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

Robert Schrecengost

R&D Program Manager, Boilers

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Imagination at work

Thick-walled Cycling Header Development Acknowledgements

DOE NETL

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- Vito Cedro

GE Power

- Reddy Ganta
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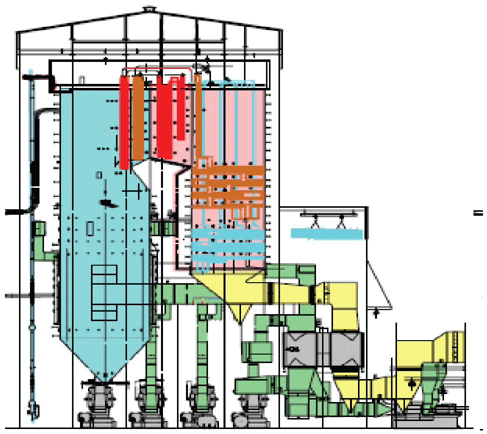
- Monica Soare
- Chen Shen

Thick-walled Cycling Header Development
Agenda

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

Thick-walled Cycling Header Development Technical Background

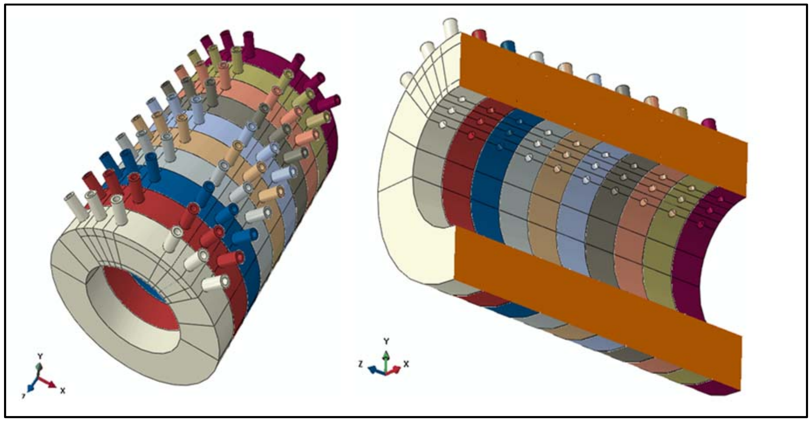


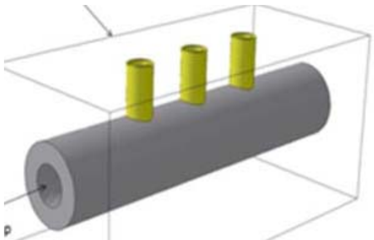
- Conceptual AUSC Boiler design steam cycle
  - ➢ temperatures are 730/760°C (1350/1400°F)
  - ➢ pressures 240-350 bar (3500-5200 psi)
- Future boiler designs require operation in daily and weekly cycling mode
- Startup-shutdowns such as weekly warm-starts have high ramp rates, 1.5% to 5% MCR/min

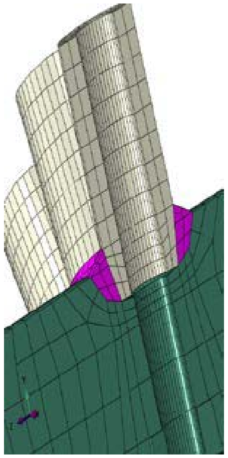
- Critical high temperature components in the boiler, such as superheater and reheater outlet headers, require latest high creep strength nickel-based superalloys Inconel 740H and Haynes 282

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

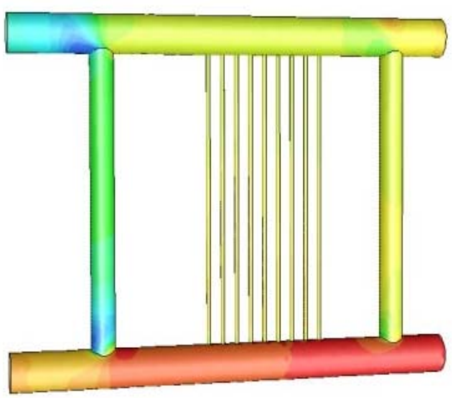


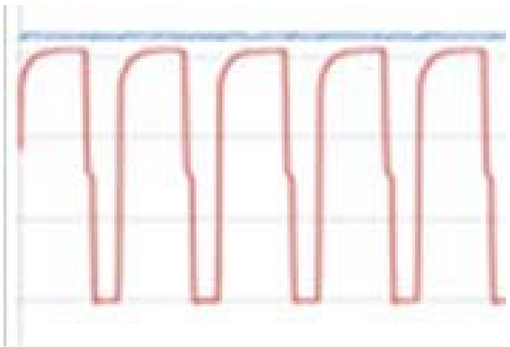


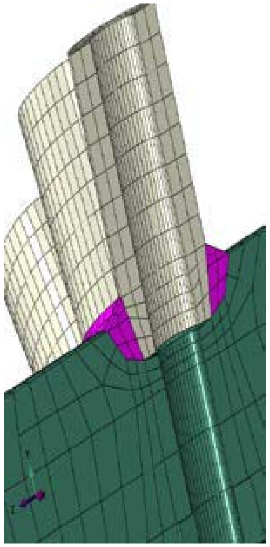


Thick-walled Cycling Header Development Technical Background

- 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).



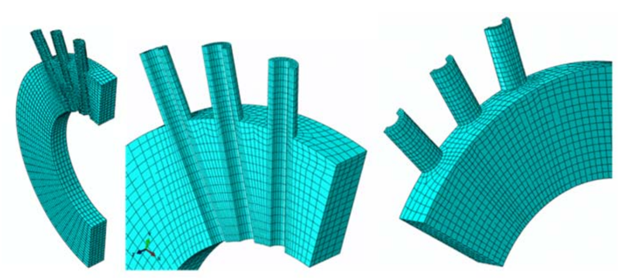


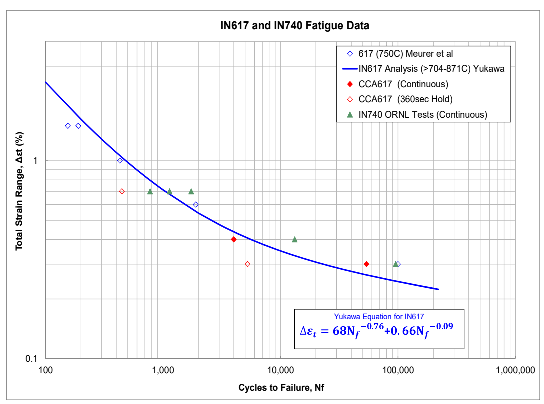


Thick-walled Cycling Header Development Objectives

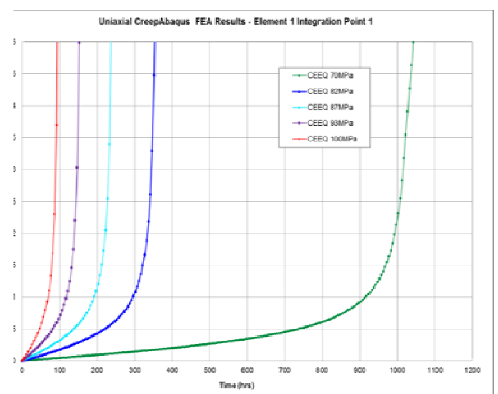
Objectives of Phase I are to demonstrate:

- 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

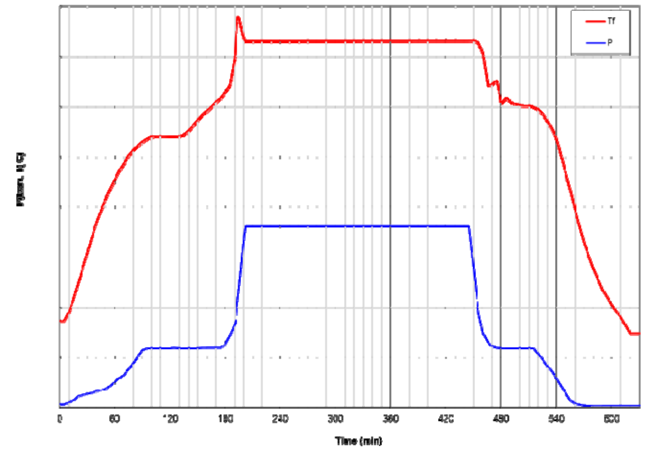


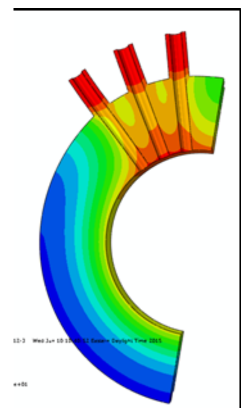
Creep Life

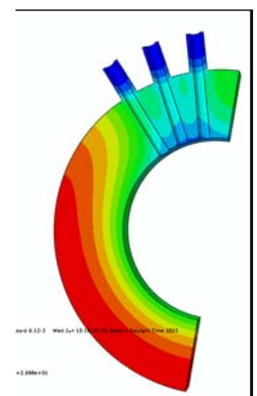
Thick-walled Cycling Header Development Objectives

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



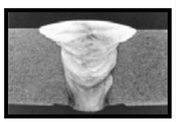
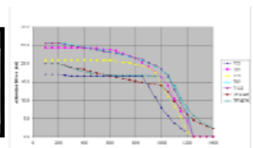




Thick-walled Cycling Header Development Roadmap to AUSC Demo

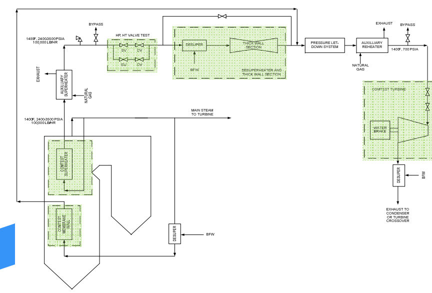
2000	2005	2010	2015	2020	2025

Materials Development	Component Mockup	Steam Loop at Plant Barry	AUSC-COMTEST	AUSC Demonstration
Laboratory TRL 2 to 3	Proof of Concept TRL 4	Component Test TRL 4 to 5	System TRL 6 to 8	Overall TRL to 9





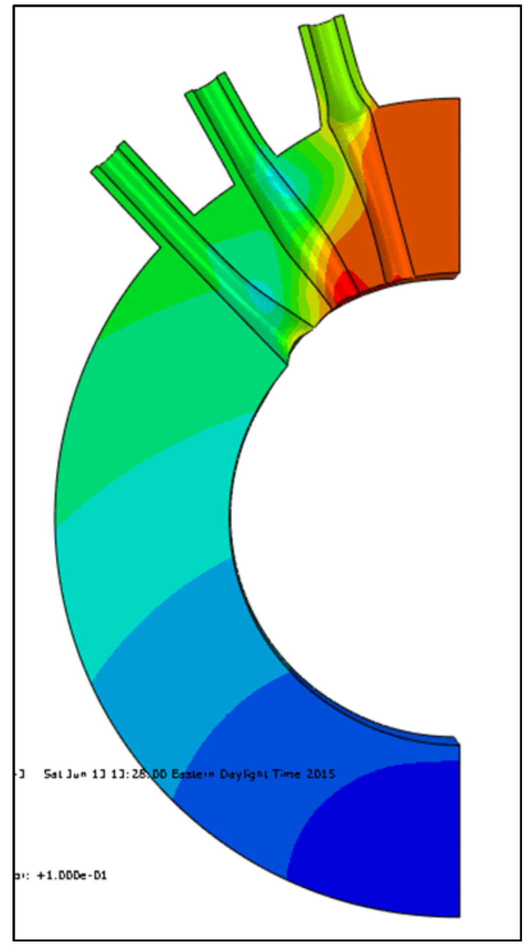



components	TRL
Tube Membrane Panel	4
Superheater	5
Turbine	4
Desuperheater	4
Header	4
Valves	4

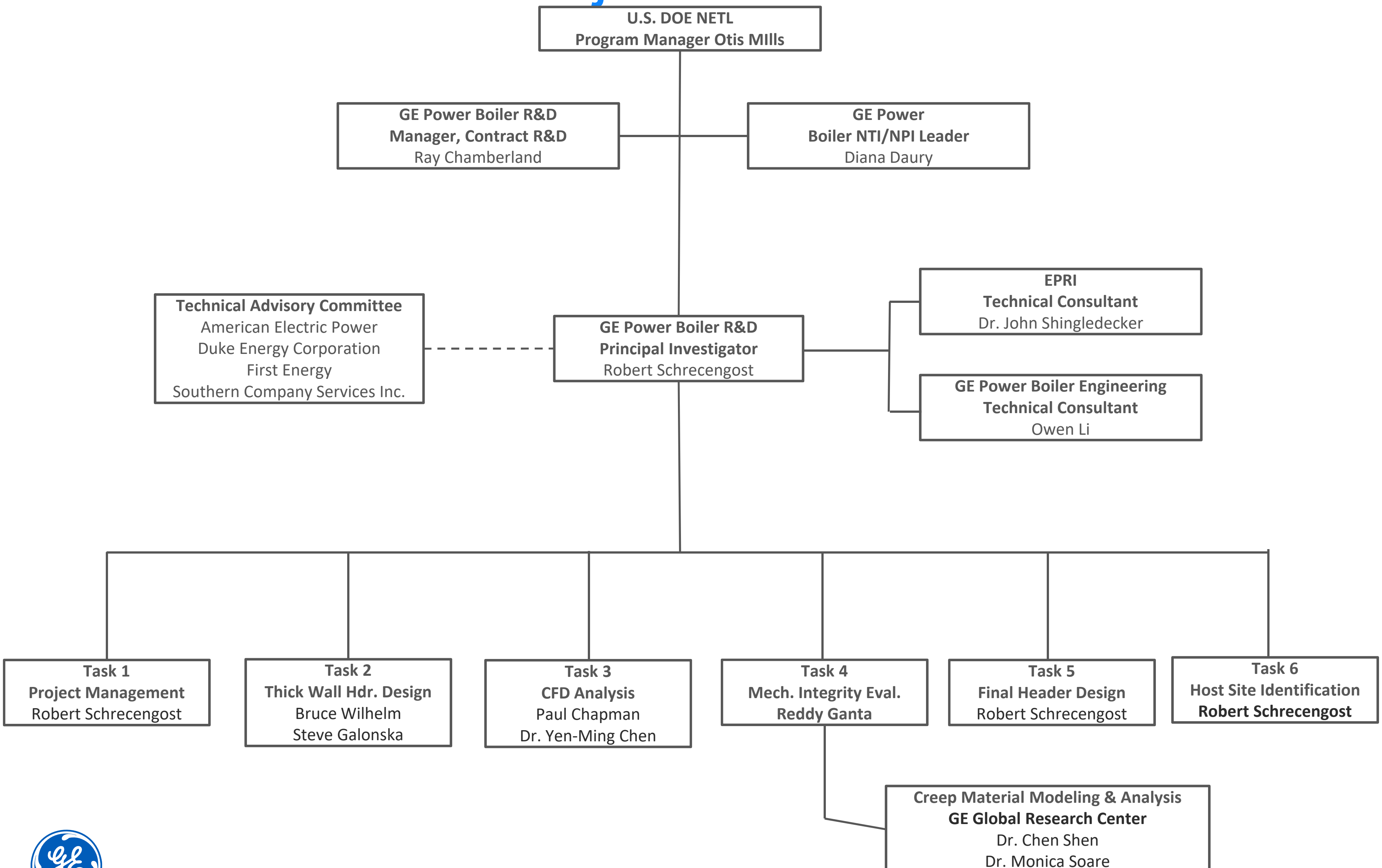
Current DOE-sponsored programs designed to bring components to TRL 5; AUSC-COMTEST will bring system to TRL 7 or 8

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

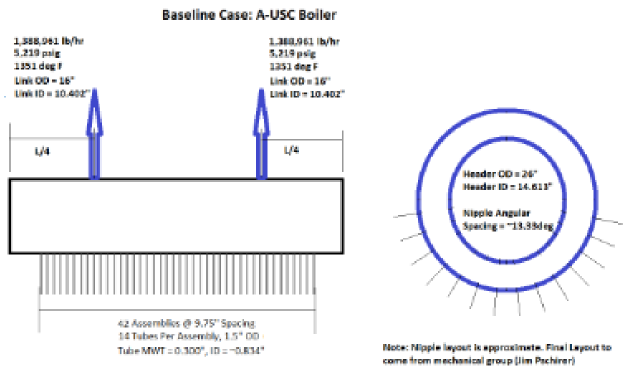
Task 6: Host facility Selection for ComTest-AUSC

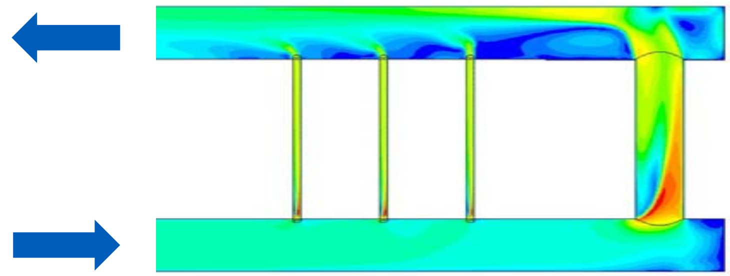
Thick-walled Cycling Header Development Deliverables

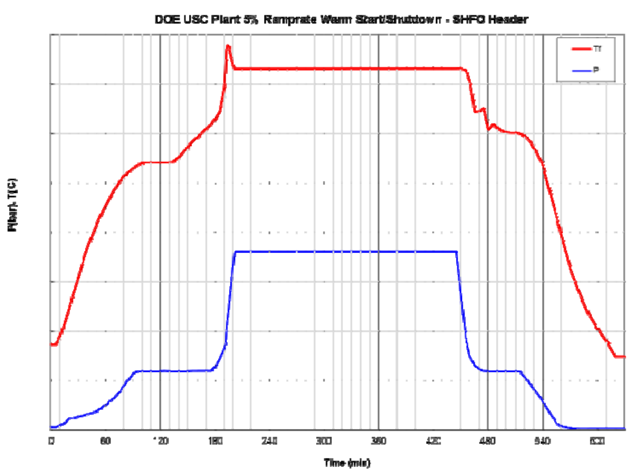
- Task 2: Process design of ComTest-AUSC cycling header layout and flow conditions (input to CFD group, done in 2016)
- Task 3: CFD Analysis to identify heat transfer rates (input to MI group, done in 2016)
  - Flow and heat transfer rates for the 1000 MWe full-scale conceptual AUSC SH outlet header 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

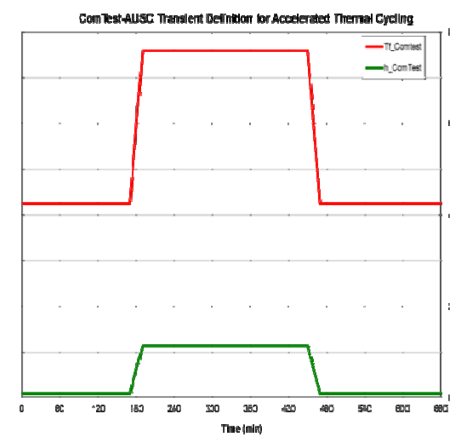
Task 2 Process Design of Thick-walled Cycling Header







Full-scale AUSC SHOH design and transient

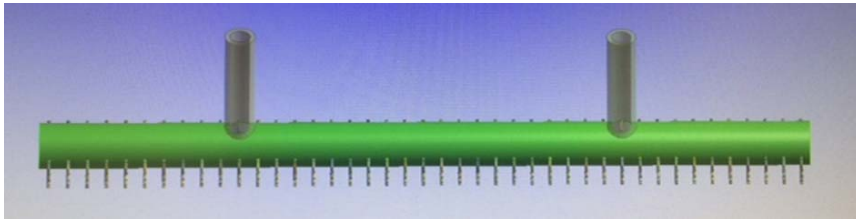


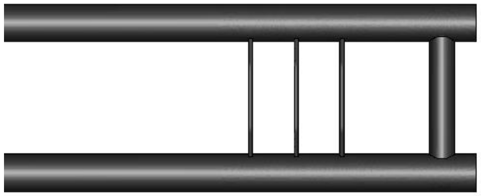
ComTest-AUSC cycling header design and transient

Thick-walled Cycling Header Development Technical Approach

Task 3: CFD Analysis of Thick-walled Cycling Header

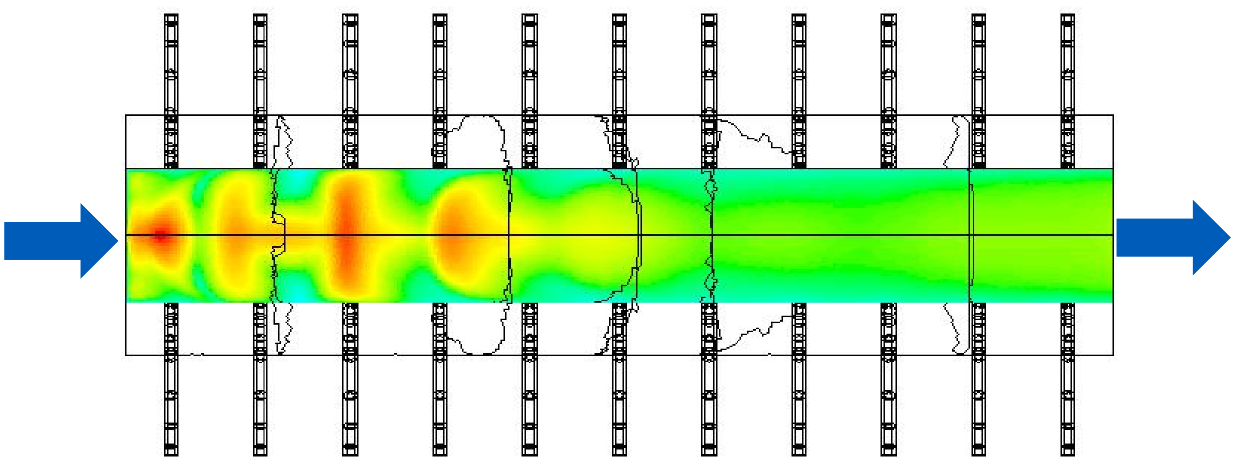
- AUSC conceptual design SH outlet header CFD analysis
- ComTest-AUSC CFD Model
  - o Host Site currently at 600 psi (currently assumed & proceeding)
  - o Southern Company with 3500 psi (if decided, design needs to be updated to Southern' s flow conditions)
- Benchmark examples from GE Power CFD experience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

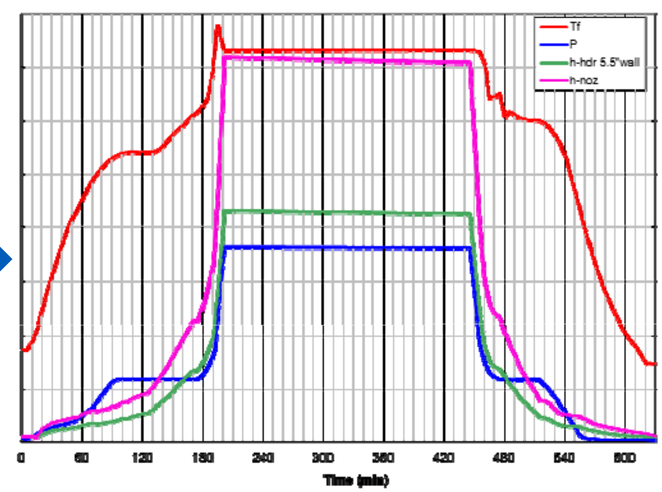




Thick-walled Cycling Header Development
Technical Approach

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



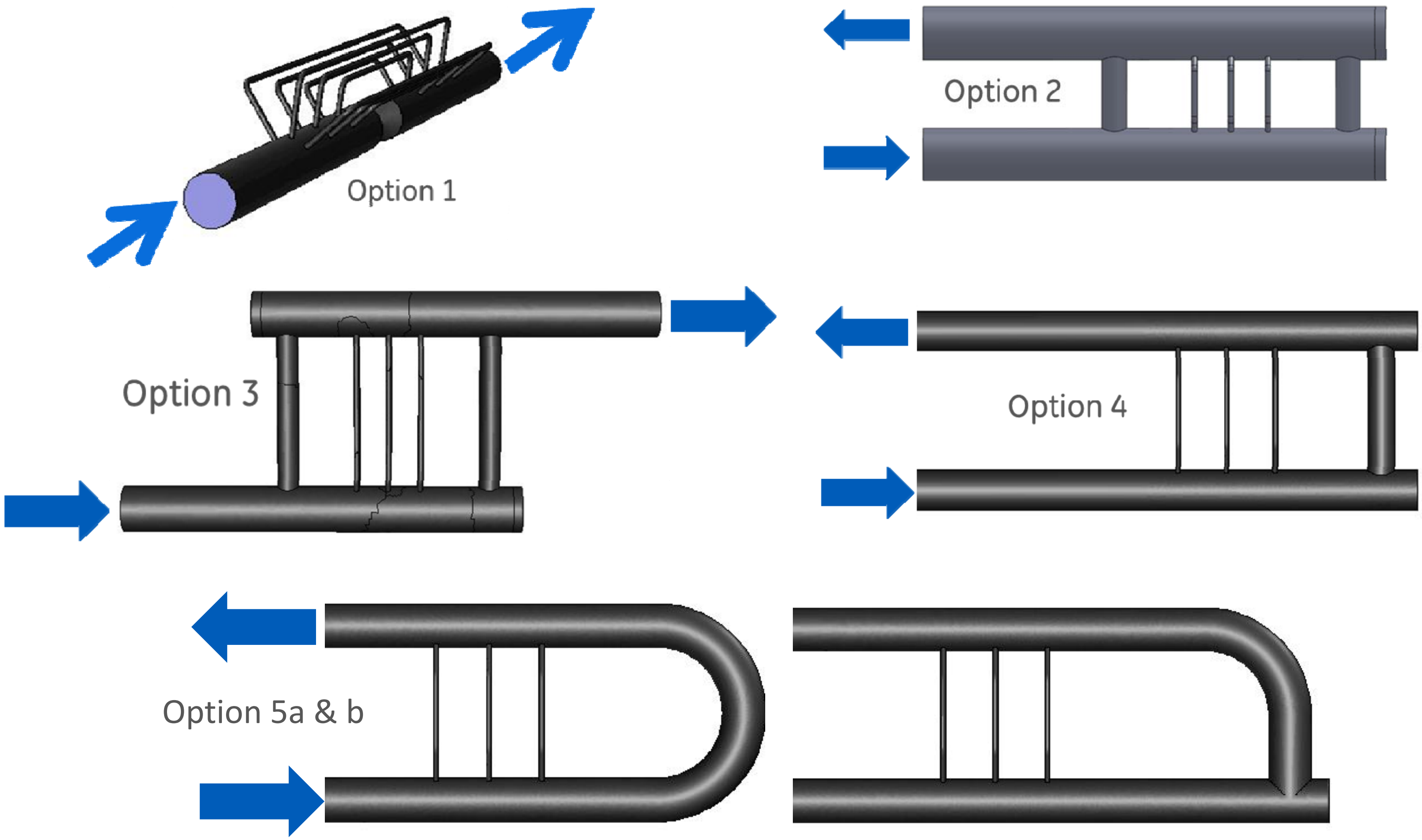


Thick-walled Cycling Header Development Technical Approach

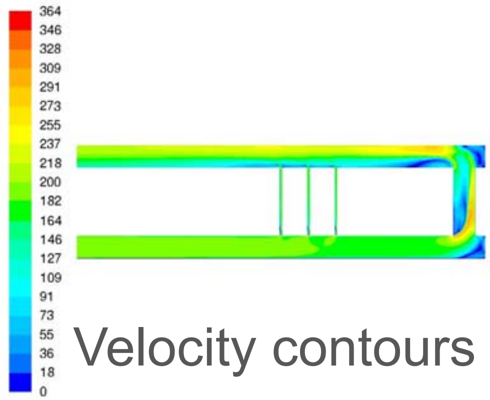
ComTest-AUSC header design

- 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

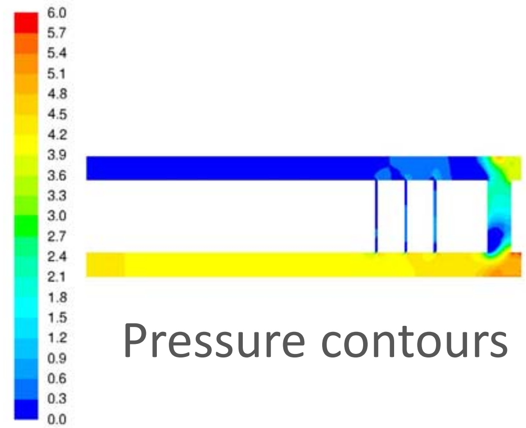


Thick-walled Cycling Header Development
Technical Approach

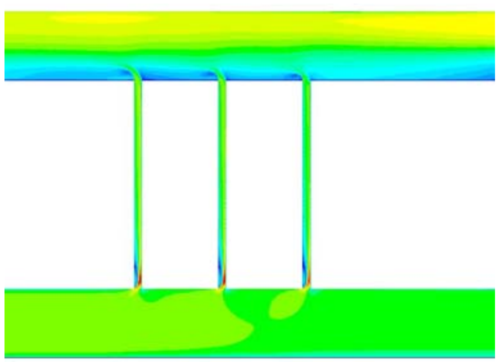


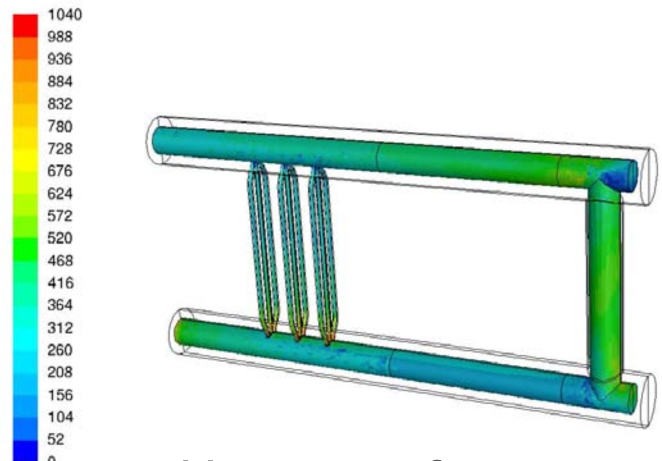
Velocity contours

Flow Split: 12.4% 87.6%



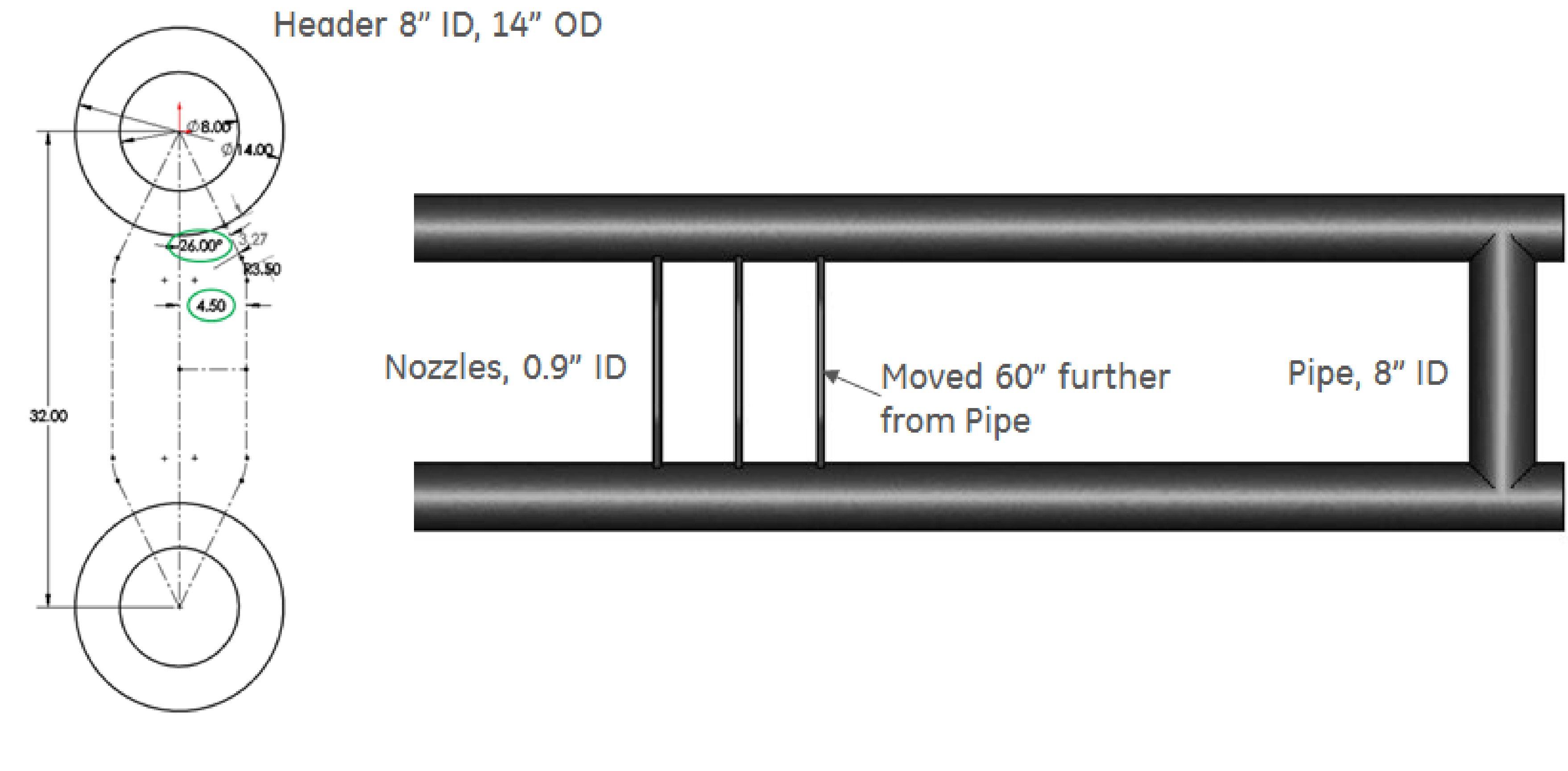
Pressure contours





Heat transfer rates

Thick-walled Cycling Header Development
Technical Approach



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)

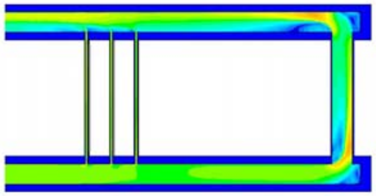
Task 4: Mechanical Integrity Evaluation

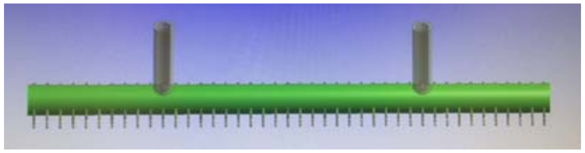
4a: ComTest-AUSC Fatigue Cycling

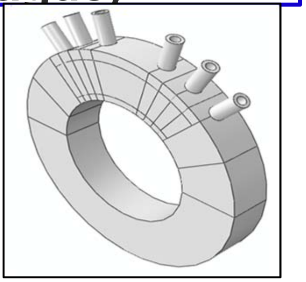
- Design ComTest header configuration
- Includes tube penetrations
- No branch nozzle in CFD studies
- Accelerated **thermal cycling**
- Test temperature 760°C (1400°F)
- Test pressure 41 bar (600psig)
- Materials: 740H & H282
- Transient cycle configured using two steady-state CFD analyses
- Fatigue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



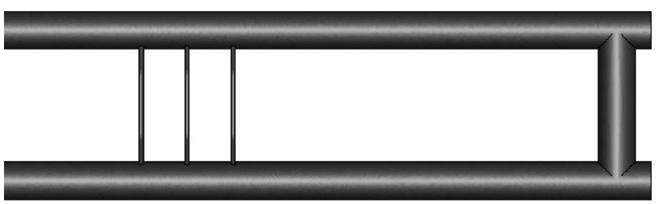




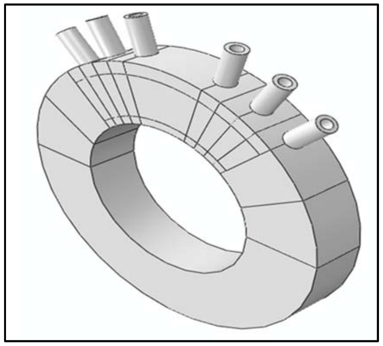
Thick-walled Cycling Header Development Technical Approach

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



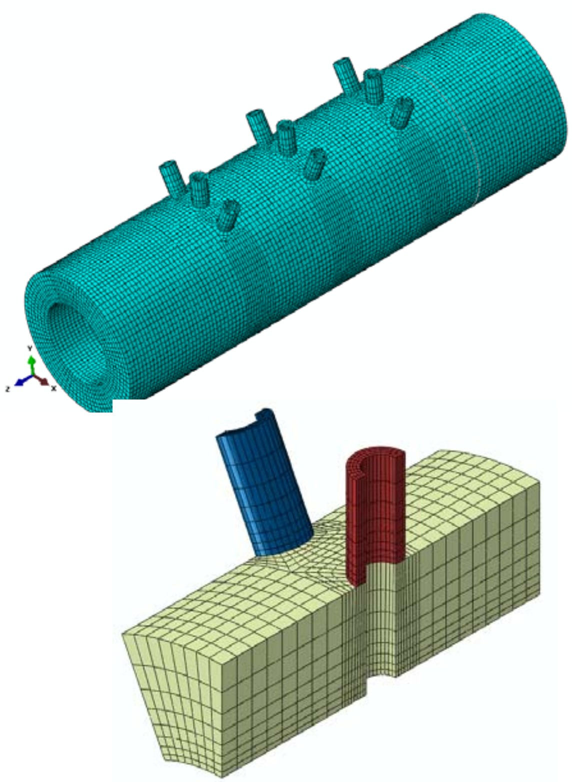
ComTest-AUSC cycling header



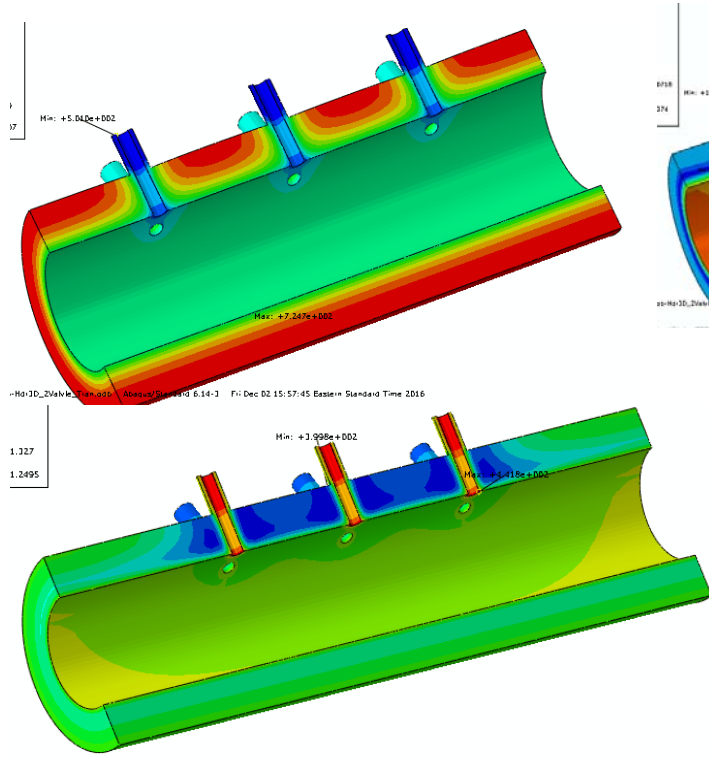
ComTest-AUSC header model

Thick-walled Cycling Header Development Technical Approach

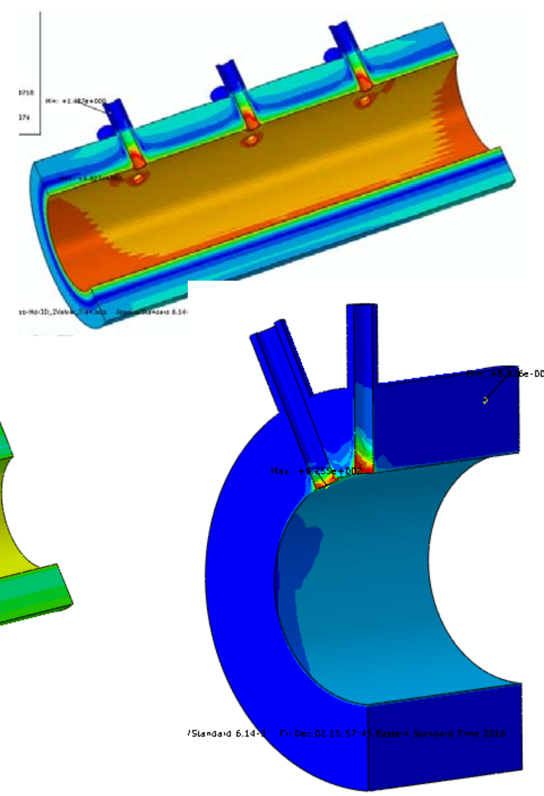
ComTest cycling header stress analysis



ComTest header models



Temperature contours

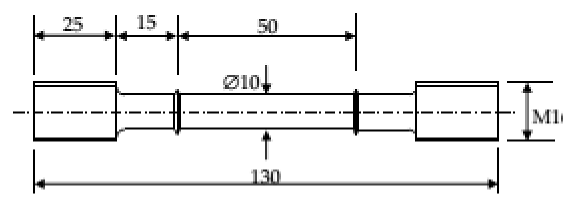


Stress contours

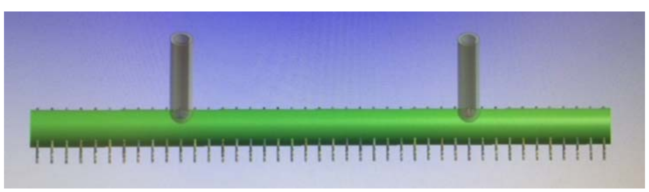
Thick-walled Cycling Header Development Technical Approach

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

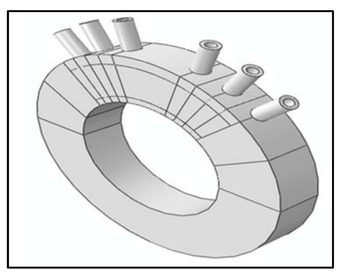
- Long term creep life assessment of full-scale AUSC SHO header using high temperature superalloy CDM models for analysis includes:
  - inlet tubes with welds
  - "Tee" section of a header with one branch nozzle and weld
  - H282 base metal model only for now
  - H282 weld material model if available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



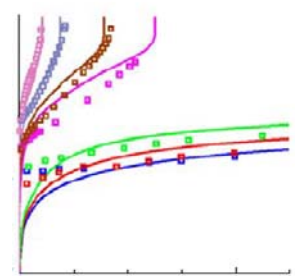
Benchmark Test Specimen



Full-scale AUSC SHOH Model



AUSC SHOH Analysis Model

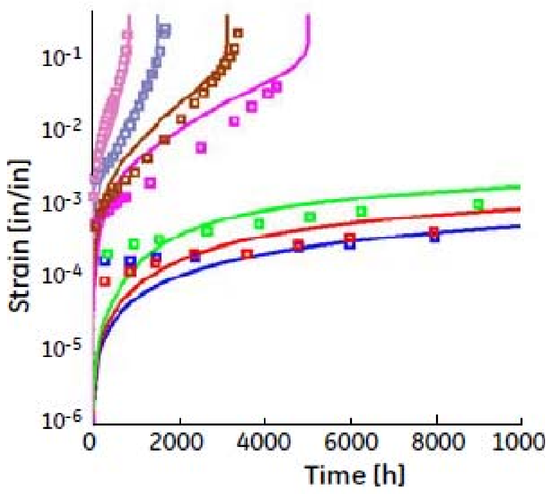


H282 CDM creep model data

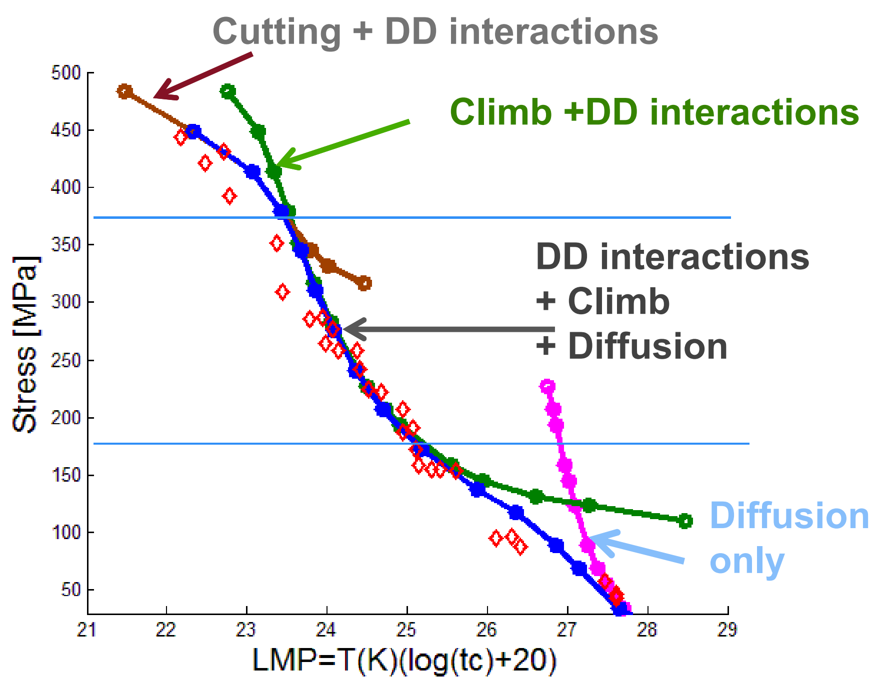
Thick-walled Cycling Header Development
H282 Constitutive Creep Model

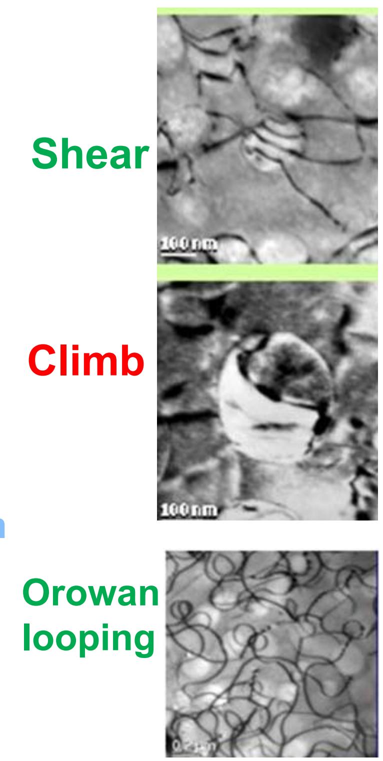
Develop macroscopic models capturing the effect physical micro-mechanisms and microstructure (e.g. dislocation climb-bypass & diffusion creep)

Base Metal H282, Creep model 1400-1700˚F

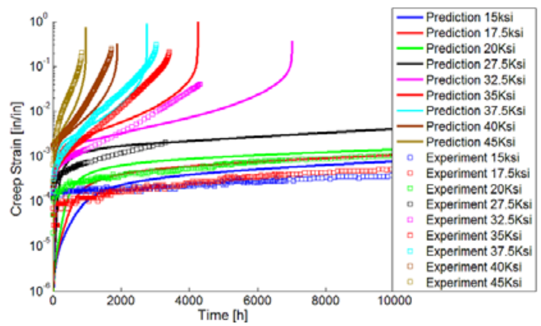


(a)

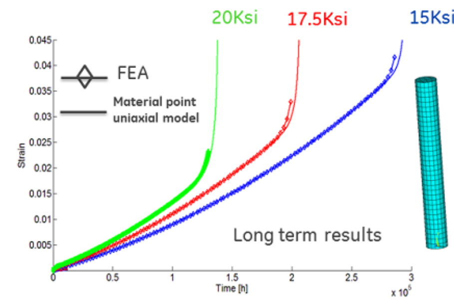




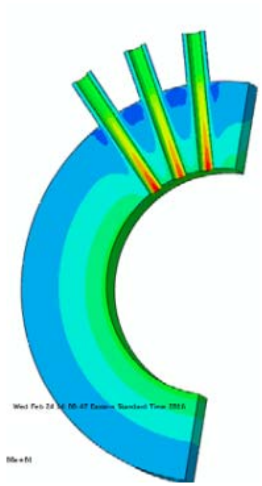
Thick-walled Cycling Header Development H282 creep model development & application



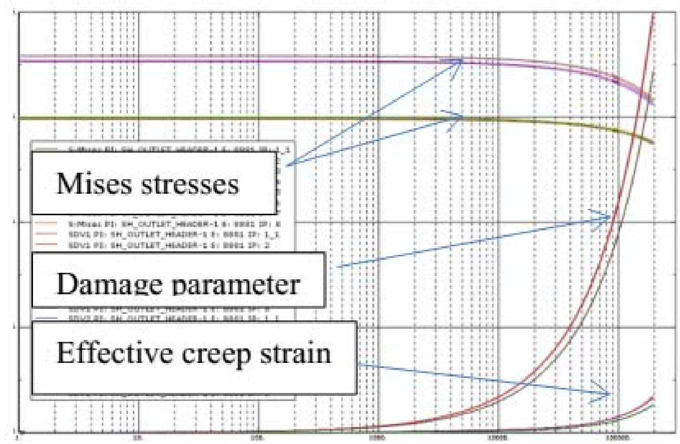
Test specimen creep strain data



Benchmark FEA Verification



Damage parameter contours



Borehole stress, creep strain & damage parameter history

Thick-walled Cycling Header Development
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

σ_o=0.25MG(T)b$\sqrt{\rho}$, ρ= ρ(C)

D-D interaction

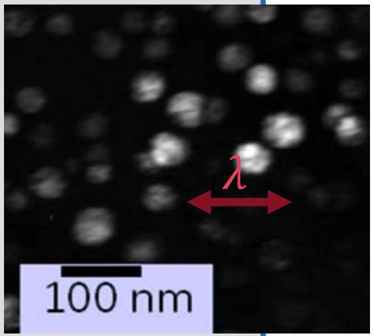
$$\rho = \begin{cases} \rho_i + (\rho_f - \rho_i)\varepsilon/\varepsilon^{crit} & if\ \varepsilon \le \varepsilon^{crit} = C\sigma_{eff} \\ \rho_f & if\ \varepsilon > \varepsilon^{crit} = C\sigma_{eff} \end{cases}$$

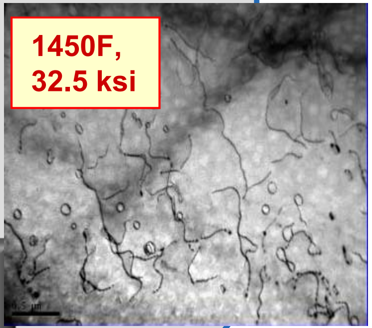
$$\sigma_{eff} = \frac{\sigma_{applied}(1+\varepsilon)}{1-\varpi}$$

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

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

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

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

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

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

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

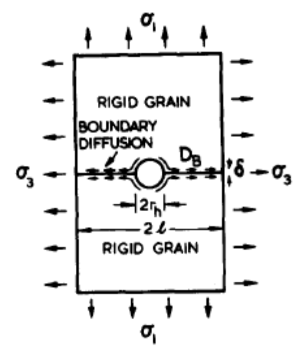
where $\beta = \frac{3D_V}{D_B\delta_B}\frac{l^3}{d^2}$ $\qquad D_V \text{ is a constant}$

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

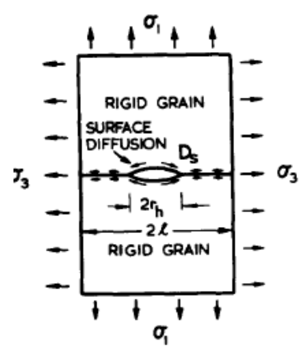
$D_B\delta_B \text{ is a constant}$

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

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



Void growth by boundary diffusion



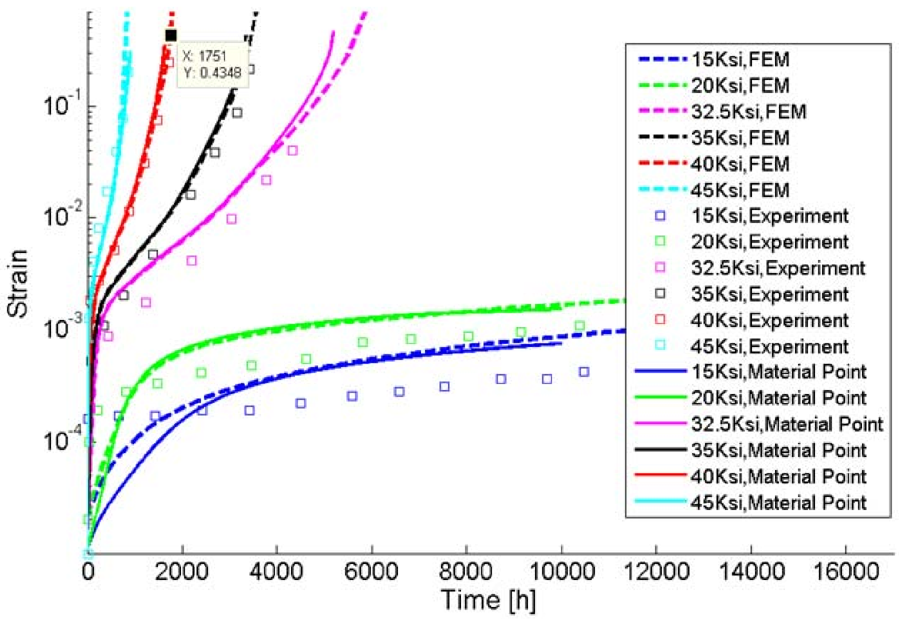
Void growth by surface diffusion

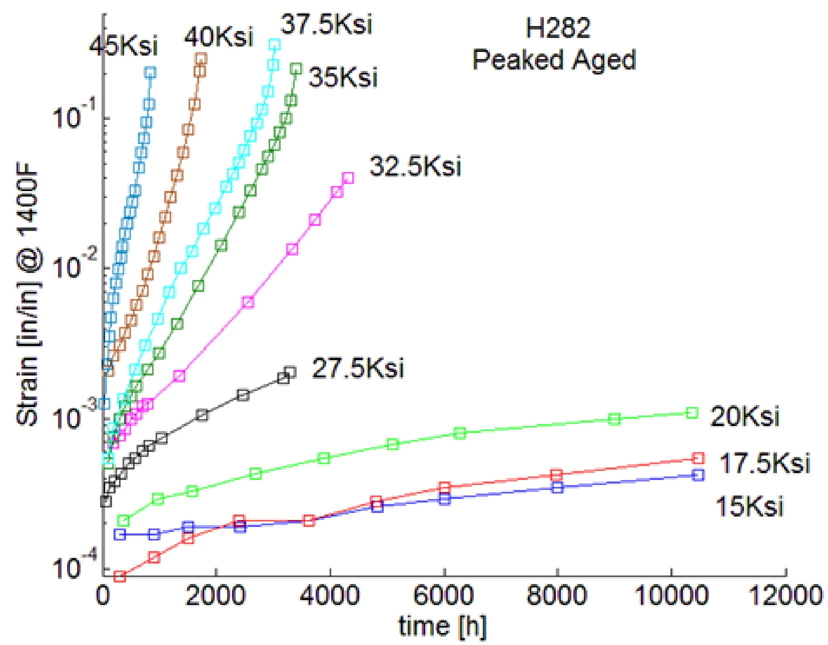
$$\alpha = \frac{D_S\delta_S}{D_B\delta_B}\frac{1}{\sqrt{2}}\frac{l^2}{d\gamma}$$

H282 model adapted for high temperatures

Thick-walled Cycling Header Development 2017 completion

3D creep constitutive model validation

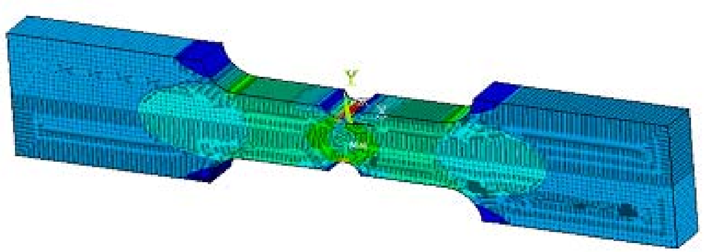


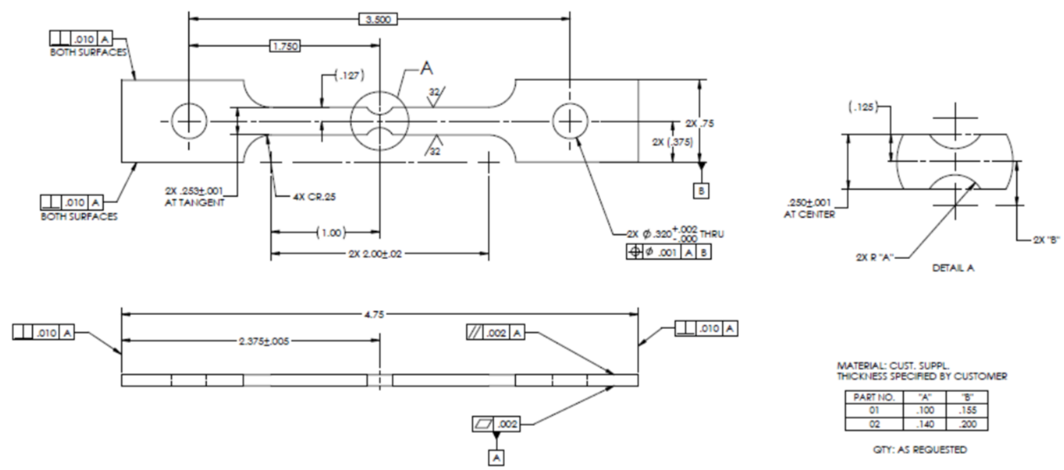


Thick-walled Cycling Header Development
2017 completion

Notched Bar Creep Tests

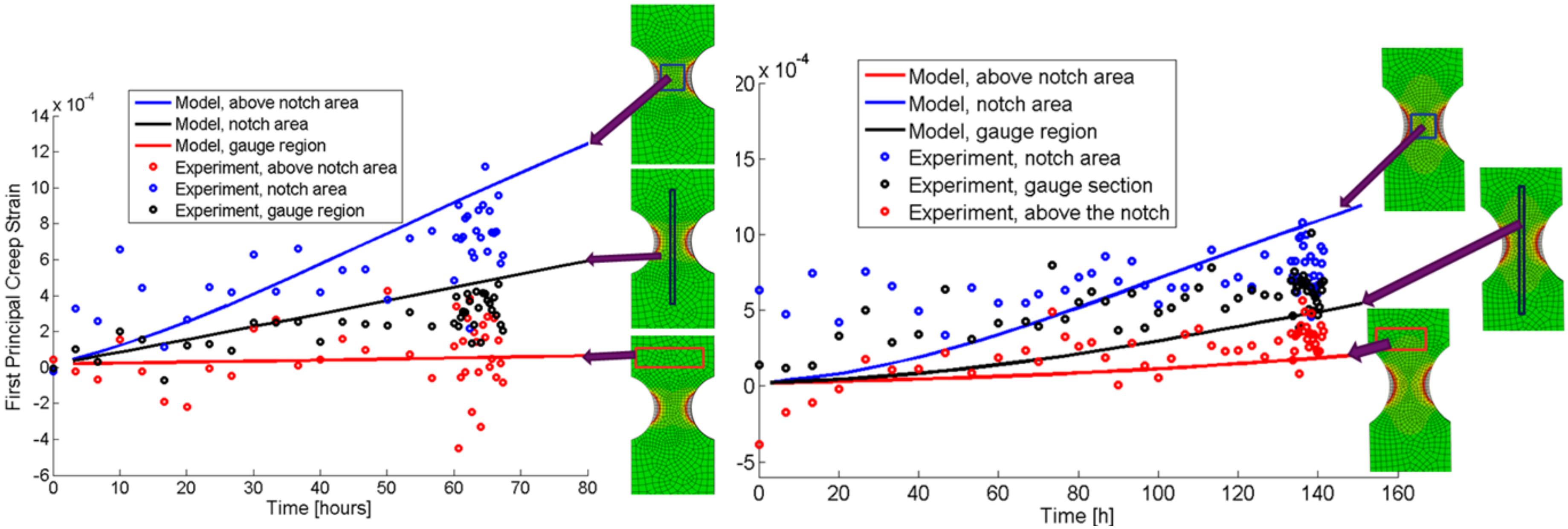
- H282 notched bar creep tests, 100 to 1000 hours
- Digital image correlation
- Simulates three-dimensional multi-axial stress effect
- Validate 3D creep constitutive models at 1400°F
- Suitable for boiler component applications



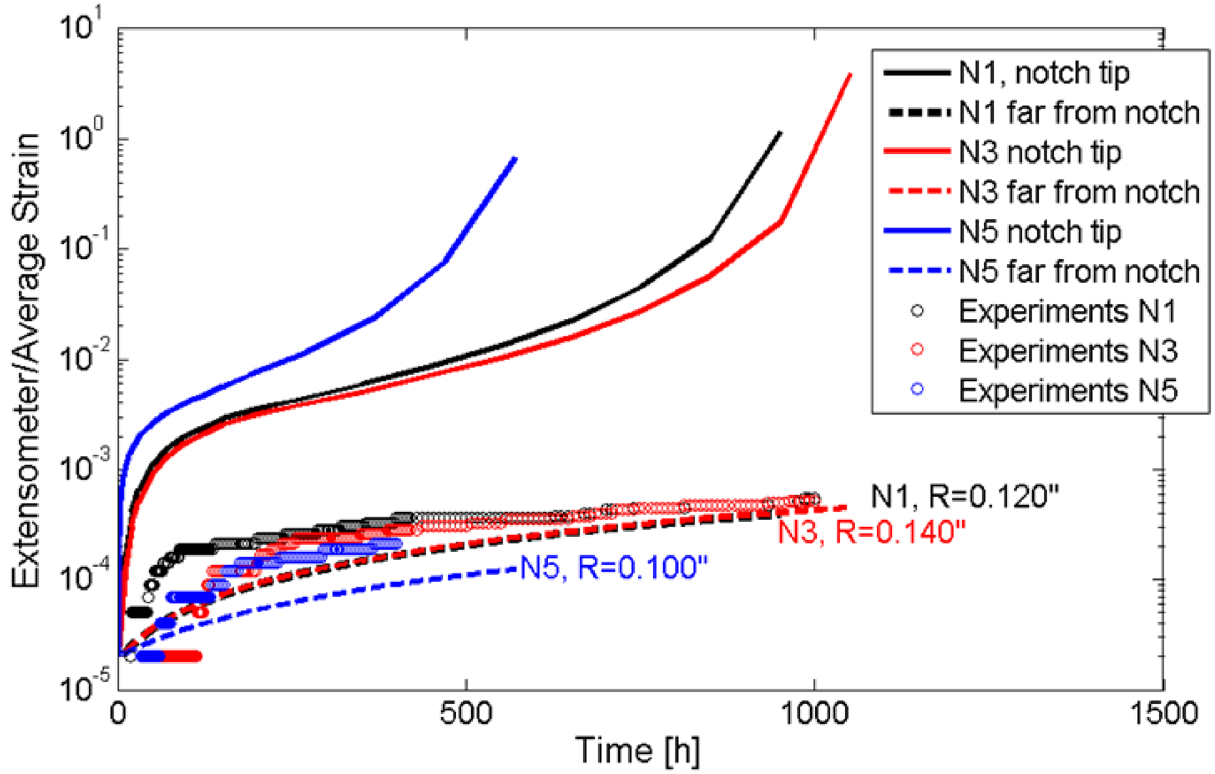


Thick-walled Cycling Header Development 2017 completion

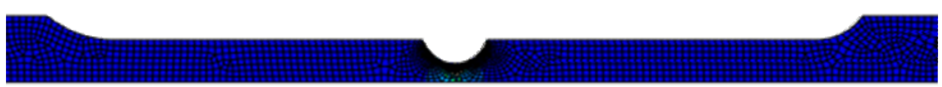
3D first principal strain distribution



Thick-walled Cycling Header Development 2017 completion



Axisymmetric model of the notched sample



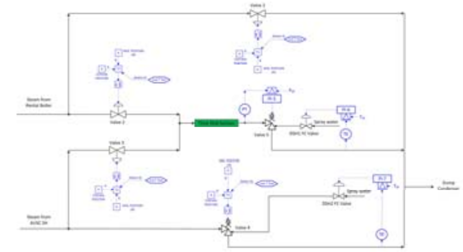
Thick-walled Cycling Header Development Technical Approach

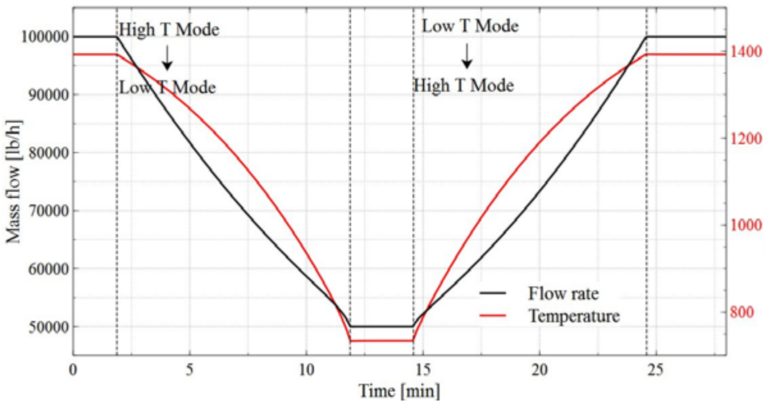
Task 5: Design of Thick-walled Header Component

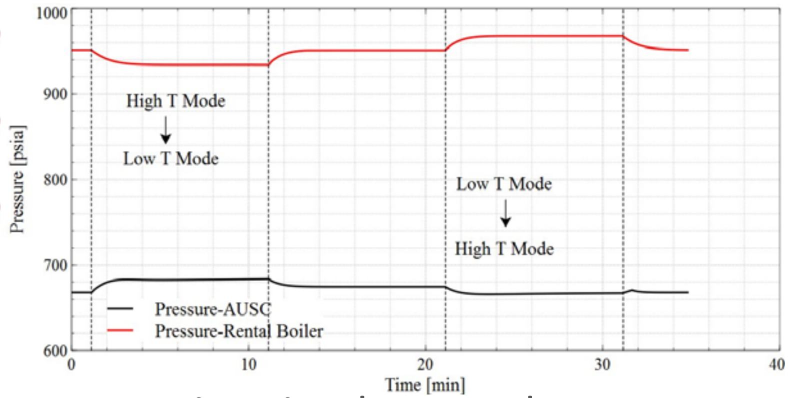
- Design layout of the ComTest-AUSC cycling header including desuperheater
- Identify instrumentation and location on the header for measurement of field data
- Define ComTest-AUSC test program including transient cycles (flow rates, temperature, pressure, ramp rates)
- Develop preliminary drawings for 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

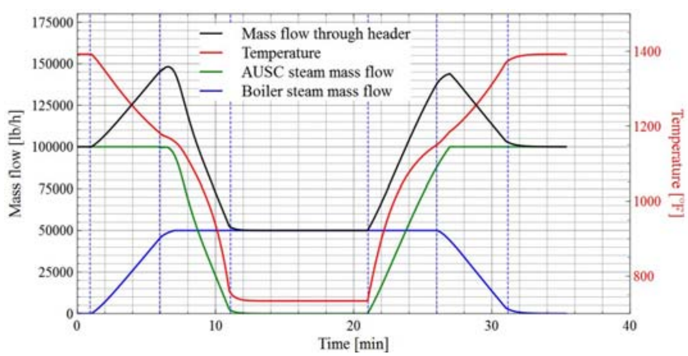
- Valve operating scenario at RH pressure
- Ramp rates
- Low and high temperature flow mix

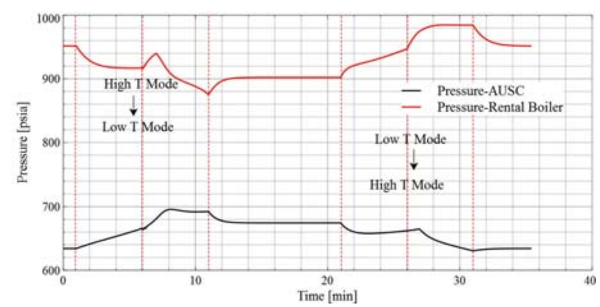






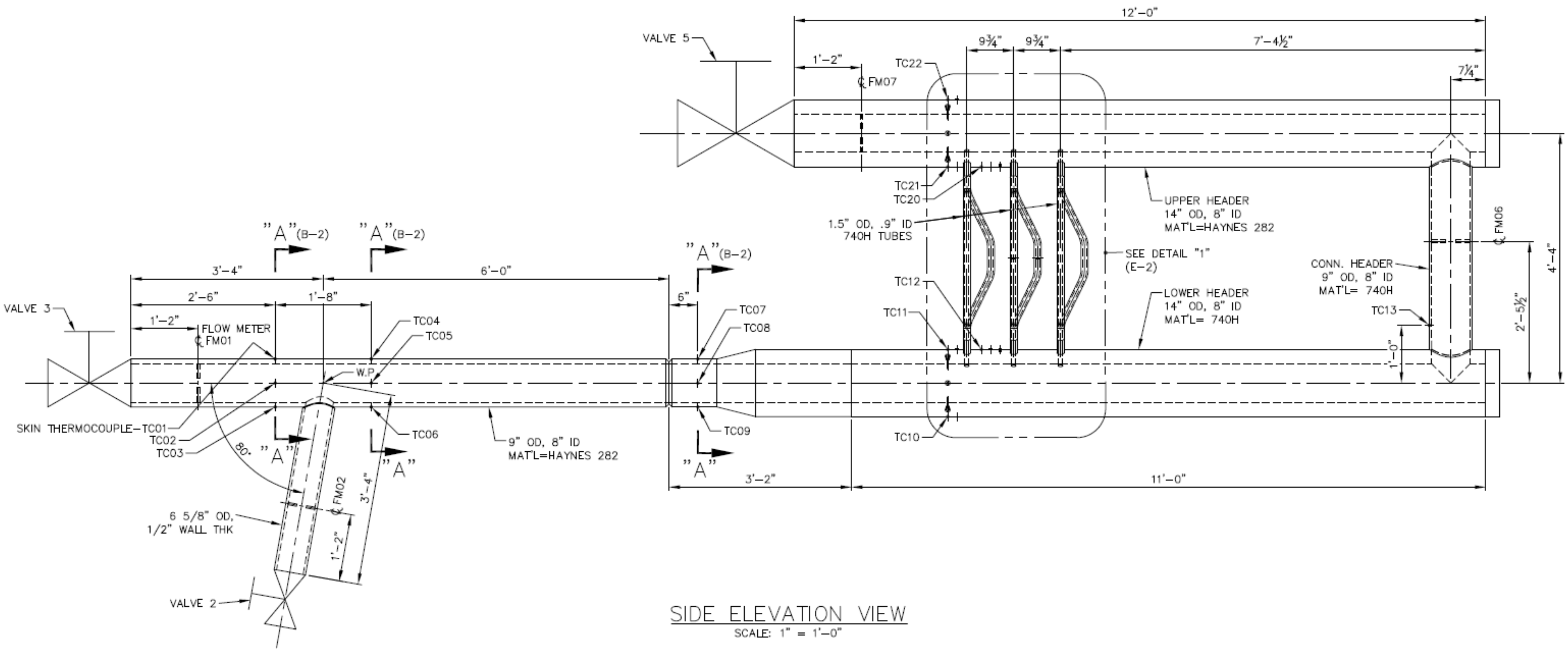
flow rate & temperature with 4 valves operating simultaneously





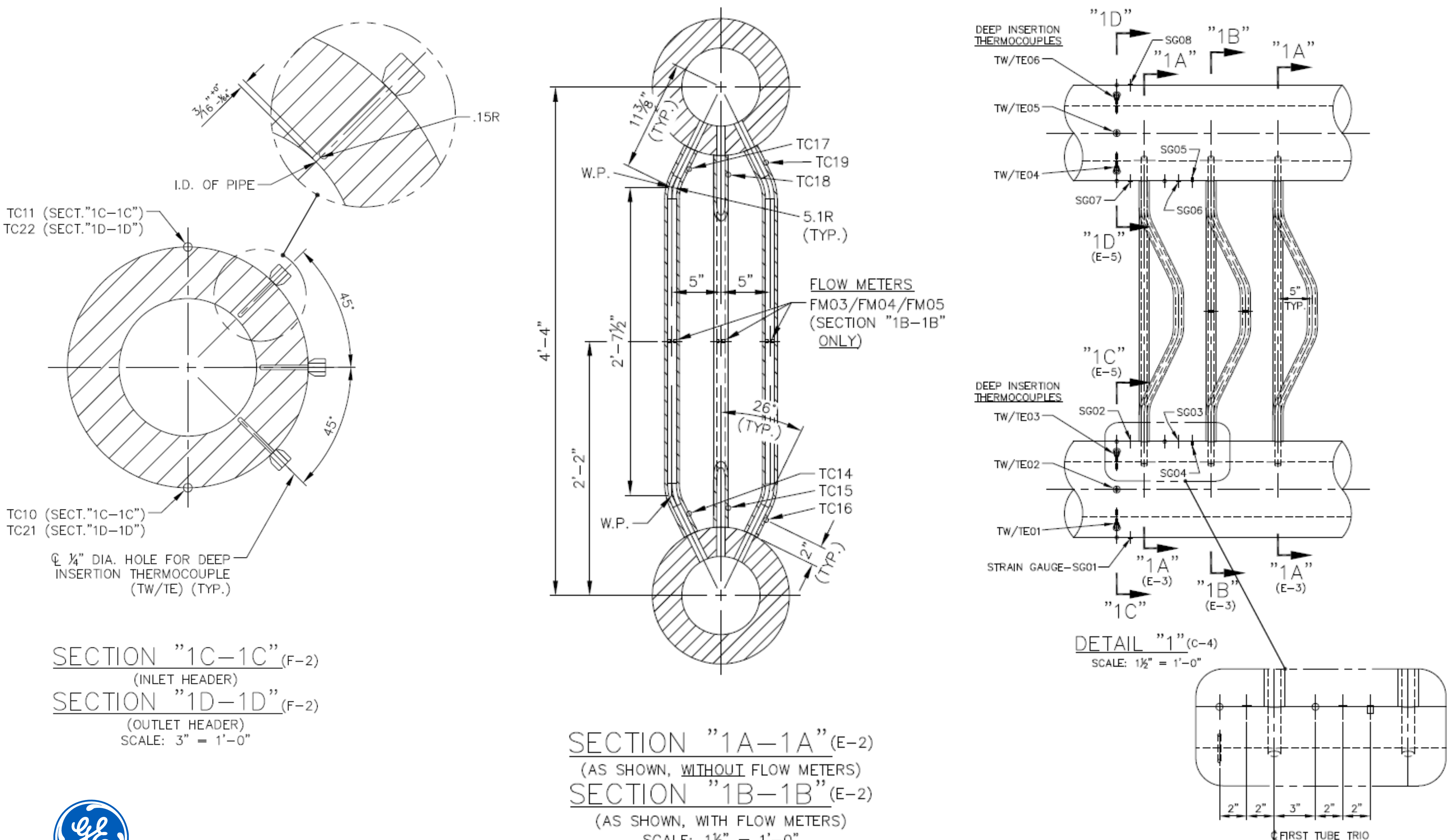
flow rate & temperature with control valves operating in two steps

Thick-walled Cycling Header Development
Mixing Tee and Header design



Instrumentation	Number
Surface (skin) thermocouples	22
Buried wall thermocouples	6
Surface strain gauges	8
Flow meters	7

Thick-walled Cycling Header Development
Header Instrumentation design



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.

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

Contacts:
JONATHAN PARKER, PHD, CENG, FIM, FIMECHE.
ELIZABETH BENTON (EBENTON@EPRI.COM)

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 Acknowledgements

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