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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- Vito Cedro

GE Power

- Jim Pschirer
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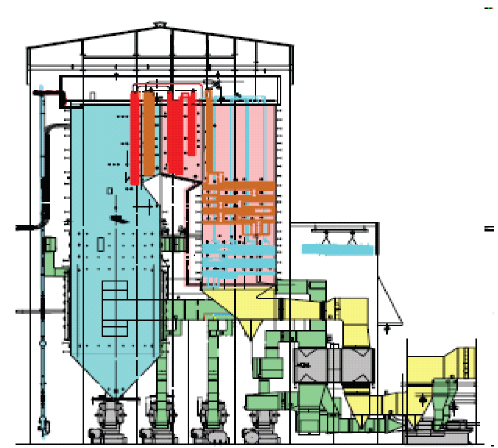
Thick-walled Cycling Header Development
Agenda

- Technical Background
- Statement of Objectives
- Potential Significance
- Project Team
- Technical Approach
- Project Schedule
- Project Status

Thick-walled Cycling Header Development Technical Background

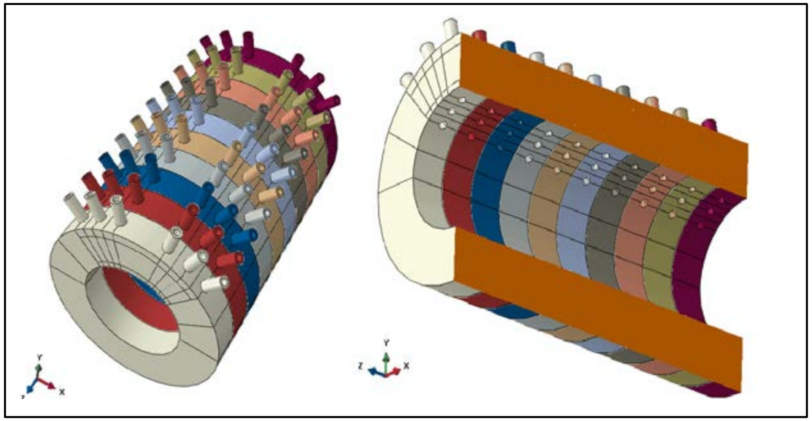
- Conceptual AUSC Boiler design steam cycle
  - temperatures are 730/760C (1350/1400F)
  - pressures 240-350 bar (3500-5200 psi)
- Future boiler designs require operation in daily and weekly cycling mode
- Startup-shutdowns such as weekly warm-starts have high ramp rates, 1.5% to 5%/min

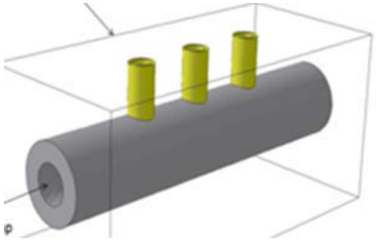


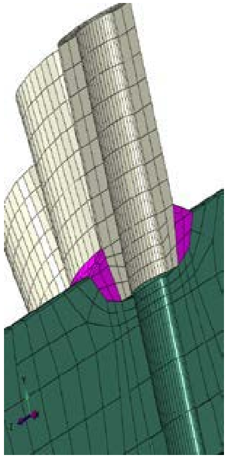
- Critical high temperature components in the boiler, such as superheater and reheater outlet headers, require latest high creep strength nickel-based superalloys Inconel 740H and Haynes 282

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

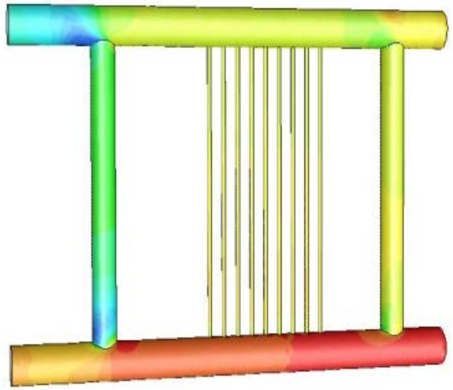


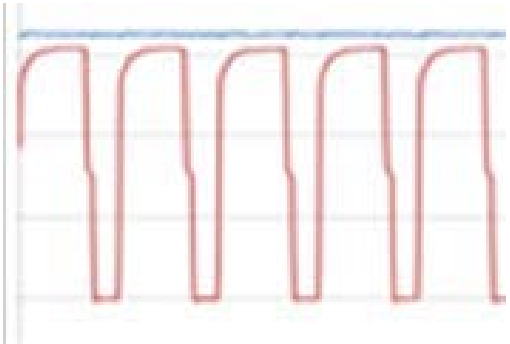


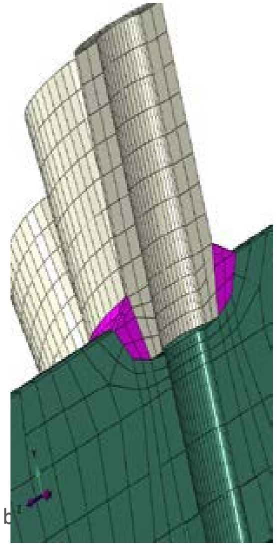


Thick-walled Cycling Header Development Technical Background

- 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).



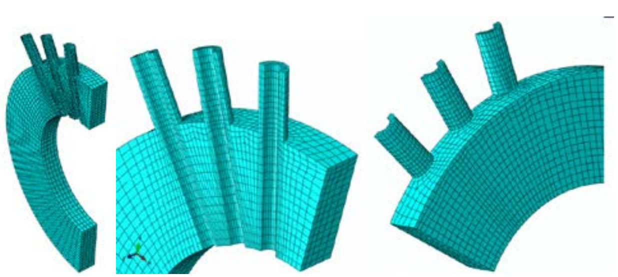


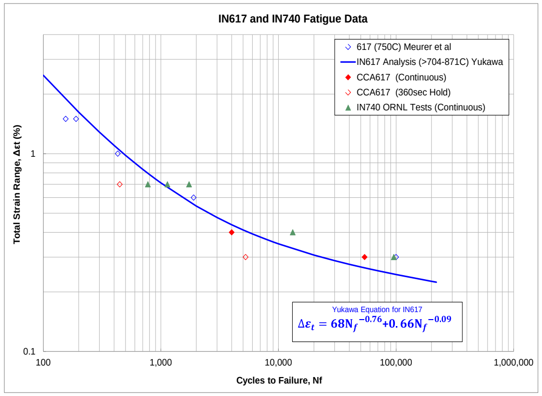


Thick-walled Cycling Header Development Objectives

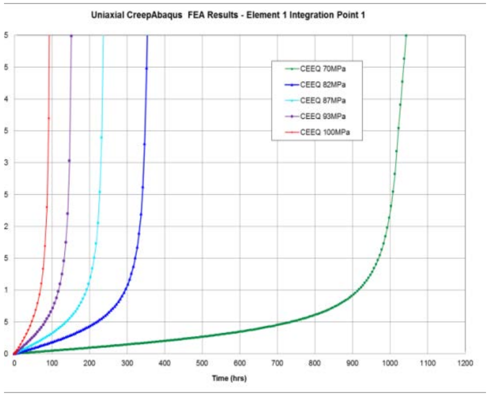
Objectives of Phase I is to demonstrate:

- 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

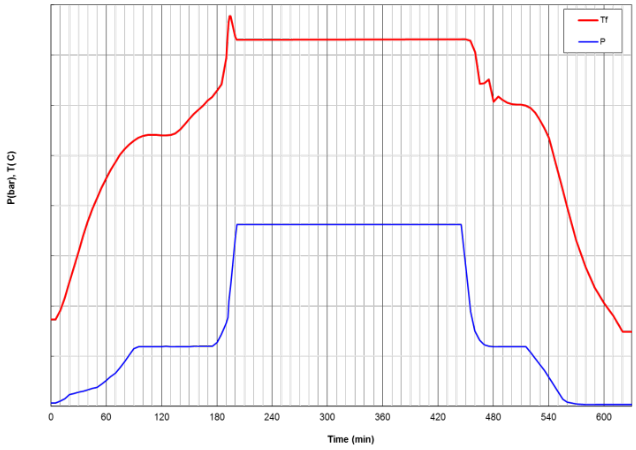


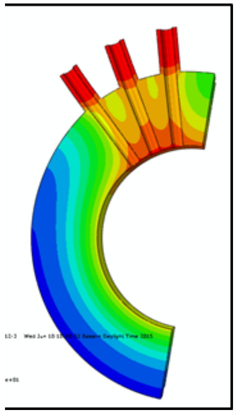
Creep Life

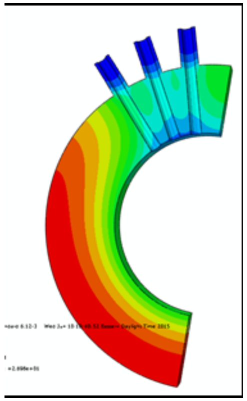
Thick-walled Cycling Header Development Objectives

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

2000	2005	2010	2015	2020	2025

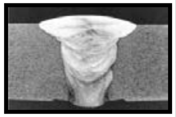
Materials Development
Laboratory TRL 2 to 3

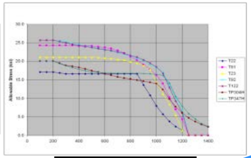
Component Mockup
Proof of Concept TRL 4

Steam Loop at Plant Barry
Component Test TRL 4 to 5

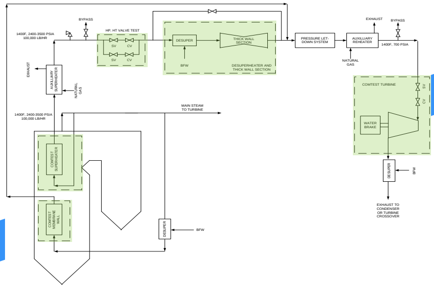
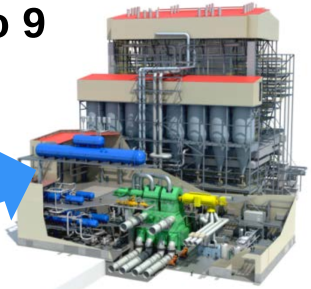
AUSC-COMTEST
System TRL 6 to 8

AUSC Demonstration
Overall TRL to 9







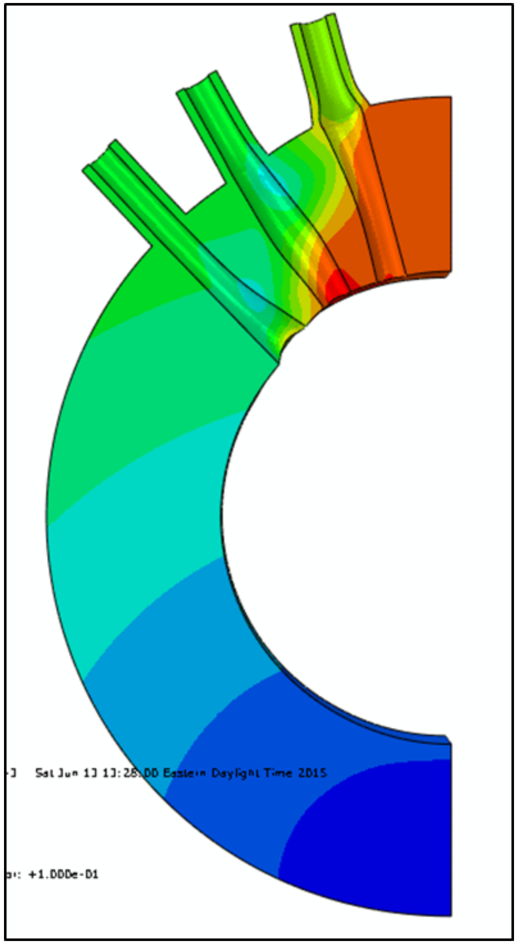




components	TRL
Tube Membrane Panel	4
Superheater	5
Turbine	4
Desuperheater	4
Header	4
Valves	4

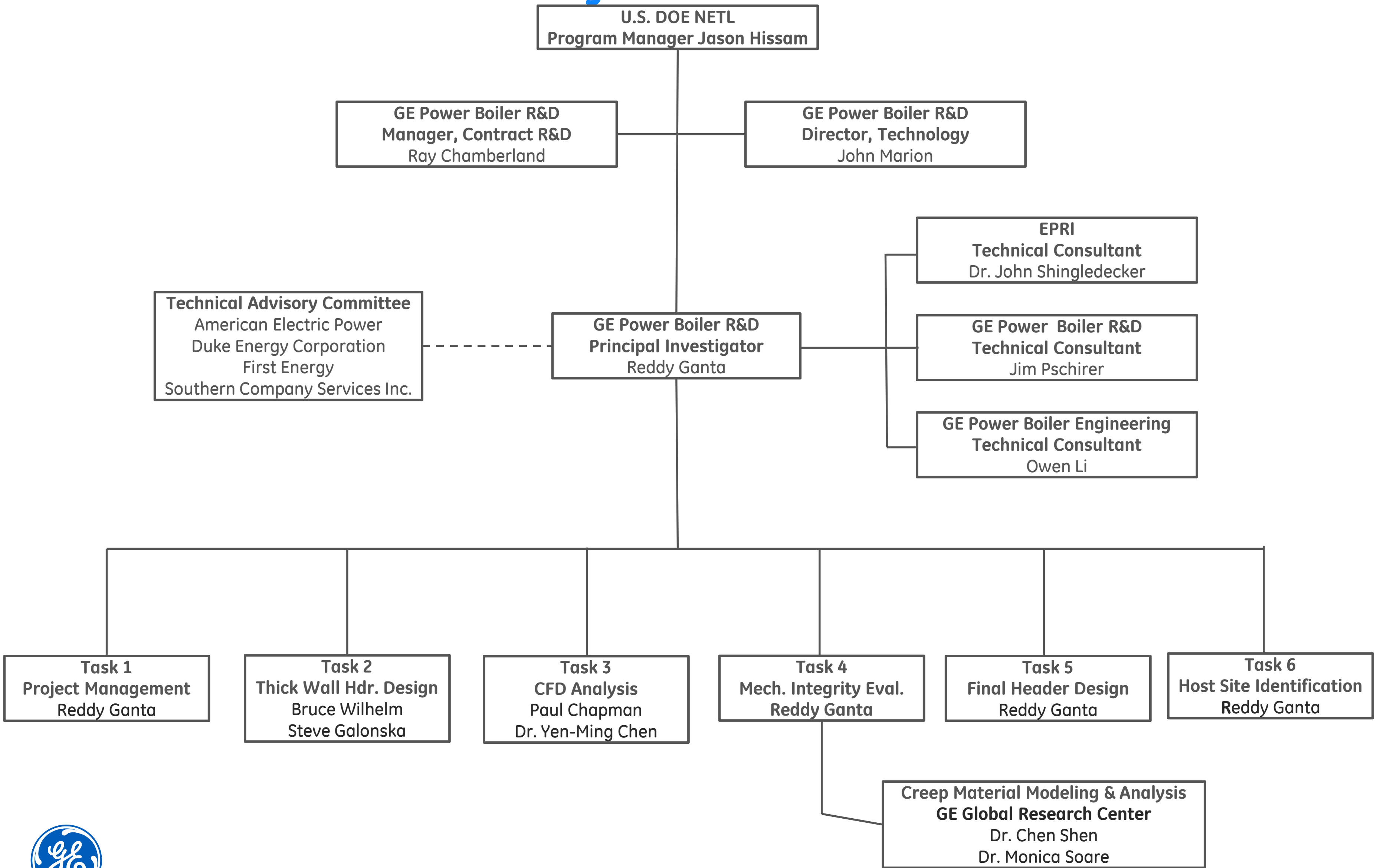
Current DOE-sponsored programs designed to bring components to TRL 5;
AUSC-COMTEST will bring system to TRL 7 or 8

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



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

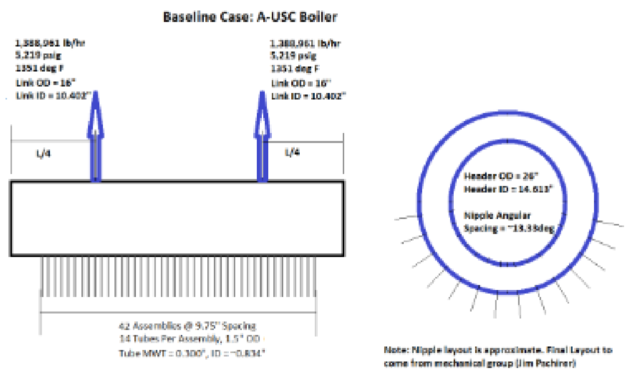
Task 4: MI Evaluation of Header, Tubing, and Welds

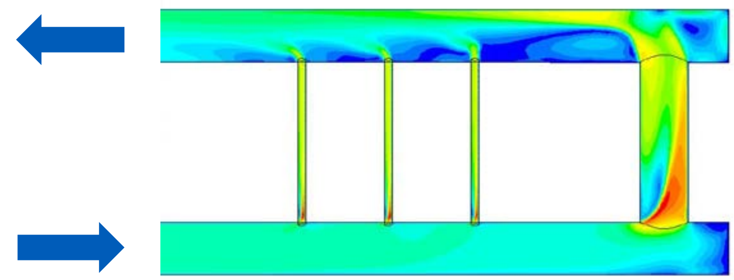
Task 5: Design of Thick-walled Header Component

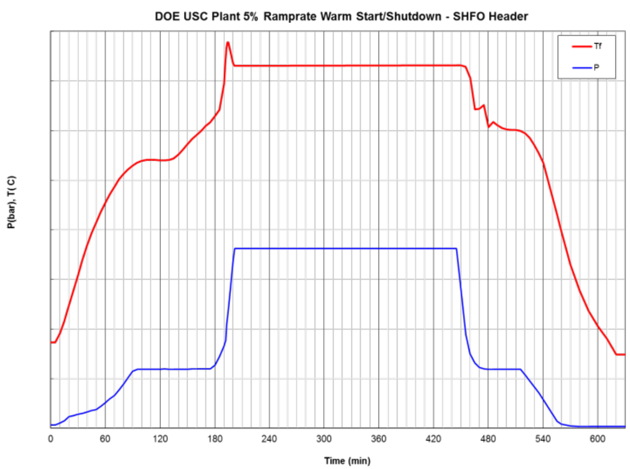
Task 6: Host facility Selection for ComTest-AUSC

Thick-walled Cycling Header for ComTest-AUSC Technical Approach

Task 2 Conceptual Design of Cycling Header







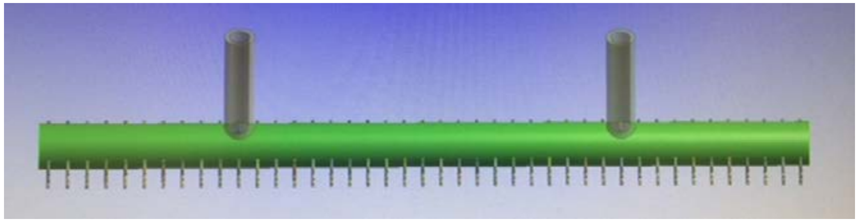
Full-scale AUSC SHOH design and transient

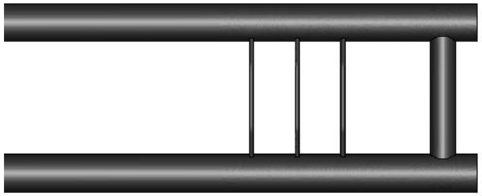
ComTest-AUSC cycling header design and transient

Thick-walled Cycling Header Development Technical Approach

Task 3: CFD Analysis of Thick-walled Header

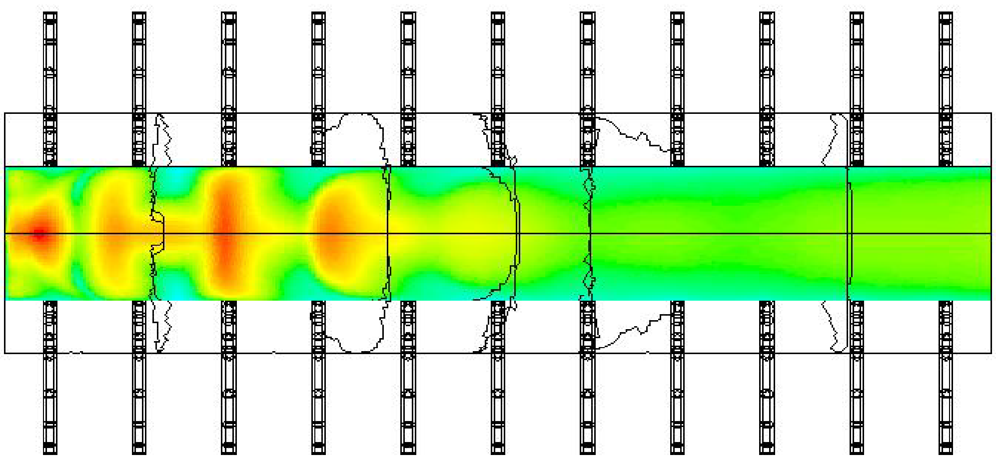
- AUSC conceptual design SH outlet header CFD analysis
- ComTest-AUSC CFD Model
    - o Youngstown with 600 psi (currently assumed & proceeding)
    - o Southern Company Barry with 3500 psi (if decided, design needs to be updated to Southern' s flow conditions)
- Benchmark examples from GE Power CFD experience
    - o Straight Pipe Flow CFD HT Coefficient Prediction
    - o Header - HTC for Molten Salt

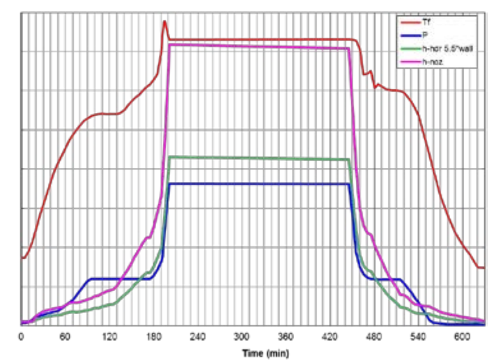




Thick-walled Cycling Header Development
Technical Approach

- 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



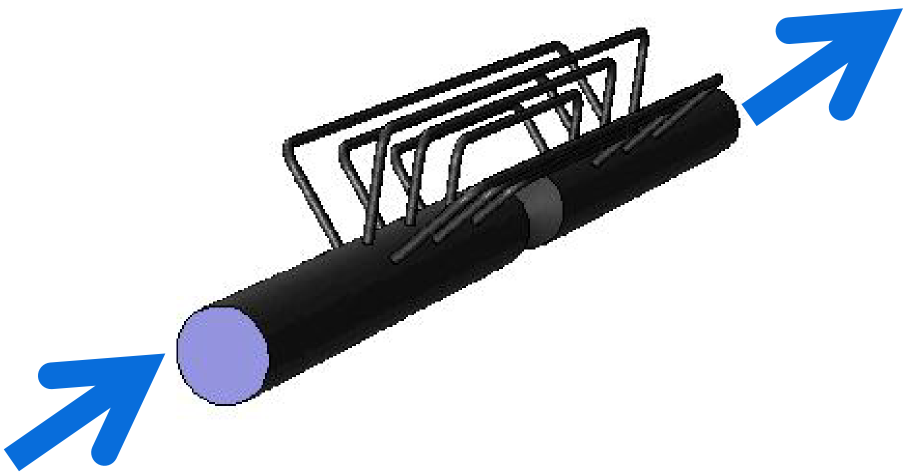


Thick-walled Cycling Header Development Technical Approach

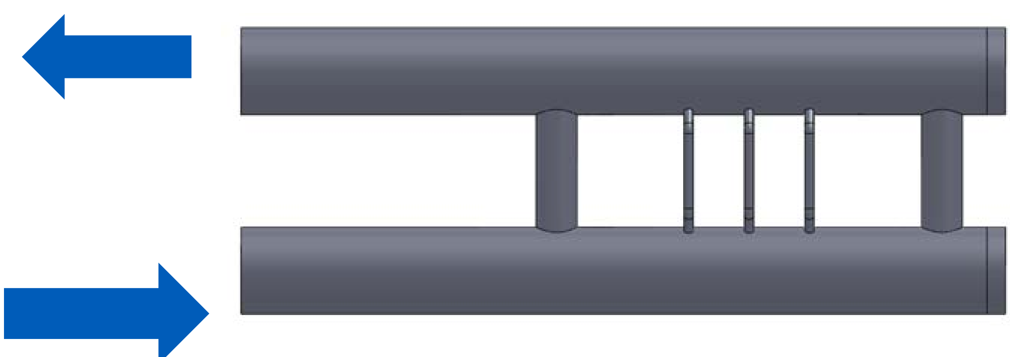
ComTest-AUSC header design

- 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

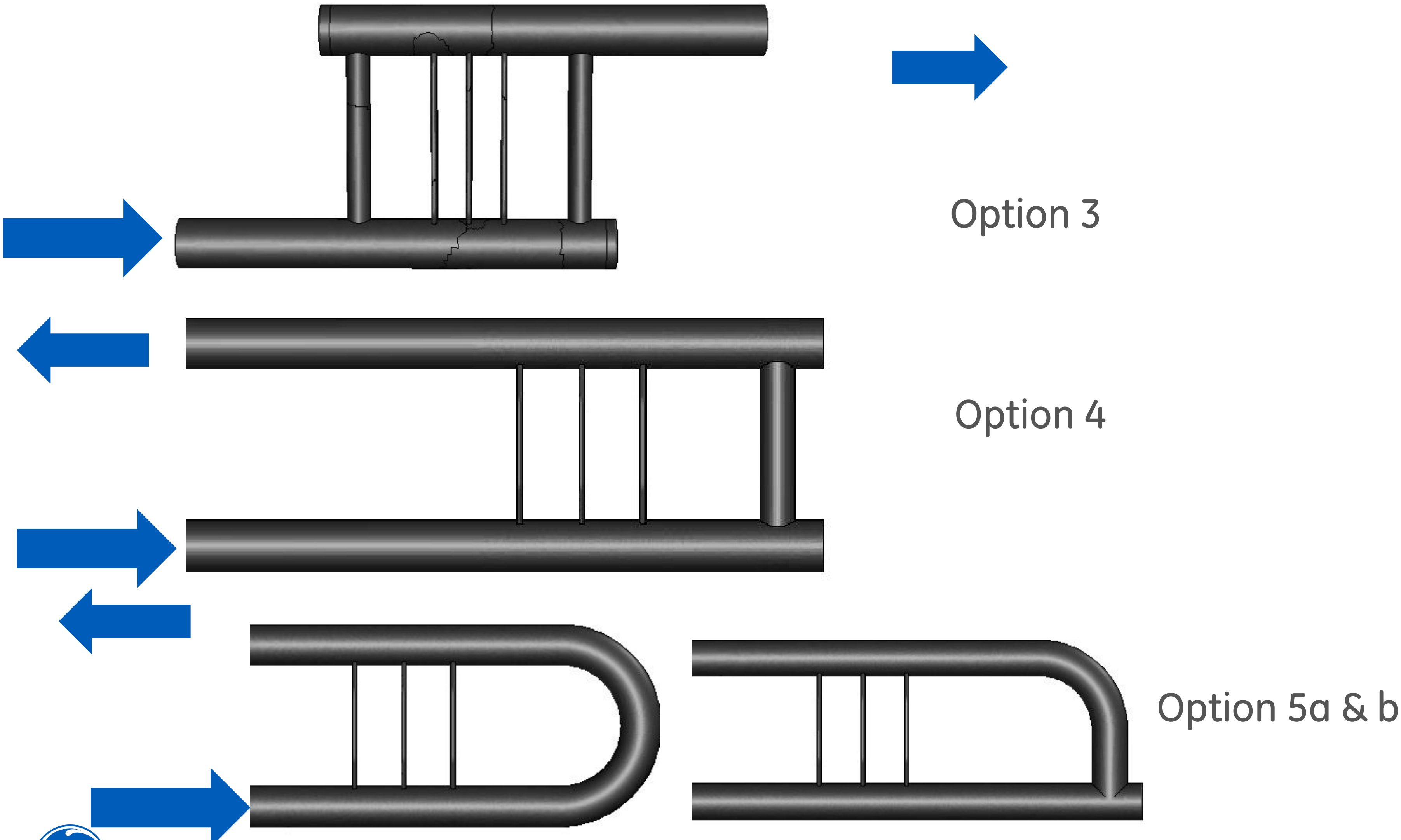


Option 1

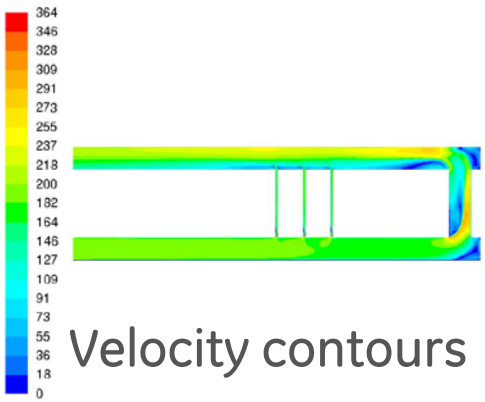


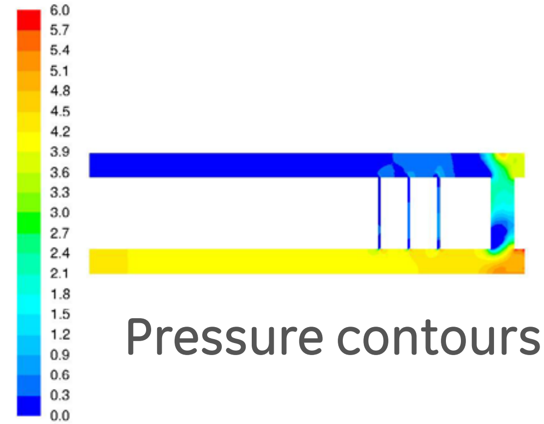
Option 2

Thick-walled Cycling Header Development
Technical Approach

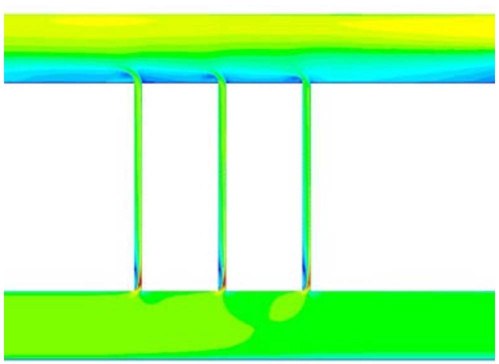


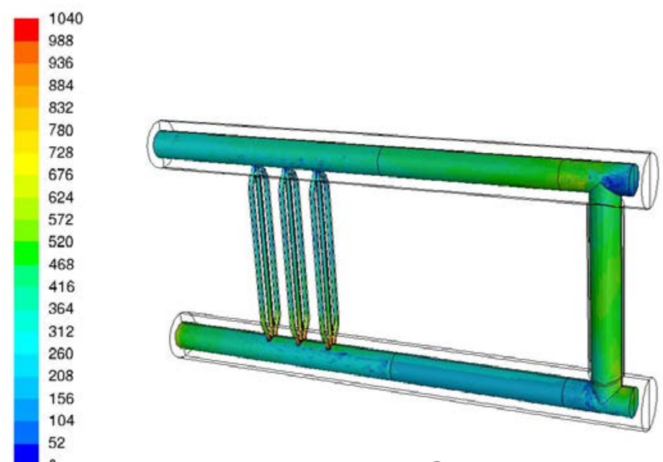
Thick-walled Cycling Header Development Technical Approach





Flow Split: 12.4% 87.6%





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)

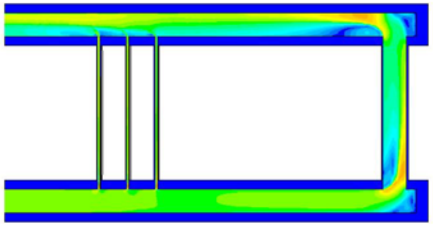
Task 4: Mechanical Integrity Evaluation

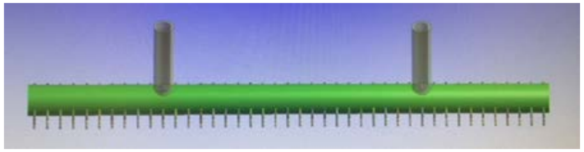
4a: ComTest-AUSC Fatigue Cycling

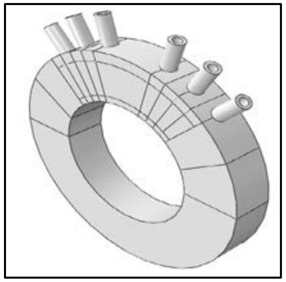
- Design ComTest header configuration
- Includes tube penetrations
- No branch nozzle in CFD studies
- Accelerated **thermal cycling**
- Test temperature 760°C (1400°F)
- Test pressure 41 bar (600psig)
- Materials: 740H & H282
- Transient cycle configured using two steady-state CFD analyses
- Fatigue 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)**



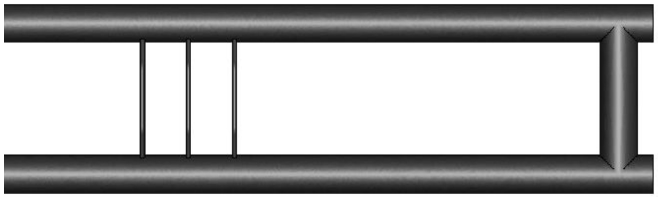




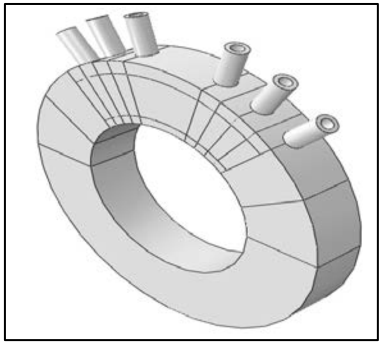
Thick-walled Cycling Header Development Technical Approach

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



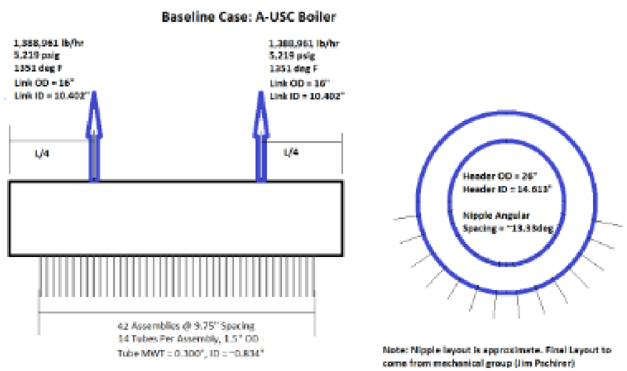
ComTest-AUSC cycling header

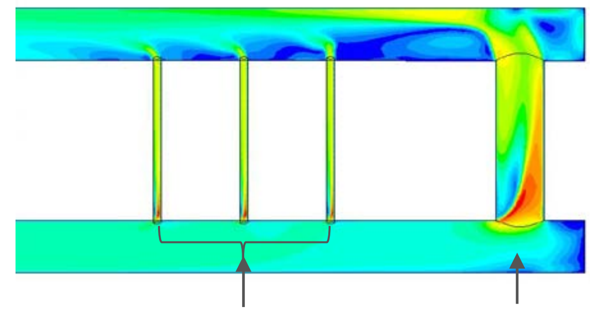


ComTest-AUSC header model

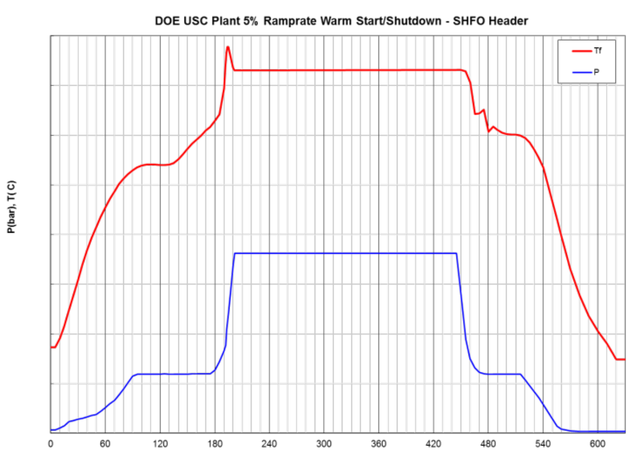
Thick-walled Cycling Header Development
Technical Approach

Full-scale SHOH and ComTest Cycling Header Transients

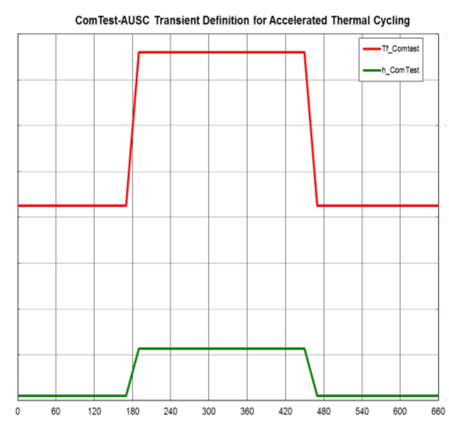




Flow Split: 17.5% 82.5%



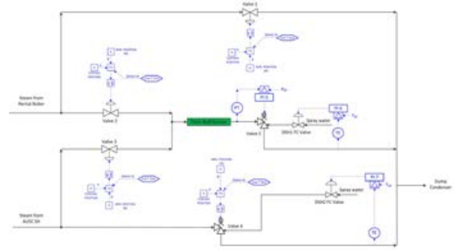
Full-scale AUSC SHOH design and transient

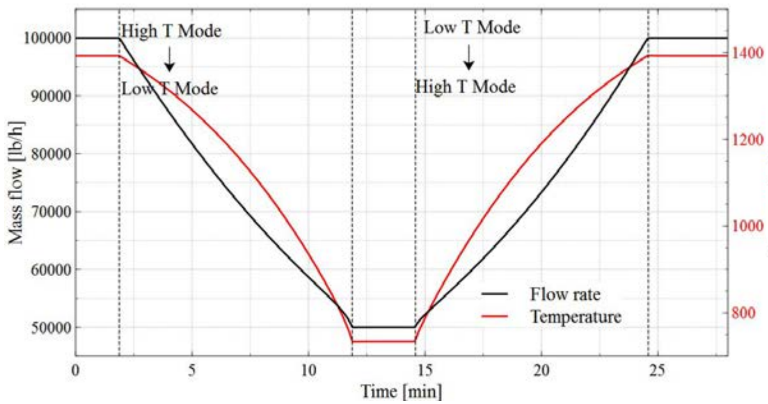


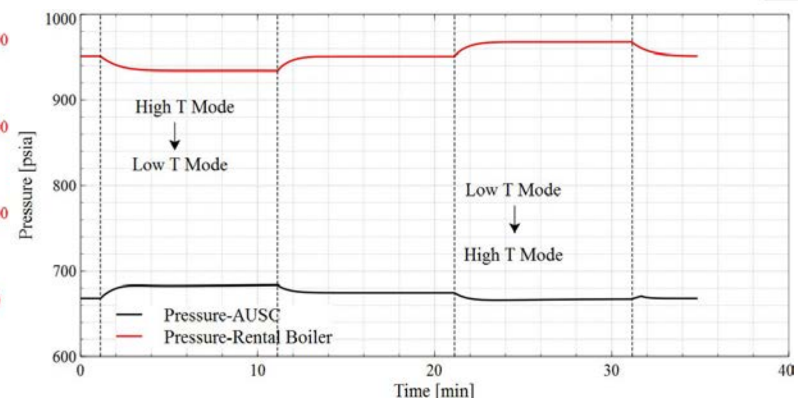
ComTest-AUSC cycling header design and transient

Thick-walled Cycling Header Development
APROS Transient Simulation

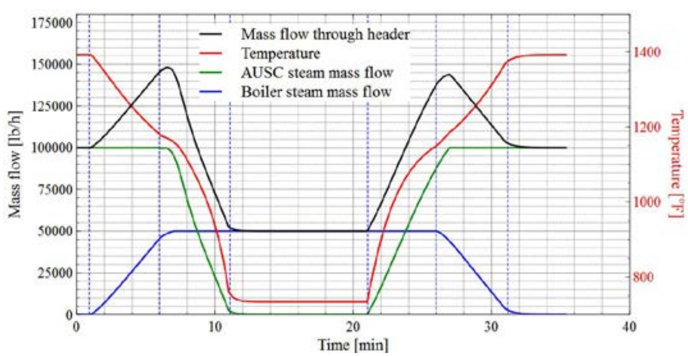
- Valve operating scenario at Youngstown
- Ramp rates
- Low and high temperature flow mix

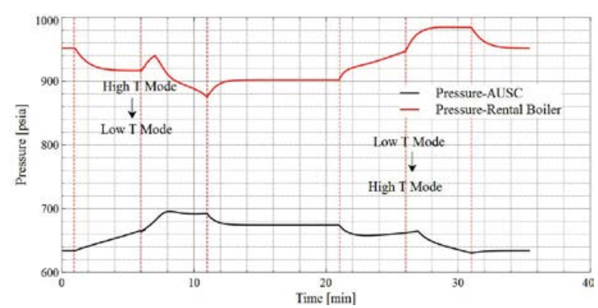






flow rate & temperature with 4 valves operating simultaneously



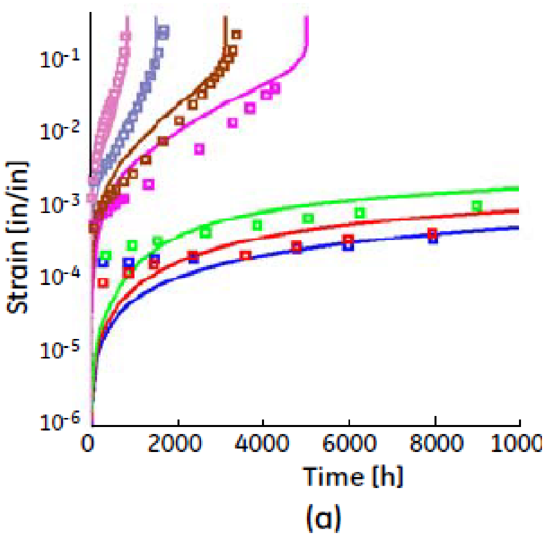


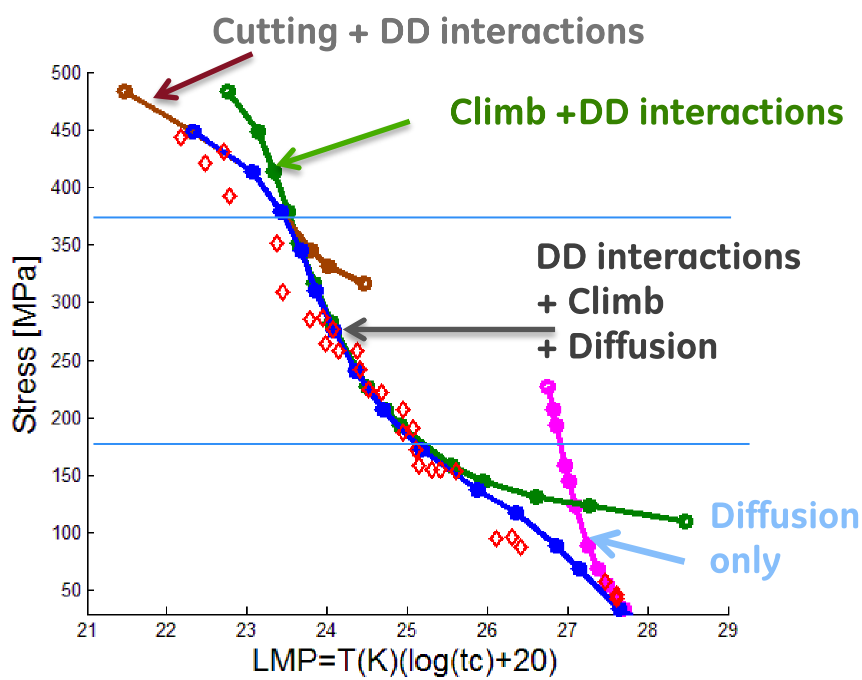
flow rate & temperature with control valves operating in two steps

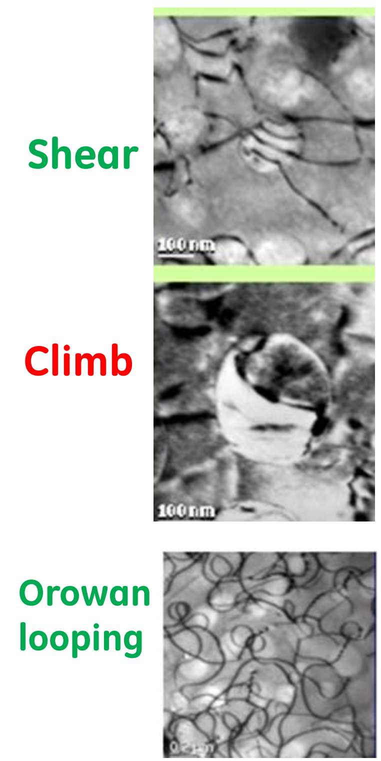
Thick-walled Cycling Header Development
H282 Constitutive creep model

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

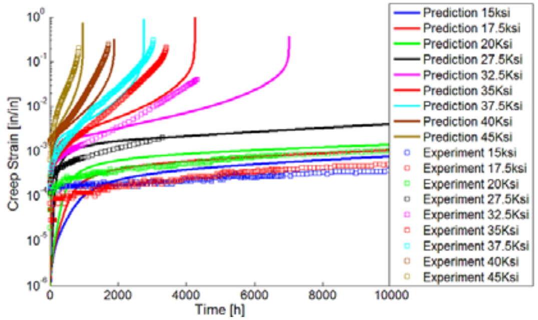
Base Metal H282, Creep model 1400-1700˚F



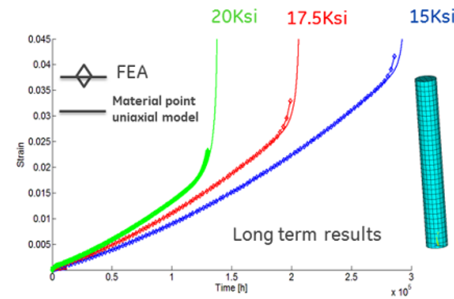




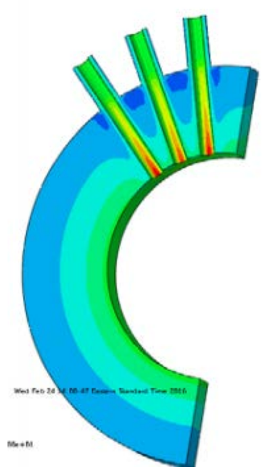
Thick-walled Cycling Header Development
H282 creep model development & application



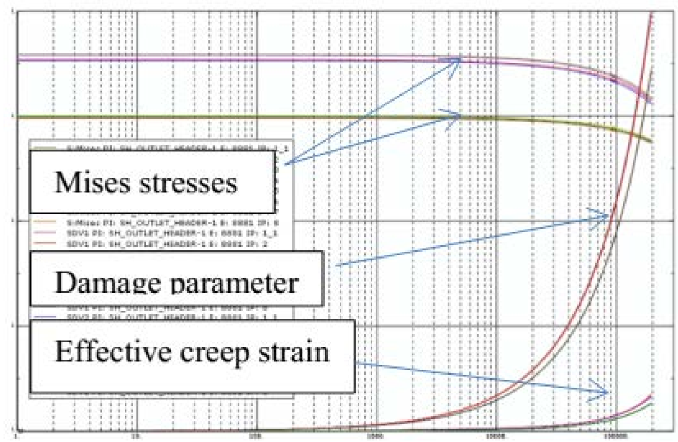
Test specimen creep strain data



Benchmark FEA Verification



Damage parameter contours

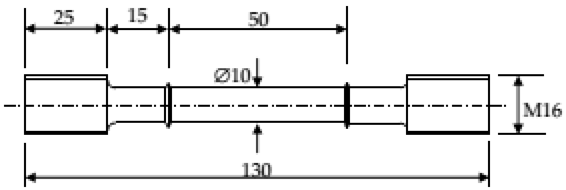


Borehole stress, creep strain & damage parameter history

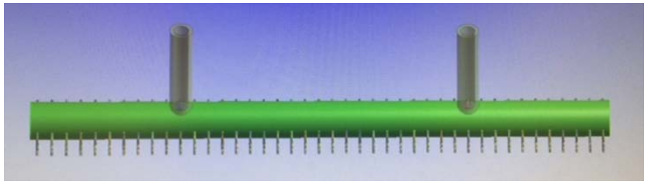
Thick-walled Cycling Header Development Technical Approach

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

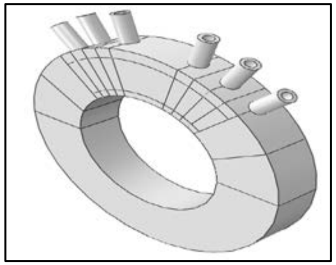
- Long term creep life assessment of full-scale AUSC SHO header using high temperature superalloy CDM models for analysis includes:
  - inlet tubes with welds
  - "Tee" section of a header with one branch nozzle and weld
  - H282 base metal model only for now
  - H282 weld material model if available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



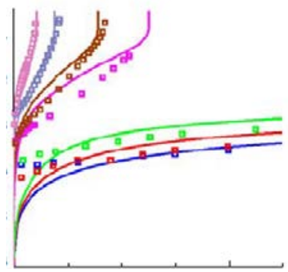
Benchmark Test Specimen



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)

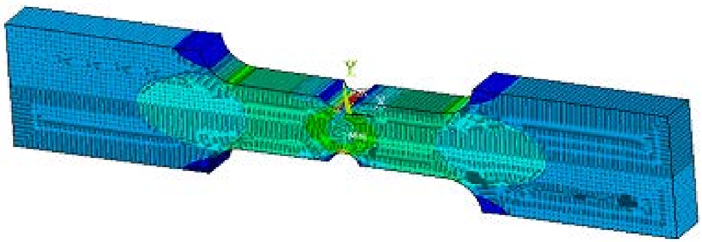
Thick-walled Cycling Header Development Project Status

- 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.**

EPRI | ELECTRIC POWER RESEARCH INSTITUTE

EPRI 2016 Creep Fatigue Workshop In Collaboration with ASME PVP

July 21-22, 2016
HYATT REGENCY VANCOUVER
655 BURRARD STREET
VANCOUVER, BC V6C 2R7 CANADA

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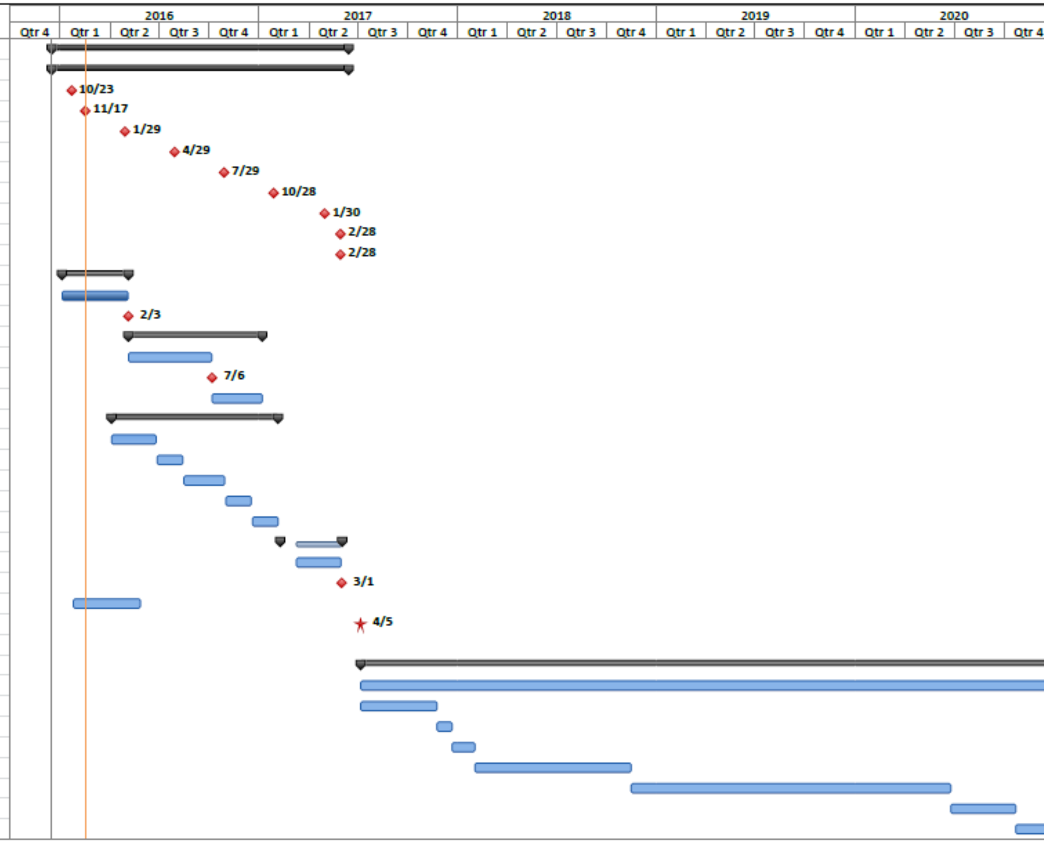
Creep Life Assessment of High Temperature Advanced Ultrasupercritical (AUSC) Conceptual Boiler Thick-Walled Pressure Components Using Continuum Damage Mechanics Approach

Reddy Ganta
GE Steam Power Systems, 200 Great Pond Drive, Windsor, CT 06095, USA
Monica Soare and Chen Shen
GE Global Research, 1 Research Circle, Niskayuna, NY 12309, USA

Thick-walled Cycling Header Development
Project Milestones – Phase I

ID	Task Name
1	Phase 1, Alstom's Thick Wall Cycling Component
2	Task 1 Project Management and reporting
3	Updated Project Management Plan
4	Project Kickoff Meeting
5	Q1 Progress / Financial Reports
6	Q2 Progress / Financial Reports
7	Q3 Progress / Financial Reports
8	Q4 Progress / Financial Reports
9	Q5 Progress / Financial Reports
10	Final Report
11	Phase I Project Closeout Meeting
12	Task 2 Conceptual Design of the Thick Walled Header
13	Conceptual design of the thick-walled header
14	Task 2 Design Review
15	Task 3 CFD analysis of Header
16	CFD analysis of test section
17	CFD Design Review
18	Coupling the CFD flow to the thermal stress analysis
19	Task 4 Mechanical Integrity Evaluation of Header, tubing, and welds
20	Develop FEA model
21	verification Analysis
22	transient analysis
23	fatigue analysis
24	Creep assessment
25	Task 5 Final Design of the thick wall header component
26	Design Header Based on Tasks 3 & 4
27	Review of Final Design
28	Task 6 Investigate Possible Component Test Site
29	Approval for Phase 2
30	
31	Phase 2, Alstom's Thick Wall Cycling Component
32	Task 1 Project Management and reporting
33	Task 7 Secure Site for Component Testing
34	Task 8 Develop Detailed Fabrication Drawings for Thick Wall Component
35	Task 9 Validate Weld Specifications and Procedures
36	Task 10 Procure Materials and fabricate header component
37	Task 11 Delivery, Installation, Startup, and Operation of Thick Wall Component
38	Task 12 Remove Thick wall Cycling Component and Perform Analytical Examination
39	Compile and publish Final Report



Project: Thick Wall Schedule R8-2
Date: Tue 11/17/15

Task	Project Summary	Inactive Milestone	Manual Summary Rollup	Deadline
Split	External Tasks	Inactive Summary	Manual Summary	Progress
Milestone	External Milestone	Manual Task	Start-only	
Summary	Inactive Task	Duration-only	Finish-only	

Page 1

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

$$\varepsilon^{creep} = \varepsilon^{disloc} + \varepsilon^{diffusion}$$

Total creep – effect of dislocation and diffusion creep mechanisms

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

$$\sigma_{climb}(T) = \frac{2f(T)}{1+2f(T)}\sigma_{eff}\left[1-\exp\left(-\frac{1+2f(T)}{2(1-f(T))}E(T)\frac{\varepsilon^{disloc}}{\sigma_{eff}}\right)\right]$$ **climb**

$\sigma_o = 0.25MG(T)b\sqrt{\rho}$, $\rho = \rho(C)$ **D-D interaction**

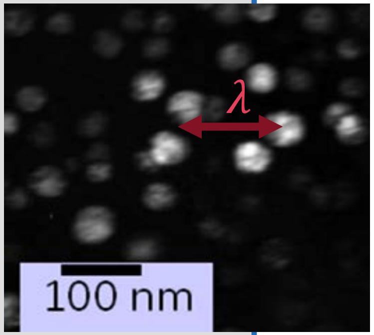
$$\rho = \begin{cases} \rho_i + (\rho_f - \rho_i)\varepsilon/\varepsilon^{crit} & if\ \varepsilon \le \varepsilon^{crit} = C\sigma_{eff} \\ \rho_f & if\ \varepsilon > \varepsilon^{crit} = C\sigma_{eff} \end{cases}$$

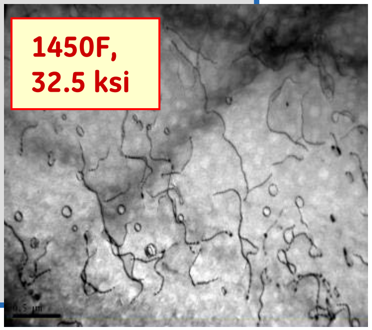
$$\sigma_{eff} = \frac{\sigma_{applied}(1+\varepsilon)}{1-\varpi}$$

$$\varpi = \varpi_{diff} + \varpi_{disloc}$$

$$\dot{\varpi}_{disloc} = D\dot{\varepsilon}^{disloc}$$

B. F. Dyson, MST 2009, p213





H282 model developed for high temperatures

Developed under DE-FE0005859 Modeling Creep-Fatigue-Environment Interactions in Steam Turbine Rotor Materials for Advanced Ultra-supercritical Coal Power Plants. Final Report. Chen Shen, GE Global Research

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

$$\dot{\varepsilon}^{diffusion} = \dot{\varepsilon}^{lattice\_diff} + \dot{\varepsilon}^{boundary\_diff} + \dot{\varepsilon}^{cavity\_boundary\_diff} + \dot{\varepsilon}^{cavity\_surface\_diff}$$

$$\dot{\varepsilon}^{boundary\_diff} = 3\pi\xi\left(\frac{l}{d}\right)^3 \sigma_{applied}(1+\varepsilon^{creep})$$

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

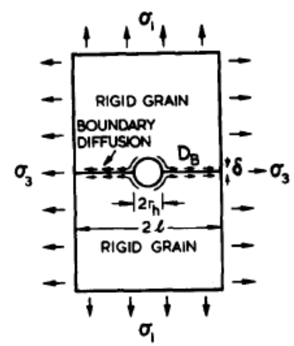
$$\dot{\varepsilon}^{lattice\_diff} = \xi\beta\sigma_{applied}(1+\varepsilon^{creep})$$

where $\beta = \frac{3D_V}{D_B\delta_B}\frac{l^3}{d^2}$

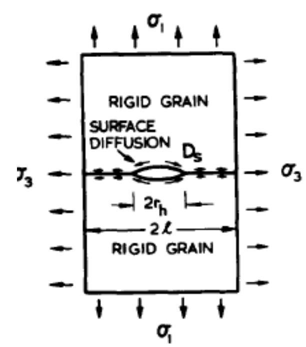
D_V *is a constant*

$$\xi = F\frac{4D_B\delta_B\Omega}{l^3 k_B T}$$

$D_B\delta_B$ *is a constant*



Void growth by boundary diffusion



Void growth by surface diffusion

$$\dot{\varepsilon}^{cavity\_boundary\_diff} = \xi\frac{l}{d}\frac{\sigma_{applied}}{\ln(1/\varpi_{boundary\_diff})}$$

$$\dot{\varepsilon}^{cavity\_surface\_diff} = \xi\alpha\frac{\sqrt{\varpi_{surface\_diff}}\,\sigma_{applied}^{\;2}}{(1-\varpi_{surface\_diff})^3}$$

$$\alpha = \frac{D_S\delta_S}{D_B\delta_B}\frac{1}{\sqrt{2}}\frac{l^2}{d\gamma}$$

H282 model adapted for high temperatures

Thick-walled Cycling Header Development Acknowledgements

This material is based upon work supported by the Department of Energy under Award Number DE-FE0026183.