NTPC Indian Power Stations
Operation & Maintenance
Conference
Sustainable Growth Strategies for
Fuel and Efficiency
New Delhi, India    February 2013

U.S. High Efficiency Strategies
for Clean Coal Systems

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NTPC-Indian Power Stations O&M Conference
Sustainable Growth Strategies for Fuel and Efficiency

Federal – State – National Laboratory
Non Profit – For Profit
Cost Sharing Consortium
Increasing Steam Temperature and Pressure Increases Thermal Efficiency and Decreases Emissions

Note: HHV Basis

“Least Regret” Strategy for CO₂ Reduction
Materials Limit the Current Technology

Average Temperature for Rupture in 100,000 hours (°F)

9-12Cr Creep-Strength Enhanced Ferritic Steels (Gr. 91, 92, 122)

Nickel-Based Alloys

Inconel 740

Std. 617

Haynes 282

Age Hardenable = A-USC

760°C (1400°F)

CCA617

9-12Cr Creep-Strength USCs

620°C (1150°F)

Solid Soln’ = A-USC

~700°C (1300°F)

Haynes 230

Steels = USCS

Minimum Desired Strength at Application Temperature

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‘Aggressive’ goals for increased steam turbine temperatures are in-line with gas turbine improvements
Primary Technical Goals of US A-USC Materials Programs

• Materials Technology Evaluation
  • Focus on *nickel-based alloys*
  • Development of fabrication and joining technology for new alloys

• Unique Conditions for US Program Considerations
  • Higher-temperatures than European Program (760°C versus 700°C) means *additional alloys* are being evaluated
  • Corrosion resistance for *US coals*
  • Data for *ASME code* acceptance of new materials
  • Phase II Boiler work includes *Oxycombustion*
Why 1400°F (760°C)?
Best Approach to Achieving Good Economics

- **Materials** will limit the maximum achievable temperature
- **Economics** will dictate the optimum temperature
- For Example: a material suitable for 1400°F will have economic advantages at 1300°F over other materials because components will have *thinner walls*
  - Lower weight = lower material cost
  - Thinner sections = easier to weld/erect
  - Reduced thermal gradients = improved cycling

*If you have to pay for nickel, make the most of it!*
Develop the materials technology to fabricate and operate an A-USC steam boiler with steam parameters up to 1400°F (760°C)
A-USC Steam Turbine Program: Phase I (complete)

- Scoping Studies – Downselect Materials
- Key Issues
  - Welded rotors materials
  - Non-welded rotor materials
  - Air Casting
  - Erosion resistance
  - Oxidation resistance
DOE/OCDO A-USC Steam Turbine Consortium Phase II

• Selected Materials from Phase I
• Tasks
  – Rotor/Disc Testing (near full-size forgings)
  – Blade/Airfoil Alloy Testing
  – Valve Internals Alloy Testing
  – Rotor Alloy Welding and Characterization
  – Cast Casing Alloy Testing
  – Casing Welding and Repair
Approach: Address Key Technical Challenges for Materials & Components

• A-USC Boiler
  – Material selection based on strength & stability
  – Fireside corrosion
  – Weldability
  – Fabrication

• A-USC Turbine
  – Materials selection based on short & long-term strength, stability, fatigue, and processing characteristics
  – Erosion and oxidation of blade materials and coatings
  – Castings
  – Welded rotors
Boiler materials selection based on strength and stability

- Codes & Standards Interface
- Long-term weldment strength
- 40,000 hr + testing

- Long-term strength
- Fabrication Effects
- Weldment behavior
- Testing for code case

- Materials Selection
- Procurement of Materials (7 alloys)

- Initial creep testing (10,000hr)
- Microstructure & Aging Studies

- Vendor Discussions/Literature Search

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Materials Selection for A-USC Alloys (Boiler Superheater/Reheater Tubing Strength)

A-USC Technology Requires Nickel-Based Alloys

Today’s Technology Limited by Steels
Successes

• Materials have been identified with the requisite strength for an A-USC boiler with steam temperature up to 1400°F (760°F)
• Testing has eliminated certain alloys
• A code case request has been submitted based on the data produced by the program for Inconel 740
• Some very long-term tests continue to add confidence to life predictions
• Testing of a new material (Haynes 282) has started
Fireside Corrosion
3 phase approach

• Air cooled probes
  • Alloys and coatings selected from lab trials
  • 3 host site with 2 probes each

• Laboratory Studies
  (3 Coals, 3 WW Temps, 3 SH/RH Temps)
  • 2nd Steam cooled loop installation, operation & analysis
  • Oxycombustion effects

• Steam-cooled loops
  • Most realistic environment
  • High sulfur coal (aggressive)
Successes: Air-cooled probes

Cleaned surface of an air-cooled probe exposed for 2 years in a coal-fired boiler at A-USC temperatures

Inconel 740 shows lower wastage than a high chromium cladding (50/50), a 23% Cr wrought alloy (HR6W), and weld overlays (WO)
Successes (cont.)

• An extensive laboratory test program has been completed on a myriad of alloys, coatings, and weld overlays to aid in materials selection for fireside corrosion.

• Six air-cooled probes have been deployed and tested in three boiler burning different fuels.

• The air-cooled probes showed Inconel 740 to perform as well or better than any other monolithic material and even outperform weld overlays in some instances.

• A steam-cooled loop was fabricated and operated in a boiler above 1300°F/700°C (steam temperature) providing realistic data on a select number of alloys and coating. Again Inconel 740 performed very well despite the highly corrosive conditions.

• A second steam loop is under construction.

Overall, the corrosion probes and loops have shown that alloys can withstand the corrosion environment of an A-USC boiler with successive tests adding confidence for material selection.
Weldability

• **Welding**
  - 7 alloys, multiple processes, thin & thick section
  - Over 20 combinations qualified
  - Some processes eliminated
  - New learning: modified weld metal chemistries, different fluxes, process selection, etc.

- Thick section success: H230, CCA617
- Save12 R&D
- Initial welding (cracking)
- EWI Study
- Creep Testing
- Special Metals R&D
- New Heats Produced
- DMW w/P87
- Final Optimized Chemistry
- Successful Qualification
- Testing Modified Heats
- Repair Welding
- 2001 2002 2003 2004 2005 2006 2007 2008 2009 2010

- Additional mechanical property testing of welds
- Report on dissimilar metal welds
- Repair welding

- **Inconel 740**
  - Tube-to-tube successfully welded
  - For thick section an extensive welding development program was needed
  - Process is now repeatable
Successes

Original Inconel 740 weld trials (Liquation cracking in heat affected zone)

Today: Repeatable 3” (75mm) thick Inconel 740 welds without cracking

Consortium research has demonstrated revolutionary progress in nickel-based alloy welding
Fabrication

- **Evaluation of fabrication processes for new alloys**
  - Bending, machining, swaging, forming
  - Cold work and recrystallization
  - Testing of tube bends to evaluate cold-work limits

- **Cold-work effects on creep properties and recrystallization**

- Demonstration articles were produced to showing multiple processes being put together


Pressurized tube bend tests and analysis
Successes

• No significant changes to fabrication techniques were required
• Initial R&D was used to make changes to ASME Section I Table PG-19 for H230 & 617
• Initial tests on Inconel 740 led to additional phase 2 work (ongoing) on cold-work effects on creep (how the bends will perform in service)
Materials selection for turbine rotors, discs, and blades

- **Phase 1 – Initial material selection**
  - Extensive literature search, thermodynamic simulation, review of boiler work
  - Selected 5 alloys for mechanical property study including multiple heat-treatment conditions
  - Standard product forms
  - Mechanical properties: tensile, creep, fatigue
  - Microstructural development

- **Phase 2 – testing of best alloys**
  - Select top candidate alloy for each component
  - Extensive testing including: hold-time effects and notch sensitivity
  - Testing for longer times of larger forgings

- Additional steam-turbine specific testing
- Longer-term data
- Properties of large forgings

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Alloy Selection & Procurement

Testing & Analysis

Program Start

2001 2002 2003 2004 2005 2006 2007 2008 2009 2010

Initiate longer-term testing
Initial Material Selection for A-USC Turbine: Behavior of HP/IP Rotor Alloys

Fatigue Behavior

Creep-Rupture

Best Candidates:

→ Nimonic 105
→ Haynes 282
→ Waspaloy
Successes: Large Forgings Research Requires an Understanding of Microstructure & Properties as a Function of Heat-Treatment

Solution Annealed

PA = SA + 8h @ 790°C

OV = PA + 250h @ 775°C

Studies on Haynes 282:

• Creep-rupture strength was relatively insensitive to heat-treatment
• Detailed microstructural studies on gamma prime precipitates after heat-treatment and creep were conducted
• Both mechanical property data and microstructure studies suggest the alloy has a large processing window making it attractive for steam turbine forgings

Erosion and Oxidation of Blade Materials and Coatings

- Oxidation studies
  - Oxidation rates/kinetics
  - Scale morphology
  - Internal penetration vs. oxide thickness
  - Bare metals (substrates) and coatings

- Erosion Testing
  - High-temperature erosion tests were conducted at 1400°F (760°C)
  - Coating and substrates
Successes

- Oxidation rates (both internal penetration and mass gain) of candidate bare metal substrates were acceptable based on laboratory studies.
- 14 candidate erosion resistant coatings were identified for high-temperature erosion testing and steam oxidation testing.
  - Erosion testing identified four coatings with best performance.
  - Oxidation testing showed unacceptable rates for some coatings including the best erosion performing coating.
- Coating T400C (Tribaloy) performed well in both tests suggesting its use for blading protection.
Castings

- **Phase 1 – National laboratory study**
  - Trial melts made of candidate wrought alloys
  - Simulated slow cooling for large casting
  - Developed new heat-treatment cycles
  - Screening creep and tensile tests including orientation effects
  - Microstructure

- **Phase 2 – testing of best alloys**
  - Select top two candidate alloy castings
  - Produce larger castings
  - Mechanical property testing
  - Weld repair of castings

- Production of larger casting
- Longer-term testing of larger castings
- Weld repair of castings
**Successes**

- A casting sub-team of OEM and National Laboratories (ORNL & NETL) was formed to address potential issues with nickel-based casing/shells
- Seven trial alloys were cast
- An innovative homogenization heat-treatment cycle was developed
- Mechanical property testing identified the best performing alloys
- Some alloys were eliminated due to lower strength or ductility compared to the wrought alloy counterpart
- Haynes 282, 263, and N105 were judged the best alloys for casting and castability trials were performed
- Based on this work, the phase 2 work on castings has a good starting point for development of larger castings
Welded rotor evaluation

- **Phase 1 – Welded rotor concept**
  - Produce welded joints at desired thickness
    - Heavy section 263-617-Steel
    - Seal weld between nickel based alloys
  - Inspection study
  - Property testing
  - Aging and toughness studies to simulate service exposure

- **Phase 2 – welded rotor**
  - Large ring weld in design thickness and diameter (2 welds planned)
  - Weld inspection
  - Mechanical property and aging evaluation

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Successes

- Successfully produced a thick-section 263-617-Ferritic Steel joint concept using traditional welding techniques.
  - Joint toughness was acceptable after aging (simulated service exposure)
- A second welded rotor configuration was evaluated for Haynes 282 to Udimet 720Li.
  - Welding development was successful and heat-treatment studies showed no evidence of strain age cracking after welding
  - Non destructive evaluation capability of joint was verified
A-USC R&D

- Current Boiler & Turbine Materials R&D
  - Effect of oxycombustion on materials
  - Improved weld/weldment performance
  - Code approval of new alloys
  - Long-term high-temperature material property databases
  - Production of larger forgings
  - Casting R&D for nickel-based alloys

- Path Forward
  - Supplier Development for full-size forgings, extrusions, and castings
  - Test facility → Demo Plant
Comparative Benefits from Program: Piping Sizes for Two A-USC Conditions

Main Steam
5000psi (34.5MPa)
9.8” (248mm) I.D.

Hot Reheat
1060psi (7.3MPa)
18.4” (467mm) I.D.

1300°F/1300°F (700°C/700°C)
1350°F/1400°F (732°C/760°C)

4” (100mm)