BOILER MATERIALS FOR ULTRASUPERCRITICAL COAL POWER PLANTS

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Abstract

The U.S. Department of Energy (DOE) and the Ohio Coal Development Office (OCDO) have recently initiated a project aimed at identifying, evaluating, and qualifying the materials needed for the construction of the critical components of coal-fired boilers capable of operating at much higher efficiencies than current generation of supercritical plants. This increased efficiency is expected to be achieved principally through the use of ultrasupercritical steam conditions (USC). A limiting factor in this can be the materials of construction. The project goal is to assess/develop materials technology that will enable achieving turbine throttle steam conditions of 760°C (1400°F)/35 MPa (5000 psi). This goal seems achievable based on a preliminary assessment of material capabilities. The project is further intended to build further upon the alloy development and evaluation programs that have been carried out in Europe and Japan. Those programs have identified ferritic steels capable of meeting the strength requirements of USC plants up to approximately 620°C (1150°F) and nickel-based alloys suitable up to 700°C (1300°F). In this project, the maximum temperature capabilities of these and other available high-temperature alloys are being assessed to provide a basis for materials selection and application under a range of conditions prevailing in the boiler. This report provides a quarterly status report for the period of April 1 to June 30, 2005.

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Executive Summary

A. Project Objective

The principal objective of this project is to develop materials technology for use in ultrasupercritical (USC) plant boilers capable of operating with 760°C (1400°F), 35 MPa (5000 psi) steam.

B. Background and Relevance

In the 21st century, the world faces the critical challenge of providing abundant, cheap electricity to meet the needs of a growing global population while at the same time preserving environmental values. Most studies of this issue conclude that a robust portfolio of generation technologies and fuels should be developed to assure that the United States will have adequate electricity supplies in a variety of possible future scenarios.

The use of coal for electricity generation poses a unique set of challenges. On the one hand, coal is plentiful and available at low cost in much of the world, notably in the U.S., China, and India. Countries with large coal reserves will want to develop them to foster economic growth and energy security. On the other hand, traditional methods of coal combustion emit pollutants and CO₂ at high levels relative to other generation options. Maintaining coal as a generation option in the 21st century will require methods for addressing these environmental issues.

This project has established a government/industry consortium to undertake a five-year effort to evaluate and develop advanced materials that allow the use of advanced steam cycles in coal-based power plants. These advanced cycles, with steam temperatures up to 760°C, will increase the efficiency of coal-fired boilers from an average of 35% efficiency (current domestic fleet) to 47% (HHV). This efficiency increase will enable coal-fired power plants to generate electricity at competitive rates (irrespective of fuel costs) while reducing CO₂ and other fuel-related emissions by as much as 29%.

Success in achieving these objectives will support a number of broader goals. First, from a national prospective, the program will identify advanced materials that will make it possible to maintain a cost-competitive, environmentally acceptable coal-based electric generation option. High sulfur coals will specifically benefit in this respect by having these advanced materials evaluated in high-sulfur coal firing conditions and from the significant reductions in waste generation inherent in the increased operational efficiency. Second, from a national prospective, the results of this program will enable domestic boiler manufacturers to successfully compete in world markets for building high-efficiency coal-fired power plants.

The project is based on an R&D plan developed by the Electric Power Research Institute (EPRI) that supplements the recommendations of several DOE workshops on the subject of advanced materials. In view of the variety of skills and expertise required for the successful completion of the proposed work, a consortium that includes EPRI and the major domestic boiler manufacturers (Alstom Power, Babcock and Wilcox (a division of McDermott Technologies Inc.), Foster Wheeler, Riley Power Inc., and Oak Ridge National Labs) has been developed.

C. Project Tasks

The project objective is expected to be achieved through 9 tasks as listed below:

Task 1.	Conceptual Design and Economic Analysis
Task 2.	Mechanical Properties of Advanced Alloys
Task 3.	Steamside Oxidation Resistance
Task 4.	Fireside Corrosion Resistance
Task 5.	Welding Development
Task 6.	Fabricability
Task 7.	Coatings
Task 8.	Design Data and Rules
Task 9.	Project Integration and Management

D. Major Accomplishments during the Quarter

- No microhardness degradation was noted on aged samples of CCA617 or Haynes 230 after 10,025 hrs at 700, 750, and 800°C or in HR6W or Super 304H after 10,025 hrs at 700°C.
- Creep-fatigue testing of CCA617 was completed this quarter.
- Short term cross weld rupture tests on Inconel 740 using 740 and 263 filler metal have been completed. Pressurized U-bend creep tests have been completed on all HR6W specimens and two Haynes 230 samples.
- The second steamside oxidation test at 800°C was completed. The ferritic alloys MARB2 and VM12 parabolic rate constants that were significantly less than most of the austenitic stainless steels. Alloys with the lowest rate were Alloy 740, CCA617, and Alloy 230.
- Post test analysis of 1600°F superheater/reheater fire side corrosion coupons was completed.
- Critical components have been delivered to the first two air cooled corrosion probe test sites. The third probe fabrication is complete.
- A visual inspection of the steam cooled corrosion probes installed in the Niles was performed on May 18th and the loops remain in excellent condition. All

control problems seem to be corrected and the loops are operating at design condition.

- A thick section SAVE12 pipe was successfully welded using a gas tungsten arc (GTAW) root pass and shielded metal arc (SMAW) intermediate passes and flux core weld fill (FCAW).
- Results for gas metal arc welding (GMAW) and hot wire gas tungsten arc welding (GTAW-HW) are encouraging.
- Dissimilar metal weld specimens using Super 304H and CCA617 tubing were completed and Inconel 740 weldments were completed with two different filler metals.
- Swaging trials were completed for SAVE12 and HR6W.
- U-bend specimens were fabricated from CCA617, IN740, and Super304H.
- To assess the cycling capability of materials, a Bree diagram is under development for typical segments from a reheat header.

E. Plans for the Next Quarter

It is anticipated that the following work will be completed during the next quarter:

- Begin U-bend creep testing of IN 740 tubing.
- A report on the microstructure of HR6W will be completed.
- Continue the third 800°C steamside oxidation test including shot blasted 347HFG and Super304H samples.
- Try to bend tubing after aging heat treatment.
- Perform swaging trials on Haynes 230.
- A final review will be completed on the weld literature review summary report and it will be issued.

F. Issues

- The boiler selected for one of the air cooled corrosion probes at Cinergy is changing coal supply. This necessitated changing plans to install the probe to a different boiler at the same site.
- The third site for an air-cooled corrosion probe has switched to a PRB coal. Discussions are underway for a new site at another First Energy location.

- Slow turnaround on invoices has slowed some research.
- Arc stability problems were encountered using the Submerged Arc Welding (SAW) process on SAVE12 base metal.
- The problems encountered welding HR6W with matching filler metal are considered insurmountable and there will be no further efforts in this area.

2.0 Taskwise Status

Task 1 Conceptual Design and Economic Analysis (Task lead EPRI)

The objective of Task 1 is to specify the temperature/pressure distribution for 760°C/35 MPa (1400°F/5000 psi) steam inlet conditions so that the data needs and the range of test parameters can be identified and the economics of material selection established.

Task 1A: Alstom Approach (Alstom Power Co.)

Objectives:

The primary objectives of this subtask are:

- Develop a conceptual boiler design for a high efficiency ultra supercritical cycle designed for 1400°F steam temperature.
- Identify tubing and piping materials needed for high temperature surface construction.
- Estimate gas and steam temperature profiles so that appropriate mechanical, corrosion and manufacturing tests of materials could be designed and conducted to prove suitability of the selected alloys.

Progress for the Task

A final report has been completed and distributed.

Task 1B: Babcock Approach

Objective:

The objectives of this subtask are the same as in Subtask 1A.

Progress for the Quarter:

No work was performed on this task this quarter.

Concerns:

Progress for the Next Quarter:

A final report has been completed and distributed.

Task 1C: Economic Analysis

Objective:

The objective of this task is to determine relative economics of the USC plant.

Progress for the Task:

A final report has been completed and distributed.

Concerns:

None

Task 2

Mechanical Properties of Advanced Alloys (ORNL)

The objective of Task 2 is to produce the mechanical properties database needed to design a boiler to operate at the steam conditions within the scope of the project.

Task 2A: Assessment of the Alloy Performance Requirements

Objectives:

The primary objectives of this subtask are:

- Focus on performance needed for boiler service in the temperature range of 650°C (1200°F) to 871°C (1600°F)
- Produce reports that justify the materials selected for the pressure retention components of the USC boiler

Progress for the Task:

A talk on precipitation phenomena in CCA617, Super304H and IN 740 was presented at the International Conference on Solid-Solid Phase Transformation in Inorganic Materials held in Phoenix, AZ between May 29 – June 3, 2005. A talk on deformation study of creep-ruptured materials was submitted for the TMS 2006 Annual meeting at San Antonio next year.

Task 2B: Detailed Test Plan

Objectives:

The detailed mechanical properties test plan is intended to provide guidance on the scope of the mechanical testing for each material to support the resolution of issues related to the tasks undertaken in the project. Categories include: mechanical characterization; data production for the development of code cases; effects of fabrication variables; weldment performance; fatigue and thermal-fatigue behavior; and the like. The six alloys, chemical compositions in Table 1 below, of most interest to the project are: SAVE12, Super 304H, HR6W, Haynes 230, CCA617, and INCONEL 740. Specific heat chemistries are available on the website.

Progress:

The characterization testing plans have been completed for the creep-rupture testing of the five tubing alloys (Super 304H, HR6W, alloy 230, CCA617, and INCONEL 740). Progress and/or problems associated with the welding (Task 5) and fabrication (Task 6) tasks will define relevant testing. Thus, to some measure the test plan continues to

evolve. Weldment test plans for HR6W, Super 304H, and CCA617 butt welded tubes have been produced. Thick section weldments plans are being produced as welded material becomes available. A test plan to evaluate 740 and 263 weld filler metals on Inconel 740 has been designed and testing has begun. Thick section weldments plans are being produced as welded material becomes available. Test matrices for verifying and determining the LCF and creep-fatigue behavior of CCA617 and Inconel 740 have been designed and testing initiated. Discussions with Task 8 members have helped define the structural tests needed by the boiler manufactures to evaluate their respective component models. Notched bar test plans for Inconel 740 have been produced to evaluate the materials notch sensitivity and multi-axial creep behavior.

TABLE 1. Compositions of USC Steam Boiler Consortium Materials															
Alloy	Nominal Compositions in Wt%														
	Fe	Cr	Ni	Mn	Mo	Ti	Nb	W	V	C	B	Si	N	Cu	Other
SAVE 12*	bal	11.0		0.2				3.00	0.20	0.10		0.3	0.04		3.0Co 0.07Ta 0.04Nd
Super 304H*	bal	18.0	9.0	0.8			0.40			0.10		0.2	0.10	3.00	
HR6W*	bal	23.0	43.0	1.2		0.08	0.18	6.00		0.080	0.003	0.4			
Haynes 230*	3.0	22.0	bal	0.5	2.0			14.00		0.10	0.02	0.4			5.0Co 0.3Al 0.02La
CCA617	0.6	21.7	bal	0.03	8.6	0.40				0.05	0.002	0.1	0.01	0.01	11.25Co 1.25Al
INCONEL 740	2	24.0	bal	0.3	0.5	2.0	2.0			0.07	0.002	0.5			19.8Co 0.8Al 0.015Zr

*Compositions are nominal and will be replaced by measured compositions in the future

Concerns:

None.

Task 2C: Long Term Creep Strength

Objectives:

The primary objectives of this subtask are:

- Identify the general characteristics of the creep behavior and damage accumulation in the candidate alloys
- Verify the creep-strength of code-approved alloys
- Assess the creep-strength non code-approved alloys; and provide creep/creep-rupture data for a code case if deemed appropriate by consortium members
- Provide accurate creep data (i.e. creep-curves) for boiler design on the candidate materials

Progress:

The status and data for five tubing alloys currently in testing is provided on the consortium website. Summary tables are included below. The results indicate that the strength of the Super 304H and alloy 230 are meeting expectations, while the HR6W is below expectations. As previously discussed, Sumitomo believes the poor creep strength is due to low W in the consortium heat, but, based on the chemistry supplied by Sumitomo, the W level is well within the specification. The CCA617 alloy is exceeding expectations in the lower temperature regime (650°C to 700°C), based on performance equivalent to alloy 617. Larson-Miller-Parameter extrapolation shows the creep strength benefit may extend to 730°C for CCA617 vs. std. 617. Additional short-term tests have been added to the CCA617 test matrix. All of the planned Super 304H and HR6W creep-rupture tests are in progress. Testing is also progressing on the INCONEL 740 tubing. 100 and 1000 hours rupture lives appear close to predictions based off previous work at ORNL and data from Special Metals but longer term tests are slightly shorter than predicted.

Creep-Rupture Testing of Super 304 H (Case Code 2328)						
Spec #	Test #	Stress (MPa)	Temp. (°C)	Estimated Life	Date Started	Life (hrs)
SM-01	30298	240	600°C	10000 Hrs	6/11/2003	
SM-02	30299	280	600°C	1000 Hrs	6/11/2003	10083.2
SM-03	30383	340	600°C	100 Hrs	12/1/2003	864.6
SM-04	30293	120	650°C	10000 Hrs	6/3/2003	
SM-05	30292	210	650°C	1000 Hrs	6/3/2003	2240
SM-06	30372	260	650°C	100 Hrs	10/21/2003	412
SM-07	30377	110	700°C	10000 Hrs	11/24/2003	8677.3
SM-08	30294	160	700°C	1000 Hrs	6/3/2003	1011.5
SM-09	30384	210	700°C	100 Hrs	12/2/2003	106.2

Creep-Rupture Testing of HR-6W (Heat #DZC1309)						
Spec #	Test #	Stress (MPa)	Temp. (°C)	Estimated Life	Date Started	Life (hrs)
HR-6W-01	30282	200	650	1000	5/21/2003	921.1
HR-6W-02	30315	175	650	6000	7/2/2003	2194.2
HR-6W-03	30330	150	650	20000	7/31/2003	5167.1
		200	675	500		
		170	675	1000		
		150	675	6000		
		200	700	50		
HR-6W-08	30426	100	700	15000	3/15/2004	
HR-6W-09	30317	150	700	1000	7/9/2003	451.3
HR-6W-10	30325	120	700	10000	7/22/2003	2056.7
HR-6W-11	30368	100	725	10000	10/14/2003	2663.2
HR-6W-12	30283	150	725	500	5/21/2003	187.5
HR-6W-13	30291	120	725	5000	6/2/2003	723.8
		140	750	400		
HR-6W-15	30405	120	750	500	2/2/2004	202.5
HR-6W-16	30425	100	750	5000	3/15/2004	844.1
HR-6W-04	30424	85	750	20000	3/15/2004	2740.2
HR-6W-05	30396	100	775	600	12/29/2003	225
HR-6W-06	30401	85	775	5000	1/14/2004	713.6
HR-6W-07	30395	100	800	150	12/29/2003	80.24
HR-6W-14	30427	85	800	1000	3/15/2004	251.8

Creep-Rupture Testing of Haynes 230						
Spec #	Test #	Stress (MPa)	Temp. (°C)	Expected Life	Date Started	Life (hrs)
H230-01	30302	350	650	200	6/16/2003	410.8
H230-02	30306	300	650	1000	6/18/2003	1071.4
H230-03		200	650	10000		
H230-04	30613	300	700	100	6/20/2005	124.2
H230-05	30301	200	700	1500	6/12/2003	1517.1
H230-06		140	700	15000		
H230-07	30614	200	750	100	6/20/2005	161.8
H230-08	30399	140	750	2000	1/6/2004	1426.8
H230-09	30402	100	750	15000	1/20/2004	
H230-10	30373	140	800	100	Test Discontinued	
H230-11	30300	100	800	2000	6/11/2003	2101.2
H230-12		80	800	20000		
H230-13	30375	140	800	100	11/3/2003	169.2

Creep-Rupture Testing of CCA617						
Spec #	Test #	Stress (Mpa)	Temp. (°C)	Estimated Life	Date Started	Life (hrs)
617-01	30303	350	650	200	6/16/2003	8242.0
617-02	30305	300	650	1000	6/18/2003	
617-03	30357	200	650	10000	9/16/2003	
617-04	30337	300	700	100	8/19/2003	2376.8
617-05	30318	200	700	1500	7/9/2003	
617-06	30553	140	700	15000	2/2/2005	
617-07	30363	200	750	100	9/30/2003	1561.8
617-08	30388	140	750	2000	12/8/2003	7265.8
617-09	30518	100	750	15000	11/11/2004	
617-10	30331	140	800	100	8/6/2003	329.9
617-11	30343	100	800	2000	9/3/2003	1831.0
617-12	30513	80	800	20000	11/3/2004	
617-13	30352	400	650	200	9/10/2003	1279.7
617-14	30387	400	700	100	12/3/2003	301.6
617-15	30550	300	750	100	1/24/2005	104.9

Creep-Rupture Testing of INCONEL 740 (Heat # CLH4663) - Aged 16hrs, 800C, Ar								
Spec #	Product Form	SA Temp(C)	Test #	Stress (MPa)	Temp. (°C)	Estimated Life (hrs)	Date Started	Life (hrs)
740-01	Tube	1120	30443	480	700	100	4/13/2004	308
740-02	Tube	1120	30448	370	750	100	5/4/2004	142.8
740-03	Tube	1120	30455	250	800	100	5/17/2004	167.5
740-04	Tube	1120	30461	150	850	100	5/26/2004	157.1
740-05	Tube	1120		370	700	6000		
740-06	Tube	1120	30575	320	750	600	4/11/2005	358.3
740-07	Tube	1120	30622	265	750	2500	6/30/2005	
740-08	Tube	1120		150	800	6000		
R740-01	Tube	1190	30551	580	650	100	1/24/2005	1191
R740-02	Tube	1190	30437	520	650	1000	3/29/2004	1599.6
R740-03	Tube	1190		465	650	10000		
R740-04	Tube	1190	30472	480	700	100	7/7/2004	392.6
R740-05	Tube	1190	30492	420	700	1000	9/15/2004	1082.2
R740-06	Tube	1190	30507	340	700	10000	10/20/2004	5227.4
R740-07	Tube	1190	30464	370	750	100	6/7/2004	289.3
R740-08	Tube	1190	30467	300	750	1000	6/11/2004	984.5
R740-09	Tube	1190	30509	220	750	10000	10/21/2004	
R740-10	Tube	1190	30449	250	800	100	5/4/2004	279.2
R740-11	Tube	1190	30439	180	800	1000	3/30/2004	1491.1
R740-12	Tube	1190	30476	130	800	10000	8/4/2004	6882.7
R740-13	Tube	1190	30463	150	850	100	6/1/2004	275.6
R740-14	Tube	1190	30457	100	850	1000	5/19/2004	1789.4
R740-15	Tube	1190	30514	70	850	10000	11/3/2004	4929.9
P740-01	Plate	1120	30628	480	700	100	6/30/2005	
P740-02	Plate	1120		440	700	600		
P740-03	Plate	1120		420	700	1000		
P740-04	Plate	1120		370	700	4000		
P740-05	Plate	1120	30629	370	750	100	6/30/2005	
P740-06	Plate	1120		320	750	600		
P740-07	Plate	1120		300	750	1000		
P740-08	Plate	1120		265	750	2500		
P740-09	Plate	1120		250	750	4000		
P740-10	Plate	1120		220	750	10000		
P740-11	Plate	1120		250	800	100		
P740-12	Plate	1120		180	800	1000		
P740-13	Plate	1120		160	800	3000		
P740-14	Plate	1120		100	850	1000		
P740-15	Plate	1120		85	850	4000		

Task 2D: Microstructural Analysis

Objective:

The primary objectives of this subtask are:

- Identify the microstructural changes that lead to significant changes in the strengthening, weakening, and internal damage characteristics of each material.

- Explore how these changes relate to the exposure conditions of the testing.

Progress:

The University of Cincinnati (UC) has been tasked with the metallurgical characterization of the USC materials (excluding the SAVE12). The characterization work at the UC includes: microhardness, optical microscopy, scanning electron microscopy (SEM) with elemental analysis by energy dispersive spectroscopy (EDS), and transmission electron microscopy (TEM). Short-term aging is being done on the USC materials at the UC in addition to longer-term aging at ORNL. Creep-tested specimens have also been analyzed. The goal of the aging is to understand the microstructural evolution of the USC materials at temperatures encountered during service in a boiler. The creep-tested specimens will be used to understand differences in microstructural evolution compared to aging without stress and how dislocations interact with precipitates and other microstructural elements.

Work done after an April progress meeting between the UC and ORNL has focused mainly on the SEM and TEM study of most recently received long term aged samples of CCA617 and H230 aged for 10,025hr at 700, 750 and 800°C, and HR6W and Super304H aged for 10,025 hr at 700°C. Microhardness measurements made on these long term aged samples, along with previous data on shorter time aged samples, indicated no apparent change in microhardness in the long term (10,025 hr) aged conditions. SEM study was completed on these 8 samples. The HR6W and H230 microstructures were mainly observed in the BSE mode; etched samples of CCA617 and Super304H were observed with SE and BSE modes. In the long term aged CCA617 samples, no apparent change in microstructure was recorded. In H230, a trend of coarse carbides breaking-up into a mesh-shaped network could be noticed, especially at 800°C. Based on EDS data acquired for several different phases in HR6W, coupled with TEM diffraction patterns and comparison with results reported by others in Cr-W-Fe alloys, Cr-rich M₂₃C₆ carbides and Fe₂W-type Laves phases were found to be the major precipitate phases in HR6W at 700°C.

TEM thin foils of CCA617, H230 and Super304H were prepared by twin-jet electropolishing, and microstructural observations of Super304H and H230 aged 800°C, and CCA617 aged 800, 750 and 700°C were conducted, with special attention being given to features such as Cu-rich precipitates, Cr₂₃C₆ carbides, and γ' size and morphology. TEM thin foils for HR6W were made using ion milling after electropolishing, and micrographs, TEM EDS data, diffraction patterns, and CBED patterns of sharp-edged Laves phases were recorded. The volume fraction of carbides in H230 has been calculated using ImageJ software; a plot of the data will be prepared after mapping of micrographs of all aged conditions. A number of papers on W-Cr containing steels were collected and a report on microstructural evolution in aged HR6W (600°C for 100 and 1000 hr, 650°C for 116 and 1000hr, 700°C for 100, 1000, 3000 and 10,025hr) is being prepared.

Task 2E: Assessment of Creep-Fatigue Properties

Objective:

The primary objectives of this subtask are:

- Verify the low cycle fatigue, creep-fatigue, and thermal mechanical fatigue properties of the thick section alloys.
- Develop a database that will lead to practical, yet conservative methods for new materials.
- Address the issue of creep-fatigue in the boiler materials.

Progress:

Testing was completed on CCA617 this quarter to verify its properties relative to the 617 database. The continuous cycle tests (LCF) correlate well with the published fatigue data on standard 617 at 750°C. Two long-term low-cycle-fatigue tests, where a 360 second hold time was imposed at the maximum strain during the cycle, showed a decrease in life compared to the continuous LCF data as expected. A summary of the results are shown below. Testing has begun to establish a LCF baseline for the Inconel 740 at 750°C.

Material: CCA617 Product Form: Plate

Specimen ID	Test Number	Material Condition	Temp. C	Waveform	R-ratio	Total Strain Range (%)	Peak Hold Time (sec)	Strain Rate (/sec)	Cycles to Failure
617-F03	30506	as-received	750	Triangular	0	0.4		0.001	4000
617-F05	30515	as-received	750	Triangular	0	0.3		0.001	53959
617-F06	30574	as-received	750	Ramp/Hold	0	0.7	360	0.001	447
617-F07	30579	as-received	750	Ramp/Hold	0	0.3	360	0.001	5253

Task 2F: Modeling of Weld Joints

Objectives:

The primary objectives of this subtask are:

- Produce the experimental data needed to model dissimilar metal and thick-section weld joints.

Progress:

Creep-rupture testing continues on Haynes® 230 plate weldments and HR6W butt-welded tubes with 617 and 82 filler metal. Testing also continues on butt-welded tubes of HR6W with 617 filler and 82 filler. Tabular results are available on the website. Cross-weld creep-rupture testing has begun on a 5/8" thick Inconel 740 plate welded with both 740 and 263 filler metal. The purpose of these tests is to evaluate the differences between the weld strength of the two filler metals. Wrought Inconel 740 has superior creep strength compared to wrought 263 but data is not available on the weld metal strength for these alloys. 263 is the preferred filler from a weldability standpoint for joining 740. Determining the strength of both types of weldments is critical to determining which filler metal should be used, and a high priority has been given to this task. Initial creep-rupture results (less than 300 hours of testing) do not show a

difference between the strengths of the filler metals. Longer (1000 hour) tests are ongoing. Large cross-weld specimens from the CCA617 2" thick plate are being machined and some testing has already begun. A macro image of the first completed test is shown below. Creep-rupture testing was performed on the SAW plate at 750°C and 140MPa. The expected life of the base metal was 2,000 hours for 617 and roughly 7,000 hours for the CCA617 based on limited creep-rupture results from CCA617 tubes. The cross-weld test ruptured in the weld metal after 361.1 hours. The specimen dimensions are: 16" overall specimen length with a gauge section 5.5" long x .32" thick x .75" wide).

Task 2G: Study of Accelerated Test Methods

Objectives:

The primary objective of this task is:

- Provide a method to rapidly characterize changes in the strength of candidate materials.

Progress:

No new materials have been identified for relaxation testing. This task is complete until an evaluation of a new material is needed or Task 8 determines a critical data need.

Task 2H: Model Validation

Objectives:

The primary objective of this task is:

- Produce a database that can be used to confirm or validate design rules that are developed in Task 8.

Progress:

Pressurized creep testing of tube U-bends, to evaluate coldwork effects, was completed on the HR6W tube bend and two Haynes 230 bends. The Haynes 230 bends were stopped after testing for 8,000 hours without rupturing, but the HR6W was removed upon rupture after 7108.9 hours. All specimens were measured and some have been sectioned for metallography. Macro images, micrographs, and strain measurements of the HR6W tube bend (35% cold strain) that ruptured are shown below. Significant I.D. creep cavitation was observed for the entire tube and O.D. cavitation was also observed at the extrados but did not cause rupture. No recrystallization was observed in the HR6W tube even after using multiple etchants.

Macro Images of HR6W Tube Bend (35% Cold Strain); Test Conditions: 775°C, 4200 psi;
Rupture Location = 90°, Life = 7108 hours

Micrograph of HR6W Tube Bend: Rupture Location (60 – see previous page for location information)

Micrograph of HR6W Tube Bend: EX Location, No recrystallization observed

Preparations for assembling the Inconel 740 tube bends began this quarter. Approximately 13lbs of Nimonic 263 filler metal was ordered to perform the necessary welding on the Inconel 740 bent tubes for pressurized creep testing.

Notched bar testing on the deeply notched 740 specimen shows significant notch strengthening as testing continues beyond 6,000 hours. The plot of this extensometer and the axial strain is shown below, and it appears the rate of creep deformation in the notch region is increasing. The long duration of the test indicates that Inconel 740 is not a notch sensitive material at this test condition: 750°C and 320MPa.

Thermal shock testing on a CCA617 tube began this quarter. Over 400 thermal cycles have been complete with a 300°C temperature gradient through the wall.

Concerns:

The high machining costs for thick section weldments specimens may limit the amount of thick section testing. One option being used to the reducing machining costs is to section the weldments before shipment from the boiler manufactures to ORNL – where overhead costs for machining are high.

HR6W 3"R 775°C @ 4200 psi				
Pt	1000 hr Strain (%)	3000 Strain (%)	7108.9 hr Strain (%)	Location
14	0.11	0.21	0.21	Near Weldment
15	0.10	0.20	0.22	Straight
16	0.07	0.16	0.18	Straight
17	0.04	0.09	0.12	Straight
18	0.03	0.07	0.09	Bend Begins
19	0.01	0.06	0.15	Bend
20	0.00	0.06	0.27	Bend
21	0.02	0.05	0.30	Bend
22	0.06	0.14	0.49	Bend
23	0.07	0.14	0.76	Bend
24	0.06	0.14	0.88	Top of Bend (90)
25	0.05	0.13	0.64	Bend
26	0.03	0.06	0.31	Bend
27	0.00	0.05	0.23	Bend
28	-0.01	0.05	0.41	Bend
29	0.06	0.17	0.43	Bend
30	0.17	0.29	0.36	Bend

Plans for Next Quarter:

The website will be updated with the most recent creep data. A report on the microstructure of HR6W will be completed by the Univ. of Cincinnati. Creep-rupture testing of all materials will continue. The creep-strength comparison for the 740 and 263 fillers for the Inconel 740 welded plates will be completed with 2,000 creep data.

LCF testing should establish the baseline fatigue curve for Inconel 740. Testing of weldments, including the thick section welds of the CCA617, will continue.

Task 3 Steamside Oxidation (B&W)

Task 3A: Autoclave Testing

Background:

Steamside oxidation tests will be performed on commercially available and developmental materials at temperatures between 650°C and 900°C (1202°F - 1652°F).

Experimental:

During the past quarter, the second exposure at 800°C was completed. The post-test condition of the test rack and coupons are shown in Figure 1.

Figure 1. Test rack and specimens after 2,000 exposure to 800°C steam

Designated coupons were removed from the test rack and weighed. One coupon from each material was then descaled and re-weighed, while a second coupon from each material was submitted for SEM/EDS analysis.

The results following the second 1,000 hour exposure to 800°C steam are in general agreement with the results from the first 1,000 hour exposure. As shown in Figure 2,

the oxide islands or nodules continue to grow on the P92 and SAVE 12 materials. The oxide on Alloy 214 retained the copper coloring (as opposed to gray oxides that developed on the remainder of the specimens) that developed after the first 1,000 hour exposure, as shown in Figure 3.

Figure 2. P92 after 2,000 hrs exposure to 800°C steam

Figure 3. Alloy 214 after 2,000 hrs exposure to 800°C steam

The ferritic alloys T23, P92 and SAVE 12 continue to exhibit high oxidation rates. The ferritic alloys MARB2 and VM12, however, displayed parabolic rate constant that were significantly less than those for most of the austenitic stainless steels that were tested (304H, SUPER304H and 347HFG). The parabolic rate constant for VM12 after 2,000 hrs in 800°C steam was actually on par with the high nickel-chromium materials that were tested. The materials exhibiting the lowest parabolic rate constants were Alloy 740, CCA 617 and Alloy 230

From an exfoliated oxide standpoint, the ferritic alloy VM12 continued to display essentially no signs of exfoliated oxide, while MARB2 exhibited a moderate level of exfoliation. All of the austenitic stainless steels displayed high levels of exfoliation, except for the SUPER304H material that contained the highest Cr level of all of the austenitic stainless steels (19.1% Cr), which displayed essentially no evidence of exfoliation. For the high nickel-chromium materials, those containing the highest Fe levels (SAVE25, HR6W and HR120) displayed the highest levels of exfoliation, however the exfoliation experienced by these materials is far less than those experienced by most of the austenitic stainless steels. The nickel-based alloys exhibited no evidence of exfoliation.

The SUPER304H and 347HFG tube sections with the shot blasted ID were received from Sumitomo. Coupons were prepared from these tubes (Figure 4) and wired onto the test rack with the remaining 800°C coupons. The third exposure at 800°C was initiated. The third exposure is scheduled to last 2,000 hours, and should be completed in August 2005.

Figure 4. Shot blasted 347HFG coupon

Concerns:

None.

Activities Next Quarter

The SEM/EDS evaluation of the specimens removed following the second exposure at 800°C will be completed. The third and final exposure at 800°C will be completed. All remaining specimens will be removed from the test rack and analyzed.

Task 3B Coating Tests

Background:

Coated specimens for steamside oxidation testing will be prepared in conjunction with Task 7 and evaluated after testing.

Experimental:

Designated chromized specimens (CrS304H, AlCrS304H and SiCrS304H) were removed from the test rack following the second 1,000 hour exposure. Weight change and descaled weight loss results suggest that the SiCrS304H is performing somewhat better than the CrS304H, which is performing significantly better than the AlCrS304H.

Concerns:

None.

Activities Next Quarter:

All remaining 800°C specimens will be evaluated following the third 800°C exposure.

Task 3C Assessment of Temperature

Background:

Based on the steamside oxidation test results, the practical temperature limits for the materials tested will be determined.

Experimental:

The activation energies calculated after 2,000 hours of exposure are similar to those calculated after 1,000 hours of exposure.

Concerns:

None.

Activities Next Quarter:

Activation energies will be re-calculated following the third 800°C exposure.

Task 3D Review of Available Information & Reporting

Background:

Available steamside oxidation literature pertaining to materials and environmental conditions of interest will be reviewed. Project status updates will be prepared and status meetings will be attended as required.

Experimental:

Monthly status reports were prepared for April and May, 2005. The Quarterly reports for January – March, 2005 and April – June, 2005 were prepared. A Steering Committee Meeting was attended in Cleveland, OH in May.

Concerns:

None.

Activities Next Quarter:

Monthly status reports will be written for July and August. A Steering Committee Meeting will be attended in Cleveland, OH in September.

Task 3E Conduct Experimental Exposures

Background:

The steam oxidation behavior of model Fe-Cr alloys will be evaluated.

Experimental:

B&W is remaining cognizant of the ORNL tests on these model alloys. BWRC made metallographic measurements on two mounts provided by ORNL using the same procedures used at ORNL. The ORNL methodology relies on oxide thickness to determine oxidation kinetics, whereas the B&W methodology relies on descaled weight loss to make this determination. Results from the B&W evaluation indicated that materials with relatively thick ($>10\text{ }\mu\text{m}$) oxide could be accurately measured; however, the oxide on nickel-based materials is too thin to accurately measure without the use of an SEM. Thus, the ORNL methodology could be practically used by BWRC only on materials that form relatively thick oxides.

Concerns:

None.

Activities Next Quarter:

BWRC will maintain cognizance of ORNL results.

Task 3F Characterization

Background:

The steamside oxidation results will be evaluated to determine the effects of material properties and environmental factors on oxidation behavior.

Experimental:

None.

Concerns

None.

Activities Next Quarter:

None.

Task 3G Data Analysis and Coordination

Background:

The steamside oxidation results will be evaluated to determine the effects of material properties and environmental factors on oxidation behavior.

Experimental:

No progress will be possible until the steamside oxidation tests have been completed (GFY2006).

Concerns:

None.

Activities Next Quarter:

None.

Milestone Chart:

Dates are listed in GFY.

Task 4

Fireside Corrosion

(Foster Wheeler)

The objective of the task is to evaluate the relative resistance of various advanced alloys for waterwall and reheater/superheater construction to fireside corrosion over the full temperature range expected for the USC plant. The corrosive environment promoted by three different coals, representative of an eastern coal, a midwestern coal, and a western coal, will be evaluated.

Task 4A: Laboratory Testing

Objective:

The objective of this sub-task is to perform laboratory corrosion tests on the candidate alloys. This will be accomplished by exposing metal coupons to various deposits and flue gases representative of three coals (e.g., eastern, midwestern, and western) at the range of temperatures expected for the USC plant.

Experimental Progress:

- The post-test analysis of the 1600°F superheater/reheater samples was completed. Preliminary wastage results (i.e., metal loss plus subsurface oxidation/sulfidation) in 1000 hours are shown in Figure 1. A summary of the microscopic examination of the samples was reported in the April 2005 Monthly.
- During the quarter we evaluated the metallographic samples from superheater/reheater tests for carburization. Where carburization was noted, the depth was measured for incorporation into the wastage data. Carburization was not detected on a regular basis, and when it was noted, it was primarily in samples exposed under Eastern and Midwestern conditions. The depth of carburization was generally shallow, typically in the 0.001-0.002 in. range. In a few cases, carburization was measured as deep as 0.005-0.006 in. Photomicrographs illustrating the microscopic appearance of carburization in some of the samples are presented in Figures 2 through 5.

Figure 1: Preliminary results of the Total Metal Wastage (wall loss plus subsurface penetration) of the 1600°F superheater/reheater specimens in 1000 hours are shown.

Figure 2: Carburization of the 214 samples tested under Eastern (top) and Midwestern (bottom) conditions at 1300°F is illustrated

Figure 3: Carburization of the HR6W specimens tested under Eastern conditions at 1200°F (top) and 1300°F is illustrated

Figure 5: Carburization of the 230 specimens tested under Eastern (top) and Midwestern (bottom) conditions at 1400°F is shown

Concerns:

No concerns at this time.

Plans for Next Quarter:

Incorporate the carburization results into the wastage data and continue to refine the results of the laboratory tests.

Task 4B Corrosion Probe Testing in Utility Boilers

Objective:

The objective of this sub-task is to install corrosion probes comprised of various alloys/coatings/weld overlays at three coal-fired power plants and control them in the temperature range expected for reheater/superheater components in the USC plant. The plants should burn coals representative of the three types specified earlier.

Experimental Progress:

- Fabrication and mechanical assembly of the probe retraction mechanisms for the third site have been completed.
- Data acquisition, instrumentation and control systems development has been completed and validation testing is under way.
- Discussions were held with Cinergy personnel, regarding changes of coal being fired at the first host site. A new location was identified at another unit within the same plant. New supports are being designed to support the probes in the newly identified locations. Quotes have been received for electrical work needed to accommodate the new installation.
- Material samples for the probes been machined and final assembly of probes for the second site is under way.
- Critical components have been delivered to the first and second host sites.
- Foster Wheeler continues to work closely with the host utility personnel to coordinate installation activities.

Concerns:

- Funding payment delays (due to DOE's new accounting system) have slowed some activities.
- Cinergy has informed us that the original first host site (firing a high-sulfur Farmersburg coal) will be switching to a low-sulfur PRB fuel blend. Another unit, at the same plant, is expected to continue firing the high-sulfur coal, and will host the

corrosion probes. Mechanical and electrical changes are being performed to accommodate this new location.

- The original third host site has indicated that their fuel is being changed to 10% low-sulfur PRB coal. This requires finding a new host site, firing a different coal (possibly Eastern / PRB blend coal). Discussions are under way with First Energy to locate another possible host site within Ohio.

Plans for Next Quarter:

- Complete mechanical and electrical modifications at the first host site.
- Finalize hosting arrangements and logistics for third host site.
- Complete the testing of instrumentation and controls systems for remaining probes.
- Complete final assembly of the remaining probes.
- Continue site installation tasks, coordinating with host utilities.
- Install probes and begin exposures at first and second host sites.

Task 4C Steam Loop Design, Construction, and Testing

Objectives:

The objectives of this sub-task are to design, build, and test an experimental USC steam loops that will operate in a commercial boiler at metal temperatures up to 1400°F. The elements of this subtask include the following:

- Design and construct the test loop using commercially-available, high-temperature corrosion-resistant alloys selected for the USC Plant.
- Install and operate the test loop at the Reliant Electric power plant, which is located in Niles, OH and is burning high sulfur Ohio coal.
- Test and monitor the relative performance of the USC tube alloys, coatings, claddings, and weld overlays, which comprise the test loops, for a period of 18 to 24 months.

Experimental Progress:

During shut down of the Reliant Energy Plant in Niles, Ohio for regularly scheduled maintenance, the USC test loops were inspected on May 18 to assess their condition and to effect repairs to the temperature sensors and other support equipment. Results confirmed that the loops remain in excellent condition.

Testing of the USC steam loops resumed at the Niles plant on June 21. With the loops being operated in automatic mode, the maximum measured steam temperatures (1200°F in Loop A and 1075°F in Loop B) correlate to maximum surface temperatures of approximately 1400°F in Loop A and 1280°F in Loop B. With consistent operation at these conditions, the test loops will continue to accrue exposure time at the desired conditions to effectively assess corrosion resistance (and oxidation resistance) of the USC materials in the field.

Concerns:

None.

Plans for Next Quarter:

- Continue to monitor operation and collect data.

Task 5 Welding Development (Alstom)

Objectives:

- To define weld metal choices for candidate materials.
- To establish acceptable welding procedures and practices.
- To evaluate the effects of manufacturing heat treatments and preheat and post weld heat treatments on weldment integrity and properties.
- To produce samples needed to determine the properties of candidate ultrasupercritical alloy welds and weldments, including the dissimilar metal weld joints between the various types of material (the actual mechanical and property testing will be performed under Task 2).

These objectives will be accomplished through execution of five sub-tasks. Where activity on these sub-tasks occurred during the reporting period, it is described below.

Task 5B: Optimization of Weld Parameters

Objectives:

The primary objectives of this subtask are to establish the baseline welding parameter values for each material/process/product form combination being studied. Included is the development of preheat and post weld heat treatment requirements.

Progress for the Quarter:

SAVE 12:

- The SAVE12 heavy wall (13.78-inch OD x 2.3-inch wall pipe) qualification efforts continued by making test beads using a submerged arc process and SAVE12 custom weld filler with both WP380 and OK76 fluxes. Examinations and chemical analyses of the resulting deposits led to the conclusion that WP380 was the best choice of flux. Using the deposit compositions, ORNL estimated the lower critical transformation temperatures (A1), which was 1495°F for the WP380 flux, and, with this additional information, a post weld heating temperature was selected for the thick-section welding.
- Following selection of WP380 as the flux for submerged arc welding, thick-section process development was continued. A root pass was made using a gas tungsten

arc process and this was followed with intermediate shielded metal arc passes and then submerged arc, all using the SAVE12 custom filler. The initial passes using the submerged arc process and the WP380 flux went well, however subsequent passes produced a considerable amount of arc instability and the deposition rate could not be controlled. These unexpected difficulties continue to be investigated.

- As an alternate approach for thick-section welding, a flux core process was considered and filler wire having the SAVE12 composition was obtained and trials were conducted. Again, trial weld deposits were first made on a flat surface, the chemistry of the deposits was confirmed, lower critical transformation temperatures (A1) of the deposits were estimated, and a post weld heat treatment temperature was established.

Following establishment of the procedure details, a thick-section pipe weld was completed using a gas tungsten arc root pass, shielded metal arc intermediate passes, and flux core fill. No difficulties were encountered and the completed joint is being examined for defects.

HR6W:

The difficulties encountered while attempting to weld HR6W using matching filler metals are considered insurmountable for this program and there will be no further efforts in this area.

Inconel 740:

- The Lincoln Electric pulsed gas metal arc welding techniques were continued at Special Metals on Inconel 740. The results are still encouraging.
- Results using a hot wire gas tungsten arc process were also encouraging.
- Special Metals has started a study on the effect of heat-to-heat composition differences with regards to microfissuring sensitivity.
- The weld deposit chemistries from gas tungsten and gas metal arc processes were compared to that from bare filler wire and no significant changes were found as a result of the welding arc.

CCA 617:

A representative from UTP, the supplier of the CCA 617 shielded metal arc welding electrodes, was in Chattanooga on May 2 and 3 to assist in solving the problems ALSTOM has encountered while attempting to join thick CCA 617 plates with this particular consumable. The UTP representative demonstrated the techniques required to weld with these electrodes, which included using a short arc length, virtually no weave, and a rather unusual rod position. The trials used a fillet configuration and the electrode position necessary to achieve satisfactory penetration and slag control might

not be possible for deep groove butt welds. Nevertheless, it has been established that the consumables supplied to ALSTOM were in accordance with UTP expectations and, now that the electrode limitations are better understood, additional attempts will be made to incorporate this knowledge into a welding procedure.

Super 304H:

Plans were made to try to make butt joints in Super 304H tubing using a gas metal arc welding process and matching filler metal. Lincoln Electric has a new machine and procedures that look promising for this process and might have better success than when the attempts were made using ALSTOM's automatic welders. The trials are scheduled for July 2005.

Concerns:

- Submerged arc welding, a high deposition rate process favored by boilermakers for thick sections, does not appear feasible for all nickel base materials. Tests on Haynes 230 and Inconel 740 have been unsuccessful because of cracking and the process is being abandoned on these two alloys.
- The unexpectedly high cost of the nickel base alloys will cause the material budgets to be exceeded and might result in program cost overruns and/or reductions in program scope.
- The difficulties encountered while attempting to weld HR6W using matching filler metals proved insurmountable for this program and there will be no further effort in this area.
- Inconel 740 appears to have a heat-to-heat sensitivity with regards to microfissuring which could require additional constraints on composition.

Plans for the Next Quarter:

- Continue submerged arc and flux core welding qualification efforts on SAVE 12 pipe butt weld processes using matching filler metals.
- Test the new Lincoln Electric machine for use in a gas metal arc welding process to make butt joints in Super 304H tubing.
- Continue to study problems with shielded metal arc welding of CCA 617 thick plates.
- Continue to study the problems with heat affected zone microfissuring in Inconel 740 when using gas tungsten arc and pulsed gas metal arc welding processes. The effect of wire size is another concern that needs to be evaluated.

Task 5C: Preparation of Laboratory Samples

Objectives:

The primary objective of this subtask is to produce multiple samples representing each of the material/process/product form combinations being studied. These samples will be evaluated by ORNL as part of the Task 2 activities.

Progress for the Quarter:

- The dissimilar metal weld specimens using Super 304H and CCA 617 tubing were completed and sent to ORNL for evaluation.
- Two, three-inch thick Haynes 230 test plates were made using pulsed gas metal arc welding and shipped to ORNL for evaluation.
- Two Inconel 740 weldments, one with Nimonic 263 filler metal and one with Inconel 740 filler, were fabricated and shipped to ORNL for creep testing.

Concerns:

None.

Plans for the Next Quarter:

- Prepare test samples from SAVE 12 tube and pipe welds using matching filler metals for ORNL evaluation.
- Prepare three-inch thick Haynes 230 test plates using pulsed gas metal arc welding for ORNL.
- Begin fabrication of Inconel 740 test plates using gas tungsten arc welding.

Task 5D Weldability Testing

Objectives:

The primary objective of this subtask is to investigate any major weldability problems that arose during the weld procedure development efforts of Subtask 5C. The advertised properties of Inconel 740 made it an attractive material for use in an ultrasupercritical boiler, however significant welding issues were encountered which necessitated fundamental weldability studies before procedure development could continue. Edison Welding Institute was commissioned to conduct these studies and four specific objectives were identified:

- Evaluate the heat affected zone liquation cracking susceptibility of Inconel 740.
- Evaluate the heat affected zone ductility dip cracking susceptibility of Inconel 740.
- Evaluate the post weld heat treatment cracking susceptibility of Inconel 740 and make a comparison with other common nickel-based precipitation-hardening alloys such as Inconel 718 and Waspaloy.
- Evaluate the mechanical properties of Gleeble-simulated heat affected zones in Inconel 740 and of Inconel 740 welded plate joints in the post weld heat treated condition.

Progress for the Quarter:

With regards to the four objectives:

Based on low and medium heat input welding conditions used in the field, thermal cycles were determined for low temperature and high temperature regions of a weld heat affected zone. Sample material was annealed and aged and subjected to the heat affected zone simulation heat treatments using a Gleeble machine. The effects of these treatments on mechanical properties have been determined and the results are being evaluated for comparison with a full-scale weldment that is being prepared.

Concerns:

None.

Plans for the Next Quarter:

- Start mechanical characterization of full-size welded joint that will be provided by B&W.

Task 5E: Examination of Dissimilar Metal Welds

Objectives:

The primary objectives of this subtask are to develop and study the dissimilar metal welds that would be required to make transitions between the various alloys included in this program and the conventional materials that would also be used in an ultrasupercritical boiler.

Progress for the Quarter:

The dissimilar metal weld specimens using Super 304H and CCA617 tubing were completed and sent to ORNL for evaluation.

Concerns:

None.

Plans for the Next Quarter:

Fabricate samples of dissimilar metal joints between the HR6W and SAVE12 tubing for testing by ORNL.

Task 5: Welding Development - Milestone Chart
(DOE Fiscal Year Basis)
(percentages indicate fraction of workscope completed as of 2005Q2)

Task	Milestone	Year 2002				Year 2003				Year 2004				Year 2005				Year 2006			
		1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
5A	Selection of Weld Filler Material • Procure base metal for weld trials. • Evaluation and selection of filler. • Procurement of candidate fillers.					100% ▲															
		▲				100%				▲											
		▲				100%				▲											
5B	Optimization of Welding Parameters • Preliminary weld trials and parameter optimization – thin section. • Preliminary weld trials and parameter optimization – thick section.					90%															
		▲				90%								▲							
		▲				90%								▲							
5C	Preparation of Laboratory Samples • Material preparation. • Sample fabrication.					85%															
						85%															
5D	Weldability Testing									80%											
5E	Examination of Dissimilar Metal Welds. • Weld trials • Metallurgical analysis • Analysis and test case.									40%											
										0%											
										0%											

Accomplishments Versus Expenditures (Alstom)

The main reason for the deviation between expenditures and accomplishments was the higher than expected costs for the nickel base materials that had to be purchased for the program.

Task 6 Fabrication (B & W)

Objectives:

The objective of Task 6 is to establish boiler fabrication guidelines for the high temperature, oxidation and corrosion resistant alloys selected for the USC Project. The principal goals in this joint effort are:

- To establish fabrication guidelines for the high temperature, corrosion resistant alloys needed for boiler components in the USC power plant.
- To determine the thermomechanical treatments or other remedial actions necessary to restore material properties which might degrade due to fabrication operations.
- To investigate prototypical manufacturing operations for producing both thick wall and thin wall components from the USC alloys.

Progress for the Quarter: Riley Power, Inc.

- For the tube swaging trials, Riley machined the 2.0" OD x 0.400" wall tubes to produce 2.0" OD x 0.200" wall tube samples for both SAVE12 and HR6W materials. Swaging trials of the tubes from 2.0" OD down to 1.75" OD, and from 1.75" OD down to 1.5" OD, were completed and Riley has been collecting data on the samples.
- Base material properties and variability are being measured and evaluated for the SAVE12 and HR6W. Although most of the welding and fabrication trials have already been completed, a particular interest is in the degree of property variation or stratification in the pipe and tube shapes, especially the SAVE12 tubes manufactured from pipe.

Concerns:

None.

Plans for the Next Quarter:

- During the next quarter, Riley Power plans to continue with the preparation of summary reports on the history and accomplishments of the material fabricability efforts.
- After the recrystallization study results are available, Riley Power will determine the appropriate heat treatments applicable to the HR6W and SAVE12 materials and additional samples of the materials may be sent to ORNL for testing.

- Riley Power Inc. is still considering the fabrication of a mock-up header / spool piece which would contain tubing components and welding of the HR6W and SAVE12 materials.

Progress for the Quarter: Alstom Power, Inc.

- Fifteen U-bend specimens were fabricated from both CCA 617 and Super 304H tubing using cold forming procedures. For each material, four specimens had a 7-inch bend radius, four had a 5-inch radius, and 7 had a 3-inch radius. One specimen from each size and material group was sent to ORNL for mechanical property testing, one is being reserved for exhibition, and two are being measured for geometric characterization and will be destructively examined. The other three having a 3-inch radius were hot formed to a 2-inch radius thereby creating another group for study. None of the bends failed during forming and no unexpected difficulties were encountered.
- Metallurgical examination of the tapered tube samples prepared for the cold working studies has been started.

Concerns:

None.

Plans for the Next Quarter:

- Complete the examination of the tapered tubes used for the cold working studies.
- Determine the sensitivity of Super 304H to strain induced embrittlement.

Progress for the Quarter: Foster Wheeler

Fabrication of IN740:

- Sent one set of U-bends (that is, having 14.8%, 20%, and 33.3% outer fiber strain) to ORNL for testing.
- Performed a dimensional analysis and hardness survey on another set of IN740 U-bends. The results of this work are presented in the Table I, shown below. Transverse cross sections were removed from the straight leg (0 degree location), half way through the bend (45 degree location), and at the center of the bend (90 degree location). In the cross sections, the extrados was labeled 0°, the intrados 180°, and the neutral axes 90 and 270°. OD measurements were obtained at the 0-180 (minimum) and 90-270 (maximum) locations, while wall thickness measurements were made at the 0, 90, 180, and 270 locations in each cross section. Hardness measurements were also obtained at the 0, 90, 180, and 270 locations. From this data, the % Ovality, % Flattening, % Wall Reduction at the Extrados, and % Wall Increase at the Intrados were calculated. The results indicated no excessive ovality or flattening in the bends. As expected, the % Wall Reduction

values at the extrados and % Wall Increase values at the intrados increased as the radius of the bend decreased. The appearance of the cross sections is shown in Figure 1, below.

Recrystallization Studies

- Completed 1000 hour exposures at 1600°F on the strained 230, 740, and HR6W material. Also performed 100 exposure at 1500°F on strained HR6W material and 124 hour/1550°F and 12.5 hour/1650°F exposures on strained 230 material.
- Samples of exposed sections were mounted for metallurgical evaluation. The main focus of the metallurgical evaluation is to acquire data in order to develop a Larson-Miller curve for the onset of recrystallization correlating temperature and time with outer fiber strain (OFS). For the 230 and HR6W material, the onset of recrystallization occurred at the following OFS for the different thermal exposures:

<u>Alloy 230</u>		<u>HR6W</u>	
Exposure Parameters	OFS-Onset of RX	Exposure Parameters	OFS-Onset of RX
1500°F/100hrs	41.8	1500°F/100hrs	13.9
1600°F/100hrs	20.5		
1600°F/1000hrs	15.5		
1650°F/12.5hrs	23.6		

For the three exposures (1500°F/100hrs, 1600°F/100hrs, and 1600°F/1000hrs) performed on the strained 740 material, the precipitation of various phases in the microstructure has made it difficult to determine if any recrystallization has occurred.

Concerns:

None.

Plans for the Next Quarter:

- Plans for next quarter are to do a microscopic analysis of the bends and perhaps try to bend some tubes that have been first subjected to an aging heat treatment.

Table 1

Dimensional Analysis and Hardness Survey of 740 Bends

Dimensional Analysis and Hardness Survey of 740 Bends

BEND	OFS	LOCATION	OD (in.)		WALL THICKNESS (in.)				HARDNESS			
			Max	Min	0	90	180	270	0	90	180	270
4-4	14.8%	0	2.004	1.996	0.392	0.397	0.404	0.401	87HRB	97HRB	97HRB	87HRB
4-4	14.8%	45	1.993	1.935	0.369	0.391	0.427	0.405	24HRC	26HRC	28HRC	96HRB
4-4	14.8%	90	2.005	1.94	0.374	0.391	0.43	0.402	23HRC	23HRC	24HRC	96HRB
4-1	20%	0	2.001	1.995	0.389	0.405	0.404	0.395	87HRB	96HRB	92HRB	84HRB
4-1	20%	45	2.013	1.932	0.356	0.403	0.439	0.398	27HRC	93HRB	25HRC	23HRC
4-1	20%	90	2.01	1.939	0.365	0.409	0.44	0.389	27HRC	95HRB	27HRC	25HRC
3-2	33.3%	0	2	1.998	0.402	0.391	0.398	0.406	93HRB	97HRB	89HRB	89HRB
3-2	33.3%	45	1.995	1.925	0.367	0.39	0.453	0.406	31HRC	29HRC	32HRC	24HRC
3-2	33.3%	90	2.01	1.9	0.366	0.398	0.457	0.411	33HRC	28HRC	32HRC	21HRC
			%Ovality	%Flat	%Wall Rd	%Wall In						
4-4	14.8%	0	0.4	0.2								
4-4	14.8%	45	2.9	3.3	5.9		5.7					
4-4	14.8%	90	3.3	3.0	4.6		6.4					
4-1	20%	0	0.3	0.2								
4-1	20%	45	4.1	3.3	8.5		8.7					
4-1	20%	90	3.6	3.0	6.2		8.9					
3-2	33.3%	0	0.1	0.1								
3-2	33.3%	45	3.5	3.7	8.7		13.8					
3-2	33.3%	90	5.5	5.0	9.0		14.8

Figure 1. Cross-sections of IN740 U-bends

Progress for the Quarter: B&W

Task 6 project activities have been on hold this quarter, awaiting authorization and distribution of funding.

Concerns:

None.

Plans for the Next Quarter:

- Examinations and characterization of alloy 230 bend microstructures (extrados, neutral axis, and intrados) are planned.
- Swaging trials with Alloy 230 tubes machined to 2" OD X 0.200MW are planned.

- Initiation of the Task 6 final report is planned.

TABLE 6
Schedule and Progress

ID	Task Name	Start	Finish	Status																				
					2002				2003				2004				2005				2006			
					Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	
1	Task 6: Fabricability	Tue 1/1/02	Fri 12/30/05	In Progress																				
2	6A: Fab Trials for SH	Tue 1/1/02	Mon 10/10/05	In Progress																				
3	6A.1 SH Trial	Tue 1/1/02	Mon 10/10/05	In Progress																				
4	Procure Materials	Wed 1/2/02	Fri 5/30/03	Complete																				
5	Shop Sched & Graphics	Tue 4/1/03	Mon 6/2/03	Complete																				
6	Travel to Shop	Mon 6/2/03	Mon 10/10/05	In Progress																				
7	Cold Bending Trials	Mon 6/2/03	Mon 10/10/05	In Progress																				
8	Cold Swaging Trials	Mon 6/2/03	Mon 10/10/05	In Progress																				
9	Butt Welding Trials	Mon 6/2/03	Fri 6/4/04	Complete																				
10	Attachment Welding Trials	Mon 6/2/03	Fri 8/6/04	Complete																				
11	6A.2 Reporting	Fri 1/3/03	Mon 10/10/05	In Progress																				
12	6A.3 SH: Met Test & Eval	Fri 1/9/04	Mon 10/10/05	In Progress																				
13	6A.3.1 Mic Bends&Welds	Fri 6/4/04	Mon 10/10/05	In Progress																				
14	6A.3.2 HT Studies&Mic	Fri 6/4/04	Mon 10/10/05	In Progress																				
15	6B: Fab Thk Wall Comp	Fri 1/9/04	Fri 12/30/05	In Progress																				
16	6B.1 Thick-Wall Fab Trial	Fri 1/9/04	Wed 8/3/05	In Progress																				
17	6B.2 Reporting	Fri 1/9/04	Thu 10/6/05	In Progress																				
18	6B.3 Thick-Wall Comp	Fri 1/9/04	Wed 8/3/05	In Progress																				
19	6B.3.1 Met Analysis	Wed 6/29/05	Tue 11/15/05	In Progress																				
20	6B.3.2 PWHT Studies&Mic	Wed 9/29/04	Thu 10/6/05	In Progress																				

Task 7 Coatings (Alstom)

Objectives for Task 7 Coatings:

- Review state-of-the-art of coating technology and identify development needs.
- Develop coating manufacturing techniques, which can provide corrosion/erosion protection for components in USC boilers, cost effectively.
- Establish manufacturing techniques for application of internal coatings for oxidation protection, cost effectively.
- Provide coated samples for corrosion and oxidation testing in the laboratory and “in the field”.

These objectives will be accomplished through execution of eight sub-tasks. Where activity on these sub-tasks occurred during the reporting period, it is described below.

Task 7G: Manufacturing Guidelines

Objective:

Investigate the requirements for production coating of boiler materials.

Progress for the Quarter:

Work efforts for this task have concentrated on the requirements for diffusion-coating of the internal surface of boiler tubing. Process steps were defined and general specifications generated for each of these steps. A preliminary layout of equipment has been established.

Concerns:

None.

Activities Planned for Next Quarter:

Continue study of the manufacturing requirements and costs for coating of internal tube surfaces.

Task 7H: Specimens for Field Corrosion/Oxidation

Objective:

Provide externally and internally coated specimens for inclusion in corrosion/oxidation testing under Tasks 3 and 4.

Progress for the Quarter:

Specimens of diffusion-coated Super 304H were prepared and delivered to Task 4 for use in the air-cooled probe studies.

Concerns:

None.

Plans for the Next Quarter:

Task has supplied specimens as needed; additional activity dependent on need for additional specimens.

Task Name	Status																
		2002				2003				2004				2005			
		Qtr 1	Qtr 2	Qtr 3	Qtr 4	Qtr 1	Qtr 2	Qtr 3	Qtr 4	Qtr 1	Qtr 2	Qtr 3	Qtr 4	Qtr 1	Qtr 2	Qtr 3	Qtr 4
Task 7: Coatings																	
Task 7A: Detailed Study of Current State of the Art																	
Alstom Task 7A: Detailed Study of Current State of the Art	Complete																
Task 7B: Coating Feasibility (Internal Coating)																	
Alstom Task 7B: Coating Feasibility (Internal Coating)	Complete																
Task 7C: Coating Recommendations																	
Alstom Task 7C: Coating Recommendations	20%																
Task 7D: Laboratory Testing																	
Alstom Task 7D: Laboratory Testing	60%																
Task 7E: Process Scale Up - Preliminary Trials																	
Alstom Task 7E: Process Scale Up - Preliminary Trials	Complete																
B&W Task 7E: Process Scale Up - Preliminary Trials	87%																
Task 7F: Process Optimization																	
Alstom Task 7F: Process Optimization	Complete																
B&W Task 7F: Process Optimization	87%																
Task 7G: Manufacturing Recommendations																	
Alstom Task 7G: Manufacturing Recommendations	20%																
B&W Task 7G: Manufacturing Recommendations	30%																
Task 7H: Specimens for Field Corrosion/Oxidation																	
Alstom Task 7H: Specimens for Field Corrosion/Oxidation	Complete																
B&W Task 7H: Specimens for Field Corrosion/Oxidation	55%																
Task 7I: Project Management																	
Alstom Task 7I: Project Management	Ongoing																
B&W Task 7I: Project Management	Ongoing																

Scope Accomplished Versus Actual Expenditures Task 7 Coatings Alstom Scope

Task 8

Design Methods and Data (Alstom)

The major objectives for Task 8 are:

- Review the methods used by Section I of the ASME Boiler and Pressure Vessel Code to utilize materials properties and behavior models in the design of ultra-supercritical boilers.
- Develop and document methodologies whereby the results of the other tasks within this program may be most effectively applied within the ASME Section I design environment.
- Pursue the incorporation of such methodologies into Section I.

These objectives will be accomplished through execution of seven sub-tasks. Where activity on these sub-tasks occurred during the reporting period, it is described below.

Task 8A: Task Management (ALSTOM)

Objective:

The primary objective of this subtask is the overall management of the task, coordinating meetings and preparing progress reports.

Progress for the Quarter:

Some subtasks were worked on this quarter. However, delayed funding release and funding issues with some participants continue to limit activities and accomplishments.

Concerns:

None.

Plans for the Next Quarter:

Continue general task management activities.

Task 8B: Material Data Collation and Processing (FW)

Objective:

The creation of documentation to ensure that quality test data is transferred between tasks and that this data remains traceable. A second objective is the analysis of such

data with the objective of improving the statistical correlation. Foster Wheeler is subtask leader, with Riley Power Inc. providing significant input to this subtask.

Deliverables:

Item	Responsible	Status
Material data transfer sheets	ALSTOM	Transfer sheets provided for creep and tensile tests.
Electronic data repository	ORNL	Website complete.
Recommendations for statistical analysis of data		
Data compendia and fits for key materials		
Code case packages and submissions to code committees	ALL	

Progress for the Quarter:

Riley Power Inc. has continued to monitor the USC data transfer website for any added completed test results for the HR6W and SAVE 12 materials, assigned to Riley. During the quarter there have been no additional postings to the website for either of the Riley materials. Riley did perform a preliminary review of the most recent creep rupture testing results, for the HR6W material, which were listed on the website in March 2005.

ALSTOM Power Inc. compiled thermo-physical material data for a number of the alloys of interest and contrasted their behavior with commonly used ferritic and austenitic steels. The data can be used to compare the thermal fatigue resistance of candidate alloys (Figure 1), and provides data for transient thermal analysis of structural components (e.g. for use in cycling studies and in post-test analysis of cyclic fatigue tests being performed at ORNL). From Figure 1, it is evident that the nickel-based alloys have thermal fatigue strength that is similar to ferritic steels and certainly better than austenitic steels, which confirms their suitability for thick-walled pressure parts. A key feature of thermal fatigue resistance is yield strength, which, it should be noted, is quite variable for the nickel-based alloys because it is highly sensitive to processing history and service exposure.

Due to funding limitations, the other participants did not perform any work on this subtask.

Concerns:

None.

Figure 1. Comparison of thermal fatigue resistance of candidate alloys

Plans for the Next Quarter:

The task participants will continue to monitor the USC data transfer web site for any additional, completed test results. Evaluations will continue to compare and contrast the strength of the materials with existing databases for similar alloys. It is projected that it will not be possible to work on statistical correlation of data for some time because of the lack of data on which to perform meaningful analysis. Support will be provided to Task 2, as needed, to address issues with additional structural feature tests, or interpretation of existing tests.

Task 8E: Continuum Damage Mechanics (B&W)

Objectives:

The objective of this subtask is to analyze uniaxial and multiaxial creep test data from Task 2 for several (three) materials to:

- establish the continuum damage mechanics (CDM) parameters,
- evaluate multi-axial strength theories and failure criteria,

- assess the implications of cyclic creep for USC materials,
- evaluate and compare CDM, reference stress and Omega models of typical ASME geometries.

Progress for the Quarter:

No data are yet available from structural feature tests being performed at ORNL, and no additional creep curve data has been posted to the web-site repository. Thus information is still too scant for a detailed modeling effort. However, a preliminary comparison was made of the creep-curve shape for conventional ferritic (Grade 91) and advanced nickel-based alloy (CCA617) to provide pointers for future efforts. The comparison, which is shown in Figure 2, highlights the extensive secondary (steady) creep rate exhibited by ferritic steels and the extensive tertiary creep exhibited by nickel-based alloys. The high ductility and prolonged tertiary creep of the nickel-based alloys promotes stress redistribution and should mean that reference stress based life estimates are applicable.

Figure 2. Comparison for creep curve shape for Grade 91 and CCA617.

To assess the cycling capability and margins against shakedown and ratcheting, a study was initiated with Stress Engineering Services to develop Bree diagrams for a typical segment from a superheater header (Figure 3) subject to normal cold startup and

rapid cooling on shutdown. The objective is to compare the relative behavior of a header made from a nickel-based alloy (CCA617), a stainless steel (S304H) and a ferritic steel (Grade 91). This will provide valuable information on the relative durability of these alloys for a similar application, and identify bounds on behavior than might ultimately limit component operation.

Figure 3. Sketch showing typical header geometry for cyclic analysis study.

Concerns:

Timely availability of creep data on ORNL web site and results of notched bar creep rupture tests.

Plans for the Next Quarter:

Monitor material data web site to see if sufficient data is available to initiate a modeling activity. Check on status of structural feature tests. Complete study comparing a cycling capability of candidate alloys.

Task 8F: Weld Analysis and Assessment (ALSTOM)

Objective:

Create simplified analysis models of welds and heat affected zones (HAZ) utilizing material properties obtained from the open literature and from Task 2 to permit accurate creep life assessment of weldments.

Deliverables:

Item	Responsible	Status
Topical review of weld analysis and assessment in creep range.	ALSTOM & RPI	In progress.
Collation of material data for weld metal and HAZ.	RPI	In progress.
Creep models for weld metal and HAZ regions.	ALSTOM	In progress.
Report documenting the simulation of welded specimens and common Code geometries.	ALSTOM	
Report documenting the development and use of approximate weld assessment methods.	ALL	

Progress for the Quarter:

Representatives from Riley Power met with representatives of ALSTOM Power on April 4, 2005 to discuss Riley's draft version of the weld literature review summary report. Action items from this meeting were; that Riley would incorporate ALSTOM's review comments into the text, and also add reviews for a few, select papers from the October 2004, EPRI, 4th International Conference on Advances in Materials Technology for Fossil Power Plants, keeping the focus on the six USC materials, under creep conditions. Also, that ALSTOM Power would add reviews to the report, for some additional papers on the subject of the design and analysis of welds in high temperature service. Riley Power completed their assigned tasks and forwarded a revised draft of the summary report to ALSTOM Power in early June, for review and incorporation of their document reviews.

Also at the April 4th interface meeting, the subtask leader requested Riley Power to perform an additional review of pertinent weld literature documents, in order to determine any simplified scoping methods for use in finite element analysis modeling. For example, methods using relative strengths between weld and base metals, or any commonality in ratios of numbers, such as varying creep rates between weldment regions. For simplification, this review would be limited to the commonly used Grade 22 and 91 materials. Riley Power is currently performing this task.

ALSTOM reviewed a number of papers documenting advanced analysis of welds. A series of analyses were also performed for a typical butt-weld geometry for which extensive experimental and numerical analysis data exist in the literature. The study showed that reference stress methods, steady state creep analysis and fully coupled continuum damage mechanics analyses yield similar results (predicted failure time) but with radically different degrees of computational effort. Reference stress methods, with the yield strength of each material zone in proportion to the creep strength of that zone, therefore offer an attractive route for advanced design.

Concerns:

None.

Plans for the Next Quarter

In the next quarter, Riley Power plans on meeting with the subtask leader for a final review, and also assisting with the issuance of the completed weld literature review summary report. Also, Riley Power will issue a memorandum to the subtask leader describing the pertinent observations and findings from the review for simplified methods.

ALSTOM plans to review the draft report prepared by Riley Power Inc. and work to expand / add sections dealing with weld analysis and design methods. Additional weld analyses will be performed to evaluate the accuracy and practicality of various methods.

Task 8G: Basic Design Rules for Cylinders (ALSTOM)

Objectives:

Review the various equations used by the ASME Code, Section I for Power Boilers to define the minimum thickness of cylinders under internal pressure and develop a single methodology applicable to ultrasupercritical boilers.

Deliverables:

Item	Responsible	Status
Report summarizing existing approaches and comparing and contrasting their predictions	ALSTOM	Complete (Aug 2003)
Report recommending a single equation with supporting theoretical data.	ALSTOM	Complete (Sept 2003)
Code case submission	ALSTOM	Complete (October 2003)

Progress for the Quarter:

No activity for this quarter.

Concerns:

None.

Plans for the Next Quarter:

None.

Task 9 Project Integration and Management (EPRI)

- The objective of Task 9 is to coordinate the project and provide reporting to DOE and Ohio Coal Development Office (OCDO).

Progress for the Quarter:

- Completed Second Quarterly Report for 2005.
- Completed Monthly Reports for April and May, 2005.
- Monthly conference calls were held and the discussions were documented.
- Conducted Steering Meeting in Cleveland on May 4-5, 2005 and provided minutes.

Concerns:

- None

Plans for the Next Quarter:

- Issue monthly reports and hold conference calls as required.
- Arrange for Steering Committee Meeting on August 31 and September 1, 2005 in Cleveland.