Annual Progress Report

Doe Award Number: DE-FC26-05NT42442
OCDO Grant Number: D-05-02(B)

Project Title: Steam Turbine Materials for Ultrasupercritical Coal Power Plants

Project Director: Robert M. Purgert, Energy Industries of Ohio

Principal Investigator: Dr. R. Viswanathan, Electric Power Research Institute

Date of Report: 10/18/2007

PERIOD COVERED BY REPORT: **10/1/2006 – 9/30/2007**

U.S. Department of Energy Disclaimer

Project Consortium Legal Notice/Disclaimer

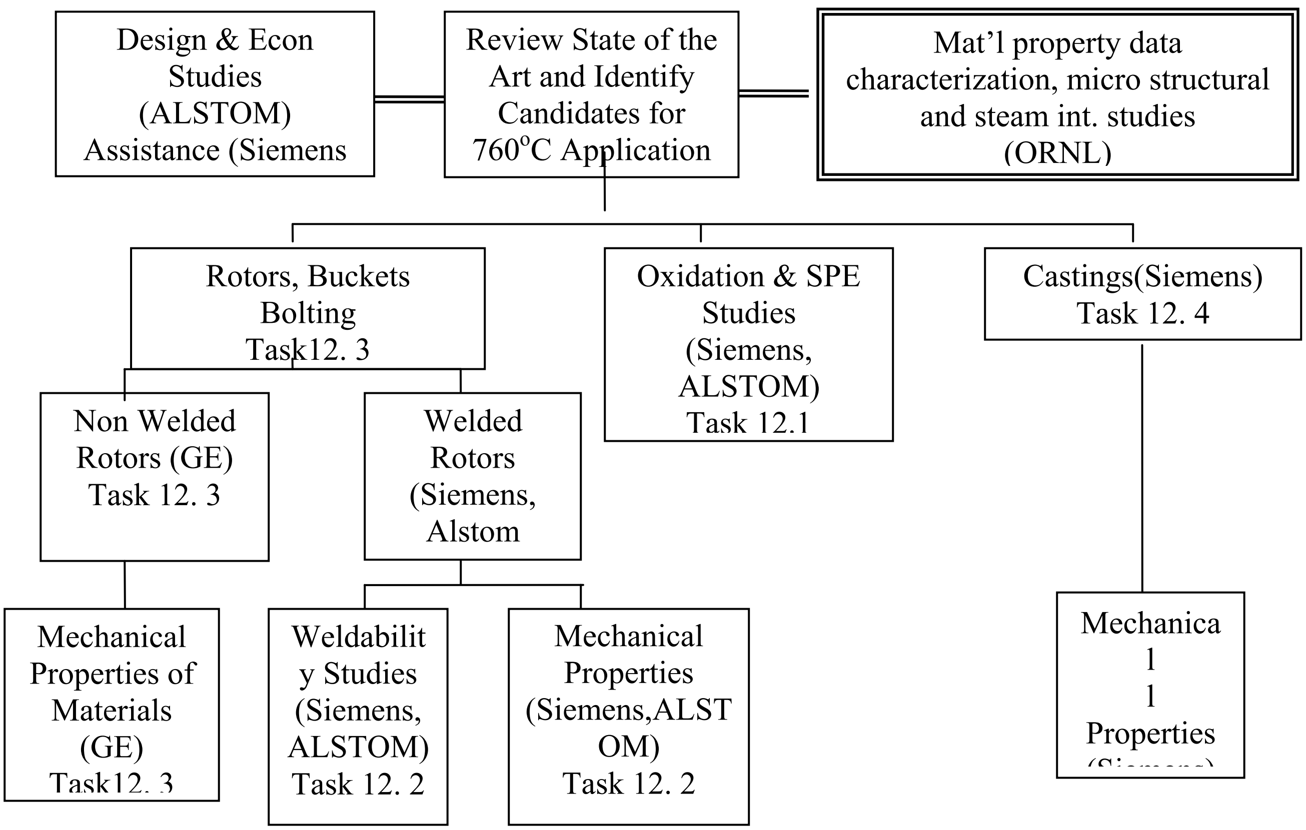
Abstract

The U.S. Department of Energy (DOE) and the Ohio Coal Development Office (OCDO) have sponsored a project aimed at identifying, evaluating, and qualifying the materials needed for the construction of the critical components of coal-fired boilers capable of operating at much higher efficiencies than current generation of supercritical plants. This increased efficiency is expected to be achieved principally through the use of ultrasupercritical steam conditions (USC). A limiting factor in this can be the materials of construction.for boilers and for steam turbines The project goal is to assess/develop materials technology that will enable achieving turbine throttle steam conditions of 760^{o}C (1400^{o}F)/35 MPa (5000 psi). This annual report describes the progress made in the steam turbine project during the period October 1 to September 30,2007

EXECUTIVE SUMMARY

The overall objective of the project is to contribute to the development of materials technology for use in ultra supercritical (USC) pulverized coal power plants capable of operating with steam up to 760°C (1400°F), 35 MPa (5000 psi). R&D is needed on advanced materials to lead to a full-scale demonstration, and eventual commercialization of USC power plants. The lack of materials with the necessary fabricability, resistance to creep, oxidation, corrosion and fatigue at the higher steam temperatures and pressures currently limit the adoption of advanced USC steam conditions in pulverized coal-fired plants. A major, five year, national effort sponsored by DOE and OCDO to develop materials for USC boilers has been in progress and is being continued for another 3 years by a Consortium of EIO, EPRI, Oak Ridge National Laboratory and all the domestic boiler manufacturers.Realising the importance of developing steam turbines with matching capabiliies, a 3 year project on USC turbine materials was started by OCDO and DOE with cost sharing and technical participation from, Alstom, EPRI, General Electric and Siemens. Oakridge National Labs was funded by NETL/DOE directly to provide support to the project

Figure 1-1 shows the basic tasks being addressed and there inter relationship:



Figur1, Program Logic and Task assignments

Summary of accomplishments:

- Completed Computer Simulation of Heat Transfer of Large IP Rotor Forging and evaluated cracking susceptibility for various ingot cooling rates
- Prepared an extensive Spread Sheet Of Mechanical, Physical And Thermo Physical Properties on 19 Candidate Alloys Selected Nimonic105,and Haynes282 For Non welded rotors. Creep tests and LCF tests are in various stages of completion
- Thermogravimetric Oxidation Studies Have Been Completed on several rotor alloys and the parabolic rate constants have been determined.
- Welded Rotor(n263/617/10crferritic)concept Developed. Welding trals for Haynes 263/In 617 have been successful . Welding trials have also been successful for 282-282 and 282-617. 282 to 720li In Progress
- Casting Candidates Selected As Nimonic 105,Haynes 282 and 740. Casing Design Completed

This is the annual report on the progress made by each member of the project consortium. during the period Oct 1 to September 30,2007.

GENERAL ELECTRIC COMPANY:

Task 12.3Materials for Non-welded Rotors

Progress During the Reporting Period:

- A spreadsheet of mechanical, physical and thermo physical properties was created for 19 Superalloys.Applying THERMOCALC calculations on the 19 alloys,,the phase stability of the microstructure at 1400F was determined. Based on the phase stability and availability, alloys Nimonic 105, Udimet 720Li, Haynes 282, and Inconel 740(1350F) were selected for more detailed evaluation. Creep testing is underway for Nimonic 105 in the as-received, precipitation strengthened and overaged conditions. Fatigue screening tests have been completed.
- Heat Transfer simulation of large IP rotor ingot under air-cooling and fan cooling was completed. Core cooling rate was determined to be half that of the surface. The likelihood of ingot cracking under air cooling was ruled out, but the situation was little less optimistic under fan cooling.
- At the present time,Creep testing continues for the 1st heat of solution annealed, precipitation strengthened and overaged Haynes 282. Fatigue screening tests have been completed.
- In summary,Two heats of Haynes282 and Nimonic 105 have been obtained.Specimens have been machined, heat treated to various conditions and subjected to creep, tensile and low cycle fatigue tests.. The tests arre in various stages of completion

Activities Planned For Next Quarter:

Mechanical tests on NImonic 105 and Haynes 282 will continue. Microstructural evaluatons will be continued.

Concerns:

- No concerns at this time.

ALSTOM

Task 12.1: Coatings for Preventing Solid Particle Erosion

Task Objective:

Identify options for coatings that will protect HP turbine components from excessive steam oxidation at inlet temperature up to 1400F (760 C). Additionally, identify coatings to provide control of solid particle erosion of candidate high-temperature alloys equal to or better than existing alloys.

How the objective will be achieved:

The consortium participants will select steam Oxidation Coatings – Candidate alloys. A review of coatings for oxidation prevention, including those used in aerospace applications and suitable for the chosen alloys, will be undertaken. A selection of representative coating approaches will be applied to test coupons. The coated test coupons, along with uncoated baseline specimens, will be exposed to atmospheric pressure steam at high temperature for up to 15,000 hours. The coupons will be periodically monitored for weight gain and occasionally examined metallographically for oxide thickness and penetration depth. Data will be examined to determine oxidation kinetic parameters. Thermal cycling of the coupons will be introduced if deemed necessary for the realistic evaluation of coating performance. Consideration will also be given to the resistance of coatings to Solid Particle Erosion (SPE) but no testing of SPE resistance will be completed; this will be the responsibility of Siemens.

Progress During the Reporting Period:

Short-term (one week duration) steam oxidation testing of candidate steam turbine alloys using the thermo-gravimetric testing apparatus (TGA) was completed. Tests at 850°C were completed on Nimonic 105 and Nimonic 263, and tests at 760, 800, and 850°C were completed on Inconel 740.

Figure 1 summarizes the TGA data, showing measured parabolic rate constants for the various alloys at different temperatures. As noted in previous reports, oxidation rates for alloys 617, 230, and 282 at 800°C were lower at 800C compared to those at 760°C. Possible reasons for this reduction have been discussed. There were no dramatic differences in oxidation rates between the different alloys, although Haynes 282 and Nimonic 263 consistently showed the highest rates and Nimonic 105 the lowest. Oxidation rates for Inconel 740 were comparable to those of the other alloys; rates at 760°C were low, comparable to Nimonic 105, but the rates at 850°C were relatively high. TGA tests on Udimet 720LI that were originally planned were not performed. This alloy is included in the long-term test matrix (see below), and TGA testing is currently considered unnecessary.

Long-term steam oxidation testing of candidate steam turbine alloys was started. In the long-term tests, rectangular test coupons of each alloy were simultaneously exposed in three tube furnaces with continually re-circulating, de-aerated steam at atmospheric pressure. The furnaces were run at temperatures of 700, 760, and 800°C; they were periodically shut down and the coupons were weighed. At every other shut-down, one coupon for each alloy was removed for metallographic analysis. The planned time series, in hours, for weighing and metallography is as follows: 225, 900*, 2025, 3600*, 5625, 8100*, 11025, 14400*. The series is linear in square root of time; at the starred times specimens are removed for metallography. Due to late availability of material, Udimet 720LI coupons were not available at the start of the long-term testing; these were added after the 900 hour exposure period and so will be on a slightly different time schedule than the other alloys.

The 225 and 900 hour exposures have now been completed for all alloys except Udimet 720 LI. Figure 2 shows the parabolic oxidation rate constants computed from the weight gain data from the two times. No indications of oxide scale spallation were observed on any the specimens. The oxidation rates measured in long-term tests were generally comparable to those measured in TGA tests, although rates at 760°C in TGA tests were considerably higher than in long-term tests for alloys CCA 617, Haynes 230, and Haynes 282. Note that rates in the long-term tests more properly scaled with temperature than the rates in TGA tests; an Arrhenius plot of rate versus 1/T for the long-term tests is shown in Figure 3. Although there is considerable scatter in the 700°C data (likely due to the very low weight gains observed), the higher temperature data all show a similar slope, which corresponds to an activation energy of approximately 290 kJ/mol.

The oxide morphologies observed were similar to those observed in TGA test coupons; i.e. a single-layer external scale and internal attack, typically along grain boundaries (Figure 4). Good correspondence was observed between scale thickness measured on metallographic sections and those calculated from the weight gain data, a further indication that oxide spallation did not occur.

TGA Test Results

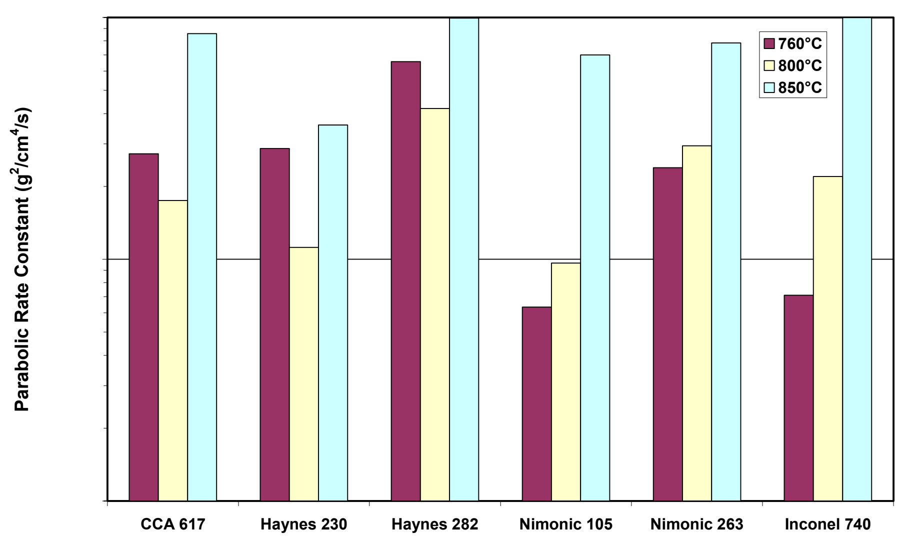


Figure 1: Parabolic steam oxidation rate constants of candidate steam turbine alloys obtained by TGA testing. One week test duration

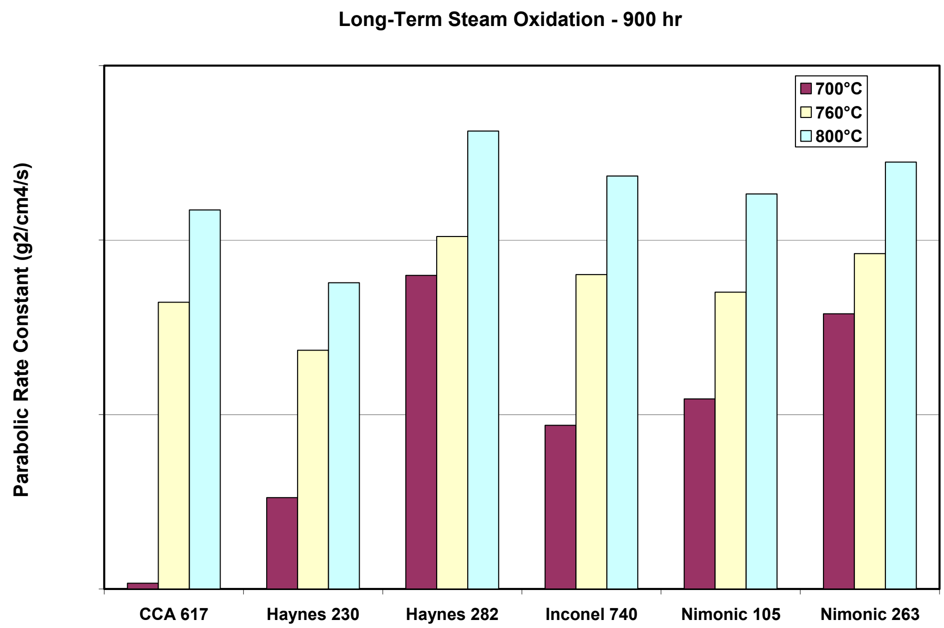


Figure 2: Parabolic steam oxidation rate constants of candidate alloys based on long-term oxidation tests upto 900hr.

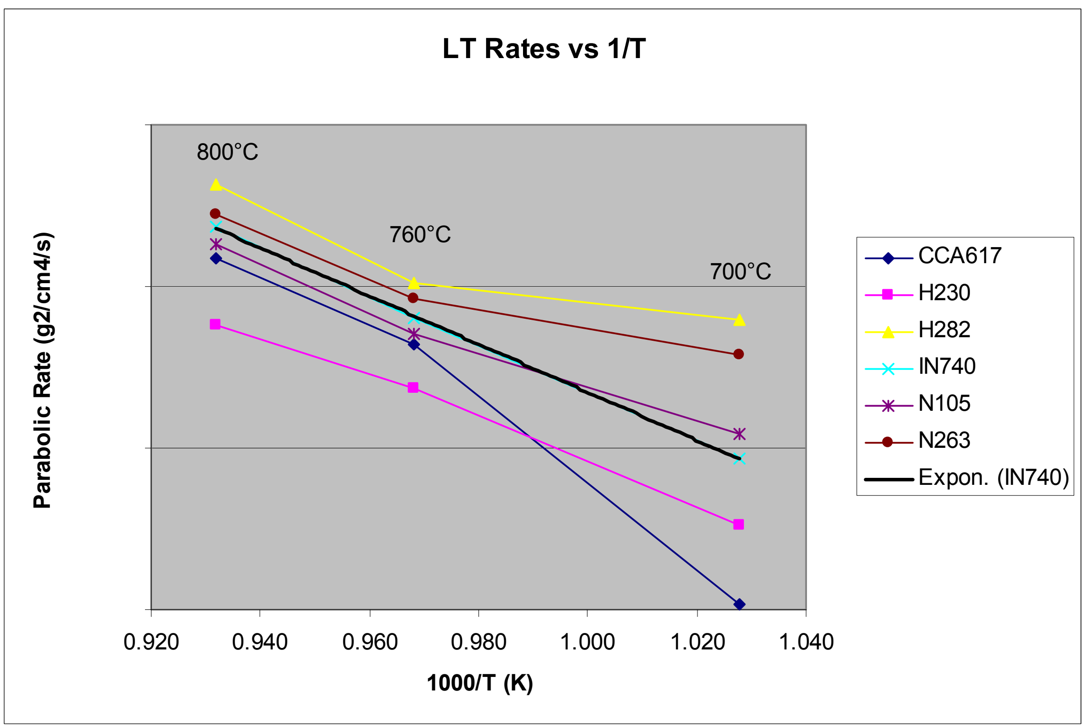


Figure 3: Arrhenius plot of oxidation rates obtained in long-term steam oxidation testing

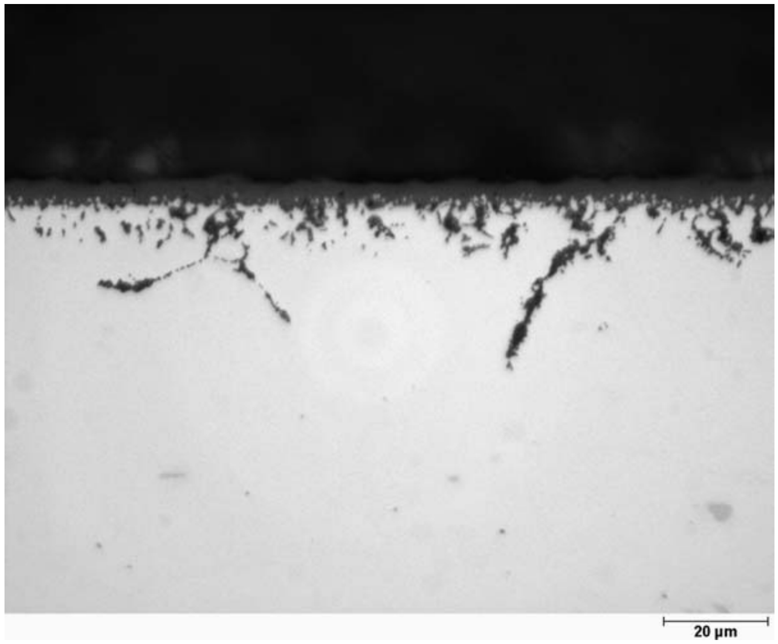


Figure4: Typical oxide scale and internal attack observed on Haynes 282, after 900 hr at 800°C

Concerns:

None

Activities Planned For Next Quarter:

Metallography will be performed on TGA specimens tested at 850°C.
Long-term exposure testing of candidate substrate alloys in flowing steam at 760 and 800°C will be continued; weight gain measurements at 2025 and 3600 hours will be made for all alloys except Udimet 720LI, for which measurements at ~1000 and 2500 hr will be made.
Further work on selection and procurement of SPE-resistant coatings will be performed in conjunction with Siemens.

Task 12.2 Welded Configuration for HP and IP Rotors

Objective:

To establish component requirements and candidate materials for welded rotors. Perform basic welding research to identify issues and best approaches for welding precipitation strengthened nickel alloys. Create test welds and perform metallurgical and mechanical testing of welds.

How the objective will be achieved:

A preliminary conceptual design study will establish the typical component dimensions and service conditions. Candidate materials will be reviewed and information on their weldability collated, drawing on experience welding similar materials in Gas Turbine applications. Having identified candidate alloys and joint types, basic welding process development will begin for a precipitation strengthened nickel alloy. Such development would likely include techniques such as varistrain testing to assess susceptibility for cracking. Based on the knowledge gained and existing experience with solution strengthened nickel based alloys, trial welds will then be created and inspected nondestructively and destructively to assess their metallurgical characteristics. Mechanical testing will be used to evaluate the tensile and creep strength of sample welds.

Progress During the Reporting Period:

The 2-inch thick Nimonic 263 – Inconel 617 weldment made previously was characterized. Metallographic cross-sections (Fig 5,Fig 6,and Fig 7) showed the weldment to be essentially defect-free, although a small lack-of-fusion (LOF) defect was observed in the last cap pass.

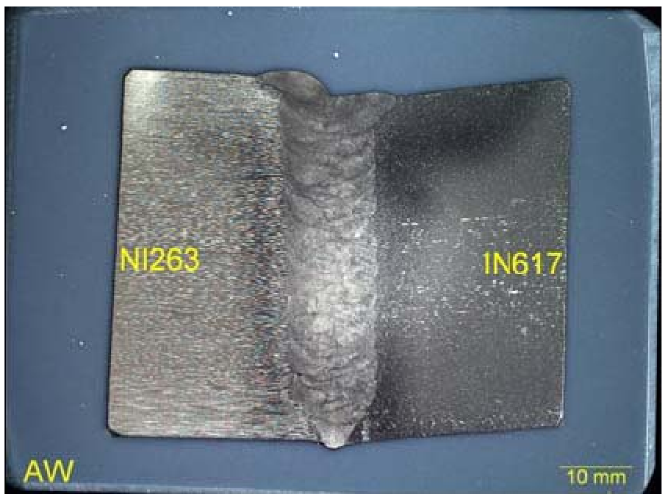


Figure5: Macro view of Nimonic 263 – Inconel 617 weld cross-section

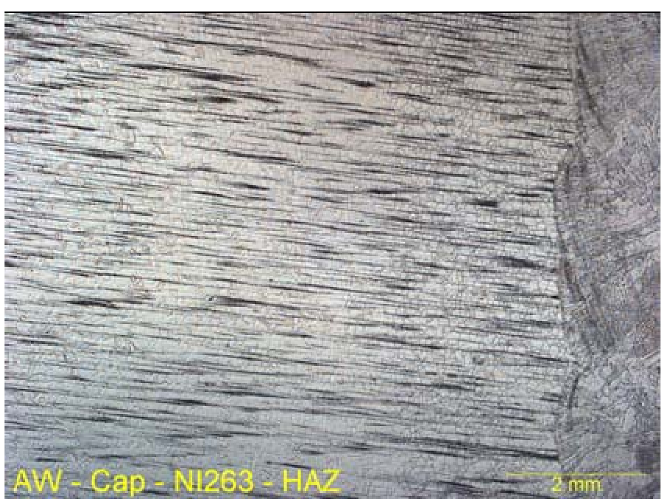


Figure 6: Microstructure of HAZ on NImonic 263 side of weld

Figure 7: Microstructure of HAZ on Inconel 617 side of weld

Hardness traverses, room-temperature tensile tests, and side-bend tests were performed in the as-welded condition, and following a post-weld heat treatment (PWHT) of 8 hours at 800°C (to age the Nimonic 263) plus 10 hours at 670°C (simulating a typical PWHT for an Inconel 617 to 10% Cr steel weld). The tensile results are summarized inTable 1. An increase in tensile strengths was observed after the PWHT, with a commensurate decrease in ductility. Hardness levels increased in the weld and both base metals after PWHT. The weld passed a side-bend test in the as-welded condition, but not after PWHT, as shown in Fig 8 and Fig 9.

Condition	Specimen Location	0.2% Yield Strength (MPa)	Ultimate Tensile Strength (MPa)	Elongation (%)	Failure Location
As-Welded	Root	367	745	47	IN617 Base Metal
As-Welded	Cap	369	743	47	IN617 Base Metal
PWHT	Root	497	837	16	IN617 Base Metal
PWHT	Cap	510	891	23	IN617 Base Metal

Table 1: Room-temperature tensile test results

Figure 8: As-welded side-bend test specimen – passed

Figure 9: PWHT side-bend test specimen – failed in Nimonic 263 base metal, cracking also in root area of weld metal

The Edison Welding Institute (EWI) prepared a summary report describing the weldability evaluation and initial weldment characterization. The remnant weldment pieces will be returned to Alstom.

An initial test plan for the remaining weldment (approximately seven inches of weld length) was prepared. All pieces will be subjected to the PWHT described above. In the as-PWHT condition, cross-weld tensile tests will be performed at room temperature, 700°C, and 750°C. Cross-weld stress-rupture tests will be performed at 700 and 750°C; six tests will be performed at each temperature at a range of stress levels. Room-temperature Charpy impact tests will be performed on the weld metal, both heat-affected zones, and the base metals.

A portion of the weldment will be further subjected to a simulated service exposure at 725°C, with duration of up to 10,000 hr. This temperature represents the highest reasonable use temperature for the alloy 617 weld and base metals. After exposure, microstructural evaluation, tensile tests at room temperature and 750°C, and room

temperature Charpy impact tests will be performed. The concern with service exposure is primarily a possible reduction in toughness and ductility due to precipitation of carbides and other phases.
To evaluate the applicability of non-destructive examination (NDE) techniques for these welds, trials will be performed on the initial weldment created by EWI as a trial run (described in the EWI report). This weldment contained a number of LOF defects and so is unsuitable for mechanical testing. The trials will include evaluation of the LOF defects by radiography and ultrasonics, as well as machining of flat-bottomed holes in the root of the weldment to evaluate NDE detection capabilities.

Concerns:

None

Activities Planned For The Next Quarter:

Perform tensile and Charpy impact tests on weldment in PWHT condition. Start stress-rupture testing of weldment in PWHT condition.
Begin long-term exposure of weldment at 725°C.
Perform NDE trials on weldment.

Task 12.5 Design and Economic Studies

Objective:

To assess the cost and performance tradeoffs associated with the use of expensive nickel-based alloys and integrate understanding developed during the project to ensure a coherent vision is developed for USC steam turbines.

How the objective will be achieved:

Based on design studies performed within this task and other task, some of the cost/performance tradeoffs (e.g. relax pressure to reach higher temperatures, cooling, etc.) will be examined and USC plant models will be used to establish costs. [For example, in the USC boiler project, a task ascertained that based on the increased cycle efficiency the capital cost of the boiler could increase by a certain percentage and still provide an economic plant.] The impact of a USC steam turbine on such plants needs to be quantified. This will require some up-front work and additional work toward the end of the project when the initial studies can be revisited based on what has been learnt. This will ultimately lead to an assessment of the benefit provided by USC steam turbines and a vision/roadmap for their future development and deployment. It is envisaged that some associated studies would also be performed to establish the cycling capability of USC turbines since this may affect their market acceptance and economic evaluation.

Progress During the Reporting Period

No activity this quarter.

Concerns:

None

Activities Planned:

Complete cycle heat balance calculations.
Begin calculations of boiler heat transfer surface sizing and determination of overall boiler performance.

Siemens Power Generation Inc.

Task 12.2 Welded rotor:

Progress During the Reporting Period:

- Mechanical tests on base materials (Haynes 282,U720LI and IN 617) are in various stages of completion. LCF tests have been completed at 700C upto 3000 cycles and up to 10000cycles at 750C. Creep tests have been completed at 700C.Creep tests have been completed up to 1000hr at 700C and up to 3000hr at 750C. Welding trials have been successfully completed for the combinations Haynes 282/Haynes 282,Haynes 282/IN 617 and Haynes 282/ U720LI.
- Design of castings has been completed..IN740,Haynes 282 and Nimonic 105 castings have been ordered.

Activities planned next quarter:

- Two more weld trials are planned with new pre-weld heat treatment for U720LI.
- Detail microstructure evaluation of the cracked U720 LI sample.
- Continuation of pre and post weld heat treatment trials.
- Completion of base material mechanical testing of candidate alloys.

Task 12.4 Castings

Progress During the Reporting Perod:

- Design of the prototype casting completed.

Activities planned next quarter:

- Cost evaluation and feasibility analysis for making the casting.