Advanced Combustion

Gordon R. Holcomb

NETL, Materials Research Engineer

Advanced Combustion Project Management Activity

- ***Activity Description:***

  Provide the mechanical and physical property information needed to allow rational design, development and/or choice of alloys, manufacturing approaches, and environmental exposure and component life models to enable oxy-fuel combustion boilers to operate at Ultra-Supercritical (up to 650^{o}C & between 22-30 MPa) and/or Advanced Ultra-Supercritical conditions (760^{o}C & 35 MPa).

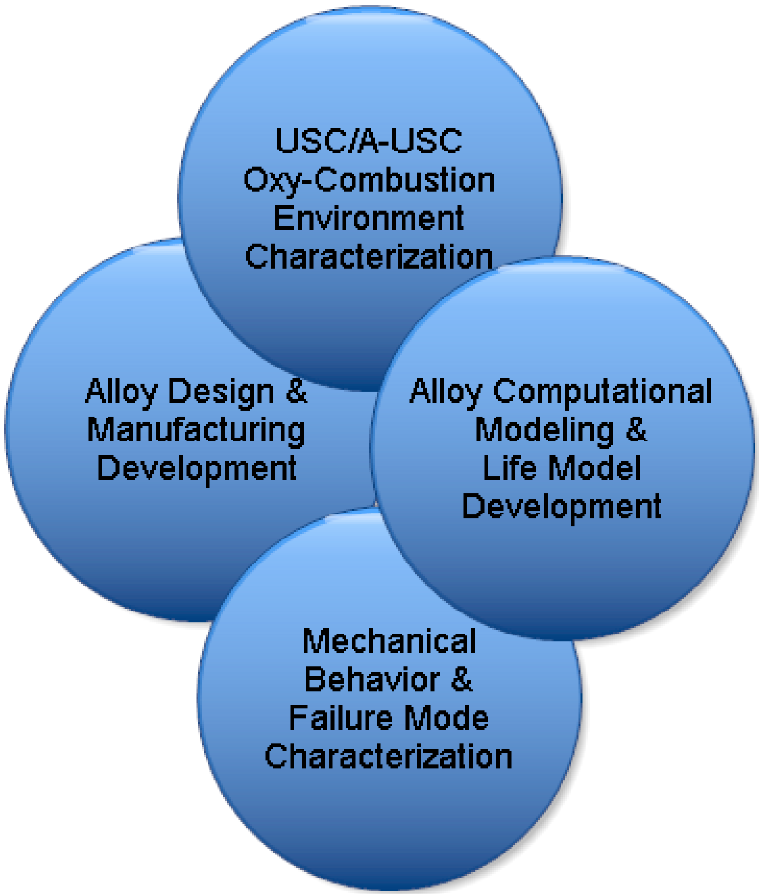
- ***Program Contribution:***
  - Higher temperatures will allow higher efficiency oxy-fuel systems.
  - Identifies how to address corrosion issues from wider coal choices/impurities.
  - Develops new heat resistant alloys for advanced power systems.
  - Contributes new manufacturing processes for large section castings of Nickel-base superalloys.

- ***Unique or Complimentary Aspects:***
  - Applies existing DOE collaborations specifically to oxy-fuel issues:
    - DOE FE 1400°F Boiler Consortium
    - US-UK FE Collaboration
  - Significant industrial collaborations in place with active collaboration.
  - Unique contribution to FE program for oxy-fuel power plant systems.
  - Results help both steam turbines and oxy-fuel power plant systems.

Advanced Combustion: Overall Approach

- Integrated multi-scale computational approach, complimented with a focused experimental program, emphasizing the design & optimization of materials for advanced combustion systems.

  - *Computational material design & optimization.*
  - *Lab-scale synthesis of materials.*
  - *Mechanical & chemical assessment of materials performance in real environments*
  - *Simulation of component life in conventional & oxy-fuel combustion environments.*



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Advanced Combustion Tasks & Key Participants

FY12 SCC Program Guidance	Advanced Combustion Project Tasks
Advanced Combustion	1. Project Management
	2. Oxy-Combustion Environment Characterization
	3. Alloy Modeling and Life Prediction (moved to IPT)
	4. Alloy Manufacturing and Process Development

NETL-RUA Advanced Combustion Research Team

ORD	CMU	PIT	PSU	Va Tech	URS
Hawk Holcomb Howard Jablonski Wen	Laughlin/ Seetharaman	Meier/ Gleeson	Liu Chen	Muryama	Gao Tafen

External Collaborators

General Electric Co.
Siemens

JCOAL w/ IHI, CCT Group & Hokkaido Univ.

DOE FE 1400F Boiler & Steam Turbine Consortium
ALSTOM
Riley Power
Foster Wheeler
Babcock & Wilcox
General Electric, Co.
Oak Ridge National Lab
Energy Industries of Ohio
EPRI

US-UK FE Collaboration
Argonne National Lab
Reaction Engineering
Carpenter Technology
University of Pittsburgh
RWE
Doosan-Babcock Energy
Cranfield University
National Physical Lab

Metal Producers
PCC, Special Metals,
Carpenter Technology,
Haynes International,
Howmet, Allvac, Doosan
Metal Tek, Flowserve & JCFC

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Advanced Combustion FY2012 Project Highlights

- Laboratory fire side corrosion made significant progress in FY2012 in exposing samples to oxy-combustion environments & analyzing the effects of the exposure. In addition, selected samples were cleaned differently to preserve the total oxide film & fire side ash covering to better understand the interdiffusion of metal & ash in the fire side degradation process. Work will continue into FY2013 on the analysis of these samples.
- Shakedown tests of the advanced ultra-supercritical (A-USC) steam autoclave continued & supercritical steam conditions were achieved with good control of the pressure. Temperature control to the desired level needs adjustment & fine tuning. The first step in the process is developing a heat transfer model to better calculate autoclave temperature at the sample.
- Creep tests from the second iteration of ferritic-martensitic steels are ongoing at NETL. Results CPJ-7 have been encouraging with experimental steel creep specimen at 103.4 MPa and 650°C still in test (and currently passed 13,584 hours).
- A *Report of Invention* (ROI) was submitted to the NETL Technology Transfer Group (TTG) on the development activities related to the CPJ-7 experimental steel, entitled "Method to Improve Creep Strength in Steel by Alloy Design and Heat Treatment," Jeffrey A. Hawk, Paul D. Jablonski and Christopher J. Cowen (submitted September 27, 2012).
- A *Report of Invention* (ROI) was submitted to the NETL Technology Transfer Group (TTG) on the development activities related to large scale Ni-base casting & subsequent heat treatment, entitled "A Computational Approach to Homogenizing Alloys," Paul D. Jablonski and Jeffrey A. Hawk (submitted September 27, 2012).
- Merit review of the Advanced Combustion Projects Subtasks 2.1, 4.1, and 4.3 was conducted at NETL on May 16, 2012. Reviewer questions and comments were addressed in writing and suggestions used to accelerate the ferritic/martensitic alloy development activities were taken under advisement & incorporated into the third iteration ferritic/martensitic steel production.

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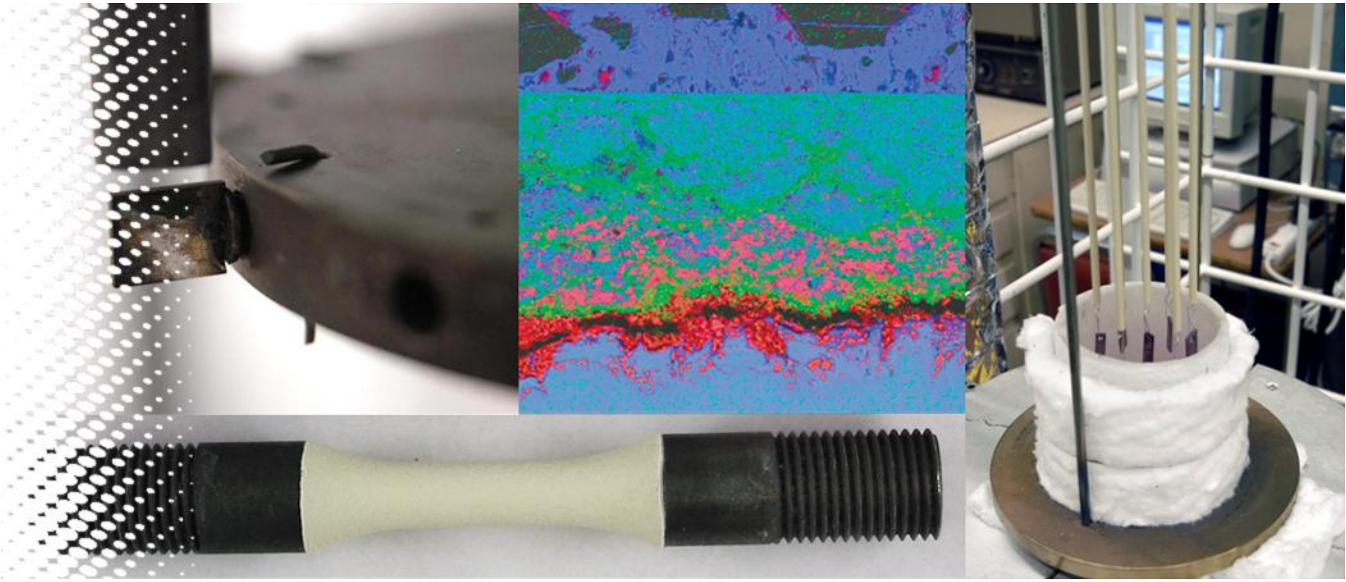

Advanced Combustion: Task 2

Oxy-combustion Environment Characterization

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Conduct & Analyze Long-term Laboratory Fireside Corrosion Tests

Condition	Oxidative, 700°C	Oxidative, 450°C	Reducing, 450°C
Air-fired	1370	1380	1200
Oxy, FGD 9% H_2O	1440	1440	960
Oxy, FGD 20% H_2O	1440	1440	960
Oxy, No FGD	1440	1440	720

- Reached decision point at 1440 hr for oxidative conditions to continue or modify tests/alloys. New tests will:
- Examine a reported extension in corrosion rate response in oxy-combustion to higher temperatures.
- Use Ni-22Cr-xMo model alloys to look at Mo effect on incubation times
- Use ash compositions to look at alkali flux
- Compare CPJ7 to T92
- Look at new boiler alloys H282 and IN740H

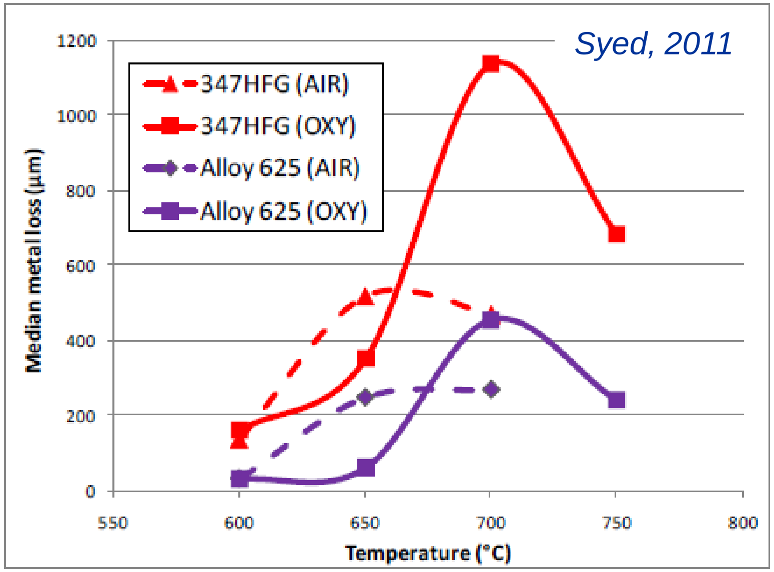

Figure 5-29: Effect of firing conditions on median metal loss damage for alloy 347HFG and 625 covered with deposit D1 after 1000 hours exposure over the temperature range from 600 to 750°C

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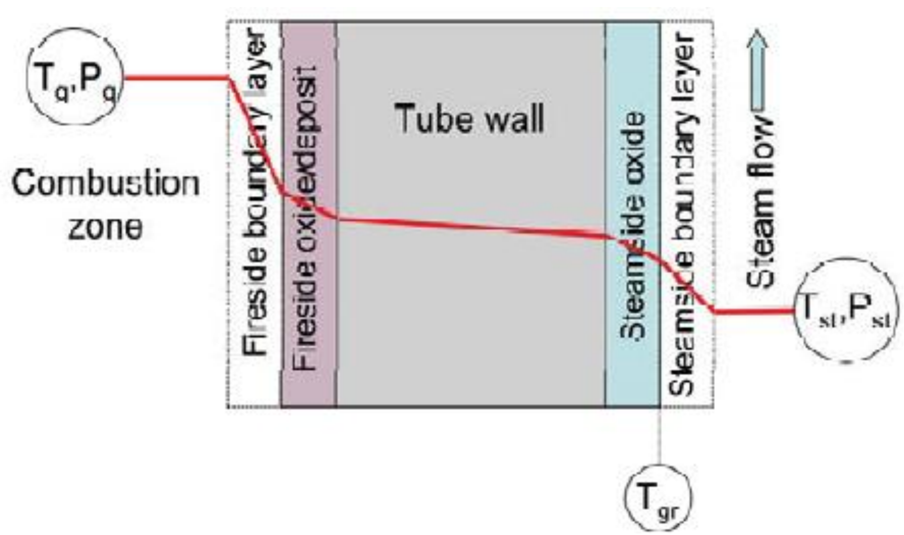
Changes in Approach

- **Ni-base alloys**
  - Model alloys Ni-22Cr, Ni-22Cr-1Mo, and Ni-22Cr-8Mo
  - Commercial A-USC alloys 282 and 740H
- **9Cr Ferritic/Martensitic Steels**
  - T92 and CPJ7B
- **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)
- **Temperatures**
  - 650, 675, 700, 725, 750°C
  - Higher than steam T
  - Extends into A-USC range



Changes in Approach

- Ash Compositions

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

- Maintain 3:1 ratio of $(Na,K)_2SO_4$:Fe_2O_3 as found in lowest melting point alkali iron trisulfates
- Represents decreasing flux of alkali sulfates
- S20 closest to current ash composition ($30\ Al_2O_3$ $30\ SiO_2$ $30\ Fe_2O_3$ $5\ Na_2SO_4$ $5\ K_2SO_4$)

Changes in Approach

T, °C	S20	S40	S60	S80	SCM
650			A		
675			A		
700	A	B	A	B	A
725			A		
750			B		

- Air- and oxy-firing, for 18 test environments.
- Estimated six 240 hour test periods (some may be shorter with more aggressive conditions, like SCM).
- Total of 108 tests, each taking 2 weeks.
- 3 furnaces, so a 72 week campaign (~ 2 years with inevitable planed and unplanned outages).
- First test A's, then B's, then fill in table where desired.

Conduct & Analyze Short-term Laboratory Fireside Corrosion Tests

- Fireside Corrosion of Alumina Forming Austenitic (AFA) Alloys:
  - OC4: Fe-25Ni-14Cr-3.5Al-2.5Nb-2Mo-2Mn-1W-0.5Cu
  - OC8: Fe-32Ni-18.7Cr-3Al-3.3Nb-0.15Mo
  - Temperature: 700°C with a Standard Corrosion Mix deposit
    (Na_2SO_4:K_2SO_4:Fe_2O_3 in a 1.5:1.5:1.0 molar ratio)
  - Gas Atmosphere: O_2 + 1000ppm SO_2
- The corrosion products were similar for both AFA alloys tested once in the propagation stage.
- OC4 (Incubation period 10-20 hr) suffered severe spallation even after 80 hours while OC8 remained intact after 320 hours.
- OC8 more corrosion resistant due to higher Cr and Ni contents extending the incubation period ≈ 320 h.
- OC4 contains more Mo (2%) than OC8(0.15%), however neither MoO_3 nor Na_2MoO_4 were found in OC4 corrosion products.

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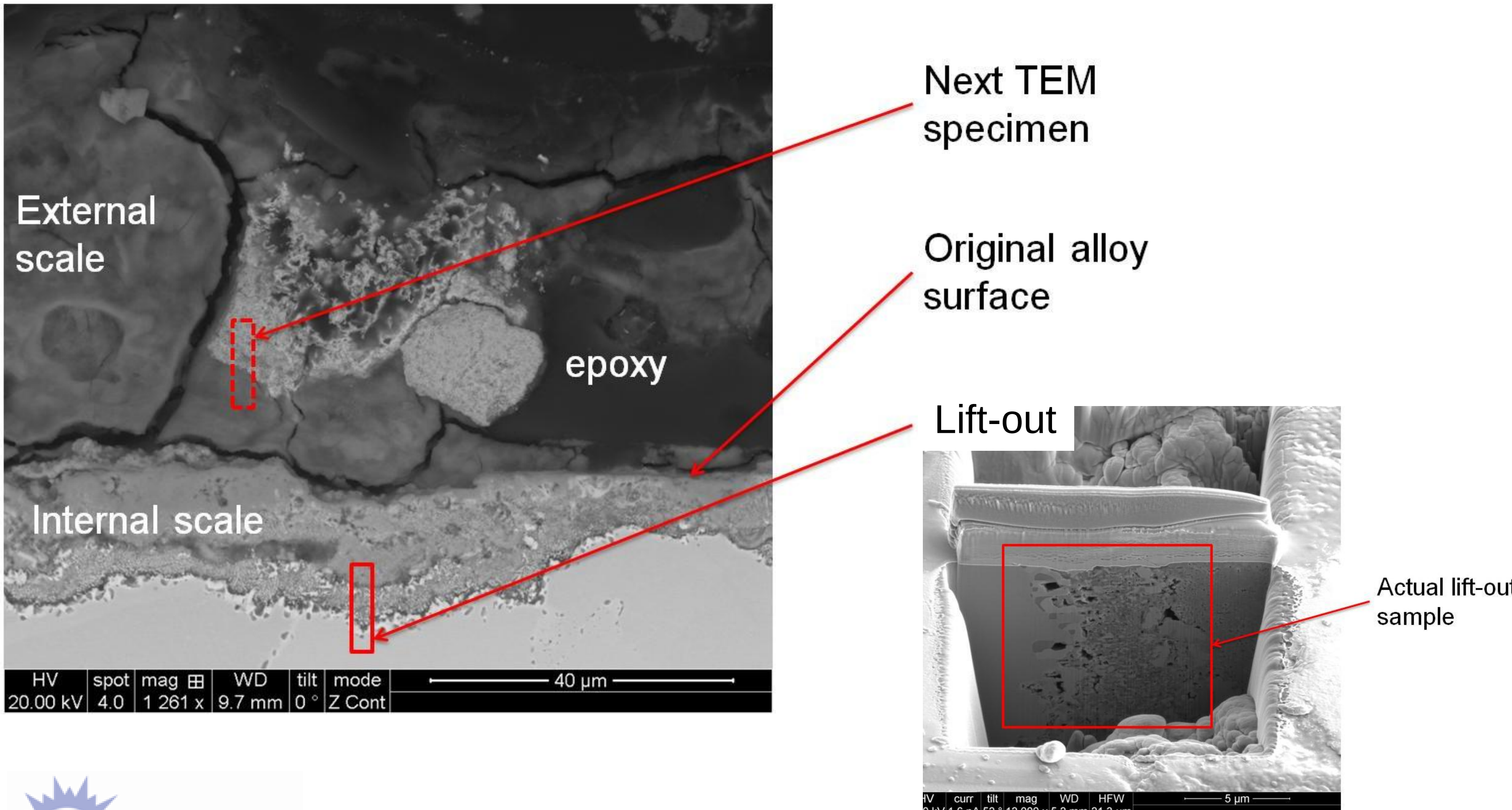
Perform Transmission Electron Microscopy Analyses of Selected Fireside Test Specimens (CMU)

*IN617-DOB, oxy-fired: CO_2+8%N_2+**20%H_2O**+2.5%O_2+**0.9%SO_2**; 700ºC & 240 h*



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Conduct Tests on Thermal Barrier Coating Protected Alloys

Nominal Alloy Composition for Alloys of Interest

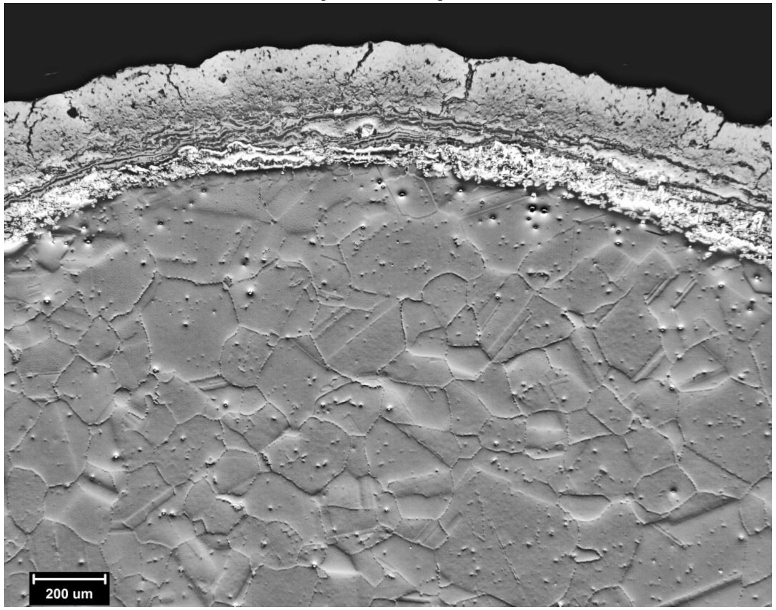
Alloy Designation	Ni	Co	Fe	Cr	Al	Ti	Si	Mn	W	Mo	Nb	Ta	C	B ppm	Other
CM 247 LC	Bal	9.0		8.0	5.6	0.7			10.0	0.5		3.2	0.07	150	0.01 Zr 1.4 Hf
Inconel 738	Bal	8.5		16.0	3.4	3.4			2.6	1.7	0.9	1.7	0.17	100	0.1 Zr
Udimet 520	Bal	12.5		19.0	2.1	3.1			1.0	6.3			0.04	70	
Haynes 282	Bal	10.0	0.8	20.0	1.5	2.1	0.08	0.2		8.5			0.06	50	
Inconel 625	Bal		2.5	21.5						9.0	3.6		0.05		
Inconel 939	Bal	19.0		22.4	1.9	3.7			1.6		1.0	1.4	0.15	100	0.1 Zr
ECY 768	10.0	Bal		23.0		0.2			7.0			3.5	0.60		
X-45	10.5	Bal		25.5					7.0				0.25	100	
HVOF SiCoat 2464	Bal			17.0	10.0										1.5 Re 0.3 Y

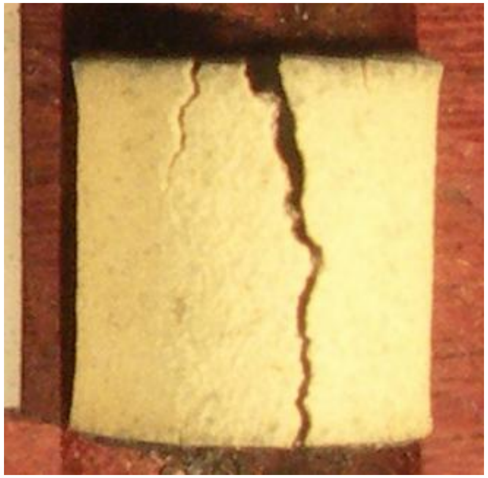
TBC Designation	ZrO_2	Y_2O_3	HfO_2
APS 8YSZ	89	10	1

8 substrate alloys, 2 bond coat thicknesses (3 & 5 mil), TBC topcoat
1010 C & 950 C exposures in H_2O + 10%CO_2 + 0.2%O_2 with 240 hr cycles
6,480 hr so far at 1010 C with 4 coating failures
960 hr so far at 950 C with no failures

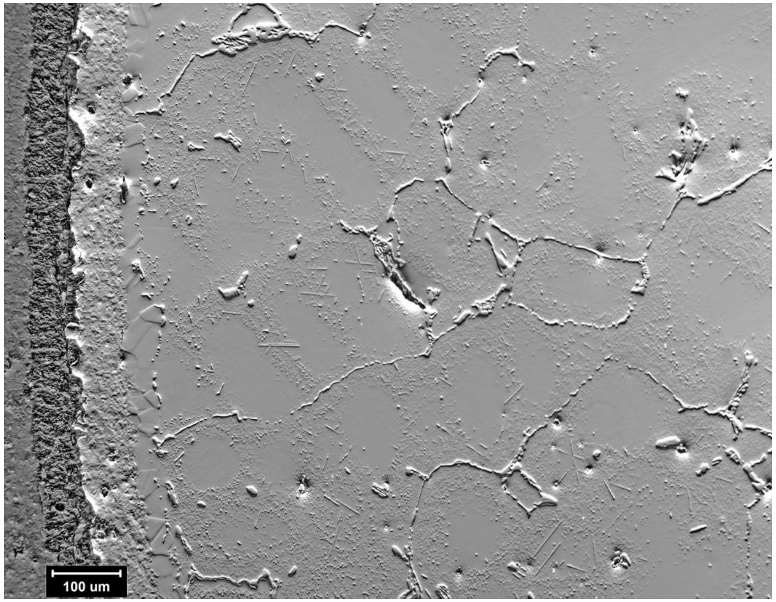
BC/TCB Exposure Tests

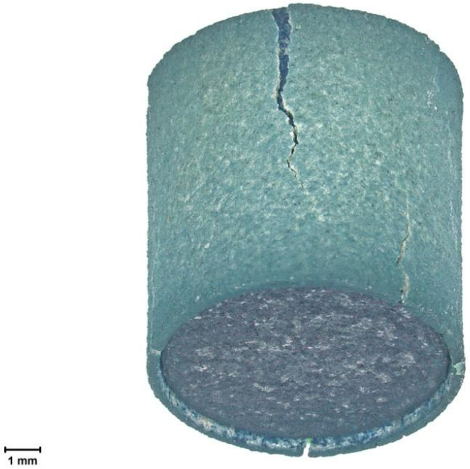
520-3H1, H-40, 4080 hr





X45-5H1, H-57, 5760 hr





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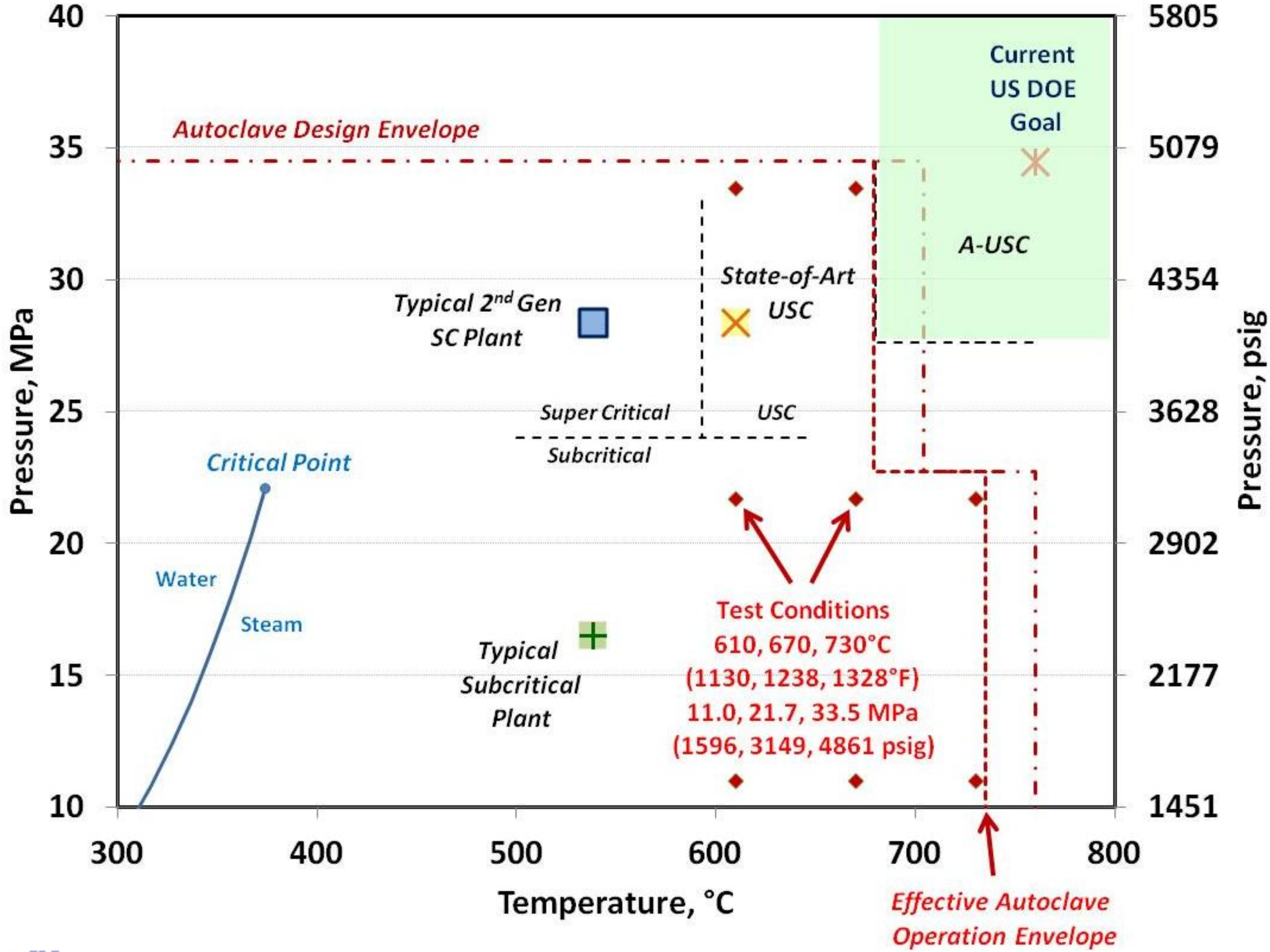
Conduct Steam Oxidation Tests

- **First High Pressure Test Completed**
  - Ran for 291 hr at 3874 psi (264 bar) and 670°C
  - 27 Samples (9 alloys with triplicate samples)
    - Ferritic Steels T22 and T91; Austenitic Steel TP304H
    - Ni-base Alloys H230, H263, H282, IN617, IN625, and IN740
  - Much higher pressure than existing facilities at ORNL (17 bar) and NPL (100 bar). Critical point pressure for water is 221 bar
  - Plan to copy temperatures and times at atmospheric pressure for a direct comparison. Will form the basis for an initial paper

NETL Autoclave Temperature & Pressure Envelope



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Advanced Combustion: Task 4

Alloy Manufacturing & Process Development

Paul D. Jablonski

Jeffrey A. Hawk

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Identify & establish agreement with casting vendor(s) for casting nickel superalloy.

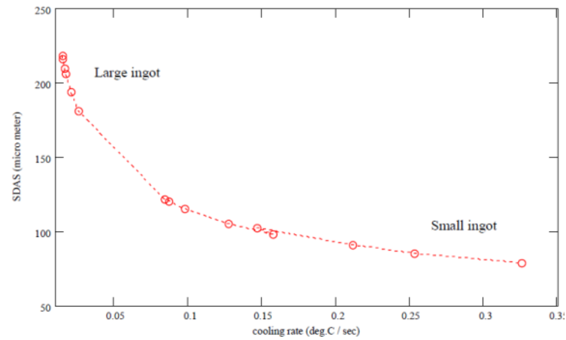
Work with GE Co. to increase the size and variety of thick wall castings of Ni-base, γ' precipitation strengthened alloys.

Support of this activity in regard to the 1400F Steam Turbine Project is ongoing. NETL continues to work with GE and their selected casting vendors over the last quarter.

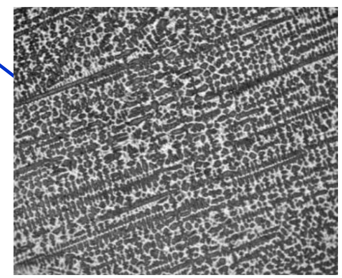
Cast blocks of alloy 263 and H282 have been supplied to GE and ORNL for welding trials and post weld evaluation. This study is well underway.

NETL has also cast a pair of “enhanced slow cooling” cylinders in H282 and alloy 263. These castings were not homogenized but simply peak aged. Tensile bar blanks were cut from these as before and specimens are in for hot tensile and creep testing.

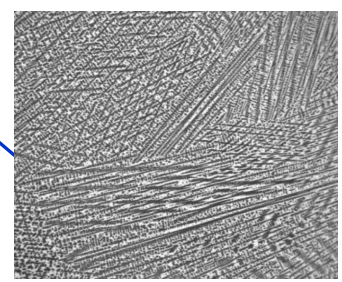
SDAS in Larger Casting



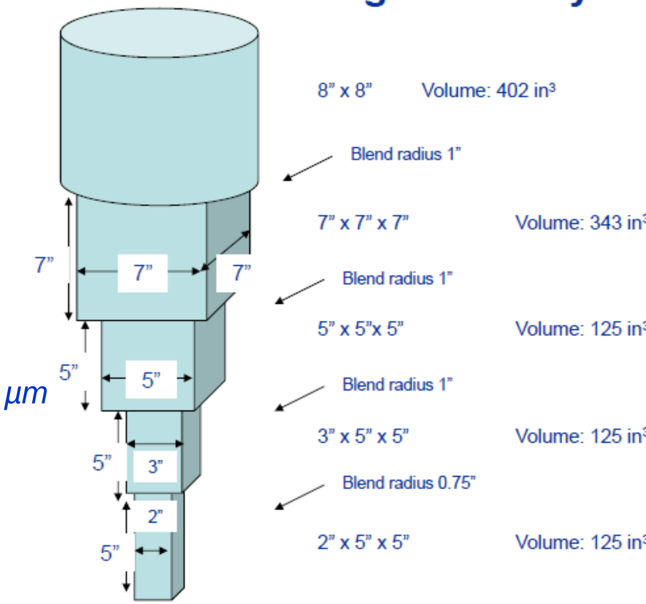
Riser Pad SDAS: 154-188 µm

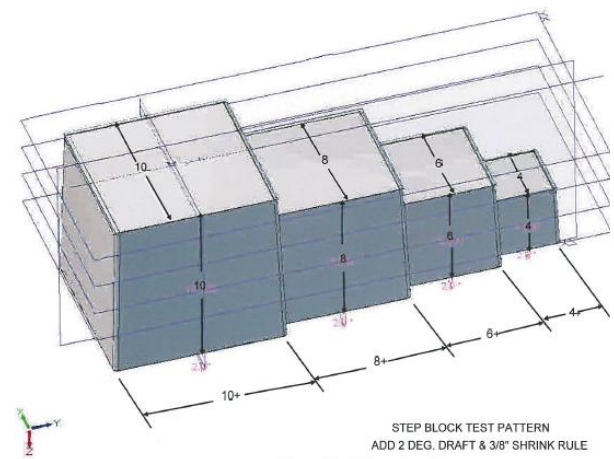


Keel Block SDAS: 67-57 µm



Casting Geometry





Interaction With Manufacturers
Homogenization Activities

ESR Ingot

Special Metals ESR/VAR Ingot of Haynes 282

VAR Ingot: 24″ (dia.) x 71″ (length); ~10,000#

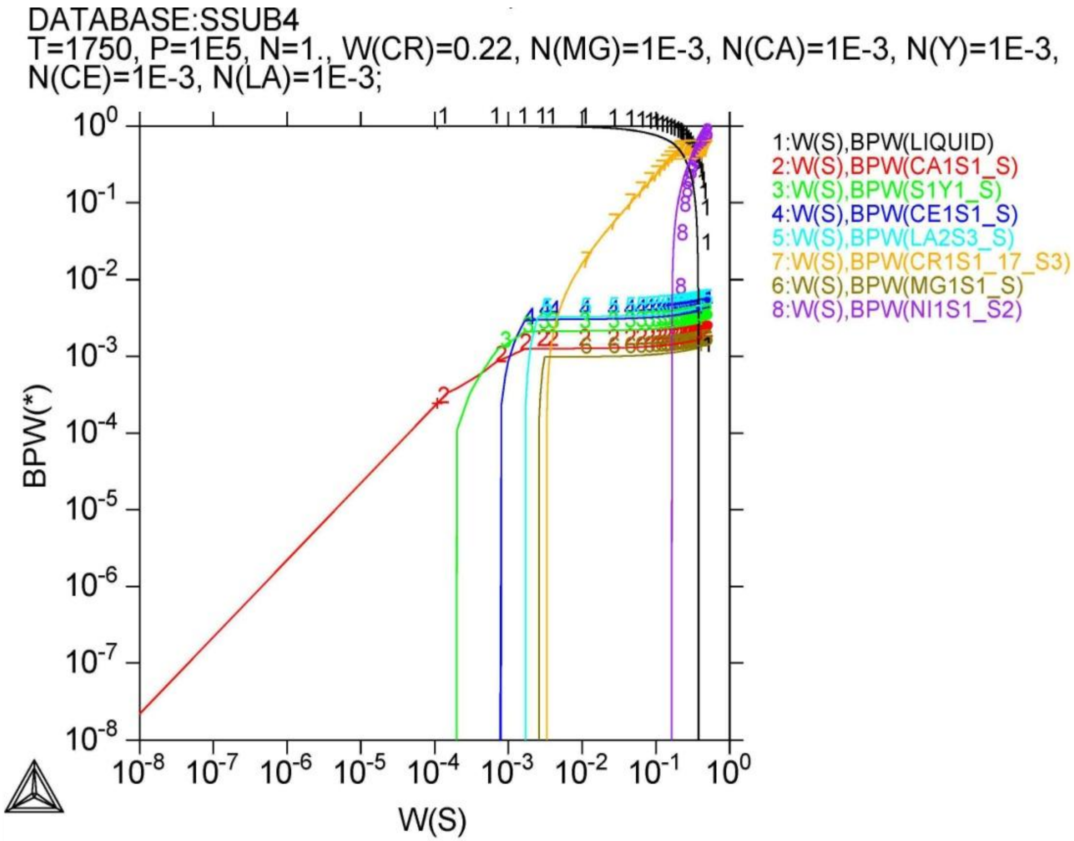
- NETL Small Ingots (15#): 1100°C/3h + 1200°C/9h
- Metaltek Step Block (300#): 1130°C/3h + 1200°C/3h + 1210°C/14h
- Flowserve Step Block (1000#): 1100°C/6h + 1200°C/48h
- SM ESR/VAR (10,000#): 1133°C/4h + 1190°C/8h + 1223°C/30h

Currently working with GE Co. to homogenize alloy 263 step block casting.

Evaluate Trace Element Control on Ni-base Alloy

NETL has begun to evaluate the activity of S in a liquid metal melt pool along with the effect of other chemical additions to 'getter' S. The kinetic predictions based on the Langmuir Loss equation were presented in the last update along with experimental results.

Let's consider a simple binary of Ni-22w/o Cr with 0.1 atomic percent of the elements from groups IIA and IIIA of the periodic table: Mg, Ca, Y, La, and Ce at 1477°C.



Below ~0.325 w/o S, the ranking in the relative amount of sulfides formed is:

La>Ce>Y>Ca>Mg

The critical S level ranking is as follows:

Ca>Y>Ce>La>Mg

Mg is the lowest rank while there is no clear winner. Let's take Ca out (does not form as much sulfide).

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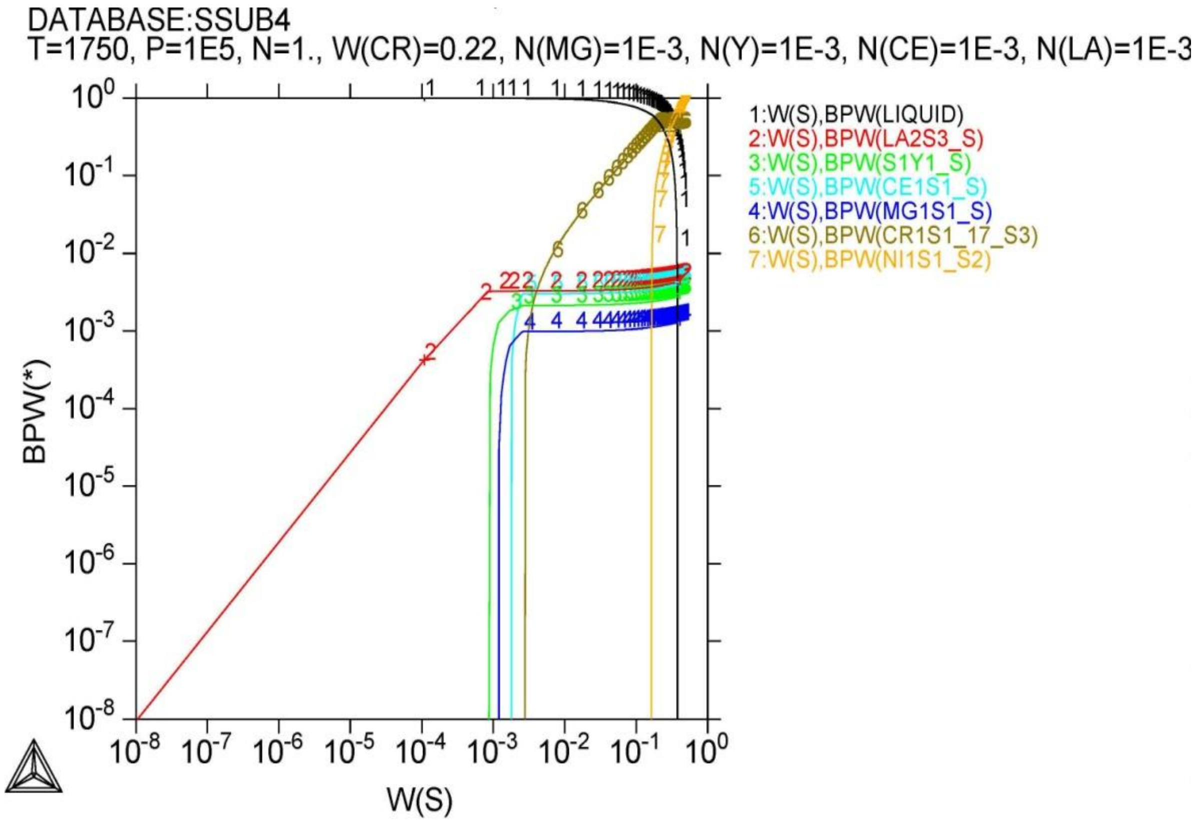

With Ca removed, the ranking in the relative amount of sulfides formed is:

La > Ce > Y > Mg

The critical S level ranking is as follows:

La > Ce > Y > Mg

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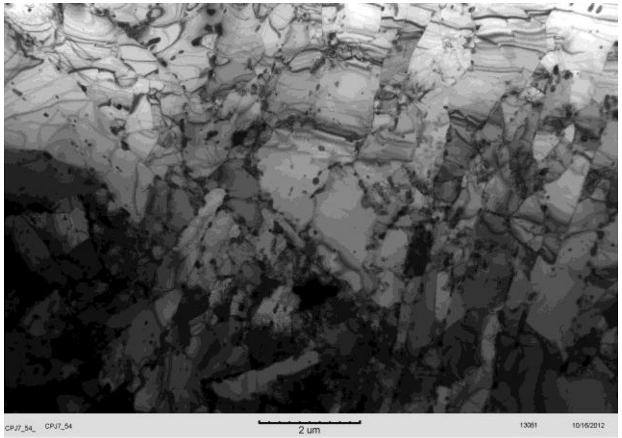
Design, cast and evaluate optimized advanced 9% Cr steel for USC applications.

Laboratory design & fabrication of 3rd iteration alloys complete with mechanical experimentation well underway.

Creep tests from the second iteration of ferritic-martensitic steels are ongoing for CPJ-7 at selected stress levels at 650°C are now available. Note the significant improvement in creep behavior for alloy series CPJ-7 has led to a patent invention disclosure presentation with follow-up patent disclosure in process.

A 3rd iteration of ferritic-martensitic steels have been manufactured. Tensile screening tests have been completed. Creep screening tests at 25.0 ksi & 650°C have also been completed. Most promising alloys (CPJ-8A & CPJ-10) are undergoing additional creep screening tests.



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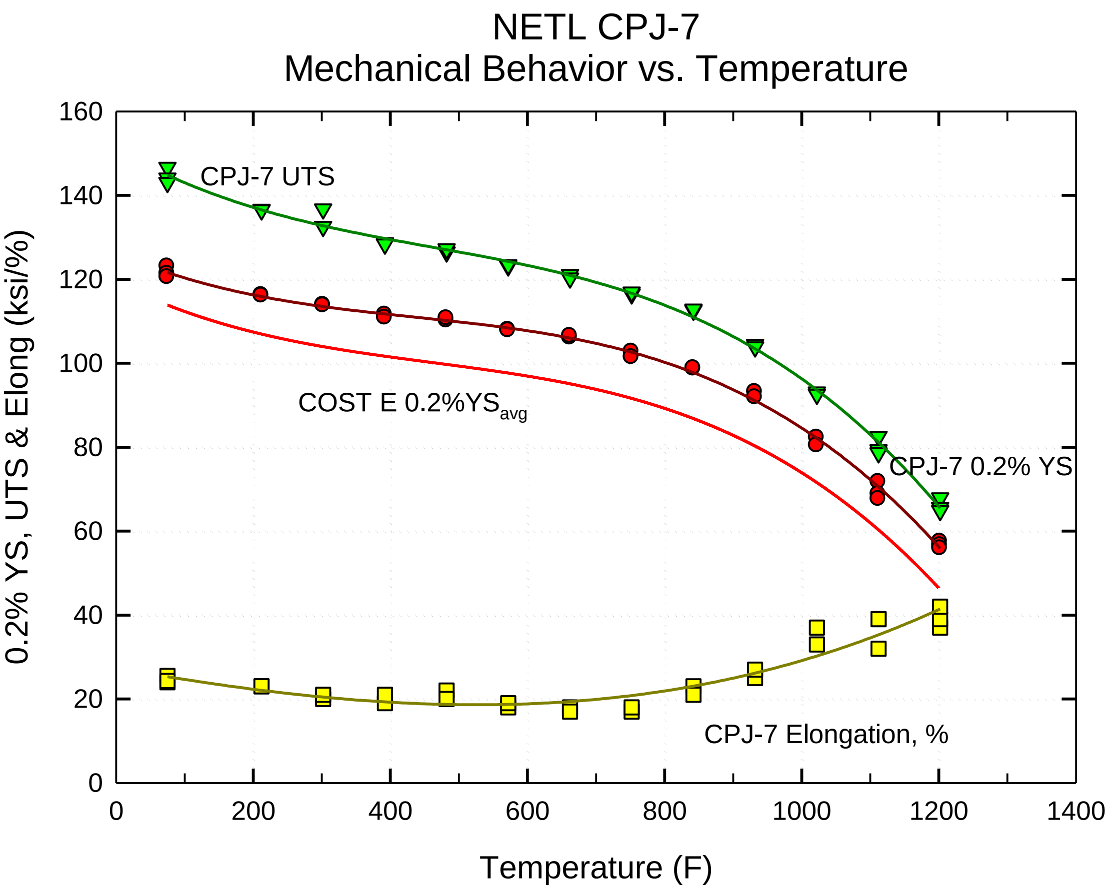
Summary of Tensile Mechanical Behavior of CPJ-7 Alloys



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

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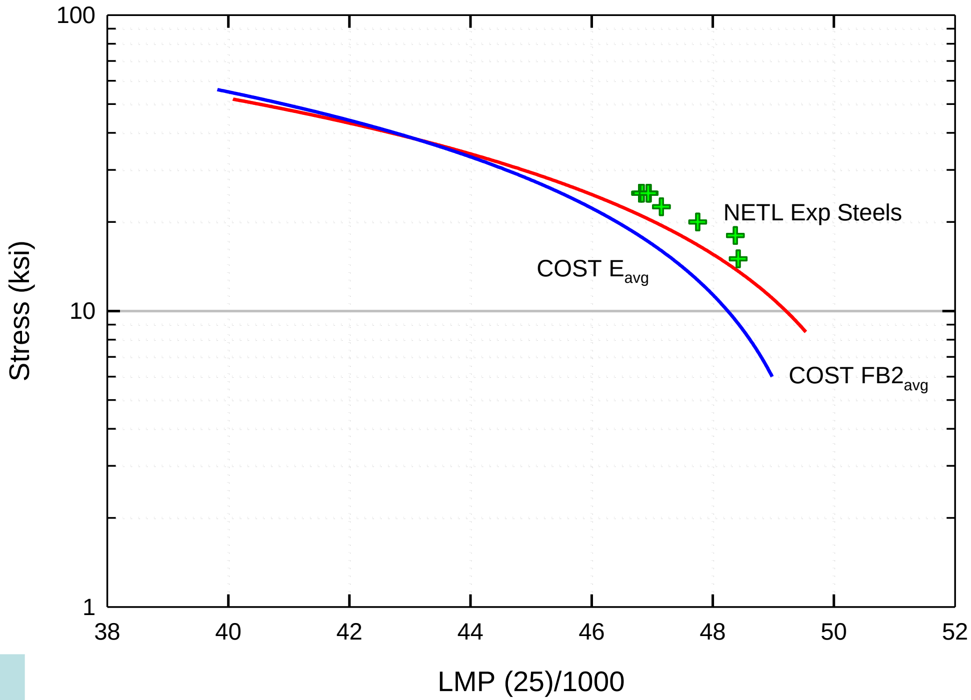
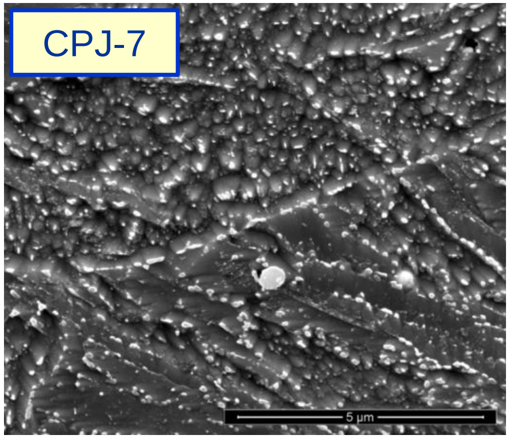
Summary of 650°C CPJ-7 Heat Creep Tests

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.

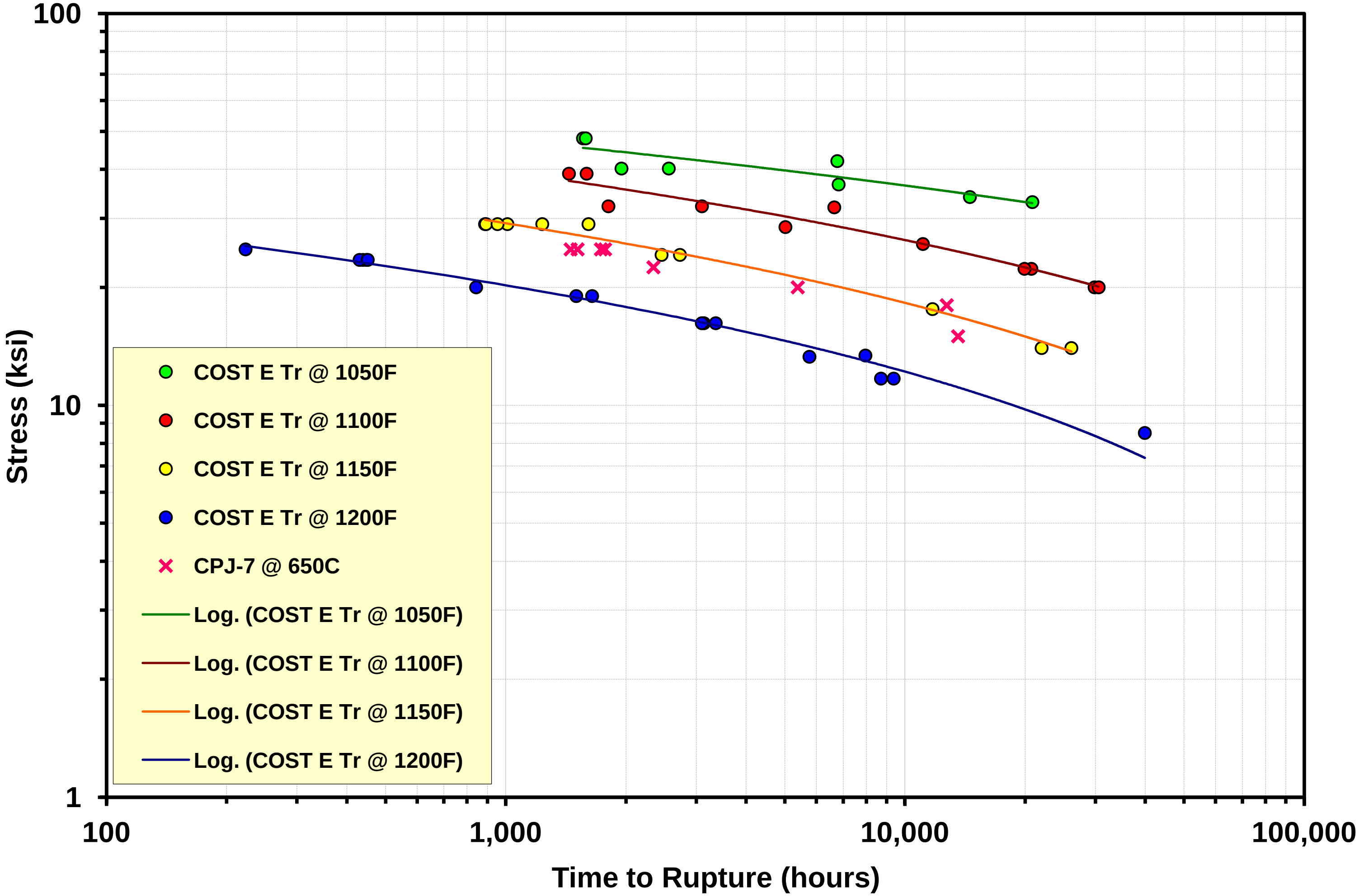


Alloy	Stress (ksi)	Stress (MPa)	Rupture Time (h)
COST FB2	25	172.4	614
COST B2	25	172.4	655
CPJ-7	25	172.4	1,454
CPJ-7B	25	172.4	1,514
CPJ-7C	25	172.4	1,774
CPJ-7D	25	172.4	1,732



SEM showing carbides in martensitic matrix around the individual laths.

Summary of 650°C CPJ-7 Creep Tests in Comparison with COST E Steel



Isothermal creep curves for COST E at temperatures from 1050°F (565.5°C) to 1200°F (648.9°C). Note the data points (×) for CPJ steel.

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Advanced 9% Cr Steel for 650°C Use
Summary of Results to Date

- Creep rupture life of CPJ-7 exceeds that of COST B2 by at least 2X at all temperatures and stresses tested. As stress level decreases, the separation between CPJ-7 experimental alloy & COST B2/FB2/E increases. This has become increasingly evident with the 650°C & 18 ksi creep test.
- Cobalt (Co) alone does not provide adequate matrix strength for improved creep life. (Microstructure as a function of Co content needs to be examined to better understand reasons for this.)
- Titanium (Ti) additions, even at 0.1 w/o greatly affect creep behavior. The effect is not beneficial.
- Tantalum (Ta) additions appear to improve both quasi-static tensile strength & creep rupture life relative to Ti additions for same heat treatment schedule (CPJ-7).
- Minor alloying additions (Ta, N, C and B) very much control microstructure & mechanical behavior.
- Homogenization treatment ~~greatly assists~~ *is critical* in the development of microstructure and strength through subsequent normalizing & tempering heat treatments.
- Addition of small amount of Cu seems to improve creep life of the CPJ-10 steel beyond that of CPJ-7. Additional testing will be used to confirm or refute.

Advanced 9% Cr Steel for 650°C Use

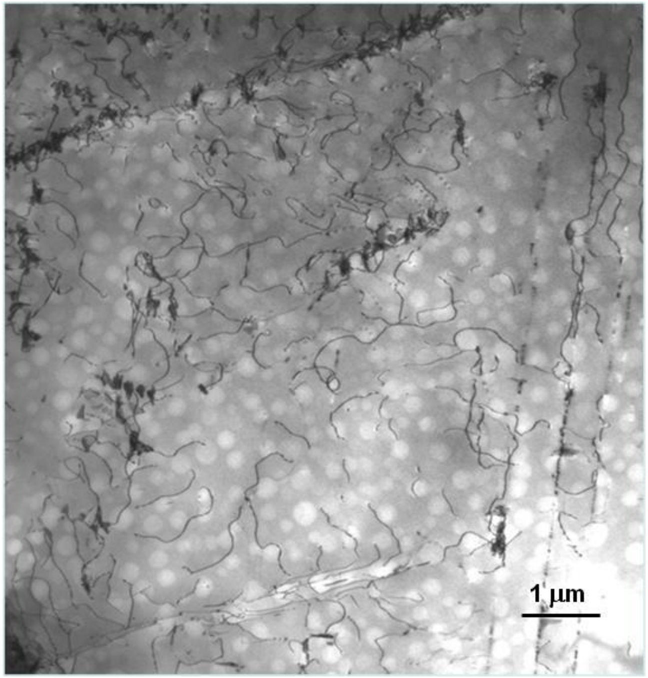
Next Steps & Future Work in Developing 650°C Capable Steel

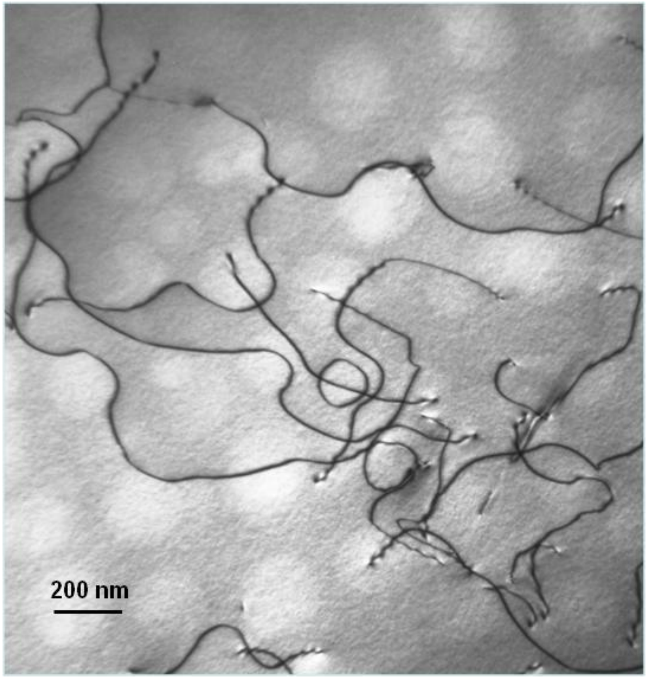
- Continue characterization of the homogenized, normalized & tempered CPJ-7 microstructures (at VaTech as part of IPT project) as well as the crept microstructures using advanced TEM techniques.
- Continue creep screening testing at 138 MPa/650°C as well as at lower stress levels for CPJ-7, CPJ-8A & CPJ-10 steels at 650°C.
- Characterize the additional 9% Cr steel heats based on CPJ-7 aim composition. Assess the effectiveness of the elements that were varied within the aim composition.
- Assess interest from OEM steam turbine manufacturers on CPJ-7 steel.

Design, Cast & Evaluate Optimized Advanced Nickel Superalloy for A-USC Applications.

Laboratory characterization is well underway & will continue throughout FY2013.

Characterization of N105 and H282 alloys has continued. It was discovered for the H282 alloy that extensive twinning occurred at some stage during deformation processing. The twins in the H282 were pinned in place by an extensive carbide network at the end termination points of the twins. Samples have been extracted from the solution annealed plate obtained from Haynes as well as plate that has been heat treated to create the peak aged condition in order to better understand the onset of twinning in the deformation processing steps.





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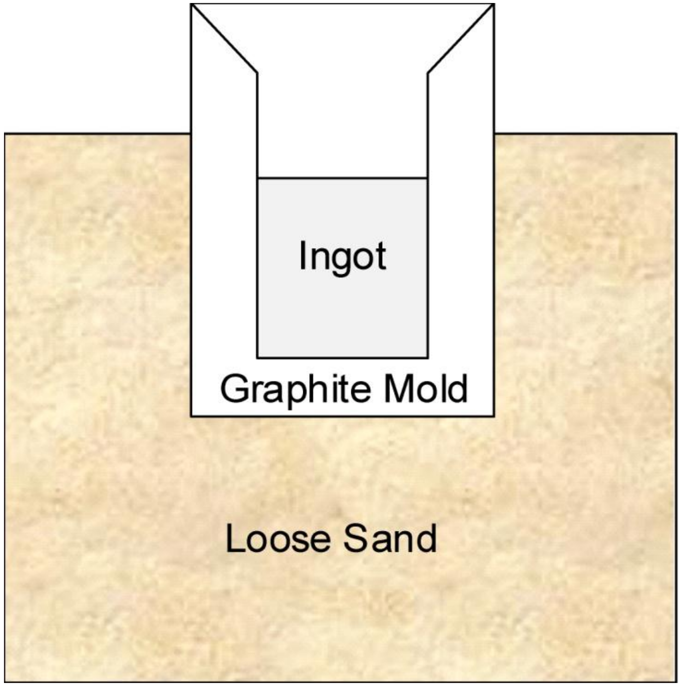
Develop Large Scale 9%Cr Steel Casting for 650°C Use

A heat of CPJ-7 was formulated and cast utilizing NETL's "enhanced" slow cooling method. 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 emulate the slow cooling conditions of a thick wall, full-size casings. The fully heat treated ingot was then bisected along the diameter. The halves were then sectioned into 0.4 in thick slabs from which 0.4 in square bars were cut. From these squares round bars were subsequently machined into traditional tensile/creep specimens.



NETL-RUA

Advanced 9% Cr Cast Steel for 650°C Use
Next Steps & Future Work in Developing 650°C Capable Steel

- Continue characterization of the homogenized, normalized & tempered CPJ-7 cast steel microstructures as well as the crept microstructures using SEM & TEM techniques.
- Run duplicate tensile & creep tests to separate underlying mechanical behavior from anomalies from casting process.
- Assess interest from OEM steam turbine manufacturers on CPJ-7 cast steel (would be used as casing for steam turbine rotor or as casing for main steam valves).

Alloy	Heat Treatment	Test Conditions (°C)	Yield Stress (MPs)	Tensile Strength (MPa)	Elongation (%)	Reduction in Area (%)
CPJ 7A-C	HTS+	RT	808	966	17	48
		600	463	539	28	74
		650	379	446	30	81
CPJ 7A-E	HTS+	RT	809	970	18	39
		600	463	484*	3*	25*
		650	371	443	31	79

NETL-RUA

Technology Transfer Activities FY2012/2013

Peer Reviewed Manuscripts (Accepted & Published)

1) C.J. Cowen; P.E. Danielson and P.D. Jablonski, "The Microstructural Evolution of Inconel Alloy 740 During Solution Treatment, Aging and Exposure at 740°C", J. Mater. Eng. Perform., 20 (6), (2011) 1078-1083.
2) P.D. Jablonski, J.A. Hawk, C.J. Cowen and P.J. Maziasz, "Processing of Advanced Cast Alloys for A-USC Steam Turbine Applications," *Journal of Metals*, 64 (2012) 271-279.
3) J. Zhu, G. R. Holcomb, P. D. Jablonski, A. Wise, J. Li, D. E. Laughlin, and S. Sridhar, "Subsurface Characterization of an Oxidation-Induced Phase Transformation and Twinning in Nickel-Based Super Alloy Exposed to Oxy-Combustion Environments," Mater. Sci. Eng. A, Vol. 550 (2012), 243-253.
4) Y. Wen, L-Q. Chen and J.A. Hawk, "Phase-field modeling of corrosion kinetics under dual-oxidants," Modeling & Simulation Mater. Sci. Eng., 20 (2012) Art. No.: 035013.
5) N. Mu, K.Y. Jung, N.M. Yanar, G.H. Meier, F.S. Pettit and G.R. Holcomb, "Water Vapor Effects on the Oxidation Behavior of Fe-Cr and Ni-Cr Alloys in Atmospheres Relevant to Oxy-fuel Combustion," Oxidation of Metals, 78 (2012) 221-237.
6) M.A. Helminiak, N.M. Yanar, F.S. Pettit, T.A. Taylor and G.H. Meier, "The Effect of Superalloy Substrate on the Behaviour of High-purity Low-density Air Plasma Sprayed Thermal Barrier Coatings," *Materials at High Temperatures*, 29, (2012) p. 264.

Conference Proceedings (Accepted & Published)

1) G. R. Holcomb, J. Tylczak, G. H. Meier, B. Lutz, K. Jung, N. Mu, N. M. Yanar, F. S. Pettit, J. Zhu, A. Wise, D. Laughlin, S. Sridhar, "Fireside Corrosion in Oxy-fuel Combustion of Coal," 8th International Symposium on High-Temperature Corrosion and Protection of Materials, May 20-25, 2012, Les Embiez, France.
2) N. Mu, K. Y. Jung, N. M. Yanar, F. S. Pettit, G. R. Holcomb , B. H. Howard, G. H. Meier, "The Effects of Water Vapor and Hydrogen on the High-Temperature Oxidation of Alloys," 8th International Symposium on High-Temperature Corrosion and Protection of Materials, May 20-25, 2012, Les Embiez, France.
3) J. Zhu, G. R. Holcomb, P. D. Jablonski, D. E. Laughlin, S.Sridhar, "Investigation of Oxidation-Induced Phase Transformation and Microstructures of Inconel® 939 in Oxy-fuel Combustion," 8th International Symposium on High-Temperature Corrosion and Protection of Materials, May 20-25, 2012, Les Embiez, France.
4) G. R. Holcomb, J. Tylczak, G. H. Meier, K. Jung, N. Mu, N. M. Yanar, and F. S. Pettit, "Fireside Corrosion in Oxy-Fuel Combustion of Coal," ECS Transactions, 220th ECS Meeting, Volume 41, Issue 42, pp. 73-84, October 9-14, 2011 , Boston, MA.
5) G. R. Holcomb, J. Tylczak, G. H. Meier, B. S. Lutz, N. M. Yanar, F. S. Pettit, J. Zhu, A. Wise, D. E. Laughlin, and S. Sridhar, "Oxy-Combustion Environment Characterization: Fire- and Steam-Side Corrosion in Advanced Combustion," Proceedings of the 26th Annual Conference on Fossil Energy Materials, Pittsburgh, PA, April 17-19, 2012.

Technology Transfer Activities FY2012/2013

Journals (Submitted/Accepted)

1) G. R. Holcomb, J. Tylczak, G. H. Meier, B. Lutz, K. Jung, N. Mu, N. M. Yanar, F. S. Pettit, J. Zhu, A. Wise, D. Laughlin and S. Sridhar, "Fireside Corrosion in Oxy-fuel Combustion of Coal," *Oxidation of Metals*, (2013).
2) N. Mu, K. Jung, N.M. Yanar, F.S. Pettit, G.R. Holcomb , B.H. Howard and G.H. Meier, "The Effects of Water Vapor and Hydrogen on the High-Temperature Oxidation of Alloys," *Oxidation of Metals*, (2013).
3) J. Zhu, A. Wise, T. Nuhfwe, G. R. Holcomb, P. D. Jablonski, S. Sridhar and D. E. Laughlin, "High-Temperature-Oxidation-Induced Ordered Structure in Inconel 939 Superalloy Exposed to Oxy-Combustion Environments," *Materials Science and Engineering A*, (2013).
4) N. Monsegue, W.T. Reynolds, J.A. Hawk and M. Murayama, "3D Characterization of $M_{23}C_6$ Precipitates after Creep in a Martensitic Steel," submitted to *Acta Materialia*, (2013).

Conference Proceedings (Submitted/Accepted)

1) K. Wu, Y. Wen and J.A. Hawk, "Phase Field Simulations on the Precipitation Kinetics of γ' in Ni-base Superalloy Haynes 282," accepted for publication *TMS Proceedings*, (2013).

Reports (Published)

1. G. R. Holcomb and J. Tylczak, "Task 1—Steam Oxidation (NETL-US) and Task 2—Materials for Advanced Boiler and Oxy-combustion Systems (NETL-US)," US-UK Energy RTD Collaboration 2009-2013: Advanced Materials, Annual Report, DOE/NETL-2012/1591, April 20, 2012.
2. D. Oryshchyn, T. Ochs, S. Bullard, C. Carney, J. Clark, S. Gerdemann, S. Harendra, G. Holcomb, C. Summers, R. Woodside, Oxy-firing and Integrated Pollutant Removal: Examination and Testing to Develop Data Sets and Engineering Tools for the Design of Oxy-fired Power Stations With CO_2 Capture, FY 2003-FY2011: Final Report, NETL, Albany, OR 2012.

Technology Transfer Activities FY2012/2013

Presentations Contributed or Invited

1) G. R. Holcomb, J. Tylczak, G. H. Meier, K. Jung, N. Mu, N. M. Yanar, and F. S. Pettit, "Fireside Corrosion in Oxy-Fuel Combustion of Coal," 220th ECS Meeting, High Temperature Corrosion and Materials Chemistry 9 — A Symposium in Honor of Professor Robert A. Rapp, October 9-14, 2011, Boston, MA.
2) K. Wu, Y. Wen, J.A. Hawk, De Nyago Tafen and M. Gao"Multi-scale Modeling on Microstructures and Microstructure-Property Relations of High Temperature Materials for Fossil Energy Applications," MS&T 2011, October 17-21, 2011, Columbus, Ohio.
3) P.D. Jablonski, J.A. Hawk, D. Purdy and P.J. Maziasz, "Cast Versions of Wrought Alloys: Candidates for Steam Turbine Casings," USC Steering Committee Meeting, December 7-8, 2011, Chicago, IL.
4) J.A. Hawk and J.S. Sears, "TEM Microstructural Characterization of Nimonic 105 and Haynes 282," USC Steering Committee Meeting, December 7-8, 2011, Chicago, IL.
5) P.J. Maziasz, B. Pint, P.D. Jablonski and J.A. Hawk, "AUSC Turbine-Cast Ni-based Casing Collaborative Project (ORNL and NETL)," USC Steering Committee Meeting, December 7-8, 2011, Chicago, IL.
6) G. R. Holcomb and G. H. Meier, "Fireside Corrosion," 3rd JCOAL/NETL Oxyfuel Workshop, January 27, 2012, Pittsburg, PA & Albany, OR.
7) P.D. Jablonski, J.A. Hawk, D. Purdy and P.J. Maziasz, "Cast Versions of Wrought Alloys: Candidates for Steam Turbine Casings," USC Steering Committee Meeting, March 7-8, 2012, Chicago, IL.
8) J.A. Hawk & J.S. Sears, "TEM Microstructural Characterization of Nimonic 105 and Haynes 282: LCF Microstructures in Nimonic 105," USC Steering Committee Meeting, March 7-8, 2012, Chicago, IL.
9) P.J. Maziasz, B. Pint, P.D. Jablonski and J.A. Hawk, "AUSC Turbine-Cast Ni-based Casing Collaborative Project (ORNL and NETL)," USC Steering Committee Meeting, March 7-8, 2012, Chicago, IL.
10) J.A. Hawk, P.D. Jablonski and C.J. Cowen, "Mechanical Behavior of Tempered Martensitic Steels for Ultrasupercritical Steam Applications," Materials in Clean Power Systems VII: Clean Coal-, Hydrogen Based-Technologies, and Fuel Cells, TMS Annual Meeting & Exhibition, March 11-15, 2012, Orlando, FL.
11) J.A. Hawk, J.S. Sears and P.D. Jablonski, "Microstructure Characterization of Crept Ni-base Alloys for High Temperature Use," Materials in Clean Power Systems VII: Clean Coal-, Hydrogen Based-Technologies, and Fuel Cells, TMS Annual Meeting & Exhibition, March 11-15, 2012, Orlando, FL.
12) J.A. Hawk and P.D. Jablonski, "Strengthening Concepts & Mechanical Behavior of Ni-base Alloys in A-USC Steam Turbines," Materials in Clean Power Systems VII: Clean Coal-, Hydrogen Based-Technologies, and Fuel Cells, TMS Annual Meeting & Exhibition, March 11-15, 2012, Orlando, FL.
13) P.D. Jablonski, J.A. Hawk, D. Purdy and P.J. Maziasz, "Impact of Casting Superheat on the Mechanical Properties of Traditionally Wrought Ni-Based Superalloys for USC Steam Turbines," Materials in Clean Power Systems VII: Clean Coal-, Hydrogen Based-Technologies, and Fuel Cells, TMS Annual Meeting & Exhibition, March 11-15, 2012, Orlando, FL.

Technology Transfer Activities FY2012/2013

Presentations Contributed or Invited

14) N. Monseque, W. Reynolds and M. Murayama, "Nano-scale Carbide Characterization in a Tempered Martensitic 9Cr Steel Used for Ultrasupercritical Steam Power Plants," Materials in Clean Power Systems VII: Clean Coal-, Hydrogen Based-Technologies, and Fuel Cells, TMS Annual Meeting & Exhibition, March 11-15, 2012, Orlando, FL.
15) Y. Wen, K. Wu, J.A. Hawk and L-Q. Chen, "Computational Modeling of Oxidation and Corrosion of Alloys in Complex Environments," Computational Thermodynamics and Kinetics, TMS Annual Meeting & Exhibition, March 11-15, 2012, Orlando, FL.
16) J.A. Hawk, "The Metallurgy and Engineering of USC and A-USC Steam Turbines," ASM International Cincinnati Chapter, March 15, 2012, Springfield Township, OH.
17) G. R. Holcomb, J. Tylczak, G. H. Meier, B. S. Lutz, N. M. Yanar, F. S. Pettit, J. Zhu, A. Wise, D. E. Laughlin, and S. Sridhar, " Oxy-Combustion Environment Characterization: Fire- and Steam-Side Corrosion in Advanced Combustion," 26th Annual Conference on Fossil Energy Materials, April 17-19, 2012, Pittsburgh, PA.
18) P.D. Jablonski, J.A. Hawk, D. Purdy and P.J. Maziasz, "Addressing Materials Processing Issues for Steam Turbines: Cast Versions of Wrought Ni-Based Superalloys," 26th Annual Conference on Fossil Energy Materials, April 17-19, 2012, Pittsburgh, PA.
19) G. H. Meier, B. L. Lutz, K.-Y. Jung, N. Mu, N. M. Yanar, F. S. Pettit, and G. R. Holcomb, "Effect of H_2O and CO_2 on the Selective Oxidation of Iron Base and Nickel Base Alloys," 26th Annual Conference on Fossil Energy Materials, April 17-19, 2012, Pittsburgh, PA.
20) J.A. Hawk, "The Metallurgy and Engineering of USC and A-USC Steam Turbines," ASM International Minneapolis Chapter, April 18, 2012, Minneapolis, MN.
21) G.R. Holcomb, and J. Tylczak, "Task 1 - Steam Oxidation (NETL-US)," US-UK Energy RTD Collaboration 2009-2013: Advanced Materials Workshop, April 19-20, 2012, Pittsburgh, PA.
22) G. R. Holcomb and J. Tylczak, "Task 2 - Materials for Advanced Boiler and Oxy-combustion Systems (NETL-US)," US-UK Energy RTD Collaboration 2009-2013: Advanced Materials Workshop, April 19-20, 2012, Pittsburgh, PA,.
23) B. S. Lutz, K. Jung, N. Mu, N. M. Yanar, F. S. Pettit, G. H. Meier, and G. R. Holcomb, "Effects of Oxyfuel Environments and Relevant Deposits on Alloy/Coating Degradation," US-UK Energy RTD Collaboration 2009-2013: Advanced Materials Workshop, April 19-20, 2012, Pittsburgh, PA.
24) P.D. Jablonski and J.A. Hawk, "Alloy Manufacturing and Process Development – Large Scale Ni-base Alloys," NETL-ORD Energy Systems Dynamics Focus Area Merit Review, 16 May 2012, Morgantown, WV.
25) J.A. Hawk and P.D. Jablonski, "Optimized Alloys for USC and A-USC Components," NETL-ORD Energy Systems Dynamics Focus Area Merit Review, 16 May 2012, Morgantown, WV.
26) G.R. Holcomb, "Oxy-combustion Environment Characterization: Fire-side Corrosion," NETL-ORD Energy Systems Dynamics Focus Area Merit Review, 16 May 2012, Morgantown, WV.

Technology Transfer Activities FY2012/2013

Presentations Contributed or Invited

27) G. R. Holcomb, J. Tylczak, G. H. Meier, B. Lutz, K. Jung, N. Mu, N. M. Yanar, F. S. Pettit, J. Zhu, A. Wise, D. Laughlin, S. Sridhar, "Fireside Corrosion in Oxy-fuel Combustion of Coal," poster at the 8th International Symposium on High-Temperature Corrosion and Protection of Materials, May 20-25, 2012, Les Embiez, France.

28) N. Mu, K. Y. Jung, N. M. Yanar, F. S. Pettit, G. R. Holcomb , B. H. Howard, G. H. Meier, "The Effects of Water Vapor and Hydrogen on the High-Temperature Oxidation of Alloys," 8th International Symposium on High-Temperature Corrosion and Protection of Materials, May 20-25, 2012, Les Embiez, France.

29) J. Zhu, G. R. Holcomb, P. D. Jablonski, D. E. Laughlin, S.Sridhar, "Investigation of Oxidation-Induced Phase Transformation and Microstructures of Inconel® 939 in Oxy-fuel Combustion," poster at the 8th International Symposium on High-Temperature Corrosion and Protection of Materials, May 20-25, 2012, Les Embiez, France.

30) J.A. Hawk and J.S. Sears, "TEM Microstructural Characterization of Nimonic 105 and Haynes 282: LCF Microstructures in Nimonic 105 and Haynes 282," USC Steering Committee Meeting, June 6-7, 2012, Chicago, IL.

31) P.D. Jablonski, J.A. Hawk and P.J. Maziasz "Addressing Materials Processing Issues for Steam Turbines: Cast Versions of Wrought Ni-Based Superalloys," June 6-7, 2012, Chicago, IL.

32) P.J. Maziasz, B. Pint, P.D. Jablonski and J.A. Hawk, "AUSC Turbine-Cast Ni-based Casing Collaborative Project (ORNL and NETL)," USC Steering Committee Meeting, June 6-7, 2012, Chicago, IL.

33) N. Monsegue, X. Jin, N.K. Yamoah, J.A. Hawk, W. Reynolds, G. Wang and M. Muryama, "3D Multi-scale Electron Microscopy for Nano-scale Carbide Mapping in a Tempered 9 Cr Martensitic Steel," International Conference on 3D Materials Science 2012, July 8-12, 2012, Seven Springs, PA.

34) P.D. Jablonski, J.A. Hawk and P.J. Maziasz "Addressing Materials Processing Issues for Steam Turbines: Cast Versions of Wrought Ni-Based Superalloys," September 5-6, 2012, Chicago, IL.

35) P.J. Maziasz, B. Pint, P.D. Jablonski and J.A. Hawk, "AUSC Turbine-Cast Ni-based Casing Collaborative Project (ORNL and NETL)," USC Steering Committee Meeting, September 5-6, 2012, 2012, Chicago, IL.

36) P. Huczkowski, T. Olszewski, B. Lutz, G.R. Holcomb, V. Shemet, G.H. Meier, L. Singheiser, W.J. Quadakkers, "Effect of SO_2 on Oxidation of Metallic Materials in CO_2/H_2O-Rich Gases Relevant to Oxyfuel Environments," EFC Workshop: Beyond Single Oxidants, DECHEMA-Haus, September 19-21, 2012, Frankfurt am Main, Germany.

37) N. Mu, K.Y. Jung, N.M. Yanar, F.S. Pettit, P. Huczkowski, T. Olszewski G.R. Holcomb, L. Singheiser, W.J. Quadakkers and G.H. Meier, "Corrosion Behavior of Fe-Cr and Ni-Cr Base Alloys in Atmospheres Relevant to Oxy-fuel Combustion," submitted to EFC Workshop: Beyond Single Oxidants, DECHEMA-Haus, September 19-21, 2012, Frankfurt am Main, Germany.

Technology Transfer Activities FY2012/2013

Presentations Contributed or Invited

38) M. Gao, P.D. Jablonski, J.A. Hawk and C.J. Cowen, "Integrated Approach to Design of Creep-Resistant Ferritic Steels," Harnessing the Materials Genome: Accelerated Materials Development via Computational & Experimental Tools, An ECI Conference, September 30-October 5, 2012, Vail, Colorado.

39) G. R. Holcomb, J. Tylczak, G. H. Meier, B. S. Lutz, N. M. Yanar, F. S. Pettit, J. Zhu, A. Wise, D. E. Laughlin and S. Sridhar, "Fireside Corrosion in the Oxy-Combustion of Coal," MS&T'12, October 7-11, 2012, Pittsburgh, PA.

40) Y. Wen, K. Wu and J.A. Hawk, "Computational Modeling of Precipitation & Oxidation Kinetics," Phase Stability, Diffusion, Kinetics & Their Application, MS&T'12, October 7-11, 2012, Pittsburgh, PA.

41) B. S. Lutz, M. N. Task, N. M. Yanar, F. S. Pettit, G. R. Holcomb and G. H. Meier, "Deposit-Induced Corrosion of Nickel-Base Alloys at Low temperatures (650-750˚C)," PRIME 2012, October 7-12, 2012, Honolulu, HI.

42) G. R. Holcomb, and J. Tylczak, "Task 1—Steam Oxidation (NETL-US)," presented at the US-UK Energy RTD Collaboration 2009-2013: Advanced Materials Workshop, Cranfield, UK October 18-19, 2012.

43) G. R. Holcomb, and J. Tylczak, "Task 2—Materials for Advanced Boiler and Oxy-combustion Systems (NETL-US)," presented at the US-UK Energy RTD Collaboration 2009-2013: Advanced Materials Workshop, Cranfield, UK October 18-19, 2012.

44) B. Lutz, N. Mu, N.M. Yanar, K. Jung, F.S. Pettit, G.H. Meier and G.R. Holcomb, "Effects of Oxyfuel Environments and Relevant Deposits on Alloy/Coating Degradation," presented at the US-UK Energy RTD Collaboration 2009-2013: Advanced Materials Workshop, Cranfield, UK October 18-19, 2012.

45) J.A. Hawk and P.D. Jablonsk, "Advanced Alloy Fabrication," 2nd Annual Energy & Innovation Conference, Track 1B: Materials Design & Development, 28-29 November 2012, Canonsburg, Pennsylvania (Invited).

46) G.R. Holcomb, "Fireside Corrosion," 4th JCOAL/NETL Oxyfuel Workshop, Pittsburgh, PA and Albany, OR, 4 December 2012.

47) G. R. Holcomb and Y. Matsunaga, "Discussion about Possibility of Closer Collaboration and Co-authoring," 4th JCOAL/NETL Oxyfuel Workshop, Pittsburgh, PA and Albany, OR, 4 December 2012.

48) P.J. Maziasz, B. Pint, P.D. Jablonski and J.A. Hawk, "AUSC Turbine-Cast Ni-based Casing Collaborative Project (ORNL and NETL)," USC Steering Committee Meeting, 11 December 2012, Mobile, Alabama.

Technology Transfer Activities FY2012/2013

Patent Disclosure Application

1) "Optimized Homogenization Heat Treatment of Single Crystal Alloys," Paul D. Jablonski, Christopher C. Cowen and Jonathon D. Miller, (presented to the NETL invention review board on November 17, 2011). S-127,575 submitted to USPO in December 2011.
2) "Method to Improve Superalloy Oxidation Resistance by Surface Treatment," Paul D. Jablonski and Jeffrey A. Hawk, (presented to the NETL invention review board on November 17, 2011). Patent application filed 2012.
3) "Method to Improve Creep Strength in Steel by Alloy Design and Heat Treatment," NETL Invention Review Board (NETL No: 12N-23), 20 December 2012, Albany, OR/Morgantown, WV/Pittsburgh, PA (J.A. Hawk, P.D. Jablonski and C.J. Cowen).
4) "A Computational Approach to Homogenizing Alloys," NETL Invention Review Board (NETL No: 12N-24), 20 December 2012, Albany, OR/Morgantown, WV/Pittsburgh, PA (P.D. Jablonski and J.A. Hawk).

Abstracts Accepted for Presentation

1) P.D. Jablonski, J.A. Hawk. D. Purdy and P.J. Maziasz, "Homogenizing Castings to improve the Mechanical Properties of Traditionally Wrought Ni-Based Superalloys for A-USC Steam Turbines," 2013 TMS Annual Meeting & Exhibition, Materials in Clean Power Systems VIII: Durability of Materials, March 3-7, 2013, San Antonio, TX.
2) J.A. Hawk and P.D. Jablonski, "Creep Life Modeling for High Temperature Processes," 2013 TMS Annual Meeting & Exhibition, Materials in Clean Power Systems VIII: Durability of Materials, March 3-7, 2013, San Antonio, TX.
3) J.A. Hawk, P.D. Jablonski and J.S. Sears, "Microstructural Evolution in Haynes 282 After High Temperature Creep Exposure," 2013 TMS Annual Meeting & Exhibition, Phase Transformations and Microstructural Evolution, March 3-7, 2013, San Antonio, TX.
4) M. Gao, D-N. Tafen, J.A. Hawk, Y. Wang, M. Widom, L. Santodonato and P. Liaw, "The Computational Modeling of High-Entropy Alloys," 2013 TMS Annual Meeting & Exhibition, Symposium on High Entropy Alloys, March 3-7, 2013, San Antonio, TX.
5) J.A. Hawk and P.D. Jablonski, "New 9% Cr Steel for Fossil Energy Use at Temperatures Up To 650°C," The 8th Pacific Rim International Conference on Advanced Materials and Processing, Waikoloa, HI, 4-9 August 2013.
6) J.A. Hawk and P.D. Jablonski, "The Use of Nickel Alloys in Advanced Ultra-Supercritical Steam Turbines," The 8th Pacific Rim International Conference on Advanced Materials and Processing, Waikoloa, HI, 4-9 August 2013.
7) P.D. Jablonski and J.A. Hawk, "Nitrogen Control in VIM Melts," International Symposium on Liquid Metal Processing and Casting 2013, 22-25 September 2013, Austin, TX.
8) P.D. Jablonski and J.A. Hawk, "The Practical Application of Minor Element Control in Small Scale Melts," International Symposium on Liquid Metal Processing and Casting 2013, 22-25 September 2013, Austin, TX.

Technology Transfer Activities FY2012/2013

Abstracts Accepted for Presentation

9) G. R. Holcomb, J. Tylczak, G. H. Meier, B. S. Lutz, N. M. Yanar, F. S. Pettit, J. Zhu, A. Wise, D. E. Laughlin and S. Sridhar, "Fireside Corrosion in Oxyfuel Combustion," 7th International Conference on Advances in Materials Technology for Fossil Power Plants, Waikoloa, HI, 22-25 October 2013.
10) J.A. Hawk and P.D. Jablonski, "Martensitic 9%Cr Steel for Ultra-Supercritical Steam Applications," 7th International Conference on Advances in Materials Technology for Fossil Power Plants, Waikoloa, HI, 22-25 October 2013.
11) J.A. Hawk and P.D. Jablonski, "Nickel Superalloys in Advanced Ultra-Supercritical Steam Turbines," 7th International Conference on Advances in Materials Technology for Fossil Power Plants, Waikoloa, HI, 22-25 October 2013.
12) P.D. Jablonski, J.A. Hawk and P.J. Maziasz, "Cast Nickel Alloys for A-USC Steam Turbine Applications," 7th International Conference on Advances in Materials Technology for Fossil Power Plants, Waikoloa, HI, 22-25 October 2013.