

**ANNUAL PROJECT REPORT  
AS OF DECEMBER 2003**

1. Project Sponsor

Energy Industries of Ohio  
Park Center One, Suite 200  
6100 Oak Tree Boulevard  
Independence, OH 44131

2. Project Manager

Robert M. Purgert  
President  
Phone: 216-643-2952  
Email: purgert@energyinohio.com

3. OCDO Grant No. CDO/D-00-20

4. PROJECT UPDATE

5. Project Title: Boiler Materials for Ultrasupercritical Coal Power Plants

6. Project Term: From 6/1/2001 to 12/31/2006

7. Budget:

<u>Name</u>	<u>Cost Share</u>
Ohio Coal Development Office	\$ 2,016,670
U.S. Department of Energy	10,456,414
Oak Ridge National Laboratory	4,665,400
McDermott Technology, Inc./Babcock & Wilcox	666,248
Alstom Power, Inc.	618,500
Babcock Borsig Power, Inc.	388,946
Foster & Wheeler Development Corp.	574,644
Electric Power Research Institute	500,000

Total Project Cost: \$19,886,822

8. Overview of Project and Objectives

In the 21<sup>st</sup> 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 US, 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 CO<sub>2</sub> at high levels relative to other generation options. Maintaining coal as a generation option in the 21<sup>st</sup> century 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 advanced materials that allow the use of advanced steam cycles in coal-based power plants. These advanced cycles, with steam temperatures up to 750°F, will increase the efficiency of coal-fired boilers from an average of 35% efficiency (current domestic fleet) to approximately 52%. This efficiency increase will enable coal-fired power plants to generate electricity at competitive rates (irrespective of fuel costs) while reducing CO<sub>2</sub> and other fuel-related emissions by as much as 29%.

The project is based on an R&D plan developed by the Electric Power Research Institute (EPRI) that supplements the recommendations of several Department of Energy (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, Inc.; McDermott Technology, Inc./Babcock & Wilcox Company; Babcock Borsig Power, Inc.; and Foster & Wheeler Development Corporation) has been developed. The Energy Industries of Ohio (EIO) will provide overall Program Management and fostered participation by other Ohio entities such as the Edison Welding Institute, NASA-Glenn Research Center, University of Akron and University of Cincinnati. Oak Ridge National Laboratory has been separately funded by the DOE to provide augmenting efforts to the project.

## 9. Work Done & Conclusions

### Task 1: Preliminary Design and Economic Studies

Design and economic studies have been completed. Alloy selection, component sizing, delineation of temperature/ stress profiles have all been completed. Economic viability has been shown. Material procurement has been completed.

The feasibility of designing and ultrasupercritical 750 MW boiler operating at 1350/1400°F. and 5000 psi with existing material technology is encouraging. This design would be capable of achieving a net plant efficiency of 45.5% HHV based on US design practice and as high as 50.5% when expressed in European format. Throttle temperature increase is concluded to be much more advantageous than throttle pressure increase for improvement of efficiency at minimal cost impact.

The USC boiler has a capital cost approximately 28% higher than the comparable subcritical boiler. This is well below the 40% increase permitted by EPRI to break-even on a cost of electricity basis. The USC plant will reduce emissions by 15 to 22%.

Haynes 230, Inco 740, CCA 617, HR 6W, Super 304 H. and SAVE 12 alloys have been selected for heavy section and tubular applications. Alloys T 92 and T 23 will be considered for application in waterwall tubing. All the alloys in the various product forms needed have been procured and distributed to the various participants.

### Task 2. Mechanical Properties

Longtime creep test have been initiated on all alloys. Preliminary data show that Super 304 H behaves as expected at 1200F(650°C); alloy HR 6W shows lower rupture life than predicted at the lower temperatures; Haynes 230 shows creep rupture behavior as expected in 1475°F(800°C) tests; CCA 617 has considerably higher rupture strength than conventional 617 in 1200°F(650°C) and 1382°F(750°C) tests; and Inconel 740 shows rupture properties that are better than expected based on prior data in European programme using Larson Miller plots. Creep rupture tests on cross weld specimens show welds of Haynes 230 to be inferior compared to base metal, with failure occurring in the weld.

### Task 3. Steamside Oxidation Tests

Steamside oxidation tests at Oak Ridge National Labs show that oxides of T 92 and T 122 apparently undergo break-away behavior in < 500 hours to form iron rich oxides. Tests at 700°C/250 psi steam show that ORNL results are in line with European data. The high-Cr alloys are found to form chromium rich oxide scales. More spallation of oxide scales was observed under pressurized oxidation conditions. Corrosion rate data for alloys have been established.

At B&W, Steamside oxidation tests have been completed up to 2000 hours. It has been found that oxidation resistance is predominantly controlled by the chromium content of the alloy, with some exceptions. Two alloy versions of 9%Cr steel provided by Dr. Abe of NIMS, Japan, were found to have oxidation resistance that was superior compared to the other 9 Cr alloys.

Interestingly, the Abe alloys were found to form chromium oxide scales on the surface. Chromized coatings on T 92 performed better than Electroless Nickel or Cereblack coatings, but the chromized T 92 specimens did not perform as well as austenitic alloys. Results of 2000 hour test on austenitic alloys shows evidence of oxide exfoliation.

#### Task 4. Fireside Corrosion

Test matrices and environmental conditions for fireside corrosion for superheater/reheater, and for water wall applications have been finalized. Materials to be tested have been finalized and procured. Steam loop testing at the Niles power station has been started by Babcock and Wilcox Company. The loop installation was completed a month ago. Host utility sites have been identified for air-cooled, probe testing by Foster Wheeler. These sites include the first Energy's Burger station, Synergy's Gibson station and Xcel Energy's Pawny station. Riley-Stoker has identified Dairyland Power Company as a host utility for their steam loop testing and are in the process of negotiating the legal agreement.

#### Task 5. Weldability Studies

It has been concluded that submerged arc welding, a high deposition rate process favored by boilermakers for thick sections, might not be feasible for nickel base materials. Tests on Haynes 230 and Inconel 740 have been unsuccessful, and the process is being abandoned, at least on these alloys. At B&W, the first 3 in. thick plate of Haynes's 230 was successfully welded using pulsed GMAW technique.

At ALSTOM, an orbital GTAW process was qualified for Super 304H and test specimens are being fabricated. Attempts to weld tubing using an automatic GMAW process were unsuccessful. Switching to type 347 filler produced acceptable welds. An orbital GTAW process was qualified for tubing of alloy 617. A SAW process was qualified for plate and test specimens are being fabricated for alloys HR6W and SAVE 12, base material has been obtained and distributed to the participants. Weld processes and filler metals have been selected. In view of special metal's experience in welding 1 in. thick plates of Inconel 740 using GMAW, they are being contacted to make the three-inch plate welds for our program. Additional weldability studies are being conducted by B&W.

#### Task 6. Fabricability Studies

Experience has been gained at B&W in welding, joining, cutting, boring, grinding and machining alloys 230, 740, HR6W., CCA 617 and super 304 H alloys during steam loop fabrication. Experience was also gained in terms of the weld overlay processing of these alloys with Inco 52, 72 and 622 alloys. Experience was gained in field welding of USC materials during test loop installation and the Niles plant. Swaging procedures have been developed. The capability of alloy 230 to cold straining has been evaluated using a tapered specimen configuration with varying strains. Other alloys will be evaluated similarly for their cold straining capabilities.

#### Task 7: Coatings

Several specimens with claddings, spray coatings (cold spray, HVOF.) and diffusion chromium, chromium-silicon, chromium-aluminum coatings have been prepared and subjected to steam oxidation tests in the lab. Results show that ferritic steels benefit most from coating; austenitic steels may benefit; Nickel-based alloys are not likely to need coatings and all. The scale-up tests for the chromizing process were completed and the evaluation of results revealed excellent reproducibility for both types of materials, Super 304 H. and T 92.

#### Task 8. Design Approaches

The scope of work for this task was defined in the course of several meetings and assignments were made to the various participants. A detailed review of literature pertaining to the reference stress approach was completed and a topical report was issued. Example problem of the reference stress concept was applied to an ASME geometry. New cylinder design rules were developed and submitted to the ASME design committees. These rules will remove some of the conservatism in the current design codes and therefore permit use of thinner wall materials or, alternately, permit use of materials that might otherwise not meet the allowable stress requirements.

#### HIGHLIGHTS/ACCOMPLISHMENTS:

- Collaboration was established with the National Research Institute For Metals (NIMS) of Japan. They have developed a nitride strengthened 9% Cr steel that is hundred times stronger in rupture tests compared to the best ferritic alloy T92. We have procured samples of this alloy for testing in our program. In addition, we also obtained from them two modified versions of the 9% Cr alloy that seem to be superior in their oxidation resistance compared to conventional 9% Cr alloys. These samples have also been tested in our program.
- Strong interaction was established with alloy vendors, Special Metals and Haynes alloys and their participation in welding developments with respect to Haynes 230 and Inconel 740 at their own expense were secured.
- Interaction has been established with utility stakeholders. Several utilities have agreed to serve as host utilities for the project. In addition, representatives from AEP, Southern Co. and National Rural Electric Cooperatives have been serving on the advisory committee.
- Very good cooperation with Oak Ridge National Lab was achieved. They have participated completely as one of the team members providing us all the data and reports as required of the other team members.
- A new alloy called CCA 617 was procured from Germany and tested. Preliminary tests at Oak Ridge National Laboratories indicate this alloy to be much superior in creep rupture tests compared to conventional alloy 617. In addition, it has also been found that Inco 740 rupture properties are much better in tests at Oak Ridge compared to prior European data. These results are very encouraging in being able to achieve the high-temperature requirements of this project.
- New cylinder design rules have been formulated. These rules are less conservative than current code practice. If accepted by code committees, these rules will enable use of lower strength materials and thinner wall designs. Under a given set of conditions.
- The economic viability of the USC boiler despite use of more expensive materials, has been established

#### 10. Plans for the Coming Year

- Task 1: This task has been completed. The conclusions from this task will be reviewed and revised at the conclusion of the project based on data generated in the course of the project.
- Task 2: Four reports pertaining to selection of ferritic, austenitic, and nickel base alloys will be issued by Oak Ridge. Creep rupture and creep-fatigue tests will be continued. Accelerated tests, notch-bar tests and tests on cross-weld geometries will be initiated. A web site for collection, and dissemination of material-property data will be established. The very high strength Ferritic 9%Cr steel samples from NIMS will be included in creep studies.
- Task 3: Steamside oxidation tests will be continued at Oak Ridge. The spalling behavior of the 9% Cr steels will be better defined. Anomalous test conditions in the atmospheric tests will be reviewed and the cause identified. Comparison will be made with exposures in the air-water vapor mixtures (from another program). At B&W analysis of the steam

oxidation test results from the 650°C (1200°F) specimens will be completed. Characterization of the scale morphologies will be completed. Test specimens will be prepared for the 800°C(1475°F) tests and the tests will be initiated.

- Task 4: Lab tests for fireside corrosion will be started. Air-cooled probe tests will be initiated on various alloys. Steam loop fabrication will be completed for installation at the Dairyland Power Co.
- Task 5: Welded plate samples of Haynes alloy 230 will be radiographed and sectioned to obtain tensile, bend and cross- weld specimens . Thin plates of Inco 740 will be welded. Thick plate welding of Haynes 230 will be completed. Thick plate welding of Inco 740 will be initiated. Super 304 H. test specimens will be fabricated using gas tungsten arc process. Gas metal arc welding of super 304 H. using type 347 filler will be quantified. CCA 617 test specimens using gas tungsten arc process and submerged arc process will be fabricated . Shielded metal arc welding of CCA 617 plate with conventional, Inco 617 electrodes, and with matching filler will be qualified. Welding efforts on HR 6W. and SAVE 12 will be initiated.
- Task 6: Strain response studies will be completed on all of the alloys in the project. Strain limit system will be established. Recrystallization the area after cold work will be investigated. Microstructural changes resulting from cold work, and from the crystallization and aging will be investigated.
- Task 7: Preliminary trials will be conducted on process scale up. Process optimization will be initiated for various coatings. Manufacturing recommendations for coatings will be generated.
- Task 8: Resolution of member commitment and sub-task leadership issues together with necessary redistribution of funding will be completed. A literature survey “ Modeling welds in creep” will be completed and published. Weld modeling will be initiated. Continuing dynamics models will be defined and initiated. A first round ASME approval of new cylinder design rules will be obtained.

#### 11. Management and Technical

- 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 materials budgets to be exceeded and might result in program cost overruns and/or reductions in program scope.
- Submerged arc welding, a high deposition rate process favored by boiler makers for thick sections, might not be feasible for nickel base materials.
- Delivery of Inconel 740 weld wire continues to be a problem. Special Metals is now quoting delivery in November, which has affected test specimen delivery schedules.
- Not exercising an option to purchase remnant Inconel 740 material for the follow-on weldability studies will delay this part of the program, assuming funding is imminent.
- One of the contractors had not correctly estimated the funding requirements for FY 2004 due to employee dislocations. Consequently, some of the work may have to be deferred to outer years. The terms of doing this are being negotiated.
- Early retirement of Bob Swindeman at Oak Ridge, initially caused some concern. However, the addition of John Shingledecker has addressed this concern adequately.
- Air in-leakage of the atmospheric steamside oxidation tests at Oak Ridge is suspected, causing conditions other than expected. This is being resolved. Oxidation rates established in the Oak Ridge tests seem to be compatible with European data. On the

other hand, data obtained by Jeff Sarver at B&W seem to be below the oxidation rates obtained in the other tests. Reasons for these anomalies need to be resolved.

- Currently, there is no procedure to study spalling of oxides specifically. Some incidental data is being obtained, which reflects on spalling tendencies. This issue needs to be looked at.
- The superior creep properties claimed by Dr. Abe for his alloy need to be further verified by tests at Oak Ridge. The superior oxidation resistance of two of the alloy versions submitted by Dr. Abe needs to be further investigated. These alloys hold great promise.
- Delays have occurred in field testing for fireside corrosion, because of delays in identifying host utilities. These delays however, are expected to be made up.
- The reason for the better creep rupture properties of Inconel 740 tested by Oak Ridge compared to the European data is unclear. It is suspected that the heat treatments may have been different. It is imperative that all the Inco 740 samples tested in our program be given the optimal heat treatment consistently.
- In many early weld tests that were carried out, the welds have been shown to be lower in properties compared to the base metal. Failure always seems to occur in the weld indicating that the weld is the weak link. Proper accounting needs to be made for this.

## 12. USC Project Related Papers

- R. Viswanathan, et al., "Materials for Ultra-Supercritical Coal-Fired Power Plant Boilers", 28<sup>th</sup> International Conference on Coal Utilization, Clearwater, Florida, 2003.
- J. Sarver, "Steam Oxidation Testing of Candidate USC Boiler Material", 28<sup>th</sup> International Conference on Coal Utilization, Clearwater, Florida, 2003.
- R. Viswanathan and W. Bakker, "Materials for Ultra Supercritical Coal Power Plants – Turbine Materials", Pittsburgh Coal Conference, 2003.
- R. Viswanathan, et al., "Ultrasupercritical Steam Turbines: Design and Materials Issues for the Next Generation", VGB Conference on Power Plants in Competition – Technology, Operation, and Environment, Cologne, March 19-20, 2003.
- R. Viswanathan, et al., "Ultrasupercritical Steam Turbines: Design and materials Issues for the Next Generation", 28<sup>th</sup> International Conference on Coal Utilization, Clearwater, Florida, 2003.
- G. Booras, et al., "Economic Analysis of Ultrasupercritical PC Plants", Pittsburgh Coal Conference, 2003.
- B.K. Schimmoller, "Boiler Industry: Surviving Rough Waters", Power Engineering and PEI Magazines, 2003. Citation to USC work.
- DOE Launches Project to Improve Materials for use in Ultra-Supercritical Coal Plants, DOE TechLine, 2003.

## Topical Reports Issued

1. Task 1 A, Conceptual Design -- ALSTOM Approach, USC T-2, February 2003
2. Task 1 B, Conceptual design, Babcock and Wilcox Approach, USC T-3, July 2003.
3. Task 1 C, Economic Analysis, USC T-1 February 2003.
4. Task 3, Steamside Oxidation of Materials -- A Review of Literature, USC T-5, June 2003.
5. Task 7, Coatings and Claddings—A Review of Literature, USC T-4, February 2003
6. Task 8, An Overview Of The Reference Stress Approach and Its Use, USC T-6, July 2003