ComTest-AUSC Thick-walled Cycling Header Development - Phase I

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Imagination at work
Thick-walled Cycling Header Development
Acknowledgements

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• Jim Pschirer
• John Marion
• Bruce Wilhelm
• Wei Zhang
• Yen-Ming Chen
• Zhiquan Zhou

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• Monica Soare
• Chen Shen
Thick-walled Cycling Header Development

Agenda

• Technical Background
• Statement of Objectives
• Potential Significance
• Project Team
• Technical Approach
Thick-walled Cycling Header Development
Technical Background

- Conceptual AUSC Boiler design steam cycle
  - temperatures are 730/760°C (1350/1400°F)
  - pressures 240-350 bar (3500-5200 psi)
- Future boiler designs require operation in daily and weekly cycling mode
- Startup-shutdowns such as weekly warm-starts have high ramp rates, 1.5% to 5% MCR/min
- Critical high temperature components in the boiler, such as superheater and reheater outlet headers, require latest high creep strength nickel-based superalloys Inconel 740H and Haynes 282
Thick-walled Cycling Header Development

Technical Background

- SH outlet headers for high pressures, even with the high strength superalloys, require large wall thicknesses, in the range of 125 to 150mm (5 to 6”)
- Thick walls and high ramp rates subject the headers to very high thermal cycling stresses causing
  - High cyclic usage of the material fatigue limits
  - Creep strain accumulation over the duration of the design life.
- Tube boreholes and outlet nozzle connection welds cause stress concentration effects and limit design fatigue/creep life
Thick-walled Cycling Header Development

Technical Background

• Latest nickel-based superalloys 740H and H282 have successfully been tested for fireside corrosion and steam-side oxidation in coal-fired boiler environments demonstrating applicability to superheater and reheater tubing in AUSC conceptual design (GE’s Plant Barry steam loop and others)
• These alloys have also been tested for high temperature creep and fatigue properties in laboratory specimens (ORNL and GRC).
Thick-walled Cycling Header Development

Objectives

Objectives of Phase I are to demonstrate:

- Adequacy of the latest available high strength nickel-based superalloys for severe thermal cycling (warm-start) fatigue transients
- Adequacy of thick-walled header components in full-scale conceptual AUSC boiler design for creep life

Fatigue Life

Creep Life
Thick-walled Cycling Header Development Objectives

Phase I project scope

- Design a simulated cycling header system for a ComTest-AUSC pilot demonstration to be performed in Phase II of ComTest-AUSC

- Develop analytical tools to be used through CFD for heat transfer rates in
  - full-scale AUSC conceptual design SHOH
  - simulated ComTest-AUSC cycling header

- Perform long term creep life assessment of AUSC conceptual design SHOH through latest available material creep constitutive equations using continuum damage mechanics (CDM) approach.

- Participate in host facility selection for ComTest-AUSC

- Detailed design layout of the ComTest-AUSC header system including instrumentation that will be required for monitoring the cycling transient conditions
Thick-walled Cycling Header Development Roadmap to AUSC Demo

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<tbody>
<tr>
<td><strong>Materials Development</strong></td>
<td><strong>Component Mockup</strong></td>
<td><strong>Steam Loop at Plant Barry</strong></td>
<td><strong>AUSC-COMTEST</strong></td>
<td><strong>Overall TRL</strong></td>
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<tr>
<td>Laboratory TRL 2 to 3</td>
<td>Proof of Concept TRL 4</td>
<td>Component Test TRL 4 to 5</td>
<td>System TRL 6 to 8</td>
<td>to 9</td>
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Current DOE-sponsored programs designed to bring components to TRL 5; AUSC-COMTEST will bring system to TRL 7 or 8

<table>
<thead>
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<th>components</th>
<th>TRL</th>
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<tbody>
<tr>
<td>Tube Membrane Panel</td>
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<tr>
<td>Superheater</td>
<td>5</td>
</tr>
<tr>
<td>Turbine</td>
<td>4</td>
</tr>
<tr>
<td>Desuperheater</td>
<td>4</td>
</tr>
<tr>
<td>Header</td>
<td>4</td>
</tr>
<tr>
<td>Valves</td>
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Thick-walled Cycling Header Development

Potential Significance

• Demonstrate adequate fatigue cycling design life for the critical pressure part components in the AUSC boiler with high ramp rates required for coal fired power plants.

• Provide design guidelines for the dynamic operation of the boiler for design conditions that result in better material fatigue conditions

• Assess the long term creep life of critical pressure part components at AUSC temperatures using the latest state-of-the-art material constitutive models for high strength nickel alloys

• Design a header component for ComTest-AUSC with full analytical evaluations and simulations to increase the probability of a successful test in Phase II of this project
Thick-walled Cycling Header Development Project Team

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GE Power Boiler NTI/NPI Leader
Diana Daury

Technical Advisory Committee
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Task 3
CFD Analysis
Paul Chapman
Dr. Yen-Ming Chen

Task 4
Mech. Integrity Eval.
Reddy Ganta

Task 5
Final Header Design
Robert Schrecengost

Task 6
Host Site Identification
Robert Schrecengost

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Thick-walled Cycling Header Development
Technical Approach

Phase I of the project has six major Tasks

Task 1: Project Management and Reporting
Task 2: Conceptual Design of Cycling Header
Task 3: CFD Analysis of Thick-walled Header
Task 4: MI Evaluation of Header, Tubing, and Welds
Task 5: Design of Thick-walled Header Component
Task 6: Host facility Selection for ComTest-AUSC
Thick-walled Cycling Header Development Deliverables

• Task 2: Process design of ComTest-AUSC cycling header layout and flow conditions (input to CFD group, done in 2016)

• Task 3: CFD Analysis to identify heat transfer rates (input to MI group, done in 2016)
  ➢ Flow and heat transfer rates for the 1000 MWe full-scale conceptual AUSC SH outlet header at full and half load conditions
  ➢ Flow and heat transfer rates for the ComTest-AUSC cycling header for RH steam parameters (pressure, temperature and flow rates) at two steady-state conditions
Thick-walled Cycling Header for ComTest-AUSC
Technical Approach

Task 2  Process Design of Thick-walled Cycling Header

Full-scale AUSC SHOH design and transient

ComTest-AUSC cycling header design and transient
Thick-walled Cycling Header Development
Technical Approach

**Task 3: CFD Analysis of Thick-walled Cycling Header**

- **AUSC conceptual design SH outlet header CFD analysis**
- **ComTest-AUSC CFD Model**
  - Host Site currently at 600 psi (currently assumed & proceeding)
  - Southern Company with 3500 psi (if decided, design needs to be updated to Southern's flow conditions)
- **Benchmark examples from GE Power CFD experience**
  - Straight Pipe Flow CFD HT Coefficient Prediction
  - Header - HTC for Molten Salt
Thick-walled Cycling Header Development
Technical Approach

- AUSC SHO Header pipe size 26” OD, 5.7” wall thickness
- Material Inconel 740H or Haynes 282
- Flow rate 5.6M lbs/hr
- Temperature 1350°F, Pressure 5200 psig
Thick-walled Cycling Header Development
Technical Approach

ComTest-AUSC header design
• Five different cases analyzed by CFD for flow rates, velocity and heat transfer film coefficients
• USC SH steam pressure at 3500 psi
  - 100k to 130k lbs/hr flow rate
  - 1400°F temperature
  - Pipe ID 4 to 8”, wall thickness 3”
• USC RH pressure at 600 psi
  - 100k to 130k lbs/hr flow rate
  - 1400°F temperature
  - Pipe ID 4 to 8”, wall thickness ~3”
Thick-walled Cycling Header Development
Technical Approach

Option 1

Option 2

Option 3

Option 4

Option 5a & b

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Thick-walled Cycling Header Development
Technical Approach

Flow Split: 12.4% 87.6%

Velocity contours

Pressure contours

Heat transfer rates
Thick-walled Cycling Header Development
Technical Approach

Header 8" ID, 14" OD

Nozzles, 0.9" ID
Moved 60" further from Pipe

Pipe, 8" ID
Thick-walled Cycling Header Development Deliverables

• Task 4: Mechanical integrity evaluation (final report being drafted this year)
  ➢ Benchmark creep analysis of test specimens using the CDM creep models
  ➢ Creep life assessment of Conceptual AUSC SHOH with H282 CDM models
  ➢ Transient analysis and fatigue evaluation of ComTest-AUSC cycling header

• Task 5: Design layout of ComTest-AUSC cycling header system including instrumentation type and locations (final report being drafted this year)
Thick-walled Cycling Header Development
Technical Approach (with two goals)

**Task 4: Mechanical Integrity Evaluation**

**4a: ComTest-AUSC Fatigue Cycling**
- Design ComTest header configuration
- Includes tube penetrations
- No branch nozzle in CFD studies
- Accelerated **thermal cycling**
- Test temperature 760°C (1400°F)
- Test pressure 41 bar (600psig)
- Materials: 740H & H282
- Transient cycle configured using two steady-state CFD analyses
- Fatigue data: Literature & ORNL data
- MI analysis for thermal transients
- Assess **fatigue life (no creep)**

**4b: Conceptual AUSC SHOH Creep Life**
- 1000MW AUSC SHO header design
- Includes tubes and branch connection
- Welds included but with a knock-down factor over the base material properties
- Temperature 730°C (1350°F)
- Pressure 220-350 bar (3200-5200psig)
- Material: Base H282
- Heat transfer rates from CFD study for the 1000 MW conceptual AUSC SHOH
- Use GE **CDM** models
- MI analysis for creep damage
- Assess **creep life (no fatigue)**
Thick-walled Cycling Header Development
Technical Approach

Task 4a: ComTest-AUSC cycling header fatigue assessment

- Comtest-AUSC cycling header fatigue analysis for test condition accelerated fatigue cycling transients
  - Actual test header design configuration with upstream header 740H and downstream header H282
  - Includes tube penetrations
  - No branch nozzle
  - Accelerated test cycling transients for fatigue
  - Assess for fatigue usage with 740H and 617 material fatigue data
Thick-walled Cycling Header Development
Technical Approach

ComTest cycling header stress analysis

ComTest header models
Temperature contours
Stress contours
Thick-walled Cycling Header Development Technical Approach

Task 4b: Full-scale AUSC SHOH Creep Life Assessment

- Long term creep life assessment of full-scale AUSC SHO header using high temperature superalloy CDM models for analysis includes:
  - inlet tubes with welds
  - “Tee” section of a header with one branch nozzle and weld
  - H282 base metal model only for now
  - H282 weld material model if available in Phase I
  - 740H base and weld material models in the future when available

[Diagram of Full-scale AUSC SHOH Model]

[Diagram of Benchmark Test Specimen]

[Diagram of AUSC SHOH Analysis Model]

[Diagram of H282 CDM creep model data]
Thick-walled Cycling Header Development

H282 Constitutive Creep Model

Develop macroscopic models capturing the effect physical micro-mechanisms and microstructure (e.g. dislocation climb-bypass & diffusion creep)

Base Metal H282, Creep model 1400-1700˚F
Thick-walled Cycling Header Development
H282 creep model development & application

Test specimen creep strain data

Benchmark FEA Verification

Damage parameter contours

Borehole stress, creep strain & damage parameter history

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Thick-walled Cycling Header Development
Constitutive creep model - Dislocation climb

\[ \varepsilon_{\text{creep}} = \varepsilon_{\text{disloc}} + \varepsilon_{\text{diffusion}} \]

\[ \dot{\varepsilon}_{\text{disloc}} = A(T) \rho(T) f(T) (1 - f(T)) \left( \sqrt{\frac{\pi}{4f(T)}} - 1 \right) \sinh \left( \frac{\sigma_{\text{eff}} - \sigma_{\text{climb}}(T) - \sigma_0(T)}{MkT} \right) \lambda(T) b^2 \]

\[ \sigma_{\text{climb}}(T) = \frac{2f(T)}{1+2f(T)} \sigma_{\text{eff}} \left[ 1 - \exp \left( -\frac{1+2f(T)}{2(1-f(T))} E(T) \frac{\varepsilon_{\text{disloc}}}{\sigma_{\text{eff}}} \right) \right] \]

\[ \sigma_0 = 0.25MG(T)b\sqrt{\rho}, \quad \rho = \rho(C) \]

\[ \rho = \begin{cases} \rho_i + (\rho_f - \rho_i)\varepsilon/\varepsilon_{\text{crit}} & \text{if } \varepsilon \leq \varepsilon_{\text{crit}} = C\sigma_{\text{eff}} \\ \rho_f & \text{if } \varepsilon > \varepsilon_{\text{crit}} = C\sigma_{\text{eff}} \end{cases} \]

\[ \omega = \omega_{\text{diff}} + \omega_{\text{disloc}} \]

\[ \dot{\omega}_{\text{disloc}} = D \dot{\varepsilon}_{\text{disloc}} \]

Total creep – effect of dislocation and diffusion creep mechanisms

H282 model developed for high temperatures

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Thick-walled Cycling Header Development
Constitutive creep model - Diffusion

\[
\dot{\varepsilon}_{\text{diffusion}} = \dot{\varepsilon}_{\text{lattice_diff}} + \dot{\varepsilon}_{\text{boundary_diff}} + \dot{\varepsilon}_{\text{cavity_boundary_diff}} + \dot{\varepsilon}_{\text{cavity_surface_diff}}
\]

\[
\dot{\varepsilon}_{\text{boundary_diff}} = 3 \pi \xi \left( \frac{l}{d} \right)^3 \sigma_{\text{applied}} (1 + \varepsilon_{\text{creep}})
\]

\[
\dot{\varepsilon}_{\text{lattice_diff}} = \xi \beta \sigma_{\text{applied}} (1 + \varepsilon_{\text{creep}})
\]

where \( \beta = \frac{3D_V l^3}{D_B \delta B d^2} \) is a constant

\( \xi = \frac{4D_B \delta B \Omega}{l^3 k_B T} \) is a constant

\[
\dot{\varepsilon}_{\text{cavity_boundary_diff}} = \xi \frac{l}{d} \frac{\sigma_{\text{applied}}}{\ln(1/\bar{\omega}_{\text{boundary_diff}})}
\]

\[
\dot{\varepsilon}_{\text{cavity_surface_diff}} = \xi \alpha \sqrt{\frac{\bar{\omega}_{\text{surface_diff}} \sigma_{\text{applied}}^2}{(1-\bar{\omega}_{\text{surface_diff}})^3}}
\]

(Cocks and Ashby, Progress in Mater. Sci. 1982)

H282 model adapted for high temperatures

Void growth by boundary diffusion

\[
\alpha = \frac{D_S \delta_S l^2}{D_B \delta B \sqrt{2} dy}
\]

Void growth by surface diffusion

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Thick-walled Cycling Header Development
2017 completion

3D creep constitutive model validation
Thick-walled Cycling Header Development 2017 completion

Notched Bar Creep Tests

- H282 notched bar creep tests, 100 to 1000 hours
- Digital image correlation
- Simulates three-dimensional multi-axial stress effect
- Validate 3D creep constitutive models at 1400°F
- Suitable for boiler component applications
Thick-walled Cycling Header Development
2017 completion

3D first principal strain distribution
Thick-walled Cycling Header Development
2017 completion

Axisymmetric model of the notched sample
Thick-walled Cycling Header Development
Technical Approach

Task 5: Design of Thick-walled Header Component

- Design layout of the ComTest-AUSC cycling header including desuperheater
- Identify instrumentation and location on the header for measurement of field data
- Define ComTest-AUSC test program including transient cycles (flow rates, temperature, pressure, ramp rates)
- Develop preliminary drawings for the layout for ComTest-AUSC header system
- Define ComTest-AUSC program thick-walled header system “flange-to-flange”
Thick-walled Cycling Header Development
APROS Transient Simulation

- Valve operating scenario at RH pressure
- Ramp rates
- Low and high temperature flow mix

flow rate & temperature with 4 valves operating simultaneously

flow rate & temperature with control valves operating in two steps
Thick-walled Cycling Header Development
Mixing Tee and Header design

<table>
<thead>
<tr>
<th>Instrumentation</th>
<th>Number</th>
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<tbody>
<tr>
<td>Surface (skin) thermocouples</td>
<td>22</td>
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<tr>
<td>Buried wall thermocouples</td>
<td>6</td>
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<tr>
<td>Surface strain gauges</td>
<td>8</td>
</tr>
<tr>
<td>Flow meters</td>
<td>7</td>
</tr>
</tbody>
</table>
Thick-walled Cycling Header Development

Header Instrumentation design

SECTION "1C—1C" *(E—2)*
(INLET HEADER)

SECTION "1D—1D" *(E—2)*
(OUTLET HEADER)
SCALE: 3" = 1'-0"

SECTION "1A—1A" *(E—2)*
(AS SHOWN, WITHOUT FLOW METERS)

SECTION "1B—1B" *(E—2)*
(AS SHOWN, WITH FLOW METERS)
SCALE: 1" = 1'-0"
Thick-walled Cycling Header Development
Technical Approach

Task 6: Host facility Selection for the ComTest-AUSC

- Identify the available site parameters for input to the cycling header design – December 2015
- Design parameters with flow rates of 133,000 lbs/hr, pressure of 600psig and temperature of 1400°F are used in the process design and CFD analyses.
- A change of design parameters to lower steam flow and AUSC SH pressure conditions will require a new process design and CFD analysis and changes in the ComTest cycling header layout.
- Final decision on the host site for the ComTest-AUSC with (or without) the thick-walled cycling header is expected in Q2 of 2017.
Thick-walled Cycling Header Development Project Publications

First application of superalloy (H282 base metal) creep constitutive model applied for long term creep life assessment of conceptual full-scale AUSC SHOH component.

Creep Life Assessment of High Temperature Advanced Ultrasupercritical (AUSC) Conceptual Boiler Thick-Walled Pressure Components Using Continuum Damage Mechanics Approach

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Monica Soare and Chen Shen
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Thick-walled Cycling Header Development
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