Development of an Improved Creep Resistant Fe-9% Cr Steel

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U.S. DEPARTMENT OF ENERGY | National Energy Technology Laboratory

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Heat Resistant Steels for Steam Power Plants

- Higher temperature operation for coal fired plants results in better power plant efficiency, leading to:
  - Reduced CO_2 production
  - Reduced coal consumption
- Higher operating temperatures require alternative materials such as higher temperature martensitic steels or Ni-based superalloys. The choice of Ni-based superalloys is:
  - Very expensive (10 – 50 times more expensive than steels)
  - Risky (no experience in steam-based power plants using Ni-based technology)
- To enable higher temperature operation while keeping costs of materials substitution low requires new formulations of martensitic steel, such as the alloy proposed in this patent disclosure.

General Background Martensitic Steels

- Ferritic/Martensitic Cr steels form the backbone of current steam delivery systems.
- These alloys are less expensive to produce & in general can be recycled.
- CrMoV, NiCrMoV & steels with < 5% Cr make up the majority in tonnage in steam power plants operated < 570°C.
- In the hotter sections of the boiler & steam turbine, i.e., temperatures greater than 570°C, advanced 9-12% Cr steels will need to be used.
- At the current time, <u>620°C</u> is the approximate projected maximum use temperature due to concerns about the long-term microstructural instability of the heat resistant steel.

Past Research on Martensitic Steels

- Research in improving temperature & pressure capability of ferritic/martensitic steels has been active area of research in the power generating industry since the 1950's.
- In the most general terms, acceptable oxidation resistance at 650°C while meeting the requirement of a creep life of 100,000 hours at 100 MPa, is the ultimate goal for heat resistant advanced martensitic steels.
- Fujita developed TAF steel in 1968 [1], which nearly met today's creep lifetime requirement. High C & B levels in base steel was major contributing factor for strength.
- However, TAF proved extremely difficult to fabricate & almost impossible to weld because of the very high boron & carbon in the steel.

[1] Fujita, Trans. JIM, (1968).

Recent Martensitic Steel Developments

1950's to date – Low alloy creep resisting steels

- 2¼CrMo; CrMoV
  - Ferritic structure, limited carbide strengthening
  - Applications up to about 540 - 570°C maximum

1980's development – P91 or "Modified 9%Cr" steel

- Introduced from early 1990's onwards
- Coal plant boiler headers and drums (UK first), steam pipework and HRSG applications worldwide
  - Martensitic structure
  - Fine scale lath structure for increased creep strength
  - Carbide precipitate chains on lath boundaries
  - Vanadium modified to add finer-scale network of VN/MX precipitates
  - Applications generally up to about 580°C (or higher if at low stress)

1990 - 2000 – P92 steel

- Replace molybdenum with tungsten in P91: Some strength increase
- Applications – e.g. 600°C main steam, 620°C hot steam reheat

Computational & Experimental Alloy Design & Process Development Approach

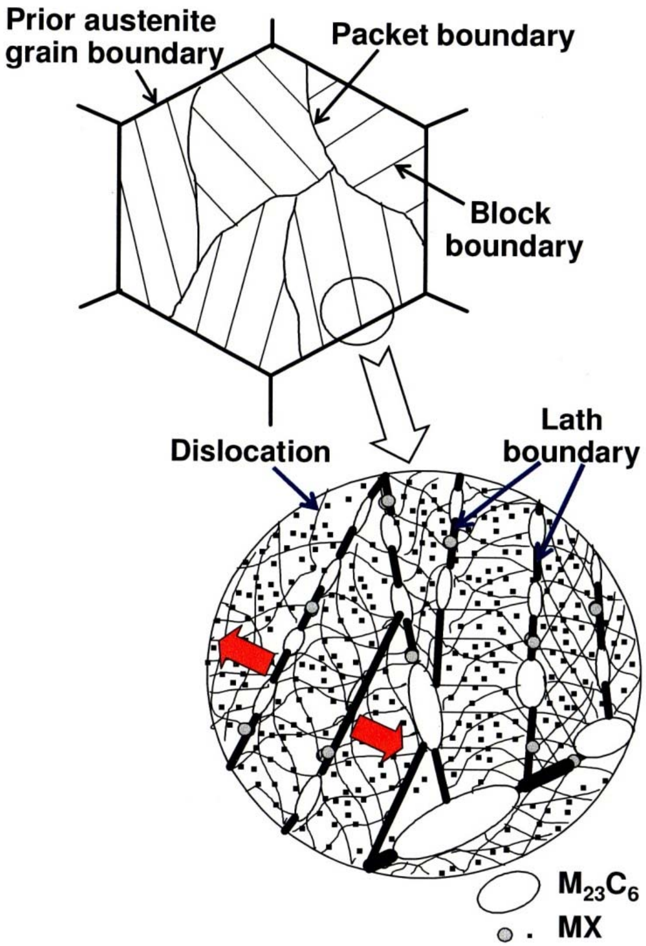
- Model & design alloys using computational thermodynamics software (ThermoCalc) to develop the phases required for creep strength & to maintain the martensitic nature of the steel.
- Formulate, melt & cast alloy heats for each composition using best melting practice for alloy formulation.
- Homogenize each alloy according to its own <u>computationally optimized</u> heat treatment schedule developed from thermodynamic (ThermoCalc) & kinetic (DICTRA) modeling approach.
- Fabricate alloys into plate form through standard hot forging & rolling operations.
- Develop desired microstructure features & steel strength through normalizing & tempering heat treatments.
- Assess creep & tensile properties against COST alloys

General Technical Approach

- Understand basic high temperature strengthening mechanisms & how to preserve strengthening effect through microstructural control.
- Achieve balance between the following competing effects:
  - *Necessary C, V, Nb, (and/or Ta) and N to generate MX (M: is metal; X: is C/N), thereby, slowing down dislocation movement in the matrix during creep.*
  - *Balanced amount of Mo and W for solution & precipitation hardening by $M_{23}C_6$ and Laves phase.*
  - *Addition of Co, Cu, Mn, and/or C to suppress δ-ferrite & to provide additional precipitate strengthening (Cu) & oxidation resistance (Mn).*
  - *Addition of B to stabilize $M_{23}C_6$ precipitates, and thus, help to stabilize the sub-grain structure.*
  - *Correct amount of Cr for oxidation resistance (e.g., Cr additions significantly greater than 9% reduce creep strength).*
  - *Optimum Si level and/or RE elements to improve oxidation resistance.*

Agamennone et. al. Acta Mater.(2006), Knezevic et al. Mater. Sci. Eng. A. (2008), Wang et al. Mater. Sci. Eng. A. (2009), Yin & Jung, J. Mater. Pro. Technol. (2009), and Chilukuru et al. Mater Sci. Eng. A. (2009).

Microstructural Hierarchy of 9-12%Cr Steels



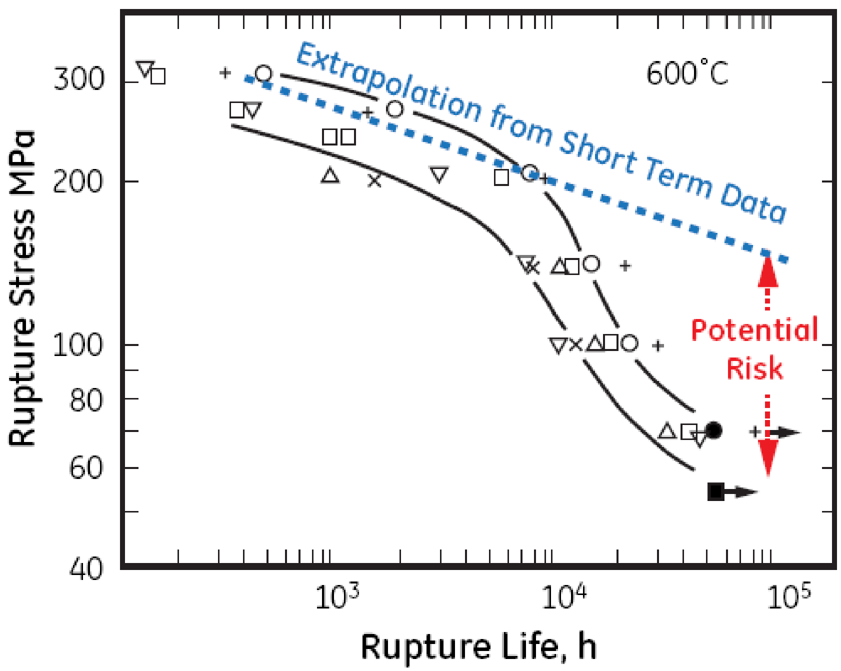
1. Prior austenite grain with associated grain boundaries.
2. Packet boundaries
3. Block boundaries
4. Lath boundaries
5. $M_{23}C_6$ carbides to stabilize lath, block, packet, and PAG boundaries
6. MX carbides to provide obstacles to dislocation motion
7. Dislocations

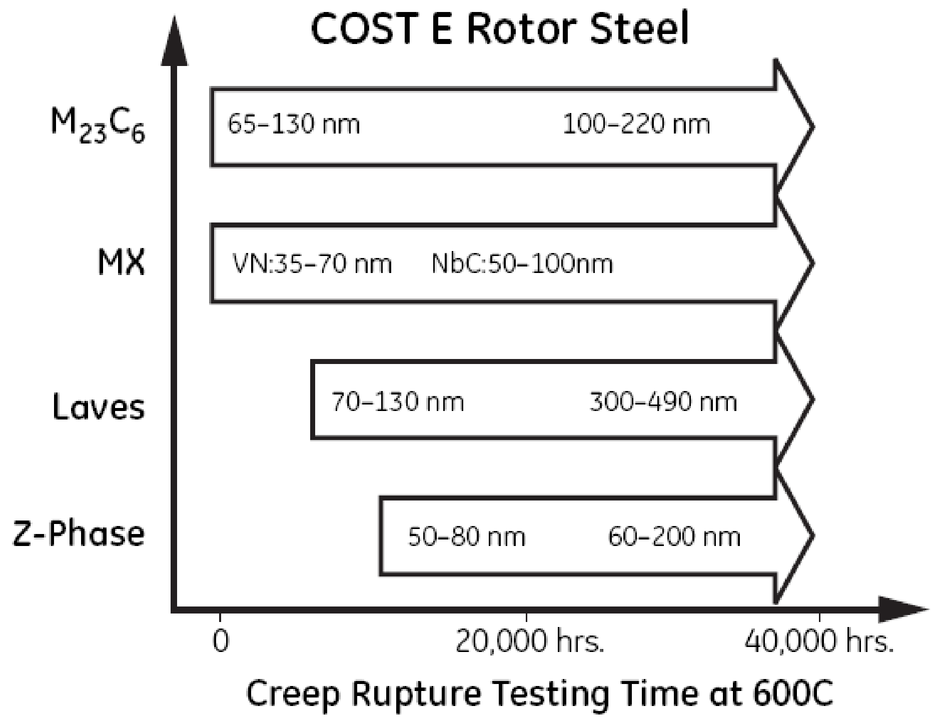
The breakdown of any of these microstructural features will destabilize the alloy and lead to increased creep rate over time. The goal of alloy design is to slow down the destabilization of these features starting with the MX and $M_{23}C_6$ particles.

F. Abe, "Metallurgy for Long-term Stabilization of Ferritic Steels for Thick Section Boiler Components In USC Power Plants at 650°C," Proceedings of the 8th Liege Conference, (2006), pp. 965-980.

Microstructural Stability of 9-12%Cr Steels

USC Materials Development Experience

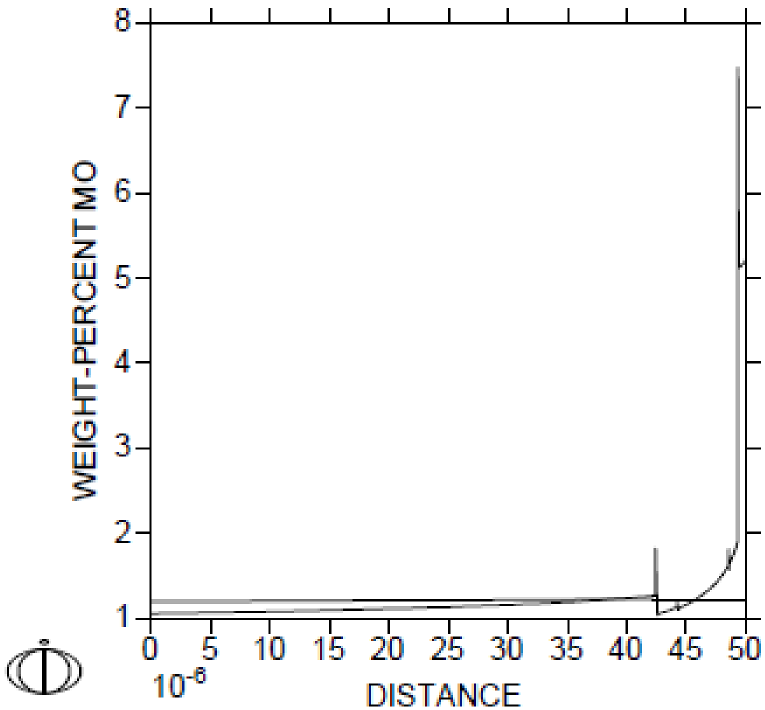




Many competing effects occur in heat resistant steels of the 9% Cr variety. Past experience has shown that the instability of any of the following, Z-phase, Laves, MX and/or $M_{23}C_6$, can cause an unexpected decrease in rupture stress as a function of time. The goal of alloy design is to slow down the destabilization of these features starting with the MX and $M_{23}C_6$ particles.

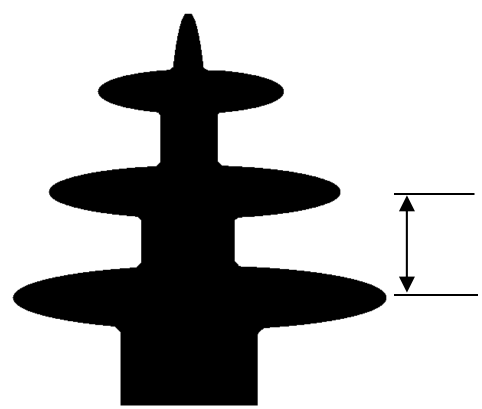
Heat Resistant Steels for 650°C Power Plants

- NETL alloy manufacturing approach focuses on homogenization step in which the incremental liquid chemistry is used to characterize the entire resulting solid inhomogeneity.
- Critical here is that the homogenization is taken to an acceptably uniform level. This is what gives the steel long term microstructural stability.



sdas approx. = 100 µm

A plot of wt. % Mo vs. Distance (m) in the as-cast condition. It can be seen that there is quite significant difference in Mo weight fraction in the region equivalent to the center of, or ½, the *sdas* length.



Heat Resistant Steels for 650°C Power Plants

- NETL alloy manufacturing approach focuses on homogenization step in which the incremental liquid chemistry is used to characterize the entire resulting solid inhomogeneity.
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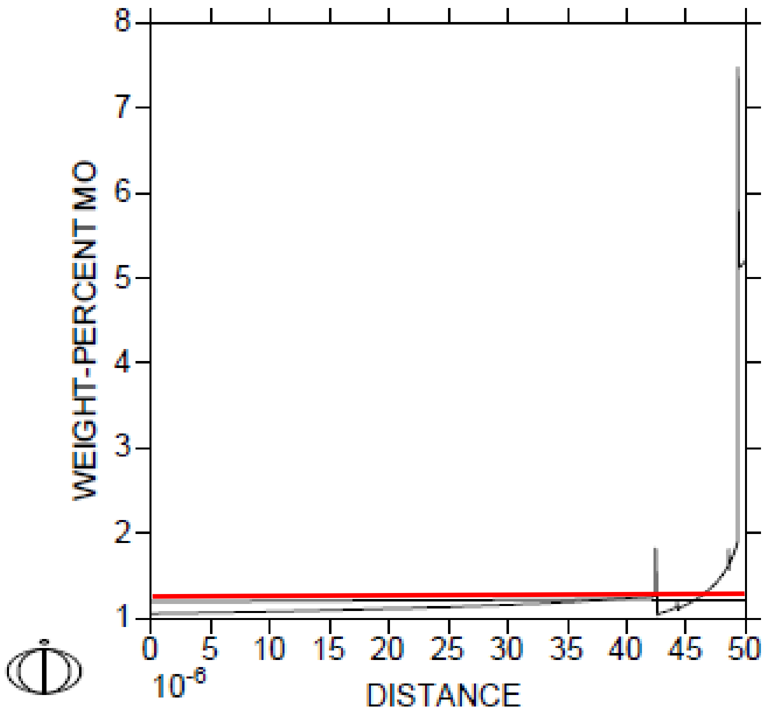

A plot of wt. % Mo vs. Distance (µm) in the as-cast and homogenized condition. After homogenization the Mo level was +/- 1% of the nominal level which was deemed adequate. Each element of the alloy was evaluated in a similar manner.

sdas approx. = 100 µm

Nominal Chemistries for Selected 1st & 2nd Iteration CPJ Alloys

Alloy	Fe	Cr	Co	Mo	Ti	Ta	W	N	C	B
CPJ-1	balance	10	3	---	0.1	---	---	0.01	0.10	0.01
CPJ-4	balance	10	3	---	0.1	---	---	0.02	0.15	0.01
CPJ-5	balance	10	3	---	0.1	---	---	0.02	0.18	0.01
CPJ-6	balance	10	3	---	---	0.1	---	0.02	0.18	0.01
CPJ-7	balance	9.75	1.5	1.25	---	0.2	0.5	0.022	0.15	0.012

Note 1: Alloys were homogenized using thermodynamic/kinetic computational approach.

Note 2: Alloys were heat treated as follows: 1150°C/30 min/AC + 700°C/1 hour/AC.

Note 3: Other minor alloying additions include: V, Nb, Mn, Ni & Si.

Mechanical Properties 1st Iteration CPJ Alloys

Alloy	Temperature (°C)	0.2% YS (MPa)	UTS (MPa)	Elongation (%)	RA (%)
CPJ-1	RT	672	785	26	72
	600	288	349	32	89
	650	207	275	41	91
COST E JCFC	RT	751	876	23	60
	600	379	447	34	88
	650	297	359	35	91
COST B2 Doosan	RT	744	880	18	56
	600	462	514	25	80
	650	389	440	29	82
COST FB2 JCFC	RT	721	861	17	38
	600	417	472	21	50
	650	341	395	20	54

CPJ HT: 1150°C/30 min/AC + 700°C/1 hour/AC

Grain Size & Carbide Fractions

Alloy	ASTM Grain Number	Nominal Grain Diameter, µm
CPJ-1	3	125
COST E JCFC	3	125
COST B2 Doosan	> 1	> 250
COST FB2 JCFC	1.5	210

Alloy	$M_{23}C_6$ Carbide Volume Percent
CPJ-1	4.1 ± 1.1
CPJ-4	7.5 ± 1.3
CPJ-5	8.1 ± 1.9
CPJ-6	11.3 ± 1.6
CPJ-7	9.2 ± 2.1
COST E (JCFC)	8.8 ± 1.9
COST B2 (Doosan)	10.0 ± 2.1
COST FB2 (JCFC)	8.5 ± 1.8

The values obtained for the CPJ-6 and CPJ-7 alloys most likely include additional types of precipitate(s) due to the nominal chemistry of these alloys.

Alloy	Cr, wt%	Fe, wt%	Mo, wt%
CPJ-1	65 ±2.8	34 ± 2.3	0
COST E	52 ± 2.5	32 ± 2.4	7 ± 0.3
COST B2	46 ± 3.7	44 ± 4.1	10 ± 0.8
COST FB2	50 ± 4.5	39 ± 5.6	10 ± 1.7

The EDS data is solely from TEM samples, and was taken only from carbides at the edge, or extending over, the hole in the sample. These values correlate well with the $M_{23}C_6$ stoichiometry for 9-12% Cr steels.

Mechanical Properties 2nd Iteration CPJ Alloys

Alloy	Temperature (°C)	0.2% YS (MPa)	UTS (MPa)	Elongation (%)	RA (%)
CPJ-4	RT	673	813	23	68
	600	291	363	36	88
	650	202	285	58	93
CPJ-5	RT	671	830	25	5
	600	285	361	40	89
	650	196	287	47	93
CPJ-6	RT	849	1001	19	63
	600	452	526	25	78
	650	370	444	28	79
CPJ-7	RT	848	1011	24	61
	600	494	569	32	81
	650	396	468	37	83
COST B2 (Doosan)	RT	744	880	18	56
	600	462	514	25	80
	650	389	440	29	82

CPJ HT: 1150°C/30 min/AC + 700°C/1 hour/AC

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	650	196	287	47	93
CPJ-6	RT	*849*	*1001*	19	63
	600	452	526	25	78
	650	370	444	28	79
CPJ-7	RT	*848*	*1011*	24	61
	600	494	569	32	81
	650	396	468	37	83
COST B2 (Doosan)	RT	*744*	*880*	18	56
	600	462	514	25	80
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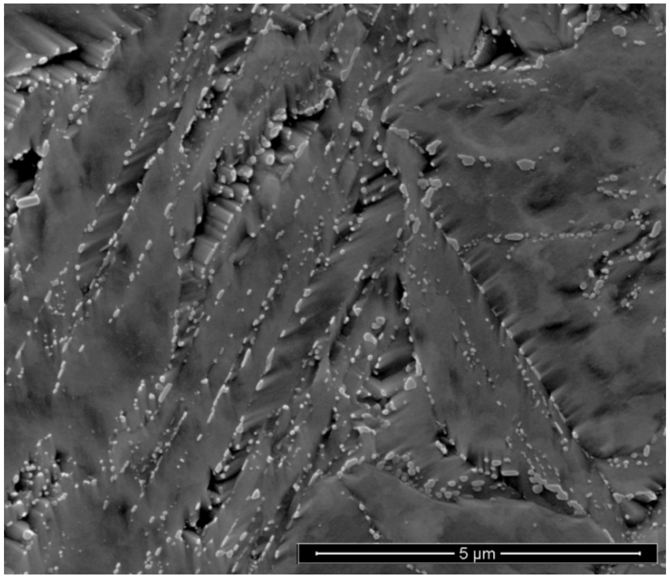
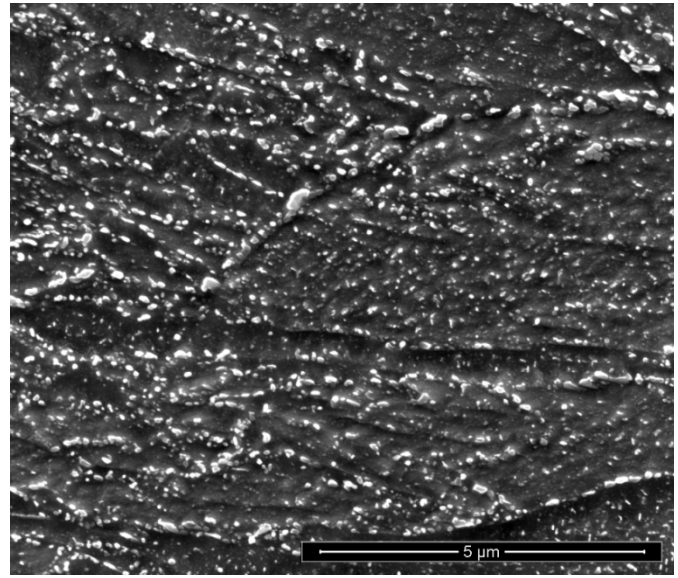
CPJ HT: 1150°C/30 min/AC + 700°C/1 hour/AC

Microstructures for CPJ Alloys 4-7

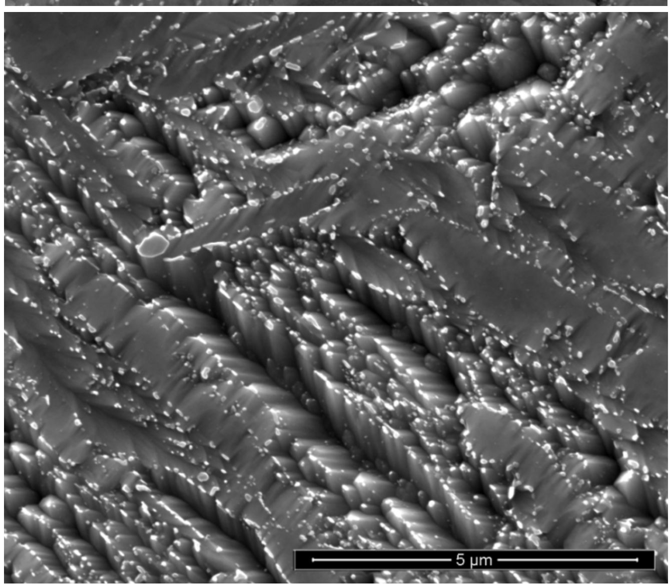
CPJ-4

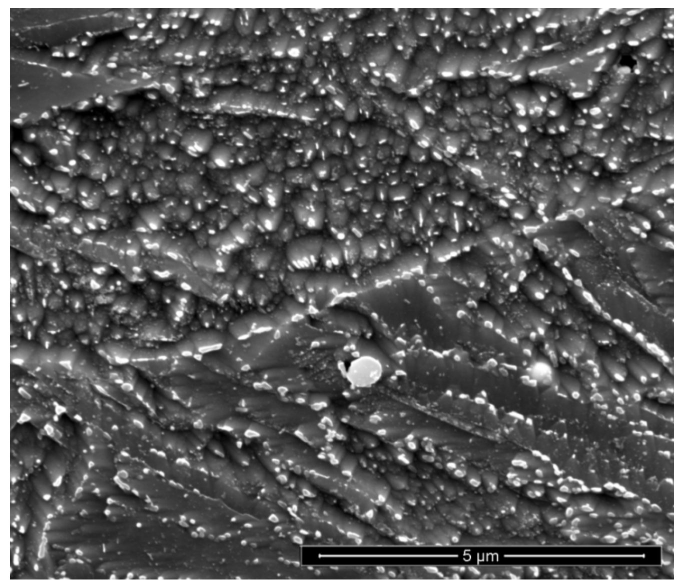




CPJ-6

CPJ-5





CPJ-7

Comparison of Creep Life at 650°C versus FB2

Alloy	Stress (ksi)	Stress (MPa)	Rupture Time (h)
FB2	20	137.9	1,783
CPJ-4	20	137.9	13
CPJ-5	20	137.9	49
CPJ-6	20	137.9	875
CPJ-7	20	137.9	5,388

CPJ HT: 1150°C/30 min/AC + 700°C/1 hour/AC

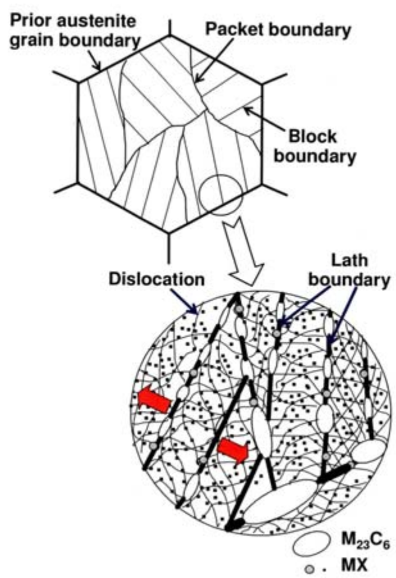
- Ti containing alloys had lower tensile strength
- Co only containing alloys had lower creep life

CPJ-7 had excellent creep life in screening test!

Summary of Major 9%-12% Cr Steels Versus CPJ-7 Alloys

Chemistry														
Material	***C***	***Mn***	***Si***	***Ni***	***Cr***	***Mo***	***V***	***Nb***	***N***	***W***	***B***	***Co***	**Fe**	**Ta**
COST FB2	0.13	0.30	0.08	0.05	9.30	1.50	0.20	0.05	0.026		0.01	1.00	Bal	
COST E	0.12	0.45	0.10	0.74	10.40	1.10	0.18	0.045	0.05	1.00			Bal	
COST B2	0.18	0.06	0.10	0.09	9.28	1.54	0.29	0.06	0.02		0.01		Bal	
CPJ-7	0.15	0.41	0.09	0.27	9.83	1.26	0.21	0.056	0.020	0.48	0.0100	1.48	Bal	0.28
CPJ-7B	0.15	0.29	0.15	0.22	9.81	1.46	0.20	0.059	0.025	0.43	0.0078	1.53	Bal	0.20
CPJ-7C	0.16	0.47	0.11	0.22	9.95	1.34	0.19	0.061	0.022	0.49	0.0086	1.59	Bal	0.20
CPJ-7D	0.16	0.43	0.10	0.22	10.12	1.31	0.21	0.054	0.024	0.53	0.0083	1.56	Bal	0.24
CPJ-7E	0.15	0.42	0.12	0.21	9.99	1.35	0.20	0.049	0.022	0.53	0.0087	1.51	Bal	0.28

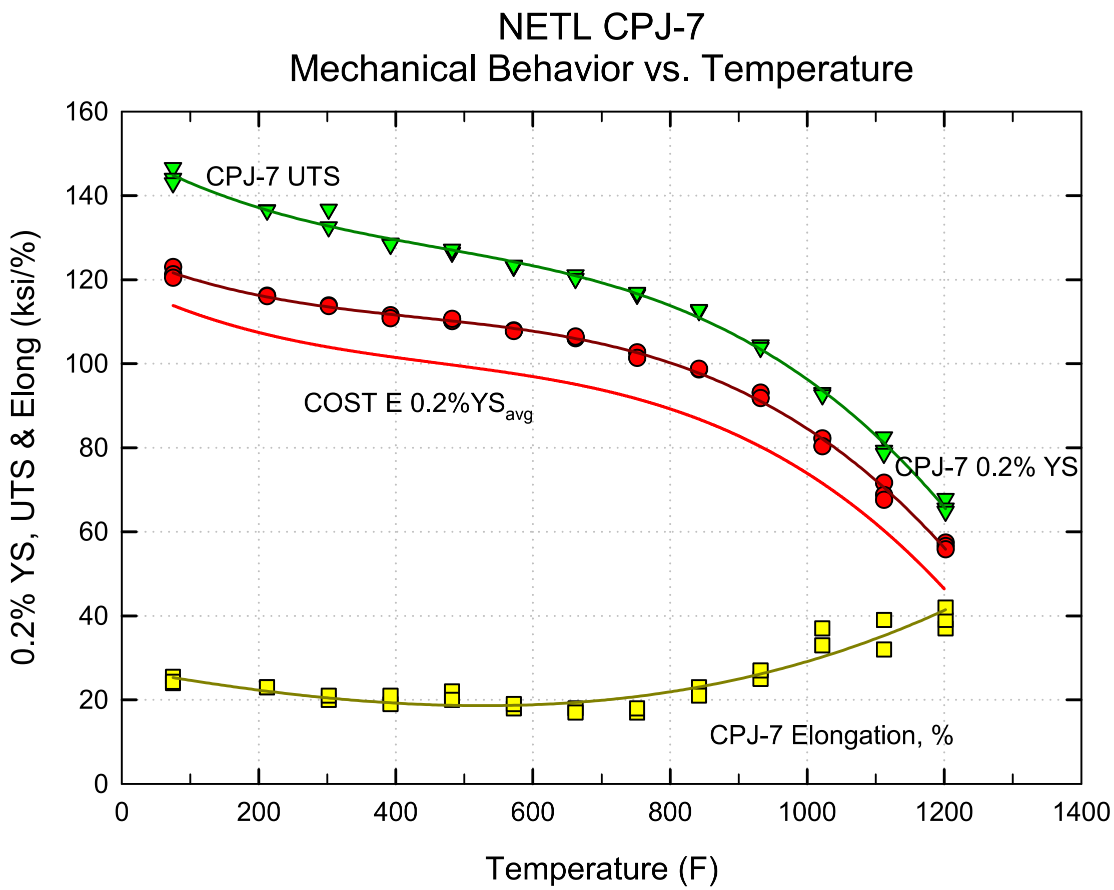
The following elements were also found in the CPJ-7 Alloys: Ti (<0.004%), Al (<0.02%), P (<0.003%), Cu (<0.003%), O (<36 ppm), and S (<58 ppm).



Alloy	$Mo_{(Eq)}$	C + N	B
COST FB2	1.50	0.156	100*
COST E	1.60	0.170	---
COST B2	1.54	0.200	100*
CPJ-7	1.501	0.170	100
CPJ-7B	1.675	0.175	78
CPJ-7C	1.585	0.182	86
CPJ-7D	1.575	0.185	83
CPJ-7E	1.595	0.172	87

$Mo_{(Eq)}$ = % Mo + ½ % W

Summary of Tensile Mechanical Behavior of CPJ-7 Alloys



Alloy	$Mo_{(Eq)}$	C + N	B
COST FB2	1.50	0.156	100*
COST E	1.60	0.170	---
COST B2	1.54	0.200	100*
CPJ-7	1.501	0.170	100
CPJ-7B	1.675	0.175	78
CPJ-7C	1.585	0.182	86
CPJ-7D	1.575	0.185	83
CPJ-7E	1.595	0.172	87

$Mo_{(Eq)}$ = % Mo + ½ % W

Summary of 650°C Creep Testing Results

Alloy	Stress (ksi)	Stress (MPa)	Time to Rupture (hours)
COST B2	25.0	172.4	655
COST B2	23.5	162.0	1,320
COST B2	23.5	162.0	1,104
COST B2	20.0	137.9	2,816
COST FB2	26.5	182.7	320
COST FB2	23.5	162.0	962
COST FB2	22.5	155.1	1,127
COST FB2	20.0	137.9	1,783
COST E	23.5	162.0	442
COST E	19.0	131.0	1,574
CPJ-7	30.0	206.8	666
CPJ-7	27.5	189.6	1,118
CPJ-7	25.0	172.4	1,454
CPJ-7B	25.0	172.4	1,514
CPJ-7C	25.0	172.4	1,774
CPJ-7D	25.0	172.4	1,732
CPJ-7	22.5	155.1	2,344
CPJ-7	20.0	137.9	5,388
CPJ-7	18.0	124.1	12,727
CPJ-7	*15.0*	*103.4*	*24,866**

* CPJ-7 alloys still in test as of 4/14/2014.

Summary of Major 9-12Cr Steels Vs. CPJ Series Steels

Chemistry														
Material	***C***	***Mn***	***Si***	***Ni***	***Cr***	***Mo***	***V***	***Nb***	***N***	***W***	***B***	***Co***	**Fe**	**Ta**
COST FB2	**0.13**	**0.30**	**0.08**	**0.05**	**9.30**	**1.50**	**0.20**	**0.05**	**0.026**		**0.01**	**1.00**	**Bal**	
COST E	**0.12**	**0.45**	**0.10**	**0.74**	**10.40**	**1.10**	**0.18**	**0.045**	**0.05**	**1.00**			**Bal**	
COST B2	**0.18**	**0.06**	**0.10**	**0.09**	**9.28**	**1.54**	**0.29**	**0.06**	**0.02**		**0.01**		**Bal**	
CPJ-7	**0.15**	**0.41**	**0.09**	**0.27**	**9.83**	**1.26**	**0.21**	**0.056**	**0.020**	**0.48**	**0.0100**	**1.48**	**Bal**	**0.28**
CPJ-7B	**0.15**	**0.29**	**0.15**	**0.22**	**9.81**	**1.46**	**0.20**	**0.059**	**0.025**	**0.43**	**0.0078**	**1.53**	**Bal**	**0.20**
CPJ-7C	**0.16**	**0.47**	**0.11**	**0.22**	**9.95**	**1.34**	**0.19**	**0.061**	**0.022**	**0.49**	**0.0086**	**1.59**	**Bal**	**0.20**
CPJ-7D	**0.16**	**0.43**	**0.10**	**0.22**	**10.12**	**1.31**	**0.21**	**0.054**	**0.024**	**0.53**	**0.0083**	**1.56**	**Bal**	**0.24**
CPJ-7E	**0.15**	**0.42**	**0.12**	**0.21**	**9.99**	**1.35**	**0.20**	**0.049**	**0.022**	**0.53**	**0.0087**	**1.51**	**Bal**	**0.28**
CPJ-8A	**0.15**	**0.42**	**0.10**	**0.28**	**10.64**	**0.50**	**0.21**	**0.056**	**0.034**	**0.51**	**0.0089**	**2.93**	**Bal**	**0.27**
CPJ-9	**0.14**	**0.40**	**0.08**	**0.27**	**10.63**	**0.51**	**0.20**	**0.055**	**0.020**	**0.52**	**0.0087**	**2.94**	**Bal**	**< 0.003**
CPJ-10	**0.15**	**0.43**	**0.11**	**0.21**	**10.03**	**1.37**	**0.22**	**0.058**	**0.028**	**0.51**	**0.0093**	**1.59**	**Bal**	**0.16**
CPJ-11	**0.15**	**0.41**	**0.10**	**0.23**	**10.18**	**1.35**	**0.21**	**0.051**	**0.022**	**0.60**	**0.0097**	**1.59**	**Bal**	***0.16***
CPJ-12	**0.15**	**0.42**	**0.10**	**0.23**	**10.62**	**0.54**	**0.19**	**0.054**	**0.030**	**0.48**	**0.0097**	**4.67**	**Bal**	**0.18**
CPJ-13	**0.15**	**0.45**	**0.10**	**0.27**	**10.53**	**0.53**	**0.24**	**0.055**	**0.033**	**0.51**	**0.0088**	**6.16**	**Bal**	**0.26**
CPJ-14	**0.15**	**0.44**	**0.10**	**0.26**	**10.74**	**0.52**	**0.20**	**0.053**	**0.038**	**0.50**	**0.0095**	**8.23**	**Bal**	**0.19**

The following elements were also found in the CPJ Steels: Ti (<0.004%), Al (<0.02%), P (<0.003%), O (<36 ppm), S (<58 ppm) and Cu (CPJ-7 = 0.003% & CPJ (8A-14) ≤ 0.03%).

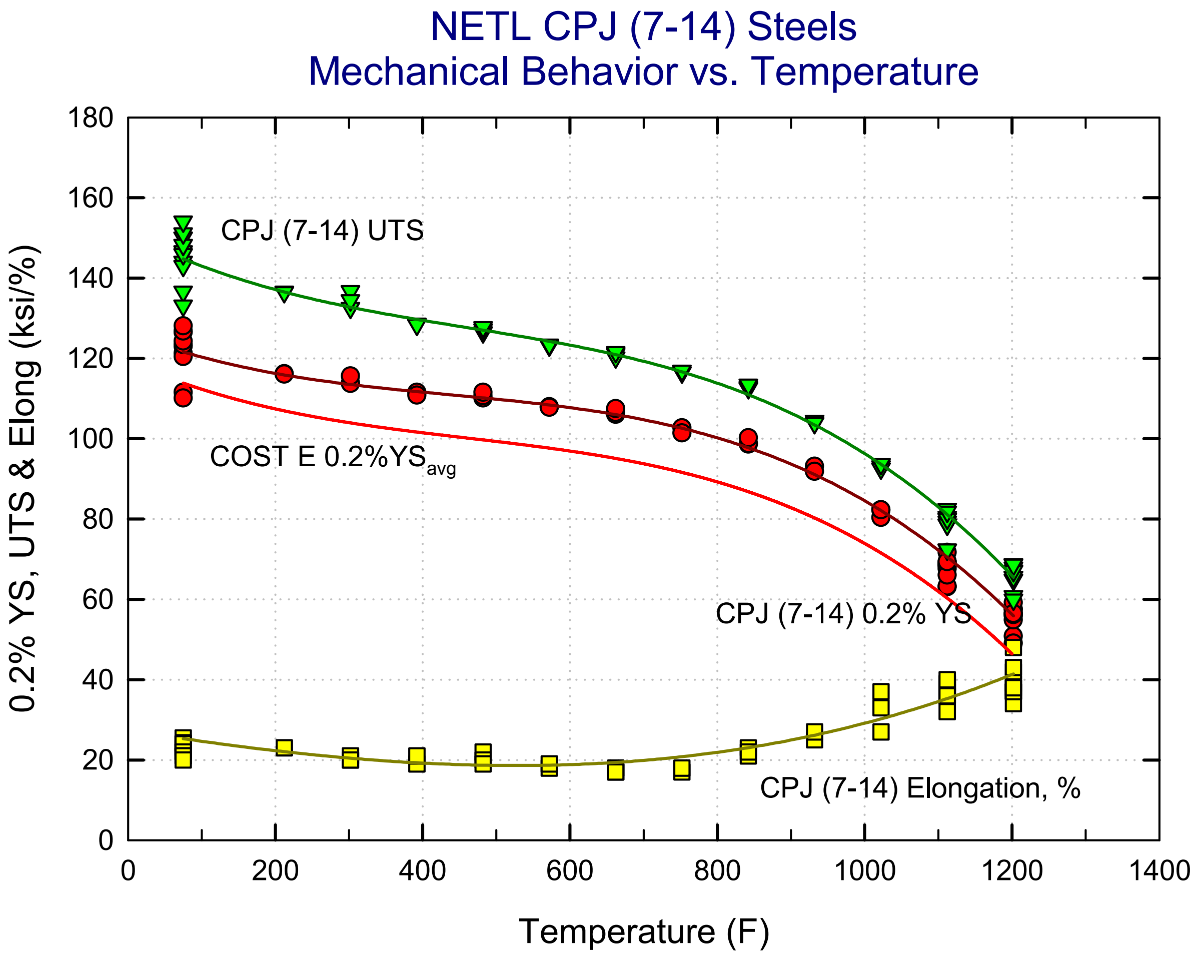
Blue: Cu effect; Red: Co effect; Green: no Ta (#9) or Hf substituted for Ta (#11)

Summary of Tensile Testing Results

		Temperature °C	Yield Stress MPa	Tensile Strength MPa	Elong. %	RA %
CPJ-7	1150°C/30m/AC + 700°C/1h/AC	RT	848	1,011	24	61
		600	494	569	32	81
		650	396	468	37	83
CPJ-8A	1150°C/30m/AC + 700°C/1h/AC	RT	872	1,035	24	60
		600	477	555	37	79
		650	408	474	34	81
CPJ-9	1150°C/30m/AC + 700°C/1h/AC	RT	769	942	22	56
		600	435	499	36	80
		650	350	419	38	85
CPJ-10	1150°C/30m/AC + 700°C/1h/AC	RT	851	1,006	23	64
		600	472	552	39	84
		650	397	463	48	87
CPJ-11	1150°C/30m/AC + 700°C/1h/AC	RT	759	918	22	55
		600	436	499	38	84
		650	338	413	43	89
CPJ-12	1150°C/30m/AC + 700°C/1h/AC	RT	857	1,022	21	55
		600	471	542	36	79
		650	378	452	37	79
CPJ-13	1150°C/30m/AC + 700°C/1h/AC	RT	874	1,042	21	55
		600	455	552	40	78
		650	387	462	37	82
CPJ-14	1150°C/30m/AC + 700°C/1h/AC	RT	883	1,062	20	55
		600	478	564	36	77
		650	389	473	38	80

Blue: Cu effect; Red: Co effect; Green: no Ta (#9) or Hf substituted for Ta (#11)

Summary of Tensile Testing Results



Blue: Cu effect: very little change in tensile behavior (CPJ-7 & 10)

Red: Co effect: tends to increase tensile strength relative to CPJ-7

Green: no Ta or Hf substituted for Ta: lower tensile strength relative to CPJ-7

Summary of 650°C Creep Testing Results

Alloy	Time to Rupture (hours)
COST B2	655
COST FB2	614
CPJ-6	269
CPJ-7	1,454
CPJ-7B	1,514
CPJ-7C	1,774
CPJ-7D	1,732
CPJ-8A	1,276
CPJ-9	1,170
CPJ-10	1,860
CPJ-11	1,181
CPJ-12	649
CPJ-13	393
CPJ-14	235

The different CPJ formulations looked at variations in Co level: CPJ 8A,12-14 (increasing levels of Co from about 2.93 w/o up to 8.25 w/o, remaining elements roughly the same).

Also, Cu was added up to 0.03 w/o in CPJ formulations 8A-14, with CPJ-10 based on CPJ-7 except for Cu level (10x greater at 0.03 w/o than CPJ-7).

The CPJ-8A steel had approximately 2X the Co level as CPJ-7 and approximately ½ the Mo equivalent at 0.75 w/o.

CPJ-9 was roughly the same as CPJ-7 except Ta was not used. This was a direct assessment of Ta on tensile and creep strength.

The CPJ-11 steel utilized Hf instead of Ta.

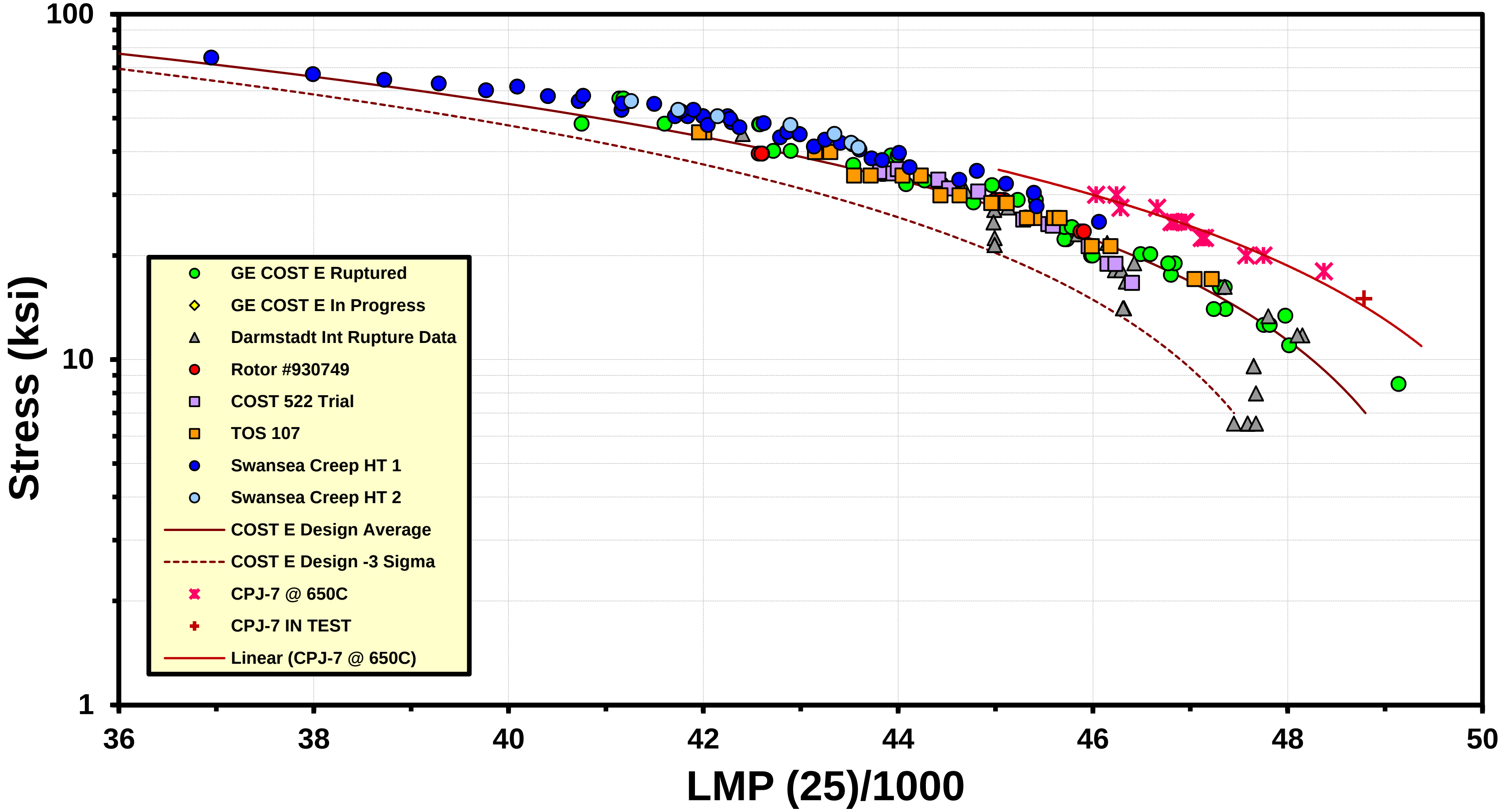
Blue: Cu effect; Red: Co effect; Green: no Ta or Hf substituted for Ta

Summary of 650°C Creep Testing Results

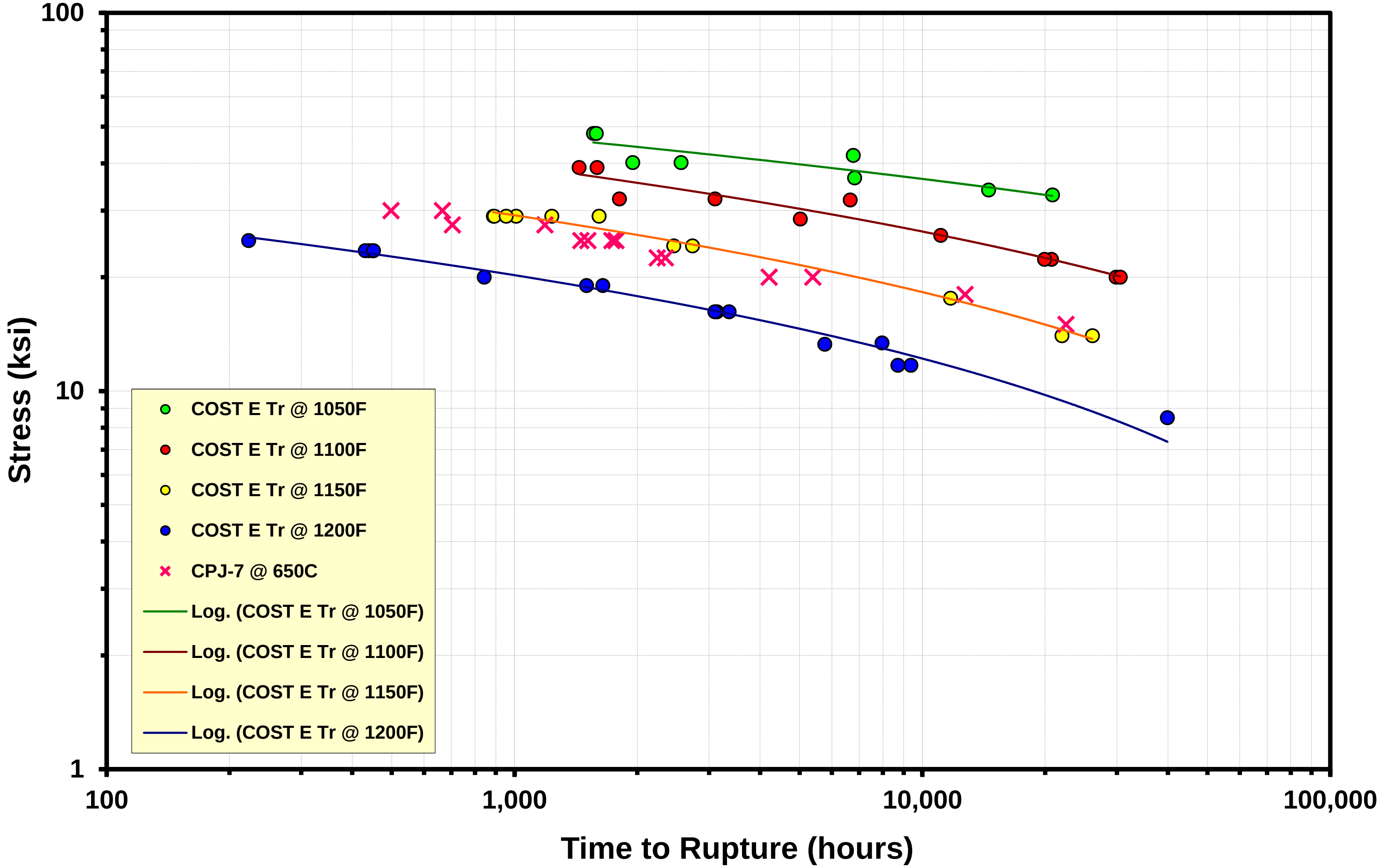
Alloy	Stress (ksi)	Stress (MPa)	Time to Rupture (hours)
CPJ-7	30.0	206.8	666
CPJ-7B	30.0	206.8	498
CPJ-7	27.5	189.6	1,118
CPJ-7E-5	27.5	189.6	704
CPJ-7	25.0	172.4	1,454
CPJ-7B	25.0	172.4	1,514
CPJ-7C	25.0	172.4	1,774
CPJ-7D	25.0	172.4	1,732
CPJ-7	22.5	155.1	2,344
CPJ-7D-5	22.5	155.1	2,239
CPJ-7	20.0	137.9	5,388
CPJ-7E-3	20.0	137.9	4,210
CPJ-7	18.0	124.1	12,727
CPJ-7	*15.0*	*103.4*	*24,866**

*** CPJ-7 alloys still in test as of 4/14/2014.**

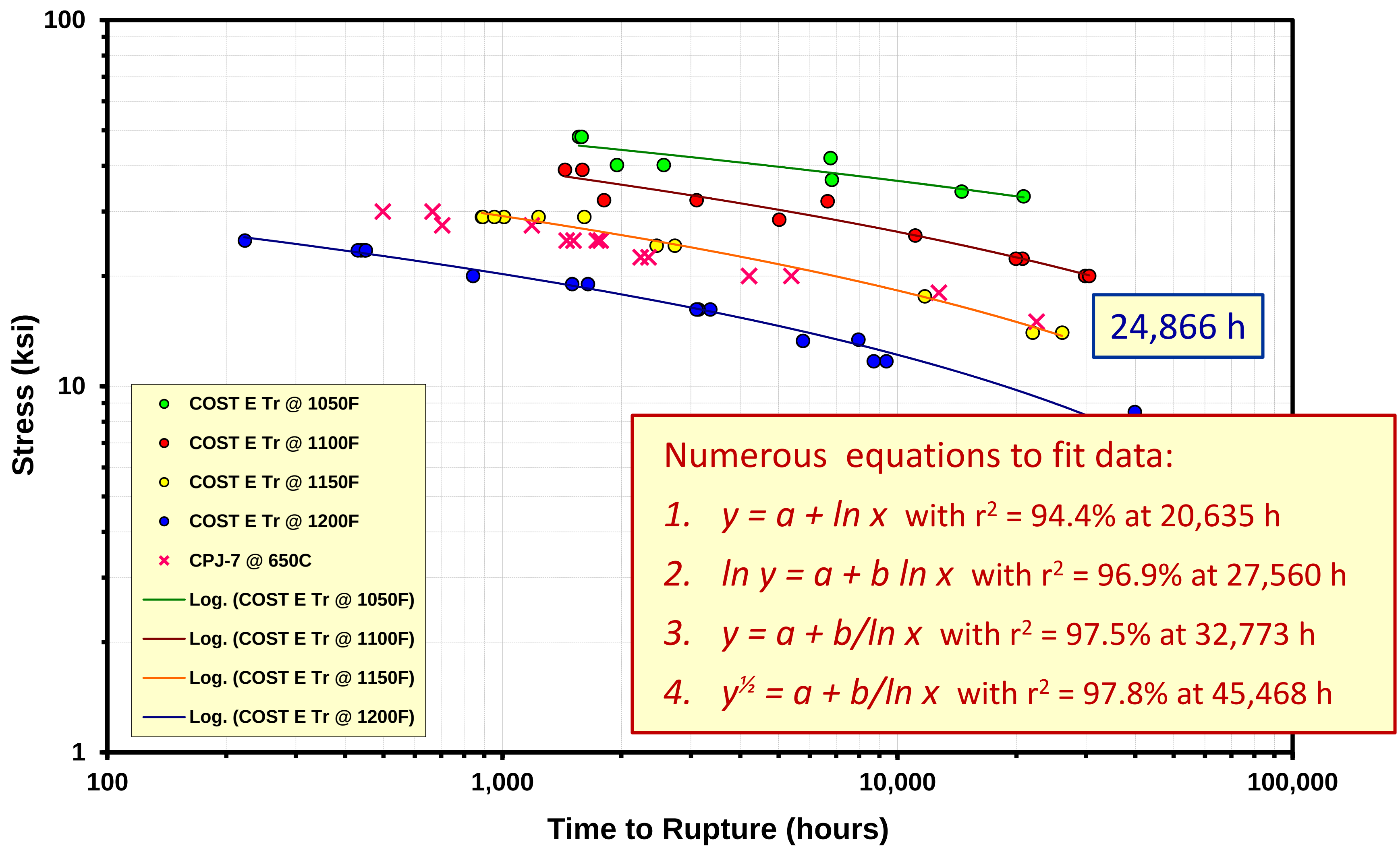
LMP for COST E & CPJ7



Larson-Miller Parameter plot for COST E at temperatures from 1050°F (565.5°C) to 1200°F (648.9°C). Note the data points (x ; +) for CPJ steel (as of 4/14/2014).



Isothermal creep curves for COST E at temperatures from 1050°F (565.5°C) to 1200°F (648.9°C). Note the data points (x) for CPJ steel (as of 4/14/2014).

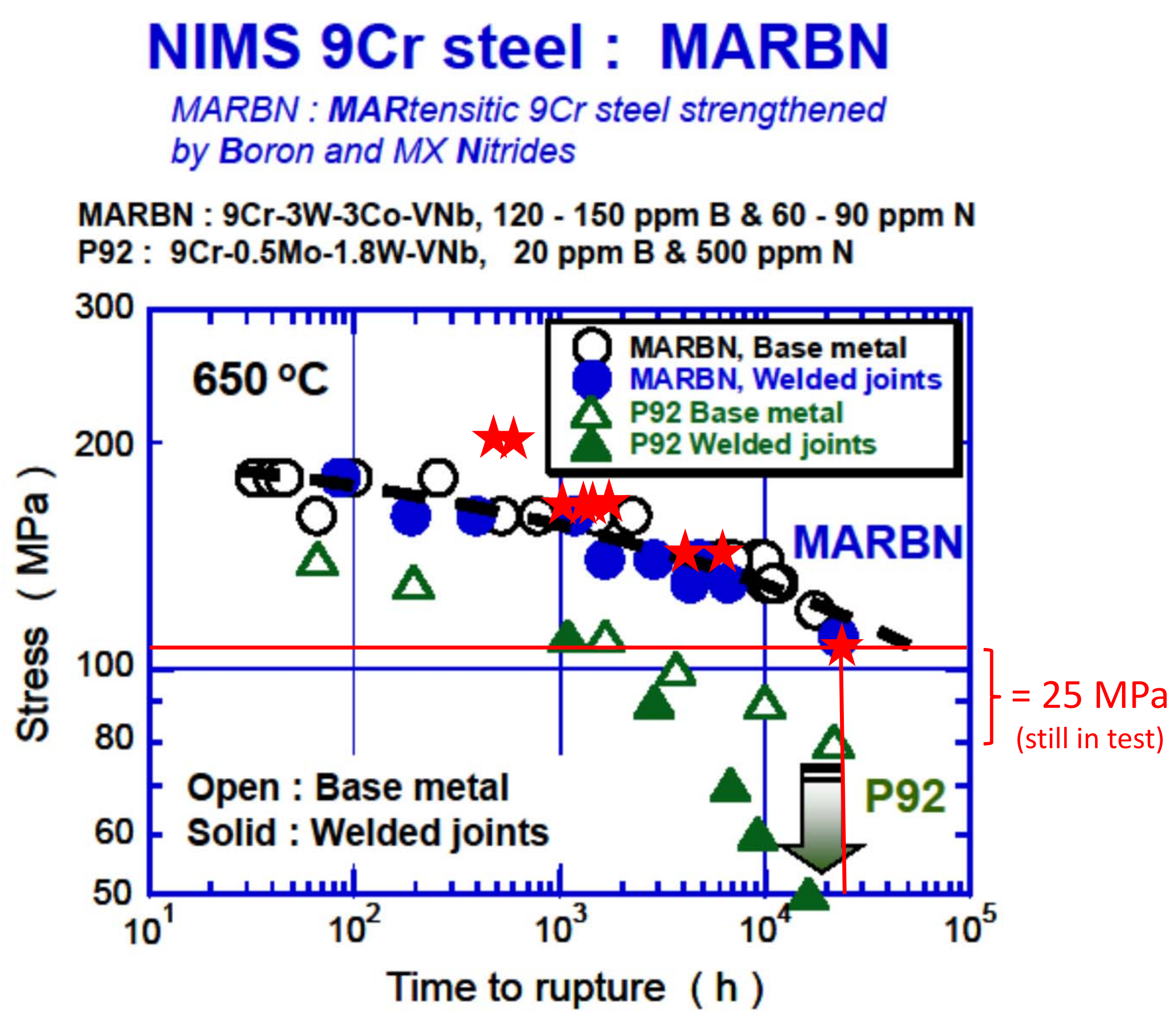


Numerous equations to fit data:

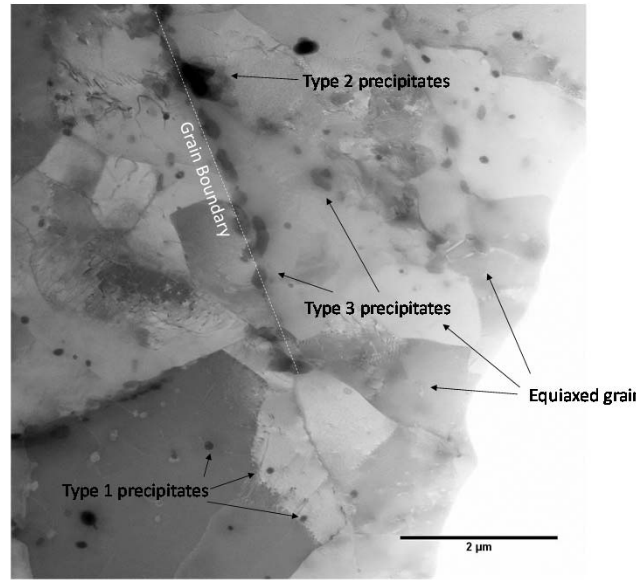
1. $y = a + \ln x$ with r^2 = 94.4% at 20,635 h
2. $\ln y = a + b \ln x$ with r^2 = 96.9% at 27,560 h
3. $y = a + b/\ln x$ with r^2 = 97.5% at 32,773 h
4. $y^{½} = a + b/\ln x$ with r^2 = 97.8% at 45,468 h

Isothermal creep curves for COST E at temperatures from 1050°F (565.5°C) to 1200°F (648.9°C). Note the data points (x) for CPJ steel (as of 4/14/2014).

CPJ7 vs State-of-Art Experimental Boiler Steel MARBN

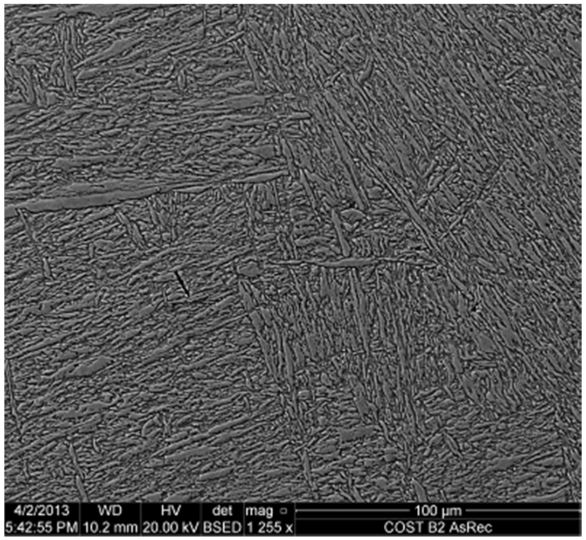


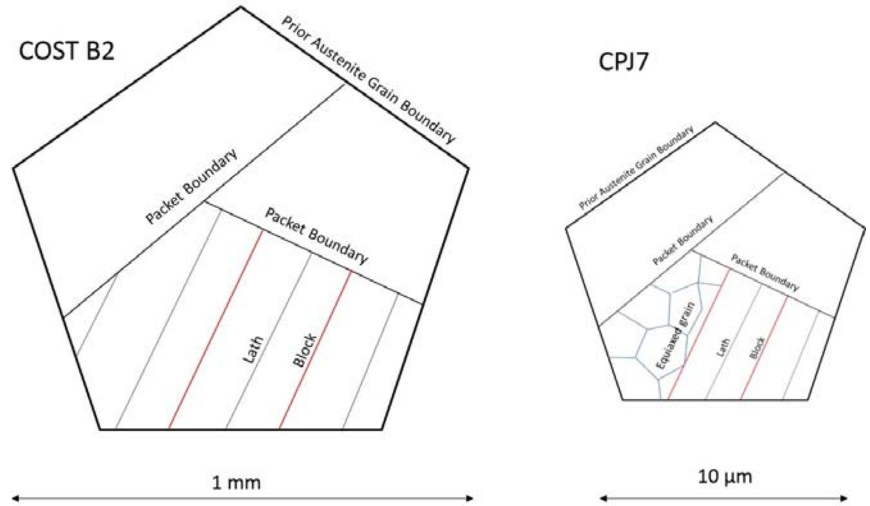
TEM of the CPJ-7 Steel Structures



Precipitate	Phase	Elements	Shape	Location
1	Laves	Ta, Nb, Fe	Spherical/ Ellipsoidal	Grain & PAG
2	$M_{23}C_6$	Cr, W, Mo, Fe	Irregular (coarsened)	PAG & Packet
3	$M_{23}C_6$	Cr, W, Mo, Fe	Plate	Lath, Packet & PAG boundaries

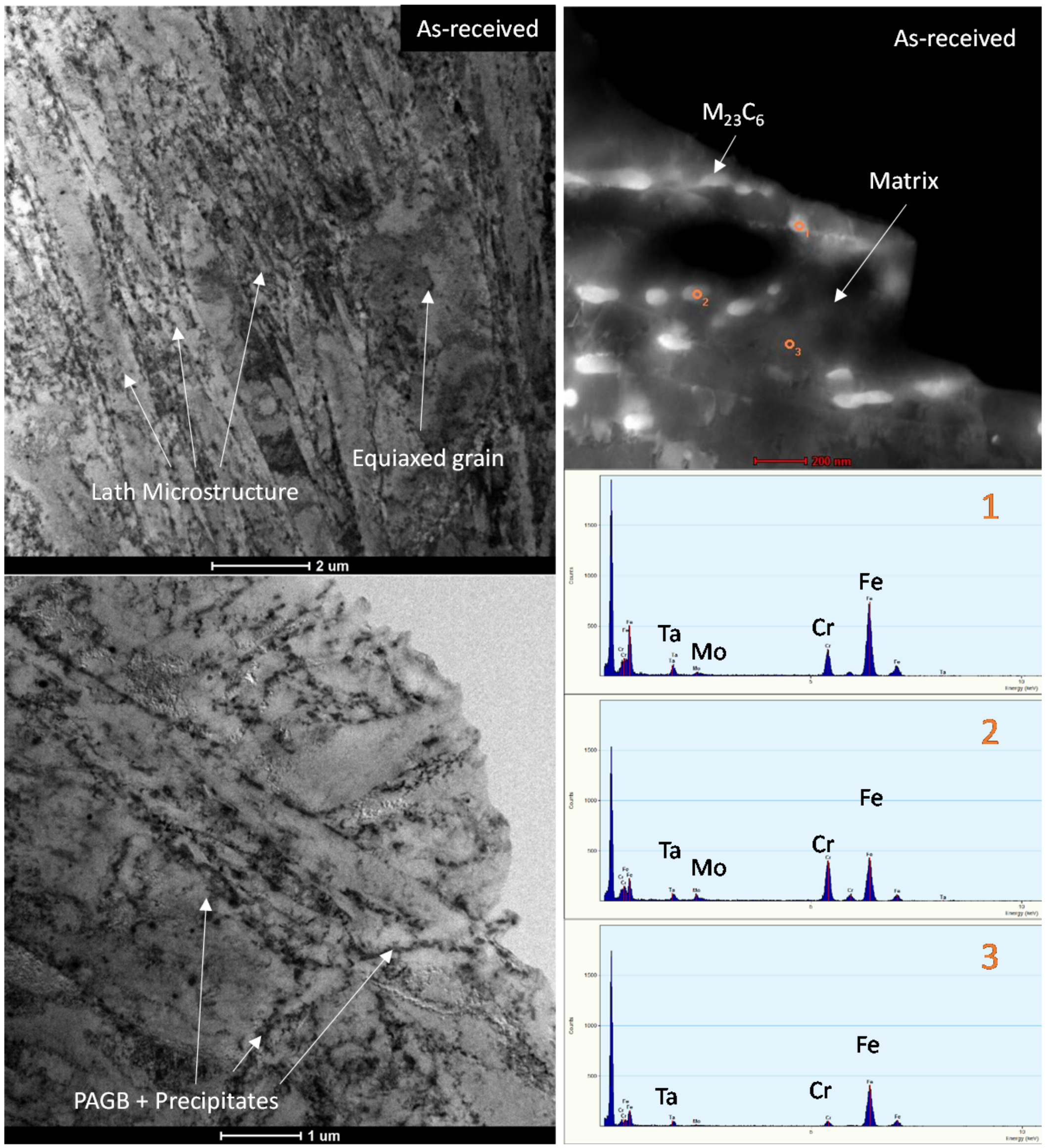
Comparison Structure CPJ-7 Steel vs. COST B2



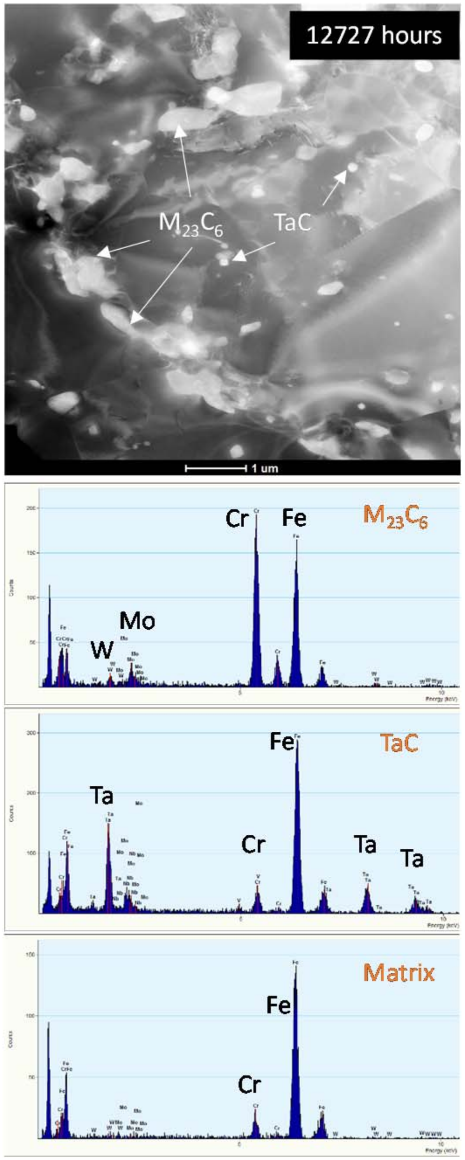


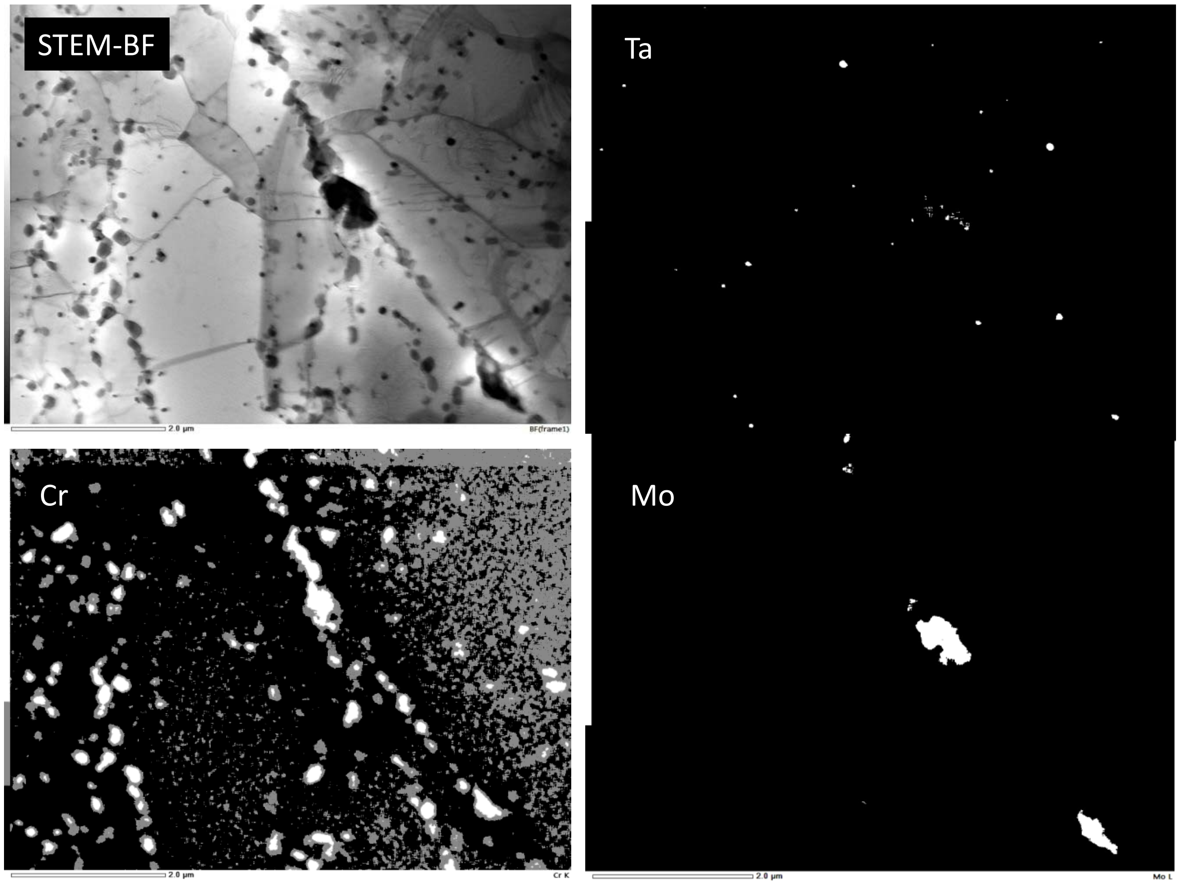
Microstructure Feature	COST B2	CPJ-7
Matrix Phase	Martensite	Martensite + Retained Ferrite or Recrytallized Grains
Prior Austenite Grain (PAG)	1 mm	6 – 15 µm
Lath Size	1 – 2 µm	1 – 2 µm
Precipitates	$M_{23}C_6$	$M_{23}C_6$ + Laves
Precipitate Location	Grain Boundaries (GB)	GB + Grain Interiors
Dislocation Density	High (due to martensitic transformation)	Mixed – Low in equiaxed grain regions & high in martensitic regions
Probable Creep Resistance Mechanisms	Boundary precipitates & high dislocation density*	Boundary precipitates, including Laves*

CPJ-7 -- Lath & Equiaxed Grains



CPJ-7 -- Effect of Ta Addition

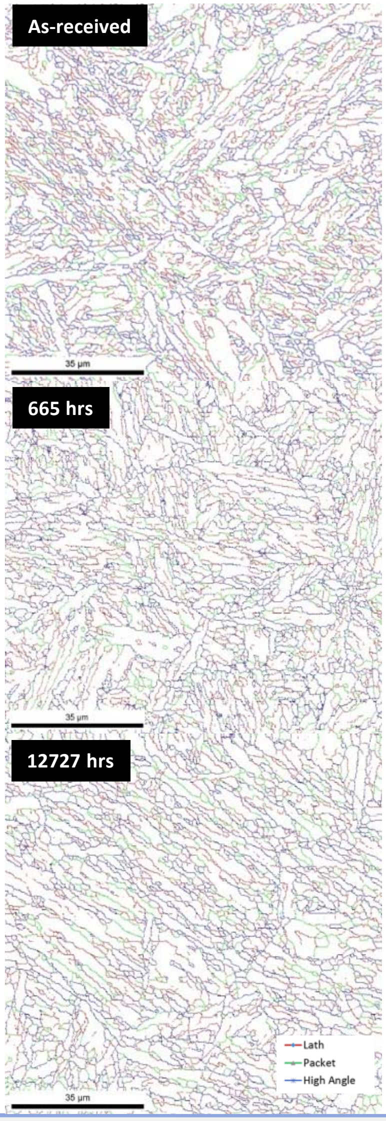


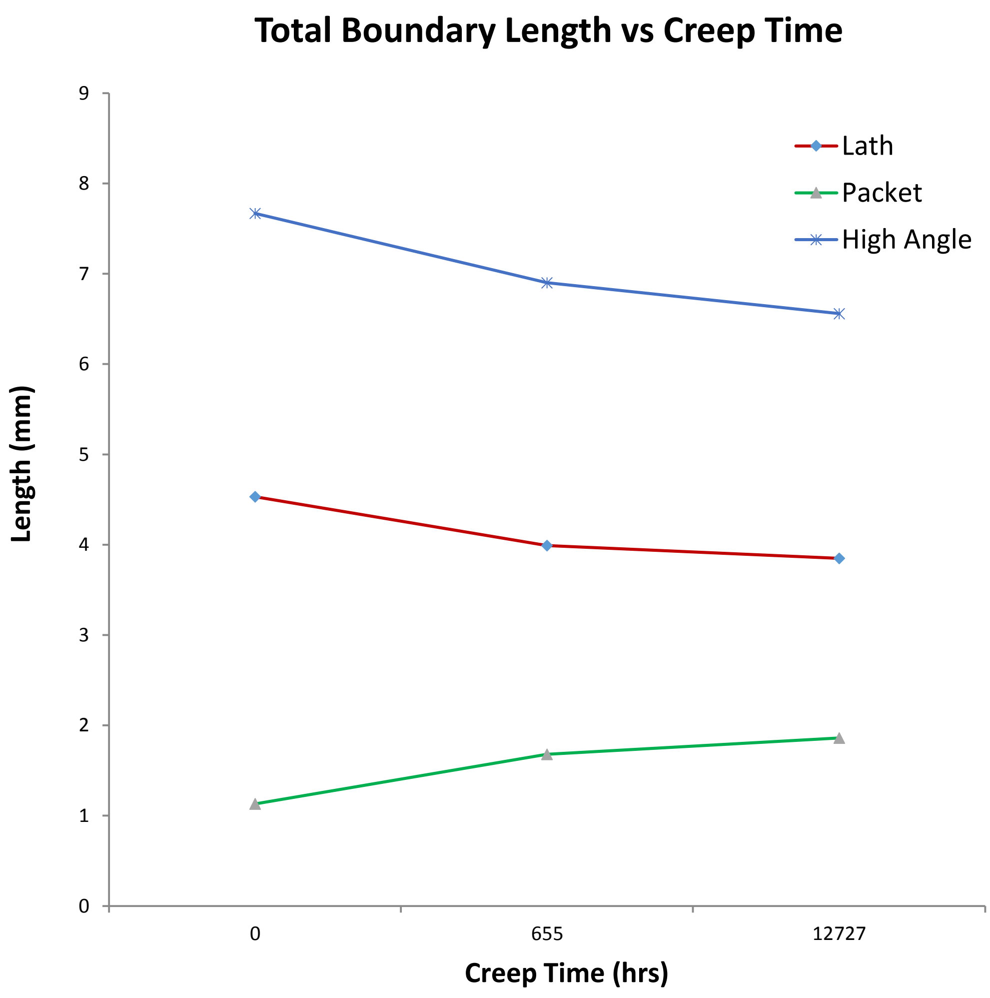


(Top left) STEM-BF of CPJ7 creep tested for 2344 h. Elemental maps showing precipitates rich in Ta (upper right), Mo (lower right), and Cr (lower left). White areas of the Cr map show areas of high concentration of while grey areas are low concentration. This map demonstrates the capability of 3D chemical mapping in electron tomography.

CPJ-7 Feature Boundary Lengths vs. Creep Time

Grain Boundary Type





Research on CPJ-7 Ferritic-Martensitic Steels

- Identified promising chemistry for ferritic-martensitic steel, CPJ-7, based on controlling minor alloying additions (C, Cu, Ta) and B/N levels.
- Developed manufacturing approach to consistently produce CPJ-7.
- Utilized NETL homogenization step in conjunction with thermo-mechanical processing to set and stabilize microstructure.
- Tested CPJ-7 chemistry robustness by varying select combinations of alloying additions: $Mo_{(eqv)}$; C + N level; B level – producing and testing four additional CPJ-7 heats.
- Assessed other minor element additions and extent of those additions on tensile and creep strength of CPJ-7 base alloy.
- Evaluated critical microstructural features as a function of creep time at 650°C; assessed microstructure against COST B2.
- CPJ-7 creep performance compares favorably to MARBN experimental steel.