U.S. DEPARTMENT OF ENERGY | Office of NUCLEAR ENERGY

EFFECTS OF SODIUM EXPOSURE ON GRADE 91 STEEL

Y. Chen, Z. Zeng, and M. Li
Argonne National Laboratory, Lemont, IL, USA

Oct 30th – Nov. 3rd, 2023

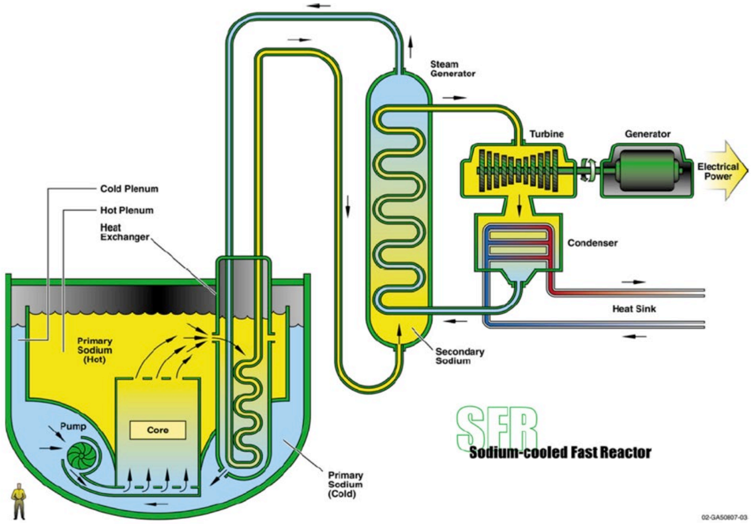
SFR Material Requirements

- **Material requirements**
  - Adequate high-temperature strength and ductility
  - Adequate radiation resistance
  - Fabricability, weldability, etc.
  - Adequate performance in sodium environments

Common to all types of advanced reactors

Unique to SFRs

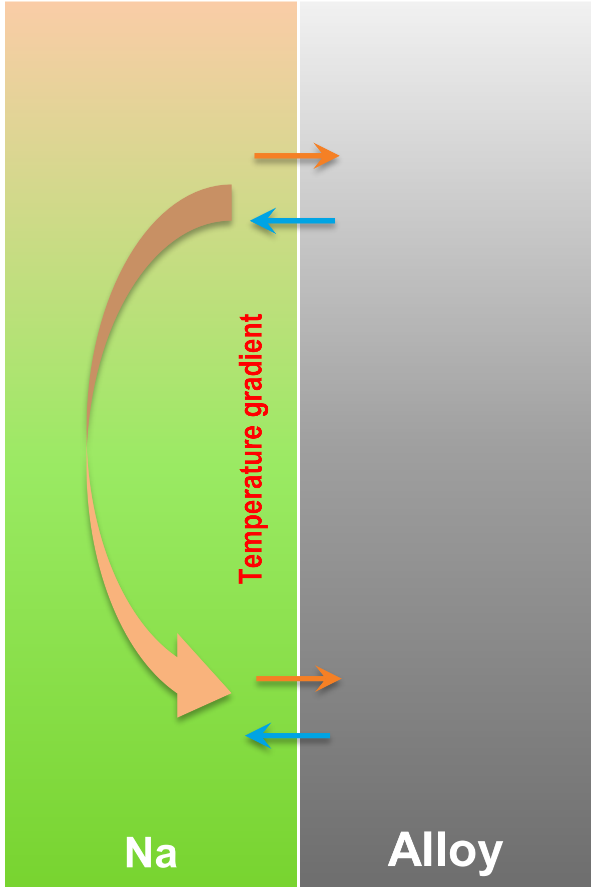
- **Materials for SFRs**
  - Austenitic stainless steels
  - Ferritic-martensitic steels
  - Recent DOE efforts have been focused on
    - Austenitic Stainless Steel: A709
    - High-Cr ferritic/martensitic steel: Grade 91



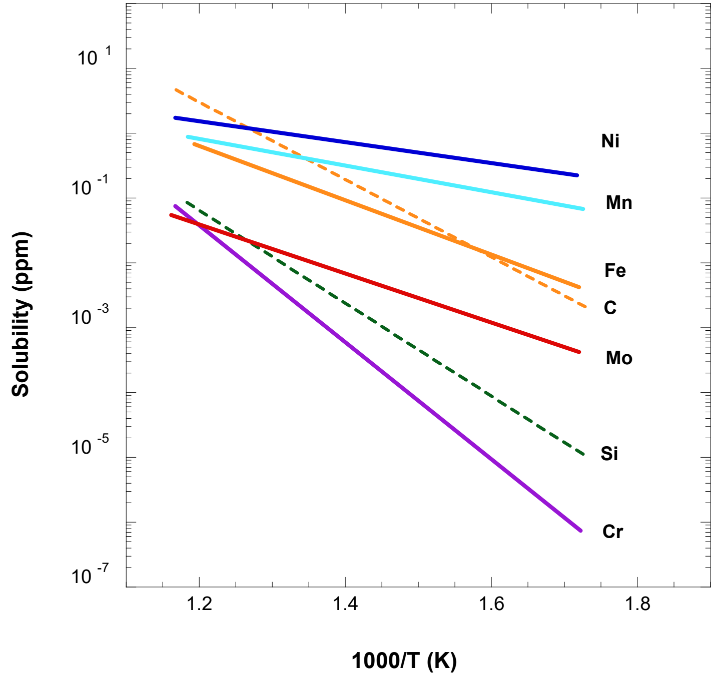
https://www.gen-4.org/gif/jcms/c_42152/sodium-cooled-fast-reactor-sfr

Materials Degradation in Na

An issue of element transfer across alloy-sodium boundary



- **Metallic element transfer**
  - Dissolution of metallic elements
    - Controlled by their solubilities in Na
    - Generally inevitable
  - Causing metal loss and formation of surface depleted zones
  - Establish a no/no-go criterion
- The solubilities of major alloying elements in austenitic and ferritic steels are < a few wppm, and they are generally compatible with Na.



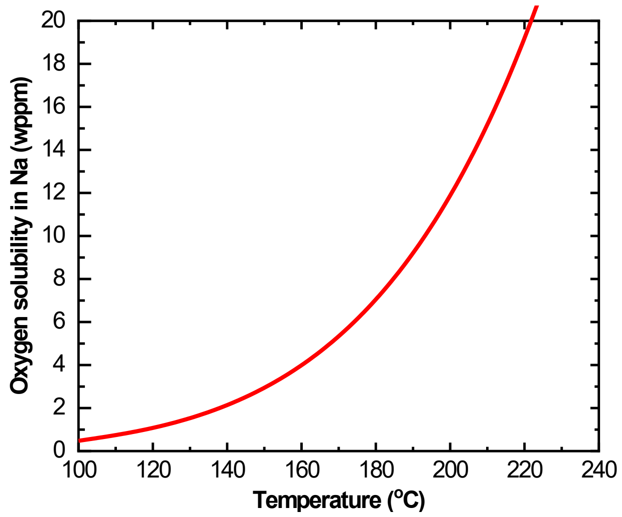
Materials Degradation in Na – Oxidation

- **Nonmetallic element transfer: Oxidation**
  - Oxygen in Na has a strong effect on the corrosion rate of a material.
  - Oxygen in Na tends to enhance the dissolution process, and forms corrosion products in the metal-sodium system.

$$2Na_2O + Cr = NaCrO_2 + 3Na$$
$$3Na_2O + Fe = (Na_2O)_2 \cdot FeO + 2Na$$

  - The higher the O content in Na, the higher the corrosion rate.

- **Control of oxygen in sodium**
  - The oxygen concentration in sodium can be effectively controlled by the cold trap method.



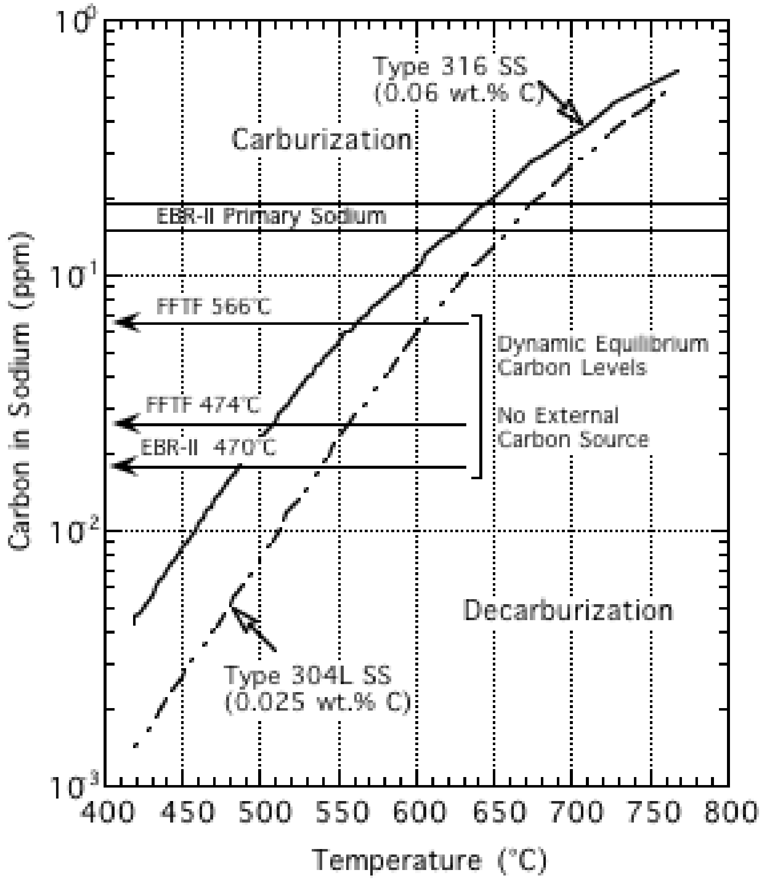
Oxygen solubility in liquid sodium

$$log_{10} S(wppm\ O) = 6.239 - 2447/T(^oK)$$

(AI-AEC-12685)

Materials Degradation in Na – Carbon Transfer

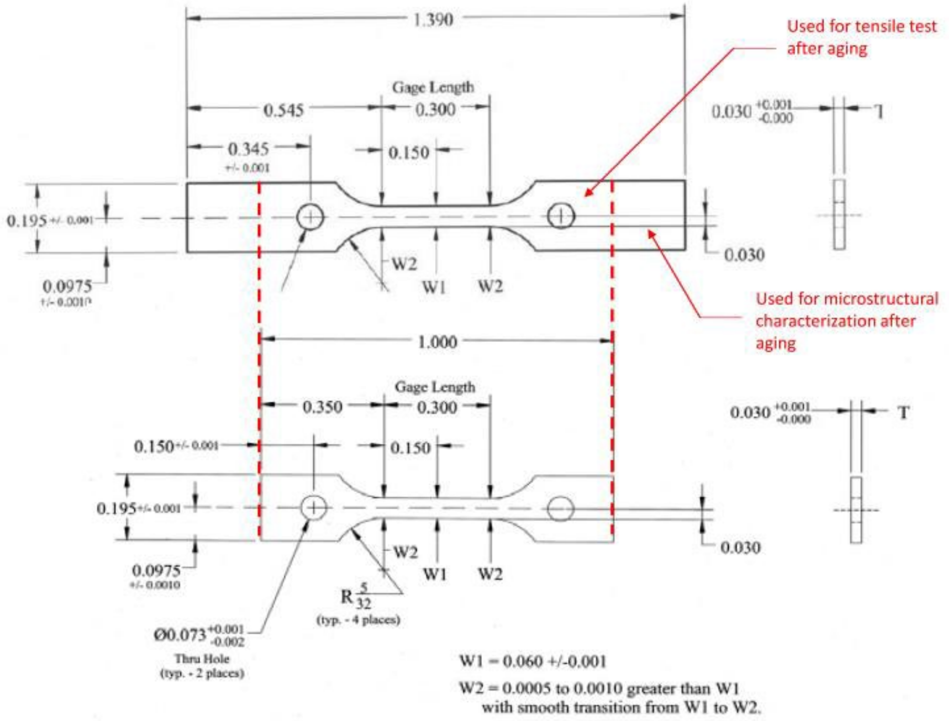
- **Nonmetallic element transfer**: **Carbon Transfer**
  - Carbon can migrate in material-sodium systems as a result of differences in chemical activity.
    - Carbon activity increases with increasing temperature
      - In mono-metallic sodium systems, the material in the high temperature region decarburizes, and carburizes in the low temperature region.
    - Ferritic steel has a higher carbon activity than austenitic stainless steel.
      - In bimetallic sodium systems, e.g. constructed of both austenitic and ferritic steels, ferritic steels tend to decarburize, and austenitic steels tend to carburize
  - Carbon is a key element that determines mechanical properties of steels.
    - Carburization/decarburization results in microstructural instability and mechanical property degradation, which ultimately affect the lifetime of reactor components

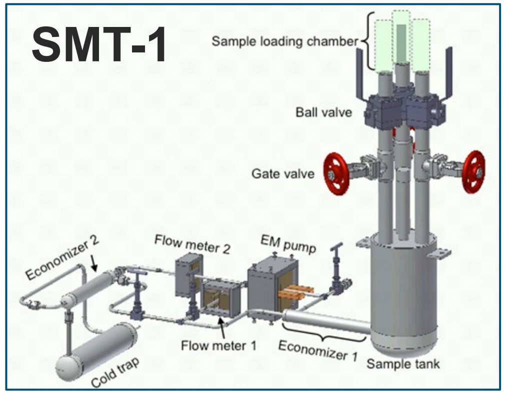


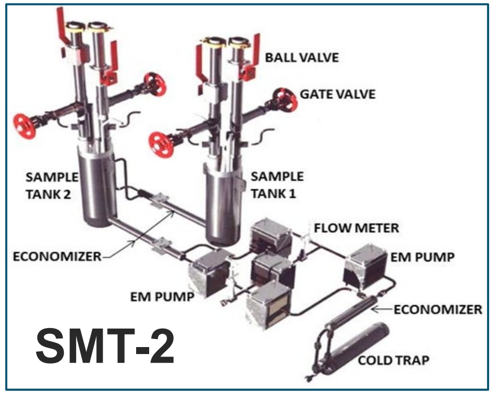
Snyder, Natesan, Kassner, International conference on liquid metal technology in energy production, Champion, PA, USA, 3 May 1976,

Materials and Na Exposure Tests – G91

Heat ID.	Fe	C	Cr	Mn	Mo	N	Nb	Si	V	W	Heat treatment
G91-H1	Bal	0.09	8.3	0.46	1.04	0.06	0.05	0.41	0.22	-	Normalized @ 1050°C for 1 hr, air cooled, tempered @ 760°C for 1 hr, air cooled
H30176	Bal	0.08	8.6	0.37	0.89	0.06	0.07	0.11	0.21	<0.01	Normalized @ 1050°C for 1 hr, air cooled, tempered @ 760°C for 2 hr, air cooled.





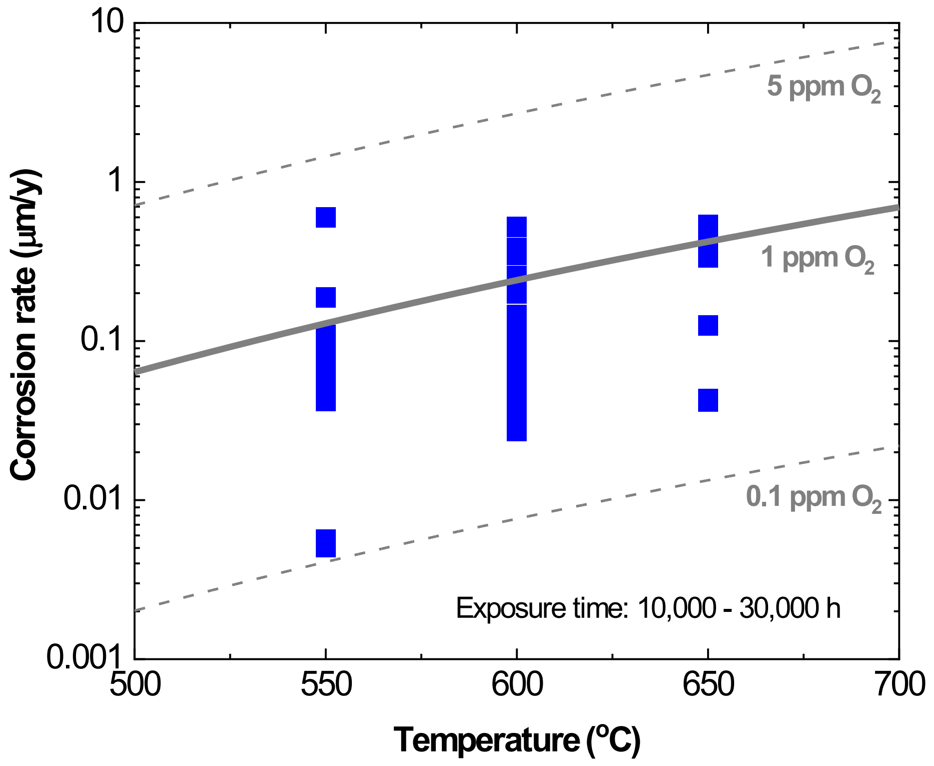


Parallel thermal aging experiments were performed for comparison.

ANL-ART-258

Corrosion Rates in Liquid Sodium

- Corrosion rates of G91 steel depend on temperature, oxygen content in Na, and sodium velocity.



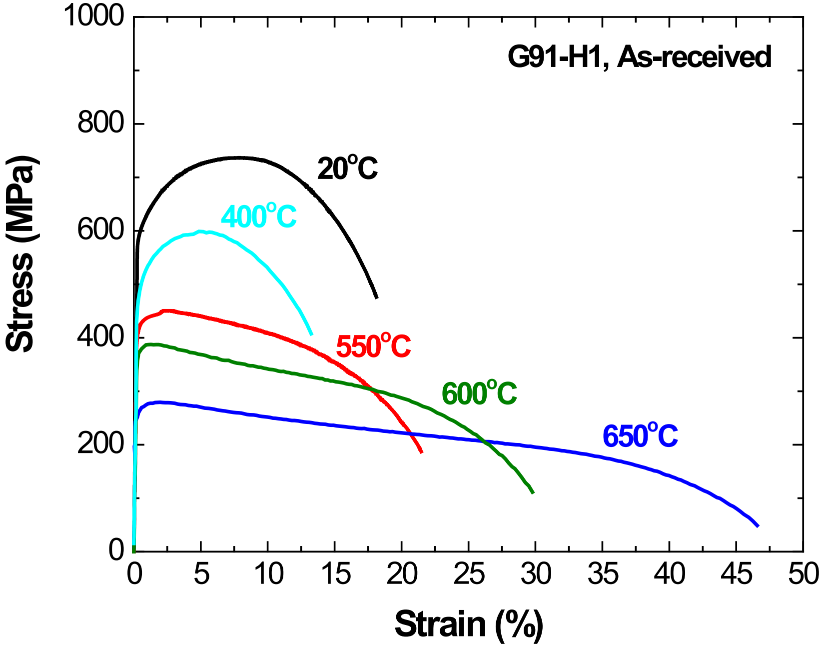
$$log_{10}R = 0.85 + 1.5log_{10}C_0 - \frac{3900}{T+273}$$

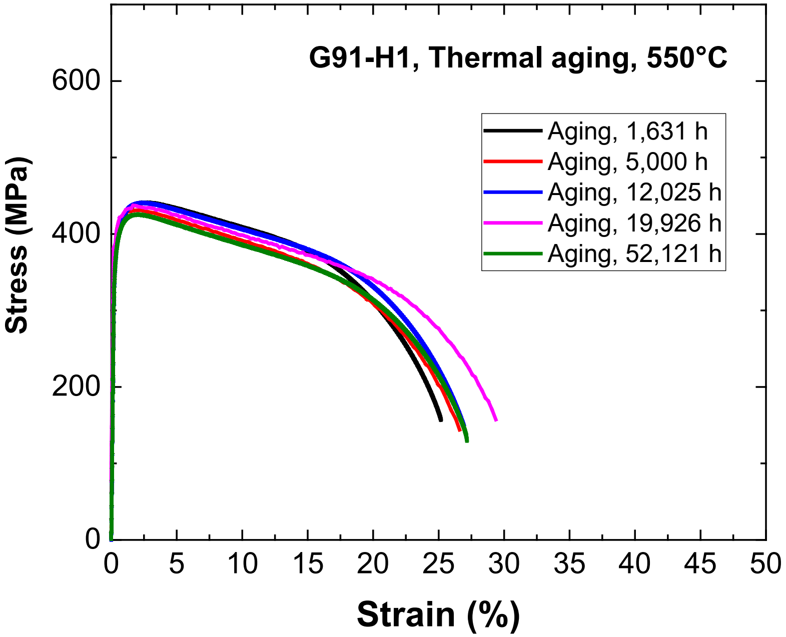
- The corrosion rate of G91 decreased with increasing exposure time and reached a steady state after ~10,000 h
- The calculated corrosion rates (lines) at three different O concentrations in Na using Monju corrosion formula.

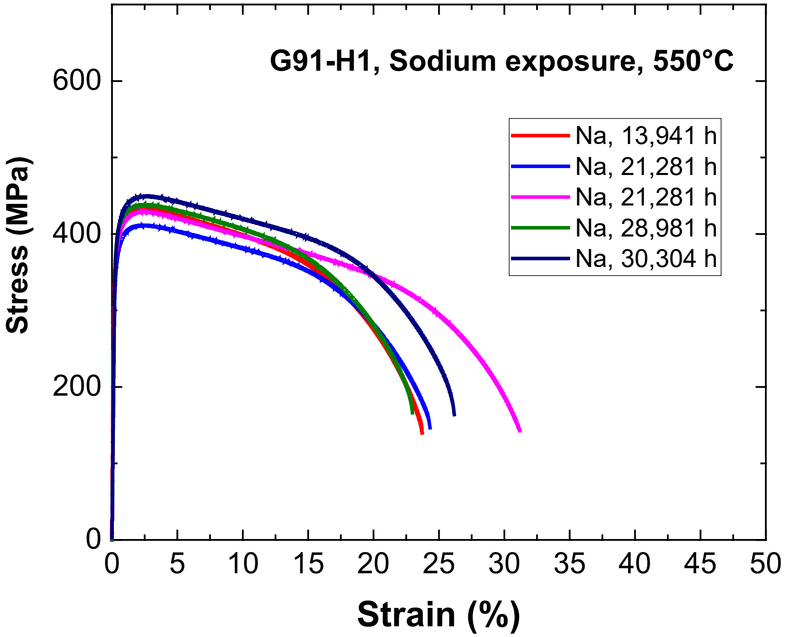
Average corrosion rate (μm/y)

	550°C	600°C	650°C
G91	0.1	0.2	0.3

Stress-strain curves G91



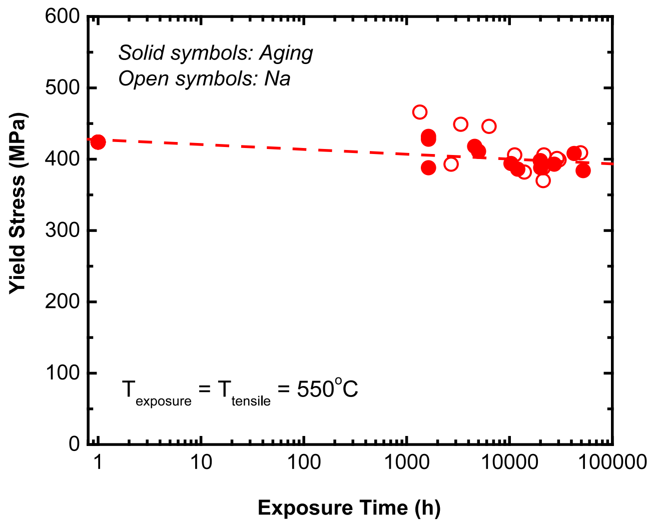


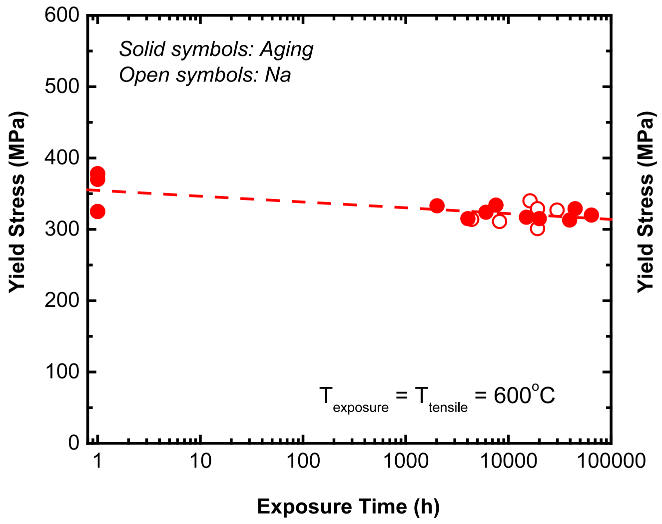


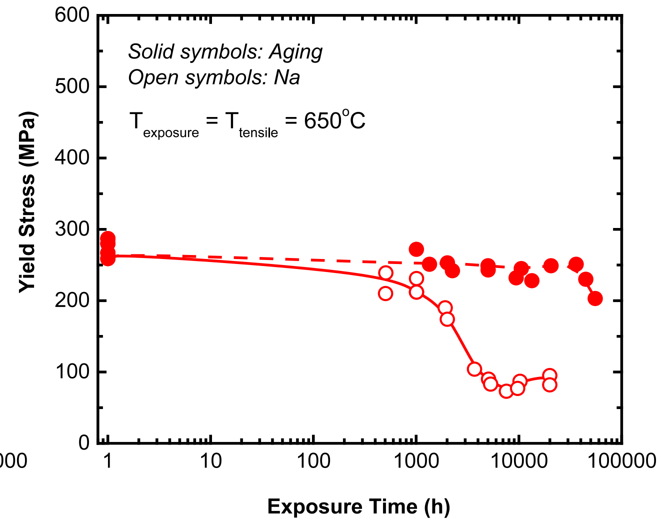
ANL-ART-258

Effect of Na Exposure

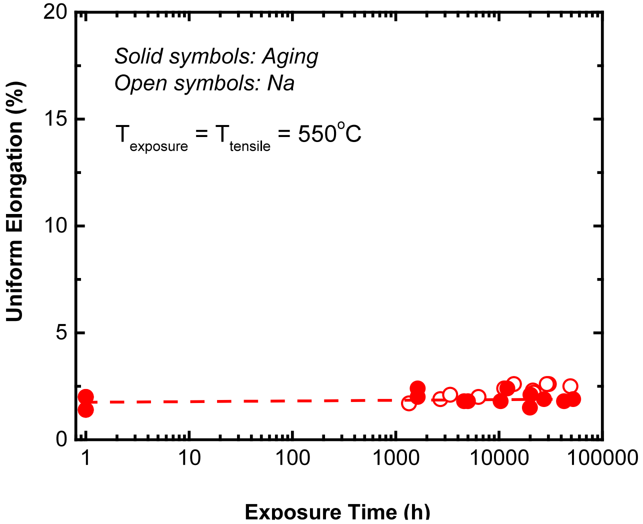
Yield stress

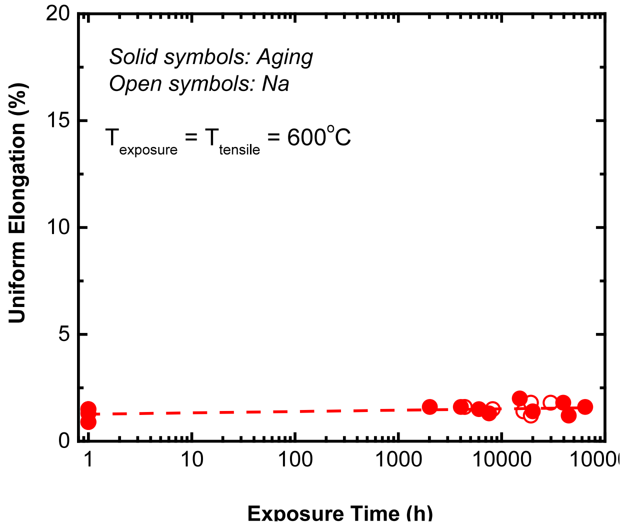


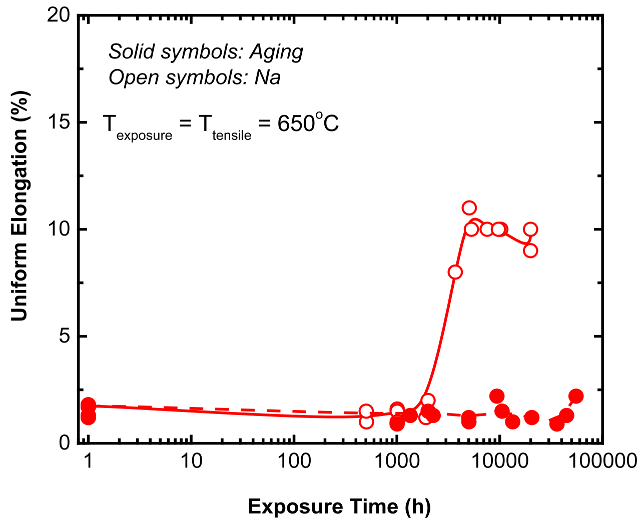




Uniform elongation





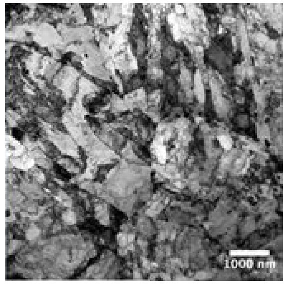


ANL-ART-258

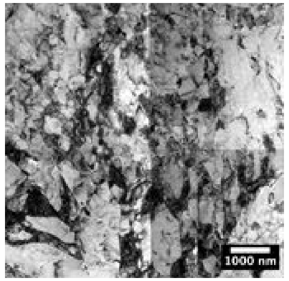
Microstructural Evolution with Sodium Exposure

Subgrain

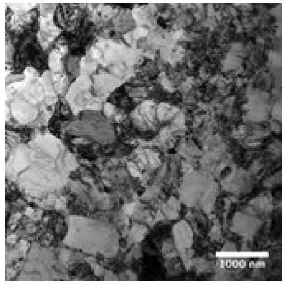
- Subgrains coarsened during Na exposures at 550 - 600°C
- Excess grain growth occurred during Na exposure at 650°C



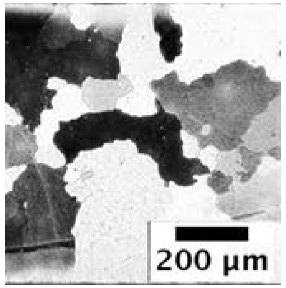
G91-H1, As-received



G91-H1, Na 550°C/19,926 h



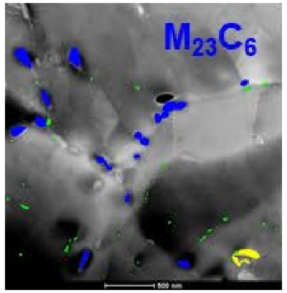
G91-H30176, Na 600°C/19,992 h



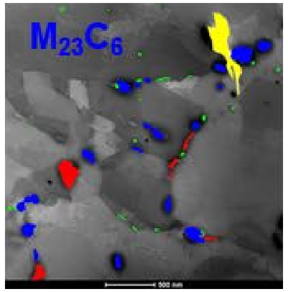
G91-H1, Na 650°C/20,531 h

$M_{23}C_6$

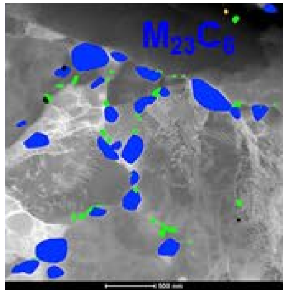
- $M_{23}C_6$ particles dissolved during Na exposures at 650°C



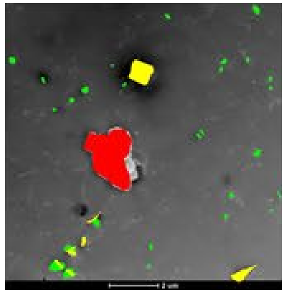
G91-H1, As-received



G91-H1, Na 550°C/19,926 h



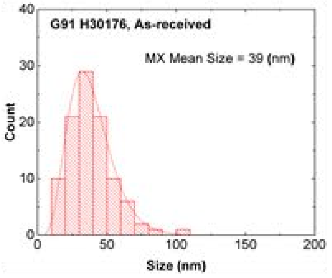
G91-H30176, Na 600°C/19,992 h

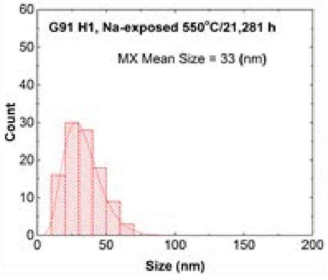


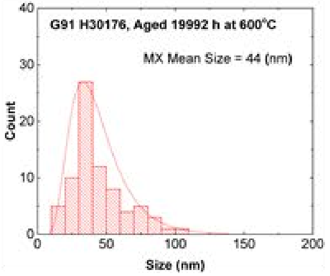
G91-H1, Na 650°C/20,531 h

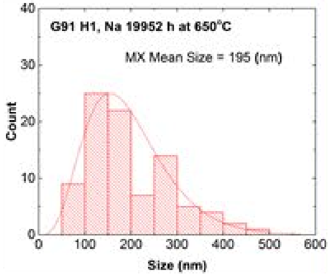
MX

- MX coarsening was insignificant during Na exposures at 550-600°C
- Significant MX coarsening occurred during Na exposures at 650°C.





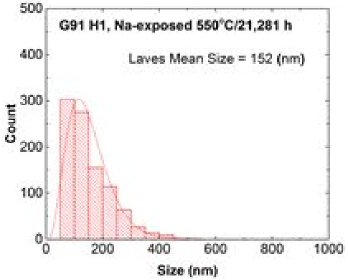


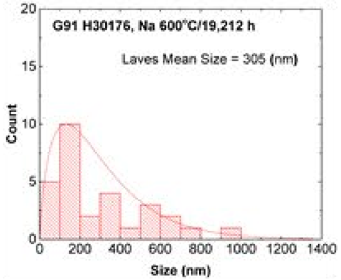


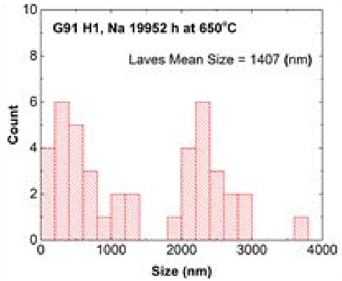
ANL-ART-258

Laves

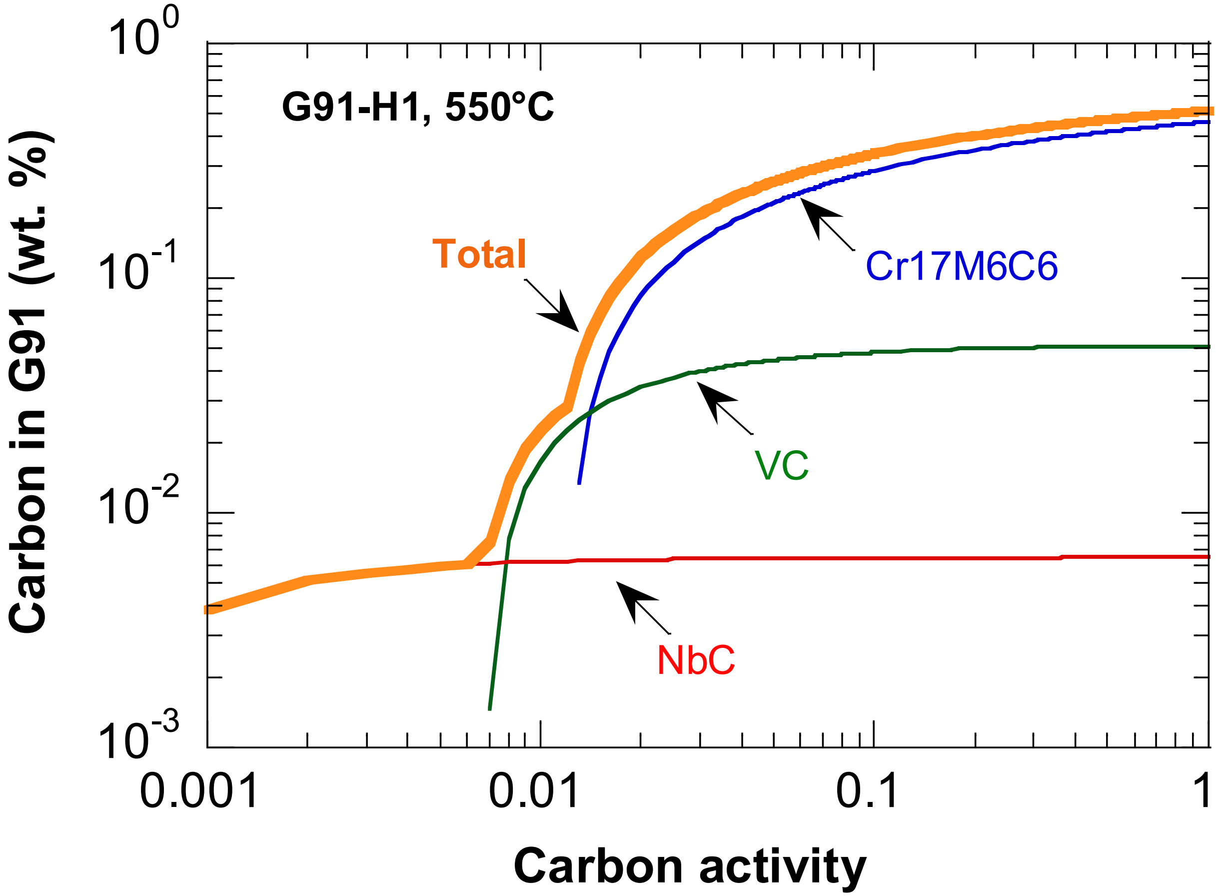
- Rapid growth of Laves phase precipitates was observed during Na exposures at 650°C.







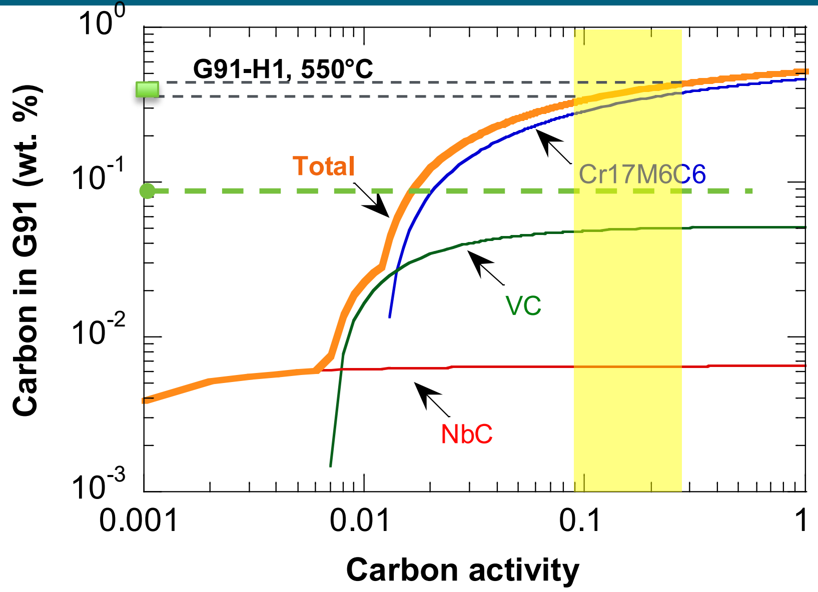
Effects of Different Carbides

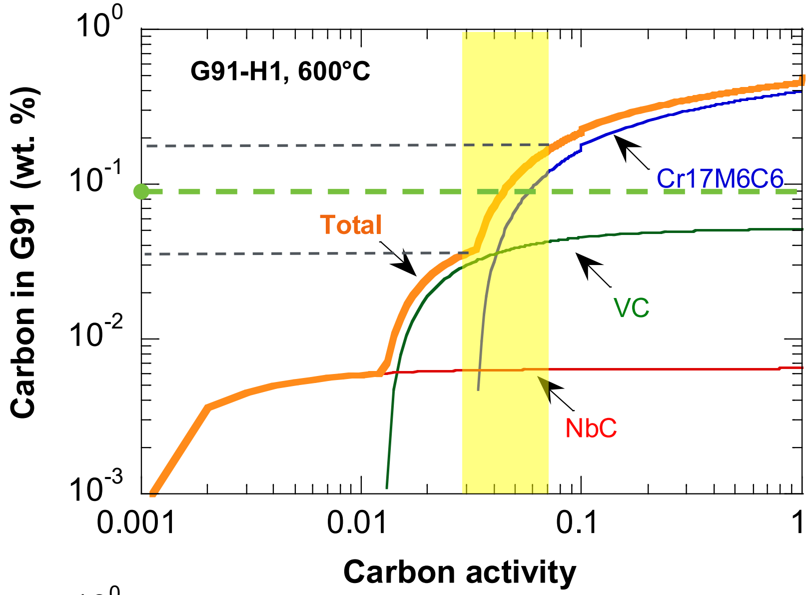


Carburization or Decarburization in Sodium Loops

C=0.09wt%

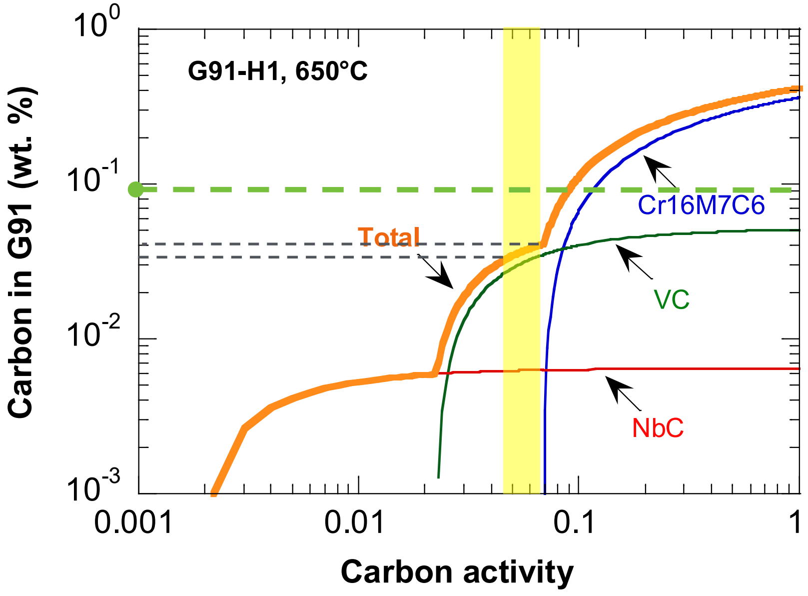
Carburization

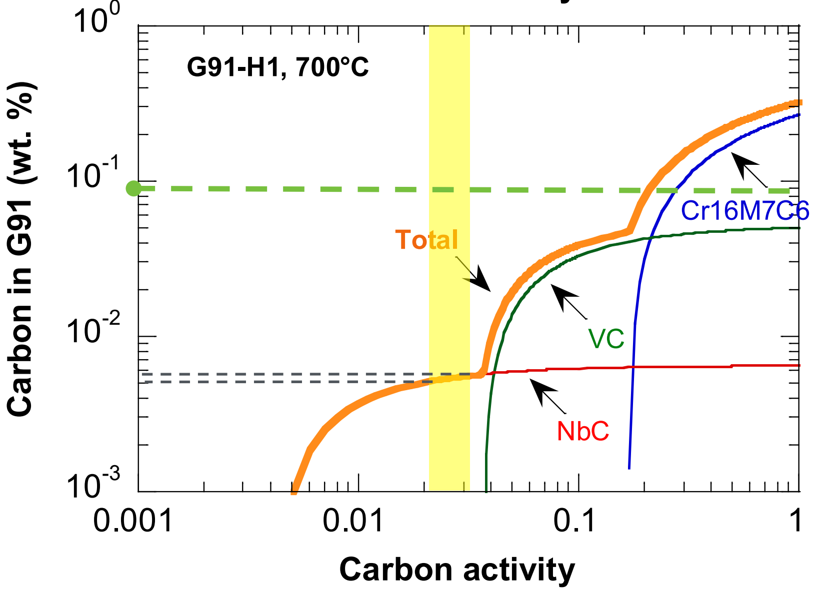




?

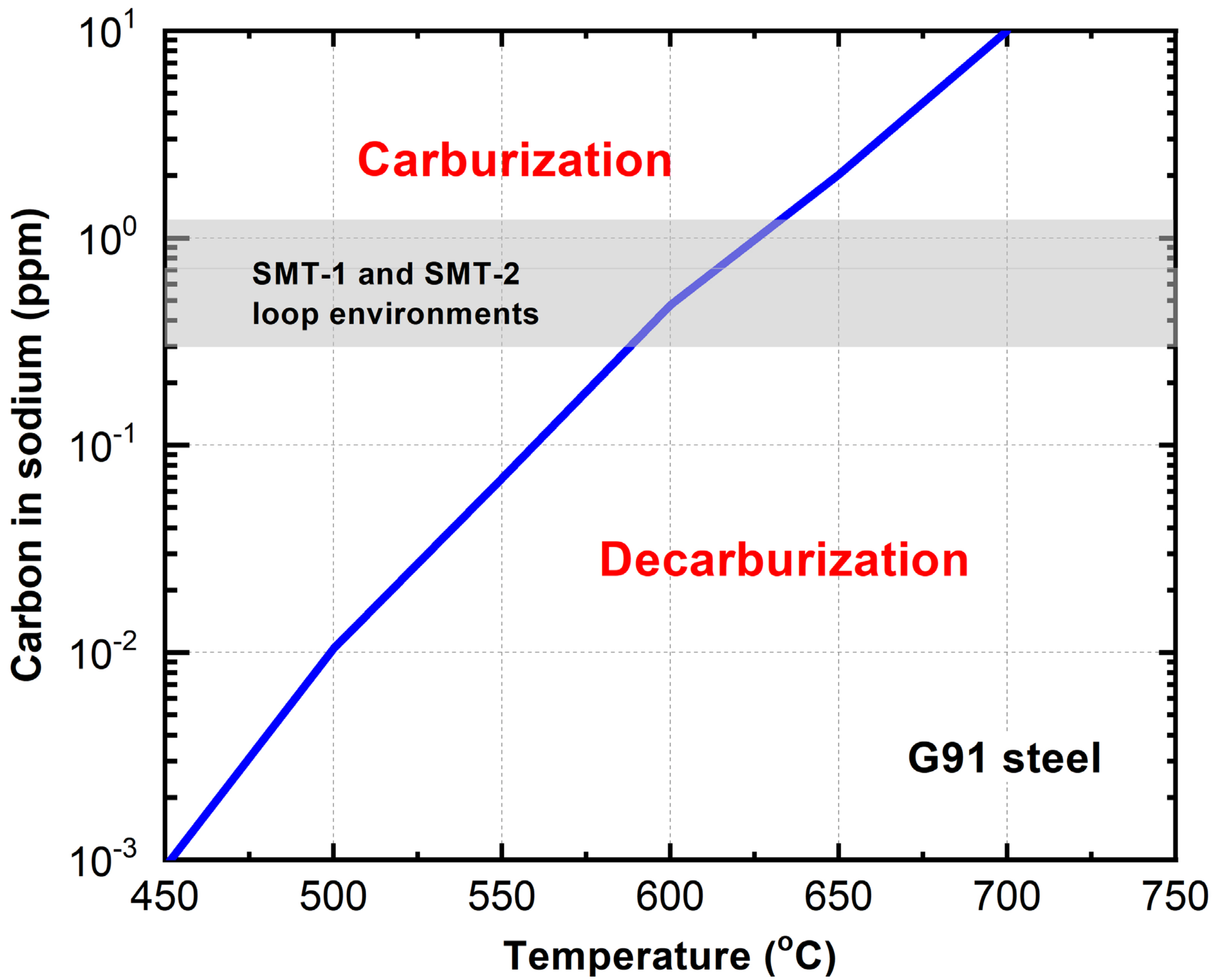
Decarburization





Decarburization

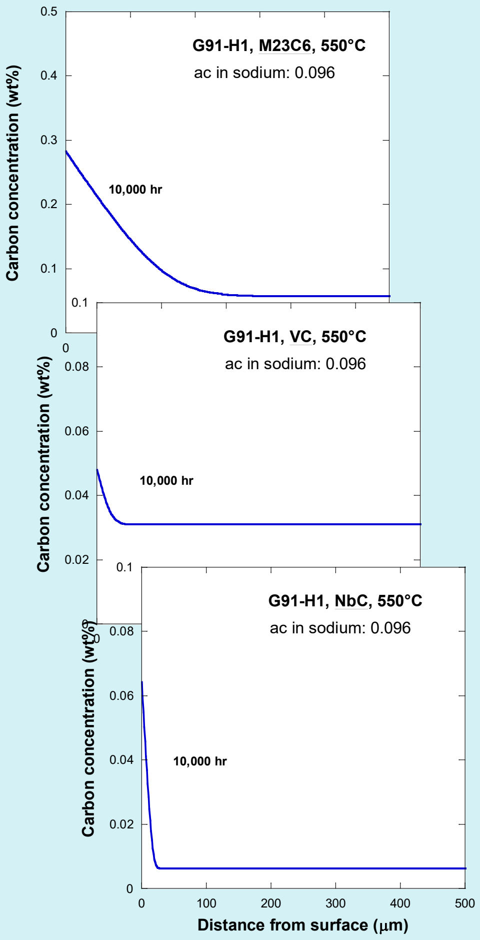
Carburization/Decarburization boundary



ANL-ART-258

Carbon Concentration Profiles

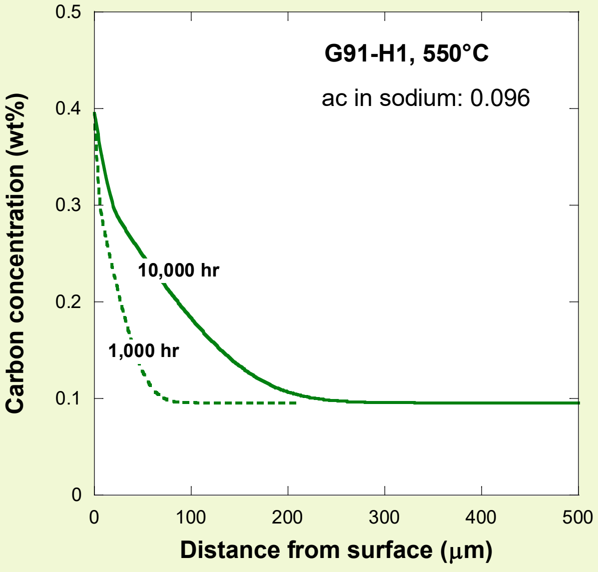
C profiles with different carbides

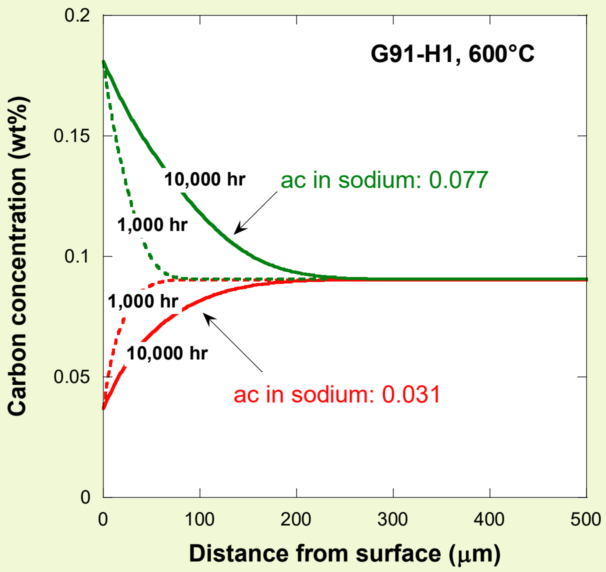


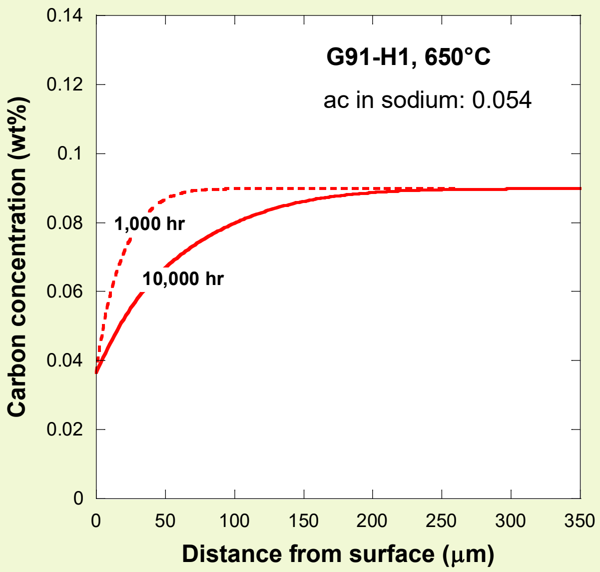
Carburization

Carburization/Decarburization

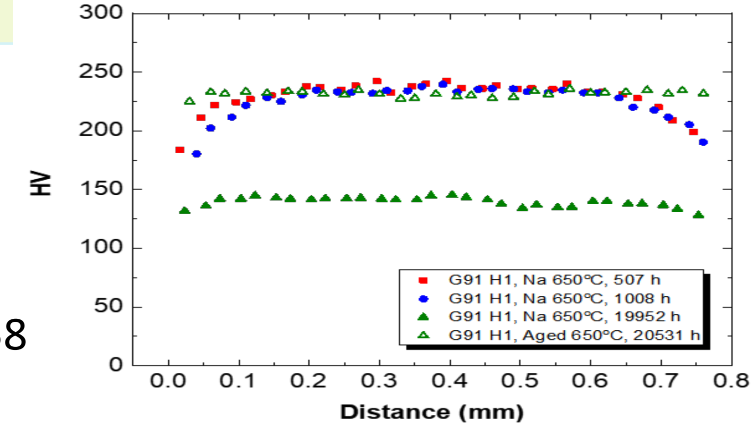
Decarburization







ANL-ART-258



Summary

- Yield strength and UTS were reduced significantly after sodium exposure at 650°C due to decarburization. The effect of sodium exposure at 550°C and 600°C was insignificant.
- The microstructural evolution resulting from sodium exposure is consistent with the tensile responses.

  (1) dissolution of $M_{23}C_6$ carbides, (2) excessive grain growth, (3) MX coarsening, and (4) Laves phase formation.

- Thermodynamic analysis shows that G91 carbonizes at 550°C and decarbonizes at 650°C in our sodium loops.
- NbC and VC play an important role in stabilizing the alloy's microstructure in low-carbon-activity environments, critical to the decarburization resistance of G91 in sodium environment.

Acknowledgments:
Yoichi Momozaki, David Rink and Joe Listwan are acknowledged for their contributions to the experimental work.
The work is support by the U.S. Department of Energy, Office of Nuclear Energy, Office of Nuclear and Reactor Technologies, Advanced Reactor Technologies under contract DE-AC02-06CH11357.

Thank you

U.S. DEPARTMENT OF ENERGY | Office of NUCLEAR ENERGY