

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 October 1 to December 30, 2003.

Table of Contents

	Page
ABSTRACT	3
1.0 EXECUTIVE SUMMARY	5
A. Project Objective	5
B. Background and Relevance	5
C. Project Tasks	6
D. Major Accomplishments During the Quarter	6
E. Plans for the Next Quarter	8
F. Issues	8
2.0 TASKWISE STATUS	9
Task 1 Conceptual Design and Economic Analysis	9
Task 2 Mechanical Properties of Advanced Alloys	12
Task 3 Steamside Oxidation	21
Task 4 Fireside Corrosion	36
Task 5 Welding Development	39
Task 6 Fabrication	45
Task 7 Coatings	50
Task 8 Design Methods and Data	63
Appendix B	71
Task 9 Project Integration and Management	73

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 and Riley Power Inc.) 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

- Reports providing an overview identifying the materials selected by the consortium and giving an indication of the scope of the mechanical testing work will be issued in January. Characterization test plans for four of the six materials selected for the project are completed. Rupture lives may be made with the expected life based on prior data. The initial rupture test results indicate that the strength of the Super 304H and alloy 230 are meeting expectations while the HR6W is below expectations.
- A paper on aged 617 was presented in November, 2003 at a TMS meeting.
- Additional aging furnace capacity has been installed at ORNL to accommodate the aging for the rest of the USC materials.
- Cross-weld stress-rupture testing of samples from alloy 230 tubes specimens is in progress.
- Deposit and flue gas compositions have been finalized for both waterwall and superheater/reheater conditions for fireside oxidation testing.

- Three host utilities were finalized for installation of corrosion test loops:
 - First Energy – R. E. Burger Station
 - Xcel Energy – Pawnee Station
 - Cinergy – Gibson Station
- Installation of the steam cooled corrosion test loops was completed and is in service.
- Dairyland Power agreed in principal to be the second host site at their John P. Magett Generating Station in Alma, Wisconsin.
- The third steamside oxidation exposure period at 650°C was started during this quarter and ran smoothly throughout the quarter.
- The ferritic materials continued to exhibit greater weight gain than the austenitic materials, with the exception of the 9%Cr Abe PO (Pre-Oxidized) and 11%Cr VM12 materials which, after 1,000 hours of exposure, exhibited comparable oxidation performance to austenitic materials.
- Based on the calculated weight change data after 1,000 and 2,000 hours, the oxidation rate constant, k_p , was calculated for each material and is presented in the Task 3 information.
- The austenitic materials that have exhibited the lowest amounts of oxidation are Nimonic 263, CCA 617 and Alloy 740.
- Results suggest that the carbon content and the boron content, along with the chromium content, play a consistent and significant role in determining the steamside oxidation behavior of ferritic materials.
- Filler metal and base metal procurement for welding tests is progressing. Welding trials for many materials is progressing.
- “U” bends in HR6W were successfully produced to 15, 20, and 35% strains.
- Intermediate annealing will probably be required during swaging of HR6W due to high work hardening.
- Tapered tube specimens were machined and strained for 230, Super 304H, CCA 617, and 740.
- Haynes 230 samples have been coated with 50Ni/50Cr and will be included in the laboratory corrosion tests. Praxair has agreed to provide a quote for developing laser-cladding parameters for this material.
- Chromizing was performed on Super 304H and T-92 and samples were prepared for testing in Task 4.

- A meeting was also held in early December to resolve the outstanding issues associated with Task 8. Representatives from all OEMs attended and provisional subtask assignments were made.

E. Plans for the Next Quarter

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

- Re-anneal the Inconel 740 tubing at 1190°C due to hardness variations around its circumferential.
- An annual report detailing the material characterization progress from August 1, 2002 to July 30, 2003, is expected in January.
- Begin stress-rupture testing of weld, longitudinal weldment, and cross weld specimens of alloy 230.
- Start fireside oxidation testing using six furnaces; three furnaces will be used for waterwall testing and three will be used for superheater/reheater testing.
- Start construction of corrosion test probes.

F. Issues

- The initial rupture test results indicate that the strength of HR6W is below expectations.
- Hardness variations around the circumference of Inconel 740 tubing was observed. A decision was made to re-anneal the material at 1190°C.
- Base material sourcing difficulties and long delivery times have, in some cases, delayed the start of welding activities by 9 to 12 months.
- Haynes 230 weldments that have been submitted to ORNL for testing have exhibited creep properties below those for base material.
- Problems were encountered while swaging Super 304H and CCA 617.

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

Due to lowering of allowable stresses for In 740, a re-evaluation of the design for an Ultra Supercritical Boiler was warranted. The difference in allowables is shown in figure 1 below.

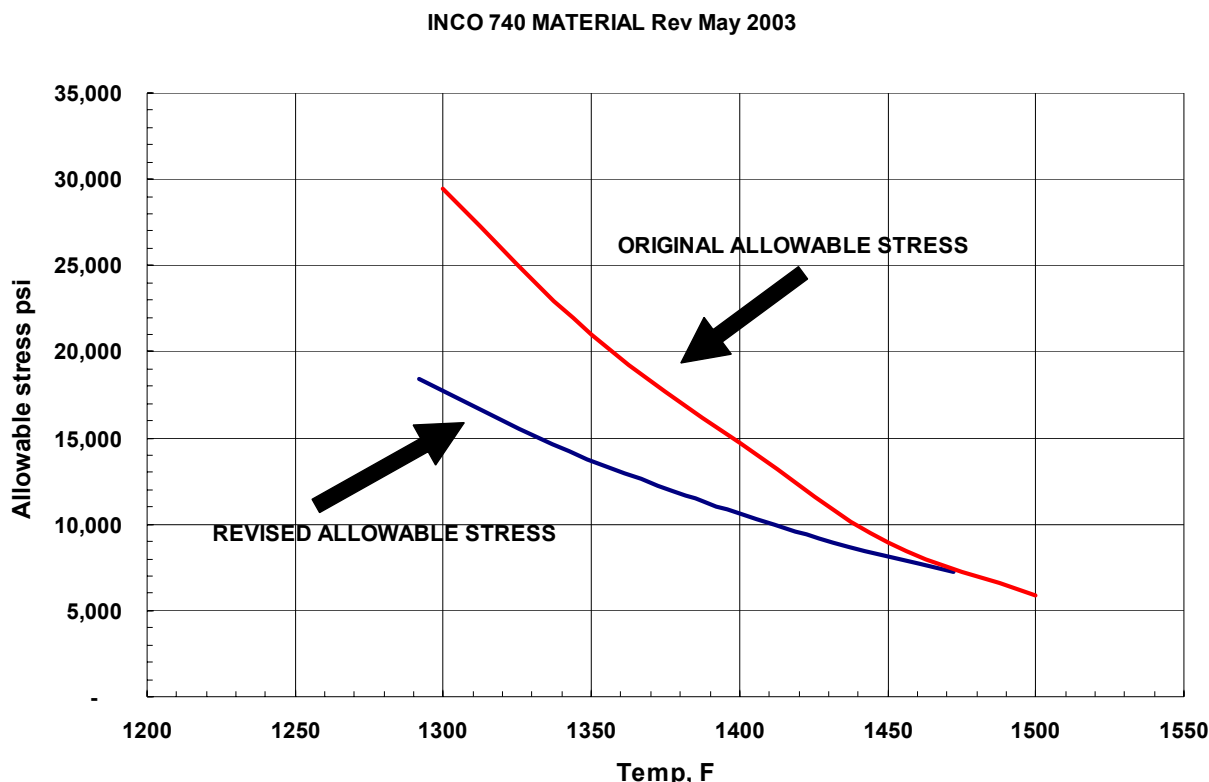


Figure 1: Difference in original allowable stress and revised allowable stress for In 740 material.

The primary component affected by the lowering of allowable stresses was the superheat outlet headers. The original design called for two headers 3.3" thick with a 24.4" OD and end outlets. This design is easier and less expensive to manufacture. The thickness limit was about as thick as desired from a cycling standpoint. To keep this as the maximum thickness the outside diameter of the headers had to be reduced to meet the lower allowables. The smaller OD required the installation of outlet tees in the center of the headers to have enough area for the steam flow required. This will add to the cost of the boiler but will not have an effect on unit capacity or efficiency. Thicker tubing and reheat headers will also be required due to the reduced allowable stress for In 740.

Concerns

None.

Plans for the Next Quarter

None.

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.

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 a report that justifies the materials selected for the pressure retention components of the USC steam boiler.

Progress for the Task

The first part of the assessment report provides an overview identifying the materials selected by the consortium and gives an indication of the scope of the mechanical testing work to meet the project needs. The second part deals with 9-12% chromium steels. Part I and II have gone through internal ORNL review and will be provided to the consortium in January. The third part dealing with austenitic iron-bearing alloys is completed and is undergoing internal review at ORNL. The fourth part, on nickel base alloys, is still in the draft form.

Task 2B: Detailed Test Plan

Progress for the Quarter

The detailed mechanical properties test plan is intended to provide guidance on the scope of the mechanical testing for each material to support 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. To some measure, the test plan is still evolving.

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. The characterization testing plans have been completed for four of the six alloys (Super 304H tubing, HR6W tubing, alloy 230 tubing, and CCA617 tubing). The creep-rupture database for Super 304H stainless steel and alloy 230 was judged to be adequate, since both materials are code alloys.

The testing plans for HR6W, SAVE 12, CCA617, and Inconel 740 are expected to be more expansive, since code cases will be needed if these materials are used. The testing plan for the thick-section materials is still under development.

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.

Progress for the Task

The status for the four 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. Modifications have been made to the HR6W creep-rupture test plan due to the lower than expected strengths at the lower temperatures. The CCA617 alloy is exceeding expectations in the lower temperature regime (650°C to 700°C) based on performance equivalent to alloy 617. Additional shorter-term tests have been added to the CCA617 test matrix.

Creep-rupture testing on the Haynes 230 tube cross-weldments is almost complete. The lower strengths compared to the base material are as expected. All ruptures have been in the weld metal. A Larson-Miller Parameter plot that compares the Haynes 230 base and weld metal database was obtained from communications with Haynes International on 12/04/03. The plot includes the ORNL generated data, as of November 2003, which agrees well for the base material and the weldments.

Inconel 740 tubing and thick section plate was obtained this quarter from Foster Wheeler. The tubing was annealed at 1120°C. Hardness variations around the circumference were observed by FW and corroborated by tensile testing at Special Metals. It is likely that the hardness variations are due to aging, where regions of the tube were subjected to slow cooling. Re-annealing the material at ORNL before testing was considered due to the hardness variations combined with the fact that the annealing temperature was lower than recommended. Based on prior work at ORNL and at the recommendation of the consortium members (during the December 2003 conference call), it was decided that the material received by ORNL would be re-annealed at 1190°C. Re-annealing and the production of test specimens will be undertaken next quarter.

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	
SM-03	30383	340	600°C	100 Hrs	12/1/2003	
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	
		200	675	500		
		170	675	1000		
		150	675	6000		
		200	700	50		
HR-6W-08		170	700	500		
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	
HR-6W-12	30283	150	725	500	5/21/2003	187.5
HR-6W-13	30291	120	725	5000	6/2/2003	723.8
HR-6W-14		140	750	100		
HR-6W-15		120	750	500		
HR-6W-16		100	750	5000		
HR-6W-04		85	750	20000		
HR-6W-05	30396	100	775	600	12/29/2003	225
HR-6W-06		85	775	5000		
HR-6W-07	30395	100	800	150	12/29/2003	80.24
		85	800	1000		

Creep-Rupture Testing of Haynes 230						
Spec #	Test #	Stress (MPa)	Temp. (°C)	Estimated 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	
H230-09		100	750	15000		
H230-10	30373	140	800	100	10/27/2003	
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	125

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	
H230-W12	30370	100	750	15000	10/14/2003	1117.8

Figure 1. Larson Miller Parameter plot of the Haynes 230 base and weld metal database (courtesy of Haynes International) including some of the testing on the USC Consortium Haynes 230 tube and tube weldments

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	
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	2476.5
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	1830.9
617-12		80	800	20000		
617-13	30352	400	650	200	9/10/2003	1279.7
617-14	30387	400	700		12/3/2003	301.6

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 for the Task

The University of Cincinnati has been tasked with the metallurgical characterization of the USC materials. Techniques for producing TEM foils have been developed for the Ni-based materials, and foils of aged alloy 617 have been examined. A paper on aged 617 was presented in November, 2003 at a TMS meeting.

An aging matrix has been developed for the USC materials. Full coverage of temperatures and times is underway at ORNL for the CCA617 and alloy 230. Exposure at half of the intended temperatures is in progress for HR6W and Super304H stainless steel. Additional aging furnace capacity has been installed at ORNL to accommodate the aging for the rest of the USC materials. Currently 3,000 hours of aging has been completed on some alloys. The University of Cincinnati will be characterizing these materials. They have also been sent samples of a modified chemistry I-740 for characterization. An annual report detailing the characterization progress from August 1, 2002 to July 30, 2003, from the University of Cincinnati to ORNL, is expected in January.

USC Steam Boiler Materials: Aging Test Matrix							
Specifications: Aging in Air ¹ , Tolerance +/- 10°C (Except for SAVE12, +/-5°C), Water Quench							
<i>(Approximately 3 specimen blanks for each time-temp combination)</i>							
Material	Heat # / Case Code	Aging Temperature (°C)	Aging Times (hours)				
			100	1,000	3,000	10,000	10,000+
Super 304H	/ 2328	600	100	1,000	3,000	10,000	
Super 304H	/ 2328	650	100	1,000	3,000	10,000	10,000+
Super 304H	/ 2328	700	100	1,000	3,000	10,000	10,000+
HR6W	DZC1309	600	100	1,000	3,000	10,000	
HR6W	DZC1309	650	100	1,000	3,000	10,000	10,000+
HR6W	DZC1309	700	100	1,000	3,000	10,000	10,000+
CCA617		700	100	1,000	3,000	10,000	
CCA617		750	100	1,000	3,000	10,000	10,000+
CCA617		800	100	1,000	3,000	10,000	10,000+
SAVE12	W310507	600	100	1,000	3,000	10,000	10,000+
SAVE12	W310507	625	100	1,000	3,000	10,000	10,000+
SAVE12	W310507	650	100	1,000	3,000	10,000	10,000+
SAVE12	W310507	675	100	1,000	3,000	10,000	
I-740		700	100	1,000	3,000	10,000	
I-740		750	100	1,000	3,000	10,000	10,000+
I-740		800	100	1,000	3,000	10,000	10,000+
Haynes 230		700	100	1,000	3,000	10,000	
Haynes 230		750	100	1,000	3,000	10,000	
Haynes 230		800	100	1,000	3,000	10,000	
¹ Oxide layer will be machined/ground from specimen blank (No encapsulation planned although it may be used in certain circumstances)							
Green = In Test							
Red = Completed							
Aging done at the Univ. of Cincinnati - 2 aged blanks returned to ORNL							

Task 2E: Assessment of Creep-Fatigue Properties

Objectives

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 for the Task

SAVE12 fatigue specimens were fabricated this quarter. The fatigue testing matrix has not been fully defined, so that testing has been delayed until such time as meaningful

creep-fatigue tests are defined. The need to produce greater creep damage in the creep-fatigue cycle is a major issue that needs to be resolved.

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 for the Task

Cross-weld stress-rupture testing of samples from alloy 230 tubes specimens is in progress, as indicated in the table above. All weld, longitudinal weldment, and cross weld specimens have been prepared from plates supplied by Task 5. Testing on these will begin next quarter.

Furnaces for testing full thickness weldments have been received and installed. Completion of two testing systems, including fixturing, temperature control, and extensometry, is expected in the next quarter.

Task 2G: Study of Accelerated Testing Methods

Objectives

The primary objectives of this subtask are:

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

Progress for the Task

Short-term creep tests are being conducted on a modified chemistry INCONEL 740 to assess possible improvements in creep strength. A request for samples of the advanced ferritic alloys being developed by Dr. Abe has been placed.

Task 2H: Model Validation

Objectives

The primary objectives of this subtask are:

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

Progress for the Task

A large furnace, capable of testing 3 tubes at a time, has been installed for testing tube bends under pressure. Temperature and pressure controls have been installed. Completion of the test system is planned for next quarter.

Electro-hydraulic equipment in the Structures Test Laboratory is now operational.

Designs for deeply-notched test bars have been completed. Specimens will be made next quarter from the thick plate 740 and the Haynes 230 bar material.

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

The third exposure period at 650°C was started during this quarter and ran smoothly throughout the quarter. Also during this quarter, the results from the first two exposures at 650°C (1202°F) were analyzed in detail. The focus of these analyses was to evaluate the oxidation behavior of the materials as a function of time. The results of these analyses are presented below under the following headings: Weight Change, Descaled Weight Loss, Exfoliation, Metallographic Evaluations, and Coated Materials.

Weight Change

- Measured Weight Change
 - The average measured weight change for the materials under test after 1,000 and 2,000 hours of exposure are presented in Table 1. In general, the materials experienced no additional weight gain after the second 1,000 hour exposure as compared to the first 1,000 hours exposure. Several of the materials (both ferritic and austenitic) experienced less weight gain after 2,000 hours of exposure than after 1,000 hours of exposure. It is believed that the lack of additional weight gain is due to exfoliation of oxide from the specimens.
 - The ferritic materials continued to exhibit greater weight gain than the austenitic materials, with the exception of the 9%Cr Abe PO (Pre-Oxidized) and 11%Cr VM12 materials which, after 1,000 hours of exposure, exhibited comparable oxidation performance to austenitic materials.
- Calculated Weight Change
 - Since it was apparent that the weight change values were inaccurate due to oxide exfoliation, weight change values for the test materials were calculated from descaled weight loss measurements. These calculations were made using the following assumptions: 1) for ferritic materials, all weight loss was from Fe atoms, 2) for austenitic materials, all weight loss was from metal with a molecular weight of 55.5 g/mole, 3) for ferritic materials, the weight gain is due to

incorporation of oxygen in the formation of Fe_3O_4 , and 4) for austenitic materials, the weight gain is due to incorporation of oxygen in the formation of a metal oxide with the composition of M_2O_3 . The calculated weight change values are also reported in Table 1.

TABLE 1

USC Task 3 - 650C Test <i>Weight Change and Descaled Weight Loss Results</i>							
Specimen #	%Cr	Measured Weight Change (mg/cm ²)		Calculated Weight Change (mg/cm ²)		Descaled Weight Loss (mg/cm ²)	
		1000 hours	2000 hours	1000 hours	2000 hours	1000 hours	2000 hours
T23	2.09	26.810	29.745	42.654	49.068	111.659	128.451
P91	8.29	3.184	-0.890	14.161	17.865	37.071	46.767
P92	8.93	7.462	4.864	5.425	7.349	14.202	19.239
AbeNN	8.95	19.378		22.264		58.282	
Abe	9.16	0.358	0.326	0.188	0.461	0.492	1.208
AbePO	9.16	0.173		0.219		0.572	
SAVE12	9.25	4.596	5.837	5.707	6.770	14.939	17.724
VM12	11.37	0.174		0.279		0.730	
304H	18.83	0.249	0.247	0.253	0.297	0.586	0.688
S304H	19.1	0.113	0.112	0.192	0.205	0.444	0.474
800HT	19.49	0.281	0.272	0.264	0.265	0.612	0.614
N263	20.02	0.146	0.123	0.086	0.129	0.200	0.299
CCA617	21.73	0.124	0.116	0.099	0.108	0.230	0.251
SAVE25	21.85	0.147	0.153	0.191	0.174	0.442	0.403
230	22.42	0.219	0.199	0.253	0.278	0.585	0.644
HR6W	23.44	0.241	0.232	0.208	0.232	0.482	0.536
740	24.31	0.138	0.096	0.087	0.112	0.201	0.258
HR120	25.94	0.208	0.161	0.204	0.228	0.473	0.529

- The calculated weight change data indicates that ferritic alloys T23, P91, P92, Abe NN, and SAVE 12 experienced significantly more oxidation than was measured by weight gain, suggesting significant exfoliation of the oxides that formed on these materials. Only small differences were observed between the calculated and measured weight change values for the remaining ferritic and austenitic materials; however, the measured weight change data tended to show less weight gain after 2,000 hours than after 1,000 hours. Since this trend was not as prevalent in the calculated weight change results, it appears that the materials that experienced only minor oxidation were also susceptible to exfoliation.

- Calculation of k_p
 - Based on the calculated weight change data after 1,000 and 2,000 hours, the oxidation rate constant, k_p , was calculated for each material assuming parabolic kinetics (weight change is proportional to the square root of time). The results are displayed in Table 2 along with k_p values recently generated by ORNL at 700°C and predicted k values for the parabolic oxidation of ferritic materials from Table III of CORROSION 2002 Paper 020377 by Wright and Pint ($k=Ae^{-Q/RT}$).

TABLE 2

Material	%Cr	From BRWC Calculated Weight Change			ORNL Results at 700°C *		Predicted k_p for Ferritic Materials** ($g^2cm^{-4}s^{-1}$)	
		Test Temperature (C)	k_p ($g^2cm^{-4}s^{-1}$)	R^2	k_p ($g^2cm^{-4}s^{-1}$)	R^2	At BWRC Test Temp	700°C
T23	2.09	631.0	4.12E-10	0.962	-----	-----	5.54E-10	5.09E-9
P91	8.29	631.0	5.10E-11	0.987	2.42E-13 - 57.6E-13	0.988 - 0.971	5.20E-11	2.06E-10
P92	8.93	638.6	8.22E-12	0.997	7.50E-11	0.995	6.12E-11	2.06E-10
Abe NN	8.95	643.5	1.37E-10	1.000	-----	-----	6.78E-11	2.06E-10
Abe	9.16	648.0	2.33E-14	0.894	-----	-----	7.45E-11	2.06E-10
Abe PO	9.16	630.4	1.32E-14	1.000	-----	-----	5.14E-11	2.06E-10
SAVE12	9.25	644.1	7.66E-12	0.972	-----	-----	6.87E-11	2.06E-10
VM12	11.37	651.2	2.14E-14	1.000	-----	-----	7.96E-11	2.06E-10
304H	18.83	650.9	1.49E-14	0.969	-----	-----		
Super 304H	19.1	652.7	7.59E-15	0.932	-----	-----		
800HT	19.49	654.5	1.34E-14	0.903	-----	-----		
Nimonic 263	20.02	638.6	2.38E-15	1.000	-----	-----		
CCA617	21.73	644.1	2.09E-15	0.942	-----	-----		
SAVE25	21.85	655.9	6.23E-15	0.846	2.20E-15	0.953		
Alloy 230	22.42	650.9	1.37E-14	0.946	-----	-----		
HR6W	23.44	656.4	9.41E-15	0.950	-----	-----		
Alloy 740	24.31	652.9	1.96E-15	0.990	2.70E-15	0.964		
HR120	25.94	648.0	9.10E-15	0.952	2.60E-15	0.993		

* - ORNL data included in e-mail from Ian Wright to Jeff Sarver, December 2, 2003

** - k calculation based on CORROSION 2002 Paper 020377 Table III (Wright and Pint)

- The rate constants calculated for T23 and P91 from the BWRC data are in excellent agreement with the predicted rate constants, indicating that the BWRC test results for baseline ferritic materials are in good agreement with results on these materials generated by other organizations. The rate constants for newer ferritic materials were much lower than the predicted values, probably because data for these materials were not available for inclusion in the Arrhenius plots used to calculate the predicted rate constants. The ORNL-generated rate

constants are significantly less than the predicted values for ferritic materials P91 and P92 at 700°C. For the three austenitic materials common to the BWRC and ORNL tests (SAVE25, Alloy 740 and HR120), the BWRC and ORNL calculated rate constants are similar.

Descaled Weight Loss

▪ Measured Weight Loss

- Following the exposures, one specimen from each material was descaled using alkaline permanganate, hot diammonium citrate and, when necessary, hot inhibited hydrochloric acid. The descaled weights are also reported in Table 1. Of the ferritic materials tested, the Abe, Abe PO and VM12 alloys have exhibited much lower descaled weight loss than the rest of the ferritic materials tested. Since the chromium content of the Abe and Abe PO alloys are approximately the same as that of other ferritic materials tested (P91, P92, AbeNN and SAVE12), the lower oxidation rates of the Abe and Abe PO alloys must be due to something other than the chromium content.
- The austenitic materials displayed descaled weight loss values that were consistently less than the ferritic materials. Thus far, the austenitic materials that have exhibited the lowest amounts of oxidation are Nimonic 263, CCA 617 and Alloy 740.

▪ Parabolic Slope

- The descaled weight loss data after 0, 1,000 and 2,000 hours were plotted against the square root of time to determine how well the test data fits parabolic oxidation behavior. The results are shown in Table 3.

TABLE 3

Descaled Weight Loss Slope and Data Fit Assuming Parabolic Oxidation Kinetics ($y=mt^{1/2}$)					
Material	%Cr	Descaled Weight Loss (mg/cm^2)		Slope ($\text{mg}/\text{cm}^2/\text{hr}^{1/2}$)	R^2
		1000 hrs	2000 hrs		
T23	2.09	111.659	128.451	3.1865	0.9621
P91	8.29	37.071	46.767	1.1219	0.9866
P92	8.93	14.202	19.239	0.4503	0.9968
Abe NN	8.95	58.282	-----	1.7452	Only 1000 hr data
Abe	9.16	0.492	1.208	0.024	0.8944
Abe PO	9.16	0.572	-----	0.0171	Only 1000 hr data
SAVE12	9.25	14.939	17.724	0.4347	0.9717
VM12	11.37	0.730	-----	0.0218	Only 1000 hr data
304H	18.83	0.586	0.688	0.0169	0.9685
Super 304H	19.1	0.444	0.474	0.0121	0.9322
800HT	19.49	0.612	0.614	0.0161	0.9027
Nimonic 263	20.02	0.200	0.299	0.0068	0.9995
CCA617	21.73	0.230	0.251	0.0064	0.9423
SAVE25	21.85	0.442	0.403	0.011	0.8455
Alloy 230	22.42	0.585	0.644	0.0162	0.9458
HR6W	23.44	0.482	0.536	0.0135	0.95
Alloy 740	24.31	0.201	0.258	0.0062	0.9901
HR120	25.94	0.473	0.529	0.0133	0.952

The R^2 results from Table 3 indicate that the descaled weight loss data follows parabolic kinetics quite well. The slopes rank the materials in the same general order as the weight loss data.

▪ Effect of Composition

- For the seven ferritic alloys in test, plots of composition vs. parabolic slope (Table 3) were constructed to evaluate the influence that the various alloying elements had on oxidation behavior. Individual plots were constructed for carbon, silicon, chromium, tungsten, nitrogen, cobalt and boron. Based on a linear data fit (R^2), it was found that chromium exhibited the best fit ($R^2 \approx 0.8$), followed by boron ($R^2 \approx 0.53$) and carbon ($R^2 \approx 0.4$). Compositional variations of the remaining elements displayed no consistent effect on the descaled weight loss. Through an iterative process, it was found that the descaled weight loss parabolic slope could be described as a function of $0.6[\text{Cr}] + 63[\text{C}] + 200[\text{B}]$ with an excellent linear fit, as shown in Figure 1.

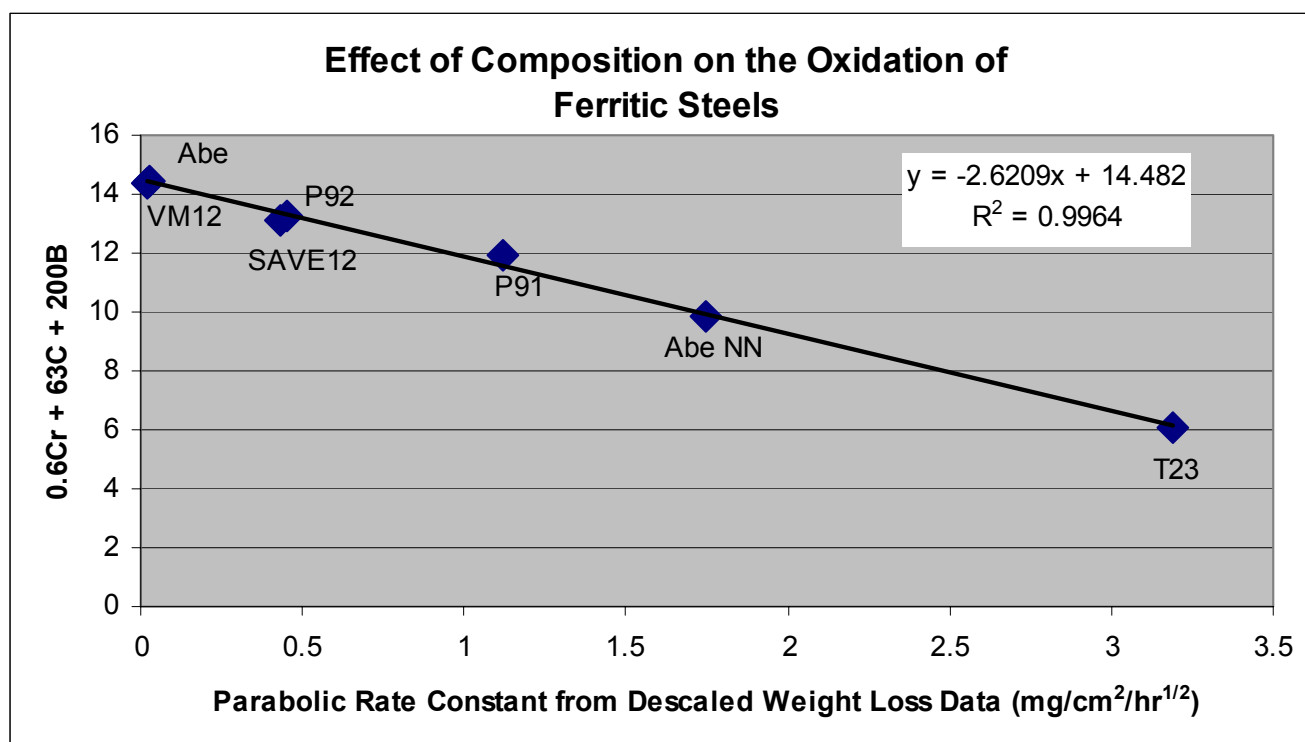


Figure 1. Effect of Composition on the Parabolic Rate Constant for Ferritic Materials Tested at 650°C

These results suggest that the carbon content and the boron content, along with the chromium content, play a consistent and significant role in determining the steamside oxidation behavior of ferritic materials.

Exfoliation

- The weight of exfoliated oxide from each material was calculated by subtracting the calculated weight change from the measured weight change (see Table 1). Since the weight change represents only the weight of the oxygen which has been incorporated into the oxide, this value was converted to mg of exfoliated oxide per unit area by assuming that the exfoliated oxide from ferritic materials was Fe_3O_4 , and that the exfoliated oxide from austenitic materials was M_2O_3 , where M had a molecular weight of 55.5 g/mole. The calculated weight of exfoliated oxide per unit area is shown in Table 4.

TABLE 4

USC Task 3 - 650C Test Calculated Exfoliated Oxide			
Material	%Cr	Calculated Weight of Exfoliated Metal Oxide (mg/cm ²)	
		1000 hours	2000 hours
T23	2.09	79.918	73.421
P91	8.29	39.615	87.566
P92	8.93	-17.800	3.966
AbeNN	8.95	12.734	-----
Abe	9.16	-0.655	0.473
AbePO	9.16	0.296	-----
SAVE12	9.25	2.926	4.164
VM12	11.37	0.486	-----
304H	18.83	-0.070	0.172
S304H	19.1	0.268	0.328
800HT	19.49	0.009	-0.108
N263	20.02	-0.191	0.064
CCA617	21.73	-0.114	-0.043
SAVE25	21.85	0.186	0.090
230	22.42	0.182	0.280
HR6W	23.44	-0.081	0.028
740	24.31	-0.128	0.066
HR120	25.94	-0.057	0.238

The results indicate that significant oxide exfoliation occurred on ferritic materials, with the exception of the Abe, Abe PO and VM12 alloys. The austenitic materials have experienced only minor oxide exfoliation after 2,000 hours of exposure at 650°C.

Metallographic Evaluations

■ Grain Size

- A question had been raised regarding whether the improved oxidation behavior of the Abe alloys may be related to a grain size effect. For a given alloy, specimens with smaller grain size typically experience lower oxidation rates. Thus, samples from P92, SAVE12 and Abe alloy were submitted for grain size determination. The specimens were etched with 10% oxalic acid and the results are as follows:
 - P92 Grain Size : ASTM 6-7
 - SAVE12 Grain Size : ASTM 2
 - Abe Alloy Grain Size : ASTM 4-5

- The grain size results indicate that grain size was not responsible for the improved oxidation behavior of the Abe alloy compared to P92 (since P92 had a smaller grain size). It is doubtful that the smaller grain size of the Abe alloy can fully account for the ~15-fold improvement in its oxidation behavior over that of SAVE12.

- SEM/EDS Results
 - Following the second 1,000 hour exposure period, one specimen from each material was submitted for SEM/EDS evaluation. These results are presented in Tables 5 and 6, along with the oxide thickness results following the first 1,000 hour exposure. Note that the Abe NN, Abe PO and VM12 specimens listed in Table 5 were added to the test matrix prior to the second 1,000 hour exposure; thus, these specimens have only been exposed for 1,000 hours.
 - The SEM/EDS results indicate that the adherent oxide on the ferritic materials is continuing to increase in thickness, with the exception of the Abe alloy. Little change was observed in the oxide thickness of the austenitic alloys between 1,000 hours and 2,000 hours.

TABLE 5

SEM/EDS Evaluation Results – Ferritic Materials					
Material	%Cr	Oxide Thickness After 1,000 Hours of Exposure (microns)	Oxide Thickness After 2,000 Hours of Exposure (microns)	Oxide Composition	Comments
T23	2.09	150 outer - 50 next - 20 next - 20 inner - 60	260 outer - 130 inner - 130	outer layers - Fe oxide inner layers - Fe oxide enriched in V & Cr	
P91	8.29	30 outer - 15 inner - 15	70-90 outer - 30-40 inner - 40-50	outer - Fe oxide inner - Fe oxide enriched in Cr	In some locations essentially no oxide was observed
P92	8.93	5-30 outer - 5-15 inner - 0-15	50 outer - 30 inner - 20	outer - Fe oxide with very minor Cr inner - Fe oxide highly enriched in Cr	In some locations essentially no oxide was observed Cr-rich zones in inner oxide are in layers
Abe NN	8.95	130-165 outer - 90 inner - 40-75	----	outer - Fe oxide with Co inner - Fe oxide highly enriched in Cr	Outer oxide layer was very defective Some outer oxide has spalled from the surface
Abe	9.16	3 outer - 1.5 inner - 1.5	3 outer - 2 inner - 1	outer - Fe oxide with some Cr inner - Cr oxide w/ significant Fe and Mn, and sl. Enriched in Co	W-rich precipitates in the matrix with elevated Cr and V
Abe PO	9.16	0	----	No oxide observed	W-rich precipitates in the matrix
SAVE12	9.25	45 outer - 25 mid - 1 inner - 19	50 outer - 20-30 mid - 1 inner - 20	outer - Fe oxide mid - Cr oxide inner - Fe/Cr oxide with Co	Cr depletion below inner oxide fine W-rich precipitates in the matrix Cr-rich zones in the inner oxide are in layers
VM12	11.37	5	----	Cr oxide with Fe and enriched in Mn and S	Cr depletion observed below oxide W-rich precipitates observed in matrix

TABLE 6

SEM/EDS Evaluation Results – Austenitic Materials					
Material	%Cr	Oxide Thickness After 1,000 Hours of Exposure (microns)	Oxide Thickness After 2,000 Hours of Exposure (microns)	Oxide Composition	Comments
304H	18.83	5 max	3	Cr oxide with Fe and Mn	2 micron wide Cr depleted zone below oxide Oxide appears to be 2 layers, but both layers are compositionally equivalent
Super 304H	19.1	2	1	Cr oxide enriched in Mn	3 micron wide Cr depletion below oxide near surface Nb particles observed
Nimonic 263	20.02	1 max	3	Cr oxide enriched in Ti and Mn	Mo/Ti precipitates observed in matrix Cr and Ti depleted zone observed below oxide
800HT	19.49	2	3-4 outer - 2-3 inner - 1	outer - Cr oxide enriched in Ti and Mn inner - Ti oxide enriched in Al	oxide fingers extend into matrix
CCA617	21.73	1	1	Cr oxide enriched in Ti and Al	oxide fingers extend ~1 micron into matrix Mo-rich particles observed below oxide fingers
Alloy 230	22.42	1	<1	Cr oxide enriched in Mn and Al	Very large W-rich globular precipitates in matrix
SAVE25	21.85	1	1	Cr oxide enriched in Mn	2 micron wide Cr depletion below oxide Nb-rich precipitates observed in matrix
HR6W	23.44	<1	1	Cr oxide enriched in Mn	some W-rich zones observed in matrix
HR120	25.94	1	1	Cr oxide enriched in Mn	3 micron wide Cr depletion below oxide
Alloy 740	24.31	<1	<1	Cr oxide enriched in Ti	

Coated Materials

- Weight Change and Descaled Weight Loss
 - The weight change and descaled weight loss experienced by the coated P92 specimens supplied by Alstom are presented in Table 7. The measured weight change and descaled weight loss data for these specimens have been corrected to eliminate the contribution from the P92 base metal that was exposed during the test. [Prior to the test, a small hole was drilled through the coupons so the coupons could be wired to a test rack. P92 base metal was exposed along the sides of this hole.]

TABLE 7

USC Task 3 - 650C Test <i>Weight Change and Descaled Weight Loss Results from Coated Materials</i>				
Material	Measured Weight Change (mg/cm ²)		Descaled Weight Loss (mg/cm ²)	
	1000 hours	2000 hours	1000 hours	2000 hours
CrP92	-0.018	0.249	0.944	2.006
SiCrP92	0.007	0.308	1.193	2.433
AlCrP92	0.735	1.623	-0.448	0.805
EllessNiP92	1.453	2.050		6.527
CBP92	3.979	-10.286		

The chromized specimens continue to perform better than most of the ferritic materials, but somewhat worse than the austenitic materials. The electroless nickel plated specimens have not performed as well as the chromized materials, and the Cereblak material has experienced extensive exfoliation.

Concerns:

- There are no concerns at this time.

Activities Next Quarter:

- The 650°C test series will conclude and the remaining specimens will be removed and evaluated.
- Specimens will be prepared for the 800°C test series, and the first 800°C test will be started.

Task 3B Coating Tests**Background**

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

Experimental

- All of the coated specimens that were provided are currently being exposed in the 650°C Steamside Oxidation Test. Results from the first specimens that were removed were discussed in Task 3A above. Alstom is to provide additional coated specimens for inclusion in the 800°C tests.

Concerns

- There are no concerns at this time

Activities Next Quarter

- The remaining coated materials will be removed from the 650°C test and evaluated.
- New coated specimens will be received from Alstom and entered into the 800°C test.

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

- No progress will be possible until results from the steamside oxidation tests at different temperatures become available.

Concerns:

- There are no concerns at this time

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

- A paper entitled "Preliminary Results from Steam Oxidation Tests Performed on Candidate Materials for Ultrasupercritical Boilers" was presented at the EPRI International Conference on Materials and Corrosion Experience for Fossil Power Plants, Charleston, SC November 18-21, 2003.
- Monthly status reports were prepared for October, November and December, 2003, and a Quarterly Report was prepared for the July-September, 2003 time period.
- An invitation was received from NIMS to present a steamside oxidation paper at the 8th Workshop on Ultra-Steel in Tsukuba, Japan in July of 2004. NIMS will cover the cost of travel, accommodations and living expenses for this workshop.

Concerns

- There are no concerns at this time.

Activities Next Quarter

- Monthly status reports will be written for January, February and March, 2004.
- A Quarterly Report will be written for October-December, 2003.

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

- There are no concerns at this time

Activities Next Quarter

- B&W will maintain cognizance of ORNL activities pertaining to model alloy test 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

- There are no concerns at this time

Activities Next Quarter

- B&W will maintain cognizance of ORNL activities pertaining to model alloy characterization.

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

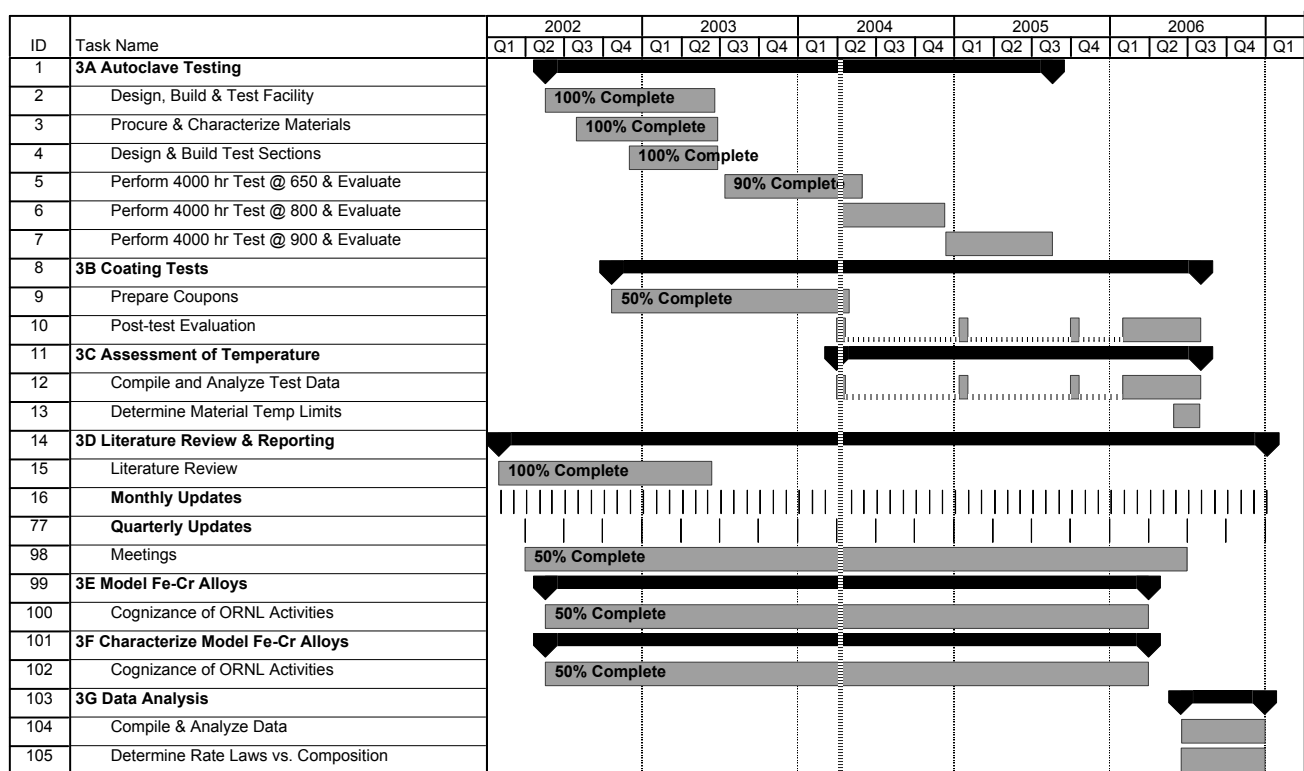
- There are no concerns at this time

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 to fireside corrosion over the full temperature range expected for the USC plant

Task 4A: Laboratory Testing

Objectives

To perform laboratory tests on candidate alloys exposed to various deposits representative of the three coals at the range of temperatures expected for the USC plant.

Progress for the Quarter

- All materials, with the exception of NF 709 have been procured and prepared for testing.
- Two additional furnaces were purchased (resulting in a total number of 6 test furnaces) and piped into the test network.
- Deposit and flue gas compositions have been finalized for both waterwall and superheater/heater conditions. Carbon will be added to both types of deposit to evaluate for carburization of the test materials.
- The reagent chemicals for deposit blending have been procured and blending has commenced.

Concerns

- None.

Plans for the Next Quarter

- Begin testing – six furnaces will be operated simultaneously; three furnaces will be used for waterwall testing and three will be used for superheater/reheater testing.

Task 4B: Corrosion Probe Testing in Utility Boilers

Objectives

To install corrosion probes of various alloys at three coal-fired power plants and control them at the temperature ranges expected for the USC plant.

Progress for the Quarter

- Three host utilities were finalized:
 - First Energy – R. E. Burger Station
 - Xcel Energy – Pawnee Station
 - Cinergy – Gibson Station
- Trip to Gibson Station was made to survey boiler for probe locations.
- Draft copies of a Host Utility Work Agreement were sent out to each utility; comments were received and discussions were held between FW and Host Utility to finalize an Agreement.
- Design of corrosion probe and supporting retraction mechanism continued.

Concerns

- Funding to build and install probes in the current fiscal year.

Plans for the Next Quarter

- Purchase equipment and materials for fabrication of probes.
- Commence fabrication of probes and retraction mechanism.

Task 4C: Steam Loop Design, Construction, and Testing (B&W and Riley Power)

Objectives

- The objectives of this subtask 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 two test loops using commercially available, high temperature corrosion resistant alloys selected for the USC Boiler Development Project.
 - Install and operate the test loops at the Reliant Electric power plant, located in Niles, OH and burning high sulfur Ohio coal, and at another utility.
 - Test and monitor the relative performance of the USC tube alloys, coatings, claddings, and welds which comprise the test loops for a period of 24 months.

Progress for the Quarter

With regard to the test loop at the Reliant Plant:

- Two steam loops were installed in the unit.

- Attemperators and related piping were installed and checked out.
- Installation of all equipment including electrical was completed (except for insulation).
- Off-line checkout of the controls and verification of all instruments was completed.
- All equipment insulation was completed.
- The unit was restarted December 21. Steam temperature is being controlled to 1000°F by the inlet flow control valve until the attemperator controls can be verified on-line.
- Modifications to the Data Acquisition Program (DAP) were initiated to accommodate the new materials.

With regard to the second test loop:

- Dairyland Power agreed in principle to be the second host site. The plant selected is the John P. Magett Generating Station in Alma, Wisconsin. The plant burns PRB coal.
- A host site agreement was drafted by RPI and is currently being reviewed by Dairyland Power.
- A schedule outage is planned for September 19 through November 2004, during which the steam loop can be installed.
- Design of the test loop is ongoing.

Concerns

- None.

Plans for Next Quarter:

- Tune and check attemperator controls on-line and initiate operation at full 1200°F steam temperature (planned for early January).
- Complete modifications to the DAP.
- Monitor operation of the Reliant loops.
- Continue all aspects of the work required for installation of the second loop at Dairyland Power.

Task 5

Welding Development

(Alstom)

The major objectives for Task 5: Welding Development are to define weld metal choices for candidate materials. Establish acceptable welding procedures and practices. Evaluate the effects of manufacturing heat treatments and preheat and post weld heat treatments on weldment integrity and properties.

Produce samples needed to determine the properties of candidate ultrasupercritical alloy welds and weldments, including the dissimilar metal weld joint 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 5A: Selection of Weld Filler Material

Objectives

The primary objective of this subtask is to select and procure appropriate filler materials for each of the welding processes to be studied. However, procurement of base materials and general planning of task activities are also included.

Progress for the Task

- The procurement of Inconel 617 and 82 filler metals for welding the HR6W tubing was completed.
- Apparently, matching filler metals are now available or are being developed for both HR6W and SAFE 12 alloys and procurement of these fillers is being explored. Riley Power Inc. has obtained quotations for the manufacture of the following weld filler materials:

Product	Size
SAVE 12 Flux cored wire	1/16
SAVE 12 Metal cored wire	3/32
SAVE 12 Electrode	1/8
HR6W Flux cored wire	1/16
HR6W Metal cored wire	3/32
HR6W Electrode	1/8

In addition, Riley Power understands from the Sumitomo Houston office that Sumitomo is currently developing weld filler metal for the HR6W material and has developed SAVE 12 filler metal for submerged arc welding.

- Grade 91 tubing was procured for use with Super 304H in dissimilar metal weld joints.
- Standard Inconel 617 filler metal was obtained for making CCA 617 plate weldments using a shielded metal arc process because of the weldability problems encountered with the matching filler metal.
- Difficulties using a matching filler to join Super 304H tubes with a gas metal arc process led to a decision to make the joints with Type 347 filler. However, a source of information at Sumitomo indicated that filler and procedures were actually available for gas metal arc welding. This prompted a renewed interest in the original plans and attempts will be made to qualify the process with both the Type 347 and the new (or matching) Super 304H fillers.

Concerns

The following concerns have been expressed before and are not new.

- Base material sourcing difficulties and long delivery times have, in some cases, delayed the start of welding activities by 9 to 12 months.
- 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 efforts to procure matching filler metals for the HR6W, SAVE 12, and Super 304H materials.

Task 5B: Optimization of Weld Parameters

Objective

The primary objective of this subtask is 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 Task

- **Super 304H**
Tubing was cut and prepared for making Super 304H samples using the qualified gas tungsten arc process.
 - CCA 617 (known in Europe as Marcko).

- Attempts to weld CCA 617 plate using a shielded metal arc welding process were unsuccessful because of poor weldability exhibited by the CCA 617 electrodes. Conventional Inconel 617 electrodes had good weldability and did not exhibit the slag control problems that plagued the CCA 617 filler material. Test plates using both electrodes were prepared with the conventional filler weldment in the flat position and the matching filler weldment inclined for slag control. Side bend specimens from the matching CCA 617 filler weldment passed but the those from the conventional electrode one fractured. A failure analysis is being conducted to determine the causes of this unexpected behavior.
- Tubing was cut and prepared for making CCA 617 test samples using an orbital gas tungsten arc process.
- Plate sections were cut and prepared for making test samples the qualified submerged arc process.
- **Haynes 230**
 - The first 3-inch thick Haynes 230 weld was performed at Haynes using a semi-automatic pulsed gas metal arc process. The plate passed radiographic inspection and was sectioned for procedure qualification coupons.
 - Weldments that have been submitted to ORNL for testing have exhibited creep properties below those for base material and this issue was the subject of a teleconference among Haynes, ORNL, and B&W ARC. Haynes considers that the current data are in line with the previously known results and that the property reduction could be due to the intentional lowering of the weld metal boron content to reduce the propensity for weld metal cracking.
- **Inconel 740**
 - The first 3-inch thick Inconel 740 plate weld was performed by Special Metals using a pulsed gas metal arc process. Liquid penetrant testing produced several indications on the ends of the weld after removing run off areas. Another section taken from the middle of the plate (halfway from the ends) produced only two indications. The weld will be radiographed and a metallographic macro specimen taken from the center of the plate for detailed examination. A decision will then be made regarding further processing of this first weld for procedure qualification or for directing efforts to eliminate the linear indications.
- **HR6W**
 - Two welding processes were qualified for joining tubing using Inconel 82 filler metal: a gas metal arc process and a combination gas tungsten arc and shielded metal arc fill process. Similar weldments were also produced using Inconel 617 filler and the qualification tests are currently underway.

▪ **SAVE 12**

- Delivery of the SAVE12 filler materials has been delayed and, although a thick-walled weldment is still planned, the possibility of machining 2" OD x 0.400" wall tubes from 13.78" OD x 2.0" wall SAVE 12 pipe spools is being considered. This would enable the initial qualification of welding processes for the SAVE12 material using thick wall tubes rather than the full pipe section currently available and provide tube bending and fabrication experience similar to that being obtained for the HR6W material.

Concerns

- Submerged arc welding, a high deposition rate process favored by boiler makers 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.

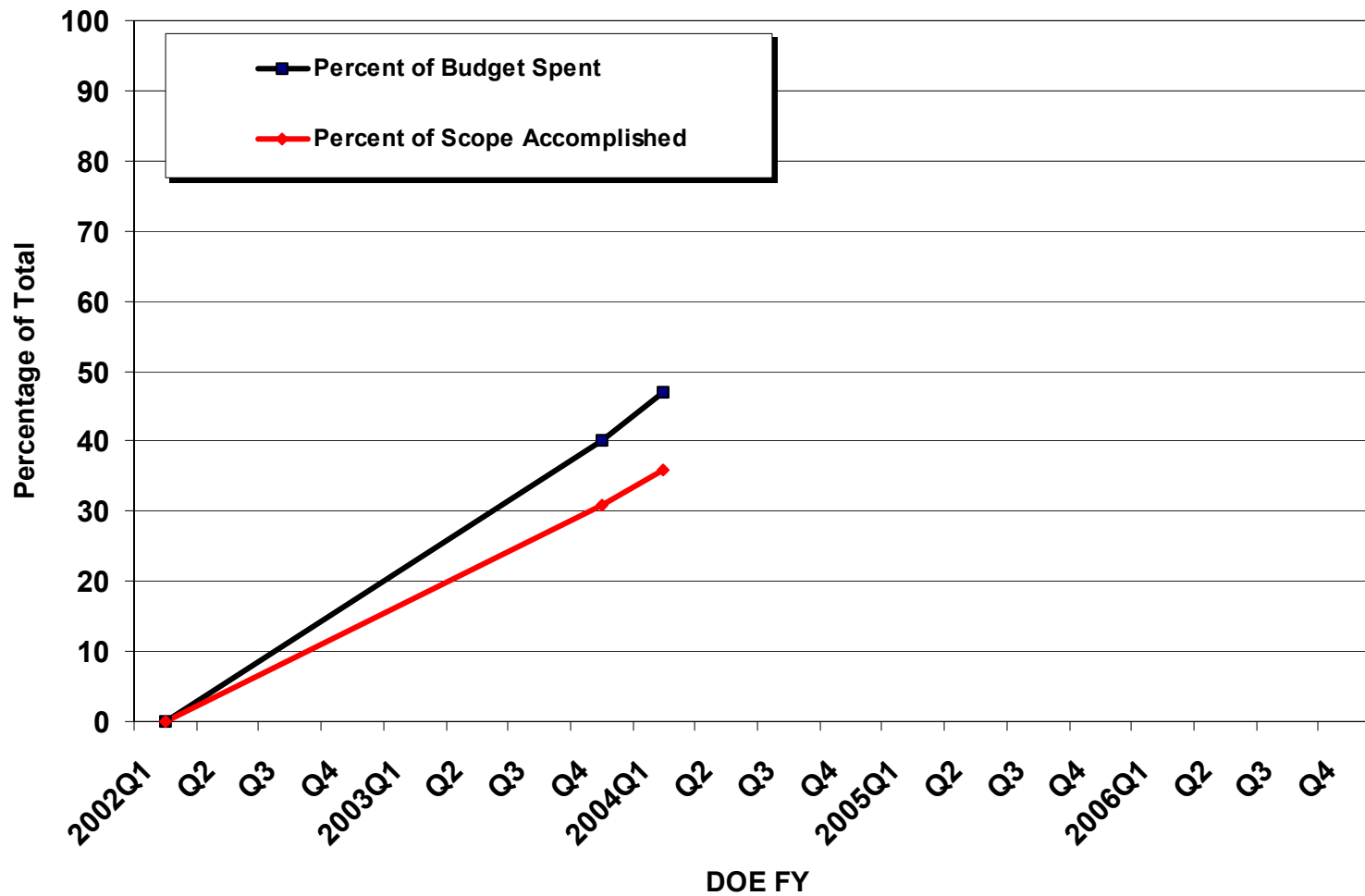
Plans for the Next Quarter

- Make five, 36-inch long weld joints for ORNL testing using 1¼" thick Inconel 740 plate.
- Investigate cause for linear indications in thick Inconel 740 welds.
- Qualify gas tungsten arc procedure and make butt welds using Inconel 740 tubing.
- Complete qualification and welding of thick Haynes 230 plates using a gas metal arc process.
- Complete qualification and welding of thick Inconel 740 plates using a gas metal arc process.
- Fabricate Super 304H test specimens using gas tungsten arc process.
- Resolve issues with gas metal arc welding of Super 304H.
- Fabricate test specimens using gas tungsten arc process on CCA 617 tubing.
- Continue investigation of difficulties with shielded metal arc welding of CCA 617 plate.
- Fabricate test specimens using submerged arc process on CCA 617 plate.
- Continue evaluation of HR6W tubing welds made with Inconel 617 filler metal.
- Discuss pulsed gas metal arc welding of nickel based alloys with Lincoln Electric engineers who have recently developed techniques for this family of alloys. Possibly perform a thick section weld with their equipment for evaluation.

Task 5: Welding Development - Milestone Chart
(DOE Fiscal Year Basis)
(percentages indicate fraction of workscope completed as of 2004Q1)

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% ▲															
		▲				95%				▲											
		▲				75%				▲											
5B	Optimization of Welding Parameters • Preliminary weld trials and parameter optimization – thin section. • Preliminary weld trials and parameter optimization – thick section.					45%				▲											
						35%				▲											
5C	Preparation of Laboratory Samples • Material preparation. • Sample fabrication.					20%				▲											
						15%				▲											
5D	Weldability Testing									0% ▲											
5E	Examination of Dissimilar Metal Welds. • Weld trials • Metallurgical analysis • Analysis and test case.					0%				▲											
						0%				▲											
						0%				▲											

Accomplishments Versus Expenditures



Task 6 Fabrication

The objective of Task 6 is to establish boiler fabrication guidelines for the high temperature, corrosion resistant alloys selected for the USC Project. The principle 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

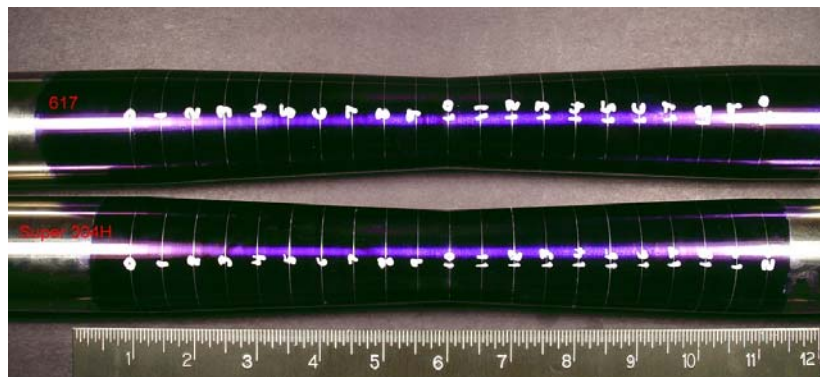
- A plan for the fabrication of the alloy materials HR6W and SAVE12 was prepared. The plan includes bending tests, PWHT requirements, machining, swaging, drilling, cutting and pressing operations for these materials.
- Sample materials of the HR6W and SAVE12 materials were sent to Foster Wheeler in order to perform recrystallization studies on these materials.
- Tube U-bends of the 2" OD X 0.400" MW HR6W tubing were produced with strains of 15%, 20% and 35% without difficulty, and results are shown in the image below.



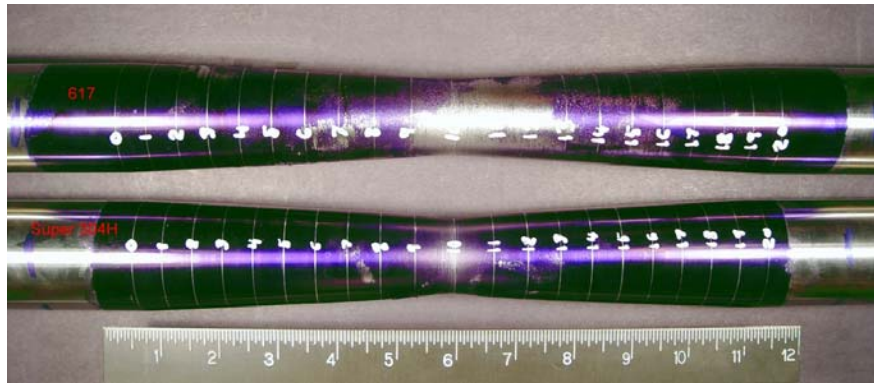
DIGITAL IMAGE SHOWING U-BENDS OF HR6W TUBING WITH STRAINS OF 15%, 20% AND 35%.

- HR6W tubing 3/16" on the OD was successful in swaged in a singular stage using deep draw and stamping lubricant. In a subsequent swage reduction attempt, the tube material stalled the machine, probably due to the high work hardening rate of the HR6W. Intermediate annealing will probably be necessary in order to achieve further reductions.

- Efforts towards developing fabricability assessment procedures and operations were continued during task member teleconferences and meetings. Existing data regarding recrystallization and phase precipitation and dissolution in Super 304H and Inconel 617 (considered reasonably representative of CCA 617) are being compiled so that details of these procedures can be established.
- Machining and straining of the CCA 617 and Super 304H tapered tubes to be used for the cold working studies was completed. These tubes were delivered to the Alstom laboratory and are being prepared for heat treatment, hardness testing, and microstructural examination.
- Initial attempts at swaging the 2-inch X 0.4-inch MWT Super 304H and CCA 617 tubes in their original configurations were unsuccessful. The Super 304H could only be swaged from 2 to 1-3/4 inches and the CCA 617 from 2 to 1-7/8 inches. Configurations commonly swaged when working with Type 347 tubing are being studied in order to plan the next attempts, which will probably involve boring the ID's to reduce the wall thicknesses.
- The configuration of the tapered-tube test specimen for the recrystallization studies was finalized.
- Tapered-tube specimens were machined from the 230, Super 304H, CCA 617, and IN-740 and strained.
- The range in strain levels achieved was: 1 - 33% (230), 1 - 36% (Super 304H), 1 - 41.4% (CCA 617), and 1- 40% (IN-740).
- The representative appearance of the specimens before and after testing is shown in the images below.



Tapered tube specimens shown before controlled strain testing.



Tapered tube specimens shown after controlled strain testing.

- A 27" alloy 230 tube sample was sent to Foster Wheeler for use in conducting strain response recrystallization/precipitation studies.
- A technical approach for conducting swaging trials with alloy 230 tubing was developed, since it is believed that attempts to swage 2.00" X 0.400 MW tubing (as delivered) will stall B&W's swaging equipment. The concept involves boring the ID of 18" lengths to establish MW of 0.200'.
- Technical literature concerning thermal treatment and carbide precipitation kinetics were reviewed to help determine optimum conditions for conducting the strain response recrystallization/precipitation studies.
- A Task 6 Committee meeting was planned and held prior to the USC Steering Committee meeting in Columbus, OH on November 12th.
- A list of questions relative to the fabrication of USC alloys was prepared and distributed for use by Task 6 participants in gaining more information from the material suppliers on fabricating these materials.

Concerns

None.

Plans for the Next Quarter

- Machining of 2" OD X 0.400" tube sample(s) from spool piece section(s) of the SAVE12 heavy wall pipe. This would involve having sections of the SAVE12 material sliced or cut from a spool piece of the 13" OD X 2.00" MW pipe spools in order to produce solid bars of the SAVE12 material and machining and boring the bar(s) to produce a 2" OD X 0.400" wall SAVE12 tubes. This process would facilitate the welding qualification of the SAVE12 material, as well as to produce SAVE12 material for a similar fabrication processes as implemented for the qualification of the HR6W material.

- Continue developing the details of tests required to assess the cold formability of CCA 617 and Super 304H tubing.
- Completing the heat treating and examination of the tapered tubes used for the cold working studies.
- Determine the sensitivity of Super 304H to strain induced embrittlement.
- Characterize materials (microstructure and hardness) in the as-strained condition.
- Research and finalize exposure temperatures/times for the strained specimens.
- Machine and prepare strain tapered specimens from the HR6W and SAVE 12 material.
- Alloy 230 U-bend samples produce last June in a B&W production facility will be sent to ORNL for testing.
- Selected microstructural specimens from the alloy 230 tube bends will be prepared and examined.
- Two 10-foot straight lengths of alloy 230 tubing will be sent to Riley Power's manufacturing plant (Erie, PA) for their use in constructing a test loop.
- Tube lengths of alloy 230 will be ID machined to produce 0.200" MW specimens for swaging.
- Plans will be finalized for conducting swaging trials at a B&W production facility.
- Selected macrostructural specimens from 3" thick alloy 230 plate (used in Task 3) will be prepared and examined to investigate grain size uniformity through the thickness of this material.
- A Task 6 teleconference will be held among Task 6 participants to jointly share information gained on fabricating USC alloys and to review plans and progress.

Task 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
1	Task 6: Fabricability	Tue 4/2/02	Thu 3/31/05	In Progress																										
2	6A: Fab Trials for SH	Wed 1/2/02	Tue 11/30/04	In Progress																										
3	6A.1 SH Trial	Tue 1/1/02	Thu 9/9/04																											
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 6/4/04	In Progress																										
7	Cold Bending Trials	Mon 6/2/03	Fri 6/4/04	In Progress																										
8	Cold Swaging Trials	Mon 6/2/03	Fri 6/4/04	In Progress																										
9	Butt Welding Trials	Mon 6/2/03	Fri 6/4/04	In Progress																										
10	Attachment Welding Trials	Mon 6/2/03	Fri 6/6/04	In Progress																										
11	6A.2 Reporting	Fri 1/3/03	Fri 1/23/04	In Progress																										
12	6A.3 SH Met Test & Eval	Fri 1/9/04	Fri 6/6/04	Planned																										
13	6A.3.1 Mic Bends&Welds	Fri 6/4/04	Wed 7/28/04	Planned																										
14	6A.3.2 HT Studies&Mic	Fri 6/4/04	Thu 8/19/04	Planned																										
15	6B: Fab Thk Wall Comp	Thu 1/2/03	Thu 3/31/05	Planned																										
16	6B.1 Thick-Wall Fab Trial	Fri 1/9/04	Mon 6/21/04	Planned																										
17	6B.2 Reporting	Fri 1/9/04	Thu 3/31/05	Planned																										
18	6B.3 Thick-Wall Comp	Fri 1/9/04	Fri 10/29/04	Planned																										
19	6B.3.1 Met Analysis	Wed 9/29/04	Mon 1/31/05	Planned																										
20	6B.3.2 PWHT Studies&Mic	Wed 9/29/04	Fri 12/31/04	Planned																										

Task 7 Coatings (Alstom)

The major objectives for Task 7 Coatings are:

- 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 7C: Coating Recommendations

Objective

Provide an evaluation of scaleup potential and costs for internal tube coating systems.

Progress for the Quarter

Waiting finalized data from other subtasks.

Concerns

No concerns at this time.

Plans for the Next Quarter

Continue evaluation of ID coating requirements.

Task 7D: Laboratory Testing

Objective

Evaluate corrosion/oxidation response of candidate coating systems.

Progress for the Quarter

No activity.

Concerns

None.

Plans for the Next Quarter

- Review need for any additional steam oxidation tests and execute as necessary.
- Define additional laboratory testing needs.

Task 7E: Process Scaleup

Objective

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

Progress for the Quarter

Part 1: B&W Effort

- ASB has completed HVOF and Cold Spray parameter development for depositing 50Ni/50Cr on carbon steel and Haynes 230 tubing. Thin plate samples were used to evaluate a matrix of parameters for both processes. Based on these results, optimum parameters were selected and used to coat Haynes 230 tubes. These tubes will be provided to Foster Wheeler (FW) for use in corrosion probe testing. Due to the nature of these coatings and due to the configuration of the test samples being used by FW, it will not be possible to include HVOF or Cold Spray coated samples in FW's laboratory test program.
- ASB has been released to begin developing plasma transferred arc (PTA) parameters for deposition of 50Ni/50Cr. Alloy powder will be used in this assessment. Initial feedback is that previous, similar tests have resulted in fouling of the plasma torch, and discussions are ongoing to resolve how to proceed. If this process can successfully be developed, the intent would be to use it to evaluate alternative coating compositions using 50Ni/50Cr as the baseline. Ideally any alternatives, including 50Ni/50Cr would be tested in corrosion probe work. However, it also may be possible to generate coupon specimens for FW laboratory testing.
- In October, Praxair agreed to provide a quote for developing laser-cladding parameters for depositing 50Ni/50Cr. At the time the earliest schedule opening for doing this work was in March 2004. They were contacted in early December and reconfirmed that they would provide the quote, but it has not been received to date. Due to the short time available to develop samples for testing by FW, alternative sources for this work are being investigated.

Part 2: Alstom Effort

- Chromizing: Samples of S304H and T-92 tubing were coated using the ALSTOM commercial formulation. The tests were conducted bringing the pack load to

temperature in a fashion to minimize the spread in temperature, as measured by control thermocouples, to less than 200 F. The packs were brought in steps, first heating with the set point at 1500 F and progressively raising the temperature to 1800 F. Once all the control thermocouples were about 20 F from 1800 F, the temperature of the pack was raised to achieve the processing temperature of 2060 ± 20 F. During all tests the temperature was not allowed to exceed 2100 F and the hold time of 16 h began when the lower temperature in the load was 2040 F.

a. S304H tubing:

- The Cr-concentration in the diffusion layer remained above 30 wt% through the layer thickness, Figure 1. The effect of temperature was primarily reflected in the coating thickness without affecting the Cr-concentration profile with a 25 μm (1 mil) difference in thickness between the ID and OD coatings as indicated by Figure 2. The diffusion layer varied from 180 to 250 μm (7 to 10 mils) in the temperature range 2050 to 2095 F for relatively similar hold times. The diffusion layer had an average microhardness of 67 RC and tended to delaminate at the coating/base metal interface upon bending. The composition of the layer suggests the formation of sigma phase. A post heat treatment followed by a quench may destabilize the hard phase making it possible to coat and bend for the construction of superheater/reheater tubing banks. The microhardness of the base metal was not affected by the coating process conditions. The diffusion layer did not present the formation of voids typical of the chromizing of low-alloy ferritic steels.

b. T-92 tubing

- The Cr-concentration profiles in the diffusion layers formed in alloy T-92 are apparently more susceptible to temperature variations. It is apparent from Figure 3 that the process requires temperatures in excess of 2060 F to achieve the required Cr-concentration of 25 wt% in the ID layers. The thickness of the ID diffusion layer varied from 355 to 500 μm (14 to 20 mils) and the difference in thickness between the ID and OD layers was as much as 7 mils, Figure 2. The microhardness of the diffusion layer varied from 96 RB at the surface of the coating to 79 RB approaching the coating/base metal interface. The base metal hardened with an average microhardness of 35 RC. The diffusion layer showed an outer layer rich in Cr and N from 1 to 2 mils in thickness; the grain boundaries of the layer were free of precipitates. The product was bent to 180° in the as-coated condition with no cracking or delamination of the diffusion layer.

▪ Cr-Al layers:

Tests were conducted to coat both S304H and T-92 type tubing material with a diffusion layer of the $(\text{Fe,Cr})_3\text{Al}$. The formulation used was based on the same

activator system to be used for the Cr-Si layers. The activator is a mixture of CaF_2 and NH_4Cl . The Cr-Si formulation was demonstrated by earlier laboratory to be forgiving in terms of process conditions leading to product consistency. From the point of view of future commercialization, the opportunity to utilize common consumables can result in savings through bulk volume purchases.

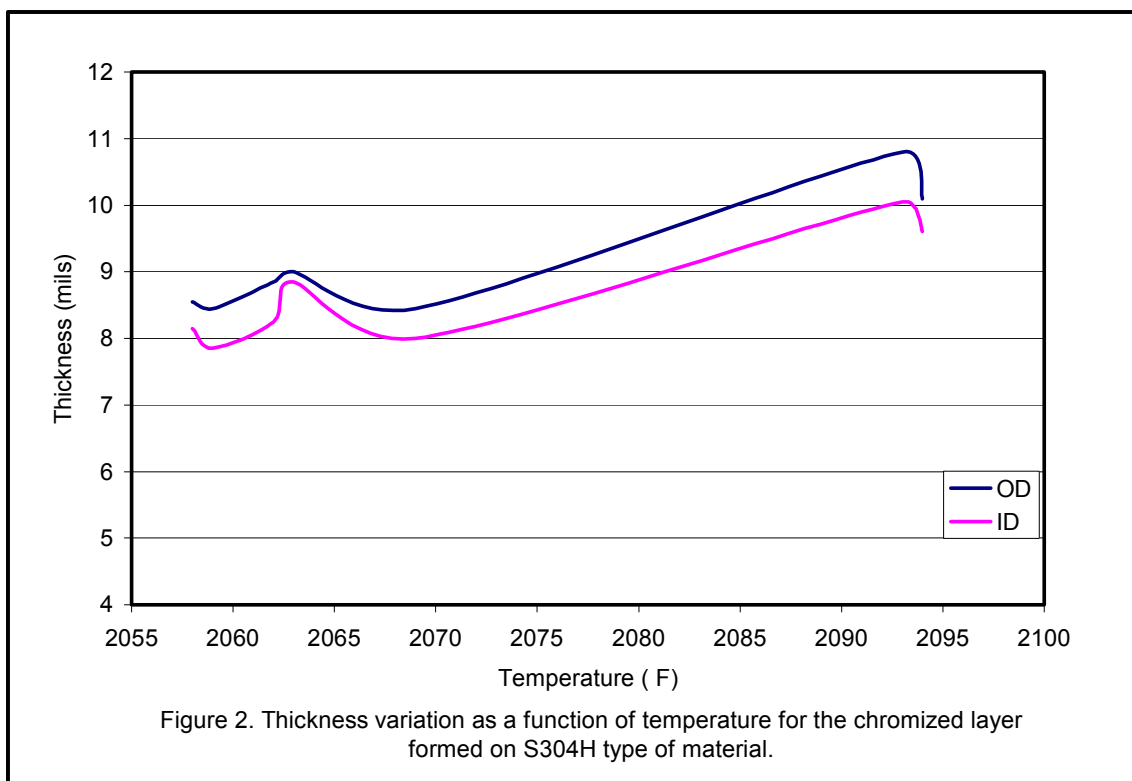
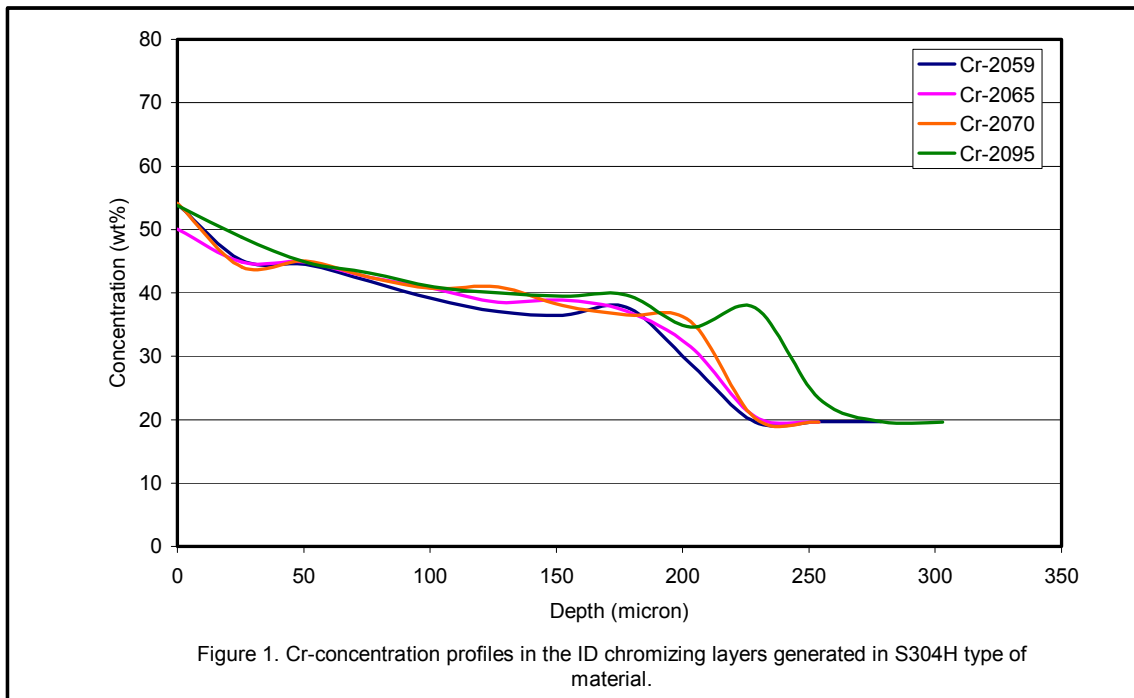
The desired product should have a maximum Al content below 16 wt% with an optimum of 10 wt % to avoid cracking upon welding and to confer acceptable oxidation performance. No limit requirements have been defined in terms of Al content for resistance to oxidation in steam.

a. S304H Tubing

- The Al and Cr concentration profiles in the ID and OD layers formed in S304H material are depicted in Figure 5. The irregular contour of the profiles is associated with the distribution of Ni in the layers. The OD layers show maximum Al-contents of nearly 10 wt%; however, in the ID layer the maximum Al-content is less than 5 wt %. The Cr-content remained above 20 wt% regardless of temperature as illustrated in Figure 6. There was no apparent variation in between the OD and ID thickness. The microhardness of the layer was below 97 RB. The appearance of Al-N particulate through halfway the coating thickness was typical of Cr-Al coatings.

b. T-92 tubing

- A similar trend in the Al and Cr concentration profiles was observed in the diffusion layers formed in T-92. The OD layers revealed maximum Al-contents in excess of 10 wt% while in the ID layer the Al-content did not exceed 4 wt%, Figure 7. The Cr-content remained above 9 wt% through the coating thickness. Similar to the layer formed in S304H the precipitation of Al-N was observed through halfway the coating thickness. The microhardness of the diffusion layer was similar to that obtained on S304H. The diffusion layers were about 50 % thicker than in S304H. Bending tests using remnant S304H and T-92 coated material are proposed as follow up activity. The lower Al-content obtained in the ID layers confirmed results reported earlier from laboratory validation tests. The lower Al-content was originally ascribed to a lower throwing power due to a limited source of pack material because of the small ID bore tubing used in the laboratory tests. However, the results using the S304 material dismiss this reason. Tests 11 through 14 to be conducted later will utilize a formulation using $\text{MgCl}_2\text{-NH}_4\text{Cl}$ activator source.



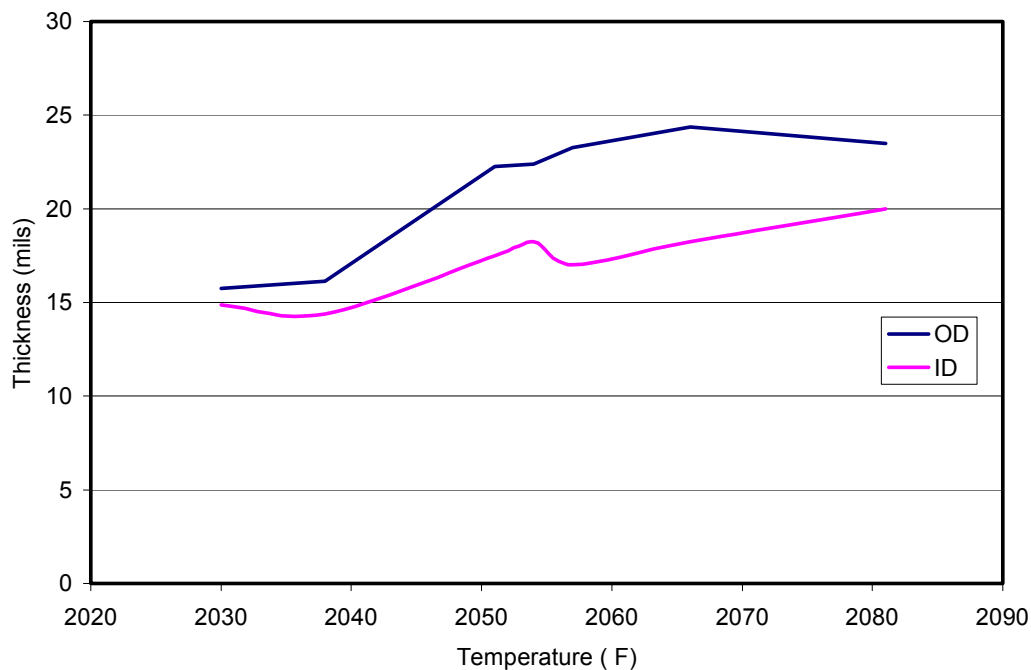


Figure 4. Coating thickness as a function of time during the chromizing of T-92 material.

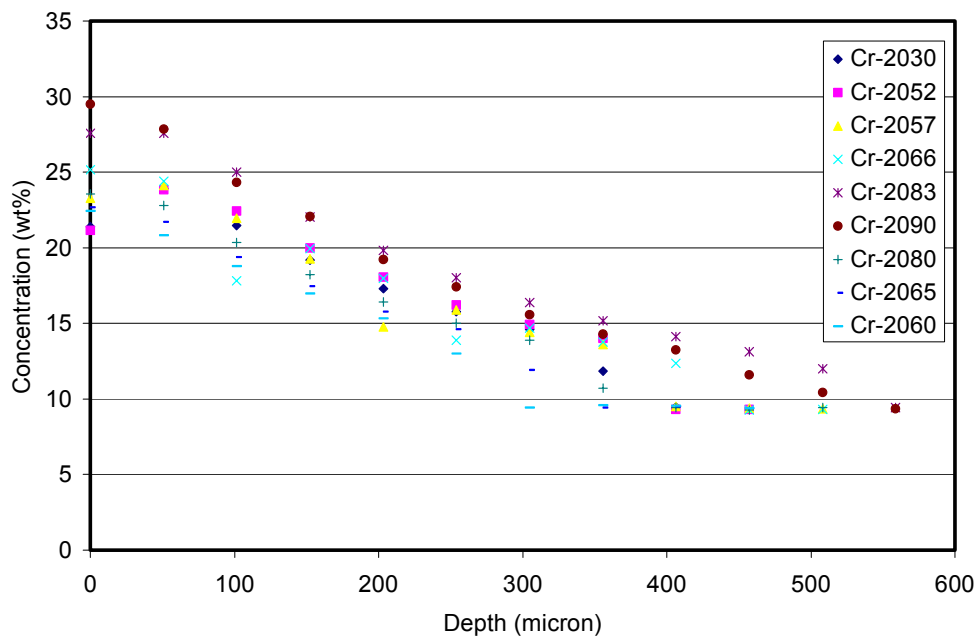
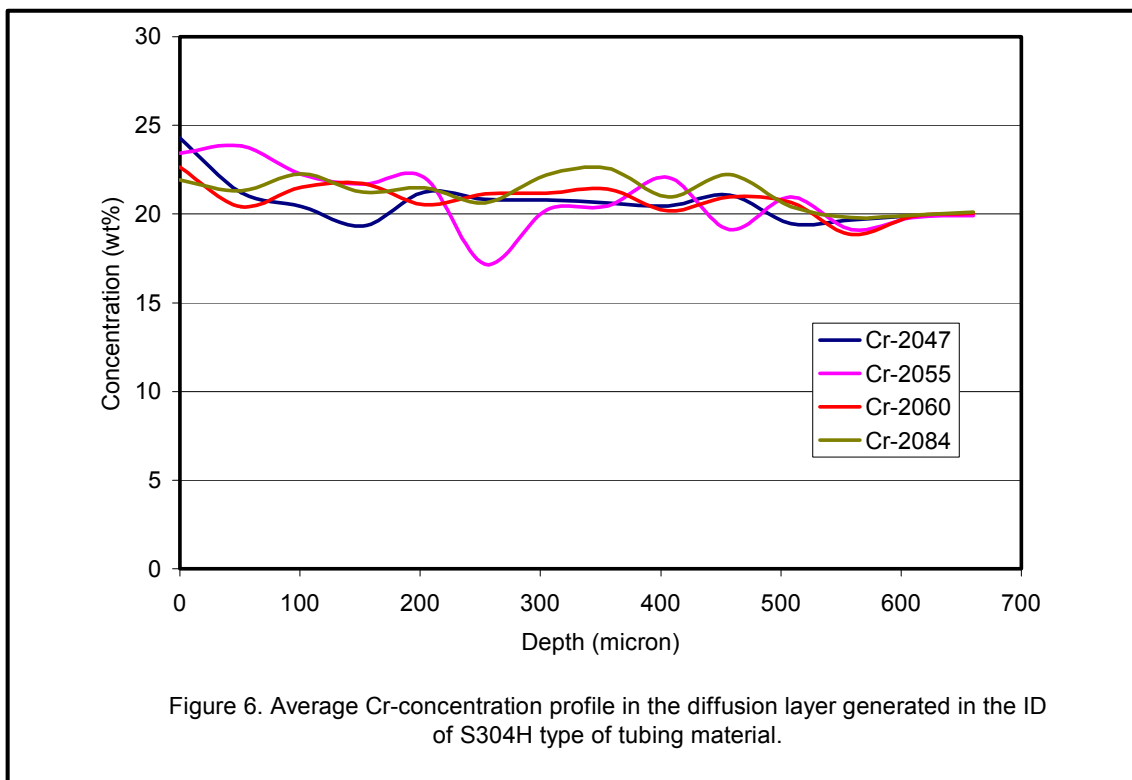
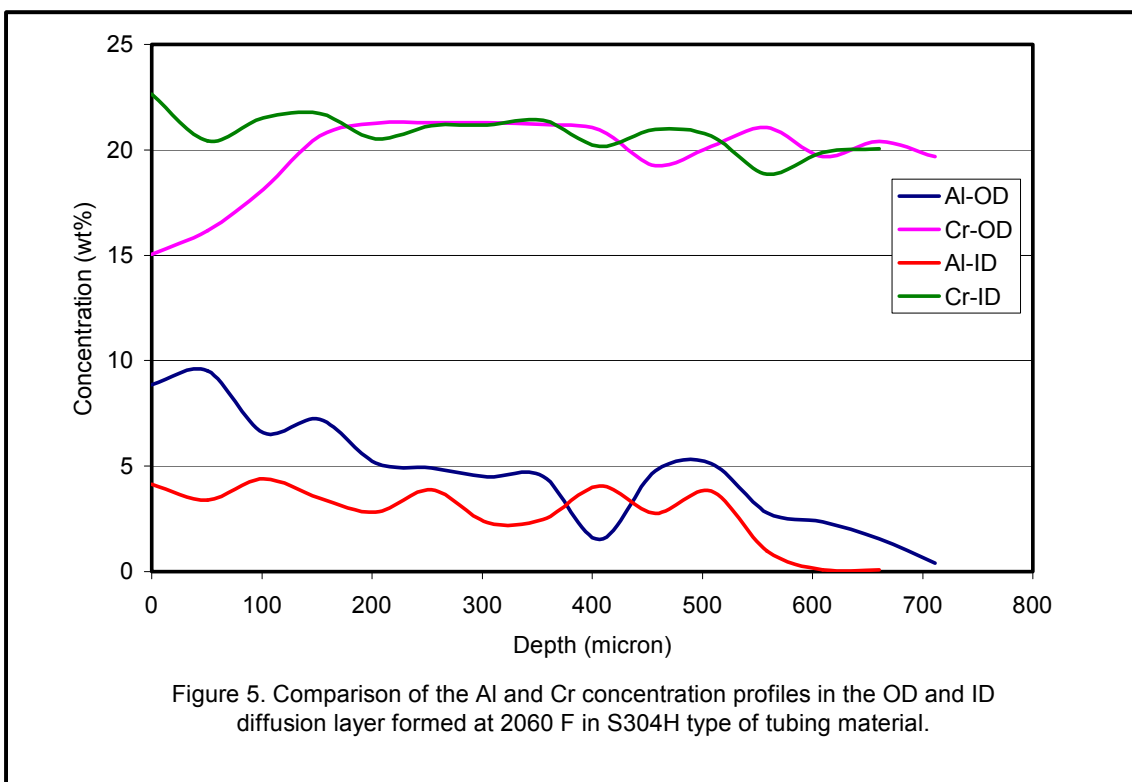


Figure 3. Cr-concentration profiles for the ID diffusion layer formed in T-92 alloy as a function of temperature.



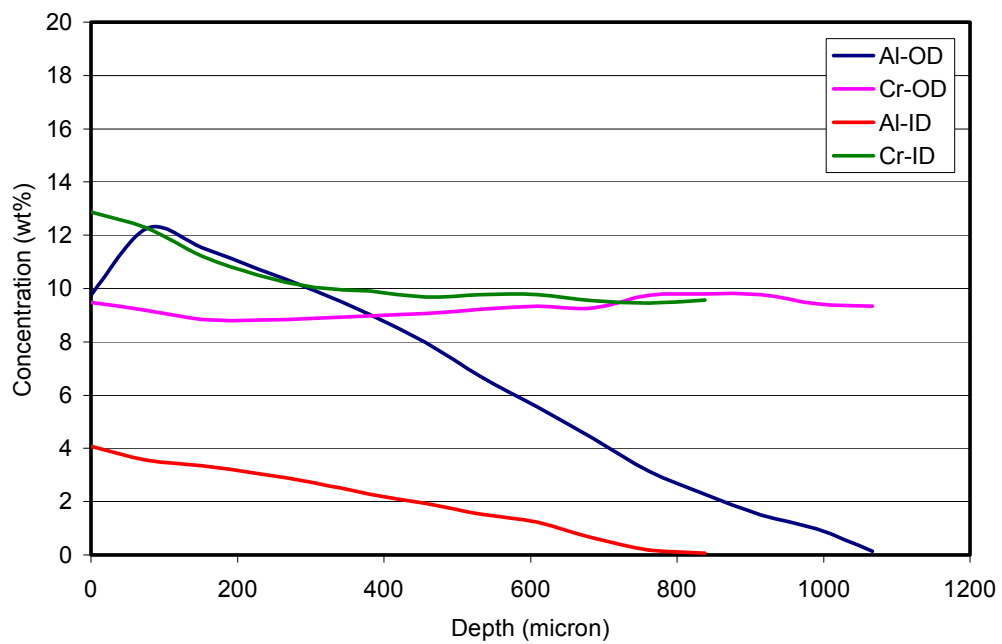


Figure 7. Comparison of Al and Cr concentration profiles formed in the OD and ID of T-92 type of tubing material at 2070 F.

Concerns

For various reasons, it may not be possible in a timely manner to develop PTA deposition or laser cladding parameters for the alloy family of interest.

Plans for the Next Quarter

- Provide HVOF and Cold Spray coated samples to FW for inclusion in their corrosion probe. Continue to pursue development of PTA and laser deposition parameters for 50Ni/50Cr and related alloys. If possible, provide samples to FW for inclusion in lab testing and for their corrosion probe work.

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

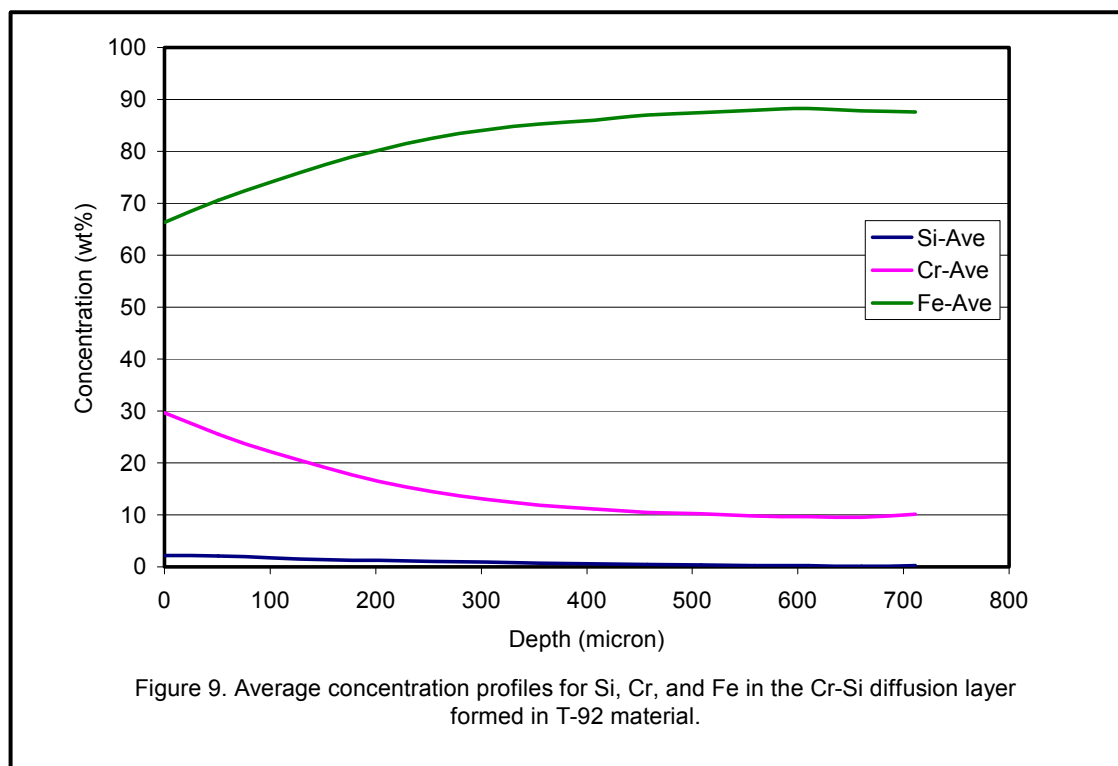
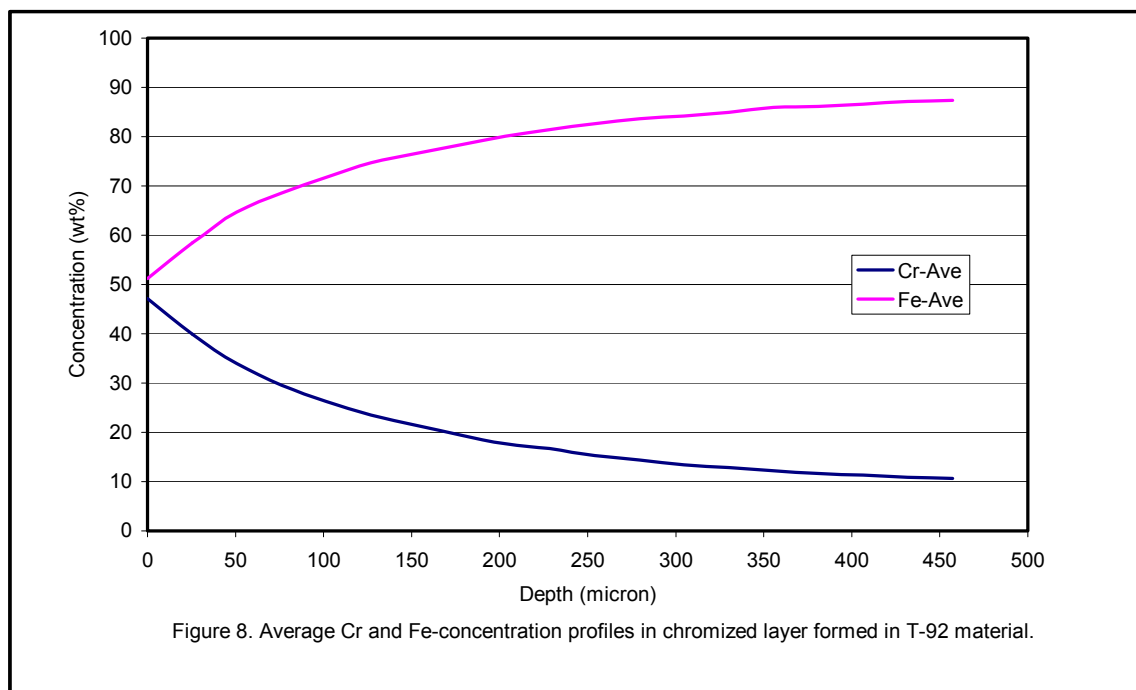
Samples of T-92 tubing were coated for waterwall fireside corrosion tests that will be conducted by Foster Wheeler as described in Task 4 of the contract. The coatings included chromizing, Cr-Si, and Cr-Al diffusion coatings. Coupons were shipped to FW in December. Table 1 summarizes the results in terms of coating thickness and maximum concentration for the major alloying elements of the coating.

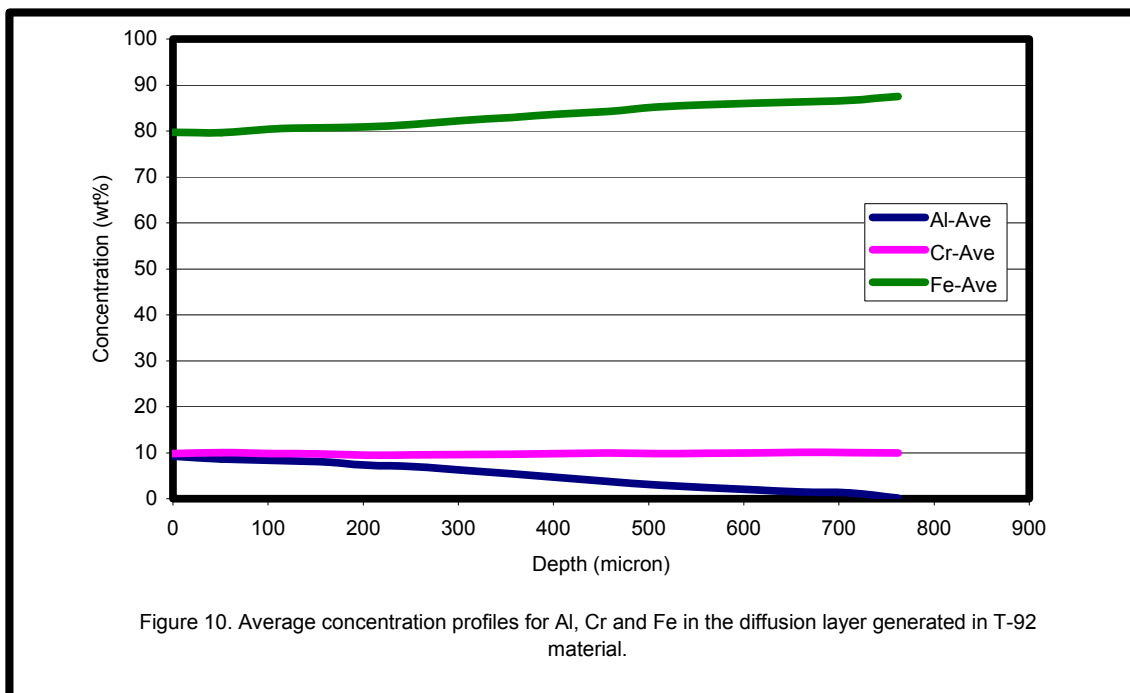
Type of diffusion coating	Thickness (mils, μm)	Concentration (wt%)
Chromizing	19 , 483	47 Cr, 51 Fe
Cr-Si	23 , 600	30 Cr, 2 Si, 66 Fe
Cr- Al	28 , 712	10 Cr, 10 Al, 80 Fe

Table 1. Characteristics of the diffusion layers generated in alloy type T-92.

The chromized layer showed clean grain boundaries with subsurface porosity limited to 25 μm from the surface, Figure 8. The Cr-concentration decreased through the coating thickness to the base metal value at the coating/base-metal interface. A Cr-N layer at the surface was not apparent in these samples.

Similarly, the Cr-Si diffusion layer also showed clean grain boundaries with subsurface porosity limited to 25 μm from the surface, Figure 9. The Cr-Al diffusion coating showed the typical precipitation of Al-N particulate with a thin outer growing layer. The maximum Al-content was at the desired value of 10wt%, Figure 10.





In addition to the fireside corrosion coupons, sets of coupons were nearly completed for the next stages of Task 3 Steam Oxidation testing by B&W. Chromized, Cr-Si, and Cr-Al diffusion coated specimens of Super 304H. These are slated for testing at 800 and 900 C. At year-end, the coating runs had been completed and will be shipped after final inspection.

Discussions are in progress with Riley Power and Foster Wheeler concerning additional tube specimens for the steam loop and corrosion probe field tests.

Concerns

None.

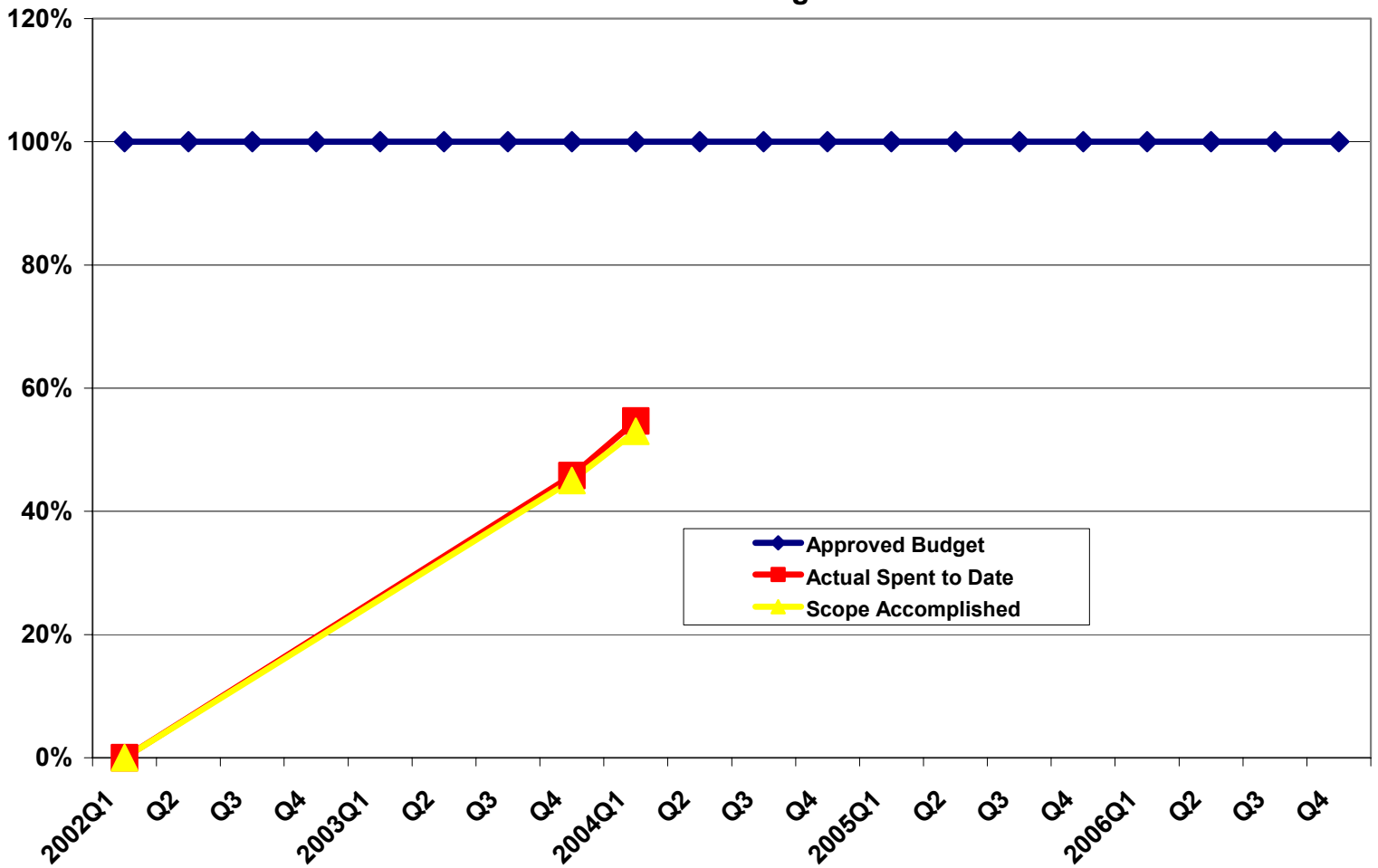
Plans for the Next Quarter:

Finalize schedule for coatings test samples for the second steam loop and corrosion probe field exposures.

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	Qtr 4
Task 7: Coatings																					
Task 7A: Detailed Study of Current State of the Art																					
Alstom Task 7A: Detailed Study of Current State of the A	Complete																				
Task 7B: Coating Feasibility (Internal Coating)																					
Alstom Task 7B: Coating Feasibility (Internal Coating)	95%																				
Task 7C: Coating Recommendations																					
Alstom Task 7C: Coating Recommendations	15%																				
Task 7D: Laboratory Testing																					
Alstom Task 7D: Laboratory Testing	50%																				
Task 7E: Process Scale Up - Preliminary Trials																					
Alstom Task 7E: Process Scale Up - Preliminary Trials	40%																				
B&W Task 7E: Process Scale Up - Preliminary Trials	25%																				
Task 7F: Process Optimization																					
Alstom Task 7F: Process Optimization																					
B&W Task 7F: Process Optimization																					
Task 7G: Manufacturing Recommendations																					
Alstom Task 7G: Manufacturing Recommendations																					
B&W Task 7G: Manufacturing Recommendations																					
Task 7H: Specimens for Field Corrosion/Oxidation																					
Alstom Task 7H: Specimens for Field Corrosion/Oxidation	40%																				
B&W Task 7H: Specimens for Field Corrosion/Oxidation	40%																				
Task 7I: Project Management																					
Alstom Task 7I: Project Management	Ongoing																				
B&W Task 7I: Project Management	Ongoing																				

Note: Dates refer to DOE fiscal year calendar 10/01/yyyy to 09/30/yyyy+1

Budget Versus Actual Expenditures
Task 7 Coatings



Task 8 Design Methods and Data (Alstom)

The major objectives for Task 8 are:

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

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

Task 8A: Task Management (ALSTOM)

Objective

The primary objective of this subtask is:

Overall management of the task, coordinating meetings and preparing progress reports.

Progress for the Quarter

Progress was made to resolve the work scope issues and contribution from each of the participants. Foster Wheeler appointed a new representative to Task 8, thereby establishing the first contribution to the task from FW. A meeting was also held in early December, at the ALSTOM offices in Windsor, CT, to resolve the outstanding issues associated with the Task. Representatives from all OEMs attended and provisional subtask assignments were made. Work continues to confirm commitments from each participant.

The Gantt chart for Task 8, showing the overall plan and progress to date is included in Appendix A.

Concerns

The basic concerns expressed last quarter have now been resolved, although continued effort is required 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

ALSTOM will work with the Task participants to update the project plan and develop the necessary information to manage the Task and report progress in accordance with the requirements of the project.

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 correlations.

Deliverables

Item	Responsible	Status
Material data transfer sheets	ALSTOM	Transfer sheets provided for creep and tensile tests.
Electronic data repository	ORNL	No progress to report.
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

Foster Wheeler volunteered to act as subtask leader, with Riley Power Inc. offering to provide significant input to this subtask.

Concerns

No progress reported by ORNL on the implementation of an electronic data repository (web or ftp site) for material test data.

Plans for the Next Quarter

Ensure that ORNL works to make test data available in electronic format. Begin developing methods and tools for statistical analysis of material data.

Task 8C: Design Rules (B&W)

Objective

Develop and present to ASME, alternative design rules incorporating the outputs of the other tasks and subtasks.

Deliverables

Item	Responsible	Status
Report on overall accomplishments for subtask	B&W	
Design rules (code case) for unwelded parts	ALL	
Design rules (code case) for parts with similar metal welds.	ALL	
Design rules (code case) for parts with dissimilar metal welds.	ALL	

Progress for the Quarter

There will be no technical progress on this sub-task until the outputs of other Tasks and subtasks are available. However, in this quarter, a number of Task 8 participants (ALSTOM, B&W and RPI) attended a workshop on "Elevated Temperature Design" organized by the Materials Properties Council and the Pressure Vessel Research Council. This provided an overview of the recent worldwide efforts to codify high temperature design.

Concerns

None.

Progress for the Next Quarter

None.

Task 8D: Reference Stress Methods (ALSTOM)

Objective

Develop and issue a description of reference stress methodology and its application to ASME geometries.

Deliverables

Item	Responsible	Status
Topical report on reference stress methods including compendium of solutions.	ALSTOM	Complete (Aug 2003)
Example ASME problem showing use of reference stress and comparison with "full" analysis.	ALSTOM	Complete (Sept 2003)

Progress for the Quarter

Subtask complete.

Concerns

None.

Progress for the Next Quarter

None.

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

Objective

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.

Deliverables

Item	Responsible	Status
Report to summarize data fitting of CDM parameters for physically based on Omega creep models.	B&W	
Report to summarize multiaxial models and recommend an appropriate model for USC materials.	ALSTOM	
User material subroutine for use with finite element code (e.g. ABAQUS) and analysis of component/feature tests.	ALSTOM	
Report on cyclic creep studies and implications for design of components.	B&W	
Report to summarize the analysis and validation tests and component simulations, including comparisons between approaches (CDM, Omega, reference stress, etc.)	ALL	

Progress for the Quarter

Subtask leader (B&W) was appointed. A subtask was added to address the implications of cyclic creep for USC materials. B&W ran preliminary benchmark procedures in order to verify understanding of CDM principles.

Concerns

Timely availability of material data in electronic format.

Progress for the Next Quarter

Review of literature and benchmarking of procedures will continue. Work will start on the Cyclic Creep subtask by evaluating a flawed header component made of P91 material.

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	
Creep models for weld metal and HAZ regions.	ALSTOM	
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

A literature review was started and some relevant papers obtained. A copy of the proceedings was obtained for a recent conference (November 2003) entitled "Integrity of High Temperature Welds". Riley Power Inc. has volunteered to assist in the literature review and development of analytical methods for weld assessment.

Concerns

This subtask has fallen behind schedule but the prognosis for the next quarter is encouraging now that work scope issues are largely resolved.

Progress for the Next Quarter

Continue literature review and prepare a report to summarize issues and methods for weld assessment. Work will begin to collate mechanical property data for weld metal and HAZ regions.

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

Objective

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:

A submission on new rules for tube wall thickness calculation was made to Section I, Sub Committee Design of the ASME Boiler Code, for comments. An extract of the submission, giving the proposed Code language, is included in Appendix B. This completes the majority of the technical work for this subtask. Further work will be undertaken as necessary to address the comments from the Code committee.

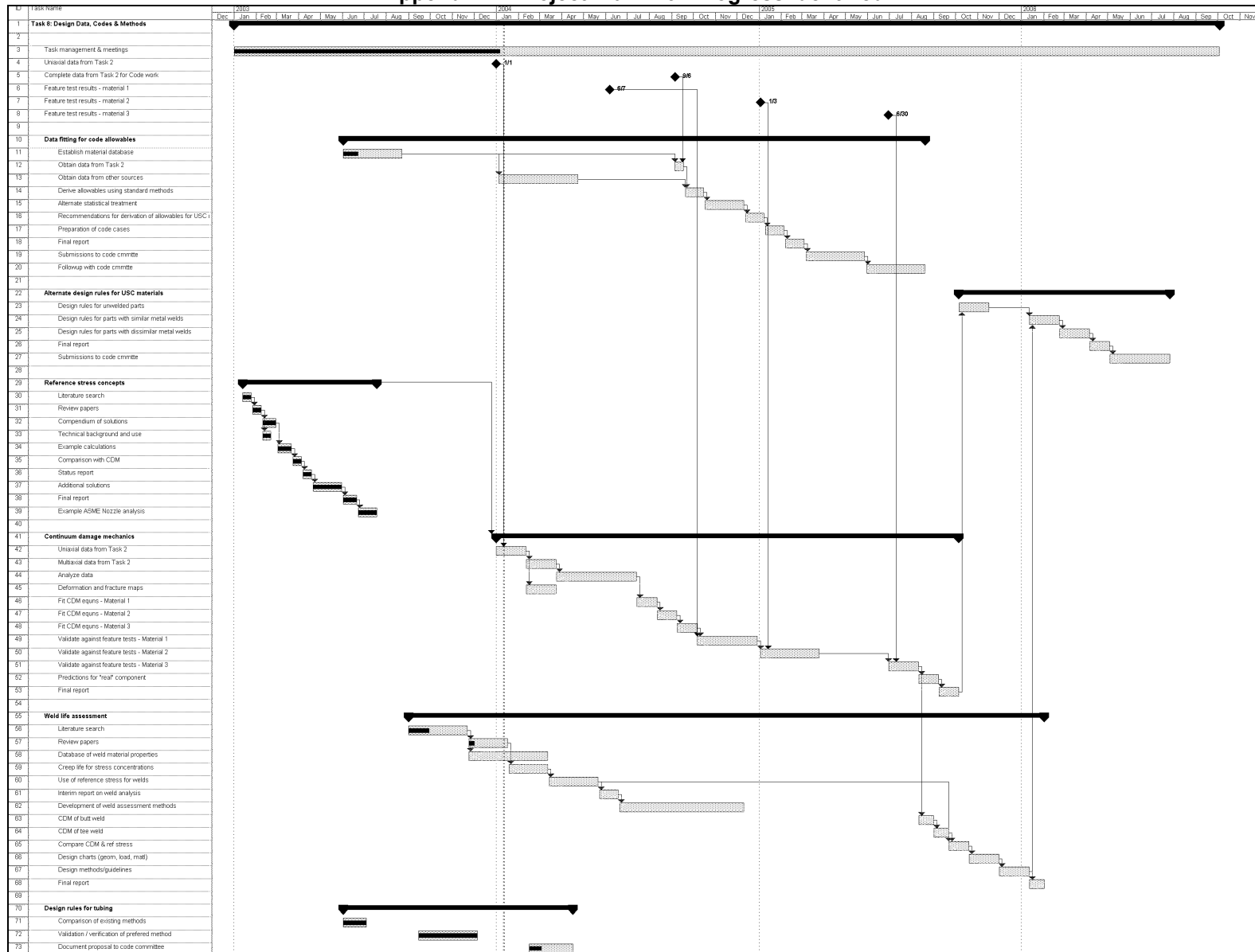
Concerns:

None.

Plans for the Next Quarter:

Address comments as necessary.

Appendix A: Project Plan with Progress Identified



APPENDIX B

Appendix VI

Proposed Code Language

Delete A-125 and rewrite PG-27 as follows:

PG-27 CYLINDRICAL COMPONENTS UNDER INTERNAL PRESSURE

PG-27.1 General. The formulas under this paragraph shall be used to determine the minimum required thickness or the maximum allowable working pressure of piping, tubes, drums, and headers for temperatures not exceeding those given for the various materials listed in Tables 1A and 1B of Section II, Part D.

The calculated and ordered thickness of material must include the requirements of PG-16.2, PG-16.3, and PG-16.4. Stress calculations must include the loadings as defined in PG-22 unless the formula is noted otherwise.

When required by the provisions of this Code, allowance must be provided in material thickness for threading and minimum structural stability. (See PWT-9.2 and PG-27.4, Notes 3 and 5.)

PG-27.2 Formula for Calculation

$$t = D_o(1 - \exp(-P/S))/(2E) + C + e$$

PG-27.2.1 For tubes of the materials listed in its title, Table PWT-10 may be used in lieu of the formula for determining the minimum wall thickness of tubes where expanded into drums or headers, provided the maximum mean wall temperature does not exceed 700°F (371°C).

PG-27.2.2 The wall thickness of the ends of tubes strength-welded to headers or drums need not be made greater than the run of the tube as determined by this formula.

PG-27.2.3 A tube in which a fusible plug is to be installed shall be not less than 0.22 in. (5.6 mm) in thickness at the plug in order to secure four full threads for the plug (see also A-20).

PG-27.2.4 Bimetallic sections meeting the requirements of PG-9.4 shall use as an outside diameter D_o in the equation above, no less than the calculated outside diameter of the core material. The outside diameter of the core material shall be determined by subtracting the minimum thickness of the cladding from the outside diameter of the bimetallic section, including the maximum plus tolerance. The minimum required thickness t should apply only to the core material.

PG-27.3 Symbols.

Symbols used in the preceding formulas are defined as follows:

t	=	minimum required thickness, in. (mm) (see PG 27.4, Note 7)
P	=	maximum allowable working pressure, psig (kPa gage) (see PG-21)
D_o	=	outside diameter of cylinder, in. (mm)
E	=	efficiency (see PG-27.4, Note 1)
S	=	maximum allowable stress value at the design temperature of the metal, as listed in the tables specified in PG-23, psi (see PG-27.4, Note 2)
C	=	minimum allowance for threading and structural stability, in. (see PG-27.4, Note 3)
e	=	thickness factor for expanded tube ends (see PG-27.4, Note 4)

PG-27.4 Notes.

Note 1:

- E = 1.00 for seamless or welded cylinders
- = the efficiency from PG-52 or PG-53 for ligaments between openings

Note 2:

The temperature of the metal to be used in selecting the S value shall not be less than the maximum expected mean wall temperature, i.e., the sum of the outside and inside surface temperatures divided by 2. For situations where there is no heat absorption, the metal temperature may be taken as the temperature of the fluid being transported, but not less than the saturation temperature.

Note 3:

Any additive thickness represented by the general term C may be considered to be applied on the outside, the inside, or both. It is the responsibility of the designer using these formulas to make the appropriate selection of diameter or radius to correspond to the intended location and magnitude of this added thickness. The pressure- or stress-related terms in the formula should be evaluated using the diameter (or radius) and the remaining thickness which would exist if the "additive" thickness had not been applied or is imagined to have been entirely removed. The values of C below are mandatory allowances for threading. They do not include any allowance for corrosion and/or erosion, and additional thickness should be provided where they are expected.

Threaded sections	Value of C , in. (mm)
3/4 in. (19 mm) nominal, and smaller	0.065 in. (1.65mm)
1 in. (25 mm) nominal and larger	Depth of thread h
(a) Steel or nonferrous pipe lighter than Schedule 40 of ASME B36.10M, Welded and Seamless Wrought Steel Pipe, shall not be threaded.	
(b) The values of C stipulated above are such that the actual stress due to internal pressure in the wall of the pipe is no greater than the values of S given in Table 1A of Section II, Part D, as applicable in the formulas.	
(c) The depth of thread h in inches may be determined from the formula $h = 0.8/n$, where n is the number of threads per inch.	
(d) Plain-end pipe includes pipe jointed by flared compression couplings, lap (Van Stone) joints, and by welding, i.e., by any method that does not reduce the wall thickness of pipe at the joint.	

Note 4:

- $e =$ 0.04 over a length at least equal to the length of the seat plus 1 in. (25 mm) for tubes expanded into tube seats, except
 - $=$ 0 for tubes expanded into tube seats provided the thickness of the tube ends over a length of the seat plus 1 in. is not less than the following:
 - 0.095 in. (2.41 mm) for tubes 1 1/4 in. (32 mm) O.D. and smaller
 - 0.105 in. (2.67 mm) for tubes above 1 1/4 in. (32 mm) O.D. and up to 2 in. (51 mm) O.D.,
 - 0.120 in. (3.05 mm) for tubes above 2 in. (51 mm) O.D. and up to 3 in. (76 mm) O.D.,
 - 0.135 in. (3.43 mm) for tubes above 3 in. (76 mm) O.D. and up to 4 in. (102 mm) O.D.,
 - 0.150 in. (3.81 mm) for tubes above 4 in. (102 mm) O.D. and up to 5 in. (127 mm) O.D.,
 - $=$ 0 for tubes strength-welded to headers and drums

Note 5:

While the thickness given by the formula is theoretically ample to take care of both bursting pressure and material removed in threading, when steel pipe is threaded and used for steam pressures of 250 psi (1 720 kPa) and over, it shall be seamless and of a weight at least equal to Schedule 80 in order to furnish added mechanical strength.

Note 6:

If pipe is ordered by its nominal wall thickness, as is customary in trade practice, the manufacturing tolerance on wall thickness must be taken into account. After the minimum pipe wall thickness t is determined by the formula, this minimum thickness shall be increased by an amount sufficient to provide the manufacturing tolerance allowed in the applicable pipe specification. The next heavier commercial wall thickness may then be selected from Standard thickness schedules as contained in ASME B36.10M. The manufacturing tolerances are given in the several pipe specifications listed in PG-9.

Note 7:

When computing the allowable pressure for a section of a definite minimum wall thickness, the value obtained by the formulas may be rounded out to the next higher unit of 10.

Note 8:

Inside backing strips, when used at longitudinal welded joints, shall be removed and the weld surface prepared for radiographic examination as required. Inside backing rings may remain at circumferential welded seams of cylinders provided such construction complies with requirements of PW-4 I.

Note 9:

The maximum allowable working pressure P need not include the hydrostatic head loading, PG-22, when used in this formula.

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 Fourth Quarterly Report for 2003
- Completed Monthly Reports for October and November
- Coordinated and provided minutes for Steering Committee Meeting on November 12-13, 2003 in Columbus Ohio.
- Monthly conference calls were held and the discussions were documented.
- Issued a call for papers for the EPRI Fourth International Conference on Advances in Materials Technology for Fossil Power Plants. This conference is being co-sponsored by DOE 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.

A final report has been completed and distributed.