Advanced Reactor Technologies Program

Fast Reactor Structural Materials

Sam Sham
Materials Science and Technology Division
Oak Ridge National Laboratory

DOE-NE Materials Crosscut Coordination Meeting

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Advanced Reactor Technologies (ART) Program supports multiple high-level objectives identified in the 2010 Nuclear Energy R&D Roadmap (2 & 3)

(2) Develop improvements in the affordability of new reactors to enable nuclear energy to help meet the Administration’s energy security and climate change goals

(3) Develop sustainable nuclear fuel cycles

…overall goal is to have demonstrated the technologies necessary to allow commercial deployment of solution(s) for the sustainable management of used nuclear fuel that is safe, economic, and secure and widely acceptable to American society by 2050.”
Program Mission:
To research and develop advanced technologies to significantly improve the efficiency, safety, and performance of advanced reactor systems
Development and qualification of advanced structural materials are critical to the design and deployment of the advanced nuclear reactor systems that DOE is developing:

- High and Very High Temperature Gas Cooled Reactors (HTGRs and VHTRs)
- Sodium Cooled Fast Reactors (SFRs)
- Fluoride Salt Cooled High Temperature Reactors (FHRs)

Structural materials must perform over design lifetimes for pressure boundaries, reactor internals, heat transfer components, etc.

Performance of metallic alloys and graphite for the long times and high operating temperatures required is being examined under the Advanced Reactor Technologies (ART) Program.
Development and qualification of graphite, improved high-temperature alloys, and ceramic composites for advanced reactor systems

Advanced Fast Reactor-100 is an example of fast reactor systems
- Targets local small grids with limited needs for on-site refueling
- 250MWt/100MWe, sodium-cooled, core life (30 years), plant life (60 years)

AREVA’s High Temperature Reactor is an example of a He-cooled system
- TRISO fueled, graphite moderated
- 625MWt/315MWe, 750°C outlet temperature to steam generator, plant life (60 years)
Advanced Materials Program Structure

**Advanced Materials**
- Technical Area Lead: Sam Sham, ORNL

**High Temperature Materials**
- Technical Lead: Richard Wright, INL

**Graphite**
- Technical Lead: Will Windes, INL

**Fast Reactor Structural**
- Technical Lead: Sam Sham, ORNL
### Active NEUP Projects (16) in High Temperature Structural Materials

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Active NEUP Projects in High Temperature Structural Materials – Geographical
Fast Reactor Structural Activities
Lizhen Tan, Yuki Yamamoto, Mikhail Sokolov, Randy Nanstad, Phil Maziasz and supporting staff (ORNL)

Meimei Li, Ken Natesan and supporting staff (ANL)

Laura Carroll and supporting staff (INL)
Advanced Structural Materials Provide Greater Safety Margin and Design Flexibility

- **Higher strength for constant temperature:**
  - Reduced commodities
  - Greater safety margins
  - Longer lifetimes

- **Higher temperature for constant stress:**
  - Higher plant performance (e.g., thermal efficiency)
  - Reduced commodities
  - Greater safety margins in accident scenarios

- **Combinations of above:**
  - Greater design flexibility
Enhanced structural performance of AFR construction materials would reduce capital costs, enable more flexible designs, and increase safety margins.

- **FY 08**: Established advanced materials development strategy
  - Alloy 709 (Fe-20Cr-25Ni base) austenitic steel
  - Grade 92 steel with optimized chemistry and thermo-mechanical treatment

- **FY 09-12**: Down-selected one austenitic steel and one F/M steel

- **FY 13-15**: Intermediate term testing to support ASME Code Qualification assessment
  - Alloy 709 – testing completed, recommended for ASME Code Qual.
  - Opt Grade 92 steel - still waiting for some longer term data before assessment can be made

- **FY 16 & Beyond**: Opt Grade 92 – to complete assessment
  - Alloy 709 – to initiate Code Qualification effort, and to integrate NEUP project activities
Alloy chemistry of optimized Grade 92 is adjusted to
- Reduce Ni, Si, and Mn contents, which tend to impair creep strength
- Reduce Cr$_{23}$C$_6$-type precipitates and increase MX-type precipitates for better high temperature performance

Computational alloy thermodynamics is used to “visualize” the effect of alloy chemistry changes on phase constituents, which provide key information to alloy microstructure and subsequent thermomechanical treatment process.
Optimized Grade 92
Thermomechanical Treatment (TMT)

- TMT can be easily implemented during conventional Grade 92 production.

- TMT, significantly introducing additional nucleation sites for MX precipitates and possible refining grain size, would noticeably increase material’s performance.

![Gr92T5A](image1.png)  ![Gr92T5B](image2.png)

![Graph](image3.png)
Creep tests have been conducted at 550, 600 and 650°C and various loads. The longest test has achieved > 12,500 h at 550°C.

The test results indicate noticeable increases in creep strength as compared to P92 and P91.

Creep cavities (lots <~2 μm and a few up to ~10 μm) formed close to the rupture site of an Opt Grade 92 specimen tested at 600°C.
Grade 91 base metal has been shown to exhibit wide variability of creep rupture ductility for the same life (can vary from 1 to 75%).

Tightening of the chemistry spec and impurities of Grade 91 is being considered by ASME to mitigate the issue.
Higher temperature and tube products (i.e., T92 and T91) tend to result in lower elongation and reduction of area (RoA).

Grade 92 Data

Grade 91 Data

[Reference data of P/T91 and P/T92: NIMS Creep Data Sheet and ASME STP-NU-019-1 (by R.W. Swindeman et al. 2009)]

* The inclusion of 597C and 649C data in both tube form and plate form
Single compound bevel U-shape groove was designed for gas tungsten arc welding (GTAW) of the 1”- and 1.6”-thick plates to accommodate standard size creep/tensile and other testing specimens.

Welds have fabricated from heats 011365 and 011449 at ORNL and a subcontract (SWM) following ASME Section IX Welding Qualifications, e.g., QW/QB-422, A/SA-182 F92 (K92460) with welding P-No. 15E.

- Current pulsing was employed for the welds because non-pulsing resulted in much more cavities in the weld metal although the cavities did not result in noticeable cracks.
The optimized Grade 92 having refined microstructure with a high density of MX precipitates helps reducing re-precipitation of Cr$_{23}$C$_6$ at boundaries in the HAZ of welds, which delays Type IV cracking with less reduction in creep life.

- Creep voids (black) formed in the HAZ after test at 650C but not associated with dispersive Laves phase (white particles).
Opt. Grade 92 fatigue cycles to failure within the scatter of available Grade 91 literature data

Note: All comparison data are estimates from the literature
Note: JAEA reference is ASME STP-NU-018-2009
Lower strain range CF testing and shorter hold time testing ongoing for Heat 8T

- CF cycles to failure degraded relative to continuous cycle fatigue
Effects of long-term thermal aging on tensile properties of Opt Grade 92 were evaluated.

The microstructural evolution is evaluated by using ThermoCalc and DICTRA to predict the microstructures over long times.

Accelerated aging experiments are conducted to validate the calculated morphologies which will enable assessment of long-term performance.

Thermal aging at 650°C resulted in a decrease in the tensile strength.

Sodium exposure at 650°C has a much stronger effect on tensile strength than thermal exposure alone at 650°C.

Precipitation of Laves phase was observed in all sodium-exposed specimens of and could be the cause of strength reduction.

Longer term aging and sodium exposures at 600 and 550°C are continuing.

Microstructural evaluations of the aged/exposed specimens will be made to assess the long-term performance of these materials in SFRs.
Alloy 709 Has Enhanced High Temperature Strengths vs Reference Material (316H)

Stress, MPa

Creep Rupture life, h

Nippon Steel Seamless Tube Data

Tested at 700°C

Approx. 2X Increase in Creep Strength

316H
Alloy 709 structural applications identified for AFR-100
  - Core support structures, reactor vessel, primary and secondary piping

Alloy 709’s higher strengths provide capital cost reduction and design advantages over reference 316H stainless steel throughout a broad temperature range
  - Thinner walls
    • Lower material quantities and reduced through-wall thermal gradients
  - Higher allowable thermal gradients
    • Potential for more compact component and plant configurations
  - Smaller piping expansion loops
  - Could open up opportunities for other design innovations
Alloy 709 allows greater thermal gradients as compared with 316H

Results in prospect of eliminating costly add-on hardware instituted in past designs to mitigate deficiency of 316H*

- French Phenix, Super Phenix; German SNR; U.S. FFTF, CRBR; Japanese MONJU

Alloy 709 Code Qualification Plan

Elevated Temperature Structural Design (Construction)

- ASME Section III Division 5, Subsection HBB (Class A) and HCB (Class B)

Support NRC Licensing & Plant Operation

- Environmental effects (sodium, irradiation)
- Verification and validation of ASME code rules
- SFR structural issues
- High temperature flaw evaluations

Effort will be initiated in FY16 to implement part of the Code qual. plan
Gaining mechanistic understanding of long term degradation mechanisms such as creep and creep-fatigue damage and thermal aging could provide guidance on the extrapolation of accelerated time-at-temperature design data to 60-year design life, and beyond, with higher confidence.

Removal of unnecessary conservatism in design methodology could lead to more flexibility in construction and operation of AFR.

Creep-Fatigue Interaction

Creep Rupture – G91

Kimura and Takahashi, 2012
THANK YOU