Power Systems Advanced Crosscutting Research Program:

Innovative Process Technologies

Task 3.0 – Materials: Design & Manufacturing Process Development

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

2015 NETL Crosscutting Research Review Meeting

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Task 3.0 – Materials: Design & Manufacturing Process Development.

- **Robert Romanosky**
- **Charles Miller**
- **Vito Cedro**

Materials: Design & Manufacturing Process Development

- **Advanced Martensitic-Ferritic Steels**

  Jeffrey Hawk, Paul Jablonski, Gordon Holcomb

- **Superalloy Design & Development**

  Paul Jablonski, Joseph Licavoli, Jeffrey Hawk, Gordon Holcomb

- **Advanced Fossil Energy Concepts**

  Joseph Licavoli, Paul Jablonski, Jeffrey Hawk, Michael Gao, Gordon Holcomb

- **Computational Aspects in Alloy Design & Life Predicition**

  You-hai Wen, Tian-le Cheng, Michael Gao

Joseph Tylczak	Chris Powell	Richard Gregory
Casey Carney	Ed Argetsinger	Dennis Burkey
John Sears	Joe Mendenhall	Jeff Briscoe

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

Jeffrey A. Hawk, Paul D. Jablonski and Gordon R. Holcomb

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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, 620°C is the approximate projected maximum use temperature due to concerns about the long-term microstructural instability of the heat resistant steel.

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 computationally optimized 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

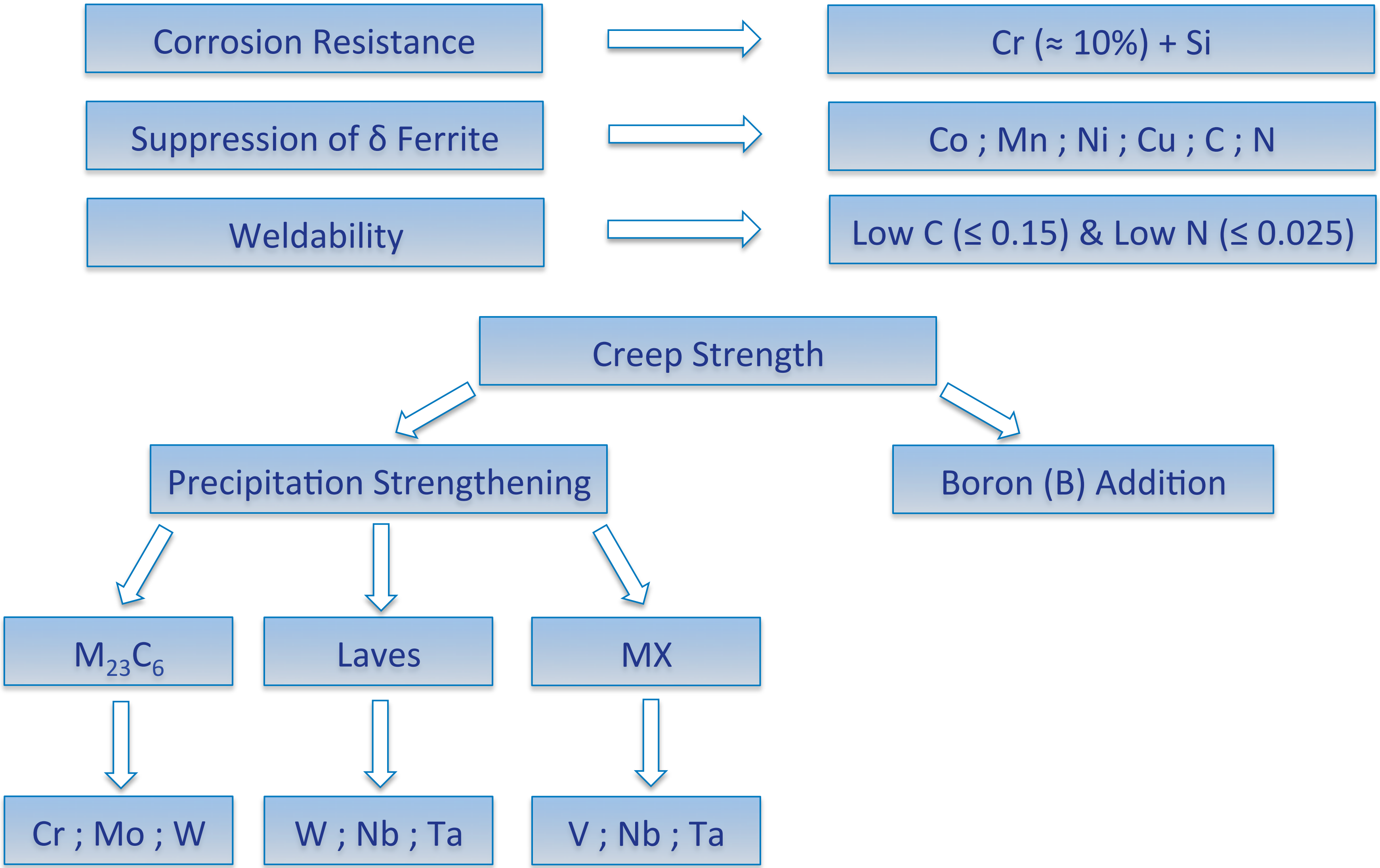
General Technical Approach

- **Understand basic high temperature strengthening mechanisms & how to preserve strengthening effect through microstructural control.**

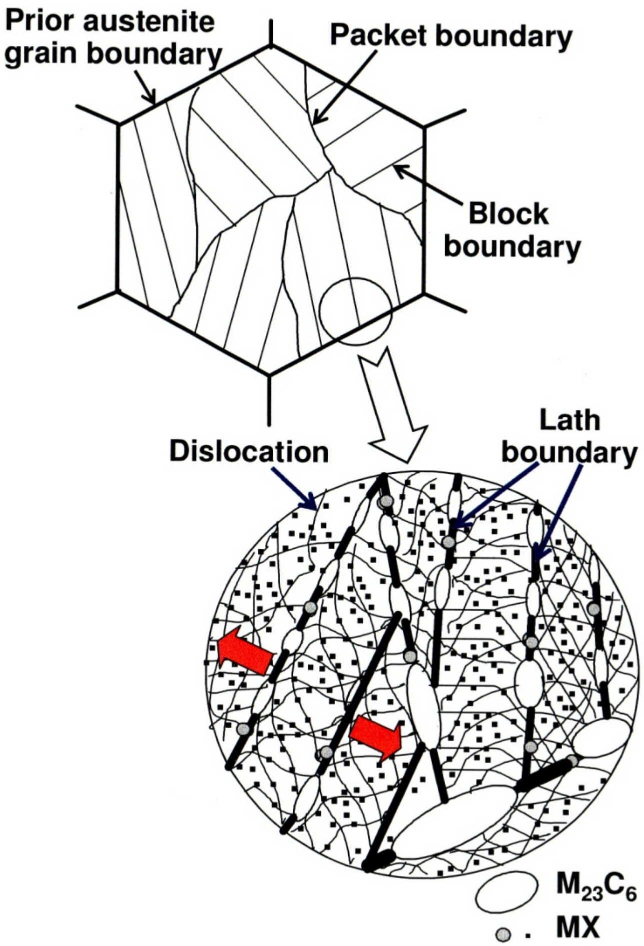
- **Achieve balance between the following competing effects:**
  - ***Necessary C, V, Nb, (and/or Ta) and N to generate MX (M: is metal and X: is C/N), thereby, slowing down dislocation movement in the matrix during creep.***
  - ***Balanced amount of Mo and W for solution & precipitation hardening (with Cr) 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.***
  - ***Higher level of Cr for oxidation resistance (however, Cr additions significantly greater than 9% reduce creep strength).***
  - ***Addition of 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).

Fundamentals of CPJ-7 Design



Microstructural Hierarchy of 9-12%Cr Steels



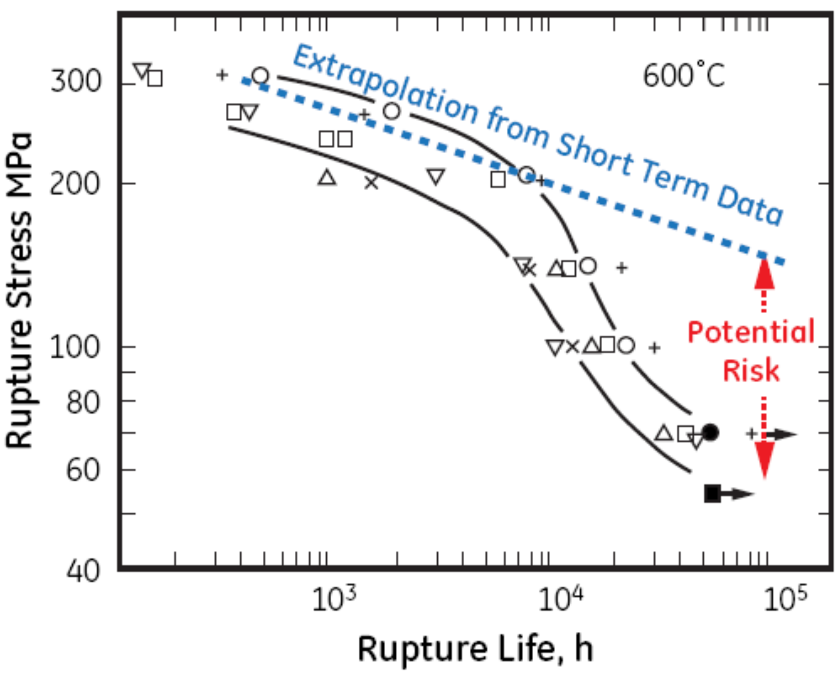
1. Prior austenite grain with associated grain boundaries.
2. Packet boundaries
3. Block boundaries
4. Lath boundaries
5. $M_{23}C_6$ carbides to stabilize lath, block, packet, and PAG boundaries
6. MX carbides to provide obstacles to dislocation motion
7. Dislocations

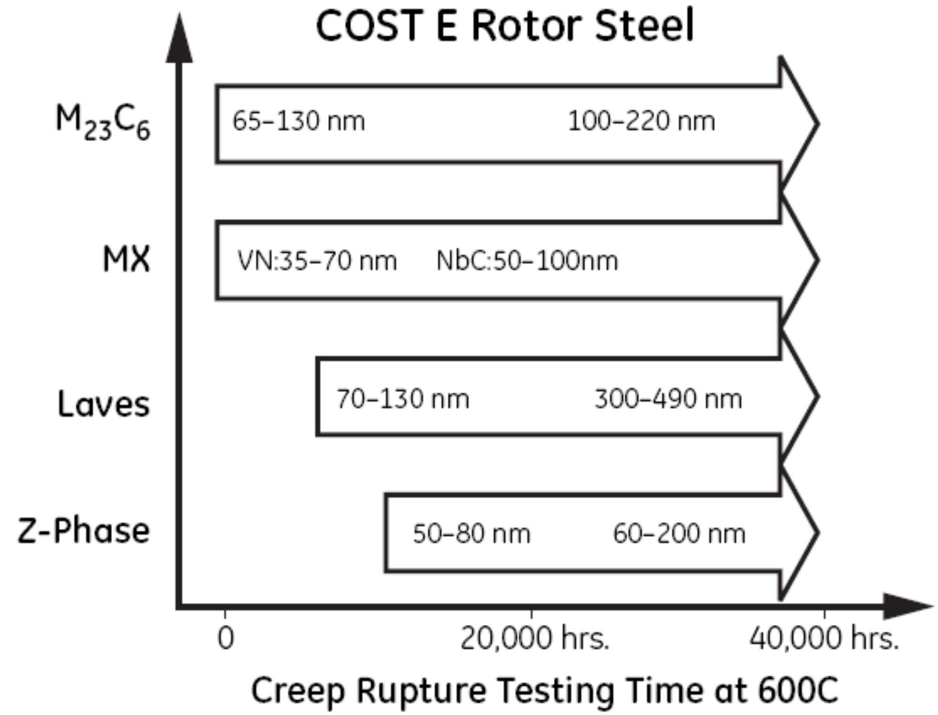
The breakdown of any of these microstructural features will destabilize the alloy and lead to increased creep rate over time. The goal of alloy design is to slow down the destabilization of these features starting with the MX and $M_{23}C_6$ particles.

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



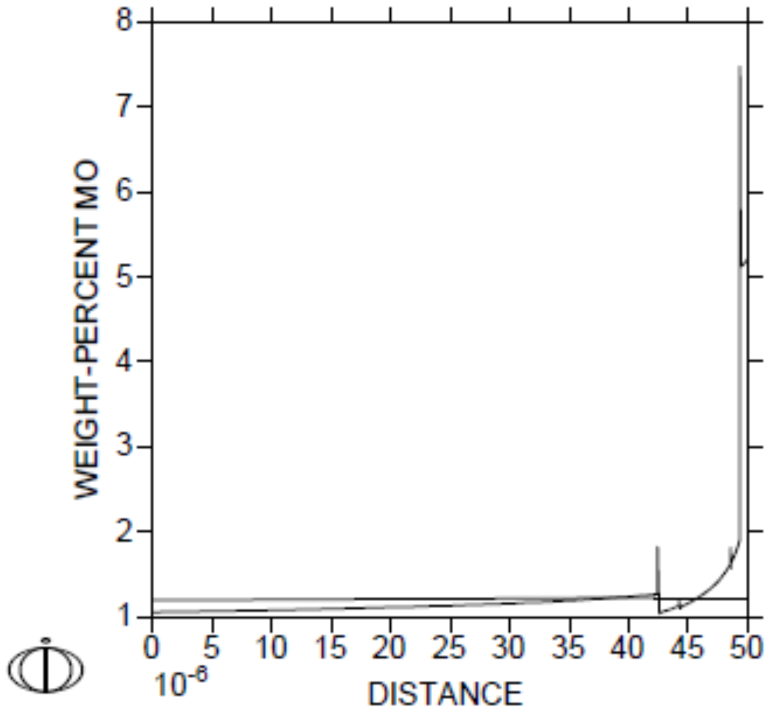


Many competing effects occur in heat resistant steels of the 9% Cr variety. Past experience has shown that the instability of any of the following, Z-phase, Laves, MX and/or $M_{23}C_6$, can cause an unexpected decrease in rupture stress as a function of time. The goal of alloy design is to slow down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

Heat Resistant Steels for 650°C Power Plants

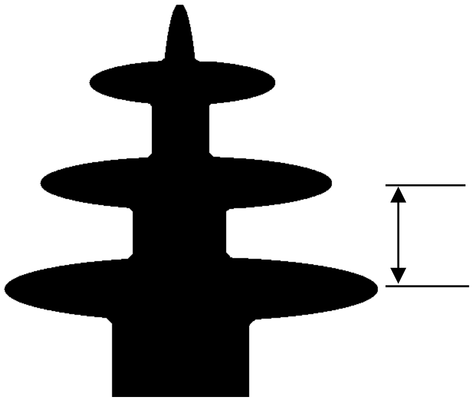
NETL alloy manufacturing approach focuses on homogenization step in which the incremental liquid chemistry is used to characterize the entire resulting solid inhomogeneity.

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.



secondary dendrite arm spacing, *sdas*

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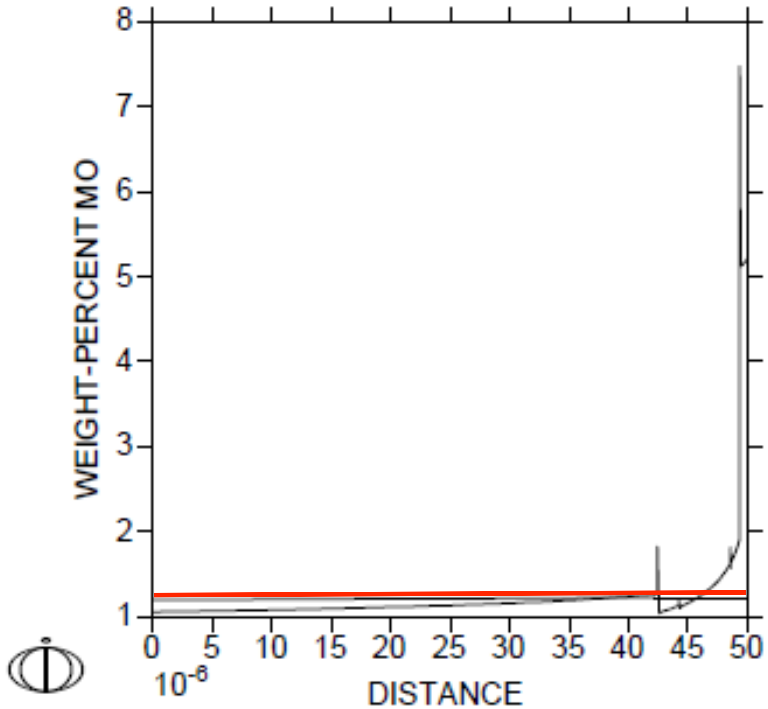

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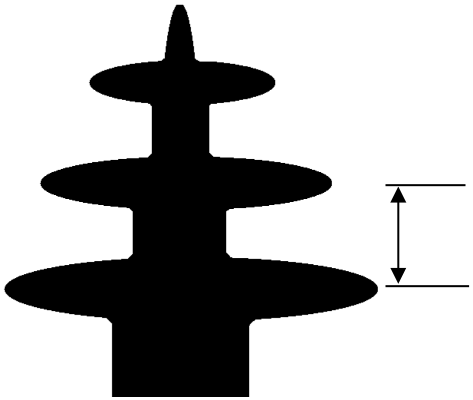
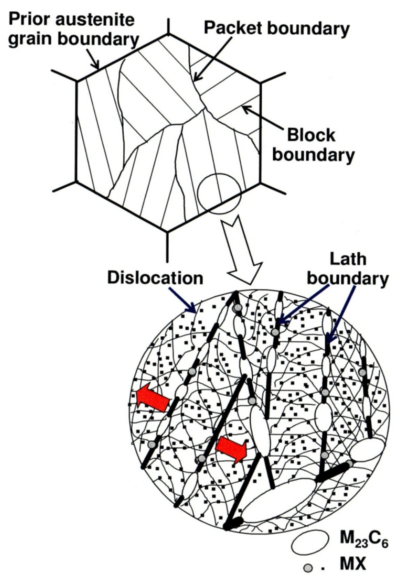


secondary dendrite arm spacing, *sdas*

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

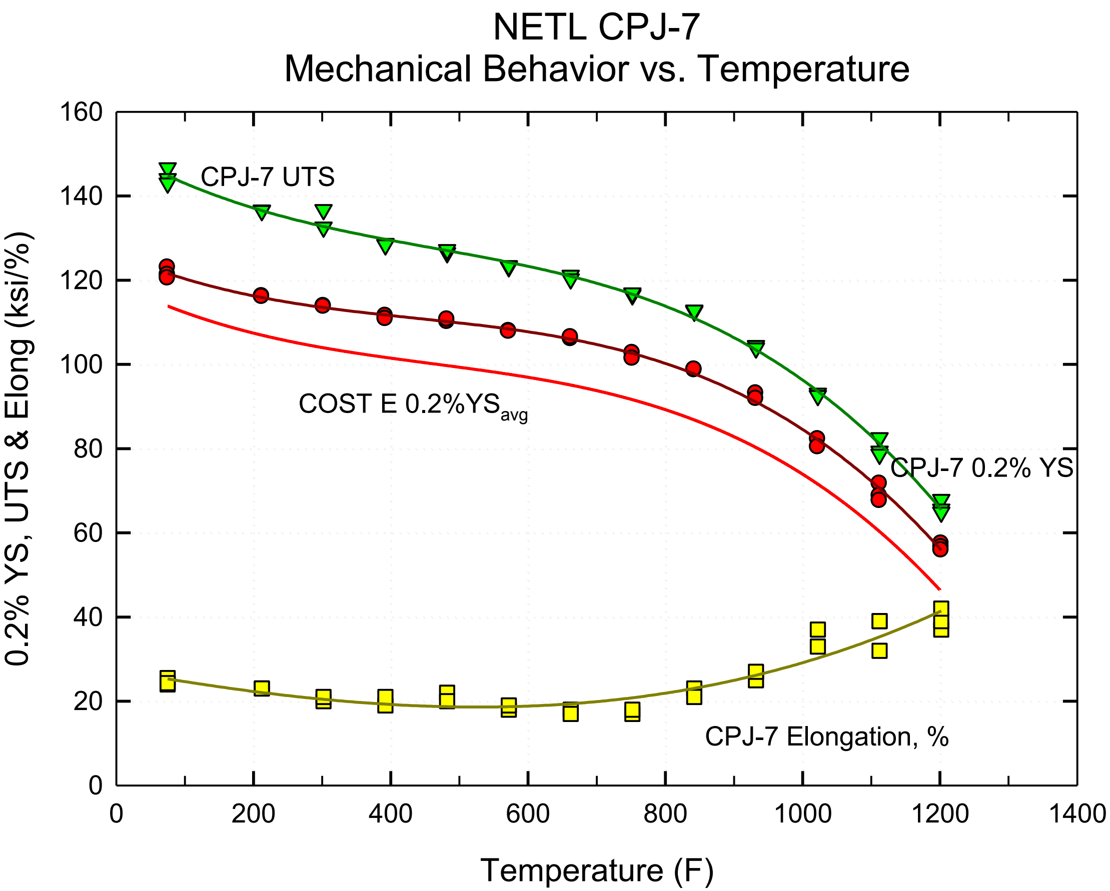
The following elements were also found in the CPJ-7 Alloys: Ti (<0.004%), Al (<0.02%), P (<0.003%), Cu (<0.003%), O (<36 ppm), and S (<58 ppm).



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



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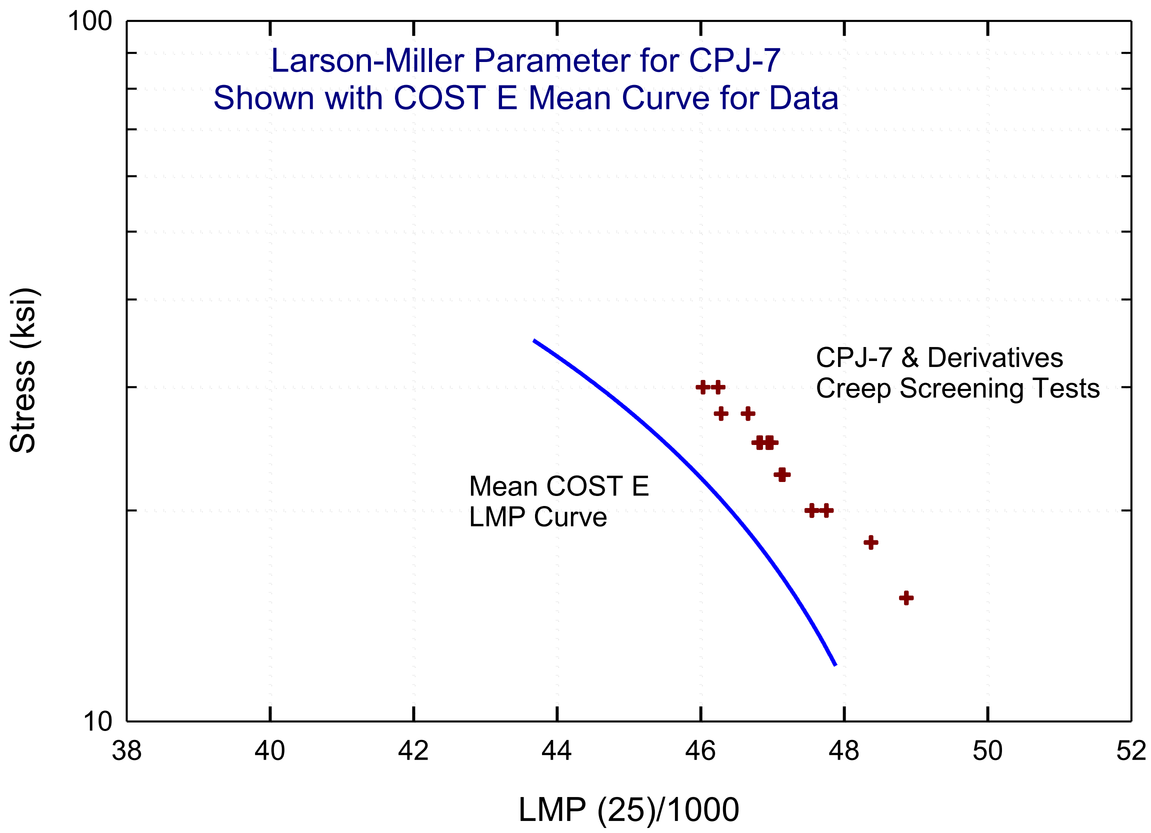
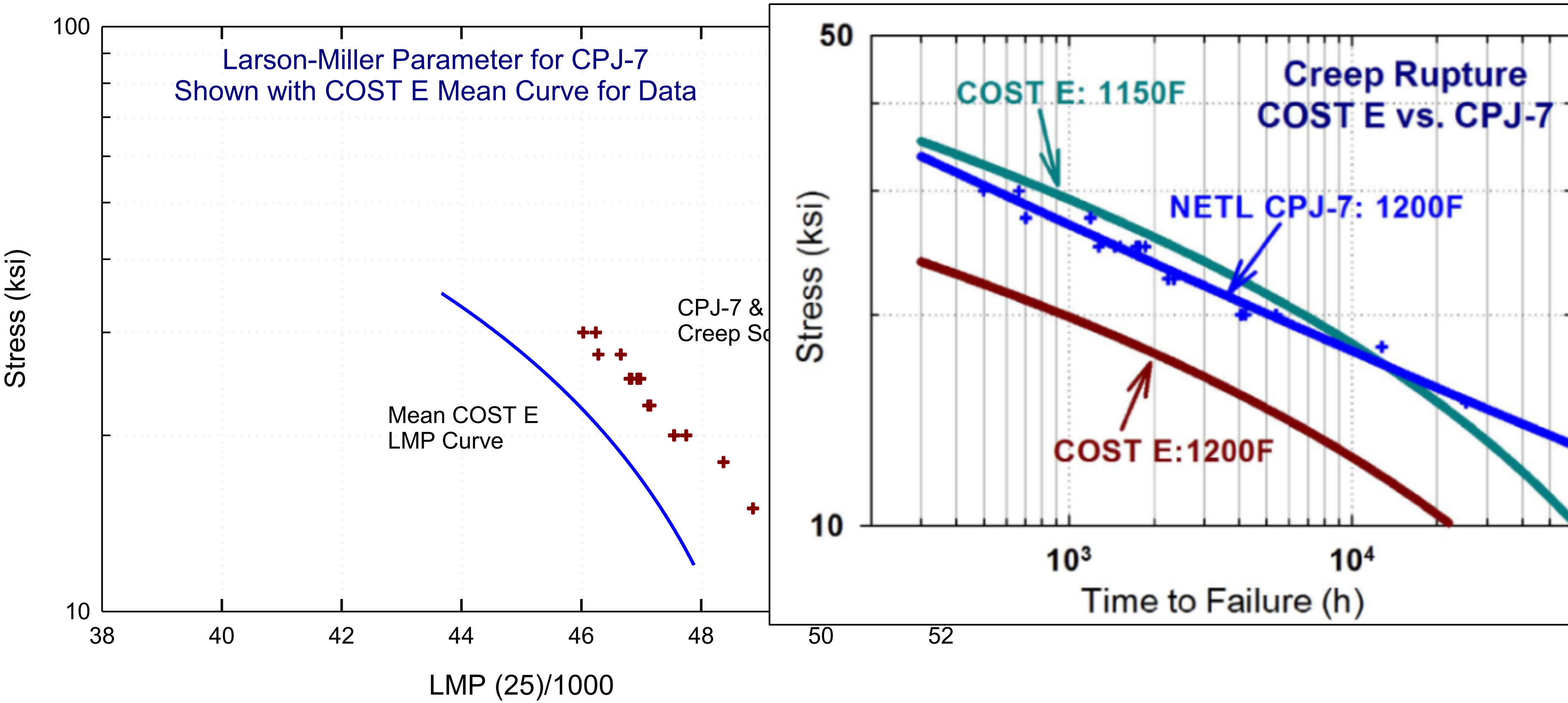
Larson Miller Parameter for COST E Steel & Wrought CPJ-7 Steel



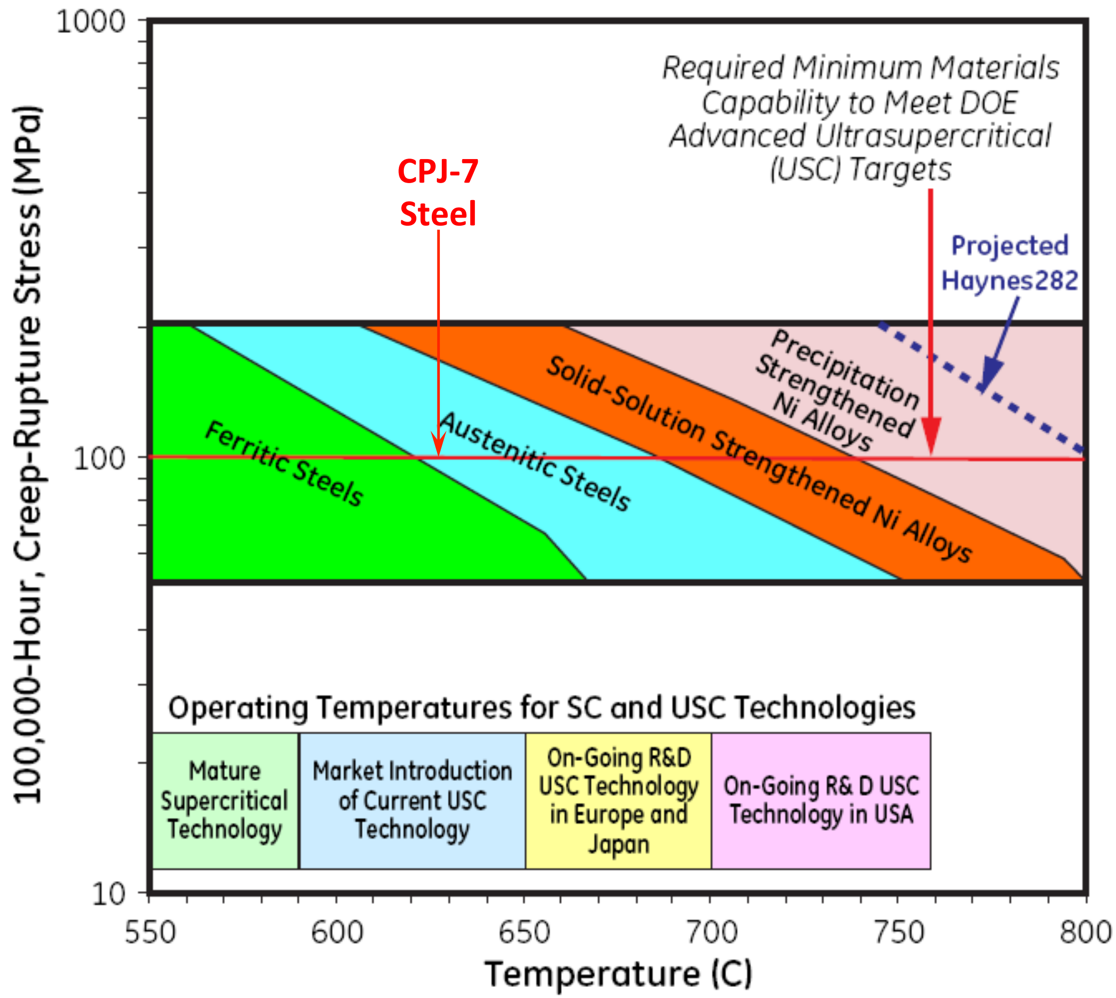
Larson-Miller Parameter plot for COST E at temperatures from 1050°F (565.5°C) to 1200°F (648.9°C). CPJ-7 testing performed at 650°C only.

Larson Miller Parameter for COST E Steel & Wrought CPJ-7 Steel



Larson-Miller Parameter plot for COST E at temperatures from 1050°F (565.5°C) to 1200°F (648.9°C). CPJ-7 testing performed at 650°C only.

Wrought CPJ-7 vs Current Materials Used for Steam Turbine Rotors in Power Plants



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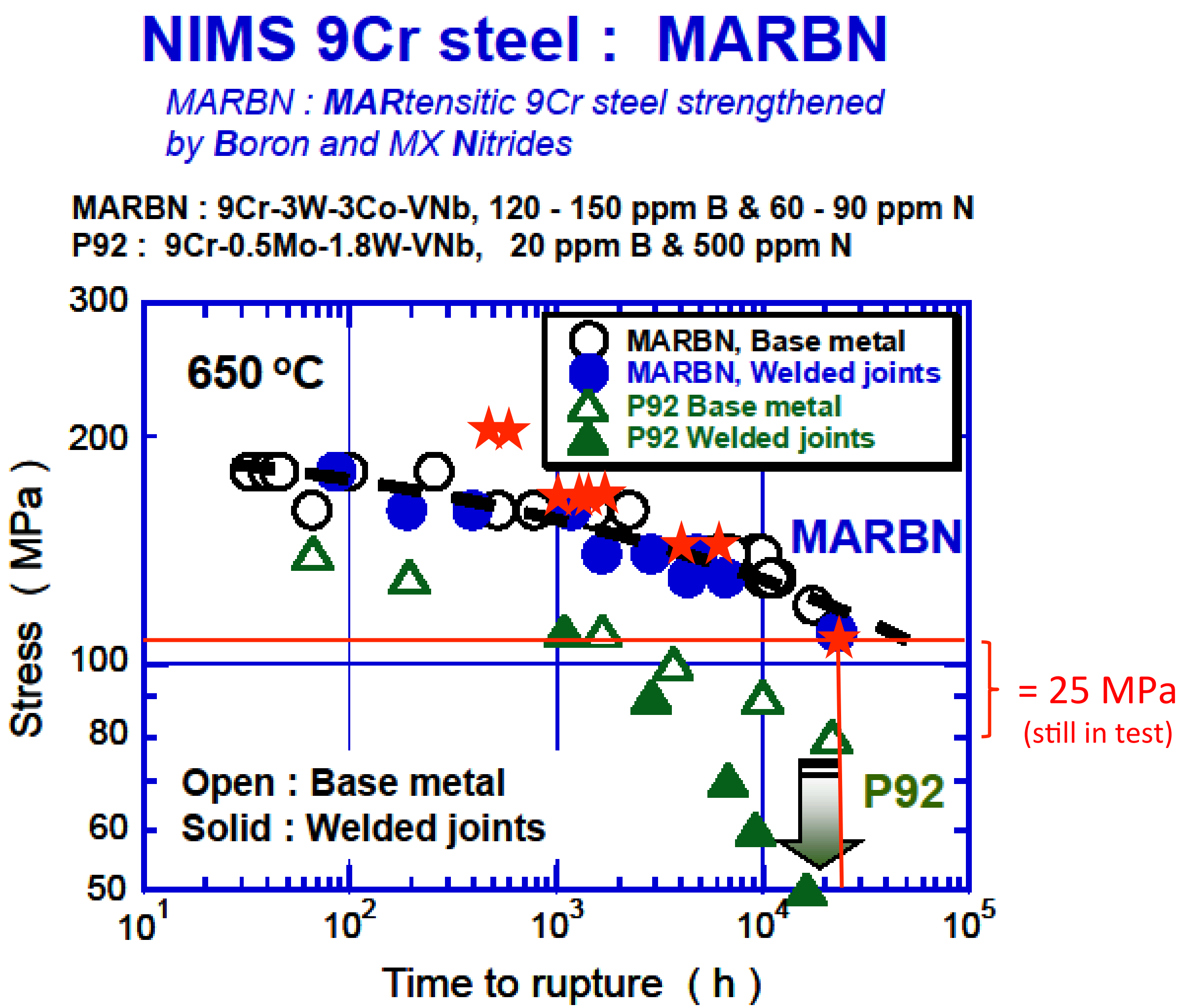
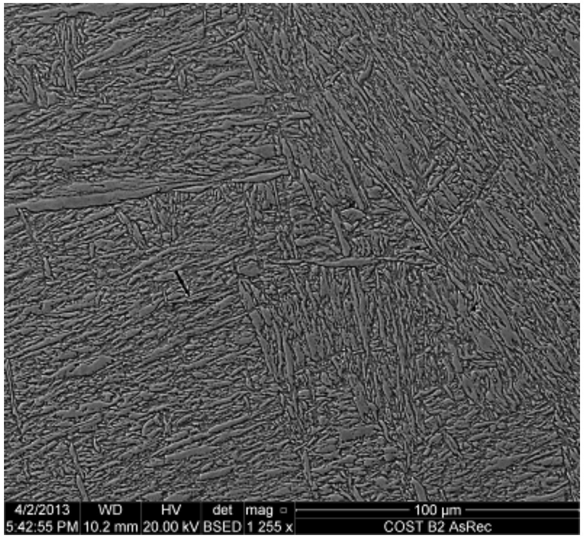
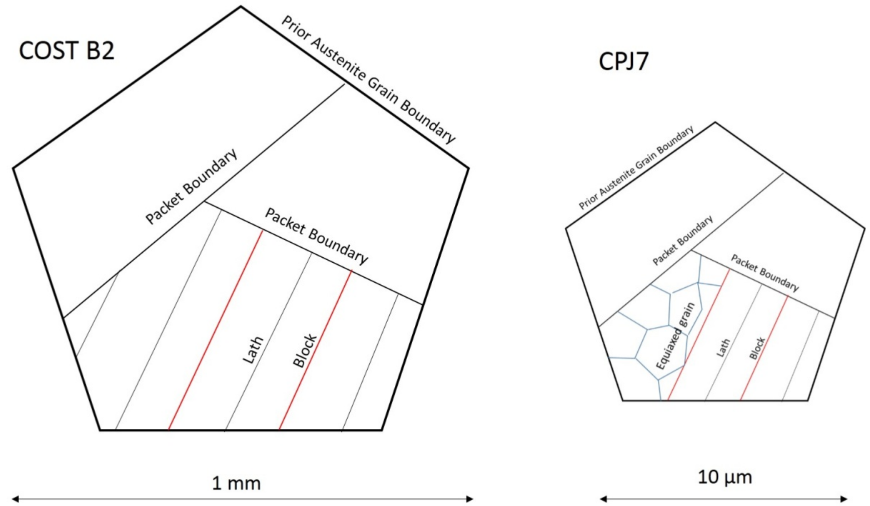
CPJ7 vs State-of-Art Experimental Boiler Steel MARBN



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*

Fireside Corrosion

- **Comparison of air-fired and oxy-fired (hot gas recycle case) conditions to examine**
  - The effects of temperature (650 to 800°C)
  - Alkali sulfate flux to the alloy surface
  - Mo content in Ni-22Cr alloys
  - **NETL developed alloy CPJ7B in comparison to T92**
- **Flue gas compositions**
  - **Air-firing: N_2-14CO_2-9H_2O-2.5O_2-0.3SO_2**
  - **Oxy-firing: CO_2-8N_2-20H_2O-2.5O_2-0.9SO_2 (hot gas recycle)**
  - **Simplified from earlier research, as flue gas compositions were not found to change overall corrosion rates (at 700°C)**

Alloys and Ash Compositions (wt%)

Alloy	Fe	Cr	Ni	Co	Mo	C	Si	Ti	Al	Mn	V	Nb+Ta	Cu	Other
T92	Bal	9.08	0.25	0.01	0.45	0.081	0.09		0.01	0.40	0.21	0.07		1.80 W
CPJ7B	Bal	9.83	0.27	1.48	1.26	0.15	0.09	0.004	< 0.02	0.41	0.21	0.336	0.03	0.48
740H	0.7	25	Bal	20	0.5		0.15	1.35	1.35	0.3		1.5		
NiCrMo1		22.18	Bal		0.02	0.043		0.01	0.08			0.01	0.01	11 ppm S
NiCrMo2		22.04	Bal		0.99	0.050			0.07			0.02	0.01	4 ppm S
NiCrMo3		22.04	Bal		7.77	0.052			0.07			0.01		11 ppm S

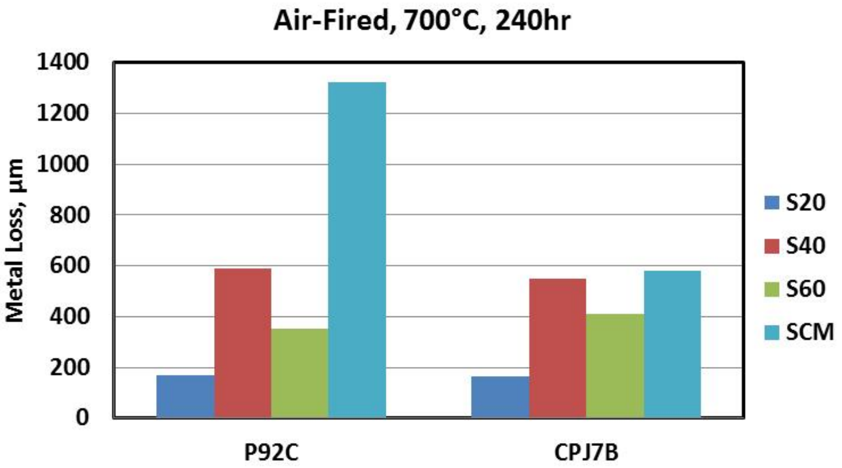
* Met target Cr, Mo, and C levels in Ni-22Cr-xMo model alloys. Low S levels obtained.

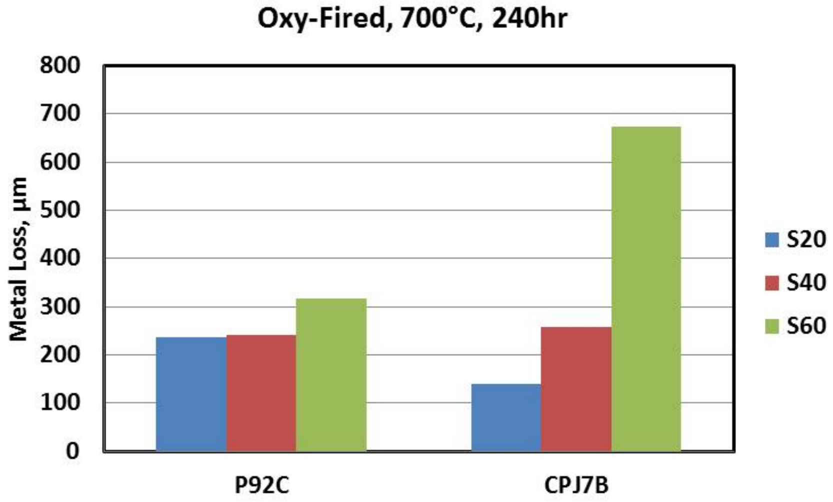
Ash Compositions

- **Maintain 3:1 ratio of $(Na,K)_2SO_4$:Fe_2O_3 as found in lowest melting point alkali iron trisulfates**
- **Different alkali sulfate fluxes to alloy surfaces**

ID	Al_2O_3	SiO_2	Fe_2O_3	Na_2SO_4	K_2SO_4
SCM	0	0	25	37.5	37.5
S80	10	10	20	30	30
S60	20	20	15	22.5	22.5
S40	30	30	10	15	15
S20	40	40	5	7.5	7.5

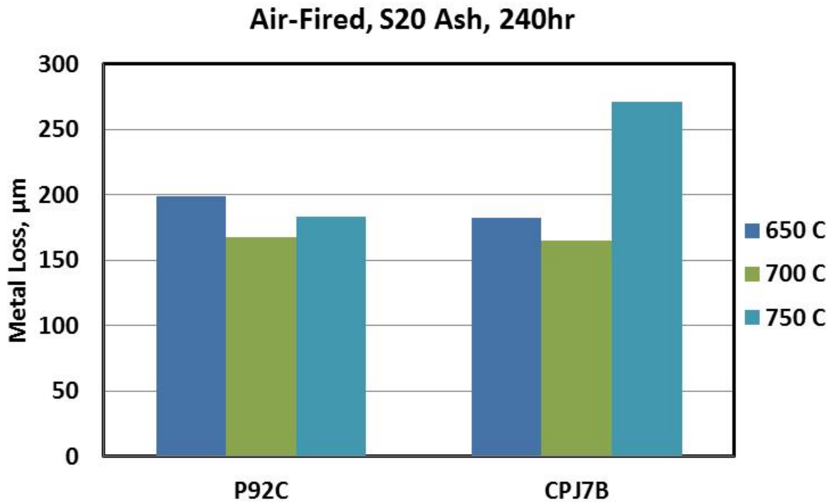
Metal Loss Results (240 h)

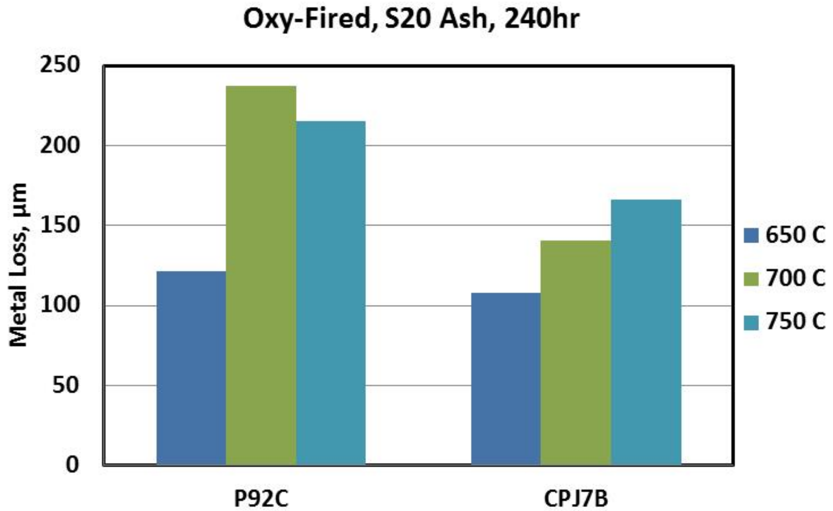




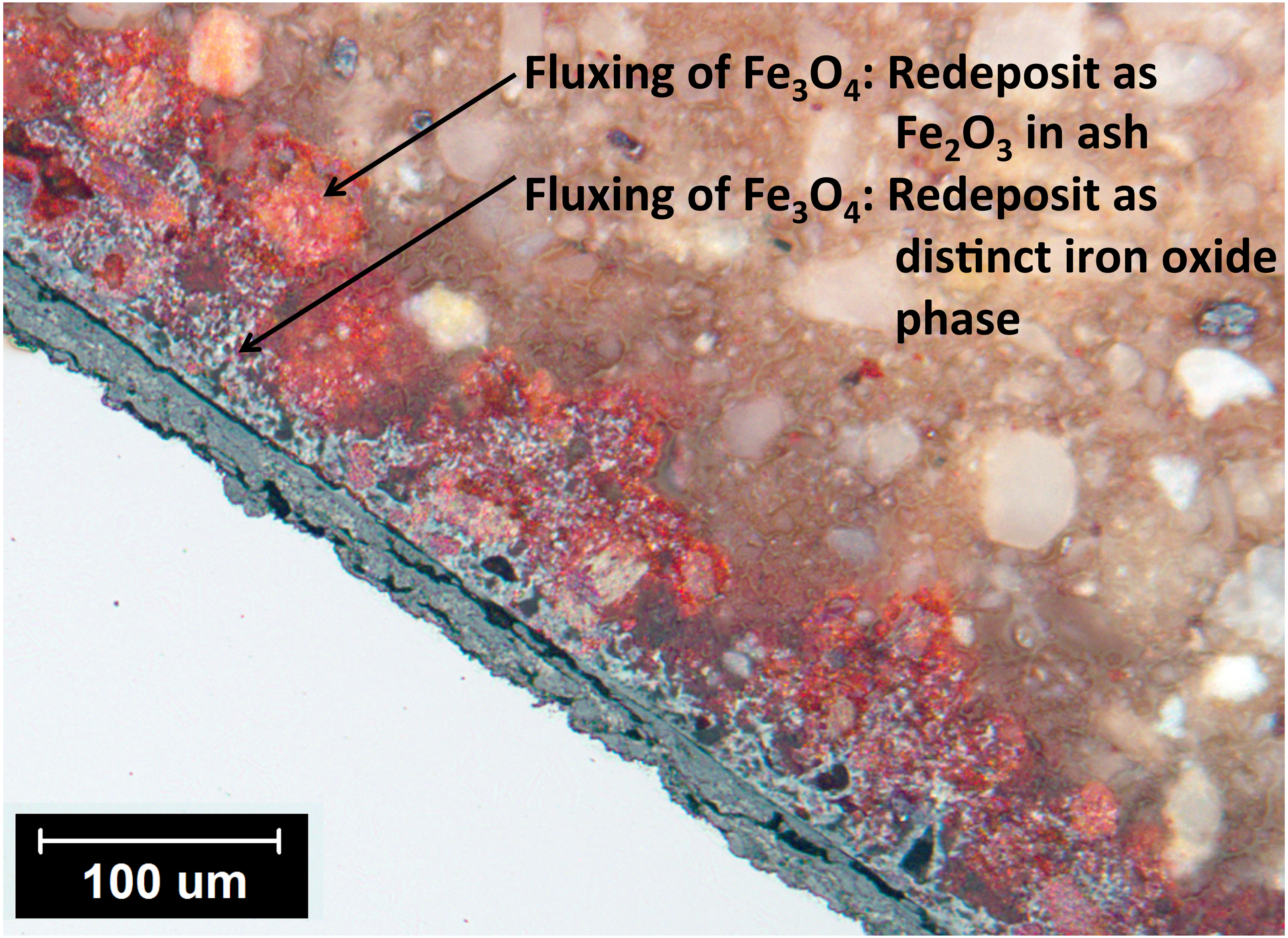
CPJ7B compared to P92C

(Comparable, or less, metal loss for CPJ7B than P92C)

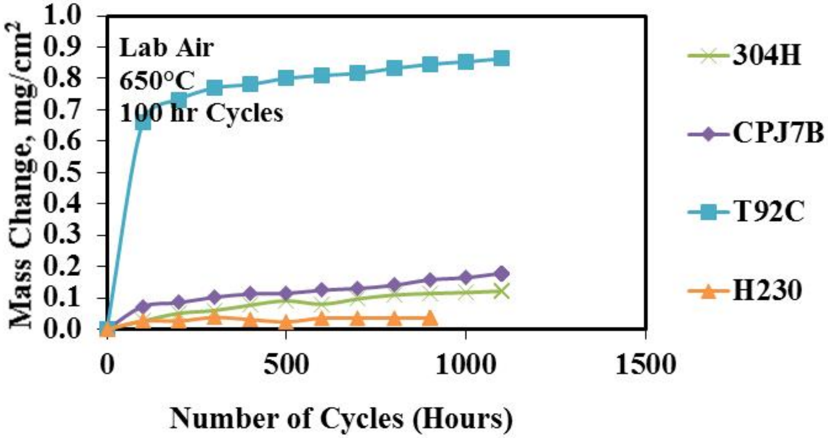


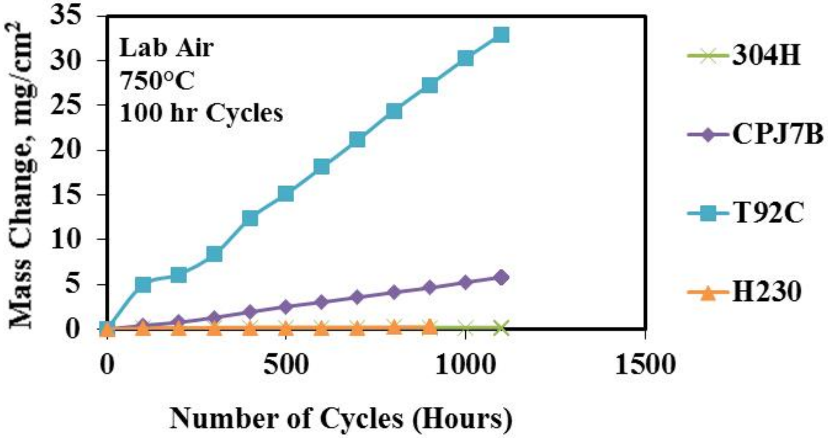


24 h Air-Fired Exposure of T92 at 700°C w/20% Alkali Iron Trisulfate Ash



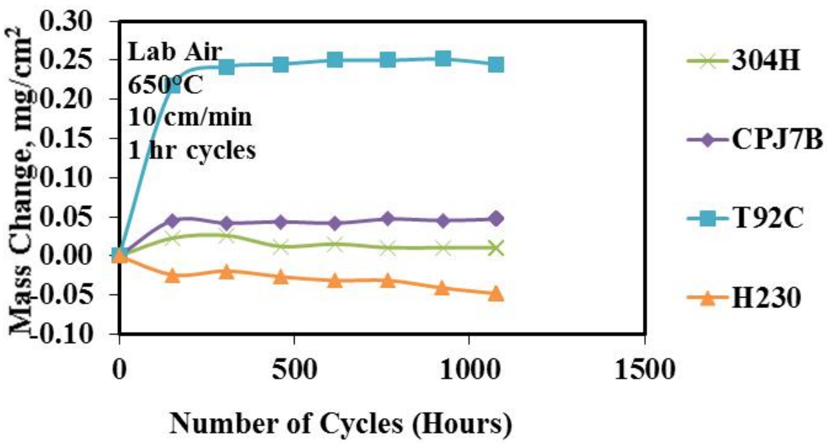
Air Oxidation

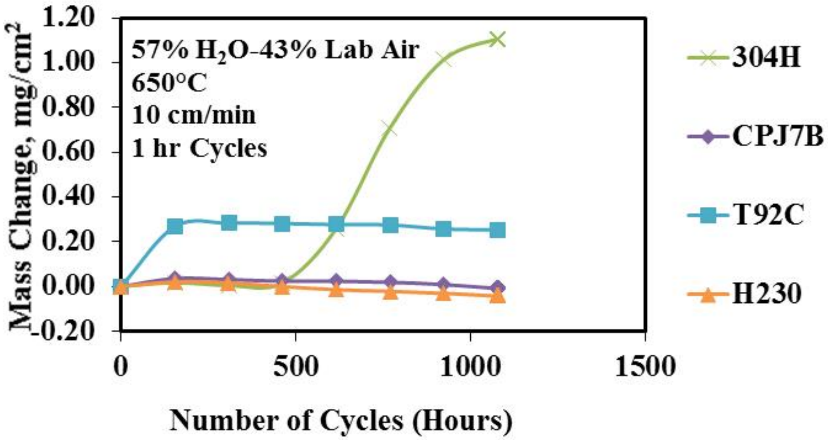




CPJ-7 performs as well as, or better than, T92 with similar Cr levels (9.1 to 9.8 wt%).

Water contributes to chromia evaporation and/or spalling.





“*Wrought*” CPJ-7 9% Cr Steel

- Identified promising chemistry for “*wrought*” ferritic-martensitic steel, CPJ-7, based on controlling minor alloying additions (C, Cu, Ta) and B/N levels.
- Developed manufacturing approach (specifically homogenization cycle prior to TMP) to consistently produce CPJ-7.
- Tested CPJ-7 chemistry robustness by varying select combinations of alloying additions: $Mo_{(eqv)}$; C + N level; B level – producing and testing five additional CPJ-7 or derivative heats.
- Assessed other minor element additions and extent of those additions on tensile and creep strength of CPJ-7 base alloy.
- CPJ-7 creep performance compares favorably to MARBN experimental boiler steel.
- Oxidation resistance in air and air/H_2O mixture very good compared to P92.

Brief Description of Cast CPJ-7 Steel

- Previous research identified NETL martensitic-ferritic steel CPJ-7. A "*wrought*" product was manufactured.
- NETL "*wrought*" CPJ-7 steel exhibited superior creep strength compared to commercially designed, thermo-mechanically processed and heat treated 9% Cr martensitic-ferritic steels used for airfoils, rotors, and other wrought components in a steam turbine as well as piping and other thermo-mechanically processed components in the combustion boiler.
- NETL applied same alloy design rationale to develop ***cast*** martensitic-ferritic 9% Cr steel. Subsequent alloy homogenization using NETL algorithmic approach with subsequent martensitic steel heat treatment produced ***cast*** version of CPJ-7 superior to any existing commercially available ***cast*** 9% Cr martensitic-ferritic steel or derivatives.

Wrought vs. Cast Manufacturing

Wrought Manufacturing Steps:

1. **Alloy Design**
2. **Melt Processing**
3. **Homogenization**
   - Improve chemical uniformity within the matrix structure
4. **Thermo-mechanical Processing**
   - Physical manipulation of the grain structure for mechanical property design & refinement
   - More homogeneous "physical" structure – i.e., a more consistent & uniform grain size
5. **Heat Treatment for Strength**

Cast Manufacturing Steps:

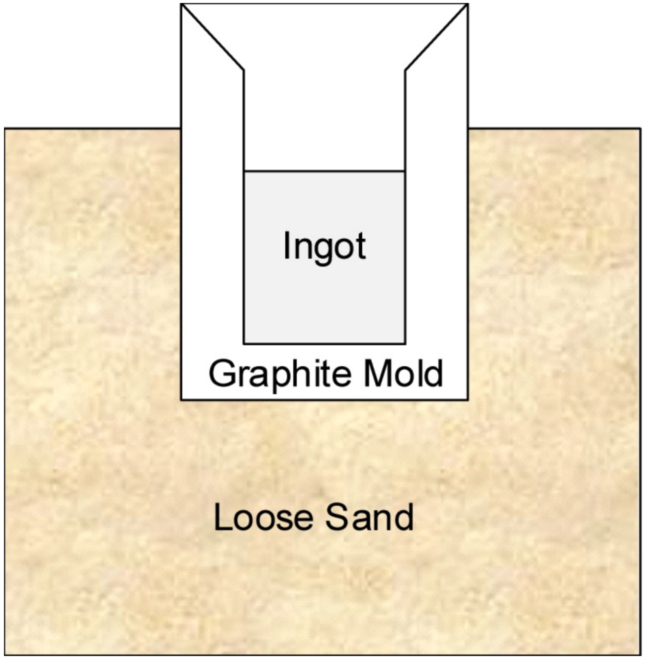
1. **Alloy Design**
2. **Melt Processing**
3. **Homogenization**
   - Improve chemical uniformity within the matrix structure
4. **Heat Treatment for Strength**

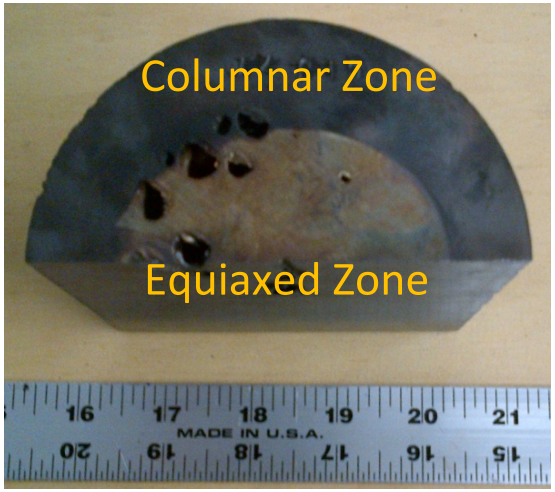
- **Major difference is no manipulation of the "physical" grain structure of the resulting solid body.**
- **Limited ability to develop strength in the solid body except through *alloy design* & *heat treatment*.**

Martensitic Steel Ingot Casting

Large-scale Steel Casting for USC 650°C Power Plants:

A heat of CPJ-7 was formulated and cast utilizing NETL's "enhanced slow cooling" methodology. The mold was submerged in loose sand to help contain the heat of the molten steel, and thereby, slow the cooling rate substantially in order to better simulate the slow cooling conditions of a thick wall, full-size steam turbine casings. The fully heat treated ingot was then bisected along the diameter. The halves were then sectioned into 0.4" thick slabs from which 0.4" square bars were cut. From these squares round tensile bars were subsequently machined into traditional tensile/creep specimens.





Cast CPJ-7 Preliminary Mechanicals

- Duplicate tests of cast CPJ-7 at RT, 600°C & 650°C, plus one additional test at 600°C for equiaxed solidification zone. Note the relative property equivalence of the two solidification zones.

Alloy	Heat Treatment	Test Conditions (°C)	Yield Stress (MPs)	Tensile Strength (MPa)	Elongation (%)	Reduction in Area (%)
CPJ 7A Columnar	HTS+	RT	808	966	17	48
			803	964	17	42
		600	463	539	28	74
			470	545	33	76
		650	379	446	30	81
			384	449	36	80
CPJ 7A Equiaxed	HTS+	RT	809	970	18	39
			813	847*	2*	5*
		600	463	484*	3*	25*
			466	538	22	62
			468	542	29	73
		650	371	443	31	79
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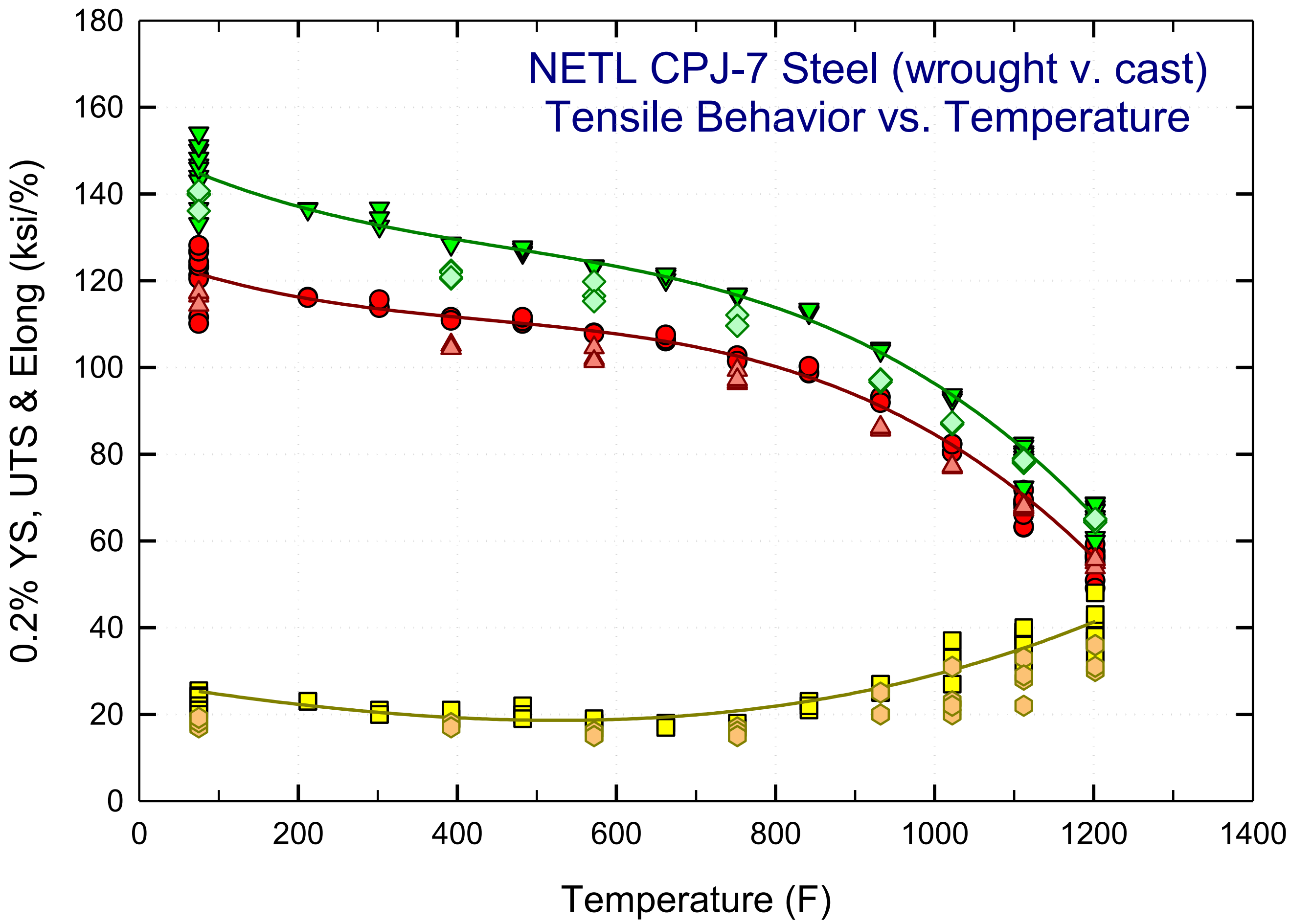
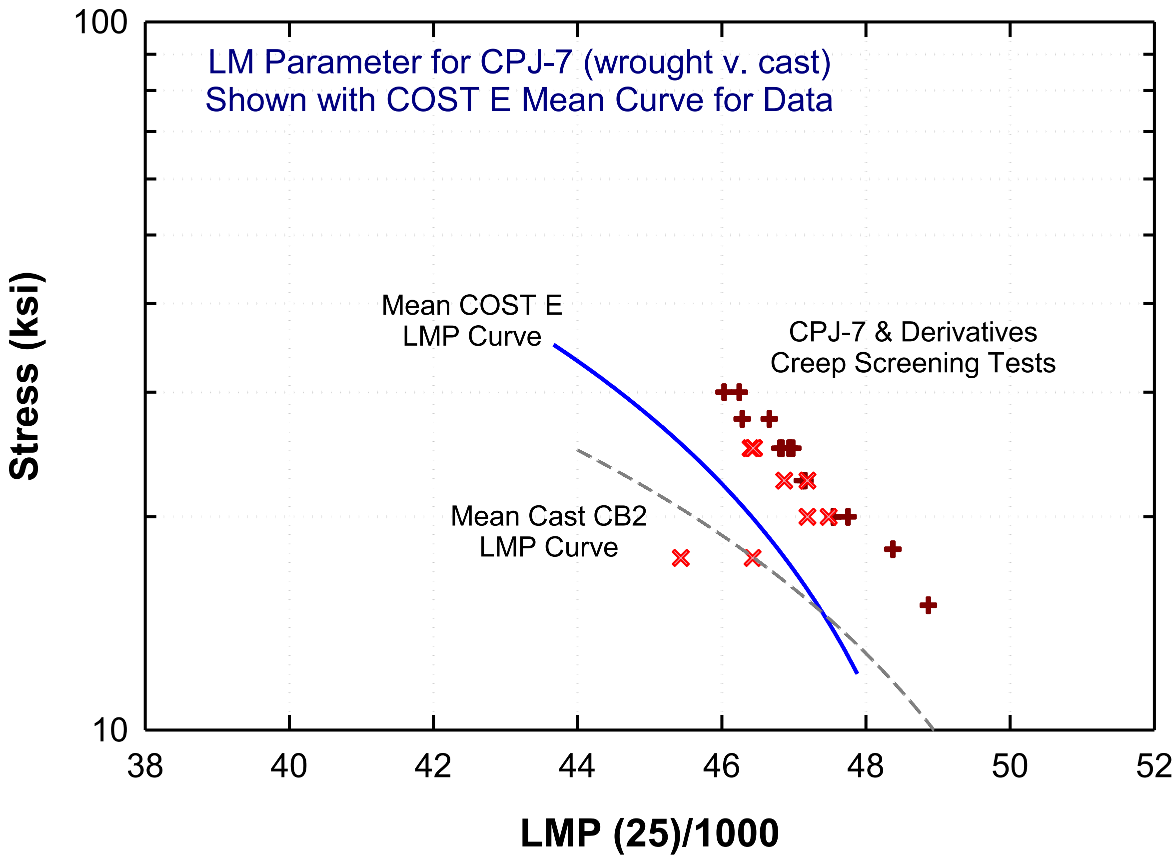
Defects more likely to be found in equiaxed region – last bit of molten metal to solidify.

Comparison Between Wrought & Cast CPJ-7



Comparison Between Wrought & Cast CPJ-7 with Representative Commercial Steels



Larson-Miller Parameter plot for COST E & cast CB2 at temperatures from 1050°F (565.5°C) to 1200°F (648.9°C). CPJ-7 (cast (x) & wrought (+)) testing performed at 650°C only.

Wrought vs. Cast CPJ-7 Creep Results at 650°C

Wrought Alloy	Stress (ksi)	Stress (MPa)	Time to Rupture (hours)
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	22.5	155.1	2,239
CPJ-7	20.0	137.9	5,388
CPJ-7E	20.0	137.9	4,210
CPJ-7	18.0	124.1	12,727

Cast Alloy	Stress (ksi)	Stress (MPa)	Time to Rupture (hours)
CPJ-7K	25.0	172.4	828
CPJ-7K	25.0	172.4	869
CPJ-7K	25.0	172.4	886
CPJ-7K	22.5	155.1	2,469[+]
CPJ-7A	22.5	155.1	1,582
CPJ-7K	20.0	137.9	2,467[+]
CPJ-7A	20.0	137.9	3,714
CPJ-7A	17.5	120.7	860[+]
CPJ-7K	17.5	120.7	216[+]

[+] Creep tests still underway as of 4/29/2015

Cast 9% Cr Martensitic Steel Chemistry

- **This new *cast* 9% Cr martensitic steel has a unique chemistry, alloy design philosophy, and microstructural control (i.e., computationally based homogenization heat treatment schedule) unlike any other alloy in it's class.**
- **Nominal/preferred alloy chemistry:**

	C	Mn	Si	Ni	Cr	Mo	V	Nb	N	W	B	Co	Fe	Ta
CPJ-7	0.15	0.40	0.10	0.30	9.75	1.25	0.20	0.06	0.020	0.50	0.0100	1.50	Bal	0.20

- **Alloy design philosophy:**
  - Slow down the destabilization of the various grain boundary & matrix strengthening features such as MX and $M_{23}C_6$ particles.
  - Avoid and/or postpone the formation of unwanted phases such as the Z-phase and Laves phase.
- **Homogenization:**
  - Induce complete chemical uniformity on the micro-scale to avoid "over rich" or "over lean" regions that could promote deleterious phase formation, thereby achieving long-term alloy stability.

Cast 9% Cr Martensitic Steel Homogenization Cycles Based on Cast Article Thickness

	Residual Inhomogeneity		
Section Size	<10%	<5%	<1%
	Maximum Heat Treat Furnace Temperature - 1250°C		
Up to 5″	1125°C/1 h + 1250°C/3 h	1125°C/1 h + 1250°C/4 h	1125°C/1 h + 1250°C/8 h
5-8″	1125°C/2 h + 1250°C/5 h	1125°C/2 h + 1250°C/8 h	1125°C/2 h + 1250°C/18 h
> 8″	1125°C/2 h + 1250°C/10 h	1125°C/2 h + 1250°C/14 h	1125°C/2 h + 1250°C/30 h
	Maximum Heat Treat Furnace Temperature - 1200°C		
Up to 5″	1125°C/1 h + 1200°C/6 h	1125°C/1 h + 1200°C/8 h	1125°C/1 h + 1200°C/16 h
5-8″	1125°C/2 h + 1200°C/10 h	1125°C/2 h + 1200°C/16 h	1125°C/2 h + 1200°C/32 h
> 8″	1125°C/2 h + 1200°C/20 h	1125°C/2 h + 1200°C/30 h	1125°C/2 h + 1200°C/62 h

Cast 9% Cr Martensitic Steel-Proof of Principle

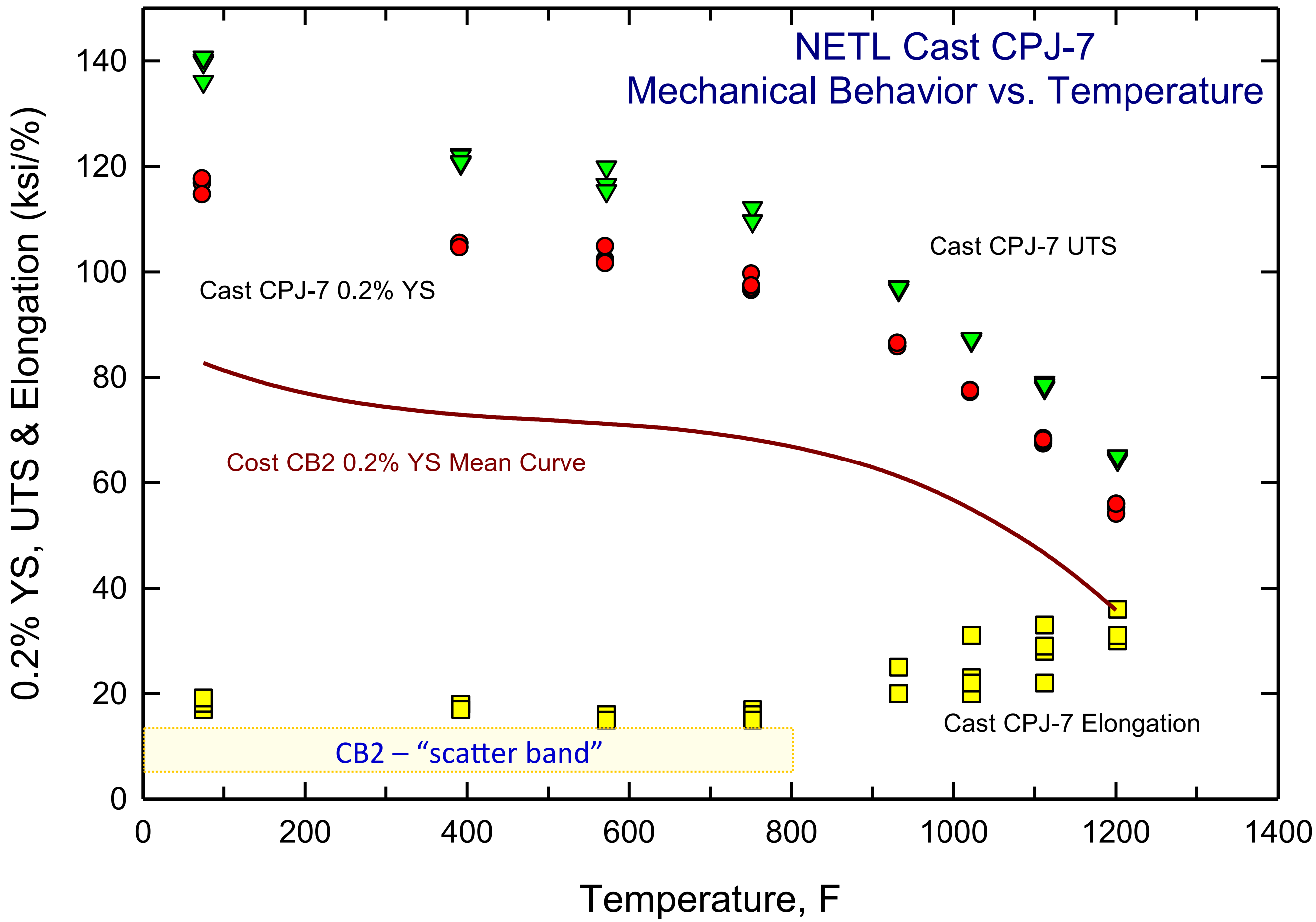
- The preferred chemistry for ***cast*** CPJ-7, 9% Cr martensitic steel, was used to manufacture two heats. ***No attempt was made to optimize the casting process at this time.***
- After homogenization, the ***cast*** CPJ-7 9% Cr steel ingot was heat treated in the following manner:
  - ***1150°C/30 min/AC + 700°C/1 hour/AC***
- Screening tensile tests were performed from material that solidified in an ***equiaxed*** manner (i.e., center of the casting) as well as from material that solidified in a ***columnar*** manner (i.e., exterior surface region of casting).
- Screening creep tests at 25 ksi and 650°C have been performed to assess the extent of creep capability relative to commercial cast steels used in power plants, (e.g., COST CB2).
- Mechanical performance looks *very good* – with ***cast*** CPJ-7 showing outstanding mechanical performance for a casting.

Cast 9% Cr Steel: *Detailed Tensile Mechanicals*

Alloy Designation	Temperature (°F)	Temperature (°C)	Yield Strength (MPa)	Yield Strength (ksi)	Tensile Strength (MPa)	Tensile Strength (ksi)	Elongation (%)	RA (%)
CPJ-7A Columnar 1150°C/30m/AC + 700°C/1h/AC	75	23.9	808	117.2	966	140.1	17	48
	75	23.9	803	116.5	964	139.8	17	42
	392	200	725	105.2	843	122.3	18	51
	392	200	725	105.2	841	122.0	18	56
	572	300	704	102.1	803	116.5	16	51
	572	300	702	101.8	803	116.5	16	54
	752	400	664	96.3	756	109.6	17	57
	752	400	667	96.7	756	109.6	16	55
	932	500	594	86.2	670	97.2	25	67
	932	500	590	85.6	670	97.2	20	65
	1022	550	533	77.3	601	87.2	23	70
	1022	550	530	76.9	599	86.9	31	72
	1112	600	463	67.2	539	78.2	28	74
	1112	600	470	68.2	545	79.0	33	76
	1202	650	379	55.0	446	64.7	30	81
	1202	650	384	55.7	449	65.1	36	80
CPJ-7A Equiaxed 1150°C/30m/AC + 700°C/1h/AC	75	23.9	809	117.4	970	140.7	18	39
	75	23.9	789	114.4	938	136.1	19	55
	392	200	720	104.4	831	120.5	---	---
	392	200	720	104.4	833	120.8	17	56
	572	300	721	104.6	826	119.8	15	50
	572	300	699	101.4	795	115.3	15	55
	752	400	685	99.4	773	112.1	15	43
	752	400	670	97.2	756	109.6	15	48
	932	500	590	85.6	666	96.6	---	---
	932	500	594	86.2	669	97.0	20	65
	1022	550	531	77.0	602	87.3	20	58
	1022	550	532	77.2	602	87.3	22	67
	1112	600	466	67.6	538	78.0	22	62
	1112	600	468	67.9	542	78.6	29	73
	1202	650	371	53.8	443	64.3	31	79
	1202	650	384	55.7	449	65.1	36	80

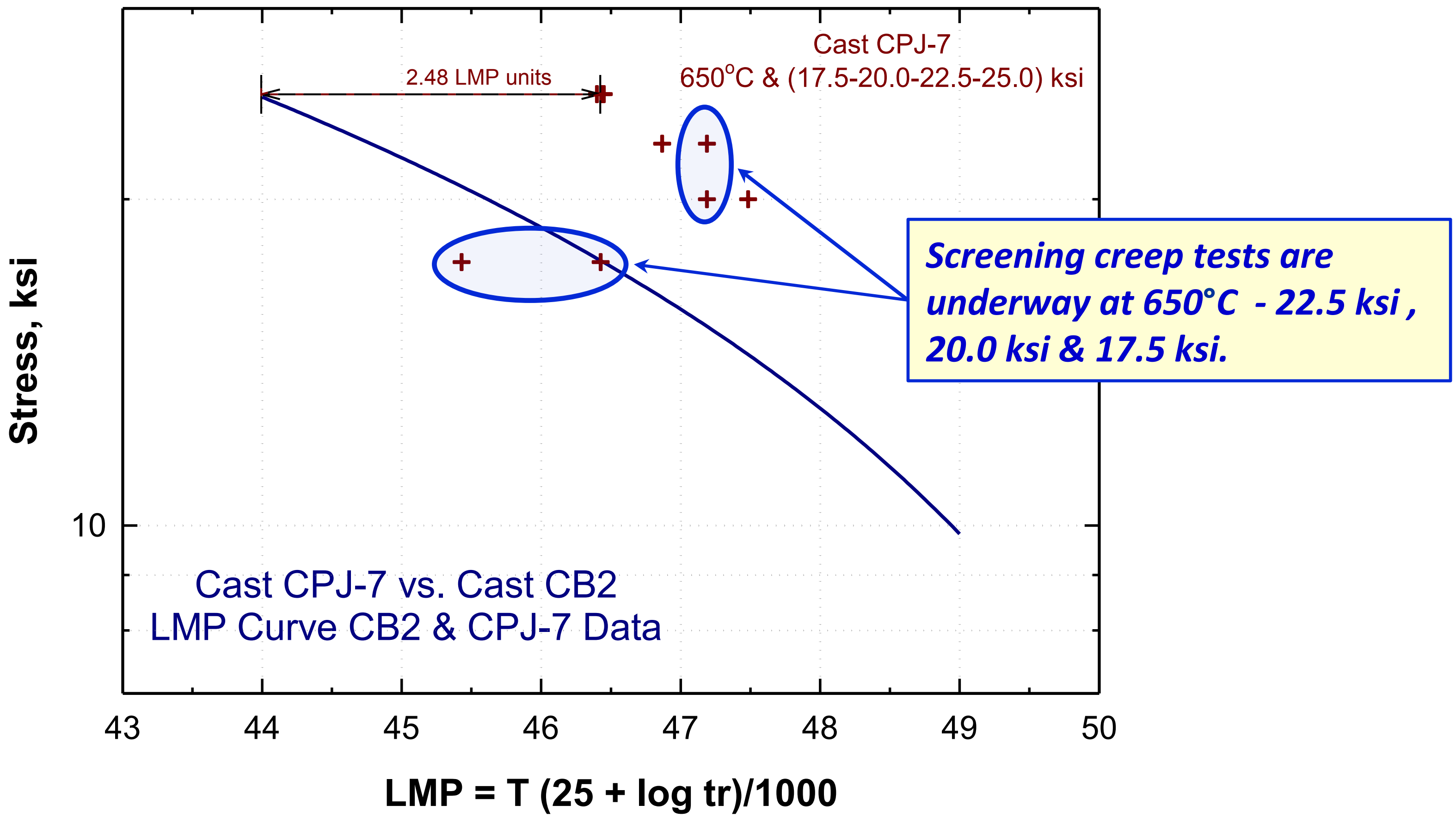
Proof of Principle

Detailed Tensile Mechanicals



Proof of Principle

Creep Life & LMP Comparison



+ Creep tests still underway as of 4/29/2015

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Proof of Principle - Summary Comparison Creep Life Cast 9% Cr Steels at 650°C

Alloy/Stress	CB2	Average LMP	Cast CPJ-7	Average LMP
25.0	27.5^	43.95^	828, 869, 886	46.43*
22.5	87.5^	44.78^	2469+, 1582	47.19+, 46.87
20.0	278.5^	45.61^	2467+, 3714	47.18+, 47.48
17.4	282 ± 257#	45.43#	860+, 216+	46.43+, 45.43+
14.5	2,716 ± 1,018#	47.23#	----	----
12.3	15,943 ± 2,802#	48.53#	----	----

* Average of three (3) creep rupture tests. + Tests in progress (4/29/2015).

\# Average of two (2) creep rupture tests (Reference: Jandova et al., 2012.)

^ Estimates of time to failure for CB2 based on LMP value from average curve at designated stress.

Estimates in Table 2 based on curve fit to actual CB2 data (English units):

D. Jandova, J. Strejcius, J. Kasl and K. Kepka, "Correlation of microstructure development of cast CB2 steel after long-term creep tests with electrochemical characteristics," 2nd International Conference on Recent Trends in Structural Materials, Plzeň, 2012, 6 pages.

Planned Next Steps

- Continue creep screening activities through fall of 2015.
- Pay more attention to optimizing the casting process in order to produce sound castings (i.e., through the use of gating system, risers, filters, etc.).
- Consider larger scale castings for welding studies (in conjunction with wrought CPJ-7). Identify vendor to perform welding trials.
- Consider making larger CPJ-7 casting via air induction melting process.
- Assess toughness & fracture energy, followed by selected fatigue screening tests at room temperature for CPJ-7.
- Solicit comments on work during IPT Crosscutting Review Meeting and incorporate all relevant suggestions & ideas.

Thank you

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