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U.S. Program on Materials Technology for Ultrasupercritical Coal-Fired Boilers

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Abstract

One of the pathways for achieving the goal of utilizing the available large quantities of indigenous coal, at the same time reducing emissions, is by increasing the efficiency of power plants by utilizing much higher steam conditions. The US Ultra-Supercritical Steam (USC) Project funded by US Department of Energy (DOE) and the Ohio Coal Development Office (OCDO) promises to increase the efficiency of pulverized coal-fired power plants by as much as nine percentage points, with an associated reduction of CO2 emissions by about 22% compared to current subcritical steam power plants, by increasing the operating temperature and pressure to 760°C (1400°F) and 35 MPa (5000 psi), respectively. Preliminary analysis has shown such a plant to be economically viable. The current project primarily focuses on developing the materials technology needed to achieve these conditions in the boiler. The scope of the materials evaluation includes mechanical properties, steam-side oxidation and fireside corrosion studies, weldability and fabricability evaluations, and review of applicable design codes and standards. These evaluations are nearly completed, and have provided the confidence that currently-available materials can meet the challenge. While this paper deals with boiler materials, parallel work on turbine materials is also in progress. These results are not presented here in the interest of brevity.

Introduction and Background

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. Traditional methods of coal combustion emit pollutants (including CO2) at high levels relative to other generation options. Maintaining coal as a generation option will require methods for addressing these environmental issues.

This project, through a government/industry consortium, is undertaking a five-year effort to evaluate and develop materials technologies that allow the use of advanced steam cycles in coal-based power plants. These advanced cycles, with target steam temperatures up to 760°C (1400°F) will increase the efficiency of coal-fired boilers and reduce emissions substantially.

Worldwide, more than a dozen plants are operating at steam conditions close to 593°C (1100°F)/27 MPa (4000 psi and plant operation at 620°C (1150°F) appears to be a near-term possibility.(1) Research, development and demonstration programs have been underway in Europe and Japan aimed at materials capable of withstanding steam conditions up to 650°C (1200°F), and over the next decade to 700°C (1300°F). It is imperative that the US boiler manufacturers match those capabilities in this advanced technology area. This is one of the objectives of the US DOE/OCDO project. Furthermore, materials technology is generic in nature and cuts across many energy systems operating at high temperatures. Consequently, materials technology developments for high-temperature applications are expected to be of enduring value. In the near term, materials developed for USC plants can be confidently used for retrofit applications in currently-operating plants to increase their reliability.

The project objectives are addressed through the eight tasks listed below:

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

The current scope of the project is nearly complete. Highlights from the results achieved so far are summarized in this paper.

Results

Conceptual Design and Economic Analysis

Based on temperature/pressure calculations performed for various sections of a conceptual boiler(2-4), possible materials selection have been performed from a creep strength point of view. Haynes® 230, Inconel® 740 and CCA 617* were selected for the highest-temperature, heavy-section applications as well as tubular components; the austenitics HR 6W and SUPER 304H were selected for tubular applications; and ferritic alloy SAVE 12 was selected for heavy sections at lower temperatures. Alloys T92, T23 and HCM 12 were considered for application in waterwall tubing. The compositions and intended applications of the alloys are shown in Table1.

* CCA617: **C**ontrolled **C**ompositional **A**nalysis, a modified composition of Alloy 617

Table 1
Candidate Alloys

Alloy	Nominal Composition	Developer	Application
Haynes 230	57Ni-22Cr-14W-2Mo-La	Haynes	P, SH/RH Tubes
INCO 740	50Ni-25Cr-20Co-2Ti-2Nb-V-Al	Special Metals	P, SH/RH Tubes
CCA 617	55Ni-22Cr-.3W-8Mo-11Co-Al	VDM	P, SH/RH Tubes
HR6W	43Ni-23Cr-6W-Nb-Ti-B	Sumitomo	SH/RH Tubes
Super 304H	18Cr-8Ni-W-Nb-N	Sumitomo	SH/RH Tubes
Save 12	12Cr-W-Co-V-Nb-N		P
T92	9Cr-2W-Mo-V-Nb-N	Nippon Steel	WW Tubes
T23	2-1/4Cr-1.5W-V	Sumitomo	WW Tubes
HCM12	12Cr-1Mo-1W-V-Nb	----	WW Tubes
P - pipe			

A tentative bill of materials for the conceptual boiler is shown in Fig 1. Overall, the feasibility of designing an ultra-supercritical 750 MW boiler operating at 760°C (1400°F)/35 MPa (5000 psi) throttle steam conditions with existing material technology is encouraging. It was estimated that such a plant will increase the plant from

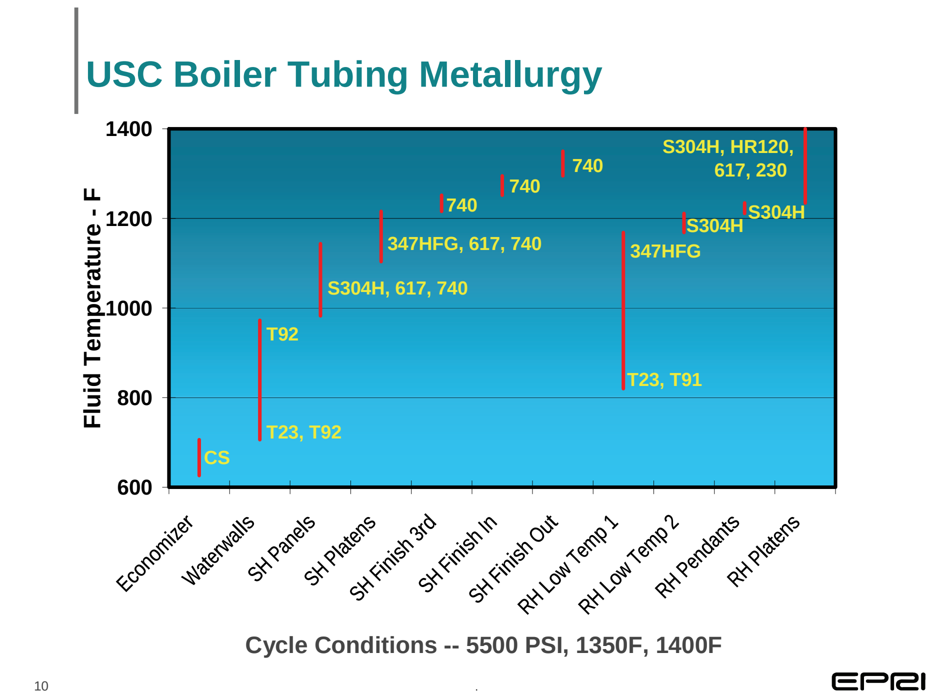

Figure 1
Alloy choices for components of a conceptual USC boiler

the efficiency from an average of 35% (HHV)* (current domestic aging sub-critical steam fleet) to approximately 45% (HHV).(2,3). For a double reheat configuration the efficiency will reach 47%. Expressed in terms of European parameters, this could be as high as 52% LHV*.

Based on a 20-year break-even consideration, an assumed capacity factor of 80%, and coal cost of \$1.42/G J. (\$1.50/MBtu), the fuel cost savings over the 20-year period, are sufficient to allow an ultra-supercritical plant to be cost competitive even if the total plant capital cost is 12 to 15% more than a comparable scale facility built using conventional subcritical boiler and cycle design (5,6),. Balance-of-plant (BOP) costs are expected to be lower than those for existing boiler and cycle designs due to smaller coal handling and pollution control systems, resulting from the improved plant efficiencies. As a result of these reductions in fuel and BOP costs and the smaller plant size due o increasd efficiency, boiler and steam turbine capital costs can be permitted to be higher compared to subcritical plant. If a potential "carbon tax" were also taken into account, the advantage of the USC plant becomes even more substantial. These economic calculations are being up dated

An alternative design consideration that mitigates the high cost of the superalloys is a design with increased throttle temperature without a major increase in throttle pressure. As mentioned earlier, the costs involved in increasing steam temperature are lower than for raising steam pressure. Reducing throttle pressure may allow the more extensive use of standard austenitic materials, while maintaining the plant efficiency gains due to higher throttle temperature. This approach of using lower pressure (in combination with the better than expected material properties observed for some alloys and the lower stresses calculated from the reference stress approach((7) as described later), favors the possibility of achieving the initial goal of 760°C (1400°F) throttle steam.

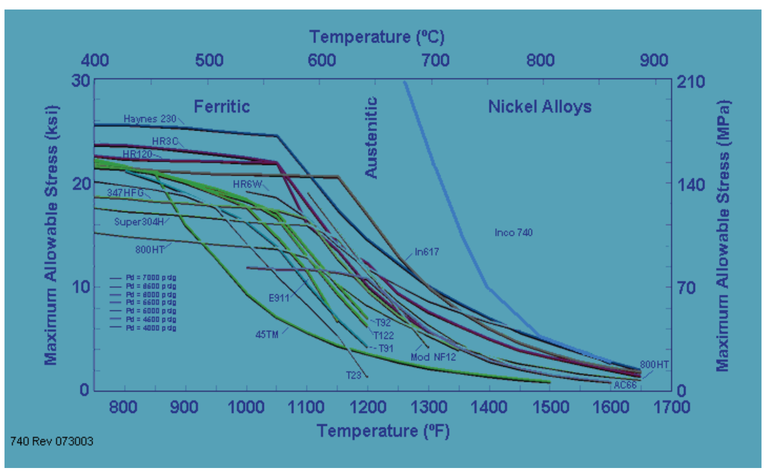

Figure 2
Allowable stresses for various classes of alloys(8)

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* HHV and LHV: Higher Heating Value and Lower Heating Value, respectively (related to the assumption regarding recovery of heat of vaporization of moisture). Efficiency calculations were based on typical US plant siting and operating practices.

Mechanical Properties

Figure 2 is a plot of the allowable stresses as a function of temperature used to compare and determine the temperature capabilities of various classes of alloys.(8) The figure also shows the actual stresses at several steam pressures.(8) The nickel-based alloys Inconel 740, Haynes 230, Inconel 625, Inconel 617, and HR 120 have much higher temperature capability, in decreasing order as listed compared to austenitic steels, followed by the ferritic steels. Purely from the creep strength point of view, at a pressure of 35 MPa (5000 psi) for a 5 cm (2 in) by 1.25cm (0.5 in.) tube (stress 60 MPa or 8.7 ksi), ferritic steels are useful up to about 620°C (1150°F) (metal temperature) and austenitic steels up to about 675°C(1250°F). At metal temperatures higher than this, Ni-based alloys are required.

Creep rupture testing has exceeded 30000hr for SAVE 12, Super 304H, Haynes 230, CCA617, and Inconel 740. Creep-rupture tests on HR6W tubing are complete, and the results confirm earlier predictions (based on short-term data) that indicated the alloy had poorer creep strength than expected from literature. Figure 3 compares the expected and measured 100,000 hour rupture strength as a function of temperature for HR6W. The measured values are 20 to 30% lower than expected. When compared to Super 304H, the creep strength of HR6W is inferior below ~675ºC while it shows an improvement over Super 304H above 675ºC.

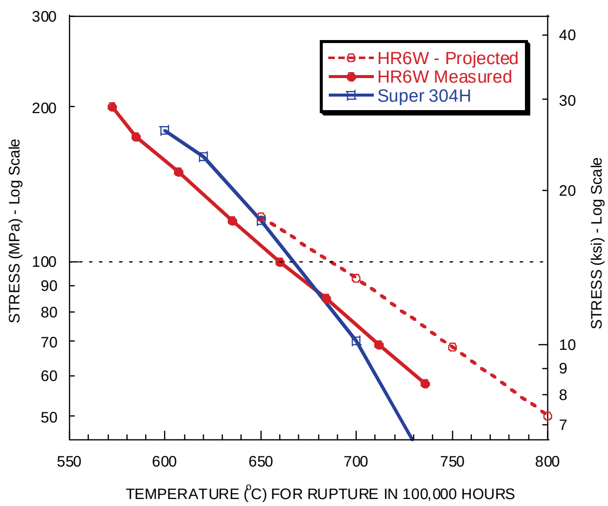


Figure 3
100,000 hour rupture life for austenitic tubing (extrapolations based on data up to ~20,000 hours). Measured strength of HR6W is significantly lower than projected values from material supplier.

Creep tests on CCA617 have exceeded expectations in the lower temperature regime (650°C to 700°C), but above 750°C the creep strength was indistinguishable from that of the standard Inconel 617. Microstructural studies suggest that this strength difference is due to the precipitation of gamma prime, but at 750°C these precipitates were found to coarsen significantly with time, and at 800°C contributed little to the hardening of the material. (9) This suggests that at 750ºC and above, no long-term strength advantaged is expected for CCA617 due to gamma prime precipitation. Figure 4 shows the extrapolated 100,000 hour rupture strengths of 617 and CCA617. The 100 MPa-100,000 hour rupture strength for CCA617 is estimated at 725ºC compared to ~700ºC for 617.

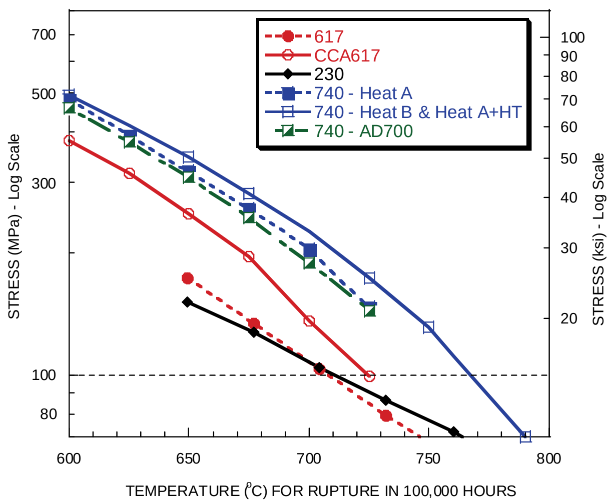


Figure 4
100,000 hour rupture life for nickel-based tubing and plates (extrapolations based on data up to ~23,000 hours). CCA617 shows improved strength compared to 617 (725ºC at 100MPa). Inconel 740 rupture strength shows heat-to-heat and heat-treatment variations. All the data suggests better strength than AD700 program reported values.

Creep testing of Inconel 740 is being performed on both tubing and thick plate. Tests on two heats of material and two heat-treatments have shown some data scatter for rupture life as shown in figure 4. All material was given a standard 800ºC-16hr heat-treatment before testing. Heat 'A' shows behavior similar (although slightly improved) to that reported on the AD700 program(10). However when Heat 'A' was subjected to an additional solution heat-treatment, its rupture behavior followed that of Heat 'B' which was significantly better than that reported by the AD700 program. Heat 'B' has a 100MPa-100,000hr estimated rupture life greater than 760ºC, which meets the aggressive strength requirements of this project. For ASME code qualification, data is required on a minimum of three heats of material. A third heat of 740 has been obtained for the required testing.

To evaluate the fabrication and welding processes developed on the program, testing is being performed on welds, weldments, and cold-bent tubes. Cross-weld creep tests on HR6W and on Super 304H have shown that 'overmatching' filler metals have superior creep strength compared to the base metal with most ruptures in the base metal at expected base metal lives. Cross-weld tests on Haynes 230 tubes and thin plates show the weld metal to be approximately 80% the strength of the base metal with all cross-weld failures in the weldments. Current cross-weld creep studies are focused on thick plate weldments in CCA617 (specimens up to 37mm in thickness), tube weldments in 617, dissimilar metal welds (DMW) in CCA617/Super 304H, and plate weldments in Inconel 740. The cross-weld tests on Inconel 740 are in support of the welding development efforts on this alloy and include matching 740 filler metal and Nimonic 263 filler metal. To examine cold-work effects, pressurized creep tests on tube bends have been performed on Haynes 230 and HR6W. At relatively high levels of cold work (20 to 35% outer fiber strain) after 8,000 hours in test, neither alloy showed large reductions in rupture life at 775ºC indicating the ASME code rules for cold-work will be conservative for the solid solution nickel-based alloys. Tests on Inconel 740 tubes bends are currently underway to examine cold-work effects in age-hardenable nickel-based alloys.

In support of design rules and model development, LCF, thermal fatigue (thermal shock experiments), and creep-fatigue tests are being performed on some alloys. These data will be used primarily to determine the effect thermal transients will have on thick-section components. This is important because the current experience for most boilers is with ferritic steels which have different physical properties compared to the nickel-based alloys.

Steamside Oxidation Tests

Steamside oxidation testing has been completed at 650°C (1 and 17 atm); 700°C (17 atm); and 800°C (1 and 17 atm). The oxidation rates primarily followed a parabolic rate law, and the rate constants derived were found to be in agreement with literature data (where this information is available)(11). Among the ferritic steels, two new steels: MARB2 (developed by NIMS) and VM12 (developed by V&M Tubes) displayed the lowest weight gains/metal loss, whereas all other 2-9% steels were subject to rapid oxidation. Ferritic steels that showed the lowest weight loss also exhibited the lowest tendency for their oxide to spall. Clear evidence of spallation was observed for alloys T23, T91 and T92. Ferritic material MARB2 and austenitic material 304H displayed the formation of oxide islands, indicative of the development of a non-protective oxide at some location. The highest tendency among the austenitics for scale exfoliation was found in 347HFG. Shot blasting was found to be beneficial in both Super 304H and in 347HFG steel. The oxidation behavior of some nominally 12%Cr steels (for example, T122) was very variable, with anomalous temperature dependence apparently resulting from the fact that their ability to form a consistently-protective scale was unusually sensitive to minor changes in factors such as levels of minor alloying elements, surface condition, and test variables. However, one nominally 12%Cr steel (VM12) was able to reliably form a protective scale, and performed as well as some austenitic and Ni-based alloys.

No spallation was observed from the austenitic steels or Ni-based alloys in the 650°C (1200°F) tests. Of the austenitic and Ni-based alloys, the Co-containing alloys Nimonic 263, CCA 617 and Inconel 740 exhibited the best oxidation behavior. All of the austenitic and Ni-based materials tested formed a dense layer of chromium oxide that will result in low oxidation rates at this temperature. The Ni-based alloys that contained between 0.5 and 1.3% Al formed near-surface intergranular aluminum oxide penetrations beneath the external (protective) chromia scales, which effectively increased the thickness of load-bearing section lost.

Results from tests at 650 and 600°C in 1 atm steam, shown in Fig. 5 indicate that the oxidation susceptibility appears to be independent of Cr level, once a threshold level of about 10% is reached.

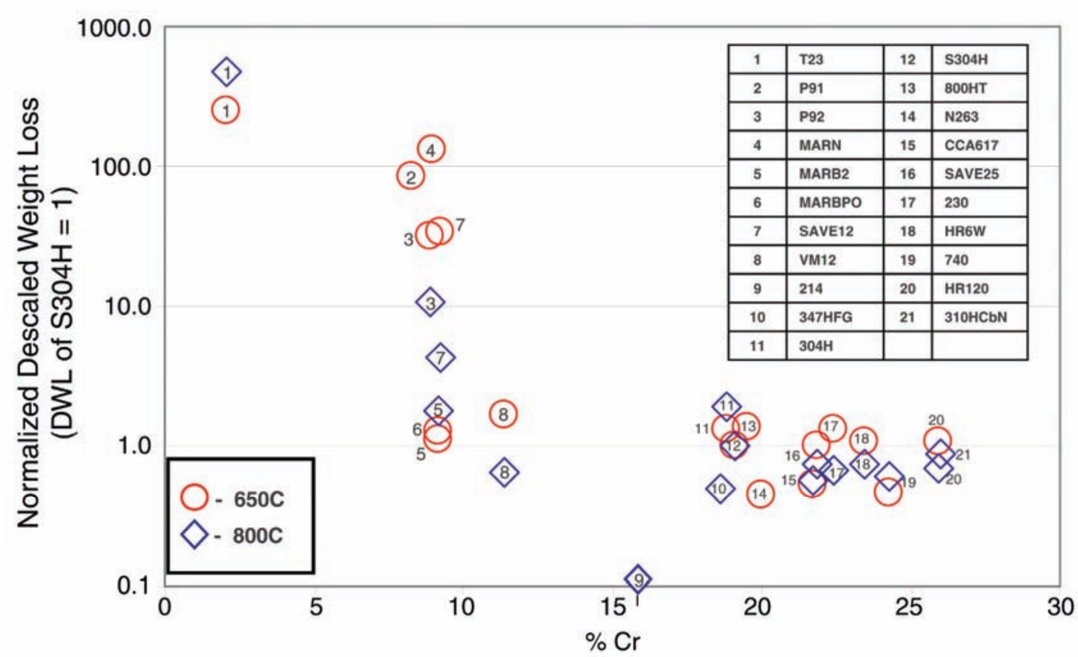


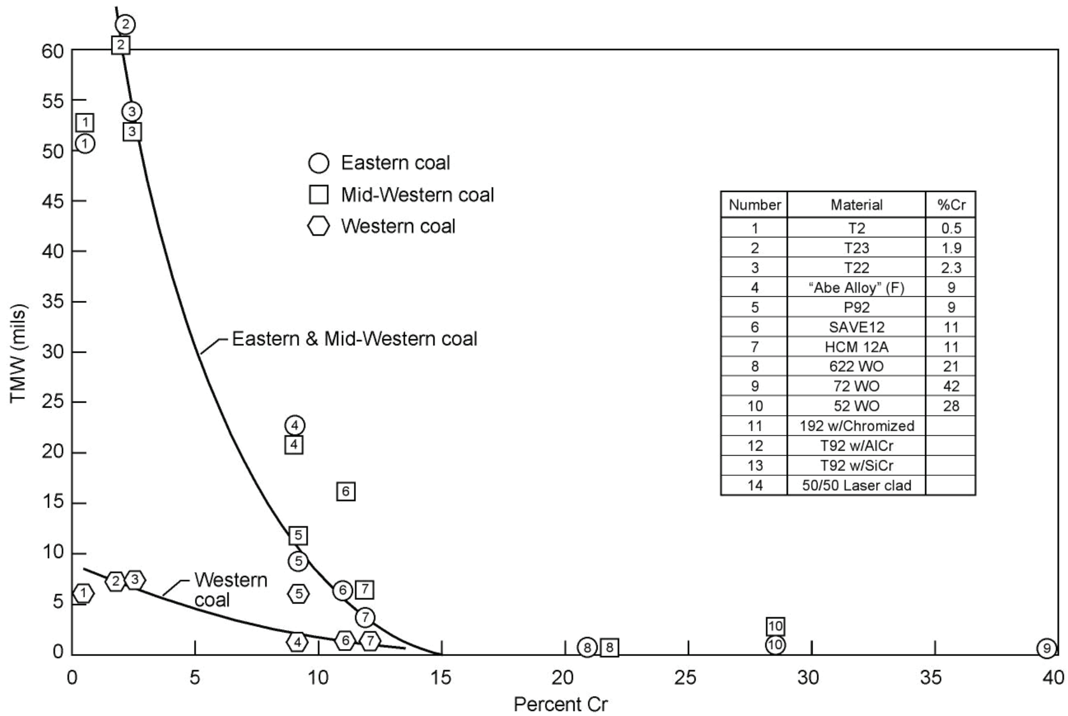
Figure 5
Normalized weight loss of sample after steamside oxidation 1000 hr at 800°C(11)

Among the diffusion coatings tested, SiCr and FeCr coatings performed much better than AlCr coatings. Based on calculated oxidation rates, it appears that the life of austenitic and Ni-based tubing was unlikely to be controlled by steamside oxidation rates rather than fireside corrosion. The primary concern with respect to steamside oxidation is oxide exfoliation.

Fireside Corrosion

The objective of this task is to evaluate the relative resistance of various candidate alloys to fireside corrosion over the full temperature range expected in an USC steam plant.(12,13) The testing involved the corrosive environments representative of three different domestic coal types: Eastern (E), Midwestern (MW), and Western (W). Also, three types of testing were undertaken: (1) laboratory testing simulating conditions expected at the waterwalls and superheater/reheaters, using appropriate deposit compositions and gas mixtures; (2) steam loops formed by welding together spool pieces of the various materials and inserted into the superheater circuit to be exposed to much higher temperature boiler conditions; and (3) retractable air-cooled probes inserted inside operating boilers. Steam loops are hydrotested prior to installation in a boiler, which burns high sulfur coal.(13,14) USC boiler design operating conditions are simulated by throttling the steam flow to achieve metal temperatures up to 760°C (1400°F). Operating parameters during the test are monitored remotely. Physical monitoring of the tubes is accomplished during outages at the plant by means of diameter measurements for hot corrosion wastage, and photographs of the surface condition.

Results of laboratory tests, In the case of the waterwall conditions, specimens tested under MW and E conditions exhibited more wastage than those tested under W-coal conditions (see Fig. 6(12)). The difference in the amount of wastage between the MW/E and W conditions was greater at



Number	Material	%Cr
1	T2	0.5
2	T23	1.9
3	T22	2.3
4	"Abe Alloy" (F)	9
5	P92	9
6	SAVE12	11
7	HCM 12A	11
8	622 WO	21
9	72 WO	42
10	52 WO	28
11	192 w/Chromized	
12	T92 w/AlCr	
13	T92 w/SiCr	
14	50/50 Laser clad	

Figure 6
Total metal wastage for alloys under waterwall conditions at 525°C (975°F), 1000 hr(12)

454°C (850°F) and 525°C (975°F) than at 593°C (1100°F). The MARB2 and SAVE12 alloys (which contain Co) exhibited higher wastage rates than did the P92 and HCM12A alloys at all three temperatures.

The Inconel-622, -52, and -72 weld overlays and laser clad 50/50 displayed significant improvement in corrosion resistance compared to the wrought alloys at all temperatures, although the Inconel-622 overlay started to show more attack at 593°C (1100°F) compared to -52 and -72. With regard to the diffusion coatings (on T92), they also exhibited significantly improved corrosion resistance compared to the wrought alloys. The chromized coating displayed the best performance, followed by the SiCr and the AlCr. As in the SH/RH tests, the AlCr coating exhibited the most subsurface attack.

The results for superheater/reheater corrosion so far confirm that:

As noted by others, of US Midwestern and Eastern coals are much more corrosive than the environment typical of a Western coal.

Corrosion behavior was a function of Cr level, with corrosion decreasing rapidly as the chromium level increased to 22-27%, and then leveling off.

Fe-Ni-Cr and Ni-Fe-Cr alloys HR3C (53Fe-25Cr-20Ni), 353 (36Fe-35Ni- 25Cr-1Si), 120 (37Ni-35Fe-25Cr), and HR6W (40Ni-25Fe-23Cr-6W) performed better than the Ni-based alloys tested.

Of the Ni-based alloys, Inconel 740 exhibited better corrosion resistance than Haynes 230 and CCA617.

Weld overlays Inconel-72 (42% Cr) and Inconel-52 (28% Cr) performed better than Inconel-622 (21% Cr).

Diffusion coatings of Cr and Cr-Si displayed better corrosion resistance than Al-Cr and were comparable to weld overlays, but because they are thinner will be breached sooner.

Of the weld overlays, Inconel-72 (typically 42 Cr) and Inconel-52 (typically 28 Cr) performed better than Inconel-622 (typically 21 Cr) at all temperatures, with 72 performing better than the 52. At 650°C (1200°C) and 704°C (1300°C), the 72 and 52 were better than the wrought alloys in the 22-27 Cr range. With regard to the diffusion coating (on Super 304H), the FeCr and SiCr compositions performed better than the AlCr, which exhibited the most extensive subsurface penetration. The FeCr and SiCr coatings were comparable to the weld overlays but, because they are thinner, will be breached sooner.

Weldability Studies

The scope of this task includes study of six alloys: SAVE12, Super 304H, HR6W, Haynes 230, Inconel 740, CCA 617. Two product forms, tubing and pipe or plate, are being studied, and welding procedures for 15 materials/product forms/welding processes combinations are being developed. Welding procedures are being developed for three dissimilar metal weld configurations, and weldments for each of the combinations are being evaluated15).

Preliminary results indicate that submerged arc welding (SAW), a high deposition rate process favored by boilermakers for thick sections, might not be feasible for Ni-based materials; tests on Haynes 230 and Inconel 740 have been unsuccessful. A 7.5cm (3 in.) thick plate of Haynes 230 was successfully welded using pulsed gas metal arc welding (GMAW) technique,.(16) Hot wire gas tungsten arc welding tests conducted on 2-inch thick Inconel 740 plates using a 25% Helium/75% Argon shielding gas and matching filler wire gave encouraging results. There were very few microfissures compared to earlier samples using a pulsed gas metal arc process. Bend and tensile tests will be conducted for further evaluation of this plate in an attempt to fully qualify a welding procedure.

An orbital gas-tungsten arc welding (GTAW) process has been qualified for Super 304H and test specimens are being fabricated. While attempts to weld tubing using an automatic GMAW process were unsuccessful, type 347 filler produced acceptable welds. An orbital GTA process was qualified for tubing of alloy CCA 617, and a SAW process was qualified for plate and test specimens are being fabricated. Attempts to perform shielded metal arc welding (SMAW) using matching filler were unsuccessful due to slag control problems with CCA 617 electrodes. On the other hand, successful SMAW welds were achieved using conventional 617 electrodes. Collaboration is being pursued with the alloy vendor (Special Metals Corp.) in view of their experience in welding 2.5 cm (1 in) thick plates of Inconel 740 using GMAW.

Fabricability Studies

The primary objective of this task is to conduct fabrication studies on the alloys of interest and to assess the effects of fabrication on material properties, so that potential fabrication problems may be identified.(17) Experience in welding, machining, cutting, boring and grinding of Haynes 230, Inconel 740, HR6W, CCA 617 and Super304H stainless steel has been gained in the course of fabrication of two steam test loops. Protective weld overlay claddings using alloys Inconel 52, Inconel 72 and Inconel 622 were successfully applied to the tube sections that form the test loops. Field welding was additionally demonstrated during installation of the test loops in the boiler. Samples of strained material required for characterizing the recrystallization/precipitation behavior of USC steam alloys were made by controlled straining (ranging from 0 to 50%) of special tapered tube specimens. Fabrication of multiple U-bends from Haynes 230 and HR6 W. tubing (2 in. OD X 0.4 in. MW) was successfully demonstrated using production equipment. Tube U-bends with strains of 15%, 20% and 35% were produced as shown in Fig 7.

USC Alloy -Participant -	Evaluation Planned	Results & Status	Comments	Follow -on Activities
Alloy 230 - B&W -	Cold U -Bend Trials	13.3% 20% & 33.3%	Good; Some ovality	P-Creep at ORNL
	Tubewelding Trials	625 Filler; 622,52,72 WOL	Good; Field Test Loops Fabricated	Fabricate Demo Article
	Machining Trials	Completed	Good; Field Test Loops Fabricated	Fabricate Demo Article
	Strain/Rx/Pptn Trials	1500 F & 1600 F	100,250,400 & 550 hrs	Assess Microstructures
	Swaging Trials	Planned Spring 2005	Machined tubes to 0.2ÓWall	Assess Microstructures
	Demo Article Fab	Planned Spring 2005	Design Completed	Fabricate; Display TBD

Figure 7
Current Status of Workplan Activities – Alloy 230

Swaging trials of two of the USC steam alloys have been completed. Data on recrystallization behavior, phase precipitation and dissolution in the Ni-based alloys are being compiled to assist in the understanding and development of fabrication procedures. Summary of results for one of Alloy 230 are shown in the table in Figure 7.(17),for illustrating the type of data being gathered

As a demonstration of the fabrication capabilities achieved in the course of this project, a mock up section of a header was fabricated, see Figure 8. The mock up illustrates capabilities with respect to fabrication of CCA 617 alloy into the header shape by bending of plate; girth welding;

seam welding; socket welding machining; swaging; hole drilling; and dissimilar welding between CCA 617 and Super304H and T91 tubing.

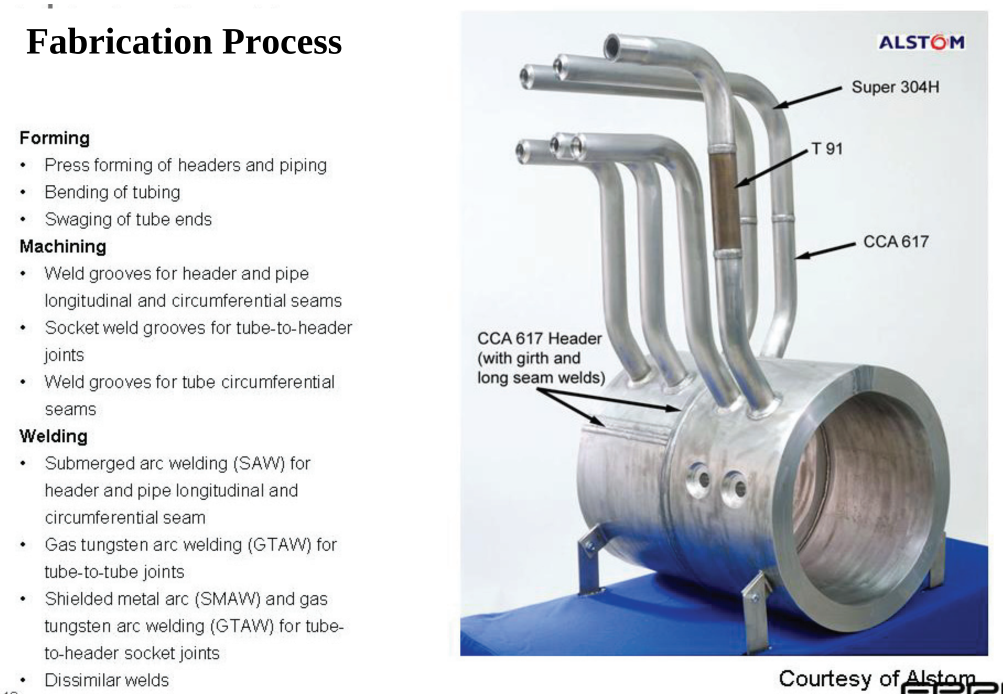


Figure 8
Demonstration of fabrication capabilities with alloys of interest for an USC steam boiler

Coatings

Several specimens with claddings, sprayed coatings [cold spray, high-velocity oxygen/fuel (HVOF)] and diffusion chromium, chromium-silicon, chromium-aluminum coatings have been prepared using commercially-viable processing.(4) Results show that ferritic steels benefit most from coatings; austenitic steels may benefit; while Ni-based alloys are not likely to need coatings at all. Process scale-up activities are being pursued. The scale-up tests for the chromizing process have been completed, and the evaluation of results revealed excellent reproducibility for both types of materials, Super304H and T 92. Development of parameters for depositing HVOF and cold spraying techniques for 50Ni/50Cr coatings also has been completed. Optimal parameters have been selected and used to coat Haynes 230 tubes. For the other coating processes of interest, parameters for deposition of 50Ni/50Cr by plasma-transferred arc and laser cladding are being measured.

Design Data and Rules

A new set of design equations has been developed for cylindrical components (tubes, pipes, headers, shells and drums). Since these are based on analysis, they are less conservative than those used in conventional design practice.(7) The impact of the new design equations will be that a consistent failure criterion will be applied to all sizes and types of cylindrical sections. This criterion incorporates a limit load approach in the time-independent regime, and a reference stress approach in the time-dependent regime. It is expected that these proposed rules will permit the use of thinner-walled components than would be permitted under the current ASME and European rules, without compromising component reliability and safety. It is estimated that in ultra-supercritical boilers, where expensive materials are required, a 12% reduction of the cost of boiler pressure parts can be achieved. Also, thinner-walled components would be less subject to thermal fatigue, and therefore the plant would be less susceptible to damage from cyclic operation. This less conservative approach also would permit use of materials with lower creep strengths under a given set of conditions, thus offering a wider selection of alloys for use at high temperatures. Proposed revisions to Section I of the ASME code to permit the use of simplified and more technically-defensible design equations were submitted to Subcommittee I, and accepted by them in September 2004. Subsequent to that, the revisions were included in the Main Committee ballot.

Summary of Accomplishments

- **Developed a USC plant heat balance design which will reduce fuel consumption and emissions by 30% compared to current state-of-the-art subcritical cycle. Developed two conceptual designs of USC boilers outlining component design and material test conditions. Performed plant cost and feasibility study showing that the cost of the advanced alloys will be more than offset by savings in balance of plant equipment cost and fuel savings within a 20-year period.**
- **Alloys with the creep strength required to withstand the target temperatures and stresses at different locations in the boiler have been identified and tested for times exceeding 30,000 hours. Tensile tests, fatigue tests, and other mechanical property tests have been completed.**
- **Laboratory steamside oxidation testing of various alloys and coatings has been completed, allowing relative ranking of materials at appropriate exposure temperatures.**
- **Laboratory and field-exposure corrosion testing of various alloys and coatings has been completed, allowing relative ranking of materials at appropriate exposure temperatures and coal ash types.**
- **Developed practical welding procedures for some alloys and identified difficulties with others.**
- **Subjected alloys to common fabrication processes and produced prototype assemblies.**
- **Identified external and internal coatings and methods, prepared samples for oxidation and corrosion testing, and evaluated the results.**
- **Proposed a more accurate and less conservative design formula which was adopted into the ASME B&PV Code Section I; Advanced the knowledge base of the boiler manufacturers and improved their competitive position vis a vis capabilities in Europe and Japan.**

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Fishburn, and many others. Their contributions are gratefully acknowledged. The project consortium consists of ALSTOM, Babcock &Wilcox, Fosterwheeler, Riley Power and EPRI, Energy Industries of Ohio is the project manager. Detailed results from the entire project have been summarized in the phase 1 Final report.

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