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Materials and Code Qualification Needs for Sodium-Cooled Fast Reactors

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Key Design Parameters for the SFR Concepts

Key Parameters	ANL Design	Industrial Teams		
		Energy Solutions	GE-Hitachi (PRISM)	INRA
Reactor Power	380 MWe	410 MWe	311 MWe	500 MWe
Reactor type	Pool	Pool	Pool	Two-loop
Fuel	Metal; Backup: Oxide	Metal; Backup: MOX	Metal	Oxide
Cladding material	HT-9	HT-9	HT-9	ODS ferritic steel
Coolant	Sodium	Sodium	Sodium	Sodium
Coolant Outlet/Inlet	510/355°C	550/395°C	499/360°C	?
Reactor Vessel Size	5.8 m dia, 14.8 m H	10.5 m ID, 20.5 m H	5.74 m dia, 16.9 m H	?
Reactor Vessel Material	Austenitic SS	?	316 SS	?
Structural/Piping Material	Austenitic stainless steel	?	316 SS	?
IHX Design	Tube-Shell	No IHX	Tube-Shell	?
IHX Material	?		304 SS	?
Piping material	?	?	2.25Cr-1Mo	High- Cr steel
Steam Generator Design	?	Double wall, straight/helical	Helical coil	Straight double wall
Steam Generator Material	?	?	2.25Cr-1Mo	High-Cr steel
Primary Pump	4 EM pumps; Backup: mechanical (centrifugal)	4 EM pumps	Two EM pumps	?
Power Conversion Cycle	Rankine steam cycle Backup: CO_2 Brayton cycle	Rankine steam cycle	Rankine steam cycle	?
Plant life	30 yr with expectation of 60-yr extension	60 yr	60 yr	60 y

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Past Experience of Structural Alloys in SFRs

Country	Reactor	Vessel	IHX	Steam Generator	
				Evaporator	Superheater
USA	Fermi	304	304	Fe-2.25Cr-1Mo	Fe-2.25Cr-1Mo
	EBR-II	304	304	Fe-2.25Cr-1Mo	Fe-2.25Cr-1Mo
	FFTF	304	316	[a]	[a]
	CRBR	304	304	Fe-2.25Cr-1Mo	Fe-2.25Cr-1Mo
UK	DFR	316	316	321	321
	PFR	321	321	Fe-2.25Cr-1Mo	316H
Russia	BOR-60	304	304	Fe-2.25Cr-1Mo	Fe-2.25Cr-1Mo
	BN-350	304	304	Fe-2.25Cr-1Mo	Fe-2.25Cr-1Mo
	BN-600	304	304	Fe-2.25Cr-1Mo	304
Germany	SNR-300	304	Fe-2.25Cr-1Mo-Nb	Fe-2.25Cr-1Mo-Nb	Fe-2.25Cr-1Mo-Nb
France	Rapsodie	316L	316	[a]	[a]
	Phenix	316L	316	Fe-2.25Cr-1Mo	321
	SuperPhenix	316	316	Alloy 800 tubes 304, 316L shell	[b]
Japan	Joyo	304	304	[a]	[a]
	Monju	304	304	Fe-2.25Cr-1Mo	304

[a]sodium to air heat exchanger; [b]evaporator and superheater are combined in a single unit.

ASME Boiler & Pressure Vessel Code - Subsection NH

- *For the sodium-cooled fast reactor, the elevated-temperature components need to be designed to meet the limits of the ASME B&PV Code, Section III, Subsection NH.*
- *The Code gives a guidance on methodology and property needs for existing materials and for advanced materials*
- *NH applies to ferritic steels at T >700°F and for austenitic steels at T >800°F.*
- *NH is based primarily on design by analysis to establish time-dependent response of complex structures.*
- *Failure is assessed by: identifying possible failure modes*
determining the damage criterion for each failure mode
establishing design rules to set limits to prevent failure
- *NH is currently applicable for a design life of 300,000 h (34 years). An extrapolation to 60 years may need additional data/analysis, especially on environmental effects.*

ASME NH Alloys and Allowables

Material	Temperature (°C)	
	Primary stress limits[a]	Fatigue
304	816	704
316	816	704
2.25Cr-1Mo	593[b]	593
Mod.9Cr-1Mo	649	538
800H	760	760

[a]Allowable stresses extend to 300,000 h (34 years).

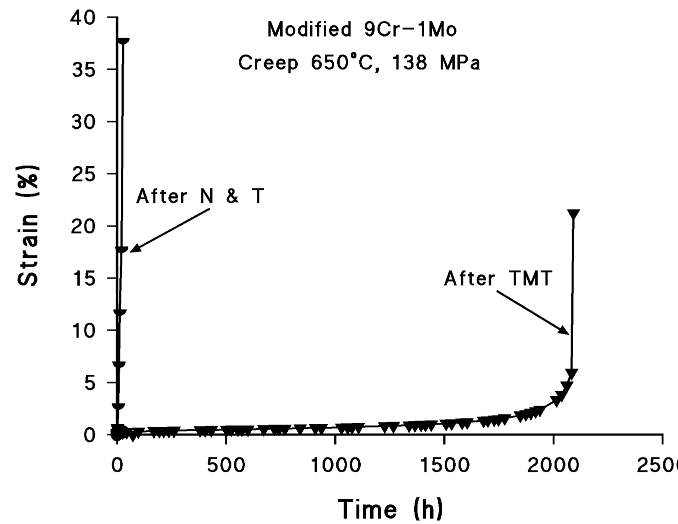
[b]Temperatures up to 649°C allowed for no more than 1,000 h.

Development of Advanced Structural Alloys for SFRs

- **Four advanced alloys were selected:**
  - ***NF616***
  - ***NF616 + TMT***
  - ***HT-UPS***
  - ***NF-709***

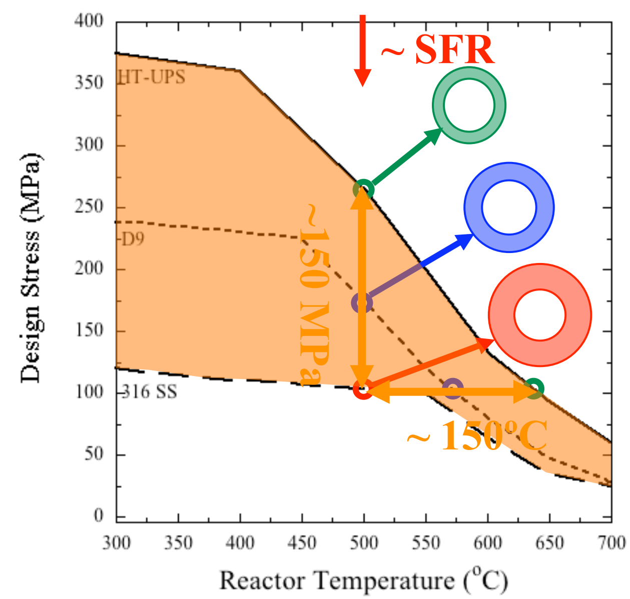
  NF616 and NF616 + TMT: **Advanced F/M**

  HT-UPS and NF-709: **Advanced Austenitics**



Klueh

- **New alloys offer significant improvements in strength and creep resistance over conventional alloys and yet maintain other critical properties at the same level.**



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Code Qualification and Licensing Issues identified for SFRs

- *Materials property database for 60 year life—modeling and simulation*
- *Reliable creep-fatigue design rules*
- *Hold-time creep-fatigue data*
- *Mechanistically based creep-fatigue life predictive tools*

  Creep Fatigue

- *Inelastic design procedures for piping*
- *Methodology for analyzing Type IV cracking in 9Cr-1Mo weldment*
- *Weldment design methodology*

  Weldment

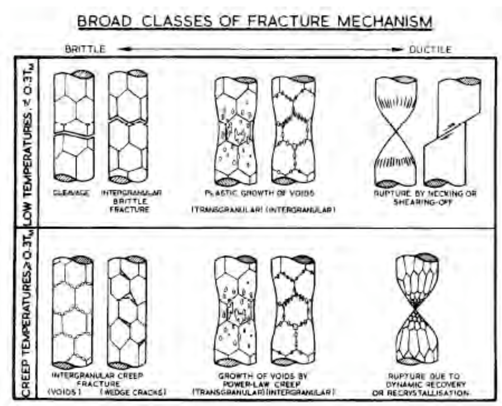
- *Understanding thermal striping of materials*
- *Material degradation under irradiation*
- *Materials degradation under thermal aging*
- *Materials degradation in sodium environment*

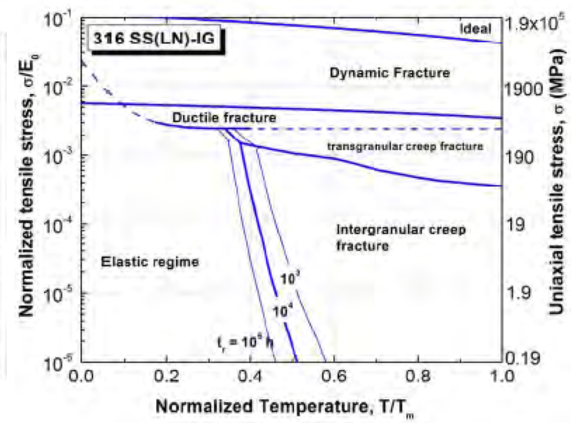
  Environmental Effects

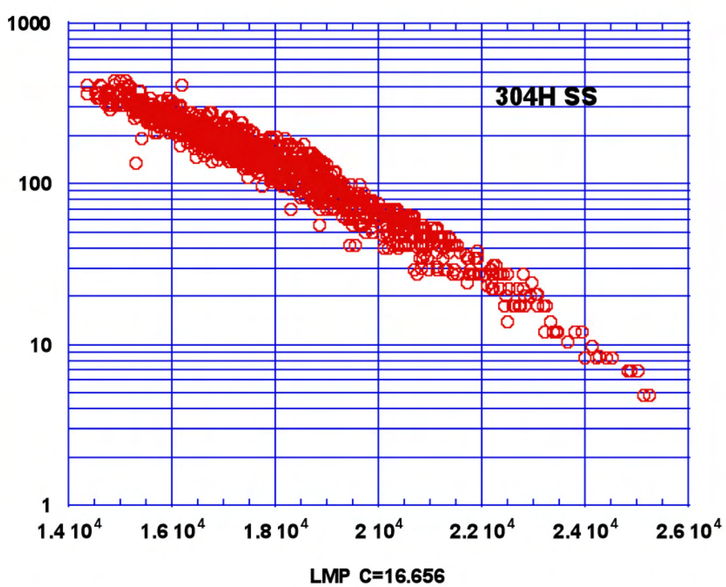
Mechanistic creep models for predicting creep rupture for 60-yr design life

- **Develop mechanism-based methodology for constructing creep fracture maps by micromechanical finite element analyses**

Fracture mechanism maps calculated by theoretical models capture various fracture modes observed at different temperature and stress regimes.







Empirical Larson-Miller plots

Creep-fatigue predictive models and design rules for the 60-year design life

- Most life-predictive methods useful for design application are empirical or semi-empirical

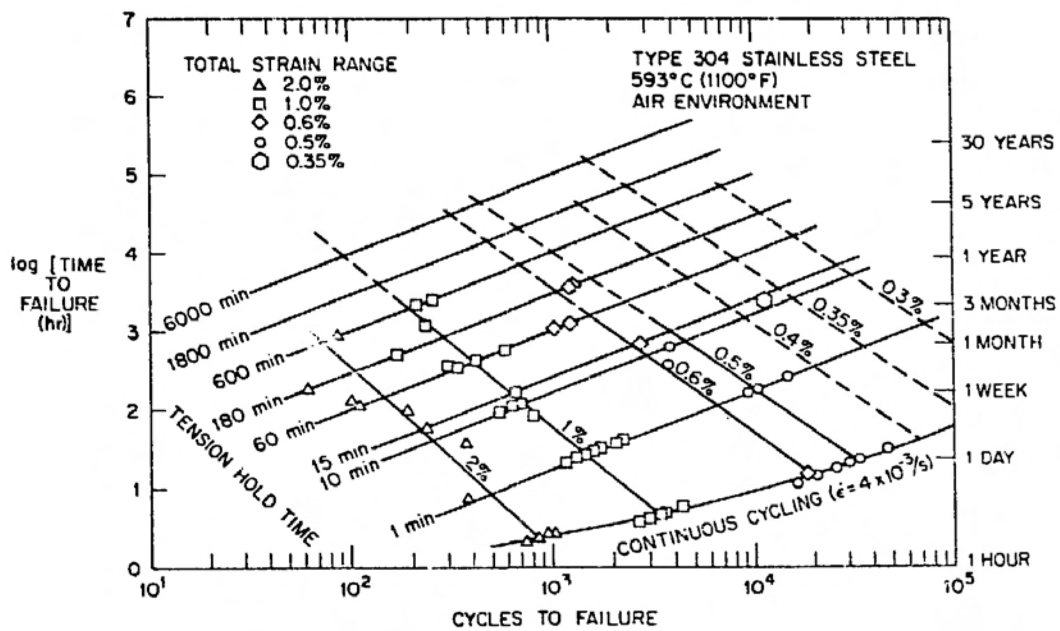
- The reliability of the life-prediction methods would be greatly enhanced if they were based on an understanding of the mechanisms underlying the damage processes.

- Mechanistic models are needed to justify/refine existing or new phenomenological approaches used in engineering designs, and ultimately replace phenomenological approaches

- A large database is needed on each material with effects of various factors including strain range, strain rate or frequency, waveform, hold time, temperature, environment, and metallurgical conditions.

Extrapolation of lab short-term hold time data to long-term hold time behavior under reactor conditions

- Reactors experience creep-fatigue loading with very long hold time periods
- Data extrapolation must rely on understanding of fundamental mechanisms for materials responses



The longest hold time in the experimental data was 10 hours

Reliable creep-fatigue design rule for ferritic steels (G91)

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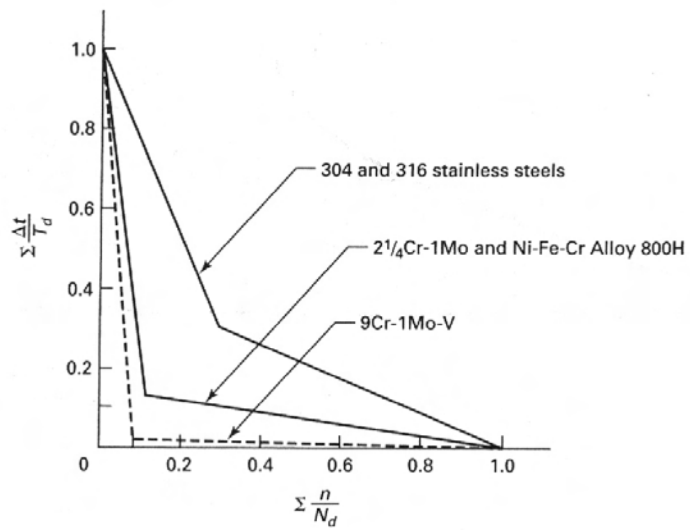
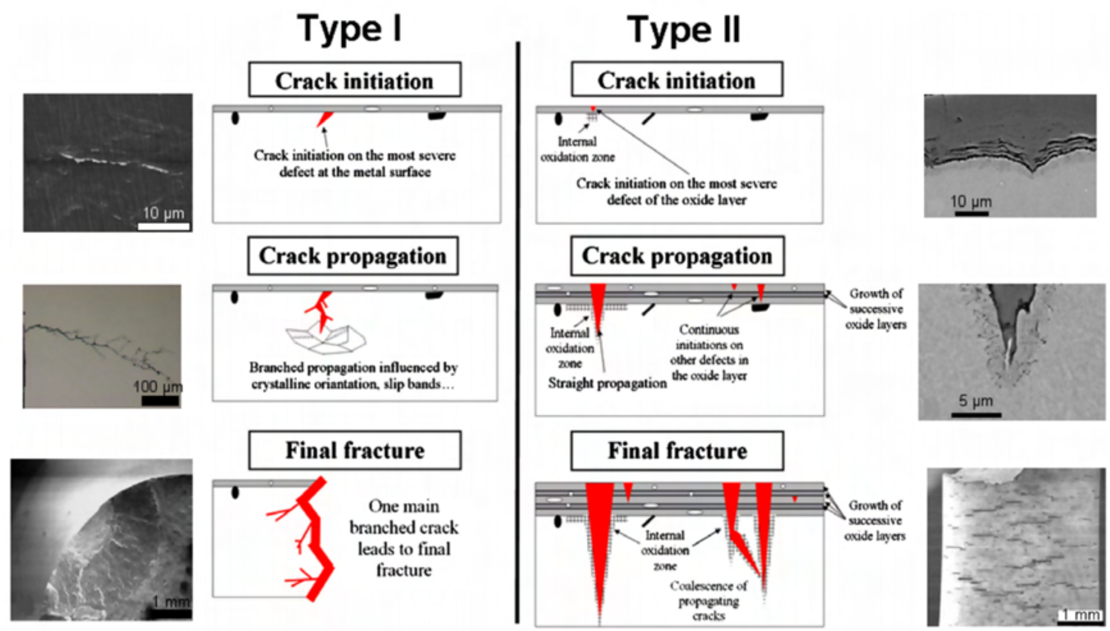
- **Improved creep-fatigue design rule for G91 needs to take into account of unique characteristics of creep-fatigue response, e.g. environmental effects, cyclic softening, strain rate dependence, thermal aging, etc.**

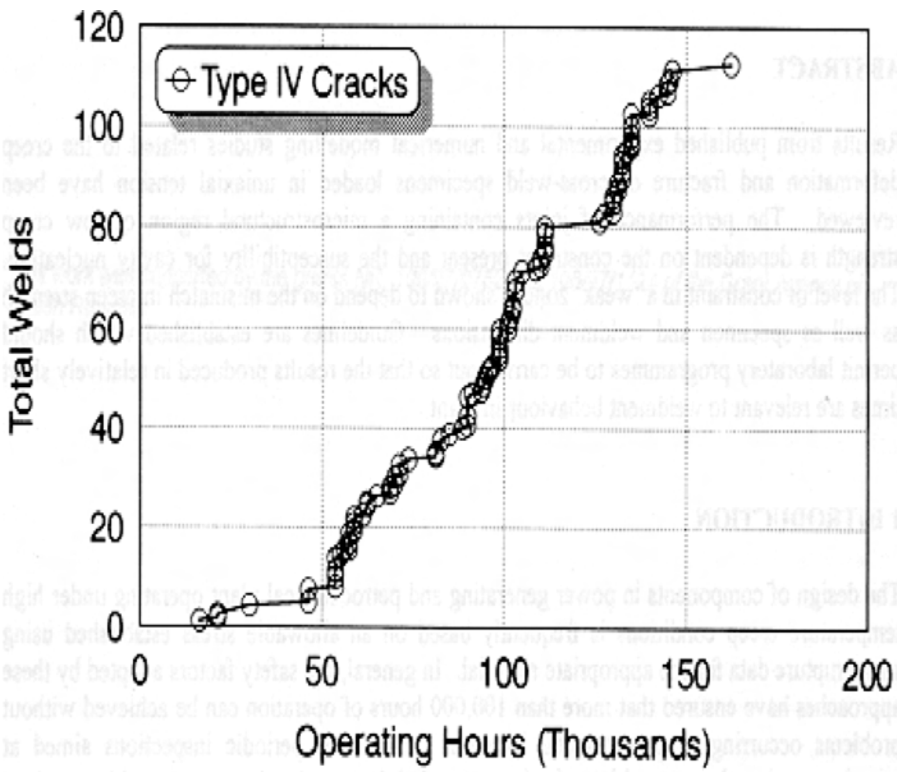




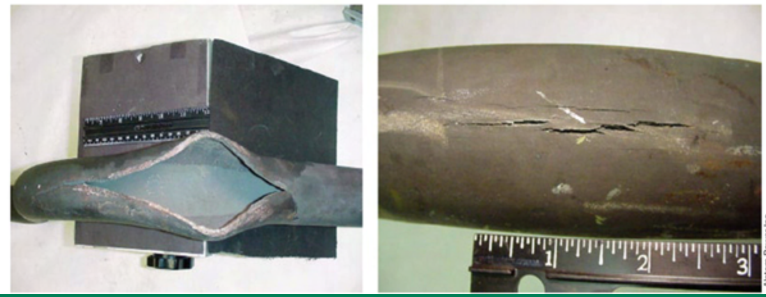
Cyclic softening and microstructural changes during creep-fatigue cycling have significant implications for high temperature structural design for ferritic steels (e.g. G91).

Type IV cracking - life-limiting factor for G91 weldments

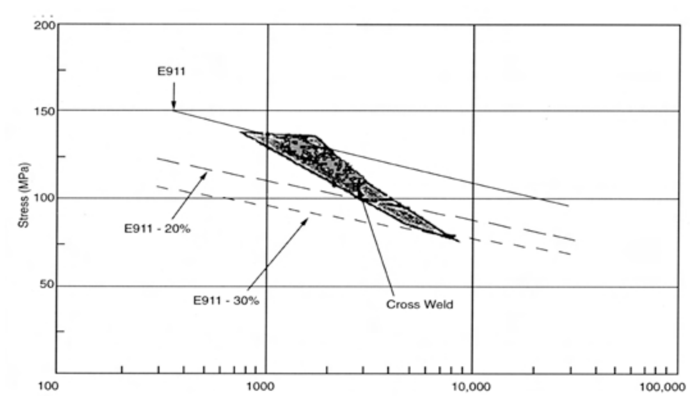
- **Type IV cracking occurs in the HAZ fine-grained region in G91.**



Type IV failures in ferritic steels [Ishibi 2002].

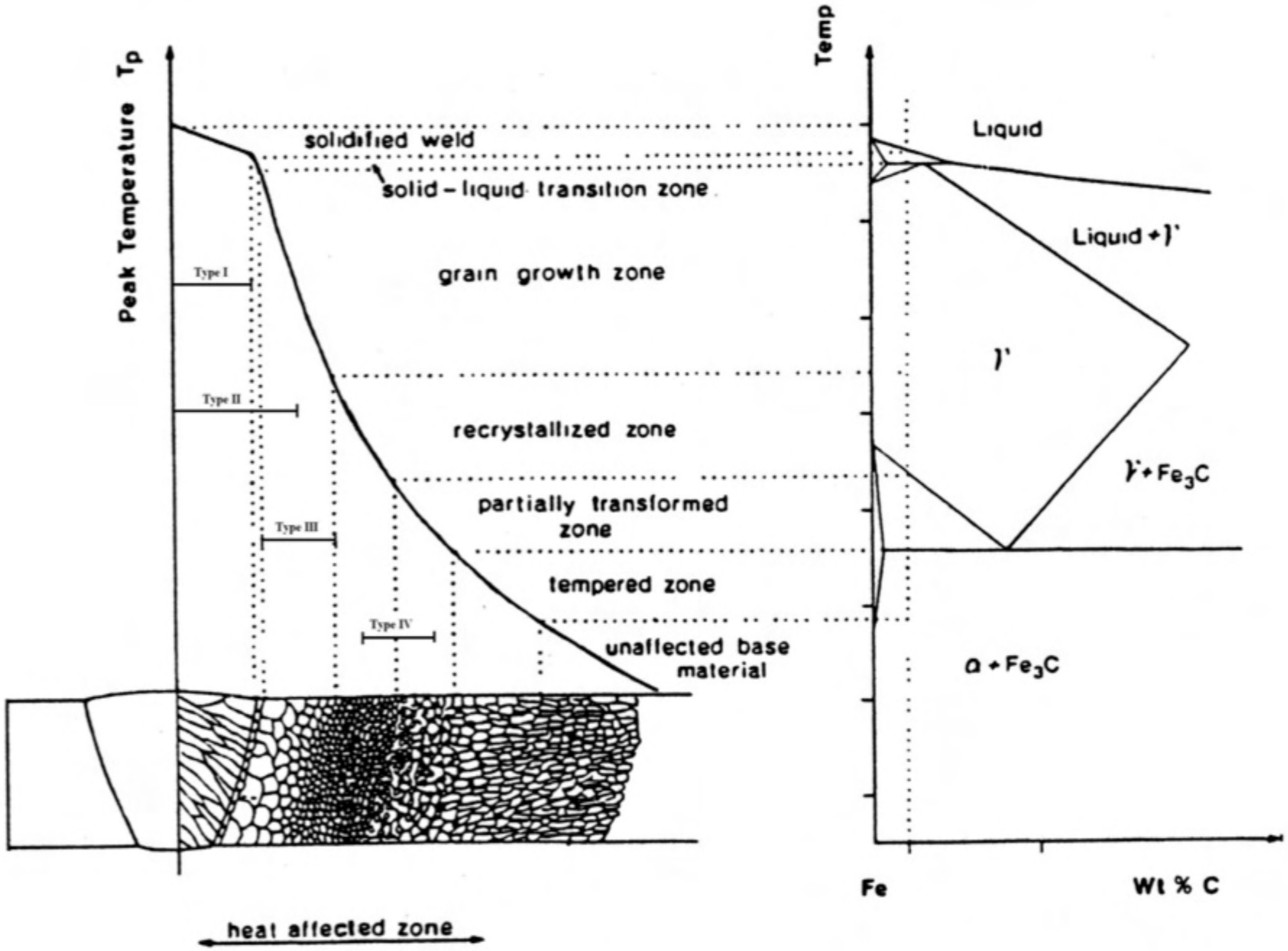


Failure of superheater tubes of T91 due to improper intercritical heat treatment. Tubes were in service for only four years [Henry 2005].



Significantly lower rupture strength of E911 cross-weld showing Type IV cracking [Orr 1998].

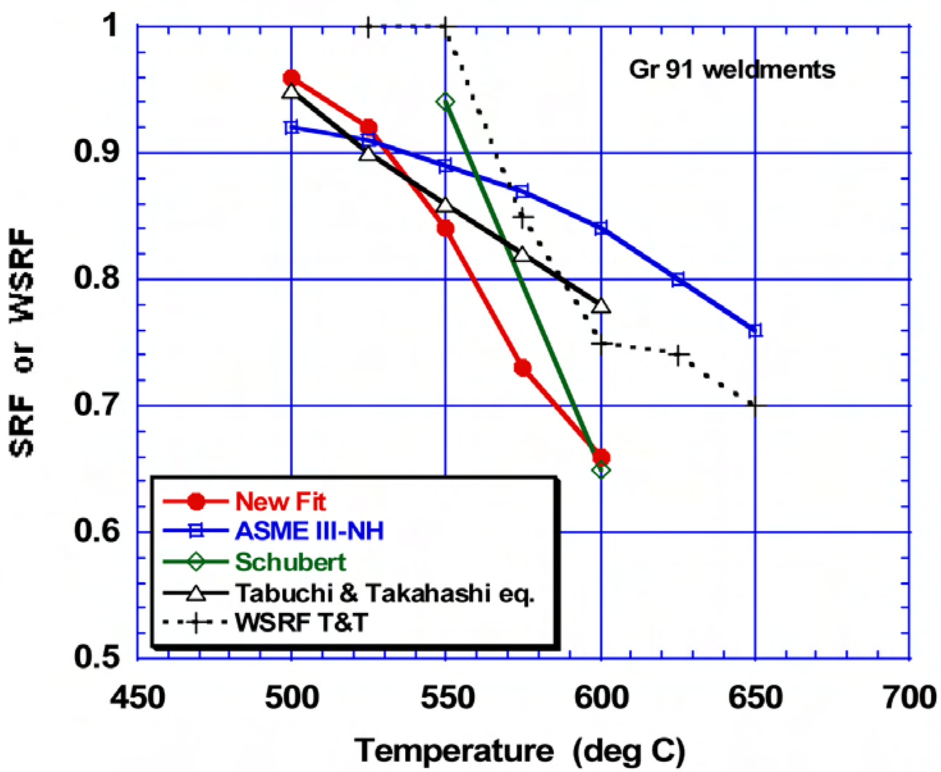
Type IV cracking - G91 weldments



Microstructure developed in HAZ. And Type IV cracking [Vlasak 1998].

Strength reduction factors for G91 weldments

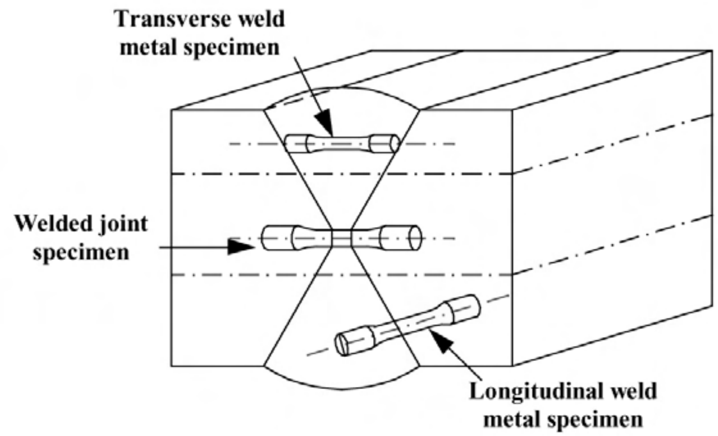
- Re-evaluation by Swinderman showed the SRFs for G91 weldments are lower than NH SRFs above 550°C



- Database insufficient to develop SRFs for long times (>100kh)

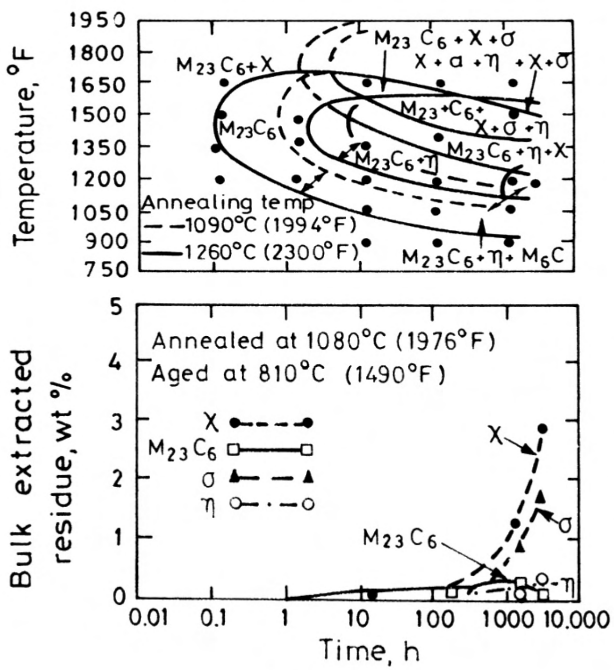
Creep-fatigue Design Rules for Weldments

- ASME NH creep-fatigue design rules were developed based on base metal properties
- Adequacy of NH creep-fatigue design rules for weldments needs to be verified with additional weldment creep-fatigue data
- Database of creep-fatigue for weldments is much less than for the base metal
- Type IV cracking in ferritic steels has not been addressed in the NH design rules and needs database for evaluation

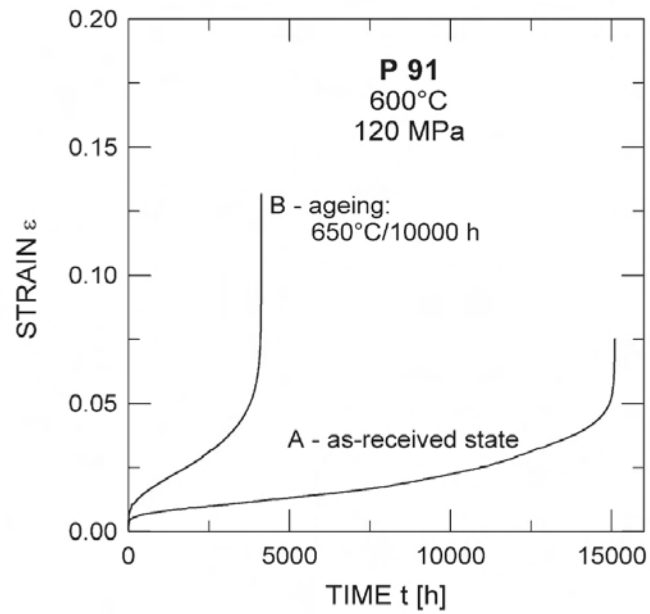


Long-term Thermal Aging Effects on Design Allowables

- ***Long-term exposure at SFR operating temperatures can result in microstructural changes and associated mechanical property degradation in NH materials and new advanced alloys***
- ***Aging data available for times up to ~100 kh; long-term data are needed***

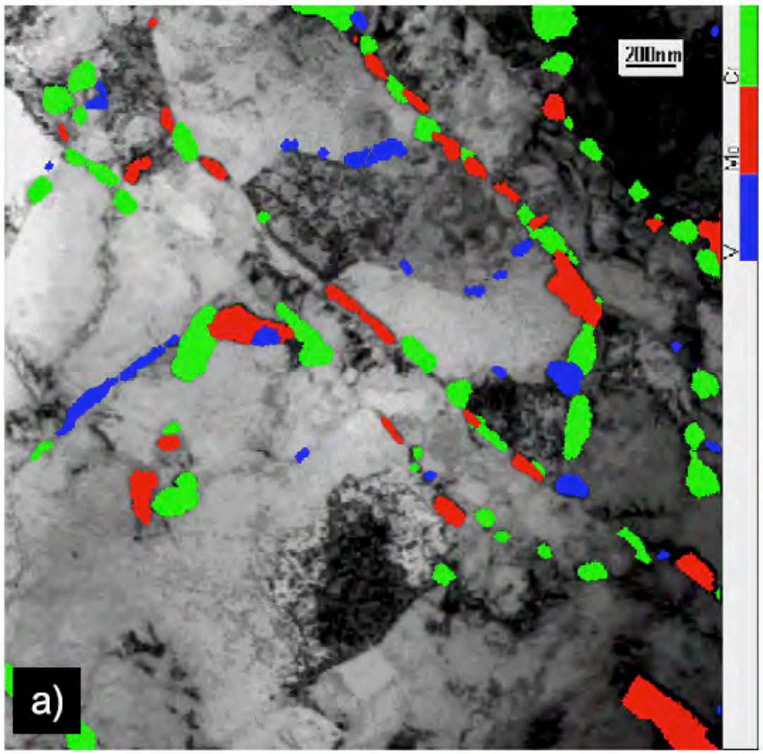


Annealed

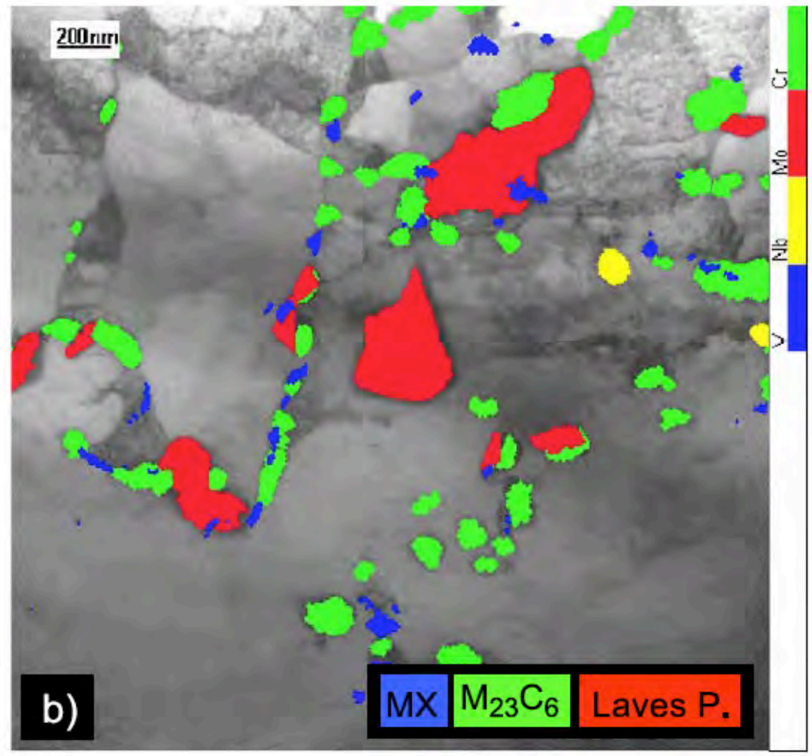


Thermal aging accelerated the creep rate and shortened the creep rupture life of G91

TEM Bright Field Images of NF616



996 h at 600°C



12,118 h at 600°C

MX: Carbonitrides (M: V, Nb, Cr; X= N, C)
Laves Phase: (Fe, Cr, Mo, W)

Hofer et al. 1998 and 1999

Materials degradation in sodium

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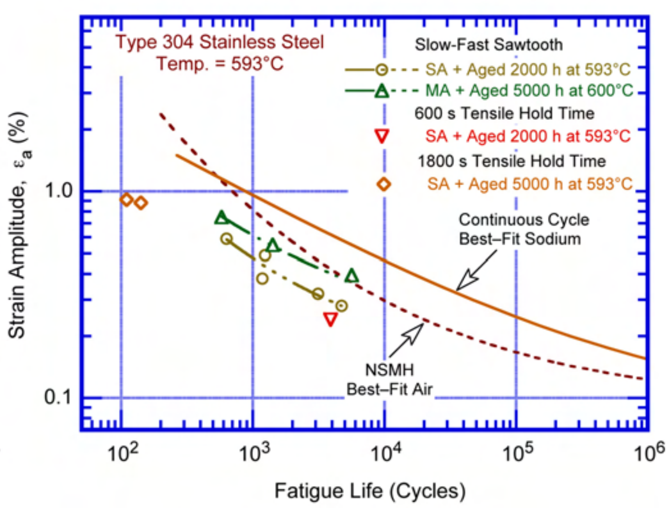
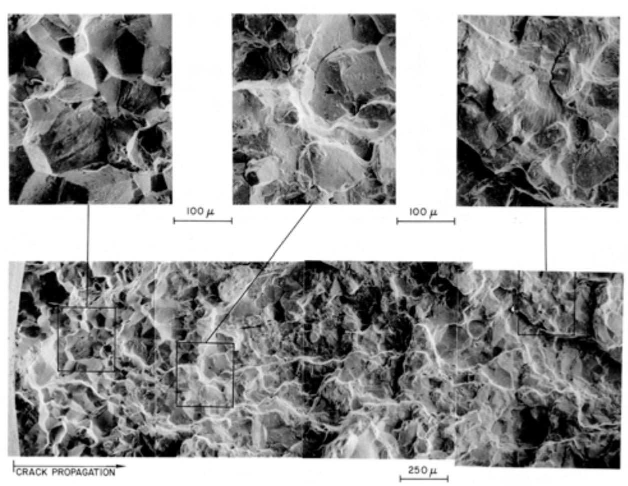
- Transfer of interstitial impurities, C, N, during long-term sodium exposure can affect its microstructure stability and mechanical performance
- Creep-fatigue damage in sodium is a significant concern
- Synergistic effect of thermal aging, sodium and neutron exposure is unknown
- Issues related to sodium effects are more complex and serious for thin-walled structures and weldments

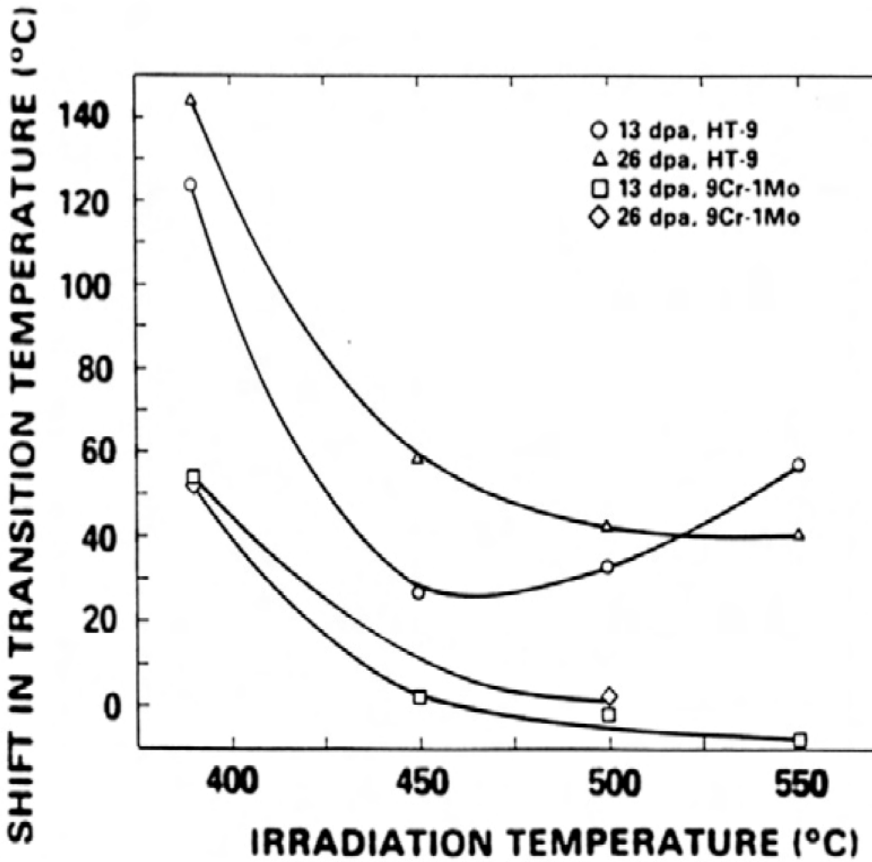




- ***Fatigue life is significantly decreased under creep-fatigue loading in sodium.***
- ***Intergranular cracking is evident.***

Materials degradation under irradiation

- **Insufficient information on effect of long-term irradiation on precipitate microstructure and mechanical properties at SFR-relevant temperatures. However, the structural materials may be subjected to ~10 dpa during lifetime. Effect on fracture toughness needs evaluation.**



High Priority R&D Needs

- ***Develop a mechanistic approach to the prediction of creep-fatigue lifetime and failure mode for reliable data extrapolation.***
- ***Develop creep-fatigue predictive models and design rules for the 60-year reactor lifetime and perform confirmatory tests to validate models.***
- ***Extrapolation of laboratory short-term hold time creep-fatigue data to long-term hold time behavior under actual reactor conditions.***
- ***Reliable creep-fatigue design rule for 9Cr-1Mo type alloys***
- ***Data needs on creep-fatigue of weldments. Perform creep-fatigue tests on mod. 9Cr-1Mo steel weldments with various welding parameters. Tests should include different test temperatures and hold times with emphasis on Type IV cracking.***
- ***Develop mechanisms-based finite element methodologies for predicting creep rupture for materials with 60-year design life.***
- ***Thermal aging effects on design allowables for the 60-year design life for base alloys and weldments. Develop mechanistic models to correlate microstructural changes with associated mechanical properties during long-term thermal aging. Perform confirmatory tests of aged and cyclic-softened materials to validate the models.***