U.S. DEPARTMENT OF ENERGY | Nuclear Energy

Advanced Reactor Concepts Program

ARC Materials Development - Accomplishments and Plans

Sam Sham
Materials Science and Technology Division
Oak Ridge National Laboratory

DOE-NE Materials Crosscut Coordination Meeting

July 30, 2013

ARC Work Packages

- **Advanced Alloy Development**
  – Lizhen Tan, Yuki Yamamoto, Phil Maziasz, Sam Sham (ORNL)
- **Advanced Alloy Testing**
  – Laura Carroll, Mark Carroll (INL)
  – Meimei Li, Ken Natesan, W. K. Soppet, J. T. Listwan, D. L. Rink (ANL)
  – Lizhen Tan, Yuki Yamamoto, Mikhail Sokolov, Sam Sham (ORNL)
- **Sodium Compatibility**
  – Steve Pawel (ORNL)
  – Meimei Li, Ken Natesan, Y. Momozaki, D. L. Rink, W. K. Soppet, J. T. Listwan (ANL)

Current Fast Reactor R&D Activities*

- **Focus on long-term, science-based R&D that supports increasing the performance of fast reactor technology.**
  - Safety enhancements**, cost reduction, increased electrical power output and improved operation or maintenance.
- **Advanced materials, inspection technologies, advanced energy conversion systems, advanced compact reactor concepts, advanced fuel handling systems and advanced modeling and simulation code development.**
- **Cost reduction**
  - design simplification, commodity reduction, advanced energy conversion, and improved material performance.
  - examination of advanced systems and components such as compact fuel handling mechanisms, advanced balance of plant systems, ultra-long-lived fast reactor cores and advanced heat exchanger technology options.
  - constructing a metal coolant test facility – the Mechanism Engineering and Testing Laboratory – at Argonne National Laboratory to test fast reactor components in a sodium environment.

* Excepted from "U.S. Research Program to Support Advanced Reactors and Fuel Cycle Options," P. Lyons, presented at FR13 Conference, Paris, France, March 4, 2013.
** Highlighted for this presentation on areas that structural materials play a role.

SFR Advanced Materials - Introduction

Enhanced structural performance of SFR construction materials would reduce capital costs, enable more flexible designs, and increase safety margins

FY 2008

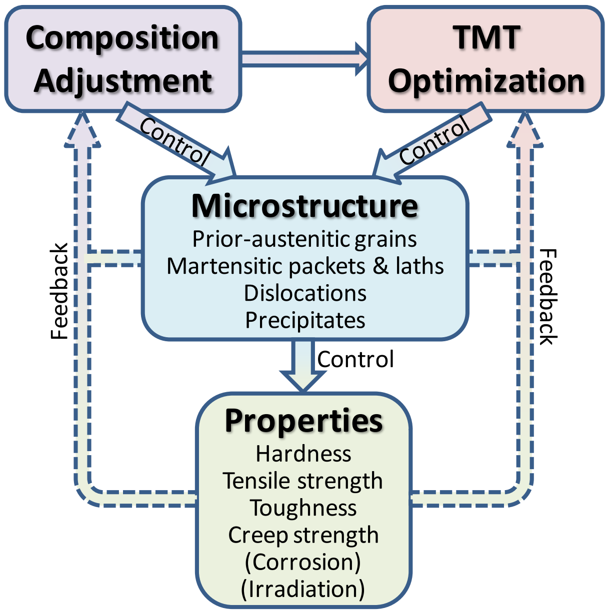
- Comprehensive assessment (5 National Labs and 5 universities) led by Busby (ORNL) established an alloy development priority list to improve structural performance
- Ferritic-Martensitic
  - Grade 92
  - TMT Grade 92
- Austenitic
  - HT-UPS
  - Alloy 709

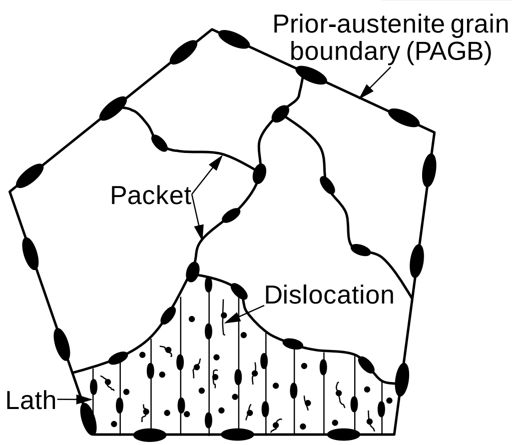
FY 2009-2012

- Alloy development and downselection conducted by ORNL, ANL and INL
- Downselection recommendation was made in FY 2012

Alloy Development for Modified Grade 92 Followed a Systematic Approach

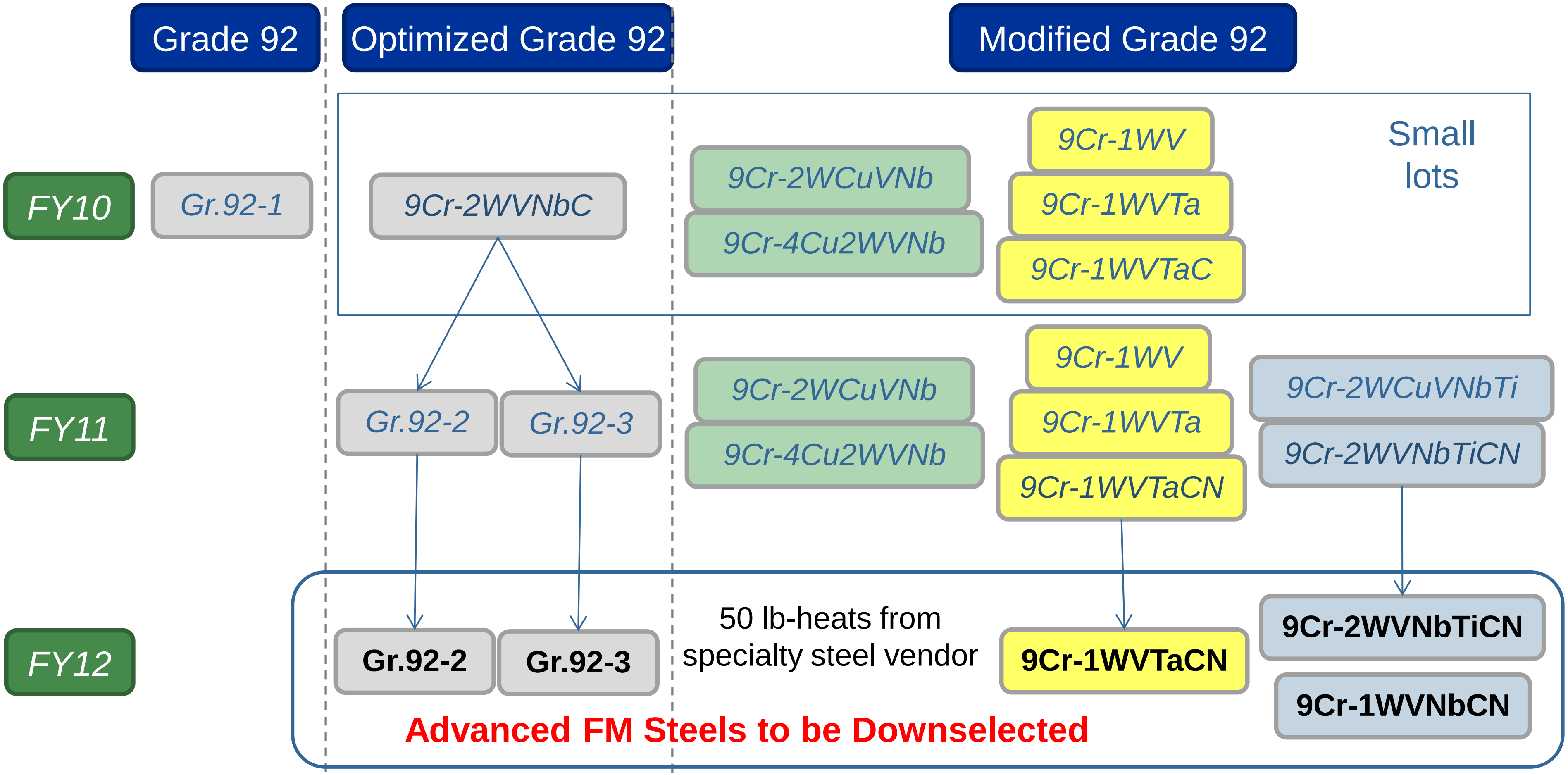
- **Methodology: Controlling microstructure by means of <u>composition adjustment</u> and <u>thermomechanical treatment (TMT) optimization</u> to produce desired properties**
- **Strategies to obtain stronger 9Cr F-M steels**
  - Compositions can be adjusted with the aid of computational thermodynamics to promote designed secondary phase strengthening
  - A variety of TMTs can be applied to the materials to control prior-austenite grain size, martensitic packet and lath density, dislocation density, and precipitate size and density
  - Want lots of nano-sized M(C/N), narrow lath widths
  - Want to reduce $M_{23}C_6$ carbides





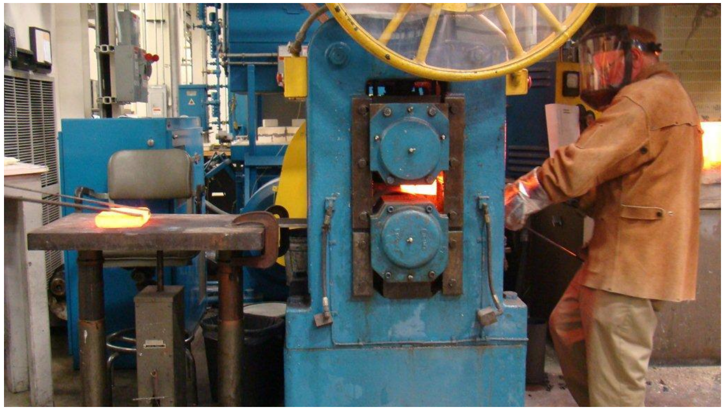
Schematic illustration of precipitates at prior Austenite grain boundaries, martensite packets and laths, dislocations, and matrix

Downselection of 9Cr FM Steels



Note:
1. Grade92 – composition and mechanical specifications meet the ASTM A213/335 standard.
2. Optimized Grade92 – composition meets the ASTM A213/335 but not mechanical specifications.
3. Modified Grade92 – both composition and mechanical specifications do not meet the ASTM A213/335 standard.

FM Procurements to Support Downselection Testing – 50 lb heats

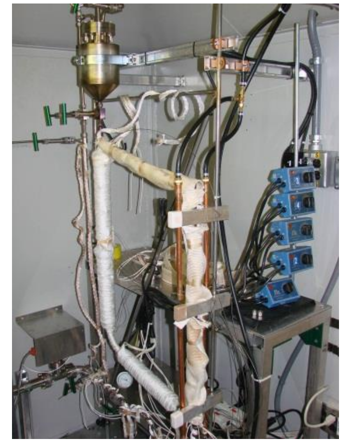


Generated a Broad Range of Data to Support Downselection

Tensile

Creep Rupture

Sodium Compatibility Testing

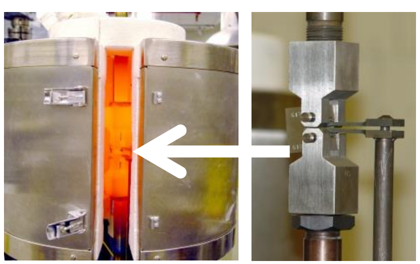


Thermal Convection Loop

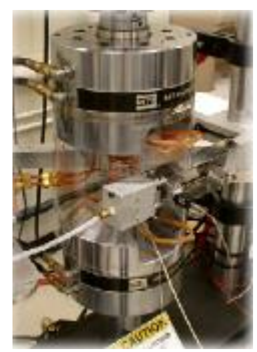
Forced Convection Loop

Charpy Impact

Microstructure Characterization

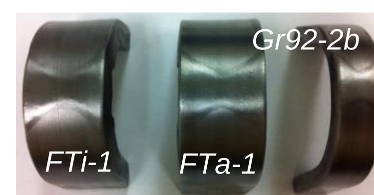


Fracture Toughness



Fatigue & Creep-Fatigue

Thermal Aging



Weldability

Metrics Used in the Downselection of Advanced 9Cr FM Steels

Metric	Commercial		Optimized-Gr92		Beyond Gr92 chemistry		
	Gr91	Gr92	Gr92-2a	Gr92-2b(TMT)	FTa-1	FTi-1	FV-1
Yield/Tensile							
Aging							
Creep							
Fatigue							
Creep-Fatigue							
DBTT							
Na-capsule							
Na-loop							
Weldability							
Low creep ductility							
Overall			○		●	◑	●

Optimized Grade 92 shows the best overall performance enhancement

Downselection of Austenitic Alloys

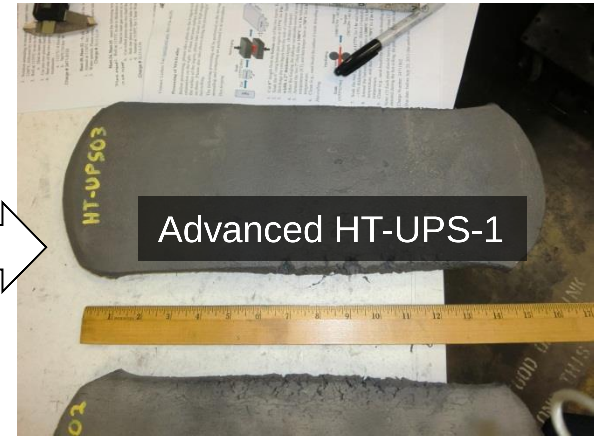
	316(H) / TP316H	Alloy 709 / TP310MoCbN	HT-UPS *	Advanced HT-UPS
Composition (wt%)	**18Cr-12Ni**-Mn-**Mo**-C	**22Cr-25Ni**-Mn-**Mo**-V-Nb-C-N	**14Cr-16Ni**-Mn-**Mo**-V-Ti-Nb-C	**13Cr-16Ni**-Mn-**Mo**-Nb-N
Strengthening mechanism	Solution hardening (Mo) + Precipitate hardening ($M_{23}C_6$)	Solution hardening (Mo) + Precipitate hardening {M(C,N), Z-phase, $M_{23}C_6$}	Solution hardening (Mo) + Precipitate hardening {MC, FeTiP, $M_{23}C_6$}	Solution hardening (Mo) + Precipitate hardening {M(C,N), $M_{23}C_6$}
Mechanical data	Tensile, creep, toughness: from datasheet (NRIM/NIMS)	Tensile, creep, toughness: from datasheet (Nippon Steel)	Tensile, creep toughness: from reports (ORNL)	Tensile, creep, toughness: Test in plan/ progress
YS/UTS/EL at RT	**205MPa**/ 515MPa/ 35%	**270MPa**/ 640MPa/ 30%	**246MPa**/ 617MPa/ 62%	n/a
Advantage	• Good oxidation resistance • **Good weldability** • Lower material cost	• **Good creep properties** • Better oxidation resistance • No problem on welding	• **Better creep properties** • **Lower material cost**	• **Better creep properties** • **Improved weldability** • **Lower material cost**
Disadvantage	• **Adequate creep properties**	• **Expensive due to higher Ni**	• Poorer oxidation resistance • **Less weldable**	• Poorer oxidation resistance

* HT-UPS (High-Temperature Ultrafine Precipitation-Strengthened)

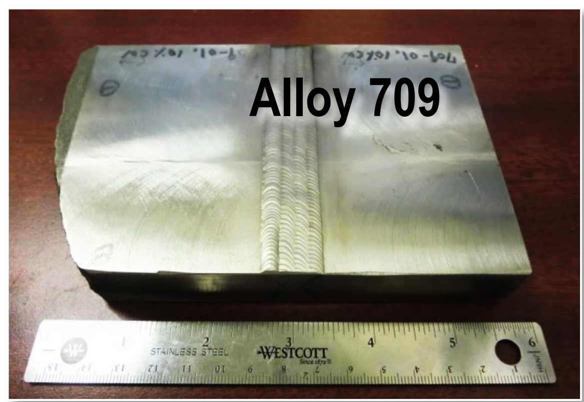
50-lb Heats Procured from Specialty Steel Vendor

Cast ingot

After hot-forging

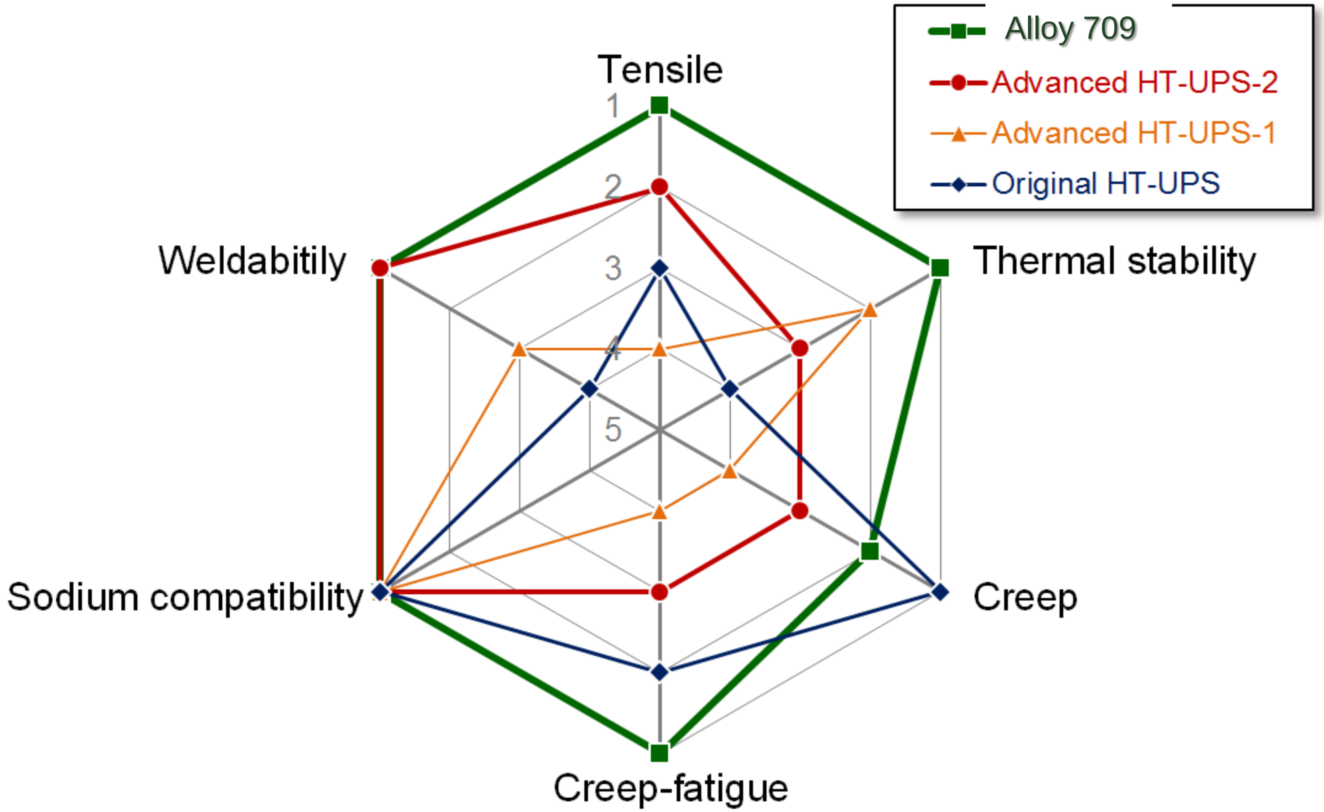


After hot-rolling



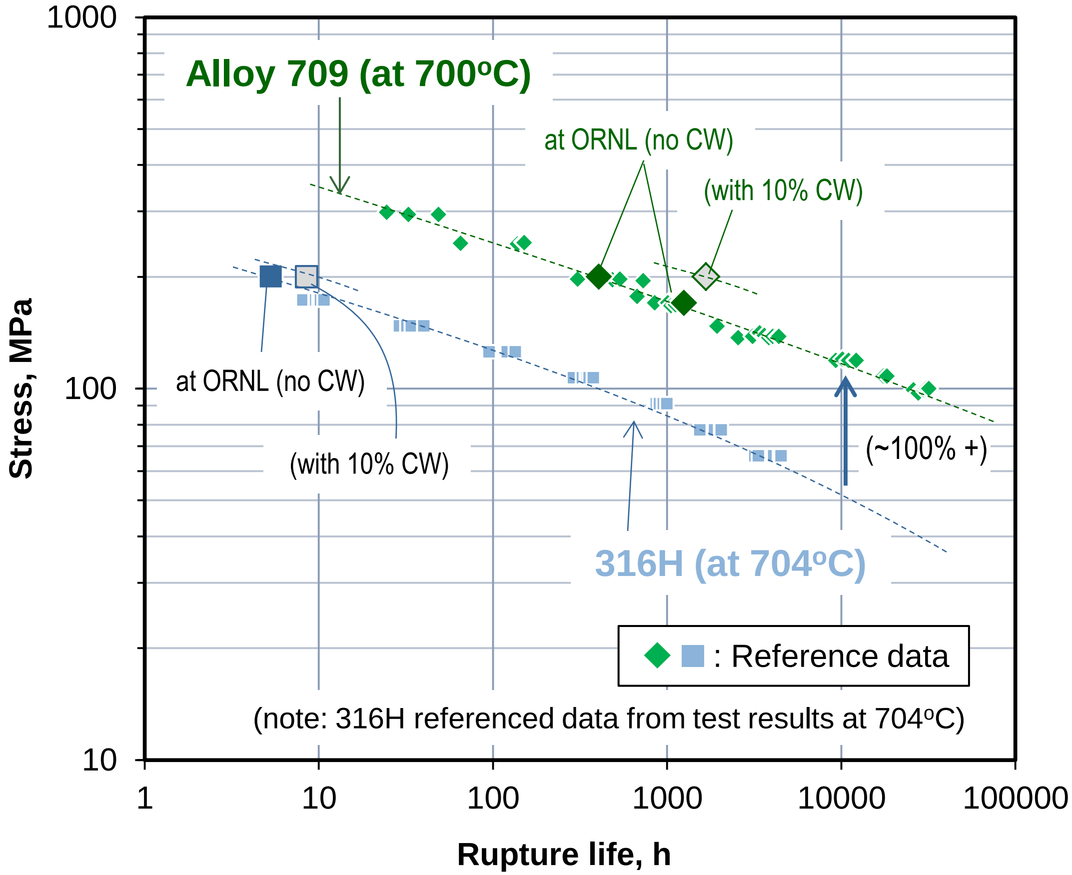
No visible defects in welds after 4t bend

Performance of Advanced Austenitic Alloys Based on Broad Range of Data



- **Alloy 709** ranked as #1 in 5 different properties.
- **Advanced HT-UPS 2** exhibited improved weldability, but less creep resistance compared to the original HT-UPS.

Comparison between Alloy 709 and 316H Stainless



Proceedings of CREEP8
Eighth International Conference on Creep and Fatigue at Elevated Temperatures
July 22-26, 2007, San Antonio, Texas

CREEP2007-26469

COLD WORK EFFECT ON CREEP RUPTURE STRENGTH OF AUSTENITIC BOILER STEELS

Fujimitsu Masuyama
Kyushu Institute of Technology
Kitakyushu, Japan

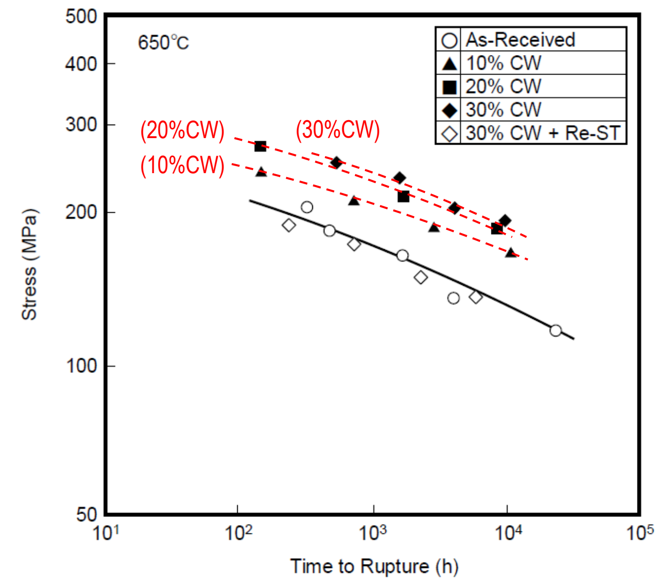


Fig. 5 Creep rupture properties of cold/warm-worked TP316H steel tube

- Creep strength of Alloy 709 is **~100% larger** than 316H at 700°C and 10,000 hr (100kh-life strength could be 70-80 MPa for Alloy 709 vs. 20-40 MPa for 316H.)
- Cold work enhances Alloy 709 creep strength by ~25%.

Programs for FY 2013

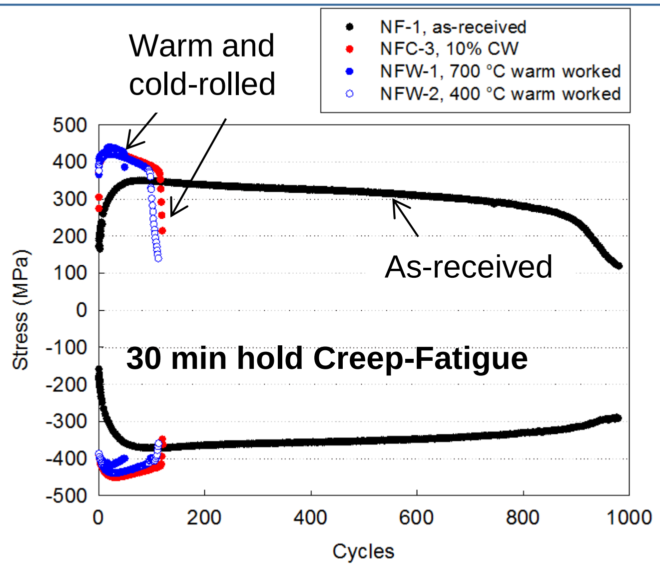
- **Further develop and refine optimized Grade 92 and Alloy 709 (thermo-mechanical treatments)**
- **Initiate intermediate term tests to confirm observed performance gains based on short-term, accelerated data from small lots and sub-sized specimens**
  - Standard-sized specimens, longer thermal aging and sodium exposure times (~10,000 hrs)
- **Understand degradation mechanisms (thermal aging and sodium exposure)**
- **Start to think about weldments**

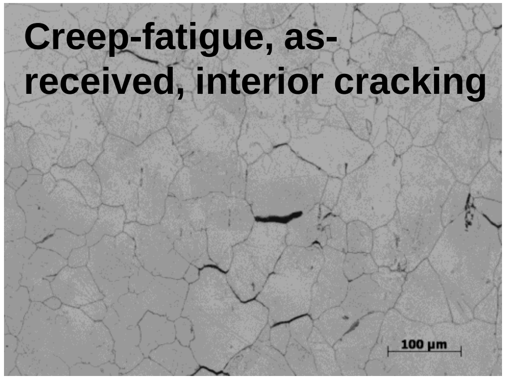
Down-select TMT for Optimized Grade 92

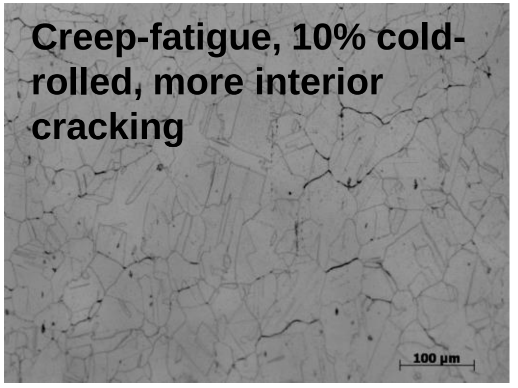
- **Thermo-mechanical treatment (TMT) is applied to control prior-austenite grain size, martensitic packet and lath density, dislocation density, and precipitate size and density**
  - Promote formation of nano-sized M(C/N), reduce lath widths, reduce $M_{23}C_6$ carbide formation
- **TMT enhances creep strength but could potentially degrade toughness**
  - Use DBTT (ductile-to-brittle transition temperature) as metric to down-select TMT
- **TMTs considered (~ 1-inch plates)**
  - Hot rolled, hot cross-rolled, hot forged
  - Hot forged gave the best overall Charpy performance
- **Will investigate effects of hot forging on thicker cross sections in future studies**

TMTs for Alloy 709

- **TMTs for austenitic alloys enhance creep strength but could potentially degrade creep-fatigue performance**
  - Use reduction in cycle life due to creep-fatigue as metric to assess TMTs for Alloy 709
- **10% cold/warm-rolled**
  - Introduce dislocations to promote precipitation of MX carbides





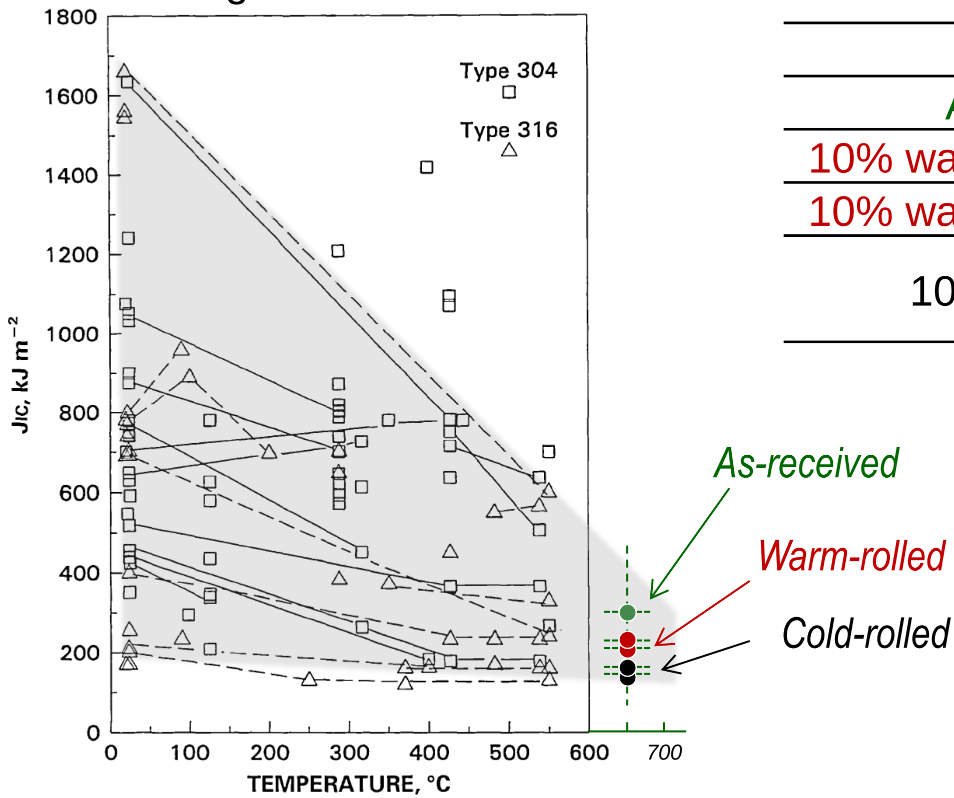


Further creep strength enhancement, but significant creep-fatigue performance degradation from cold/warm rolled specimens

Alloy 709 - High Temperature Fracture Toughness

- **Preliminary high temperature fracture toughness test completed.**

Fracture toughness of commercial SS



5 Effect of test temperature on J_{IC} fracture toughness for types 304 (Refs. 8–13, 23, 29, 30, 32–44, 48–55) and 316 (Refs. 4, 6, 13–16, 28, 30, 31, 35, 39, 40, 44–47, 52, 56–58); J_{IC} values for same heat are connected by line

(Mills, 1997)

Fracture toughness at 650C

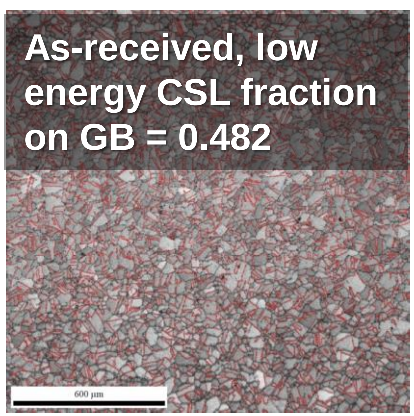
Sample	J1c (kJ/m^2)
As received	292
10% warm-rolled at 700°C	232
10% warm-rolled at 400°C	216
10% cold-rolled	156
	138

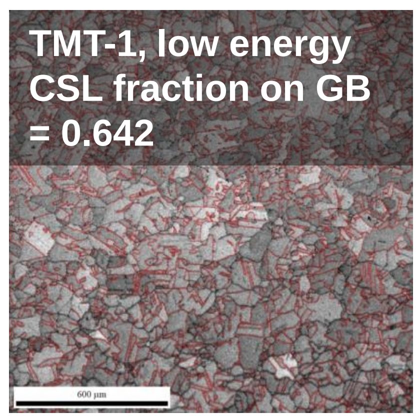
- Warm rolling resulted in much less reduction of fracture toughness compared to cold-rolling.

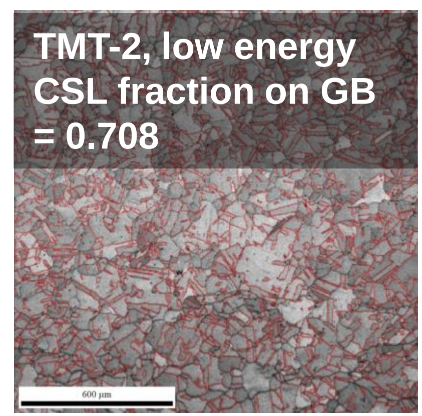
TMTs for Alloy 709

- **TMT-1 and TMT-2**
  - Increase fraction of low energy CSL (coincident site lattice) boundaries to reduce propensity of grain boundary defect formation
- **Creep-fatigue tests on going**

Increasing low energy CSL fraction →





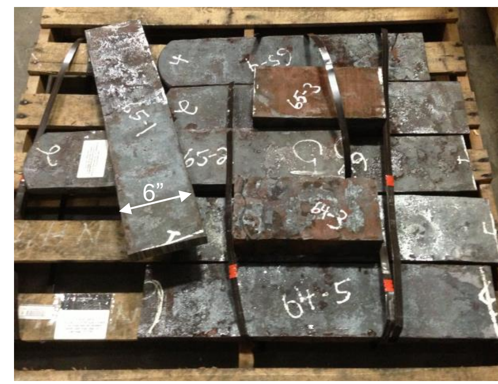


Procure New Heats of Optimized Grade 92 and Alloy 709

Carpenter Technology Corporation (USA)

- Delivered two 300-lb optimized Grade 92 heats, Vacuum Induction Melting (VIM) and Electro-Slug Remelting (ESR) ingots + hot forging into plates
- Delivered one 400-lb Alloy 709 heat, VIM-ESR ingot + hot forging into plates

Alloy 709



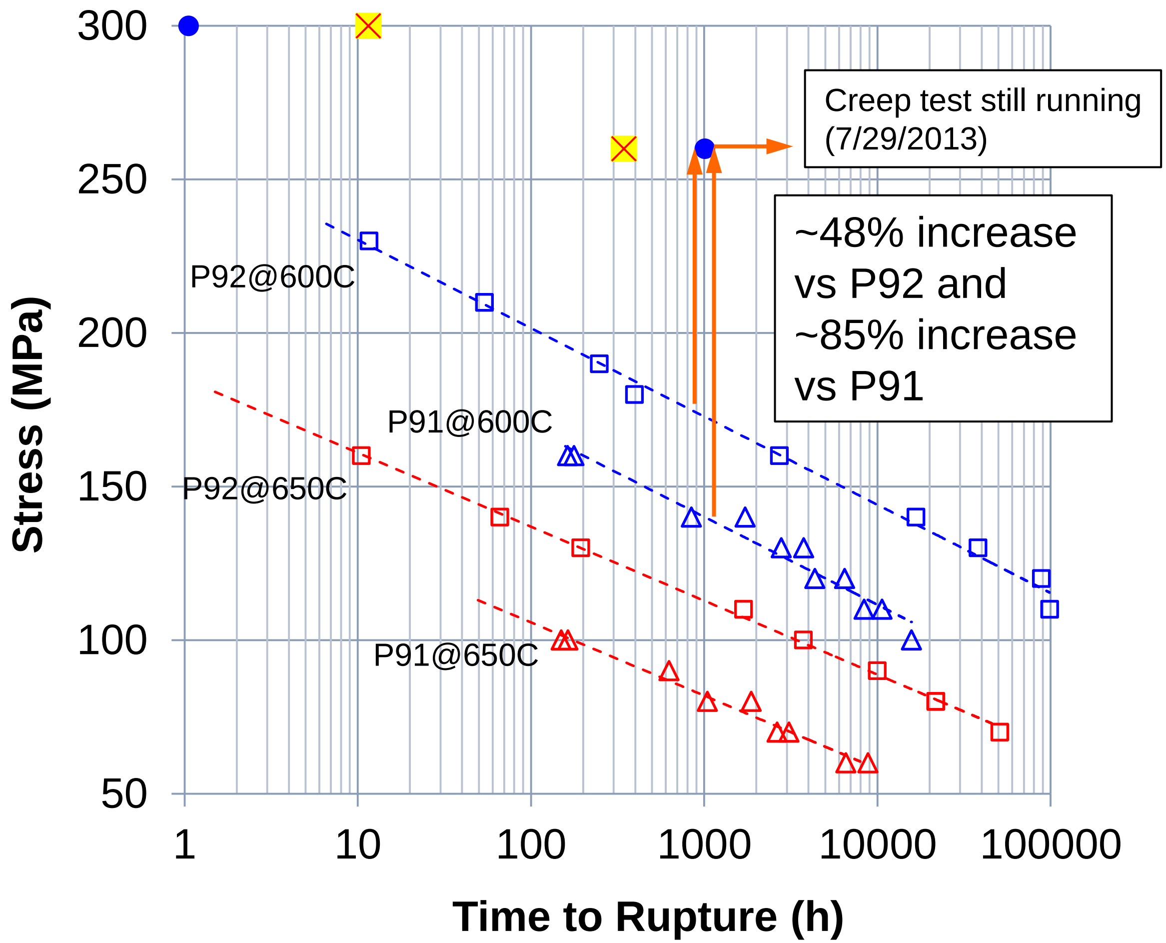
Optimized Grade 92

Nippon Steel & Sumikin Technology Co., Ltd. (Japan)

- Ordered one 330-lb Alloy 709 heat, VIM ingot + hot rolling into plates
- Schedule to be delivered in September 2013

Properties Screening of New Optimized Grade 92 TMT Heat

- Accelerated screening tests using sub-sized creep specimens show that the new TMT heat is delivering comparable, or better, creep performance enhancement as the FY12 procurement



600° C

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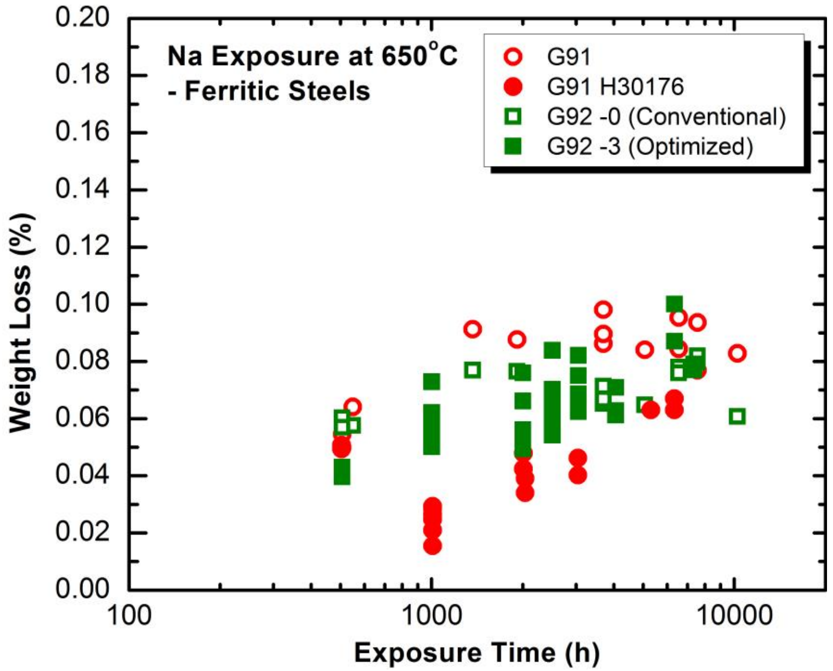
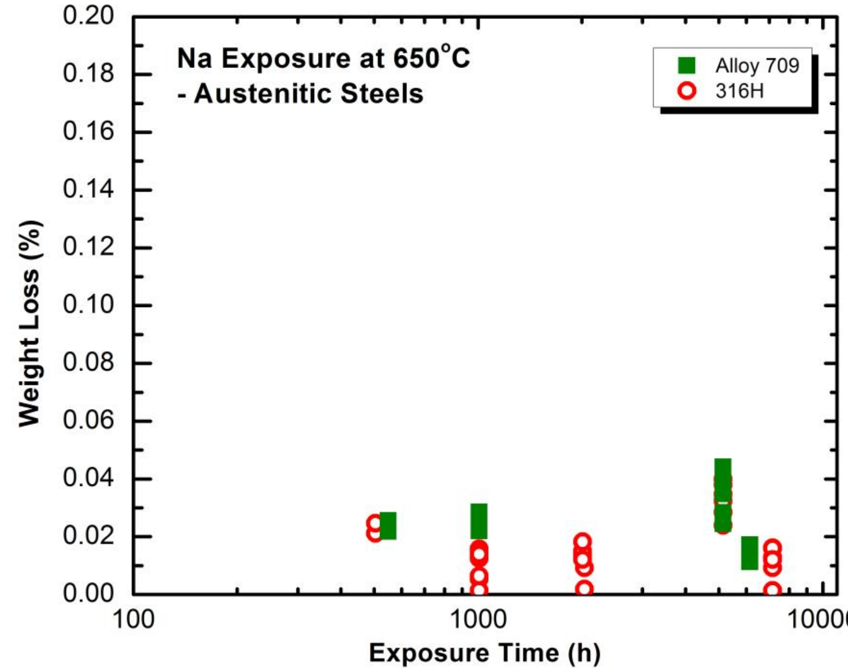
Additional Testing Capabilities are Added to Support Intermediate Term Testing

- **A second sodium loop, with two specimen exposure vessels that can accommodate standard-sized specimens, is being constructed at ANL**
- **Additional creep frames identified to support creep rupture tests of two base metals and two weldments**

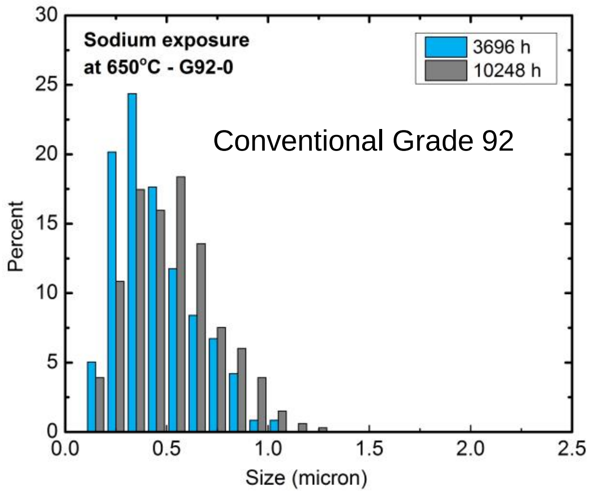
Corrosion Performance of Ferritic-Martensitic and Austenitic Steels in Sodium

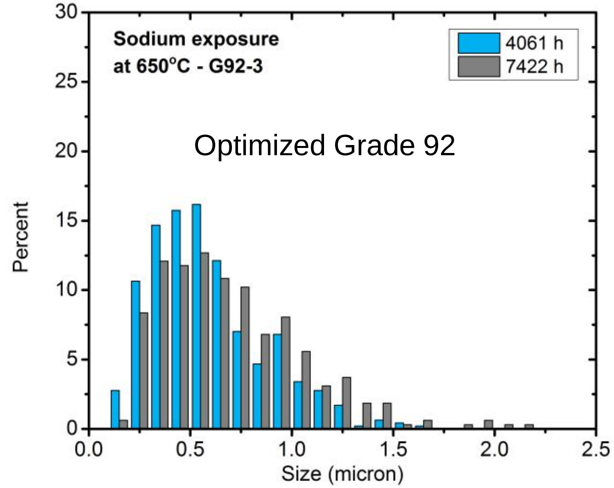




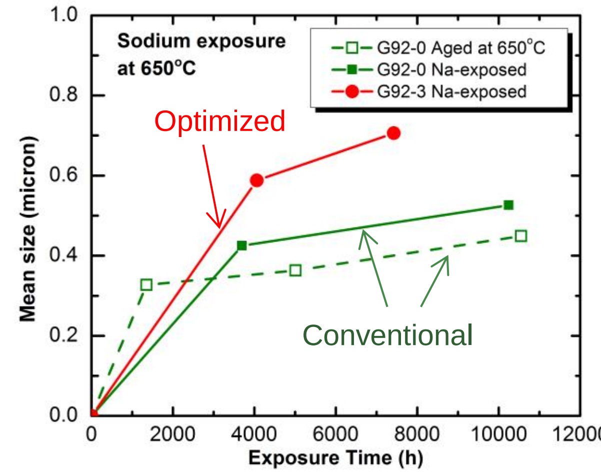
- Completed sodium exposure tests on optimized G92 steel for >7,000 h and Alloy 709 steel for >6,000 h at 650°C
- All ferritic-martensitic and austenitic steels exhibited weight loss after sodium exposure at 650°C.
- Ferritic-martensitic steels, G92 and G91 showed higher weight losses than austenitic steels, Alloy 709 and 316H.
- Weight loss of optimized G92 is similar to that of conventional G92 and G91 steels; Alloy 709 shows similar weight loss to 316H.

Coarsening of Laves Phase and Effect on Tensile Properties

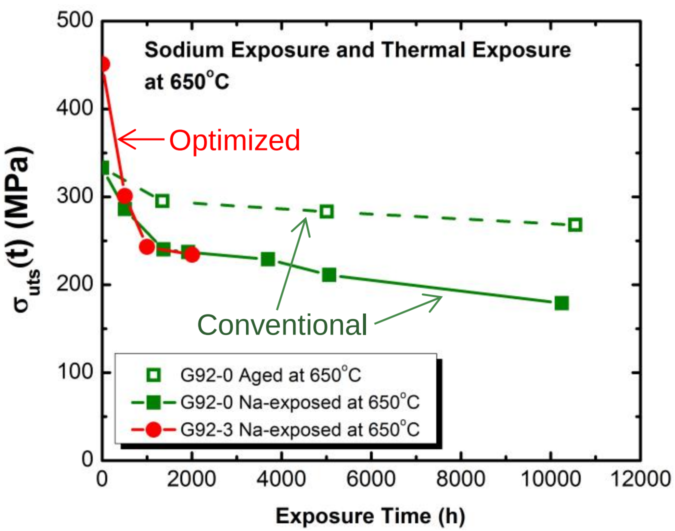




Laves phase coarsened faster in optimized G92-3 than in conventional G92-0 during sodium exposure



Sodium exposure accelerated Laves phase coarsening in comparison with thermal aging



Laves phase formation and coarsening in G92 steels can be correlated with the strength reduction due to thermal/sodium exposures

Summary - SFR Advanced Materials R&D Plan

Enhanced structural performance of SFR construction materials would reduce capital costs, enable more flexible designs, and increase safety margins

FY 2008

- Comprehensive assessment (5 National Labs and 5 universities) established an alloy development priority list to improve structural performance
- Ferritic-Martensitic
  - Grade 92
  - TMT Grade 92
- Austenitic
  - HT-UPS
  - Alloy 709

FY 2009-2012

- Alloy development and down selection conducted by ORNL, ANL and INL
- Grade 92, with optimized chemistry, and Alloy 709 showed enhanced performance over current generation SFR materials

FY 2013-2015

- To further develop and refine optimized Grade 92 and Alloy 709 (thermo-mechanical treatments)
- To confirm observed performance gains based on short-term, accelerated data
- To generate weldment data
- To understand degradation mechanisms (thermal aging and sodium exposure)
- To recommend whether to pursue ASME Code qualification

FY 2016 and Beyond

- If recommended and approved, develop and execute Code qualification plans for optimized Grade 92 and Alloy 709 so that SFR designers can take advantage of the improved properties of these alloys in their designs