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

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Imagination at work
Thick-walled Cycling Header Development

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Thick-walled Cycling Header Development

Agenda

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

- Conceptual AUSC Boiler design steam cycle
  - temperatures are 730/760C (1350/1400F)
  - 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%/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 (Alstom’s Plant Barry steam loop and others).

• These alloys have also been tested for their high strength creep and fatigue properties in the laboratory specimens (ORNL).
Thick-walled Cycling Header Development

Objectives

Objectives of Phase I is 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

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Thick-walled Cycling Header Development

Objectives

Phase I project scope

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

• Analytical development of 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.

• Identify host facility for the 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

<table>
<thead>
<tr>
<th>Year</th>
<th>Materials Development</th>
<th>Component Mockup</th>
<th>Steam Loop at Plant Barry</th>
<th>AUSC-COMTEST</th>
<th>AUSC Demonstration</th>
</tr>
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<tbody>
<tr>
<td>2000</td>
<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>Overall TRL 7 to 9</td>
</tr>
</tbody>
</table>

Current DOE-sponsored programs designed to bring components to TRL 5;
AUSC-COMTEST will bring system to TRL 7 or 8

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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
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 for ComTest-AUSC Technical Approach

Task 2 Conceptual Design of 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 Header**

- **AUSC conceptual design SH outlet header CFD analysis**
- **ComTest-AUSC CFD Model**
  - Youngstown with 600 psi (currently assumed & proceeding)
  - Southern Company Barry 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 1350F, 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
• Southern USC steam pressure at 3500 psi test
  - 100k to 130k lbs/hr flow rate
  - 1400F temperature
  - Pipe ID 4 to 8”, wall thickness 3”
• Youngstown pressure 600 psi
  - 100k to 130k lbs/hr flow rate
  - 1400F temperature
  - Pipe ID 4 to 8”, wall thickness ~3”
Thick-walled Cycling Header Development
Technical Approach

Option 1

Option 2
Thick-walled Cycling Header Development
Technical Approach

Option 3

Option 4

Option 5a & b
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

- CFD analysis performed for steady-state conditions at two different flow rates
  1) full flow rate and 1400F temperature
  2) ~800F with full or partial flow rate
- Heat transfer coefficients for the transient between the lower temperature and full load temperature will be interpolated according to flow rate and steam properties at temperatures.
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

ComTest-AUSC cycling header
ComTest-AUSC header model
Thick-walled Cycling Header Development
Technical Approach

Full-scale SHOH and ComTest Cycling Header Transients

Flow Split: 17.5%  82.5%

Full-scale AUSC SHOH design and transient

ComTest-AUSC cycling header design and transient
Thick-walled Cycling Header Development
APROS Transient Simulation

- Valve operating scenario at Youngstown
- 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

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
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 in Phase I
  - 740H base and weld material models in the future when available

Benchmark Test Specimen

Full-scale AUSC SHOH Model

AUSC SHOH Analysis Model

H282 CDM creep model data
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”

Task 6: Host facility Selection for the ComTest-AUSC

- Input to the site selection criteria - October 2015
- Identify the available site parameters for input to the cycling header design – December 2015
- Input to process design and CFD groups for analysis – Youngstown Thermal as test facility
Thick-walled Cycling Header Development
Project Status – Host Facility Decision

• Currently host facility test site is to be Youngstown Thermal (YT) plant in Youngstown, Ohio

• Design parameters with flow rates of 133,000 lbs/hr, pressure of 600psig and temperature of 1400F are used in the process design and CFD analyses.

• A change of the host site from YT to Southern Company with SC 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 the thick-walled cycling header is expected to be confirmed as YT Thermal.
Thick-walled Cycling Header Development Deliverables

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

- Task 3: CFD Analysis to identify heat transfer rates (input to MI group)
  - 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 YT site steam parameters (pressure, temperature and flow rates) at two steady-state conditions

- Task 4: Mechanical integrity evaluation (final report)
  - Benchmark creep analysis of test specimen 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)
Thick-walled Cycling Header Development

Project Status

- Project awarded in mid September 2015
- Kick-off meeting with DOE PM, 17th November 2015.
- Process design of ComTest-AUSC configuration completed, input provided to CFD group
- CFD for the full-scale conceptual AUSC SHOH and ComTest-AUSC cycling header test have been completed. Two-header system with a single branch connection selected for proper flow split and heat transfer rates.
- An analytical evaluation of simulated transient for ComTest-AUSC cycling header configuration performed using simple pipe geometry.
- Different valve operating scenario simulated through APROS for obtaining proper ComTest transient cycle temperature transient, pressure drop and flow rates identified.
- Long term creep life assessment model for Haynes 282 parent material developed by GE GRC, verified through the test specimen benchmark problems and applied on a conceptual full-scale AUSC SHOH design for long time creep life assessment.
- A paper on the creep assessment of full scale AUSC header component using the H282 nickel alloy CDM model has been submitted to the ASME/EPRI Conference to be held in July 2016.
- Analysis of ComTest-AUSC cycling header test configuration for thermal fatigue has been started.
Thick-walled Cycling Header Development
Going forward –

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 1400F
• Suitable for boiler component applications
Thick-walled Cycling Header Development
Project Status

- First application of superalloy (H282 base metal) creep constitutive model applied for the long time creep life assessment of conceptual full-scale AUSC SHOH component.
Thick-walled Cycling Header Development
Project Milestones – Phase I
**Thick-walled Cycling Header Development**

Constitutive creep model - Dislocation climb

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

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

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

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

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

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

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

**H282 model developed for high temperatures**


Total creep – effect of dislocation and diffusion creep mechanisms

B. F. Dyson, MST 2009, p213

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Thick-walled Cycling Header Development
Constitutive creep model - Diffusion component

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

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

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

where \( \beta = \frac{3D_V}{D_B \delta_B \frac{l^3}{d^2}} \)
\( D_V \) is a constant
\( \xi = F \frac{4D_B \delta_B \Omega}{l^3 k_B T} \)
\( D_B \delta_B \) is a constant

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

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

H282 model adapted for high temperatures
Thick-walled Cycling Header Development

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