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). The project goal initially was to assess/develop materials technology that will enable achieving turbine throttle steam conditions of 760°C (1400°F)/35 MPa (5000 psi), although this goal for the main steam temperature had to be revised down to 732°C (1350°F), based on a preliminary assessment of material capabilities. The project is 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 to June 30, 2004.

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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, and DOE's Vision 21. 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

- Parts I and II of the material assessment reports were completed by ORNL. These reports were issued as topical reports, T7 and T8 and were titled "Overview & Recommendations" and "Advanced Ferritic Martensitic Steels".
- Major observations/findings from microstructural evolution of standard 617, CCA617, Super 304H, Haynes 230 and Inconel 740 include:
 - Evaluation of long-term aged (20,000 to 65,000 hours) 617 showed a need to modify the 617 TTT diagram.
 - The enhanced creep strength of CCA617 relative to 617 is attributed to appreciable gamma prime precipitation in the CCA617. However, long-term aged and creep tested specimens need to be analyzed to determine the long-term stability of the microstructure.
 - The Super 304H aged at 700°C contained a small volume fraction of spheroidal, nanoscale Cu-rich precipitates, whose coarsening rate, though following a $d^3 - d_o^3 = kt$ behavior, was low.
 - The Haynes 230 microstructure was composed exclusively of carbides of the WC and M₂₃C₆ types.

- Standard and modified Inconel 740 showed rapid age hardening in the 700°C to 800°C range. Eta phase was not observed after 500 hours aging at this temperature.
- Rupture testing of Haynes 230 indicated that the plate weldments have better creep strength than the tube weldments.
- SAW welds in CCA617 appeared good but SMAW welds show small pits/cracks/inclusions.
- If we can get some material, AL 20-25+Nb (NF709), 347W, and Sanicro 25 will be added to the next 800°C oxidation exposure.
- Oxidation results are presented for 1000 hr tests at 650°C and 800°C. In general, descaled weight loss was consistent with chromium content with the exception of Alloy 214 which was substantially less. The MARB2 also performed better than expected at 650°C. The Co-containing Ni-based materials tested at 650°C exhibited the lowest descaled weight loss.
- In general, nickel based alloys that contain significant aluminum experienced intergranular oxide penetrations.
- 1000 hr corrosion exposures at 975°F and 1500°F were completed. Testing at 1100°F and 1300°F was started. Results are presented for 850°F, 975°F, 1200°F, and 1500°F. A correlation of corrosion vs. molybdenum content was developed that indicated high molybdenum.
- Visual inspection of the steam cooled corrosion loops installed in the Niles plant was performed. Overfire air will be adjusted to allow for 1425°F operation of the loops.
- A gas tungsten arc welding (GTAW) procedure was qualified for Save 12 piping using P92 filler metal. Procedures were also qualified for HR6W using Inconel 617 and Inconel 82 filler metal.
- Thin Inconel 740 plate was welded with matching filler metal and Nimonic 263 was completed.
- Two dissimilar welds using Super304H/Grade 91 and CCA 617/Super 304H were completed.
- Studies of 740 and 230 indicated no re-crystallization at 1500°F after 100 hrs.
- Samples coated with "Nanocomp" were produced which will be included in future corrosion evaluations.

- Internal chromizing tests were completed on T11 base metal tubing. To achieve good results, the tubing required use of end caps during the process.
- Revisions to Section I of ASME to permit the use of simplified design equations were accepted by Subcommittee 1 and forwarded to the Main Committee letter ballot.

E. Plans for the Next Quarter

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

- Continue welding qualification efforts on SAVE 12, HR6W, Super 304H, CCA 617, and IN 740.
- Swaging trials on HR6W and SAVE 12 will be completed.
- Mock-up headers which would contain tubing and thick section components using fabrication and welding techniques will be started.
- Re-crystallization studies will continue on Alloy 230, HR6W, and SAVE 12 materials.
- Swaging trials will be completed on Alloy 230.

F. Issues

- SMAW welds in CCA 617 show small pits/cracks/inclusions.
- Results from laboratory corrosion tests have required a re-evaluation of material selection and probe design for the air cooled corrosion probes.
- Welding procedures using the similar SAVE 12 and HR6W filler metal compositions failed bend tests.
- Re-solution heat treatment of Inconel 740 was unable to develop consistent hardness around the circumference of tubing.
- Availability of creep data and results of notch bar creep tests.
- Funds to support Task 8 activity at B&W and Alstom.

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 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 649°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:

Part I and II of the assessment report were completed and sent to EPRI for publication.

A paper was presented at the 2004 Pittsburg Coal Conference (September 13-17, 2004: Osaka, Japan). A paper and poster abstract were submitted and accepted for the 2004 ASM Materials Solution Conference (October 18-21, 2004: Columbus, OH). Two abstracts were submitted and accepted for the EPRI Materials Conference (October 26-28, 2004: Hilton Head, SC).

Task 2B: Detailed Test Plan

Progress:

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. Progress and/or problems associated with the welding (Task 5) and fabrication (Task 6) tasks will determine testing specifics. Thus, to some measure the test plan continues to evolve. The testing plans for the thick-section materials, SAVE 12, CCA617, alloy 230, and Alloy 740 are still under development. Continued discussions with Task 8 members are beginning to determine specific tests that need to be addressed.

The six alloys, chemical compositions in Table 1 below, of most interest to the project are: SAVE12, Super 304H, HR6W, Haynes 230, CCA617, and Alloy 740. The characterization testing plans have been completed for five of the six tubing alloys (Super 304H, HR6W, alloy 230, CCA617, and INCONEL 740). The creep-rupture database for Super 304H stainless steel and alloy 230 was judged to be adequate, since both materials are code alloys. A test plan for INCONEL 740 tubing has been designed. Priority has been given to producing a database for the INCONEL 740 tubing. These data will provide the main body creep/creep-rupture data needed to produce a code case on the material. To fabricate thick plate weldments of 740, it may be necessary to overage the base material prior to welding. It is anticipated that this heat treatment will alter the creep strength of the alloy. Therefore, testing on the plate will not begin until a heat-treatment is decided upon by the consortium.

TABLE 1. Compositions of USC Steam Boiler Consortium Materials															
Alloy	Fe	Cr	Ni	Mn	Nominal Compositions in Wt%							Si	N	Cu	Other
					Mo	Ti	Nb	W	V	C	B				
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															

*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 for five tubing alloys currently in testing is provided in the tables below. In each table, comparison of the rupture lives may be made with the expected life based on prior data. The initial results indicate that the strength of the Super 304H and alloy 230 are meeting expectations, while the HR6W is below expectations. A plot at the end of the section shows the rupture results of the consortium heat of HR6W vs. data scaled from a Sumitomo HR6W product brochure obtained from Riley. As seen, the Sumitomo data are based off 4 heats of material with one heat being weaker than the other three. In fact, the Larson-Miller Parameter plot clearly shows the deviations between the 3 'strong' heats and the one 'weak' heat. The consortium data fall directly on the 'weak' heat data points. Based off discussions with Sumitomo, this is due to low W in the heat, but this has yet to be verified by ORNL. 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 above 750°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 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. Minor short-term differences are observed between alternate annealing temperatures. The as-received material (1120°C mill annealed condition) and the re-solution annealed material (1200°C) showed rupture lives of approximately 150 hours and 280 hours respectively for identical test conditions. Overall, total testing time has surpassed 10,000 hours (over one year) for some USC candidate alloys.

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	
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		
		470	675	1000		
		450	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
		440	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		300	700	100		
H230-05	30301	200	700	1500	6/12/2003	1517.1
H230-06		140	700	15000		
H230-07		200	750	100		
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		140	700	15000		
617-07	30363	200	750	100	9/30/2003	1561.8
617-08	30388	140	750	2000	12/8/2003	
617-09		100	750	15000		
617-10	30331	140	800	100	8/6/2003	329.9
617-11	30343	100	800	2000	9/3/2003	1831.0
617-12		80	800	20000		
617-13	30352	400	650	200	9/10/2003	1279.7
617-14	30387	400	700	100	12/3/2003	301.6
617-15		300	750	100		

Creep-Rupture Testing of INCONEL 740 (Heat # CLH4663) - Aged 16hrs, 800C, Ar								
Spec #	Product Form	SA Temp(C)	Test #	Stress (MPa)	Temp. (°C)	Expected Life	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
R740-01	Tube	1190		580	650	100		
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		420	700	1000		
R740-06	Tube	1190		340	700	10000		
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		220	750	10000		
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		
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		70	850	10000

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 will also be 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.

During this quarter, analyses were performed on creep tested specimens of CCA617 and Super 304H.

A majority of the effort this quarter has been devoted to analyzing the microscopy data produced. Two papers have been written for the Hilton Head Conference which focus on the microstructural evolution of standard 617, CCA617, Super 304H, Haynes 230 and Inconel 740. A few of the major observations/findings are as follows:

- Evaluation of long-term aged (20,000 to 65,000 hours) 617 showed a need to modify the 617 TTT diagram
- The enhanced creep strength of CCA617 relative to 617 is attributed to appreciable gamma prime precipitation in the CCA617. However, long-term aged and creep tested specimens need to be analyzed to determine the long-term stability of the microstructure.
- The Super 304H aged at 700°C contained a small volume fraction of spheroidal, nanoscale Cu-rich precipitates, whose coarsening rate, though following a $d^3 - d_0^3 = kt$ behavior, was low.
- The Haynes 230 microstructure was composed exclusively of carbides of the WC and M₂₃C₆ types.
- Standard and modified Inconel 740 showed rapid age hardening in the 700°C to 800°C range. Eta phase was not observed after 500 hours aging at this temperature.

Task 2E: Assessment of Creep-Fatigue Properties

Objective:

The primary objectives of this subtask are:

- Develop a database that will lead to practical, yet conservative methods.
- Address the issue of creep-fatigue in the boiler materials.

Progress:

A creep-fatigue machine has been operated successfully. Data acquisition equipment has been received for the machine. Check-out tests have been conducted on a continuous fatigue machine with a new extensometer. CCA617 and Inconel 740 specimens have been machined. Testing on CCA617 will begin next quarter.

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 tubing and plate weldments. The tests include: cross-weldments on plate and tube, parallel welded plate, and weld-metal-only tests. The tube cross-weldment tests have been completed. Initial results show that the plate weldments have better creep strength than the tube weldments. A number of creep tests continue on the HR6W with the 617 and the 82 filler welds. Thick plates (2" thick) of welded (SAW and SMAW) CCA617 were received at ORNL. A thin section of each plate was removed for archival purposes. These sections were polished and macro-etched. Visually, the SAW plate weldment appears good, but the SMAW weldment shows small pits/cracks/inclusions in the interface region between the weldment and the base material. X-rays of both plates did not show any defects. Specimen design has begun for removing specimens from plate. Butt-welded tubes of Super 304H and CCA617 with matching filler metal were received and cross-weld specimens are being produced. Dissimilar metal weldments between Super 304H and T91 were also received. Some of these have been put into aging. It is anticipated that these materials will be tested with a tensile load and internal pressure with thermal cycling. The results of all ongoing tests are included in the table below.

Creep-Rupture Testing: Haynes 230 (Tube 5) Cross-Weldments						
Spec #	Test #	Stress (MPa)	Temp. (°C)	Base Metal Expected Life	Date Started	Life (hrs)
H230-W01	30311	350	650	200	6/26/2003	84.9
H230-W02	30290	300	650	1000	6/3/2003	825.4
H230-W03	30313	300	700	100	7/1/2003	22.7
H230-W04	30319	200	700	1500	7/10/2003	207.1
H230-W05	30320	200	750	100	7/14/2003	30.7
H230-W06	30327	140	750	2000	7/23/2003	170.6
H230-W07	30328	200	650	10000	7/24/2003	1550.6
H230-W08	30332	140	700	15000	8/6/2003	1472
Creep-Rupture Testing: Haynes 230 (Tube 2) Cross-Weldments						
H230-W09	30361	100	800	2000	9/23/2003	231.6
H230-W10	30365	80	800	20000	10/1/2003	419.2
H230-W11	30369	60	800		10/14/2003	7610.5
H230-W12	30370	100	750	15000	10/14/2003	1117.8

Creep-Rupture Testing: Haynes 230 Weld Metal (Plate 3)						
Spec #	Test #	Stress (MPa)	Temp. (°C)	Estimated Life (hrs)	Date Started	Life (hrs)
W3-01	30403	200	650	1500	1/22/2004	2426.2
W3-02	30454	140	700	1500	5/13/2004	
W3-03		100	750	1500		
W3-04*		100	750	1500		
W3-05		80	800	1500		
*Fusion Zone Sample						

Creep-Rutture Testing:Haynes 230 Cross Weld (Plate 2)						
Spec #	Test #	Stress (MPa)	Temp. (°C)	Estimated Life (hrs)	Date Started	Life (hrs)
CW-01	30418	200	650	1500	3/2/2004	
CW-02		140	700	1500		
CW-03		100	750	1500		
CW-04		80	800	1500		

Creep-Rupture Testing:Haynes 230 Parallel Weld (Plate 2)						
Spec #	Test #	Stress (MPa)	Temp. (°C)	Estimated Life (hrs)	Date Started	Life (hrs)
PW-01	30419	200	650	2000	3/2/2004	
PW-02		140	700	2000		
PW-03		100	750	2000		
PW-04		80	800	2000		

Creep-Rupture Testing of HR6W Tubing w/617 Welds						
Spec #	Test #	Stress (MPa)	Temp. (°C)	Estimated Life	Date Started	Life (hrs)
617W-01	30459	175	650		5/24/2004	
617W-02	30460	120	700		5/24/2004	
617W-03		85	750			

Creep-Rupture Testing of HR6W Tubing w/82 Welds						
Spec #	Test #	Stress (MPa)	Temp. (°C)	Estimated Life	Date Started	Life (hrs)
82W-01	30465	175	650		6/9/2004	
82W-02		120	700			
82W-03		85	750			

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:

The 9Cr ferritic Abe Alloy (nano-nitride) was of interest to the consortium. Two thick plates (1" thick) were received from Abe and stress-relaxation specimens were machined. A number of relaxation runs were performed on the material at 650°C. Compared to the HCM12A, the material showed lower relaxation rates.

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, continues on two Haynes 230 bends and one HR6W bend. The test temperature was set at 775°C. It was agreed, through discussions with Task 8, that this temperature would be aggressive enough to produce recrystallization during the tests while keeping the pressures within safety limits. The internal pressure was set to produce rupture in 24,000 hours; based off the current ASME Section I formula for tubes. The tubes were measured using a CMM (Coordinate Measuring Machine) before testing. The tubes were removed after 1,000 hours and after 3,000 hours (total test time) and measured. The data for the 3,000 hours is not yet available. The specimens will be put back into the test apparatus this quarter and run for a minimum of 3,000 hours (6,000 hours total test time).

The thermal shock test has been delayed due to a grounding problem with the thermocouples. Once this problem is fixed, the thermal shock test should begin on the CCA617 specimen.

Notched bar testing began this quarter. The figure below illustrates the test set-up. The test material is Inconel 740 (from plate) and the notch configuration is a modified Bridgeman notch previously approved by Task 8. For this structures test, the reduced section of the notch is one inch in diameter. The test conditions were set to produce rupture in 2,500 hours at 750°C assuming 20% notch strengthening. A 200:1 lever arm creep machine was utilized to achieve the desired load, which was above 30,000 lbs. Both axial and diametral strain are measured via a tube and rod extensometer and a 'hook' type air cooled MTS diametral extensometer. The quartz attachment for the diametral extensometer was custom fabricated in-house at ORNL. More details as to the testing set-up will be presented in a paper completed for the Hilton Head Conference.

Test Set-up for Large Diameter (1 3/4" - 1" Dia.) Notched Bar Testing

Concerns:

The consortium heat of HR6W does not match the strength reported by Sumitomo for other HR6W heats. The result may be improperly characterized effects in the cross-weld data and the U-bend tube tests due to strength less than that of the eventual commercial alloy. The data transfer website has not been updated in a timely manner. Web software has been purchased and is being used to update the site. A regularly updated site is expected by the end of next quarter.

Plans for Next Quarter:

Work on the third assessment report will continue. Numerous papers, presentations, and a poster will be given at the ASM Materials Solution Conference and the EPRI sponsored Hilton Head Conference. Characterization work on creep tested specimens and longer-term aged Inconel 740 specimens will continue. The website will be updated with recent data. Cross-weldment testing on CCA617 and Super 304H weldments should begin. The pressurized U-bend tests will be restarted for testing beyond 3,000 hours. Thermal shock testing should begin.

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:

Specimens from the first exposure period at 800°C (1,006 hours) were evaluated by SEM/EDS during this quarter. An updated plot of descaled weight loss vs. Cr content was also constructed for the results obtained after 1,000 hours at 650°C and 800°C. This plot and the SEM/EDS results are presented below. Discussions were also initiated regarding additional materials that should be included in the remaining 800°C exposures. If material is available, AL 20-25+Nb (NF709), 347W and Sanicro 25 will be added to the next 800°C exposure. In September, Greg Stanko of Foster Wheeler provided some AL 20-25+Nb.

Descaled Weight Loss

Figure 1 describes the 1,000 hours descaled weight loss results for materials tested at 650°C and 800°C. This figure shows the consistent effect of temperature in increasing the descaled weight loss of the materials tested. The same trend of descaled weight loss vs. Cr content was observed at both temperatures. The most obvious departure from this trend was the Ni-based Alloy 214 which contained only 16% Cr. The reasons this material exhibited such low descaled weight loss will be described in the discussion of the SEM/EDS results.

The 9% Cr ferritic alloy MARB2, which performed as well as the 12% Cr ferritic alloy VM12 at 650°C displayed significantly greater descaled weight loss than VM12 at 800°C. At 800°C, MARB2 still performed better than any of the other 9% Cr materials. The descaled weight loss experienced by VM12 at 800°C was only slightly greater than at 650°C after 1,000 hours of exposure. The Co-containing Ni-based materials tested at 650°C exhibited the lowest descaled weight loss, however this trend is not obvious at 800°C.

Figure 1. Descaled Weight Loss of Materials Tested for 1,000 Hours at 650°C and 800°C

SEM/EDS Results

The thickness of the oxide measured during the SEM evaluation is displayed in Table 1. The SEM evaluation indicated that the ferritic alloy MARB2 experienced the formation of localized islands of oxidations at 800°C (Figure 2). Unlike MARB2, other 9% Cr alloys (P91, P92 and SAVE12) exhibited this behavior at 650°C. As shown in Figure 3, the austenitic alloy 304H also displayed the formation of oxide islands. It is believed that the formation of oxide islands is a precursor to break-away oxidation. As mentioned above, SAVE12 exhibited these islands at 650°C, and exhibited extremely heavy localized regions of oxidation at 800°C. The formation of these islands on 304H suggests that the same oxidation mechanism that occurs on the 9% Cr ferritic alloys also applies to this austenitic alloy.

TABLE 1
Results After 1,000 Hours at 800°C

Material	Descaled Weight Loss (mg/cm²)	Oxide Thickness (microns)
T23	>939	Not Measured (Specimen Completely Oxidized)
P92	20.687 (oxide could not be completely removed)	Not Measured
MARB2	3.426	4 (with islands of 120 µm)
SAVE12	8.278 (oxide could not be completely removed)	900 (in areas of severe localized oxidation)
VM12	1.277	2
214	0.000	1
347HFG	0.974	4
304H	3.768	4 (with islands of 50 µm)
Super304H	1.950	3 (with intergranular penetrations of 1 µm)
CCA617	1.099	3 (with intergranular penetrations of 16 µm)
SAVE25	1.436	10
230	1.294	2 (with intergranular penetrations of 15 µm)
HR6W	1.458	4
740	1.168	4 (with intergranular penetrations of 14 µm)
Mod 740	1.428	Not Measured
HR120	1.363	3
310HCbN	1.685	5

Figure 2. SEM/EDS Images of Oxide Islands on MARB2

Figure 3. SEM/EDS Images of Oxide Islands on 304H

It is also interesting to note in Table 1 that the Ni-based alloys that contain significant Al concentrations (CCA617, Alloy 230 and Alloy 740) experienced intergranular oxide penetrations of approximately 15 μ m, as shown in Figure 4. Ni-based alloy HR6W, which does not contain Al, did not exhibit these penetrations. The EDS spectra displayed in Figure 4 provides definitive evidence that these penetrations are associated with Al. Formation of this penetration raises potential concerns about the long term mechanical properties of these materials at temperatures around 800°C.

Figure 4. Intergranular Aluminum Oxide Penetrations in Alloy 740

The Ni-based materials that contained the highest Al concentration (Alloy 214; 4.43% Al) exhibited, by far, the lowest descaled weight loss of any material tested. The SEM/EDS results from this material (Figure 5), indicates that this material forms an aluminum oxide instead of a chromium oxide. This material also experienced no intergranular oxide penetrations. The results from this material thus far suggest that an aluminum oxide is more stable and/or protective than a chromium oxide under these conditions.

Figure 5. Aluminum Oxide Formation on Alloy 214

Concerns:

Due to funding uncertainties and current facility unavailability, the start of the next exposure at 800°C will not be started until the 2nd quarter of GFY05.

Activities Next Quarter:

Preparations will be made for the second exposure at 800°C. Specimens from any new materials will be prepared, cleaned, measured, weighed and attached to the test rack prior to the second exposure.

Task 3B Coating Tests

Background:

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

Experimental:

The SEM/EDS results for coated materials that were exposed for 1,000 hours at 800°C are presented below.

Figure 6. SEM/EDS Images of Cr-Coated S304H

Figure 7. SEM/EDS Images of AlCr-Coated S304H

Figure 8. SEM/EDS Images of SiCr-Coated S304H

From the images in Figure 6, it appears that the CrS304H specimen has formed a surface oxide composed entirely of chromium. The base metal immediately below the chromium oxide is enriched in iron and nickel, and depleted in chromium. For the

AlCrS304H material shown in Figure 7, the oxide contains a mixture of aluminum, chromium, iron, nickel and copper. The outer oxide that formed on the SiCrS304H shown in Figure 8 was composed of chromium and displayed a chromium depleted zone in the base metal beneath this oxide.

The thickness of the oxides that formed on the coated materials after a 1,000 hour exposure at 800°C is shown in Table 2, along with the descaled weight loss that was previously reported.

TABLE 2
Oxide Thickness of Coated Materials After 1,000 Hours at 800°C

Material	Oxide Thickness (µm)	Descaled Weight Loss after 1000 Hours (mg/cm²)
CrS304H	7	3.281
AlCrS304H	50	72.026
SiCrS304H	4	2.267

The oxide compositions, thickness and descaled weight loss results suggest that the CrS304H and SiCrS304H formed more protective oxides in this environment than the AlCrS304H material.

Concerns:

None.

Activities Next Quarter:

Prepare for next 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:

Initial activation energy calculations based on 1,000 hour results at 650°C and 800°C were presented previously. Additional progress will be made as test results become available.

Concerns:

None.

Activities Next Quarter:

None.

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 July and August, 2004.

A technical paper for the 8th UltraSteel Workshop in Tsukuba, Japan was presented in July 2004.

The Steering Committee Meeting for the USC project was attended in August in Columbus, Ohio.

A technical paper for the Hilton Head Conference in October, 2004 was prepared. The presentation for this paper was also prepared and submitted.

Concerns:

None.

Activities Next Quarter:

Monthly status reports will be written for October and November. The Quarterly report for the July - September, 2004 timeframe will be prepared.

A technical paper will be presented in October, 2004 at the 4th International Conference on Advances in Materials Technology for Fossil Power Plants in Hilton Head, SC.

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.

Concerns:

None.

Activities Next Quarter:

None.

Task 3F Characterization

Background:

Samples of the model Fe-Cr alloys fabricated in Task 3E will be characterized before and after steamside oxidation testing using metallographic and electron optic techniques.

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

Objectives:

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 1000-hour exposure for the first series of laboratory testing was completed. The test temperatures were 975°F for waterwall conditions and 1500°F for superheater/-reheater conditions. (Note: The deposit and flue gas compositions, representing eastern, midwestern, and western fuels, used in the tests were reported in the January – March Quarterly report.) The third series of testing, which is being performed at 1100°F for waterwall conditions and 1300°F for superheater/reheater conditions, also commenced. At the end of the quarter, 800 hours of testing in this series was completed.

The post test analysis of the 850°F waterwall and 1200°F superheater/reheater specimens was completed. The results of the Total Metal Wastage (wall loss plus subsurface penetration) of the superheater/reheater and waterwall specimens in 1000 hours are shown in Figures 1 and 2, respectively.

The post-test analysis of the 1500°F superheater/reheater and the 975°F waterwall specimens was started. Preliminary wastage results in 1000 hours are shown in Figures 3 and 4, respectively. [Note: The microscopic examination of all of the specimens has not been completed.] One observation that was noted in the former was the effect of molybdenum (Mo) on corrosion behavior, particularly in the samples tested under the Midwestern conditions, which are the most aggressive. Figure 5 illustrates the results of five samples with varying Mo content tested under the Midwestern conditions. In the case of the CCA617 (9Mo) and 263 (5.8Mo) samples, the coupon was essentially

consumed in the 1000-hour exposure, while the 622 weld overlay (12Mo) and the 230 (1.3Mo) samples exhibited appreciable attack. The 740 sample, which had the lowest Mo (0.5Mo) content of the five, displayed the least attack, but suffered more wastage than the other 25Cr materials that do not contain Mo.

Figure 6 illustrates extensive subsurface sulfidation that accompanied the thickness loss in the 263 and 622-weld overlay samples, while Figure 7 shows that the attack in the 230 and 740 samples was in the form of subsurface sulfidation/oxidation. In the case of sample 230, the attack was primarily intergranular. In contrast, the 22-25Cr alloys that did not contain Mo developed a thin scale on the surface and experienced scattered subsurface sulfidation as shown in Figure 8 in the HR3C and HR6W samples. (Note: The photomicrographs presented in Figure 8 are at higher magnification than those shown in Figures 6 and 7.)

Regarding the 1500°F results of the superheater/reheater samples, preliminary comments are:

- The 214 alloy (16Cr, 76Ni, 4.5Al) suffered extensive wastage under the eastern and Midwestern conditions.
- Under Midwestern conditions, the Mo-containing alloys experienced more attack than the alloys without Mo; the higher the Mo content, the greater the wastage.
- The Mo factor aside, the 18-20Cr alloys displayed more wastage than the 21-27Cr alloys.
- Of the weld overlays, the 622 (typically 21Cr) material experienced significant wastage (because of the aforementioned Mo effect) under the eastern and Midwestern conditions. While the 52 (typically 28Cr) and 72 (typically 42Cr) displayed similar thickness loss, the 52 overlay exhibited more widespread subsurface penetration than the 72 overlay as shown in Figure 9.
- The 50/50 laser clad exhibited notable subsurface attack under the Midwestern and eastern conditions as also illustrated in Figure 9.
- With regard to the diffusion coatings, the FeCr and SiCr coatings performed better than the AlCr coating, which exhibited extensive subsurface attack (see Figure 10).

Concerns:

No concerns at this time.

Plans for Next Quarter:

- Finish 1000-hour cycle at 1100°F for waterwall samples and 1300°F for superheater/reheater samples.
- Finish analyzing specimens from first 1000-hour cycle and start analyzing specimens from the third 1000-hour cycle.

- Start fourth 1000-hour test cycle for superheater/reheater.

Figure 1: The results of the Total Metal Wastage (wall loss plus subsurface penetration) of the 1200°F superheater/reheater specimens in 1000 hours are shown.

Total Metal Wastage (Loss + Penetration at 850°F WW Condition)

Figure 2: The results of the Total Metal Wastage of the 850°F waterwall specimens in 1000 hours are presented.

Figure 4: The preliminary results of the Total Metal Wastage of the 975°F waterwall specimens in 1000 hours are illustrated.

Figure 5: The appearance of five specimens with varying Mo contents are displayed after 1000 hours at 1500°F under Midwestern conditions. The presence of Mo in the material appeared to have a detrimental effect on corrosion resistance.

Figure 6: Extensive subsurface penetration in the Nimonic 263 alloy (top) and 622 weld overlay (bottom) is shown in specimens tested for 1000 hours at 1500°F under Midwestern (263) and eastern (622) conditions.

Figure 7: Subsurface attack is illustrated in the 230 (top) and 740 (bottom) specimens after 1000 hours at 1500°F under Midwestern conditions.

Figure 8: The HR6W (top) and HR3C (bottom) specimens after 1000 hours at 1500°F under Midwestern conditions exhibited a thin surface scale and scattered subsurface penetration.

Figure 9: After 1000 hours at 1500°F under Midwestern conditions, the 52 (top) and 72 (middle) overlay specimens contained a thin scale and exhibited subsurface penetration, which was more widespread in the 52 overlay. The 50/50 laser clad specimen (bottom) exhibited more subsurface attack than the weld overlays.

Figure 10: Of the diffusion coatings tested for 1000 hours at 1500°F under Midwestern conditions, the AlCr coating (top) suffered extensive subsurface attack, whereas the FeCr (middle) and SiCr (bottom) coatings contained thin surface scales.

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 assembly of the first four probe retraction mechanisms, as shown in Figure 11, has continued, along with the development of the related data acquisition, instrumentation and control systems. These retraction mechanisms will be installed at two coal-fired plants. The two plants that were selected for the initial installations were Cinergy Gibson Generating Station (Indiana) and Xcel Energy Pawnee Station (Colorado). Gibson is firing a high-sulfur Farmersburg coal, while Pawnee is firing a low-sulfur PRB (e.g., Eagle Butte) coal.
- Results of the recently completed 1500°F laboratory tests (Task 4A) require a re-thinking of materials selection for the probes. Modifications will have to be implemented in a more unique probe design, for each site, to prevent possible premature failures. New materials and equipment will need to be incorporated in the probe designs. This activity has a high priority and will need to be completed soon in order to maintain the planned 2-year testing schedule. Foster Wheeler is working closely with the host utility personnel to coordinate installation activities in order to minimize the overall schedule impact of any delays related to revised probe material selection.
- The re-design of the corrosion probe and support core, incorporating the overlay and coated samples, accounting for recent Task 4A results, is ongoing. The list of candidate probe materials to be tested is shown in Table 1. Fuel differences at each host site must be accounted for in the re-design effort. As an example of the unique probe designs that are being developed, the materials planned to be included in the initial Gibson Generating Station probe are shown in Table 2, for each temperature zone.
- Progress on Task 4B was presented at the August 2004 steering committee meeting. Feedback from the committee members has been incorporated into our ongoing efforts.

Concerns:

- The unexpected results recently obtained from the laboratory corrosion tests, performed in Task 4A, have required Foster Wheeler to re-evaluate the material

selection, and resulting probe design. Material availability issues may delay probe construction. The approved contractor at one host utility has work related to an outage at another unit that may impact schedule.

Plans for Next Quarter:

- Re-design and construct the corrosion probes, accounting for the results recently obtained from the laboratory corrosion tests performed in Task 4A.
- Complete the fabrication of the first four probe retraction mechanisms.
- Continue site installation tasks, coordinating with host utilities.
- Construct the instrumentation and controls systems.

Figure 11. Illustration of corrosion probe retraction mechanism.

Table 1: Probe Material List

Material	Cr	Ni	Co	Fe	Mo	W	Nb	Si	Al	Cu	Ti
Super 304H	18	9		68			0.4	0.23		3	
347 HFG	18.5	11		67			0.8	0.5			
800HT	21	31		45				0.4	0.3		0.6
NF709	22	25		48	1.5		0.25				<0.2
Sanicro 25	22	25	1.5	42		3.5	0.5	0.2		3.0	
CCA 617	22	52	12.5	<3	9.0			<1.0	1.2	<0.5	0.6
230	22	48	<5	<3	2.0	14		0.5	0.35		
SAVE 25	22.5	18.5		50		1.8	0.45	<1.5			
HR6W	23	40		25		6	<0.2	<1.0			<0.2
HR3C	25	20		51			0.4	<0.75			
740	25	48	20	0.7	0.5		2	0.5	0.9		1.8
HR120	25	37	3	35	2.5		0.7	0.6	0.1		0.1
45TM	27	46		23				2.8			
Sanicro 28	27	31		35	3.5			0.2		1.0	
AC66	27	32		39			0.8	0.2			
690	29	62		9							
33	33	31		32	1.4			0.3		0.6	

Table 2: Probe Materials Planned for Gibson Generating Station

No.	1200°F	1300°F	1400°F	1500°F	1600°F
1	HR6W	740	617	740	72WO
2	HR3C	617	230	HR3C	HR3C
3	S304H	230	740	72WO	52WO
4	SiCr Diffusion	FeCr Diffusion	FeCr Diffusion	52WO	HR6W
5	622WO	800HT	33WO	HR6W	602CA
Transition	HR3C	HR3C	HR3C	HR3C	HR3C

Task 4C Steam Loop Design, Construction, and Testing

Objectives:

The objectives of this sub-task are to design, build, and test two 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 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:

With regard to the test loop at the Reliant Plant:

- The two steam loops were installed in the unit – materials in the loop include 230, 740, CCA617, HR6W, Super 304H, RA333, Save12, and weld overlays 52, 72, and 622.
- The unit was restarted December 21, 2003. Steam loop has operated for the first nine months at metal temperatures below the maximum target temperature of 1400°F due to thermocouple problems and a failure of an attemperator fitting. In addition, it was previously reported that as a result of over-fire air (for ozone control) and the cooler gas temperature at the furnace exit, the maximum target temperature of the sections would be difficult to obtain until September when the ozone restriction is lifted. (If there are no major problems with the loop after the 18 month exposure period, consideration may be given to extend the exposure time to achieve an 18 month period at the maximum target temperature.)
- On September 28, the unit was shut down for a two-week outage (unrelated to the project). The loops, shown in Figure 12, were inspected visually to identify any problems and OD measurements were made with calipers to assess wastage as illustrated in Figure 13. The specimens were found to be in excellent condition with no signs of apparent degradation or wastage during the initial 9 months of testing (much of which was not at temperature due to equipment problems). However, the support lugs at the lower bends of both loops had detached from the baffle wall, allowing some lateral movement. The support lugs at the upper bends remained sturdy and intact. The diametric measurements at selected locations of both upper

and lower sections of each loop showed no indications of wastage as shown in Figure 14. With completion of the maintenance in early October, the boiler will be restarted and the overfire air will be adjusted to allow operation of the test loops at the desired conditions where metal temperatures up to 1425°F should be established

Concerns:

None.

Plans for Next Quarter:

- Continue to monitor operation and collect data
- Repair the shorted thermocouple

Figure 12: The appearance of the test loops in the Niles plant during the September outage is shown.

Figure 13: Inspection of the test loops during the September outage involved obtaining OD measurements to assess the metal wastage for the nine months of operation.

Figure 14: OD measurements for different sections of the test loops are indicated.

Task 5 Welding Development (Alstom)

Objectives:

The major objectives for Task 5: Welding Development are:

- 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:

- A gas tungsten arc welding process was developed and qualified for butt joints in the 2-inch OD x 0.400-inch MWT tubes cut from the SAVE 12 piping. A Grade 92 filler metal, similar to P92 base material, was used and the tubes were normalized and tempered before welding, as recommended by Sumitomo.
- The qualification of welding processes for butt joints in the 2-inch OD x 0.400-inch MWT tubes using the custom SAVE12 weld filler materials was also attempted. Samples using a gas tungsten arc process passed radiographic testing but failed the bend tests. Similarly, samples using a gas tungsten arc root and a shielded metal arc fill process passed radiographic tests but failed in bend testing. The

microstructures and hardnesses of the weldments are being studied in order to help identify the problems and plan process changes.

HR6W:

- Gas tungsten arc welding processes were developed and qualified for butt joints in HR6W 2-inch OD x 0.400-inch MWT tubes using Inconel 617 and Inconel 82 filler materials. The WPS and PQR for each of the welding processes were also prepared.
- Attempts were made to develop weld processes for butt joints in HR6W tubes using the custom HR6W fillers. Joints prepared with a gas tungsten arc process passed radiographic testing but failed bending tests and also had low tensile strengths. Joints using a gas tungsten arc root and a shielded metal arc fill process failed radiographic testing and were not evaluated further. It was found that the custom filler material for the shielded metal arc welding did not run smoothly and more investigation of these filler materials is required.

Inconel 740:

- A weld on thin Inconel 740 plate using a gas metal arc process and matching filler was made by Special Metals to investigate the effect of shield gas on heat affected zone microfissures. The test was successful in that no microfissures were detected, however the 2T bend test of an aged weld failed. Overaging of welds was then attempted and this procedure provided additional ductility and allowed the specimens to pass a 2T bend.
- Nimonic 263 filler was also tried with good results in the overaged condition. This filler has advantages over Inconel 740 in that less surface oxidation occurs, which makes post-weld cleaning easier. Use of this filler is an option worth considering for future work.

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.

Plans for the Next Quarter:

- Continue qualification efforts on SAVE 12 tube butt weld processes using matching filler metals. The heavy wall welding of the 13.78-inch OD x 2-inch MWT SAVE12 pipe will be attempted if the tube process qualification is successful.
- Continue qualification efforts on HR6W tube butt weld processes using matching filler metals.
- Determine efforts required to develop a gas metal arc welding process using Type 347 filler to make butt joints in Super 304H tubing.
- Continue to study problems with shielded metal arc welding of CCA 617 thick plates.
- Make welds in thin Inconel 740 plates using mixed gases to try to get the benefits of both argon and helium.

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:

HR6W:

- Tube butt joint samples were prepared using the gas tungsten arc process that had been qualified using Inconel 617 filler material and the samples were shipped to ORNL for testing.
- Tube butt joint samples were prepared using the gas tungsten arc process that had been qualified using Inconel 82 filler material and the samples were shipped to ORNL for testing.

SAVE 12:

Tube butt joint samples were prepared using the gas tungsten arc process that had been qualified using Grade 92 filler material and the samples were shipped to ORNL for testing.

Concerns:

None.

Plans for the Next Quarter:

None.

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.

Progress for the Quarter:

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. Therefore, Edison Welding Institute was commissioned to conduct these studies and a workscope and schedule have been established. Bar stock for the research was solution annealed and quenched by Special Metals and then delivered to Edison Welding Institute.

Concerns:

None.

Plans for the Next Quarter:

Monitor the program at Edison Welding Institute.

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 Grade 91 tubing and a gas tungsten arc process were completed and shipped to ORNL for the Task 2 testing.
- A gas tungsten arc process for making dissimilar metal weld butt joints between CCA 617 and Super 304H tubing was developed and two-thirds of the required test samples have been prepared

Concerns:

None.

Plans for the Next Quarter:

- Complete CCA 617/Super 304H test samples.
- Begin work to qualify a dissimilar metal joint between the HR6W and SAVE12 tubing.

Task 5: Welding Development - Milestone Chart
(DOE Fiscal Year Basis)
(percentages indicate fraction of workscope completed as of 2004Q4)

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.					75%								▲							
						75%								▲							
5C	Preparation of Laboratory Samples • Material preparation. • Sample fabrication.					75%								▲							
						75%								▲							
5D	Weldability Testing									▲				0%							
5E	Examination of Dissimilar Metal Welds. • Weld trials • Metallurgical analysis • Analysis and test case.									30%				▲							
										0%				▲							
										0%				▲							

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.

Accomplishments Versus Expenditures (Alstom)

Task 6 Fabrication (B & W)

Objectives:

The objective of Task 6 is to establish boiler fabrication guidelines for the high temperature, 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.

- The fabrication development plans established by Riley Power Inc. for the evaluation of the HR6W and SAVE12 were delayed this quarter due to other business obligations requiring extended foreign travel.
- Riley Power Inc. is currently working with Foster Wheeler who has been subcontracted to conduct controlled strain/recrystallization studies of HR6W and SAVE12 materials

Concerns:

None.

Plans for the Next Quarter:

- During the next quarter Riley plans to swage the 2" OD HR6W and SAVE12 tubing after machining the ID of samples to establish a mean wall thickness of 0.200".
- Pending review of the project budget, Riley is 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.

- Fourteen sets of tapered tube samples have been prepared for metallurgical examinations. These include seven sets from each of the CCA 617 and Super 304H tubing materials and represent the as-formed conditions as well as 1, 10, and 100-

hour exposures at 1300F and 1400F for the Super 304H and 1400F and 1500F for the CCA 617.

- Construction was started on a mockup to demonstrate the progress that has been made while studying the fabricability of the CCA 617 and Super 304H materials. Two-inch thick CCA 617 plate was formed to simulate a header shape and drilled to accept nipples. CCA 617 and Super 304H tubing sections were bent into typical nipple configurations and welded into the header. Additional features, including a swaged tube section and a dissimilar metal weld, are also being prepared.

Concerns:

None.

Plans for the Next Quarter:

- Make the series of Super 304H and CCA 617 U-bend specimens required for Task 2 testing.
- Complete the examination of the tapered tubes used for the cold working studies.
- Determine the sensitivity of Super 304H to strain induced embrittlement.
- Complete the demonstration mockup.

Progress for the Quarter: Foster Wheeler

Recrystallization Study:

- We characterized the strained 740 and 230 samples that were exposed to 1500°F for 100 hours. The characterization consisted of a microhardness survey and documentation of the microstructure at each of the ten gage marks representing different levels of strain. No recrystallization was evident in either sample. In this regard, Figures 1 and 2 presented below respectively show a comparison of the microstructures at the location of highest strain in the as-strained and strained/thermally-exposed 740 and 230 samples. If recrystallization had occurred during the thermal exposure, it would have done so at this location. While no recrystallization is apparent in the microstructures, there is evidence of a fine precipitate that developed during the thermal exposure in the strained matrix of the 230 sample (Figure 2).
- Based on the results of the 1500°F/100 hour exposure, a conference call was held among representatives of B&W, FW, and Haynes. Dr. Dwaine Klarstrom of Haynes was not surprised that recrystallization had not occurred at the 1500°F/100 hour thermal exposure and suggested a 1600°F/100 hour exposure be conducted. This exposure was performed, and the samples were prepared for metallurgical

examination and hardness testing. Analysis of the exposed samples is planned in October.

Figure 1

Top: 740 - As-strained

Bottom: 740 - Strained and thermally exposed (1500°F for 100 hours)

Figure 2

Top: 230 - As-strained

Bottom: 230 - Strained and thermally exposed (1500°F for 100 hours)

Fabrication of 740:

- Special Metals (SM) tried twice to re-solution anneal the 740 tubing in order to minimize the hardness differential around the circumference in the as-supplied tubing. To summarize, the as-supplied tubing exhibits a hardness differential of 11 points HRB around the circumference (84-95 HRB). The hardest zone comprises a small arc of the circumference, approximately 60 degrees, and extends along the length of the tubes. According to SM, the hard zone is believed to have developed as a result of a slower cool in this region compared to the rest of the circumference; the slower cool promoting the formation of a phase (probably gamma prime) and, therefore, resulting in the higher hardness. Since the effect of the hardness/strength variation around the circumference on making the cold U-bends is unknown, one length of tubing was sent to Special Metals for re-solution annealing. While both re-solution annealing attempts by SM minimized the hardness differential around the circumference, the final hardness of the tube was higher than desired, i.e., in the 95-102 HRB range compared to a target hardness in the high 80's/low 90's HRB. SM then concluded that the as-supplied material is the best condition they could currently provide.
- The status of the 740 tubing was stated in an September 24 e-mail to various members of the consortium along with possible avenues on how to proceed with the bending trials. Suggestions, comments, and other possible alternatives were asked for.

Concerns:

None.

Plans for the Next Quarter:

- Next quarter, FW plans to complete the characterization of the 230 strained materials after the 1600°F/100 hour exposure. FW also plans to perform a first thermal exposure (temperature/time conditions not yet established) on the HR6W and SAVE 12 strained material and to characterize the resulting microhardness and microstructure. After assessing the data, a second thermal exposure of these materials will be planned and conducted.

Progress for the Quarter: B&W

- Six alloy 230 tube samples, 18 inches in length, were ID machined to establish a 0.2" thin wall in preparation for swaging trials this fall at B&W's production facility in Cambridge.
- A telephone conference among Dr. Dwaine Klarstrom (Haynes International), Greg Stanko (FW), Jim Tanzosh (B&W), and Walt Mohn (B&W) was held September 14th to discuss results of a 1500°F/100 hour thermal exposure trial with Alloy 230 as part of the controlled strain/recrystallization/precipitation studies that B&W has

subcontracted to Foster Wheeler. No recrystallization was observed in the microstructures at these conditions, so another trial has been conducted at 1600°F/100 hours in accordance with Dr. Klarstrom's recommendation. Microstructures of these thermally exposed specimens are currently being analyzed.

- Metallurgical samples of alloy 230 cold U-bends with strains of 13.3%, 20%, and 33.3% were cut and analyzed for wall thickness and ovality. Ovality is the distortion of the cross section of a tube from its normal (round) shape, usually expressed as a percentage of the difference between the major and minor axes of the starting material compared to the OD before bending.

Figure 3 Digital image (left) showing the three sizes of Alloy 230 U-bends produced in a B&W production facility and sketch (right) showing the 0°, 45°, and 90° locations (with respect to the clamp end) where cross-sectional ring specimens were cut for measurements of wall thickness and ovality. Baseline tubing was 2.00" OD, with measured wall thickness ranging from 0.429" to 0.442".

U-bend Percent Strain = $100r/R$, where r = nominal outside radius of tube and R = nominal bending radius to centerline of tube, as outlined in ASTM Boiler & Pressure Vessel Code, Section I, PG-19.

Table 1
Wall Thickness Measurements of Cross-Sectional Ring Specimens
Cut from the 0°, 45°, and 90° Locations of Alloy 230 Cold U-Bends
Produced with 13.3%, 20%, and 33.3% Strains

Specimen Location (see Fig. 1)	13.3% Strain (Wall Thicknesses)	20% Strain (Wall Thicknesses)	33.3% Strain (Wall Thicknesses)
0°			
45°			
90°			

Top of each ring specimen coincides with the extrados of the U-bend.

Processing parameters for Alloy 230 U-bends in these initial trials were not optimized.

Figure 3 Digital micrograph showing the baseline microstructure (before bending) of alloy 230 tubing in the solution annealed condition.

Etchant: 10 ml nitric, 10 ml acetic, 15 ml hydrochloric, 2-5 drops glycerol

Table 2
Diametric Measurements and Ovality Calculations for the
Alloy 230 Cold U-Bend Produced with 13.3% Strain

OVALITY DATA				
PROJECT #: 085EZE7670EN				
CUSTOMER: USC				
MATERIAL SPECIFICATION: Haynes 230 15% R-7.5				
DATE:		RECORDED BY: D.Zeigler		
Sample Number	Nominal Dia.	Maximum Dia.	Minimum Dia.	% Ovality
0 deg	2.0	2.004	1.996	.4
10 deg	2.0	2.006	1.984	1.1
20 deg	2.0	2.005	1.966	1.95
30 deg	2.0	2.005	1.967	1.90
40 deg	2.0	2.003	1.974	1.45
50 deg	2.0	2.005	1.969	1.8
60 deg	2.0	2.007	1.972	1.75
70 deg	2.0	2.002	1.973	1.45
80 deg	2.0	2.005	1.971	1.70
90 deg	2.0	2.005	1.972	1.65
Comments:				

Processing parameters for Alloy 230 U-bends in these initial trials were not optimized.

Table 3
Diametric Measurements and Ovality Calculations for the
Alloy 230 Cold U-Bend Produced with 20% Strain

OVALITY DATA				
PROJECT #: 085EZE7670EN				
CUSTOMER: USC				
MATERIAL SPECIFICATION: Haynes 230 20% R=5.0"				
DATE:		RECORDED BY: D.Zeigler		
Sample Number	Nominal Dia.	Maximum Dia.	Minimum Dia.	% Ovality
0 deg	2.0	2.005	2.005	0
10 deg	2.0	2.009	2.001	.4
20 deg	2.0	2.016	1.982	1.7
30 deg	2.0	2.004	1.949	2.75
40 deg	2.0	2.000	1.948	2.6
50 deg	2.0	2.005	1.950	2.75
60 deg	2.0	2.003	1.945	2.9
70 deg	2.0	2.001	1.949	2.6
80 deg	2.0	2.009	1.948	2.95
90 deg	2.0	2.007	1.950	2.85
Comments:				

Processing parameters for Alloy 230 U-bends in these initial trials were not optimized.

Table 4
Diametric Measurements and Ovality Calculations for the
Alloy 230 Cold U-Bend Produced with 33.3% Strain

OVALITY DATA				
PROJECT #: 085EZE7670EN				
CUSTOMER: USC				
MATERIAL SPECIFICATION: Haynes 230 U-Bend 33%,R=3.0"				
DATE:		RECORDED BY: D.Zeigler		
Sample Number	Nominal Dia.	Maximum Dia.	Minimum Dia.	% Ovality
0 deg	2.0	2.006	2.000	.3
10 deg	2.0	2.008	1.993	.75
20 deg	2.0	2.016	1.986	1.5
30 deg	2.0	2.020	1.957	3.15
40 deg	2.0	2.022	1.934	4.4
50 deg	2.0	2.024	1.889	6.75
60 deg	2.0	2.030	1.868	8.1
70 deg	2.0	2.043	1.857	9.3
80 deg	2.0	2.059	1.845	10.7
90 deg	2.0	2.068	1.827	12.05
Comments:				

Processing parameters for Alloy 230 U-bends in these initial trials were not optimized, and ovality of bends could be significantly reduced.

- The design for an Alloy 230 (fabrication) demonstration article was refined and completed, and procurement of materials and subcomponents for construction was initiated.

Concerns:

- Completion of B&W's Task 6 activities in accordance with the originally planned schedule is strongly dependent on timely appropriation and distribution of project funding for GFY 2005.

Plans for the Next Quarter:

- Microstructures of alloy 230 bends (extrados, neutral axis, and intrados) will be examined, characterized, and compared to microstructures produced in the controlled strain/recrystallization/precipitation studies.
- Swaging trials with Alloy 230 tubes machined to 2" OD X 0.200MW are planned.
- Construction of an Alloy 230 (fabrication) demonstration article will begin.

TABLE 6
Schedule and Progress

ID	Task Name	Start	Finish	Status	2000				2001				2002				2003				2004				2005				2006	
					Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2
2	6A: Fab Trials for SH	Mon 2/4/02	Fri 12/31/04	In Progress																										
3	6A.1 SH Trial	Tue 1/1/02	Fri 12/31/04	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	Fri 12/31/04	In Progress																										
7	Cold Bending Trials	Mon 6/2/03	Fri 12/31/04	In Progress																										
8	Cold Swaging Trials	Mon 6/2/03	Fri 12/31/04	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	Fri 12/3/04	In Progress																										
12	6A.3 SH: Met Test & Eval	Fri 1/9/04	Fri 12/31/04	In Progress																										
13	6A.3.1 Mic Bends&Welds	Fri 6/4/04	Fri 12/31/04	In Progress																										
14	6A.3.2 HT Studies&Mic	Fri 6/4/04	Fri 12/31/04	In Progress																										
15	6B: Fab Thk Wall Comp	Thu 2/6/03	Thu 5/5/05	In Progress																										
16	6B.1 Thick-Wall Fab Trial	Fri 1/9/04	Fri 12/31/04	In Progress																										
17	6B.2 Reporting	Fri 1/9/04	Thu 3/31/05	In Progress																										
18	6B.3 Thick-Wall Comp	Fri 1/9/04	Fri 12/31/04	In Progress																										
19	6B.3.1 Met Analysis	Mon 1/3/05	Thu 5/5/05	Planned																										
20	6B.3.2 PWHT Studies&Mic	Wed 9/29/04	Fri 12/31/04	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 7F: Process Optimization

Objective:

Perform coating process optimization at an intermediate scale between laboratory and commercial size.

Progress for the Quarter:

Part 1: B&W Effort

Activity reported under Task 7H.

Part 2: Alstom Effort

Testing efforts completed this quarter; sample evaluations still in progress. Quarterly activity is reported in detail in Appendix 1 to this report.

Concerns:

Availability of released funds to support Task 7 activities at B&W and ALSTOM is a concern.

Activities Planned for Next Quarter:

Complete detailed analysis of sample specimens.

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:

- Weld-clad (B&W) and diffusion coated (ALSTOM) samples were supplied to Foster Wheeler for inclusion in the Task 4 corrosion probes.
- Sample coupons coated with “Nanocomp” were procured from Nanovations Inc. and supplied to Foster Wheeler for inclusion in the Task 4 laboratory evaluations. The coating is intended to reduce corrosion and shed ash deposits.

Concerns:

None.

Plans for the Next Quarter:

None at this time.

Task Name	Status	2002				2003				2004				2005				2006			
		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	Qtr 1	Qtr 2	Qtr 3	
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	100%																				
B&W Task 7E: Process Scale Up - Preliminary Trials	87%																				
Task 7F: Process Optimization																					
Alstom Task 7F: Process Optimization	70%																				
B&W Task 7F: Process Optimization	87%																				
Task 7G: Manufacturing Recommendations																					
Alstom Task 7G: Manufacturing Recommendations																					
B&W Task 7G: Manufacturing Recommendations	30%																				
Task 7H: Specimens for Field Corrosion/Oxidation																					
Alstom Task 7H: Specimens for Field Corrosion/Oxidation	75%																				
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

Appendix 1

Diffusion Coating Progress Report (Alstom Power Inc.)

Introduction

The optimization tests scheduled within task 7F were completed in September 2004. The objective of this task was to optimize the processing conditions required to generate ID diffusion layers of adequate thickness and composition. The commercial targets are a diffusion layer with a minimum thickness of 10 mil with a maximum Cr-content greater than 25 wt% and a Si-concentration of at least 2 wt% through the layer thickness. A total of five tests were conducted utilizing waterwall panels constructed with T-11 tubing. Two diffusion-coating formulations were tested including chromizing and the Si-Cr pack cementation formulation. Table 1 lists the compositions for the pack powders used to coat the ID of the T-11 tubing.

Process	Powder Formulation
Chromizing	30 % Cr 3 % NH ₄ Cl Bal. Al ₂ O ₃
Si-Cr	3 % Si, 30 % Cr 1 % NH ₄ Cl, 1 % CaF ₂ Bal. Al ₂ O ₃

Table 1. Pack-powder formulations used to generate ID diffusion layers.

The proprietary commercial formulation of ALSTOM Power was modified for the ID coating chromizing tests while the Si-Cr pack cementation formulation was based on the patent # 5,972,429 by Bayer & Wynn's. Although the preliminary test matrix was completed as scheduled, the subsequent metallographic analyses have not been completed yet. This report will summarize the results from the first three tests.

Experimental:

The scale-up tests were conducted using waterwall panels constructed with T-11 material. The test panels were four (4)-ft long and thermocouples were strategically attached to each test panel to monitor the heating characteristics of the pack. The tubular components and a relatively small amount of pack powder were assembled in a steel retort that was sealed with a welded lid with a vent for the gases produced during the decomposition of the activator system. The exhaust pipe was continuously purged

with Nitrogen gas to prevent condensation and subsequent plugging. The joint of the Nitrogen lance to the exhaust pipe was heated to 200 F using a heat mantel. A wall-fired gas furnace was utilized to conduct the tests. The temperature of the pack was recorded using an analog reader coupled with a digital converter to store the data in a lap top computer.

Selected tubing in the test panels were packed with powder. These pieces of tubing had thermocouples attached at various locations along the length of the test panel. The hold time for these tests was 16 hours. All tests were conducted with a single temperature excursion. Hold time was initiated when the cooler thermocouple in the assembly reached 2040 F. The heating characteristics of the retort were controlled to avoid temperatures in excess of 2100 F for any significant length of time. The target hold temperature for both coating systems was between 2060 and 2080 F. Modifications to the test facilities and adjustments to processing parameters were implemented as needed. The objective of these tests was to define the optimum processing conditions to generate a consistent product. The tests began using the chromizing formulation followed by the Si-Cr. The test matrix included a limited number of tests where the OD was coated using arrangements different from conventional pack powder systems.

Results:

Although there is no sufficient experimental data to define coating requirements for steam-side applications, those currently imposed by fireside corrosion will be used as a baseline. For ferritic alloys the desirable thickness should be equal or greater than 10 mils. Within subtask 7F we were interested in learning if the ID of tubing could be coated without the requirement of OD pack powder. The OD pack powder offers the advantage of supporting the components to be coated. In the absence of OD pack powder, waterwall panels can be supported placing calcined alumina powder in between panels. A layer of calcined alumina 1" thick was required to minimize warping and to avoid metal-to-metal contact at the tubing crowns.

The amount of OD powder was decreased by 2/3rds impacting favorably the heat up and cool down rates with a 25 % reduction in overall processing time, Figure 1. During the heat up, the temperature spread was as low as 20 F. However, during the first test very little or no ID coating was generated. It was apparent that during heat up the ID pack was exhausted and the gases responsible for the coating growth were diluted into the "empty" retort. During the subsequent test 100 lb of a chromizing formulation were added to the retort to generate a positive pressure enough to maintain an adequate $\text{CrCl}_2(\text{g})$ vapor pressure to minimize the loss of ID throwing power. The metallographic work indicated that the ID coating chemistry and thickness varied along the length of the test panel, Figure 2. The ID layers formed toward the center of the tubing pieces had an adequate Cr-content and the appearance was typical of a good diffusion layer, Figure 3. The diffusion layer toward the tubing ends had a maximum Cr-content below 20 wt% with Kirkendal porosity extending almost halfway through the layer, Figure 4. The ID formulation was intended to generate a Si-Cr layer. The Si-content remained

above 2 wt% through the coating thickness. During these two tests the end of the tubing pieces were closed using high temperature tape as it was done during the scale-up tests of phase 7D.

During the third test, the ID packed tubing pieces were end capped. Two hundred fifty pounds of OD chromizing pack powder were used during this test arranged in between selected panels to provide support and to explore the possibility of OD single-sided coated panels. The thickness of the ID layers averaged 10 mil regardless of the location along the length of the test panel, Figure 5. Figure 6 depicts the average Cr-content as a function of temperature. Figure 7 compares the Cr-concentration ID profiles between test #3 and a typical full packed chromizing run from task 7E. The major difference resides in the overall thickness of the layer. Both profiles reflect the formation of a Cr-N-C surface layer with the Cr-content in excess of 20wt% below this surface layer. Temperature and time are the major parameters determining the thickness of the diffusion layer. The comparison provided in Figure 7 is for the same processing temperature and time. No clear argument can be raised to explain the difference in thickness apart from the possible variation in the vapor pressures for the vapor species responsible for the generation of the coating. Another possible argument might be the base metal. The alloy T-92 was used during the scale-up tests in Task 7E. However, the preliminary laboratory data did not indicate any significant differences among the ferritic alloys based on substrate chemistry. Test #4, not reported here, is the reproducibility test for this condition. Evaluation of that load has not been completed yet and the results should be available for the monthly report of October 2004.

During test # 3, the OD pack was used in between selected panels to explore the feasibility of one-side chromizing OD panels. The appearance of the layer is shown in Figure 8 while the composition profile is depicted in Figure 9. By comparison, the layer formed in the OD of alloy T-92 was almost twice as thick.

A similar arrangement was used for test # 4. The reproducibility of the data will be reported in October 2004. Both alloys formed a surface Cr-N-C layer and the Cr-content below the layer exceeded 20 wt%.

Conclusion:

A reduction in the OD pack powder results in an appreciable reduction in process time associated with faster heat-up and cooling rates.

ID diffusion layers of adequate thickness and composition can be achieved provided that the tubing pieces are end-capped.

The need of a given amount of OD pack powder is apparent to maintain adequate gradients in the vapor pressures of the gaseous species responsible for the growth of the diffusion layers.

One-side OD chromizing is feasible.

Figure 3: Appearance of the ID diffusion layer toward the center of the tubing.

Figure 4: Appearance of the ID diffusion layer toward the end of the tubing in the test panel.

Figure 5: Appearance of the ID chromized layer formed during test # 3.

Figure 8. Diffusion OD layer formed in alloy T-11.

Task 8 Design Methods and Data (Alstom)

Objectives for Task 8:

- 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:

- Work continues to confirm commitments from each participant.
- The Gantt chart for Task 8, showing the overall plan and progress to date is included at the end of this report.

Concerns:

Continued effort is ongoing to confirm commitments of each participant, update the project plan and develop curves to report scope completed as a function of spend.

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 accessed the USC material properties data transfer web site, maintained by ORNL. The currently available test results were downloaded for HR6W and SAVE12 materials, which are assigned to Riley. The results consist of four completed and one incomplete creep rupture test for HR6W. There are no test results available for SAVE12. Riley has plotted the curves for the completed creep test results, which are in the form of percent creep strain versus time to rupture, at given test temperature and stress values.

As previously reported by ORNL (5/26/04 conference call), the HR6W creep data appears to fall short of that expected for the longer term tests, with the actual times to rupture being considerably less than the expected life values. In addition, per the 4/1/04 meeting notes, John Shingledecker or ORNL has been discussing the creep testing results with Sumitomo, the material supplier. Sumitomo is developing an alternate heat of HR6W geared for enhanced creep performance for a European research program, and would send a sample of that heat to ORNL.

ALSTOM Power Inc. reviewed the available data for CCA617 and Super304H alloys. Both alloys are performing close to expectations. The CCA617 material exhibits enhanced strength compared to conventional IN617 at high stress but present data indicate that the strength at lower stress levels will merge with the IN617 data.

Further guidance was provided to Task 2 on testing to meet needs of Task 8. Specifically, ALSTOM met with Bob Swindeman of ORNL to discuss of test conditions for structural feature tests, both with and without welds

Concerns:

None.

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 structural feature tests that should commence in the next quarter.

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:

Funding issues for both ALSTOM and B&W hampered progress. Furthermore, only a few test results are presently available on the ORNL data transfer web site, which limits the progress that could be achieved. As reported in Task 8B, ALSTOM is actively supporting ORNL to ensure that the needs of Task 8 are met by the Task 2 test program. However, since structural feature (e.g. notched bar) tests are only now about to start then it is unlikely that significant progress will be made on this subtask for at least another six months.

Concerns:

Timely availability of creep data on ORNL web site and results of notched bar creep rupture tests. Availability of funds to support Task 8 activities at B&W and ALSTOM also remains a concern.

Plans for the Next Quarter:

Monitor material data web site to see if sufficient data is available to initiate a modeling activity.

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:

ALSTOM and Riley continued work on the literature review. Progress at ALSTOM was slowed by a temporary redistribution of project funding from Task 8 to other tasks for which supporting immediate progress as more critical.

Riley Power finalized the testing and assessment portion of the summary report on the weld literature review and submitted a draft version to ALSTOM for review and comment. This expanded version of the literature review contains added sections on creep crack growth and weld strength reduction factors. It also includes review summaries from a number of pertinent technical papers that were presented at the 2nd International Conference on the Integrity of High Temperature Welds in November 2003. This draft document, combined with the efforts at ALSTOM to address the analysis of welded components, represents significant progress toward meeting the

milestone of delivering a topical report on the issues and available methods for weld life assessment.

Concerns:

Resource problems at ALSTOM continue hampered progress on this activity.

Plans for the Next Quarter

ALSTOM will work on their portion of the weld literature review and work with Riley Power to issue the completed summary report. Riley will expand their contribution to include a discussion of thick wall thresholds and dissimilar metal welds.

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:

The revisions to Section I of ASME, to permit the use of simplified and more technically defensible design equations, were submitted to Subcommittee I and accepted by them on September 2, 2004. Subsequent to that, they were included in the Main Committee ballot. Feedback on the voting will come during the next couple of months and, if there are negative votes (which is likely) some additional effort will be required so that the motion can be resubmitted in December.

Concerns:

None.

Plans for the Next Quarter:

Address questions and issues raised by negative votes to support resubmittal of the proposed design equations at the December meeting.

Appendix A: Project Plan with Progress Identified

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 Task:

- Completed Third Quarterly Report for 2004.
- Completed Monthly Reports for July and August, 2004.
- Monthly conference calls were held and the discussions were documented.
- Work is ongoing on the EPRI Fourth International Conference on Advances in Materials Technology for Fossil Power Plants. This conference is being co-sponsored by DOE/OCDO and will include presentations on many of the developments from this project. The conference will be held at the Hilton Oceanfront Resort in Hilton Head Island, South Carolina on October 26-28, 2004.
- Papers have been accepted and a Conference Announcement has been distributed.
- Presented a review of the project at the Pittsburgh Coal Conference in Osaka Japan on September 16th.

Concerns:

None.

Plans for the Next Quarter:

- Conduct the Fourth International Conference on Advances in Materials Technology for Fossil Power Plants in Hilton Head, SC.
- Conduct a Steering Committee Meeting on December 8-9 in Columbus, Ohio.
- Issue monthly reports and hold conference calls as required.