BOILER MATERIALS FOR ULTRASUPERCRITICAL COAL POWER PLANTS

U.S. DOE NO.: DE-FG26-01NT41175

OCDO NO.: D-00-20

Fourth Quarterly Report for FY 2006 July 1 – September 30, 2006

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October 20, 2006

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Abstract

The U.S. Department of Energy (DOE) and the Ohio Coal Development Office (OCDO) have recently initiated a project aimed at identifying, evaluating, and qualifying the materials needed for the construction of the critical components of coal-fired boilers capable of operating at much higher efficiencies than current generation of supercritical plants. This increased efficiency is expected to be achieved principally through the use of ultrasupercritical steam conditions (USC). A limiting factor in this can be the materials of construction. The project goal is to assess/develop materials technology that will enable achieving turbine throttle steam conditions of 760°C (1400°F)/35 MPa (5000 psi). This goal seems achievable based on a preliminary assessment of material capabilities. The project is further intended to build further upon the alloy development and evaluation programs that have been carried out in Europe and Japan. Those programs have identified ferritic steels capable of meeting the strength requirements of USC plants up to approximately 620°C (1150°F) and nickel-based alloys suitable up to 700°C (1300°F). In this project, the maximum temperature capabilities of these and other available high-temperature alloys are being assessed to provide a basis for materials selection and application under a range of conditions prevailing in the boiler. This report provides a quarterly status report for the period of July 1 to September 30, 2006.

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Executive Summary

A. Project Objective

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

B. Background and Relevance

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

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

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

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

The project is based on an R&D plan developed by the Electric Power Research Institute (EPRI) that supplements the recommendations of several DOE workshops on

the subject of advanced materials. In view of the variety of skills and expertise required for the successful completion of the proposed work, a consortium that includes EPRI and the major domestic boiler manufacturers (Alstom Power, Babcock and Wilcox (a division of McDermott Technologies Inc.), Foster Wheeler, Riley Power Inc., and Oak Ridge National Labs) has been developed.

C. Project Tasks

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

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

D. Major Accomplishments during the Quarter

- Final analysis of the creep and rupture behavior of HR6W was completed.
- Creep rupture testing is complete for HR6W and Haynes 230.
- Microstructural evaluation of tube bends continues.
- CA617 weldments have shown a large reduction in strength compared to base metal for the SAW (submerged arc weld) process.
- New filler metals were recommended for welding of thick section SAVE12.
- The first 1,000 hr. steam side oxidation exposure at 750°C was completed.
- Correlations of steam side oxidation vs. chromium content were determined.
- Materials for the third air cooled corrosion probe have been machined and assembled.
- Steam cooled corrosion probes are operating as expected.
- Tube-to-tube welds were completed for many materials.
- ID Surface diffusion coating of boiler tubing work continued.
- A review of allowable stresses for many of the alloys was completed based on the most recent rupture tests.

- A continuum damage model was created for Inconel 740.

E. Plans for the Next Quarter

- The second 750°C oxidation exposure will be completed.
- Activation energies for the alloys will be re-calculated following the 750°C test.
- Monitoring of steam and air cooled corrosion probes will continue.
- Complete thick section Inconel 740 weldments.

F. Concerns

- Much of the materials characterization, including low cycle fatigue testing, has been slowed due to lack of funding of ORNL.
- The third air-cooled fireside corrosion probes are awaiting contract negotiations.
- Thick walled SAW welding of SAVE12 continues to be a challenge.
- Lack of ductility in filler metal used for Inconel 740 welds may require special treatment by Code bodies.

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:

None

Progress for the Next Quarter:

A final report has been completed and distributed.

Task 1C: Economic Analysis

Objective:

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

Progress for the Task:

A final report has been completed and distributed.

Concerns:

None

Task 2: Mechanical Properties of Advanced Alloys (ORNL)

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

Task 2A: Assessment of the Alloy Performance Requirements

Objectives

The primary objectives of this subtask are:

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

Progress

A presentation on the progress of Task 2 was given at the joint USC Steam Boiler and Steam Turbine meeting in August. This included the evaluation of tube bend ruptures and a final analysis on the creep and rupture behavior of HR6W. An invited presentation was given at the 8th Liege conference. This paper entitled, "Evaluation of the Materials Technology Required for a 760°C Power Steam Boiler," included some of the work being done at ORNL as part of the USC Steam Boiler Consortium. The work received the approval of the consortium for presentation and publication in the 3rd quarter of 2006.

Task 2B: Detailed Test Plan

Objectives

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

Progress

The characterization testing plans have been completed for the creep-rupture testing of Super 304H, HR6W, alloy 230, CCA617, and INCONEL 740. HR6W and Haynes 230

base metal testing is complete. Weldment test plans continue to evolve as new welded material (mainly thick section plate) becomes available. This quarter Inconel 740 tube bends were received and specimens machined. A test plan is being developed for testing next quarter. Additional planning is still required for Inconel 740 based on the code-case needs (which may be changing due to recent activities within the ASME B&PV code). Currently, two heats of three heats of Inconel 740 are being tested. At a minimum, stress-rupture data is still needed on a third heat of material, but this testing has been delayed in FY2006 due to funding.

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

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

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 of 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 major emphasis of the current creep-rupture testing is: (1) completing long-term creep-rupture tests, (2) producing the necessary creep data on three heats of Inconel 740 for a code case, and (3) evaluating the welding processes developed by the consortium for both tubing and thick-section materials through long-term stress-rupture testing of cross-weldments.

Creep tests are complete for HR6W and Haynes 230. Long-term tests in excess of 29,000 hour continue for CCA617 and Super 304H. Limited testing on SAVE12 is also

ongoing. Testing is also progressing on the INCONEL 740 tubing and plate. There exist some differences between the heats and heat treatments as well as differences with the AD700 reported data. The longest test times have reached approximately 10,000 hours and lower stress tests have been added to the matrix with expected rupture lives of 10,000 to 20,000 hours. All of these data were updated on the website in the second quarter of FY2006 and another update is planned for the early fourth quarter of 2007.

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

A significant number of microstructural evaluations were completed this quarter on tube bends. Current characterization work is focused on evaluating the microstructural changes during creep of Inconel 740. At the University of Cincinnati, gamma prime precipitate volume fraction as a function of time and temperature has been measured for crept specimens up to ~8,000 hours. The results agree well with thermodynamic models evaluated at ORNL.

Task 2E: Assessment of Creep-Fatigue Properties

Objective

The primary objectives of this task are:

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

Progress

LCF testing on Inconel 740 (Heat #BLT2819 - plate) was stopped this quarter due to mechanical difficulties with the induction heating unit. Due to funding considerations, the repair of the unit has been delayed.

Task 2F: Modeling of Weld Joints

Objectives

The primary objectives of this task are:

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

Progress

Testing is ongoing for the large cross-weld specimens from the SAW and SMAW CCA617 2" thick plate weldments. Rupture results at 700 and 750°C have shown a large reduction in strength compared to the base metal for the SAW, but the results from the SMAW have been within the scatterband for 617. A macro image of a recent rupture result on a SAW weldment is shown below. The rupture was near the centerline of the weldment.

Figure 1: Macro image of CCA617 SAW rupture. Rupture was in the weld metal and rupture time was below the scatterband for the 617 database and well below rupture time for CCA617.

Testing of butt-welded tubes of CCA617, Super304H, and CCA617 to Super304H continued this quarter. The cross-weld rupture results on the Super 304H to CCA617 DMW matched the rupture life predictions for Super 304H. All of the observed ruptures were in the Super 304H base metal. Haynes 230 ¼" thick welded plate tests continue as well. All results on Haynes 230 show that the Haynes 230 weld metal has 80% the strength of the base metal.

Riley contacted ORNL for assistance in helping resolve welding issues on thick section SAVE12. ORNL performed thermodynamic and solidification calculations and made recommendation to Riley. The details and data for this are included in the appendix. Based on this work, ORNL recommended reducing the W concentration of the SAVE12 weld metal; this should improve resistance to solidification cracking and reduce the tendency to retain delta ferrite.

Task 2G: Study of Accelerated Test Methods

Objectives

The primary objective of this task is:

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

Progress

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

Task 2H: Model Validation

Objectives

The primary objective of this task is:

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

Progress

Microstructural analysis for cavitation and recrystallization of pressurized creep experiments on Inconel 740 tube bends continue. Microstructural analysis on the first two ruptures were completed and presented to the consortium this quarter. The final tube ruptured this quarter and will be analyzed next quarter. Earlier tube bend ruptures on Haynes 230 showed that the current ASME B&PV Code rules will be conservative for solid solution nickel-based alloys.

Thermal shock testing on Super 304H continued beyond 6,000 cycles this quarter (max temp 700C). Additional CCA617 thermal shock specimens have been fabricated and testing should begin next quarter.

Accomplishments

- A presentation was given at the 8th Liege Conference entitled, "Evaluation of the Materials Technology Required for a 760°C Power Steam Boiler."
- Progress in characterizing the microstructure development (gamma prime and eta phase) in Inconel 740 has been made. The work shows that the computational thermodynamic models and the microstructure data are in agreement on the primary strengthening phase – gamma prime.
- In support of the welding process development, ORNL recommended reducing the W concentration of the SAVE12 weld metal to improve resistance to solidification cracking and reduce the tendency to retain delta ferrite based on thermodynamic and solidification modeling.

Concerns

Decrease in funding for FY2006 has delayed a number of activities. A further decrease in funding is currently projected for FY2007. This will further delay those activities put on hold in FY2006 and slow/stop other important activities such as testing a third heat of Inconel 740 in FY2007.

Plans for Next Quarter

Creep-rupture testing of all materials will continue. Post-test evaluation of Inconel 740 tube bends will be completed. Testing of weldments, including the thick section welds of the CCA617, will continue. Additional thermal shock testing on CCA617 will begin.

Appendix (for consortium member only)

EVALUATION OF SAVE12 WELDING

General physical properties

Figure A. Scheil solidification simulation prediction using a weld metal composition of Fe-10.21Cr-3.73Co-0.6Mn-0.07Mo-0.06Nb-0.09Ni-0.76Si-0.31V-3.12W-0.06C-0.032O-0.031N, wt%

Figure A shows all the solid phases including their cumulative totals calculated for the solidification of SAVE12. Silica forms in the liquid before the solid metal phases. Solidification of the metallic weld metal alloy starts around 1474°C. The first solid metal phase to form from the liquid alloy is ferrite. Ferrite remains the only stable metallic phase until the temperature drops to around 1385°C where the amount of ferrite is about 92 vol%. At 1385°C, austenite becomes the more stable phase and it forms instead of ferrite. As the temperature continues decreasing eventually several carbide phase should form. The microstructure represented by this behavior would be dendrites composed primarily of ferrite with austenite films and carbide particles distributed at the dendrite boundaries, i.e., interdendritically. As this solidification microstructure continues cooling it will undergo additional transformations.

Two features of the solidification behavior could contribute to cracking. First, the solidification temperature range is large, $\sim 274^{\circ}\text{C}$. Around 98% of the solid forms after cooling about 100°C . Then it takes another 174°C for about 2% more solid to form. The solid will contract as it cools. Having a wide temperature range over which a small amount of liquid exists, increases the probability contraction strains will create solidification cracks. Second, austenite forms on the dendrites after the ferrite. Generally, ferrite is more resistant to solidification cracking because it has higher solubility for trace elements like P and S. Having austenite form in the interdendritic regions at the end of the solidification process could contribute to increased susceptibility to solidification cracking by magnifying any influence of P and S segregation into the last remaining liquid.

Figure B provides some insight into how ferrite near dendrite cores will transform as cooling continue to ambient temperatures. According to equilibrium considerations, the composition at this location should transform to a ferrite + austenite mixture and become completely austenite as it cools from its local solidification temperature of about 1470°C . With further cooling this composition should again pass through the lower intercritical ferrite + austenite phase field. Under normal circumstances, kinetics prevents the lower transformation from occurring, thus producing the martensitic microstructure normally observed.

Extended physical properties

Figure B. Equilibrium prediction for ferrite composition near dendrite core (solid fraction = 0.17): Fe-9.59Cr-3.08Co-0.47Mn-0.06Mo-0.015Nb-0.08Ni-0.6Si-0.28V-2.49W-0.017C-0.012N, wt%

Figures C & D show the equilibrium compositions of the ferrite and austenite phases in the upper temperature range where they are expected to coexist, around 1100-1300°C.

Figure E; the Cr, Co, and W compositions of delta ferrite and austenite in the temperature range of 1300-1100°C. The data show that the ferrite becomes enriched in Cr and W compared to austenite, while the austenite becomes enriched in Co. While the compositions of the phases are changing the amount of austenite is increasing. The growth rate of the austenite will depend on how fast these element diffuse away from the advancing austenite-ferrite interface. It is reasonable to expect in welds that critical elements like Cr and W will not diffuse fast enough to permit the austenite to completely transform. This type of behavior will contribute to stabilizing delta ferrite.

Fe-9.6Cr-3.08Co-0.47Mn-0.06Mo-0.015Nb-0.08Ni-0.6Si-0.28V-2.49W-0.017C-0.012N, wt%

Figure C. Prediction of variation of equilibrium ferrite composition with temperature for solid fraction = 0.17

Figure D. Prediction of variation of equilibrium austenite composition with temperature for solid fraction = 0.17

Fe-9.6Cr-3.08Co-0.47Mn-0.06Mo-0.015Nb-0.08Ni-0.6Si-0.28V-2.49W-0.017C-0.0

Figure D. Prediction of variation of equilibrium austenite composition with temperature for solid fraction = 0.17

Figure E. Compositional data for Cr, Co, and W from the above plots are summarized on this one

One alloying element that potentially contributes both to increased susceptibility to solidification cracking and stabilization of delta ferrite is W. Tungsten segregates strongly to the liquid phase during solidification where it contributes to depressing the melting temperature. Also, W is generally believed to diffuse relatively slowly in both ferrite and austenite. Consequently, equilibration of the ferrite and austenite compositions in the 1100-1300°C temperature range could be problematic, especially under the relatively fast cooling conditions that welds experience. Because of this, W segregation could prevent the alloy from becoming completely austenitized near dendrite core regions of the microstructure. This would then stabilize delta ferrite. Reducing the W concentration of the weld metal could improve resistance to solidification cracking and reduce the tendency to retain delta ferrite.

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 800°C (1202°F - 1472°F).

Experimental

During the past quarter, preparations of the specimens and facility for the 750°C steam test were completed. The first exposure (1,000 hour duration) was completed on the materials listed in Table 1.

TABLE 1

Materials Tested in the First Exposure (1,000 hrs) at 750°C	
Material	Nominal Composition
VM12	Fe-11.5Cr-1.5W-1.5Co
347HFG Tube	Fe-18.5Cr-12Ni-1Nb
Shot Blasted 347HFG Tube	Fe-18.5Cr-12Ni-1Nb
304H	Fe-19Cr-11Ni
SUPER304H	Fe-19Cr-9Ni-3Cu
SUPER304H Tube	Fe-19Cr-9Ni-3Cu
Shot Blasted SUPER304H Tube	Fe-19Cr-9Ni-3Cu
Alloy 282	Ni-19.5Cr-10.5Co-8.5Mo-2Ti-1.5Al
Nimonic 263	Ni-20Cr-19.5Co-6Mo-2Ti
2025+Nb	Fe-25.5Ni-20.5Cr-1.5Mo
CCA617	Ni-22Cr-9Mo-11.5Co-1Al
SAVE25	Fe-22Cr-19Ni-1.5W-4Cu
Alloy 230	Ni-22.5Cr-1.5Fe-1.5Mo-14W
HR6W	Ni-23.5Cr-24Fe-6W
Alloy 740	Ni-24.5Cr-1Fe-19.5Co-2Nb-1.5Ti
RA602CA	Ni-25Cr-9.5Fe-2.5Al
HR120	Ni-26Cr-35Fe-0.5Nb
310HCbN	Fe-26Cr-20Ni-0.5Nb
Chromized SUPER304H	Fe-19Cr-9Ni-3Cu
Silicon-Chromized SUPER304H	Fe-19Cr-9Ni-3Cu
Aluminum-Chromized SUPER304H	Fe-19Cr-9Ni-3Cu
Alloy 230 Weld	Ni-22.5Cr-1.5Fe-1.5Mo-14W
CCA617 Weld	Ni-22Cr-9Mo-11.5Co-1Al
Alloy 740 Weld	Ni-24.5Cr-1Fe-19.5Co-2Nb-1.5Ti

Following the 1,000 hour exposure, the test rack was removed from the retort and two specimens from each material were removed from the test rack. Specimens from the materials listed in Table 2 were then added to the test rack, the rack was returned to the retort, and the second exposure in 750°C steam was started. It is anticipated that the second exposure will be completed in early November.

TABLE 2

Materials Added for the Second Exposure (1,000 hrs) at 750°C	
Material	Nominal Composition
P92	Fe-9Cr-1.5W
MARB2	Fe-9Cr-3.3Co-2.5W
SAVE12	Fe-9.5Cr-3W-2.5Co
Alloy 214	Ni-16.5Cr-3.5Fe-4.5Al
Deep Rolled 347HFG Tube (2 conditions)	Fe-18.5Cr-12Ni-1Nb

The specimens removed following the first exposure were photographed and then weighed. Half of the specimens have been submitted for descaling, the other half will be submitted for SEM/EDS evaluation.

The 750°C results suggest that the austenitic stainless steels are experiencing oxide exfoliation. Specimens from the SUPER304H Tube and SUPER304H materials experienced weight loss after 1,000 hours at 750°C which clearly indicates that their oxides have exfoliated during the exposure. The fact that the Shot Blasted SUPER304H Tube specimens experienced weight gain during the first exposure suggests that the shot blasting process was at least somewhat successful in mitigating oxide exfoliation from the ID surface of the tubing. This trend was not observed for the 347HFG Tube and Shot Blasted 347HFG Tube materials.

Of the highly alloyed materials that were included in the first exposure at 750°C, RA602CA exhibited the lowest weight change, followed closely by HR6W and 20-25+Nb (NF709). It is expected that the low weight change experienced by RA602CA is most likely due to the formation of an aluminum oxide (RA602CA contains 2.3% Al). This behavior was previously observed by Alloy 214 which contains ~4.4% Al. The color of the oxide that formed on RA602CA is also significantly different than that which formed on the other highly alloyed materials (bronze as opposed to gray), as shown in Figure 1.

Figure 1. Color of Oxides Formed on RA602CA, HR6W and 2025Nb After 1,000 Hours in 750°C Steam

Concerns

None.

Activities Next Quarter

The second exposure at 750°C (1,000 hours) will be completed and the specimens will be weighed. Half of the specimens removed after the first 750°C exposure will be descaled and re-weighed, the other half of the specimens will be submitted for SEM/EDS evaluation.

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 chromized, silicon-chromized and aluminum-chromized SUPER304H specimens that were prepared by Alstom were included in the 750°C test. As with the 800°C 1,000 hour results, the chromized specimens lost weight during the exposure, while the silicon-chromized and aluminum-chromized SUPER304H specimens gained weight.

Concerns

None

Activities Next Quarter

The second exposure at 750°C (1,000 hours) will be completed and the coated specimens will be weighed. Half of the coated specimens removed after the first 750°C exposure will be descaled and re-weighed, the other half of the coated specimens will be submitted for SEM/EDS evaluation.

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

A normalized plot of the parabolic rate constant (k_p) vs. chromium content for materials tested at 650°C and 800°C was constructed and is displayed in Figure 2.

The plot of k_p vs. % Cr shows that, depending on the specific alloy, steam oxidation rates are lower when the chromium concentration exceeds approximately 9-12%. At 800°C, the 12% Cr ferritic VM12 clearly outperforms the 9% Cr ferritic MARB2. The austenitic stainless steels with $<\sim 19\%$ Cr performed significantly worse than the austenitic materials with $>19\%$ Cr. This poor performance was due to the oxide exfoliation experienced by the austenitic stainless steels with $<\sim 19\%$ Cr. Alloy 214 exhibited the lowest k_p of any material evaluated due to the formation of an aluminum oxide barrier layer during the exposure.

Figure 2. k_p vs. % Cr for Tests Performed in 650°C and 800°C Steam

Concerns

None

Activities Next Quarter

Activation energies will be re-calculated following the 750°C exposures.

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, 2006. A Quarterly Report was prepared for July - September, 2006. A Steering Committee Meeting was attended in Cleveland, OH in August, 2006 where Task 3 results were presented from BWRC and ORNL results.

Concerns

None.

Activities Next Quarter

Monthly status reports will be written for October and November, 2006. A Quarterly Report will be written for October – December, 2006.

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

BWRC will maintain cognizance of ORNL results.

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 (GFY2007).

Concerns

None.

Activities Next Quarter

None.

Milestone Chart

Dates are listed in GFY

Task 4 Fireside Corrosion

(Foster Wheeler)

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

Task 4A Laboratory Testing

Objective

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

Experimental Progress

During the quarter, analysis of the data from the laboratory tests on both superheater/reheater and waterwall materials was continued in preparation for final report.

Concerns

No concerns at this time.

Plans for Next Quarter

Continue to refine the results of the laboratory tests.

Task 4B Corrosion Probe Testing in Utility Boilers

Objective

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

Experimental Progress

- First pair of corrosion probes was installed in a Mid-Western host utility site during January 2006. Exposures for the one-year and two-year probes are ongoing.
- The second pair of corrosion probes was installed at a Western utility host site during June 2006. Exposures for the one-year and two-year probes are ongoing.
- Material samples for the third pair of probes (Eastern coal) have been machined and assembled. Deployment of the third pair of probes is pending signing of the host agreement by an Ohio utility.
- Foster Wheeler continues to work closely with the host utility personnel to coordinate continuing exposures, maintenance tasks, and installation activities, as needed.
- Changes in fuel at the original Eastern coal host site have necessitated locating a new host site. Several discussions were held with a new plant in Ohio to replace the original third host site. Home office and plant personnel have generally agreed to host the third pair of corrosion probes. Final determination should be made shortly.

Concerns

The original third (Eastern coal) host site has changed to 100% low-sulfur PRB (Western) coal. This required that we locate a new host site, firing a different coal (possibly Eastern / PRB blend coal). Negotiations are currently under way with a possible host site within Ohio. This utility has already allowed us to install new penetrations for the probes, during a recent outage. However, if the parties involved were unable to reach a mutual agreement, a new Eastern coal site would have to be selected.

Plans for Next Quarter

- Monitor ongoing exposures at the installed probe sites firing Mid-western and Western coals.
- Finalize hosting arrangements and logistics for third host site (Eastern coal).
- Continue site installation tasks for the third site, coordinating with host utility.
- Complete mechanical and electrical modifications at third host site.
- Install probes at remaining host site.

Task 4C Steam Loop Design, Construction, and Testing

Objectives

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

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

Experimental Progress

Modifications were made to the steam control system during the quarter. The valve position indicator for Loop A and several pressure transmitters were recalibrated and both Loops A and B are operating as expected (Loop A is designed for metal temperatures up to 1400°F and Loop B is designed for metal temperatures up to 1280°F) Loop A temperature is limited at times due to the use of overfire air. As fall progresses, this will not be a problem.

Plans for Next Quarter

- Continue to record data.

Task 5

Welding Development

(ALSTOM)

Objectives for Task 5 Welding Development:

- 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 third attempt at SAVE12 heavy wall (13.78-inch OD x 2.3-inch wall pipe) submerged arc weld qualification was made using the newly formulated filler wire and the Bavaria SchweiBtechnik GmbH WP380 flux. The weldment passed radiographic examination but failed side bend testing when the weld metal cracked. Examination of the weld metal structure revealed a martensitic matrix and large amounts of delta ferrite, which indicated an imbalance between ferrite and austenite formers. Both the filler metal and the flux are being examined in order to correct this imbalance.

Inconel 740:

Bend testing of a thick plate welded with Nimonic 263 filler failed the 2T bend tests but basic lack of ductility, not microfissures, caused the failures. Special Metals, the filler metal supplier, now agrees that the weld metal in the aged condition is not ductile enough to pass a 2T bend.

- Another weld was made using aged Inconel 740 plate and Nimonic 263 filler to further explore bend test ductility. This weld will be aged and destructively evaluated with bend tests conducted at 2T, 3T, and 4T radii to quantify the ductility.

General:

Efforts to prepare a final comprehensive Task 5 report continued.

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 was abandoned on these two alloys.
- The difficulties encountered while attempting to weld HR6W using matching filler metals proved insurmountable for this program and there will be no further effort in this area.
- Inconel 740 appears to have a heat-to-heat sensitivity with regards to microfissuring and this could require additional constraints on composition.
- The use of matching filler metal for welding thick section CCA 617 plates does not appear practical.
- Lack of ductility in filler metal used for Inconel 740 welds will require special treatment under the ASME code if this material is to be used in boiler fabrication. The aged Nimonic 263 material will not pass a 2T bend test (20% elongation of the outer fibers) and the filler metal supplier agrees that elongations of 10 to 15% are all that can be expected.

Plans for the Next Quarter:

- Consider a fourth attempt to qualify welding of the SAVE 12 thick wall pipe material using a submerged arc process.
- Evaluate the ductility of Nimonic 263 filler metal by subjecting a 3-inch thick Inconel 740 weldment to various radii bend tests.
- Continue preparation of final comprehensive report.

Task 5C: Preparation of Laboratory Samples

Objectives:

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

Progress for the Quarter:

- The welding, radiographic examination, and post weld heat treatment of a butt joint in a section of thick-wall P92 pipe (6.3-inch OD x 1.1-inch wall) were completed using a previously qualified procedure. A 180-degree segment of the weldment was supplied to ORNL for further testing and evaluation.
- Inconel 740 tube butt joint weld samples were completed and shipped to ORNL for testing.

Concerns:

None.

Plans for the Next Quarter:

Fabricate and age a thick test plate using Inconel 740 base material and filler and supply this weldment to ORNL for evaluation. This will allow a comparison between Inconel 740 and Nimonic 263 fillers when used for thick-section welding.

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

Dissimilar metal tube butt joints were completed between Inconel 740 (aged prior to welding but not after welding) and Haynes 230, Super 304H, and CCA 617. Samples of these tube-to-tube welds were shipped to ORNL for evaluation.

Concerns

None.

Plans for the Next Quarter

None

Task 5: Welding Development - Milestone Chart

(DOE Fiscal Year Basis)

(percentages indicate fraction of workscope completed as of 2006Q3)

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.	△						100%	▲												
	• Evaluation and selection of filler.		△					100%				▲									
5B	Optimization of Welding Parameters																				
	• Preliminary weld trials and parameter optimization – thin section.				△			100%													▲
	• Preliminary weld trials and parameter optimization – thick section.				△			98%													▲
5C	Preparation of Laboratory Samples																				
	• Material preparation.							△	95%												▲
5D	Weldability Testing												△		100%					▲	
5E	Examination of Dissimilar Metal Welds.																				
	• Weld trials											△	100%								▲
5E	• Metallurgical analysis												△	10%							▲

Task 6: Fabrication (ALSTOM)

Objectives

- The objective of Task 6 is to establish boiler fabrication guidelines for the high temperature, oxidation and corrosion resistant alloys selected for the USC Project. The principal goals in this joint effort are:
 - To establish fabrication guidelines for the high temperature, corrosion resistant alloys needed for boiler components in the USC power plant.
 - To determine the thermomechanical treatments or other remedial actions necessary to restore material properties which might degrade due to fabrication operations.
 - To investigate prototypical manufacturing operations for producing both thick wall and thin wall components from the USC alloys.

Progress for the Quarter: Riley Power, Inc.

- Preparation of Riley Power's contribution to the Task 6 topical report continued.

Concerns

- None

Plans for the Next Quarter

- Preparation of Riley Power's contribution to the Task 6 topical report will be completed.

Plans for the Next Quarter: Alstom Power, Inc.

- Preparation of Alstom's contribution to the Task 6 topical report continued.

Concerns

- No new concerns.

Plans for the Next Quarter

- Preparation of Alstom's contribution to the Task 6 topical report will be completed.

Progress for the Quarter: Foster Wheeler

- Preparation of FW's contribution to the Task 6 topical report continued.

Concerns

- None

Plans for the Next Quarter

- Preparation of FW's contribution to the Task 6 topical report will be completed.

Progress for the Quarter: B&W

- Preparation of B&W's contribution to the Task 6 topical report was completed.

Concerns

- None

Plans for the Next Quarter

- Preparation of the Task 6 topical report on Fabrication, through integration of separate subtask element reports prepared by Riley Power, Alstom, Foster Wheeler, and B&W, will be completed and submitted for review.

Task 7: Coatings (ALSTOM)

Objectives

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

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

Task 7G: Manufacturing Guidelines

Objective

Investigate the requirements for production coating of boiler materials.

Progress for the Quarter

Work efforts for this task have concentrated on the requirements for diffusion-coating of the internal surface of boiler tubing. Editing of the task report was again deferred to next quarter.

Concerns

None.

Plans for the Next Quarter

Issue a report of the manufacturing requirements and costs for coating of internal tube surfaces.

Scope Accomplished Versus Actual Expenditures Task 7 Coatings Alstom Scope

Task 8: Design Methods and Data (ALSTOM)

Objectives

- 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

Progress for this quarter concentrated on review of material allowable stresses for IN740 and interacting with ORNL to ensure that their structural feature test effort was appropriately supported.

Concerns

None.

Plans for the Next Quarter

Continue general task management activities.

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

The creation of documentation to ensure that quality test data is transferred between tasks and that this data remains traceable. A second objective is the analysis of such data with the objective of improving the statistical correlation. Foster Wheeler is subtask leader, with Riley Power Inc. providing significant input to this subtask.

Deliverables

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

Progress for the Quarter

Riley Power Inc., has continued to monitor the USC data transfer website for any added completed test results for the HR6W and SAVE 12 materials, assigned to Riley. A preliminary draft version of the summary report of the creep rupture test results for HR6W, has been submitted to the subtask leader at ALSTOM Power Inc., for review. Currently for HR6W, the only missing results are for metallography.

ALSTOM Power Inc. reviewed the draft report on HR6W submitted by Riley Power and some suggestions were made to ensure consistency with conclusions and insight gained from Task 2. In addition, ALSTOM reviewed the allowable stress values for IN740 in preparation for future project work. This confirmed the updated values from the B&W Task 1 report are valid based on recent data provided by Task 2. A review of allowable stresses for other materials identified that some changes to values in the ASME code for IN617 and H230 mean that these two alloys now have similar allowable stress in the temperature range of interest. The allowable stress values remain consistent with test data from the project. The material allowable stress summary spreadsheet was updated and was sent to Riley Power for review and distribution to the project team.

Interactions continued with ORNL to discuss mechanical feature testing, specifically the thermal shock testing of CCA617. Specific items discussed this quarter were the axial temperature gradient in the specimen and the depth of penetration of the RF field into the specimen. Additional data was gathered by ORNL (Task 2) and submitted to ALSTOM for future analysis work.

Concerns

None

Plans for the Next Quarter

Riley will interface with the subtask leader on the direction and detail, for completion of the summary report of the creep rupture test results for the HR6W material.

Support will be provided to Task 2, as needed, to address issues with additional structural feature tests, or interpretation of existing tests.

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

Objectives

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

- establish the continuum damage mechanics (CDM) parameters,
- evaluate multi-axial strength theories and failure criteria,
- assess the implications of cyclic creep for USC materials,
- evaluate and compare CDM, reference stress and Omega models of typical ASME geometries.

Progress for the Quarter

Despite the scarcity of long-term creep data for the candidate materials, ALSTOM, as part of their evaluation of allowable stresses for IN740, created a continuum damage mechanics model for the creep behavior of IN740. The shape of the creep curves was well represented, particularly when large deformation theory was used to account for the increase in stress as the constant load test progresses. The creep model was then used to simulate the notch bar creep test on IN740. The failure time for the notched bar correlated well with the von-Mises stress across the throat of the notch, explaining the notch strengthening exhibited by the specimen. Also, the predicted accumulated creep strain at the notch root was approximately equal to the uniaxial failure strain at the failure time for the test.

ALSTOM received comments from EPRI on the draft topical report on a cycling assessment of a typical boiler header. These comments were reviewed and the document updated.

Concerns

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

Plans for the Next Quarter

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

Task 8F: Weld Analysis and Assessment (ALSTOM)Objectives

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

No progress was made this quarter because of activities on the other Subtasks.

Concerns

None.

Plans for the Next Quarter

In the next quarter, ALSTOM will complete their portion of the weld literature review and work with Riley Power to issue the weld literature review summary report.

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

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

Deliverables

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

Progress for the Quarter

No activity for this quarter.

Concerns

None.

Plans for the Next Quarter

None.

Task 9 Project Integration and Management (EPRI)

Task 9: Project Integration and Management

- Objective: The objective of Task 9 is to: coordinate the project and provide reporting to DOE and Ohio Coal Development Office (OCDO).
- Progress for the Quarter:
 - Completed third Quarterly Report for 2006
 - Completed Monthly Reports for July and August, 2006
 - Monthly conference calls were held and the discussions were documented.
 - A steering committee meeting was conducted in Cleveland on Aug 30-31.

Plans continue for the next Advanced Materials Conference to be conducted at the Marriott Marco Island Resort on October 3-5, 2007.
- Concerns: No concerns at this time.
- Plans for next Quarter:
 - Issue monthly reports and hold conference calls as required.