Understanding Damage Mechanisms In Ferritic/Martensitic Steels

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There Are Several Reasons For Concern About Damage Mechanisms In Advanced Ferritic Steels

- They will be used extensively in fossil energy
- Their strength has a higher temperature dependence than "conventional" steels
- Their microstructures are relatively unstable
- Their long-time data bases are meager
- They are used for thick-section components where high integrity is required

This Talk Will Focus on 9Cr-1Mo-V Steel As Representative of the Advanced 9-2%Cr Steels

- **A summary of microstructural and property changes will be presented**

- **A summary of some emerging damage accumulation models will be provided**

Chemistry (Wt %)

Element	std Gr 9	Gr 91
C	0.15 max	0.08 - 0.12
Mn	0.30 - 0.60	0.30 - 0.60
P	0.30 max	0.020 max
S	0.030 max	0.010 max
Si	0.25 - 1.00	0.20 - 0.50
Cr	8.00 - 10.00	8.00 - 9.50
Mo	0.90 - 1.10	0.85 - 1.05

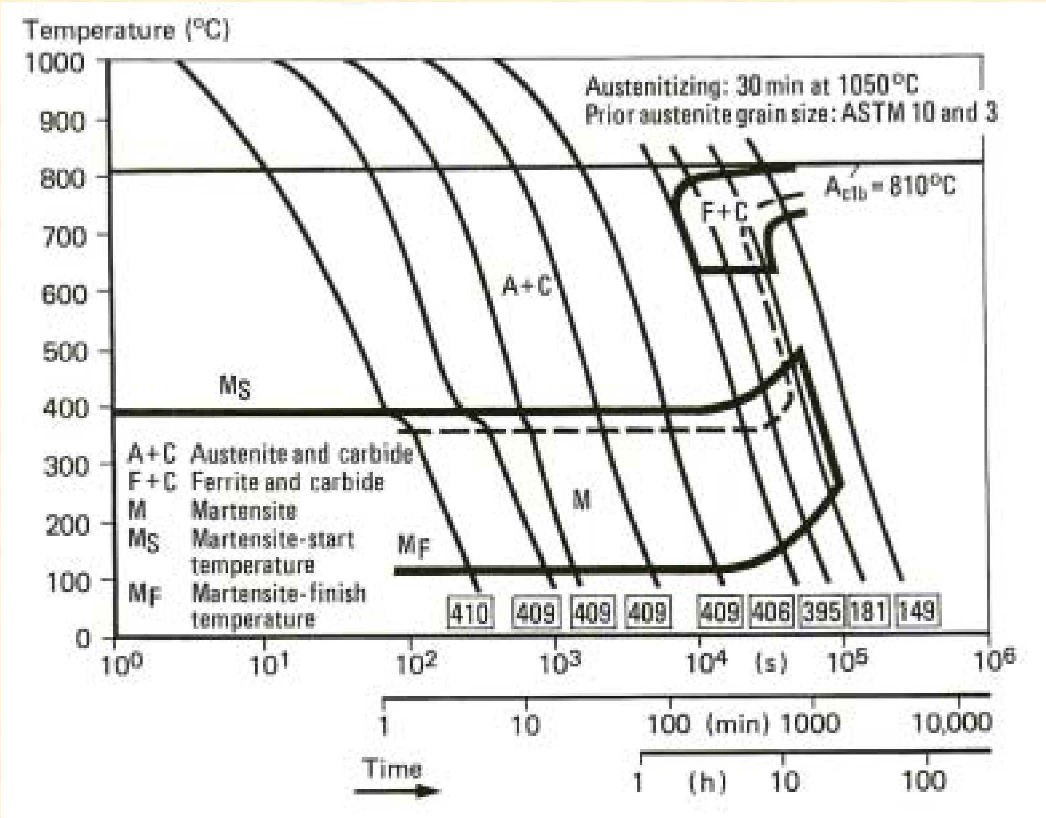
Plus Ni, V, Nb, N, and Al contents are specified for Gr 91

Gr 91 Chemistry Modifications

Element	Content (wt %)
Ni	0.40 max
V	0.18 - 0.25
Nb	0.06 - 0.10
N	0.030 - 0.070
Al	0.04 max

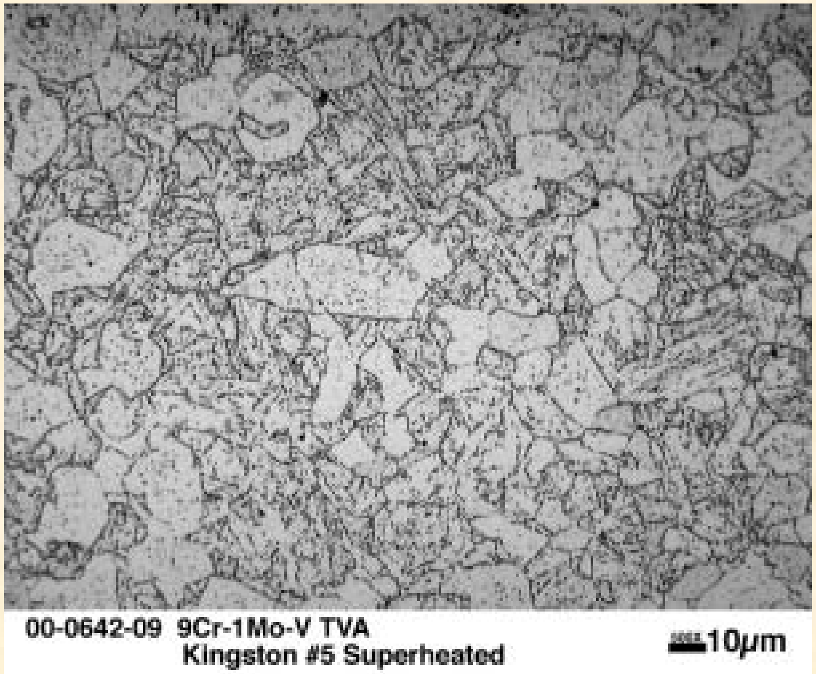
The Chromium-Nickel Balance is adjusted to produce only Martensite

Heat Treatment (CCT)

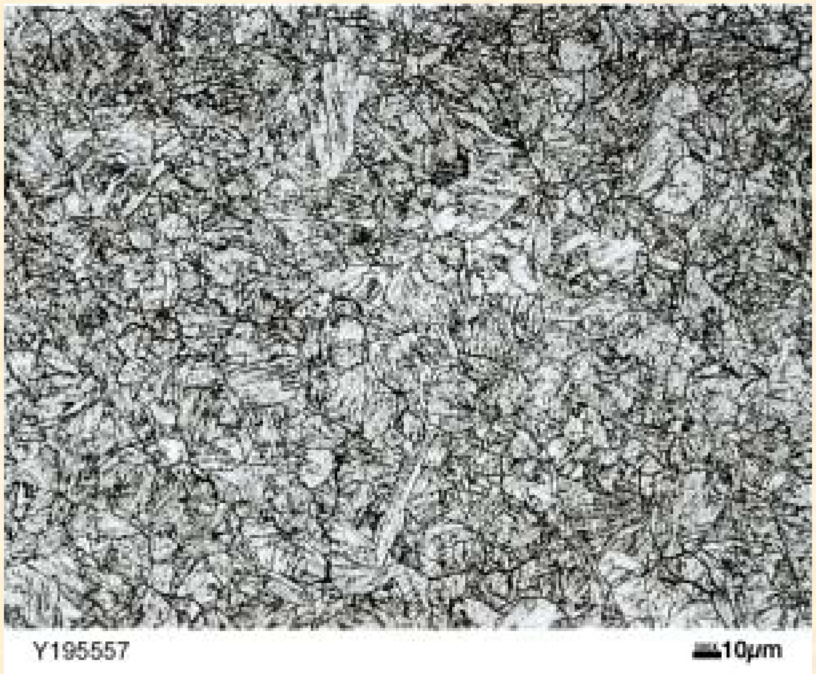


When cooled from 1040°C faster than 6 °C/minute Gr 91 has an Martensite start near 400°C and a finish above 100°C

The Tempered Microstructure Changes During Long-Term Service Of 9Cr-1MoVNb at 550-590°C

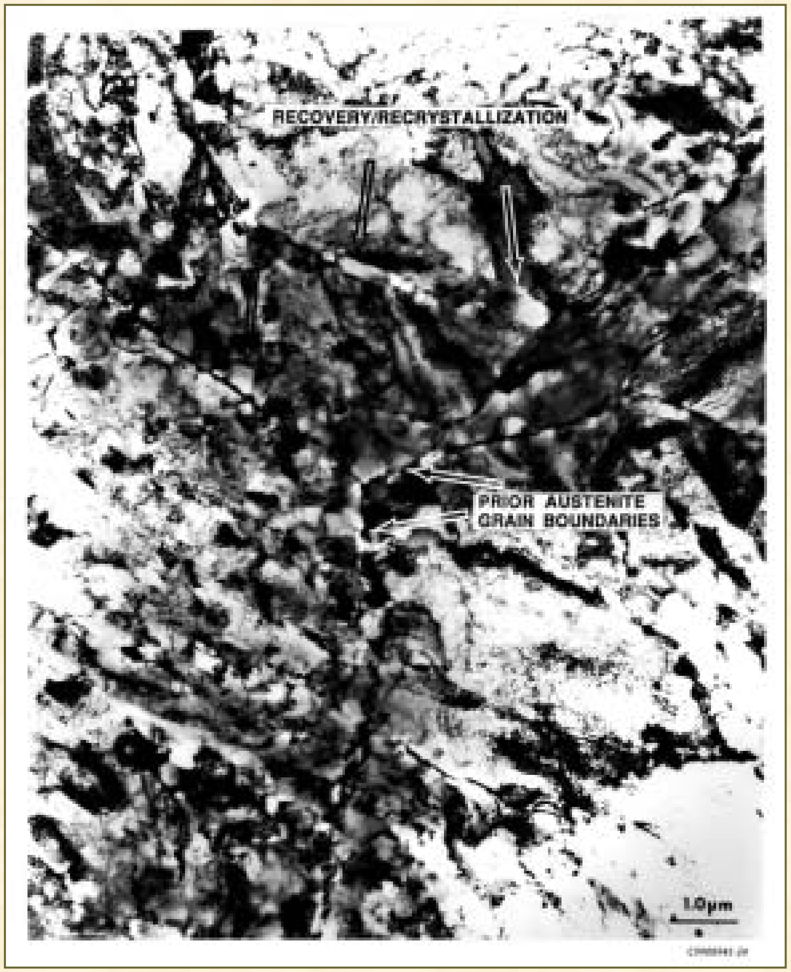


Super heater tubing after 143,000 h



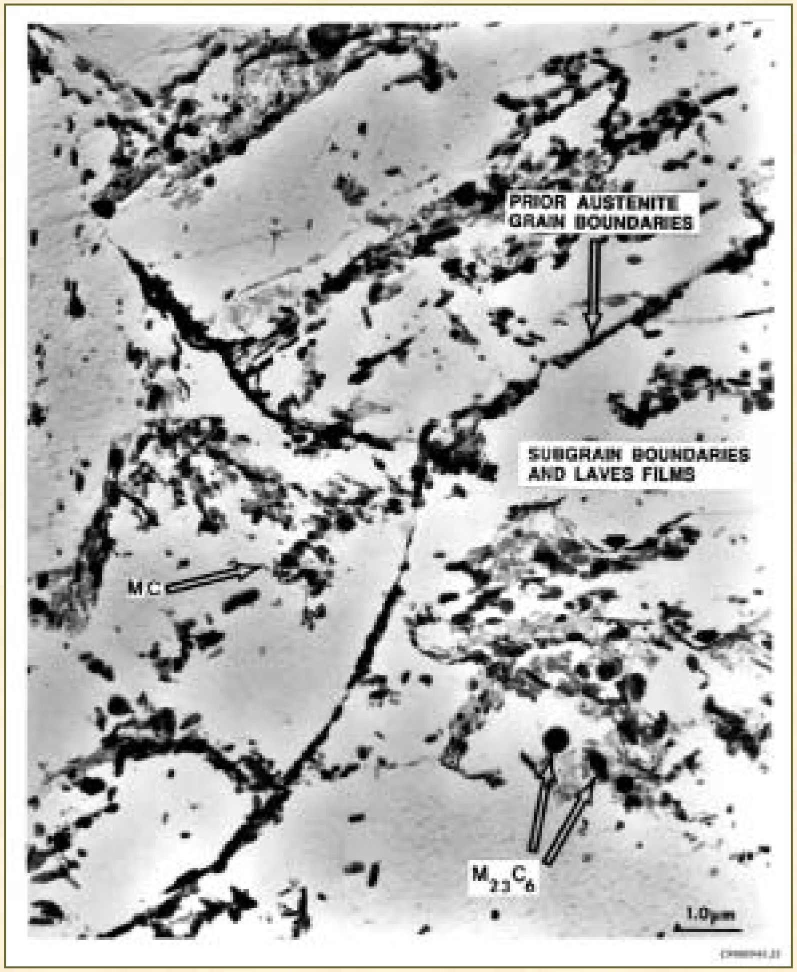
Unexposed, as-tempered

Long-Term Aging of 9Cr-1MoVNb Steel At 482°C Produces Some Recovery And Recrystallization Near Heavily Precipitated Boundaries



9Cr-1MoVNb
(heat 30176)
aged 75,000h
at 482°C

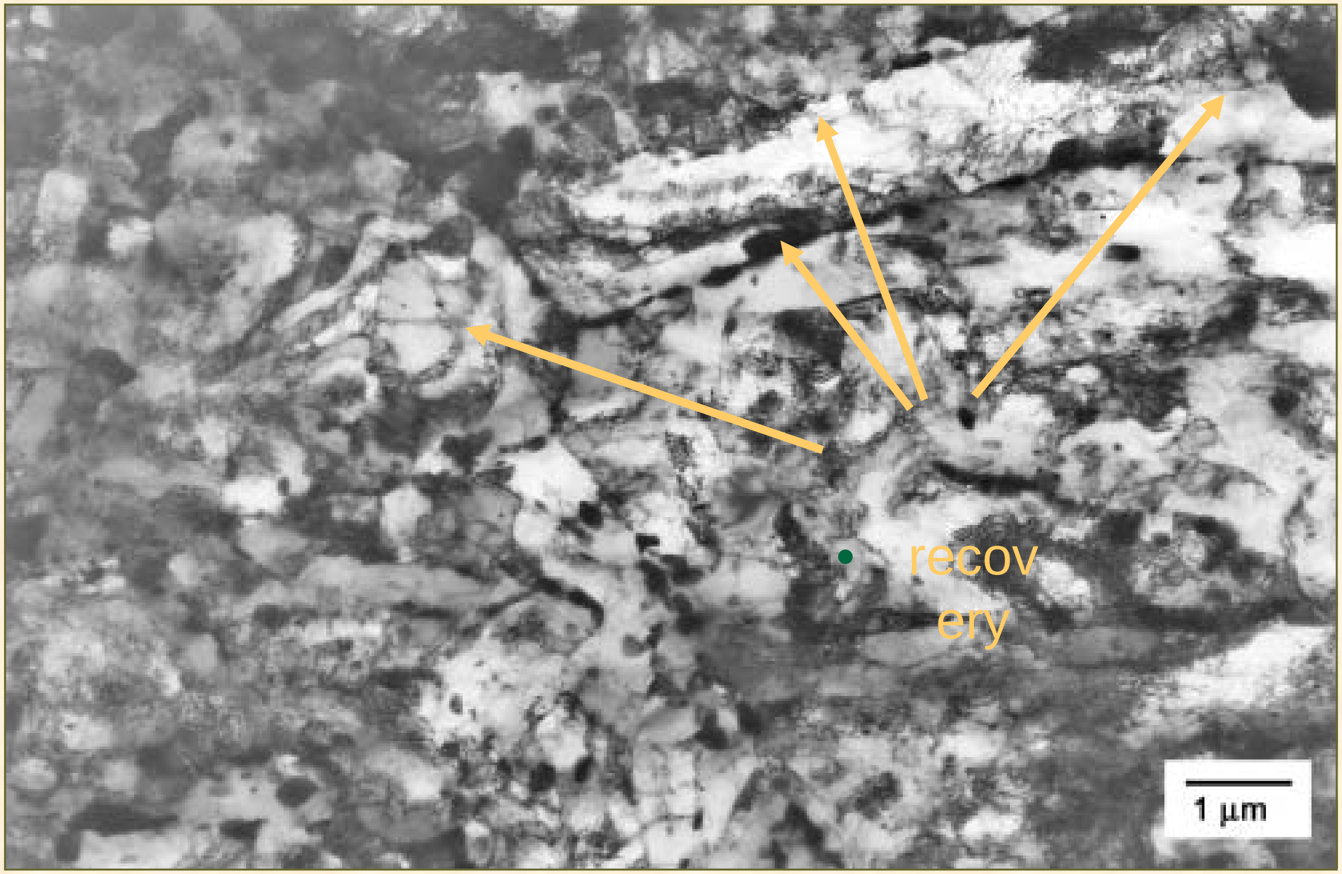
Long-Term Aging of 9Cr-1MoVNb Steel At 482°C Produces Significant Laves Phase Precipitation Along Boundaries And In-Between Carbides



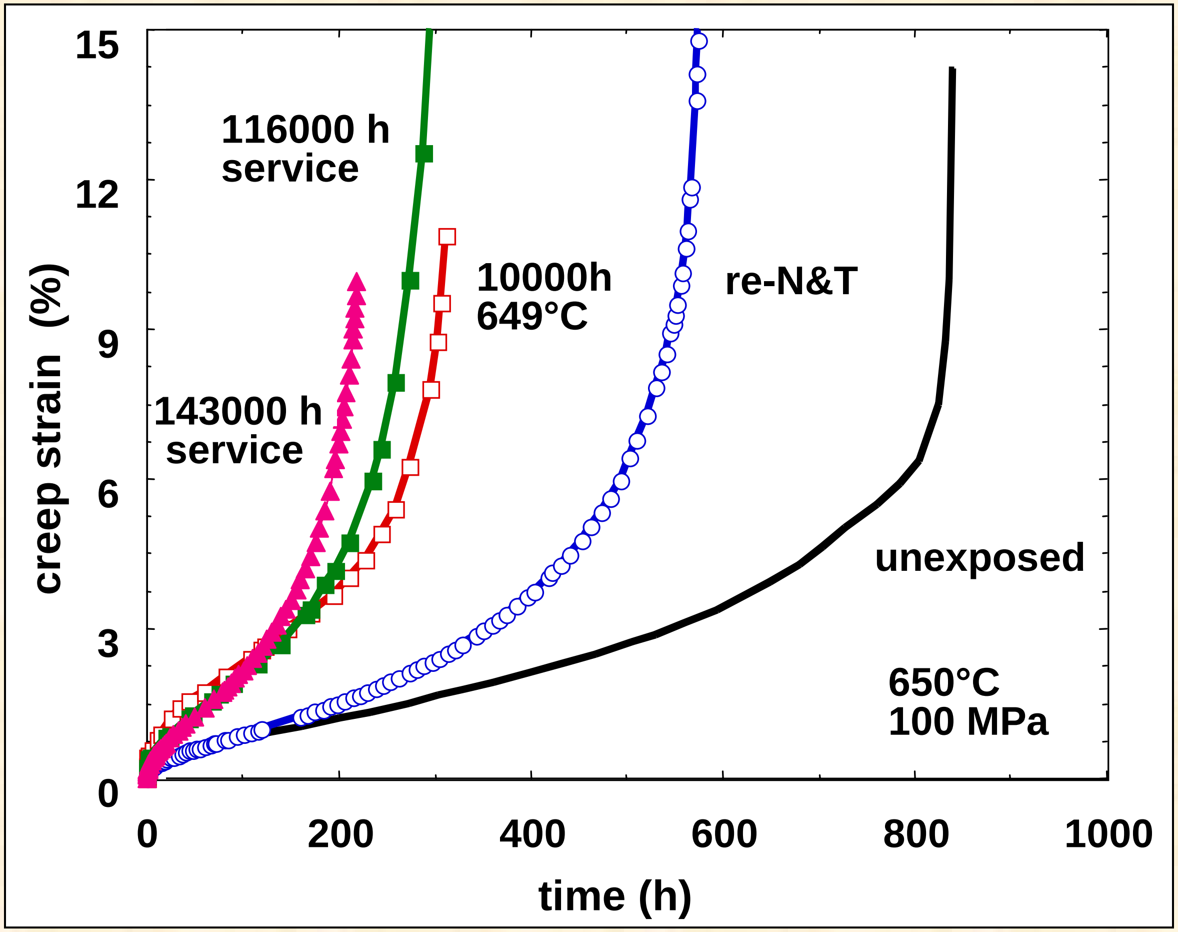
9Cr-1MoVNb
(heat 30176)
aged 75,000h
At 482°C

Microstructural Changes During Aging At 538°C Cause Transient Hardening, But At 650°C Cause Softening Relative To As-Tempered 9Cr-1MoVNb Steel

Exposure of 9Cr-1MoVNb Tubing For 143,000 h At 550-590°C Produces Laves Phase Precipitation And Substructure Recovery



Creep Testing Revealed A Higher Creep Rate And Shorter Rupture Life After Service



Results were consistent with expectations based on aging studies.

In Summary, Aging and Service Exposures Produced Many Changes

- **Coarsening of substructure**
- **Precipitation of intermetallic phases**
- **Loss of yield and ultimate strengths**
- **Loss of creep resistance**
- **Loss of toughness**

Some of these effects are incorporated into damage models

Four Damage Accumulation Models Are Being Evaluated

- **Life Fraction**
- **Monkman-Grant**
- **API 579 Omega Method**
- **Dyson Continuum Damage Mechanics (CDM)**

The Life Fraction (Robinson's) Rule Is A Simple And Useful Damage Accumulation Model

$$\sum \frac{t_i}{t_{Ri}} = 1$$

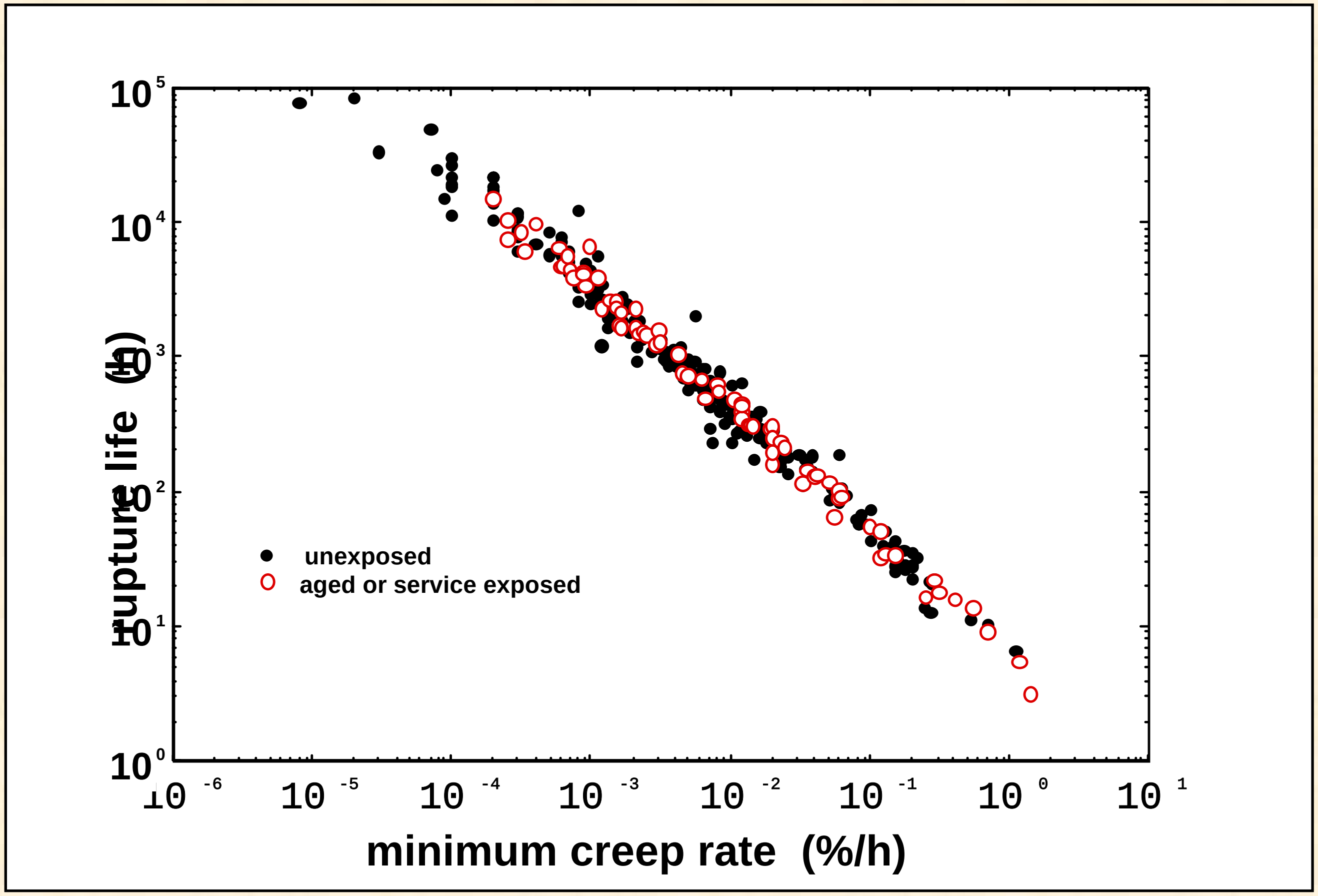
One only needs to estimate t_{Ri} for each stress-temperature

The Monkman-Grant Requires Knowledge of The Minimum Creep Rate (MCR) For The Damaged State

$$t_{Ri} = A\ mcr^{n}$$

- **Assuming that A and n are constants and independent of history and damage**

Data for the Three Conditions Were Compared on the Basis of the Monkman-Grant Correlation



All followed a similar trend

The API 579 Omega Method Assumes That The Damage Parameter, Ω_p is Reflected in The Tertiary Creep Curve

$$\ln \dot{\varepsilon} = \ln \dot{\varepsilon}_o + \Omega_p \varepsilon$$

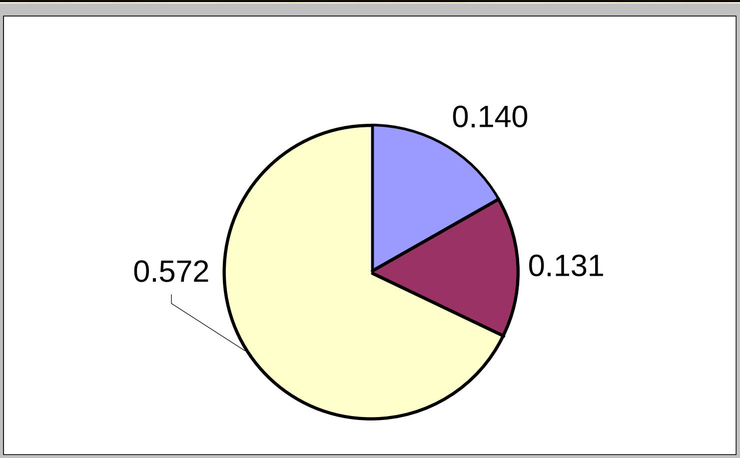
- **The parameter includes all damage components (area change, strain, and aging)**

The Omega Method Is Being Exercised for 9Cr-1Mo-V Steel

Material		9Cr-1Mo-V
State of Stress		Pressurized Cylinder or Cone

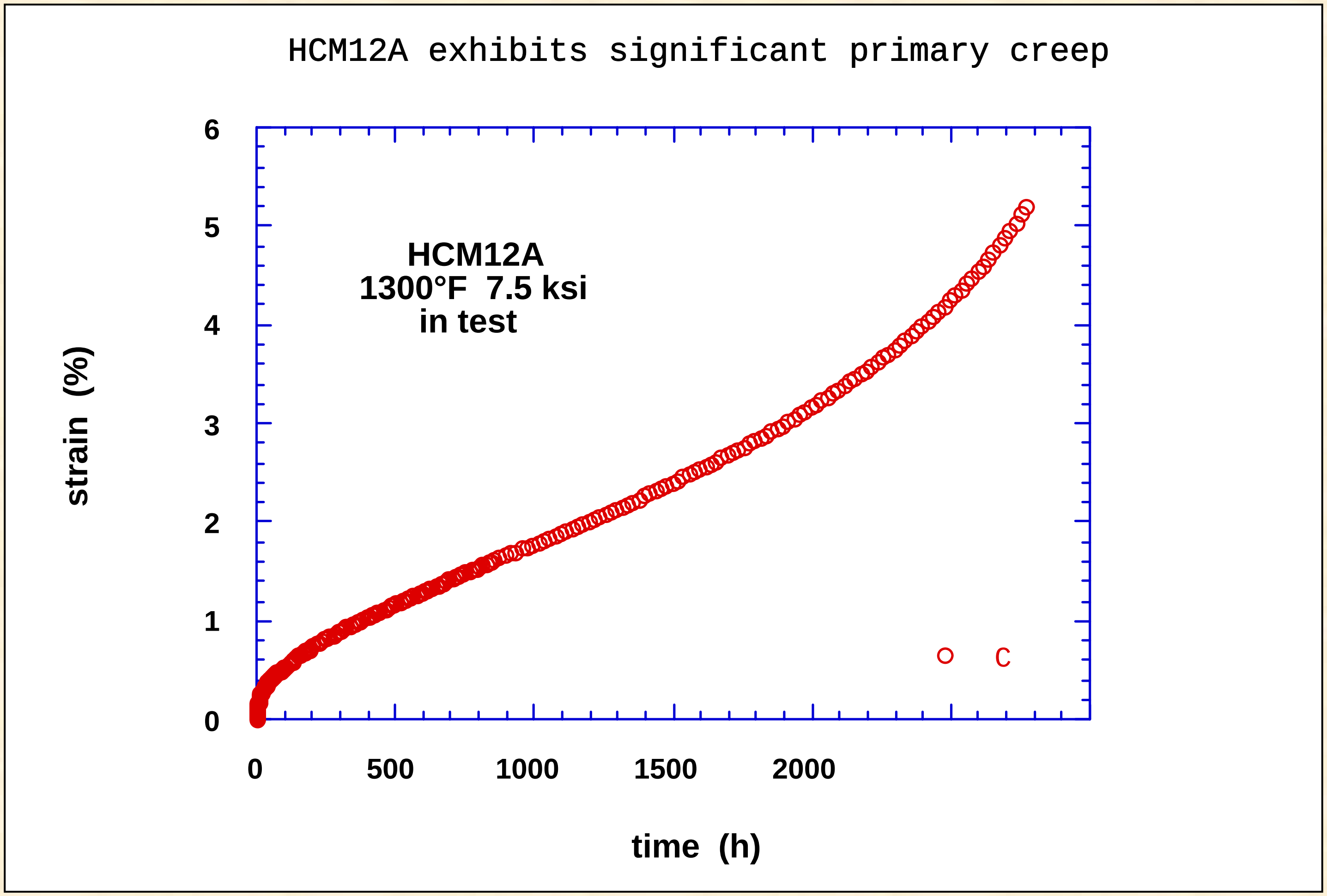
Material Parameter	Omega Parameter	Strain Rate Parameter
C_0	-2	-34
C_1	7200	73201.8
C_2	-1500	-2709
C_3	0	-4673
C_4	0	-569

State-of-stress Factor	α	2
Prager Factor	β	0.33

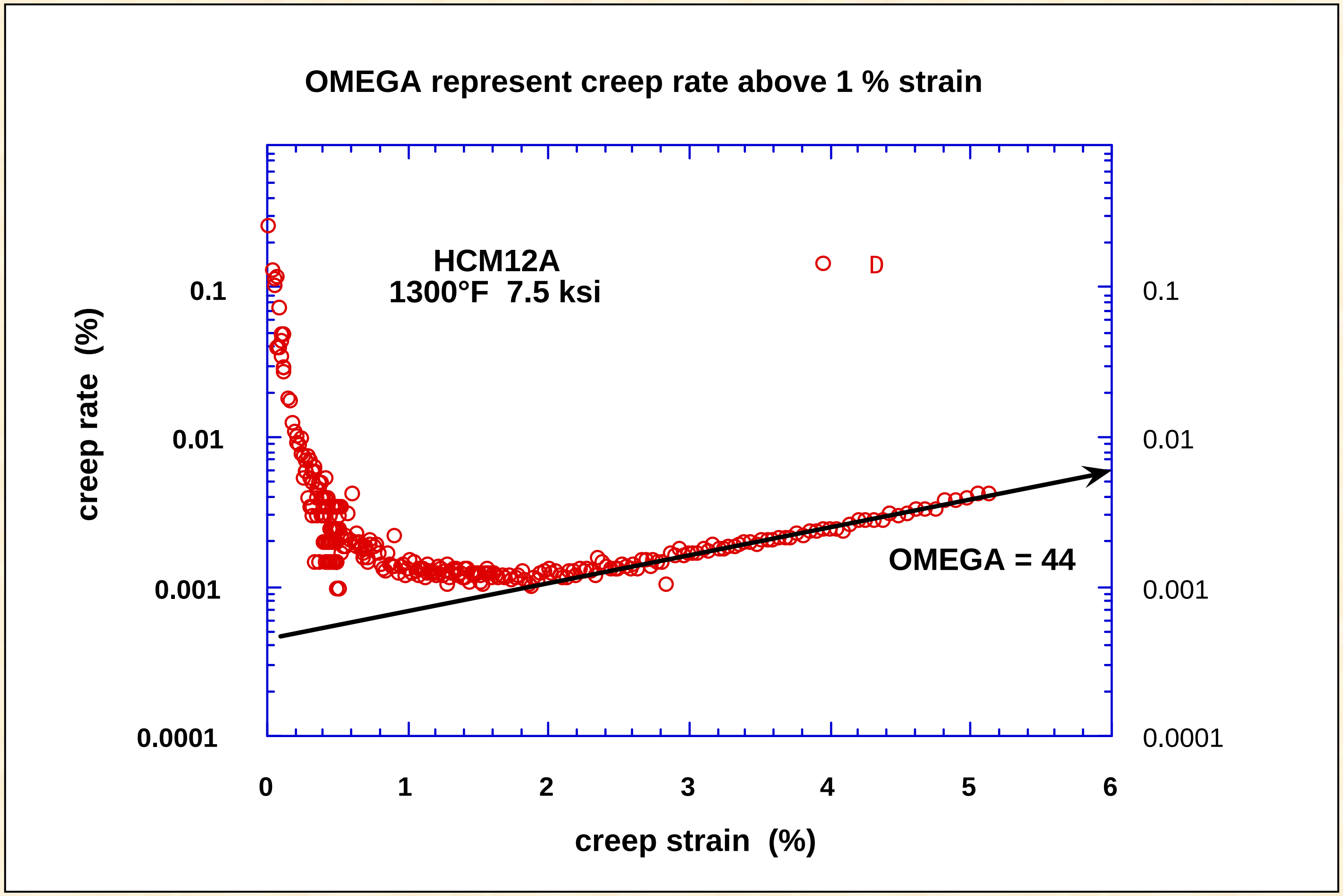


Stage	Temperature T (F)	Primary Stress σ_1 (ksi)	Time t_i (hrs)	Creep Ductility Adjustment Factor Δ_{cd}	Scatter Band Adjustment Factor Δ_{sr}	Fraction of Life D_i
1	1050	14.5	116,000	0	0	**0.140**
2	1067	14.5	40,000	0	0	**0.131**
3	1112	14.5	14,000	0	0	**0.572**
Remaining Life						**0.157**

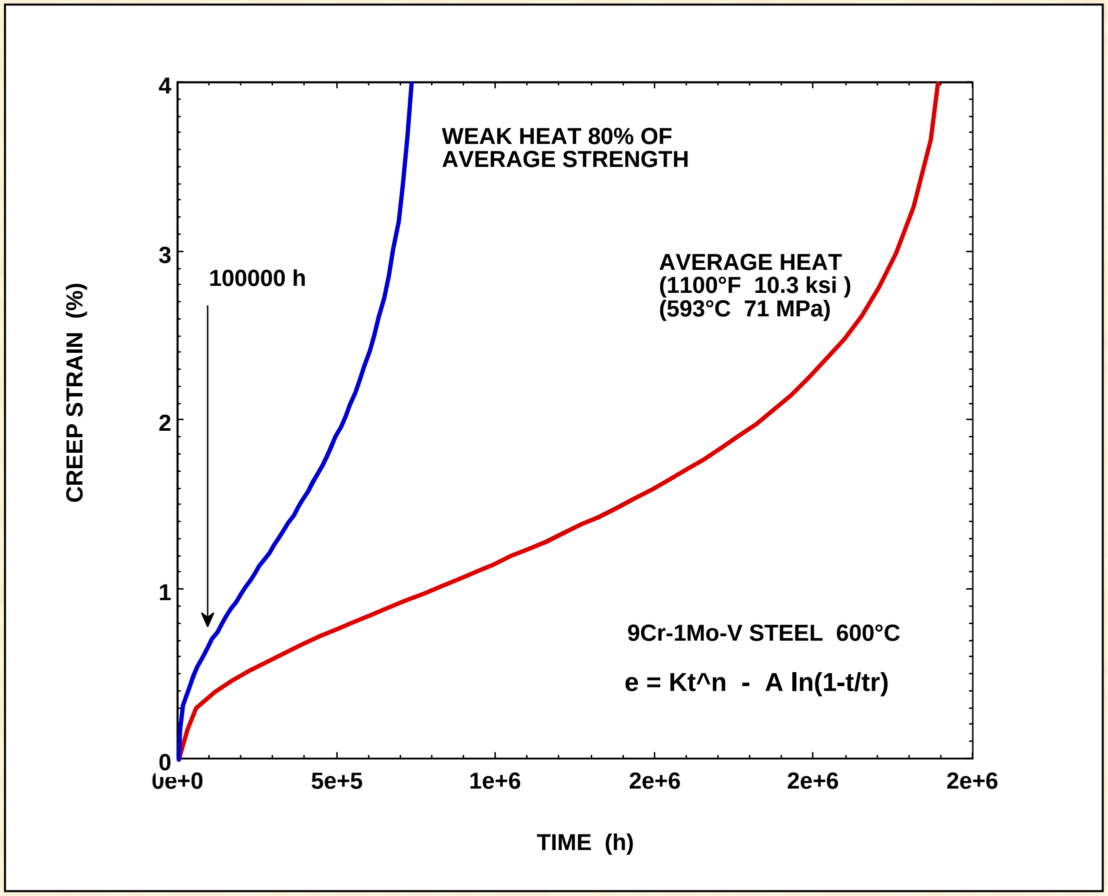
The Advance 12Cr-W-V Steels Exhibit Creep Curves Similar To 9Cr-1M-V Steel



The Omega Parameter is Valid Once Primary Creep Is Exhausted



For Most Service Conditions To Be Encountered In The Next 10 Years, Gr 91 Will Be In The Primary Creep Stage



Damage assessment that identifies the creep stage would be helpful

The Dyson CDM Model Takes A Materials Science Approach

- **Strain-induced damage includes deformation and cavitation**
- **Thermally-induced damage includes aging effects**
- **Environment damage includes surface corrosion and internal oxidation**

The Parametric Parameters For the Dyson CDM Model Are Under Development

Test Conditions

Initial Stress	σ	150	MPa
Analysis Time	t	131400	hrs
Output / Maximum Time Increment	dt	*131.4*	hrs
Temperature	T	1123	K
Load Condition	L	Constant Load (CL)	

Basic Parameters for the Dyson Model (eqs. 8)

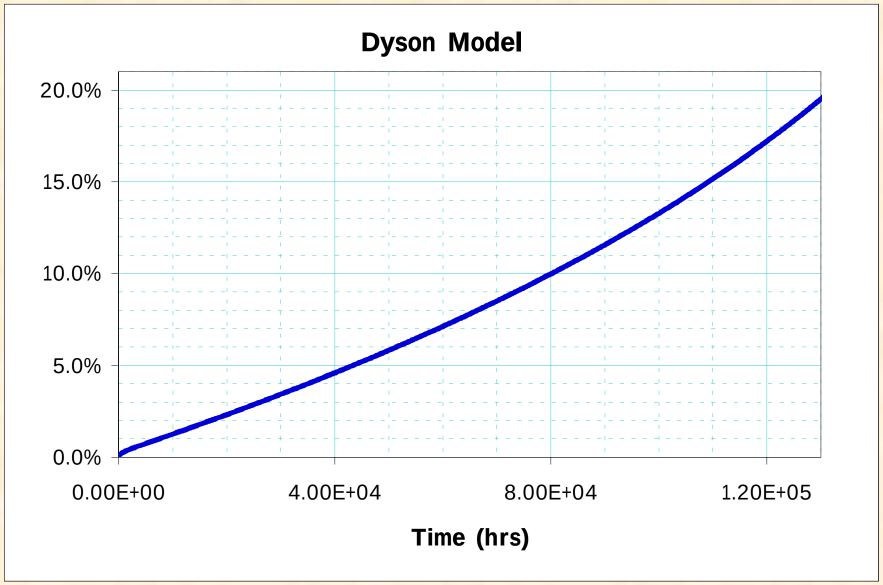
Stress parameter (function of temperature)	σ_0	*21.30875118*	MPa
Strain rate Paramater (function of Temeperature)	ε_0	*7.9867E-12*	1 / sec
Proportionality Constant for Primary Creep	h'	4.00E+04	MPa
Maximum allowable value for H	H^*	0.4	
Material Constant for Mobile Dislocations	C	0	
Rate Constant for Particle Coarsening	K_p	*0*	1 / sec
Cavitation Constant (0 - 1/3)	K_n	0	
Failure Strain	ε_{fu}	0.2	

Parameters for Calculating ε_0, σ_0

Universal Gas Constant	R	*0.008314*	kJ / mol-K
Parameter	ε'_0	2400	1 / sec
Activation energy for diffusion and jog formation	$Q_{d/j}$	311.25	kJ / mol
Parameter	$\sigma_{0,m}$	33	MPa
Enthalpy of Solution	ΔH	49.8357788	kJ / mol
Solvus Temperature	T_s	1394	K

Parameters for Calculating K_p

Particle Coarsening, coefficient	K'_p	0.00E+00	1 / sec
Particle Coarsening, activation energy	Q_p	300	kJ / mol



Minimum Creep Rate	***mcr***	**1.03E-06**	1 / hr

Efforts Are Being Made to Obtain Data Needed To Exercise The Dyson Model

- **Precipitation modeling is underway at Loughborough University**

- **Quantitative metallographic data will be collected in collaboration with the Australian Nuclear Science and Technology Organization**

Summary

- An understanding of damage mechanisms in advanced ferritic/martensitic steels is a key to their success in future fossil applications
- Good progress has been made in developing and exercising damage accumulation models