaly determined Grain Coarsening Temperatures, $T_{GC}$

- Critical to ensure that all precipitates are dissolved so that **a uniform final microstructure** is obtained in the as-hot-worked condition.
- Important for both **as-rolled** as well as **as-forged** product forms.




## Experimentally determined Continuous Cooling Precipitation (CCP) Diagram

- Critical information for different product forms




**No precipitation was detected using SEM and dilatometry for the ATI A709 samples cooled at 10C/s and 1C/s**

**Prior to the CCP study, it was necessary to experimentally determine the grain coarsening temperature**

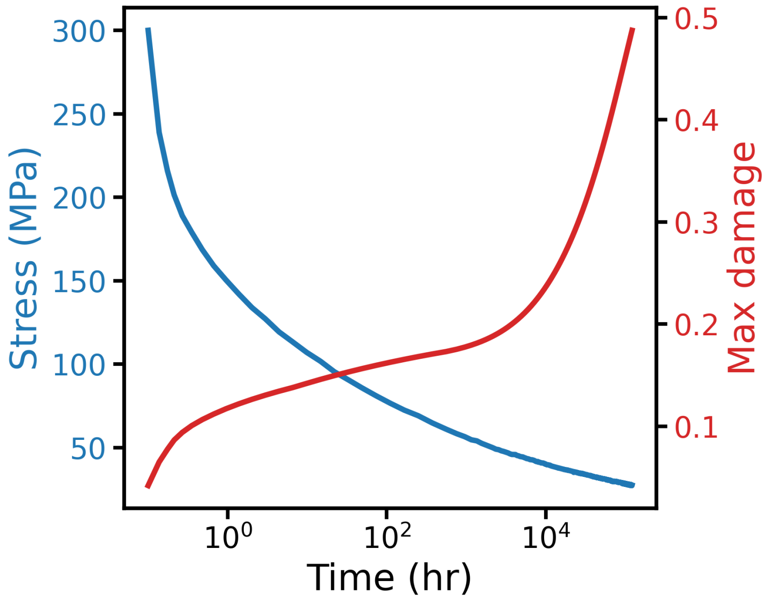
**Thermal Mechanical Processing (TMP)**

**FY25 and Beyond**

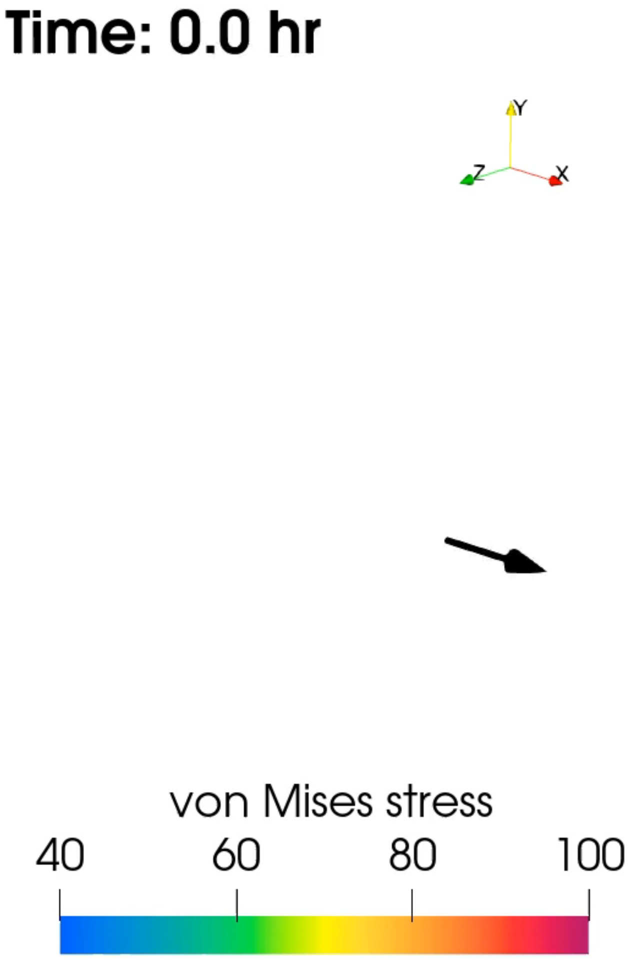
# Physics-Based Simulations of Long-Term Stress Relaxation in A709

Funded by NEAMS

- NEAMS supported the development of a physics-based model for A709 long-term creep in FY23
- FY24 use the model to look at long-term stress relaxation
  - Representative loading for fast reactors (low primary stress, high secondary stress)
  - No long-term test data
  - Could impact on A709 design rules
- Key questions:
  - Is there a threshold for stress relaxation?
  - Can the material fail under pure strain control?
  - If so, does damage continue to accumulate at the threshold stress?
- Additional work: tie precipitation hardening model to TC-PRISMA simulations (versus fit to thermal aging data)




A709 stress relaxation at 650°C, 1% strain. Plot shows stress relaxation profile and maximum GB damage. Video shows development of von Mises stress and GB damage in the microstructure.



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# A709 Design Parameters Development From Test Data

# Required Design Parameters to be Generated from Design Data

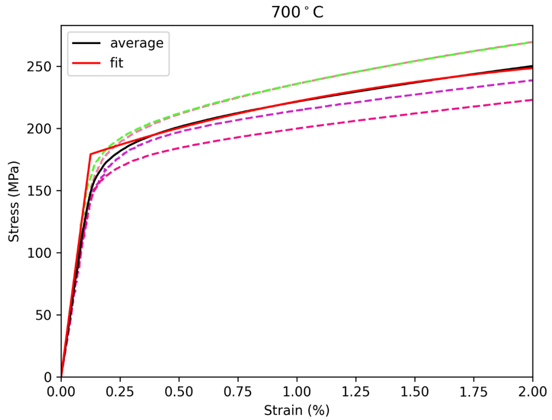
| Design Parameters | Required Test Data | Design Parameters | Required Test Data |
|---|---|---|---|
| • $S_r$: based on stress to rupture | Creep rupture data with full creep curves (time-dependent) | • Creep-fatigue interaction diagram | Strain-controlled cyclic test data with hold times from base metal and weldment |
| • $S_t$: based on time to 1% total strain, time to onset of tertiary creep, time to rupture | Creep rupture data with full creep curves (time-dependent) | • EPP strain limits and creep-fatigue | Data from two-bar and SMT tests; cyclic stress-strain curves, and tests with alternating fatigue and creep loading on the same specimen |
| • $S_{mt}$: lesser of $(S_m, S_t)$<br>• $S_0$: lesser of $(S, S_{mt}@300{,}000h)$ | Derived design parameters | • EPP strain limits and creep-fatigue | Data from two-bar and SMT tests; cyclic stress-strain curves, and tests with alternating fatigue and creep loading on the same specimen |
| • Thermal aging factors on yield and ultimate | Tensile data of aged material (time-dependent) | • EPP primary load | Data from creep curves to determine minimum creep rates |
| • $R$: Stress rupture factor - based on rupture strengths of base metal and weldment | Stress rupture data from base metal and weldment (time dependent) | • Huddleston effective stress parameters | Multiaxial creep rupture data |
| • Isochronous stress-strain curves constructed based on creep tests | Tensile stress-strain curves (time-independent), and creep strain data up to 3% (time-dependent) | • External pressure charts | Data from tensile stress-strain curves (time-independent) |
| • Relaxation strength | Stress relaxation data | • Time-temperature limits for external pressure charts | Developed from isochronous strain-strain curves |
| • Fatigue design curves | Strain-controlled continuous cycling test data | • Inelastic constitutive model | All tensile, creep, fatigue and creep-fatigue data |

# A709 Isochronous Stress-Strain Curves Modeling

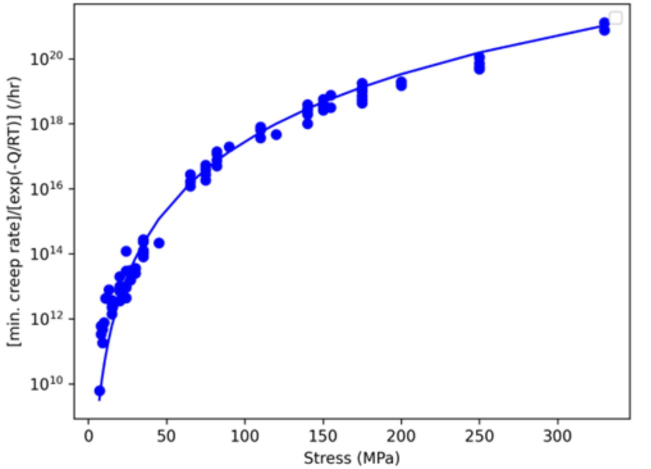
- Time independent plastic strain modeling
  - Voce-hardening model
    - $\varepsilon_p = \begin{cases} 0 & \sigma \le \sigma_1 \\ \frac{-1}{\delta}\ln\left(1 - \frac{\sigma-\sigma_1}{\sigma_p-\sigma_1}\right) & \sigma > \sigma_1 \end{cases}$
  - Database
    - Tensile tests at constant strain rate

- Creep strain modeling using minimum creep rate
  - Power-law creep model:
    - $\varepsilon_c = A\exp\left(-\frac{Q}{RT}\right)\sigma^n t$
  - Database
    - Minimum creep rate data from full creep curves
  - We will update in the future with a primary creep term to compare – may not be needed

- A709 Tensile Data
  - 82 tests
  - RT to 1000°C




- A709 Creep Data
  - 84 tests
  - 625°C to 1000°C

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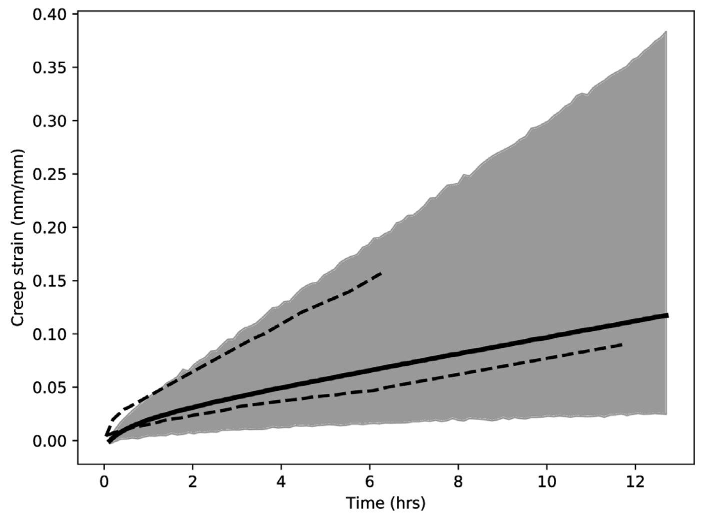
# A709 Inelastic Constitutive Model Development

- Initiated in FY24
- Complete unified model to describe high temperature cyclic and creep deformation
- Adopting "unified" model form under development through ART Gas-cooled Reactor Program, HTDM WP
- Work in progress using ANL's "pyoptmat" tool

Creep at 130 MPa and 700°C




Example of one model output (here for 800H): statistical predictions for creep curves

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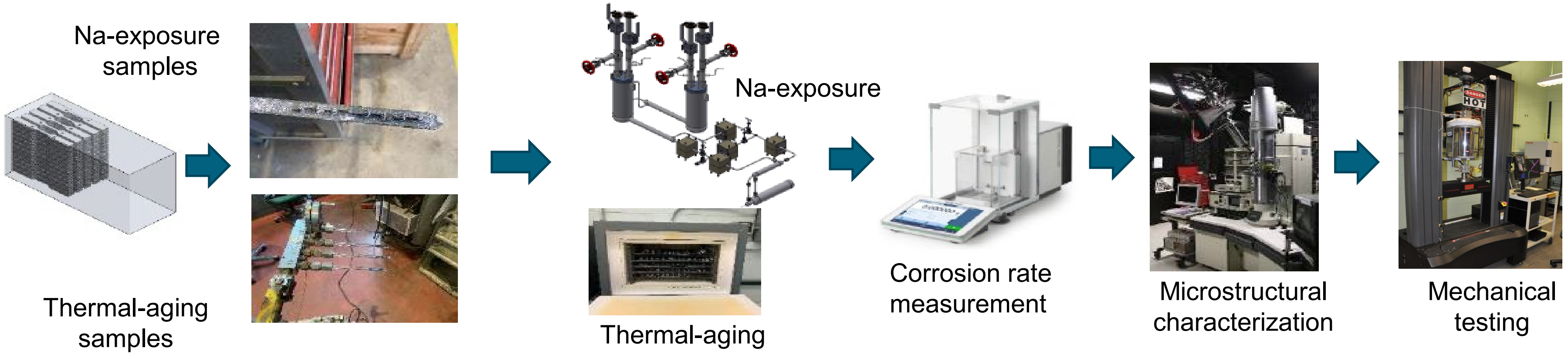
# A709 Performance in Liquid Sodium

# Sodium Compatibility WP Overview

**Objective - Support the regulatory acceptance of A709 for SFR applications**

- Evaluate the effects of sodium exposure on the service performance of A709
- Understand the microstructural stability of A709 in sodium environment

**Experimental evaluation:**

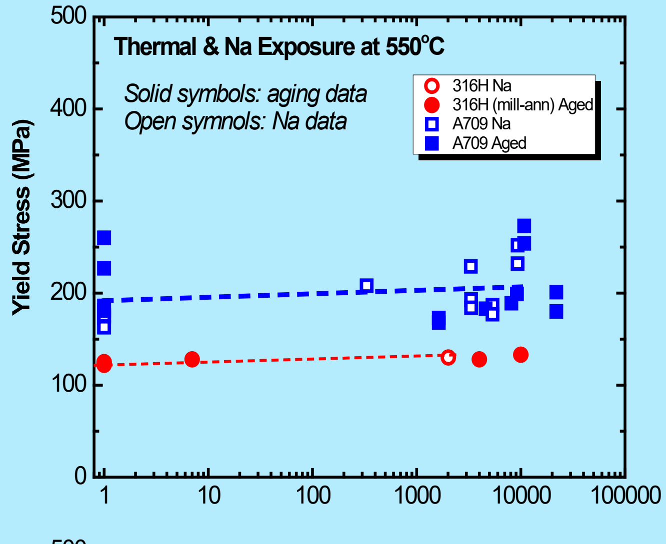


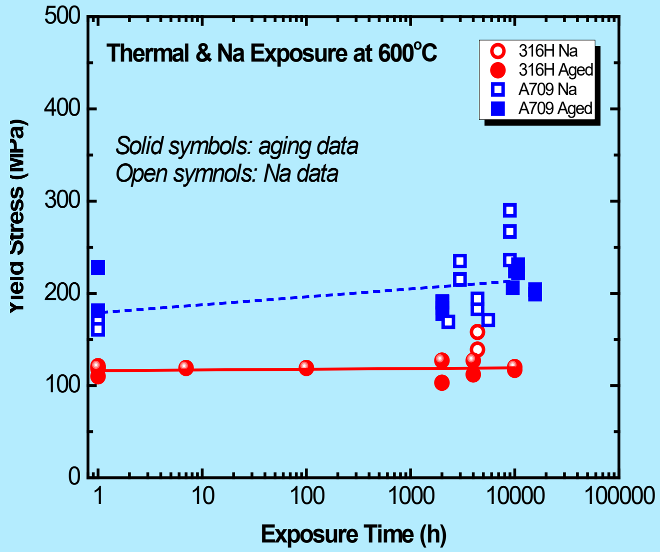

**Carburization/decarburization analysis**

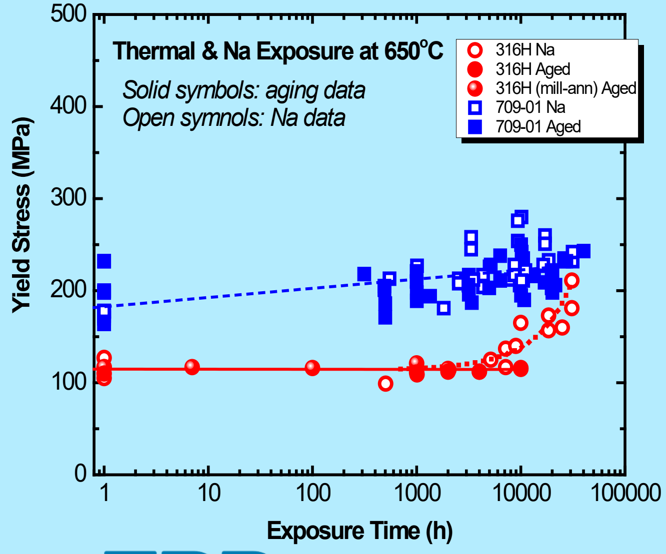
- Calculate carbon activity in A709 – influenced by different carbides
- Determine the crossover concentration for carburization and decarburization
- Carbon diffusion analysis in A709

| Heat ID | Plate thickness | Solution anneal temperature | Precipitation heat treatment |
|---|---|---|---|
| H58776 Carlson | 1.1" | 1,100°C | - |
| | | 1,150°C | - |
| | | | 775°C, 10 hr |
| 529900 ATI-1 | 1.75" | 1,150°C | - |
| | | | 775°C, 10 hr |
| | 2.0" | 1,150°C | - |
| | | | 775°C, 10 hr |

# Additional Tensile and Corrosion Data



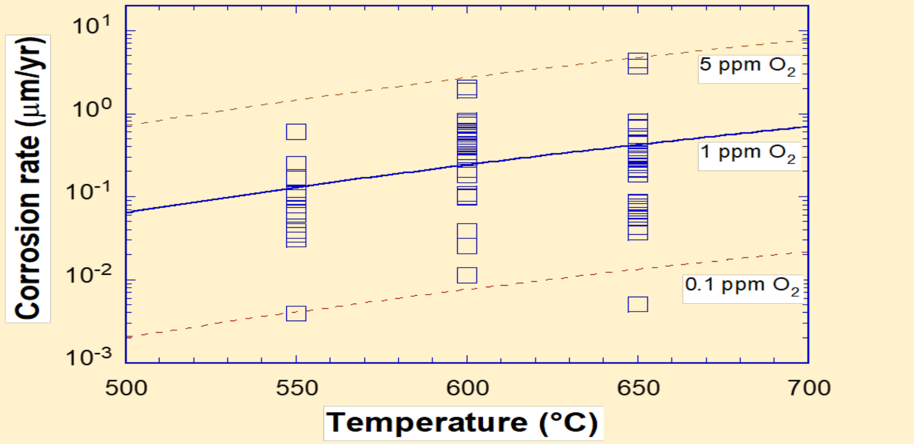




Blue symbol : A709
Red symbol : 316H SS
Open symbol : Na-exp
Close symbol : Aged

**Additional tests show that the sodium-exposure and thermal-aging data overlap significantly for A709, suggesting little or no sodium effect.**

**Corrosion rates obtained so far are low and can be bounded by the Monju model lines at 0.1 and 5 ppm oxygen level**

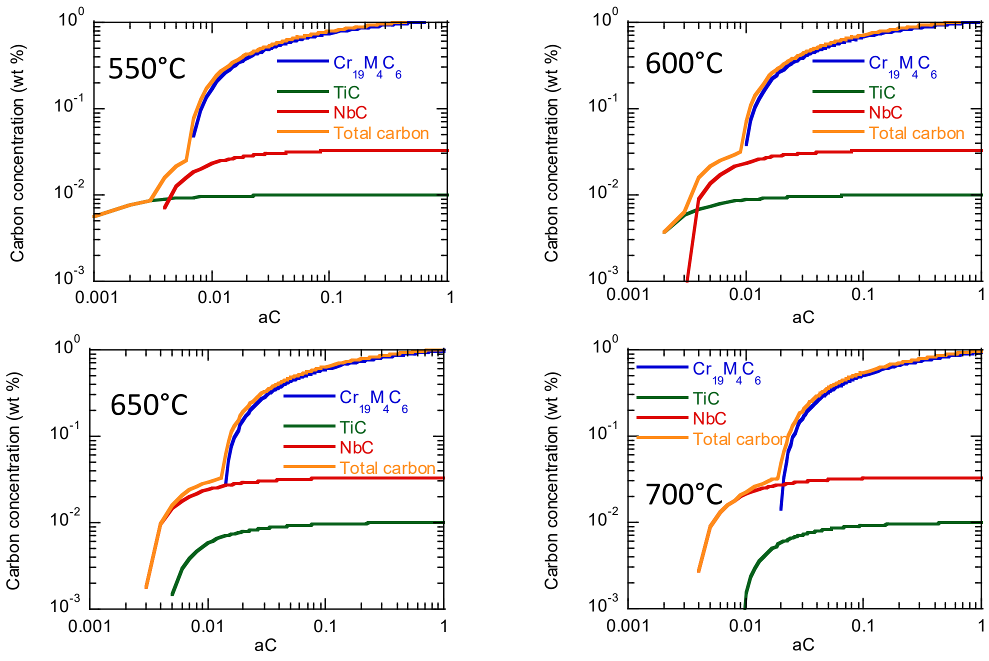



**Exposure experiments completed by 2023** (*On-going experiments)

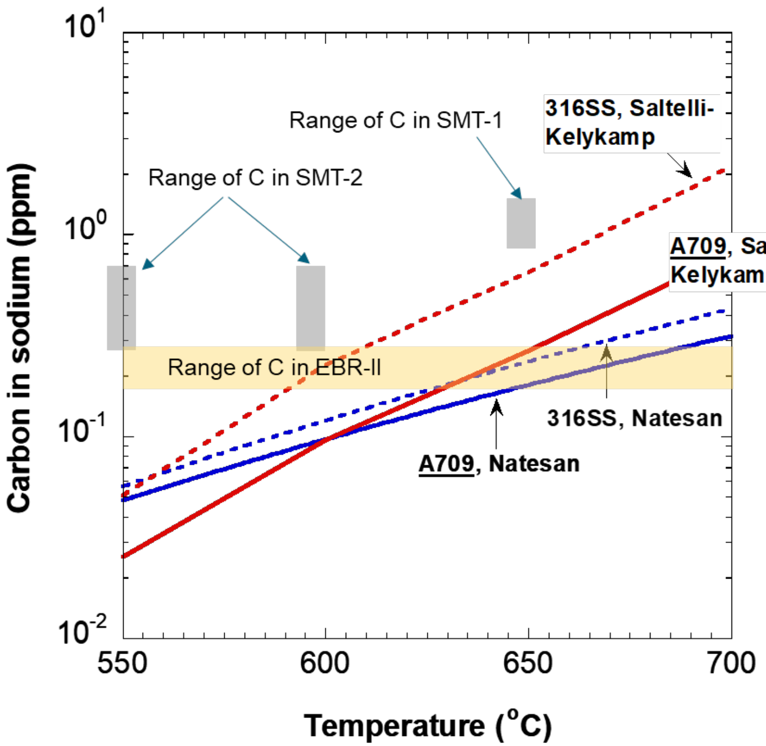
| Heat ID. | Heat-treatment conditions | Na-exposure time, hr | | | Thermal-aging time, hr | | |
|---|---|---|---|---|---|---|---|
| | | 550°C | 600°C | 650°C | 550°C | 600°C | 650°C |
| H58776 Carlson | SA 1,100°C | 3k, 9k | 3k, 9k | 3k, 10k, 17k | 3k, 10k | 3k, 10k | 3k, 10k, 20k |
| | SA 1,150°C | 3k, 9k | 3k, 9k | 3k, 10k, 17k | 3k, 10k | 3k, 10k | 3k, 10k, 20k |
| | SA 1,150°C + PT 775°C | - | - | 9k | - | - | 10k |
| ATI529900 ATI-1 | SA 1,150°C | - | - | - | 3k, 5.5k* | 3k, 5.5k* | 3k, 5.5k* |
| | SA 1,150°C + PT 775°C | - | - | - | 3k, 4.8k* | 3k, 4.8k* | 3k, 4.8k* |

# Carburization-Decarburization Behavior

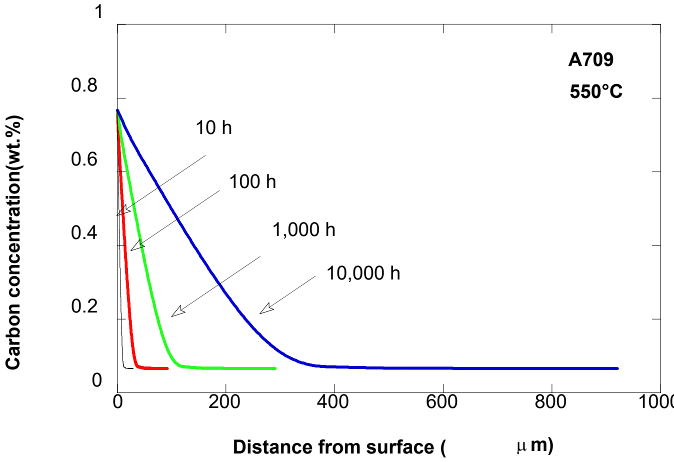
**Carbon activity evaluated with $M_{23}C_6$, TiC and NbC in A709**




**Carburization-decarburization regimes with carbon concentration in sodium**




**< 400 μm carburized layer at 550°C**




**Carburization-decarburization boundary of A709 is lower than that of 316 SS, suggesting that A709 is less likely to be decarburized in low-carbon-activity environment.**

# Future Work

- In addition to the A709 Code Case and sodium compatibility data package, additional A709 data are needed by reactor developers for reactor component design, construction and licensing
- Activities to address these issues are still under discussion and are not finalized

# Notional Timeline for Developing A709 Irradiation Design Data

- Irradiation design data are needed for the design and licensing of reactor vessel and core supports
- Currently, there are no end-of-life design data for irradiated A709
- Need to expand PIE capacities for generating design data

| | |
|---|---|
| Year 1 | • Conduct initial preparations for A709 irradiation campaign:<br>• Test plan development, design and analysis of irradiation capsule, and specimens fabrication |
| Year 2 | • Continue design and analysis of irradiation capsule, and specimens fabrication<br>• Fabricate capsule/basket hardware, assemble experiment for irradiation |
| Year 3 | • Shipment of assembled experiment and begin irradiation at ATR |
| Year 4 | • Continue irradiation at ATR<br>• Begin post-irradiation characterization, including mechanical properties testing and microscopy |
| Year 5 | • Continue irradiation at ATR<br>• Continue post-irradiation characterization |
| Year 6 | • Complete irradiation at ATR<br>• Continue post-irradiation characterization |
| Year 7 | • Complete post-irradiation characterization, including mechanical properties testing and microscopy |

# Establish Optimized Thermomechanical Processing Parameters for A709 Deployment

- A709 product forms such as plate, bar, pipe, fitting and forging are required for reactor component construction (vessel, core barrel, piping, tubing, etc.)
- Previous experience with 316SS and other alloys showed that thermomechanical processing parameters have significant influence on the microstructure and mechanical properties of the component (particularly forgings)
  - Develop optimized thermomechanical processing parameters
  - Establish acceptance criteria for forgings (testing of prolongations, etc.)
- Work with material vendor/component fabricator to produce a scaled, forged mockup vessel to demonstrate the effectiveness of the optimized processing and acceptance criteria
- Conduct instrumented thermal cycling of the scaled, forged mockup vessel to failure to generate validation data for ASME design rules

# Thank you for your attention

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