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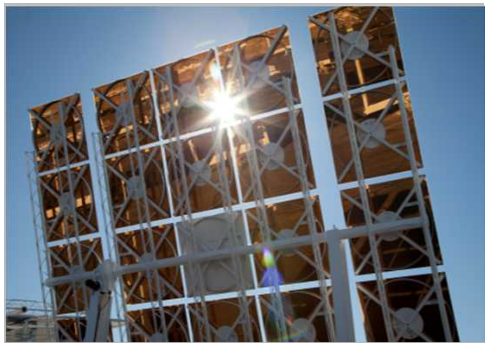

STRUCTURAL ANALYSIS OF A DIRECT HEATED TUBULAR SOLAR RECEIVER FOR SUPERCRITICAL CO_2 BRAYTON CYCLE

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PowerEnergy2015-49464

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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Agenda

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- Background & Problem Statement
- Methodology
- Analytical Creep-Fatigue Analysis
- Creep-fatigue Modeling
- Results
- Conclusions & Future Work

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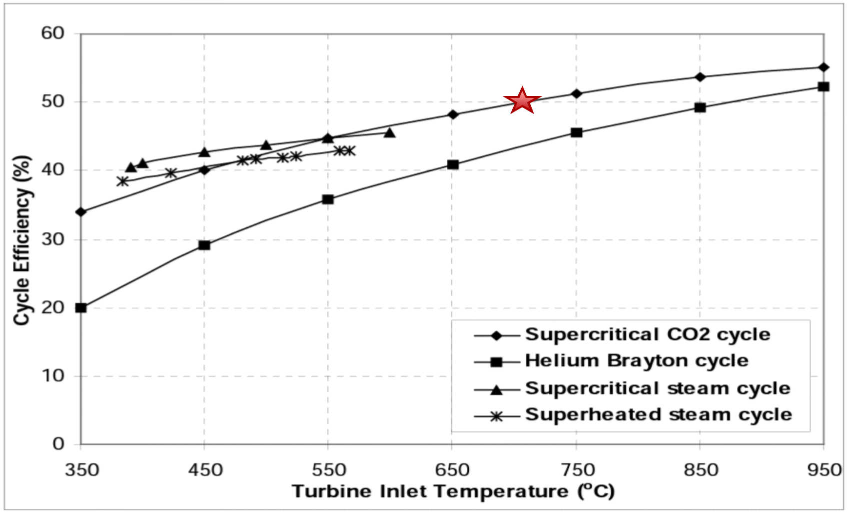
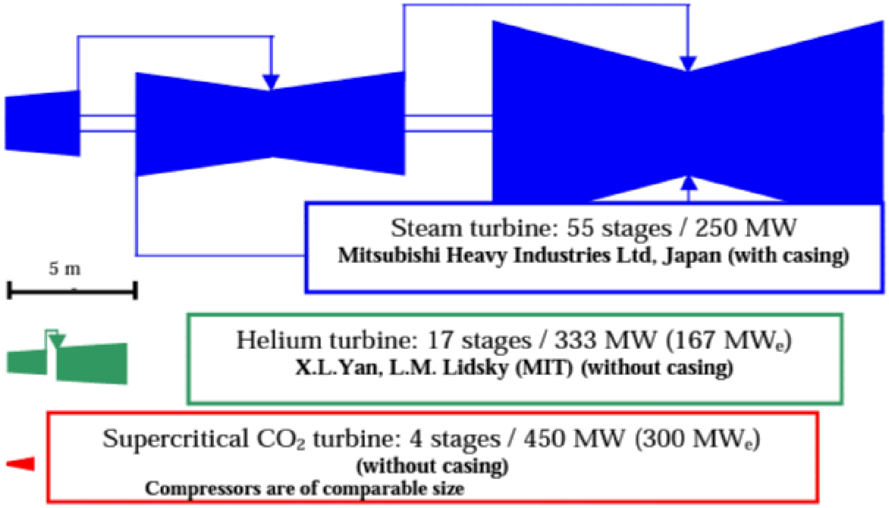
Background

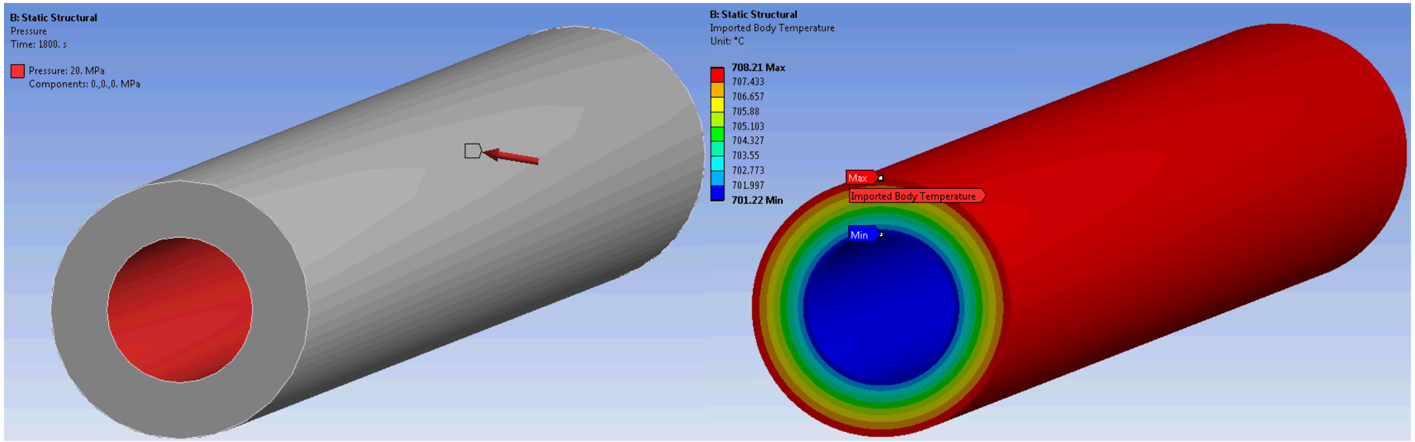
- Current efforts of solar power technologies to approach 50% cycle efficiency include the possibility of transitioning from conventional Rankine to Brayton power cycles.
- Closed-loop super-critical carbon dioxide (sCO_2) Brayton cycles are considered higher energy-density systems when compared to the equivalent super-heated steam Rankine cycles, due to the high working temperatures/pressures.





Problem Statement

- In this study, a thermal-structural model was developed using ANSYS Fluent and Structural to design and analyze the tubes of the receiver that will provide the heat input for a ~2 MW_{th} plant.
- The structural finite element analysis (FEA) was developed to define the structural integrity of the tubes of the receiver over the desired lifetime (>100,000 hrs.).



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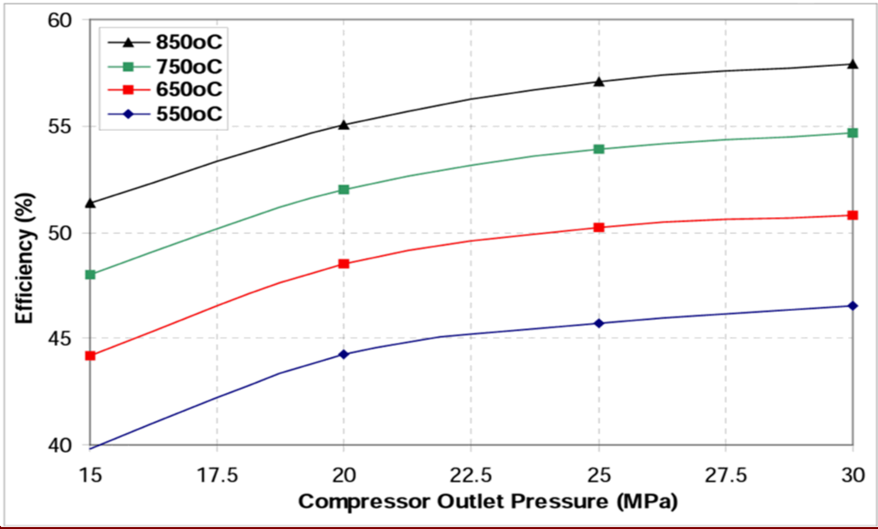
Receiver Design Parameters

- Required Heat Input for receiver
  - 2 MWth
- Working Fluid Pressure and Temperature
  - 20 MPa to 700 C
  - 25 MPa to 650 C
- Mass Flow Rate
  - 10 kg/s (1MWe generation)



Material Selection

- Obtained material properties with respect to temperature from the ASME Boiler and Pressure Vessel Code.
- Seven materials were reviewed and their mechanical properties were compared.
  - Haynes 230
  - Inconel 617
  - Inconel 625
  - Hastelloy X
  - Incolloy 800H (Previously used in Solar One)
  - Incolloy 800 HT
  - Stainless Steel 316 (Previously used in Solar Two)

Tube Sizing

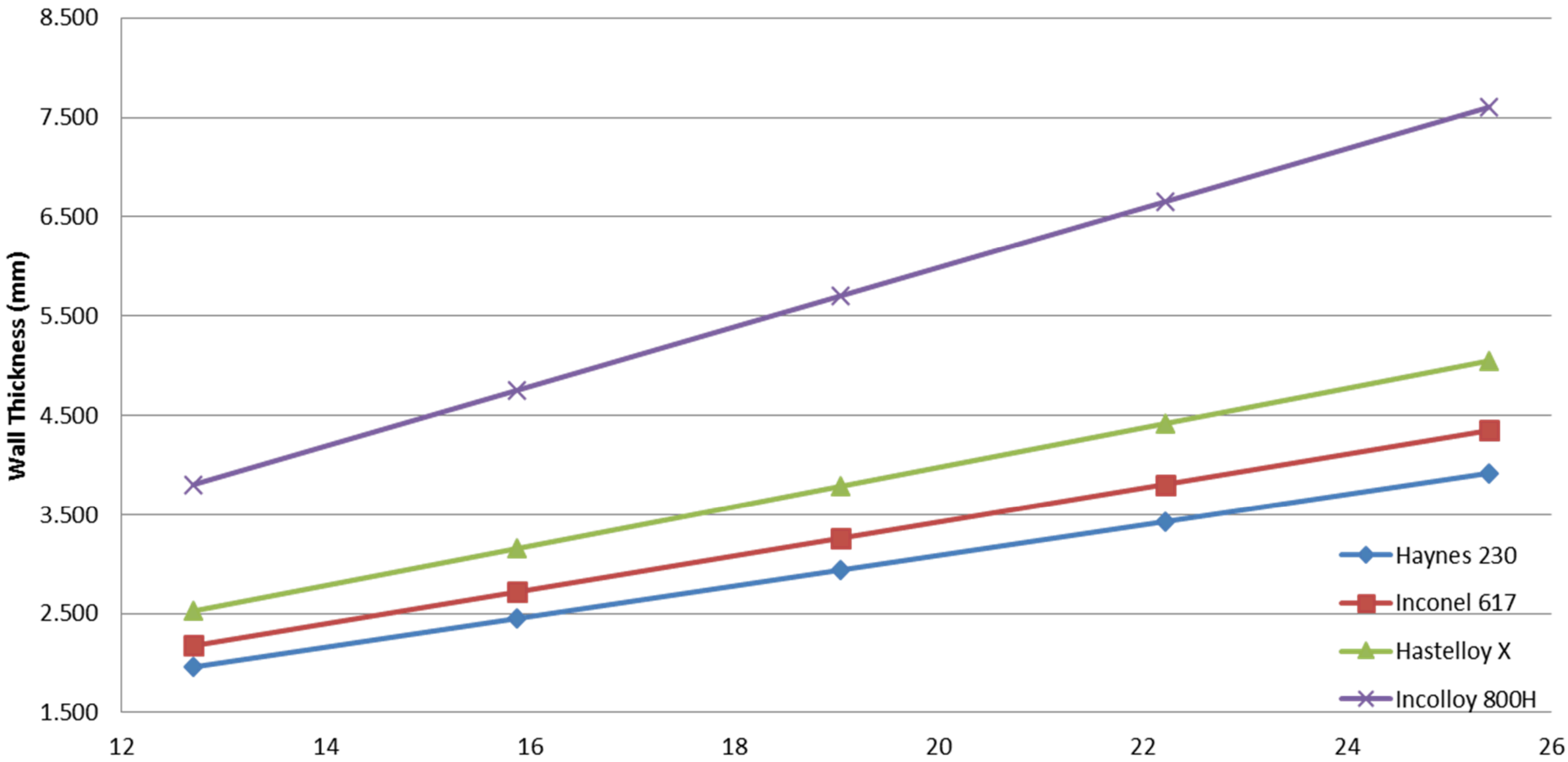
- ASME B31.1 design equation for power/pressurized pipes.

$$t = \frac{P \ Do}{2 \ (S \, E \ + \ P \, y)} + C$$

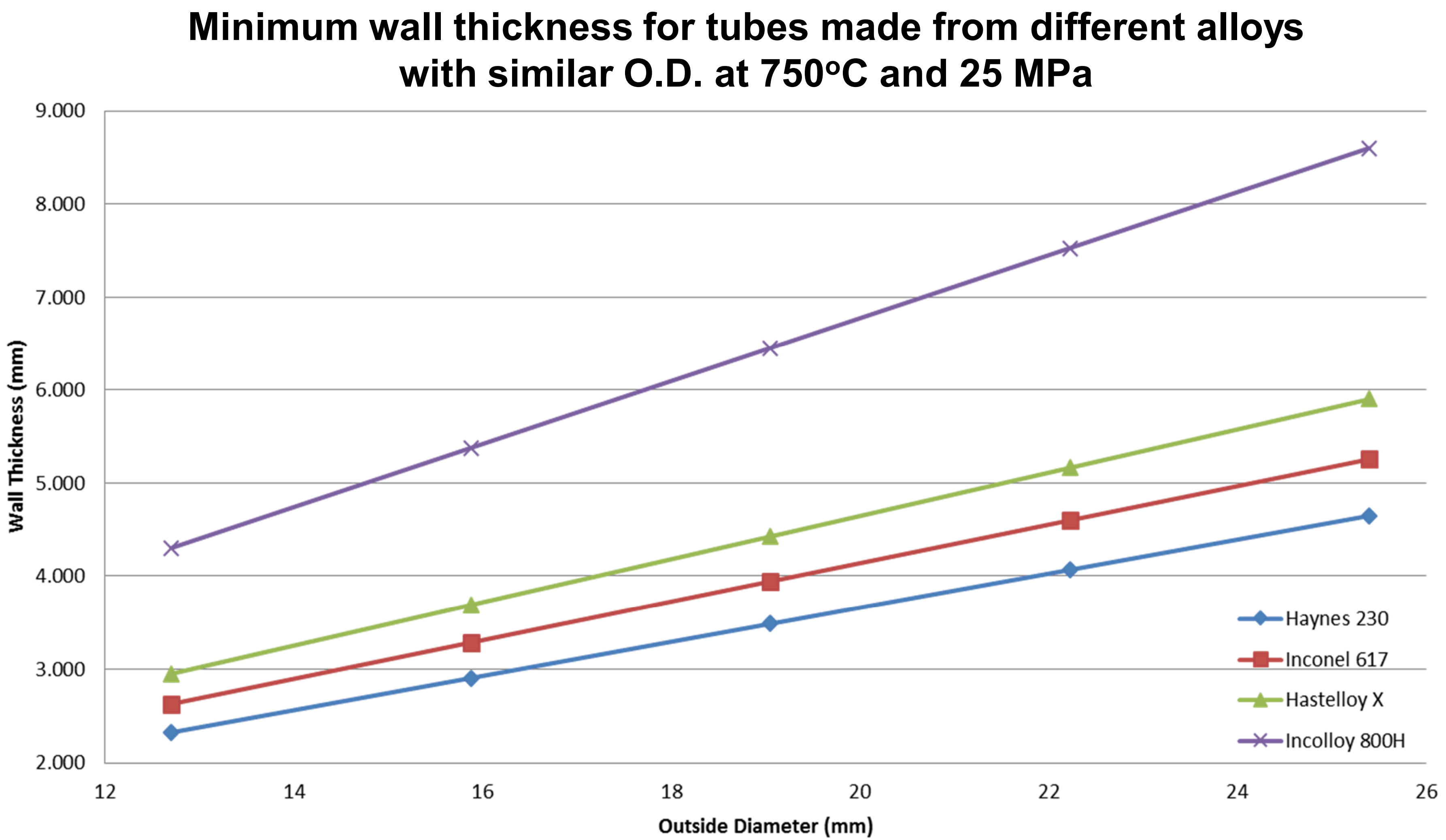
t: Minimum thickness required excluding manufacturing tolerance and allowances for corrosion
P: Working pressure
Do: External Diameter
S: Maximum allowable stress at temperature
E: Joint efficiency factor
y: Temperature coefficient
C: Corrosion allowance

Material & Tube Selection

Minimum wall thickness for tubes made from different alloys with similar O.D. at 750°C and 20 MPa



Material & Tube Selection



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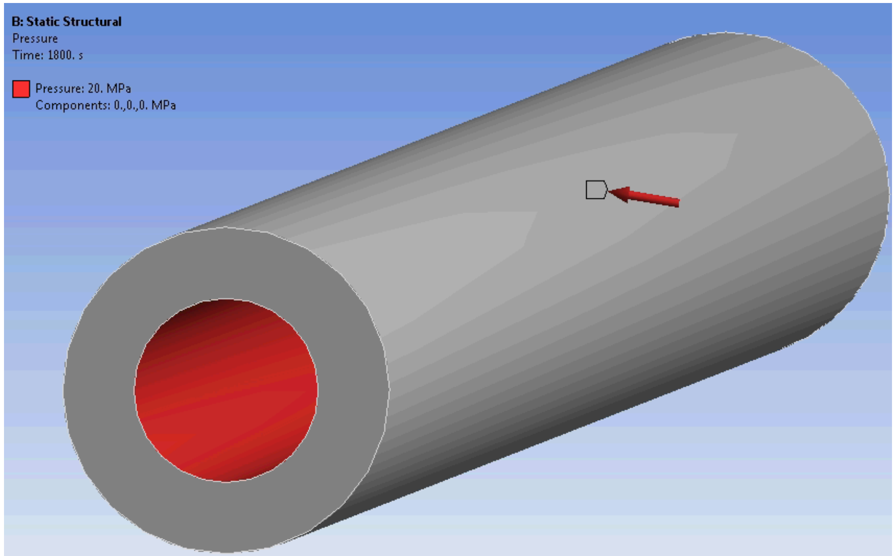
Analytical Creep-Fatigue Analysis

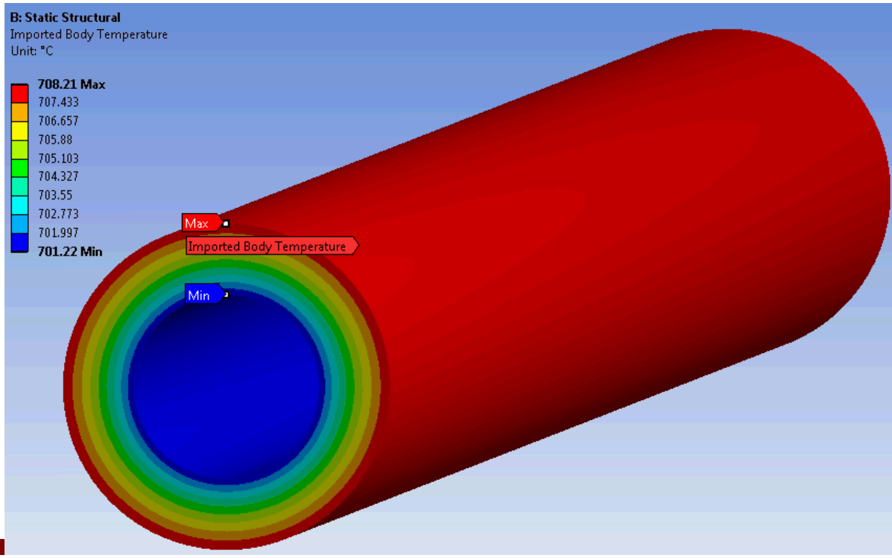
- Analytical Stress Calculations
  - The procedure followed is presented by Neises Et al. [2],
  - Two cases were selected. Exit fluid temperature of 700°C and pressure of 20 MPa and exit fluid temperature of 650°C and pressure of 25 MPa.
  - For the analytical study, 10,000 applied cycles and 100,000 hours of load time were assumed to simulate approximately 30 years of life.

	Mechanical Stress	Thermal Stress
Radial Stress (σrr)	$\sigma = \frac{P_{in} {r_{in}}^2}{({r_{out}}^2 - {r_{in}}^2)}(1 - \frac{{r_{out}}^2}{r^2})$	$\sigma = \frac{\alpha E \Delta T}{2(1-\vartheta)\ln(\frac{r_{out}}{r_{in}})}[-\ln\left(\frac{r_{out}}{r}\right) - \frac{{r_{in}}^2}{({r_{out}}^2 - {r_{in}}^2)}(1 - \frac{{r_{out}}^2}{r^2})\ln\left(\frac{r_{out}}{r_{in}}\right)]$
Tangential (Hoop) Stress ($\sigma\theta\theta$)	$\sigma = \frac{P_{in} {r_{in}}^2}{({r_{out}}^2 - {r_{in}}^2)}(1 + \frac{{r_{out}}^2}{r^2})$	$\sigma = \frac{\alpha E \Delta T}{2(1-\vartheta)\ln(\frac{r_{out}}{r_{in}})}[1 - \ln\left(\frac{r_{out}}{r}\right) - \frac{{r_{in}}^2}{({r_{out}}^2 - {r_{in}}^2)}(1 - \frac{{r_{out}}^2}{r^2})\ln\left(\frac{r_{out}}{r_{in}}\right)]$
Axial Stress (σzz)	$\sigma = \frac{P_{in} {r_{in}}^2}{({r_{out}}^2 - {r_{in}}^2)}$	$\sigma = \frac{\alpha E \Delta T}{2(1-\vartheta)\ln(\frac{r_{out}}{r_{in}})}[1 - 2\ln\left(\frac{r_{out}}{r}\right) - \frac{2{r_{in}}^2}{({r_{out}}^2 - {r_{in}}^2)}\ln\left(\frac{r_{out}}{r_{in}}\right)]$

Variable	
P	Working Pressure (Pa)
r	Radius (m)
α	Coef. Of Thermal Expansion (1/ °C)
E	Young's Modulus (Pa)
ΔT	Wall Temperature Difference (°C)
ϑ	Poisson's Ratio

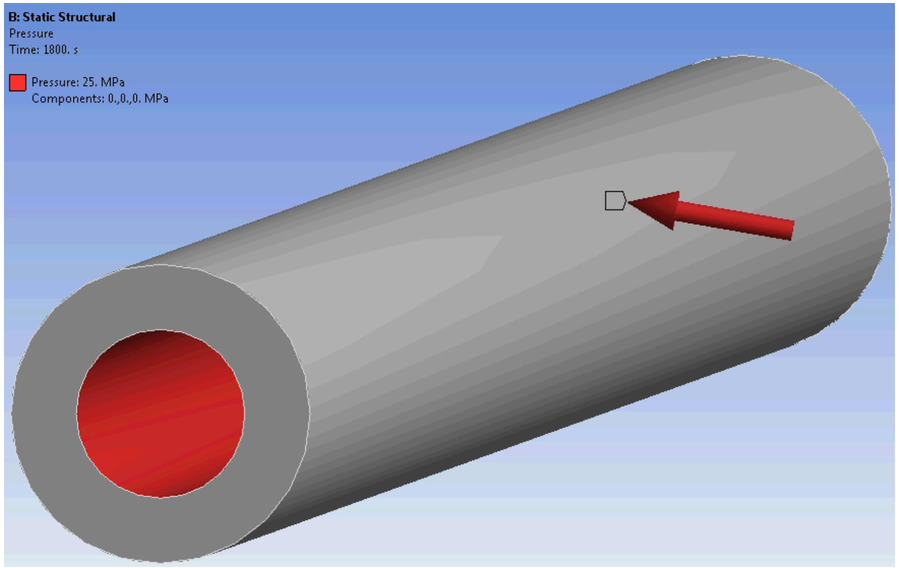
Boundary Conditions (Case 1)

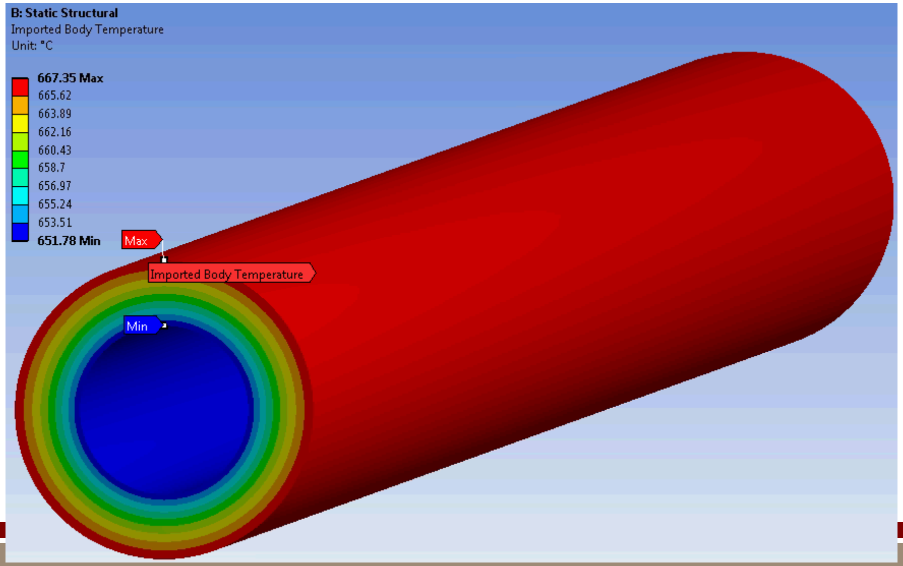




Parameter	Value (Units)
O.D./Thickness	12.7/2.7686 (mm)
I.D./O.D. Temperatures	701.22/708.21 (°C)
Internal Pressures	20 (MPa)
E (Young's Modulus)	164 x10^3 (MPa)
α (thermal expansion coefficient)	17.1 x10^{-6} (1/ °C)
ν (Poisson's ratio)	0.31 (-)

Boundary Conditions (Case 2)





Parameter	Value (Units)
O.D./Thickness	12.7/2.7686 (mm)
I.D./O.D. Temperatures	651.78/667.35 (ºC)
Internal Pressures	25 (MPa)
E (Young's Modulus)	168 x10^3 (MPa)
α (thermal expansion coefficient)	16.8 x10^{-6} (1/ ºC)
ν (Poisson's ratio)	0.31 (-)

Analytical Creep-Fatigue Analysis

- Simplified design rules based on the nuclear code were developed for CSP receivers and documented in an interim design standard for solar energy applications (SAND79-8183) [3]. This approach simplifies the design methodology for a creep-fatigue analysis with a cumulative damage approach.

$$\sum_{j=1}^{p}\left(\frac{n}{N_d}\right)_j + \sum_{k=1}^{q}\left(\frac{t}{T_d}\right)_k \leq D$$

- The general creep-fatigue damage equation for p number of unique loading cycles, and q number of unique creep loads, where N_d is the number of allowable and n is the number of applied cycles at known loading cycle j, T_d is the allowable creep rupture time and t is the applied load time at loading condition k. Therefore, D, the total allowable accumulated damage is a material property and varies between alloys. Reference material for Haynes 230 suggests that D≈ 1.0 [4].

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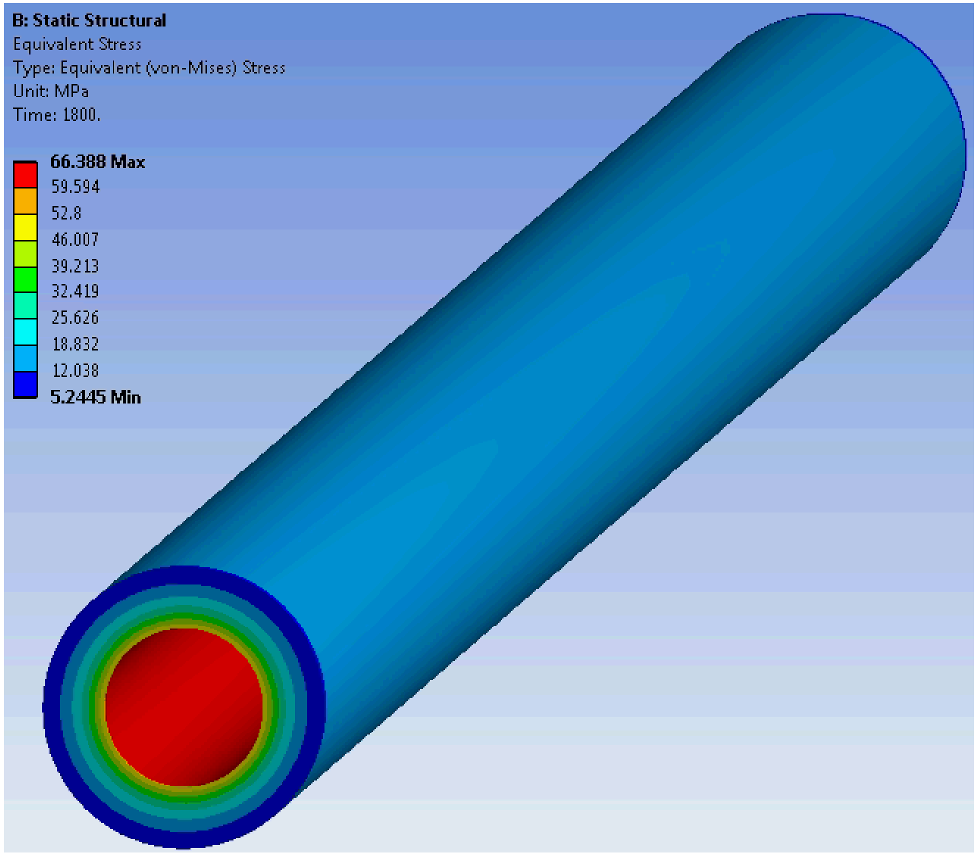
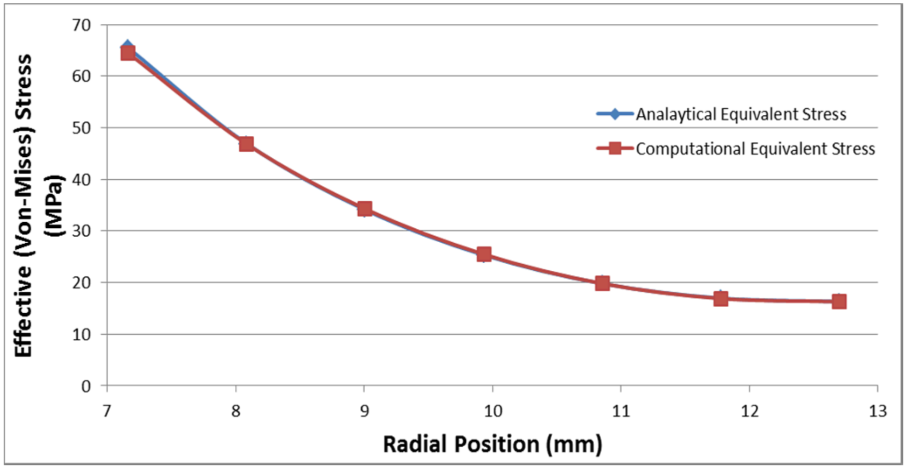
Thermal-Structural Analysis

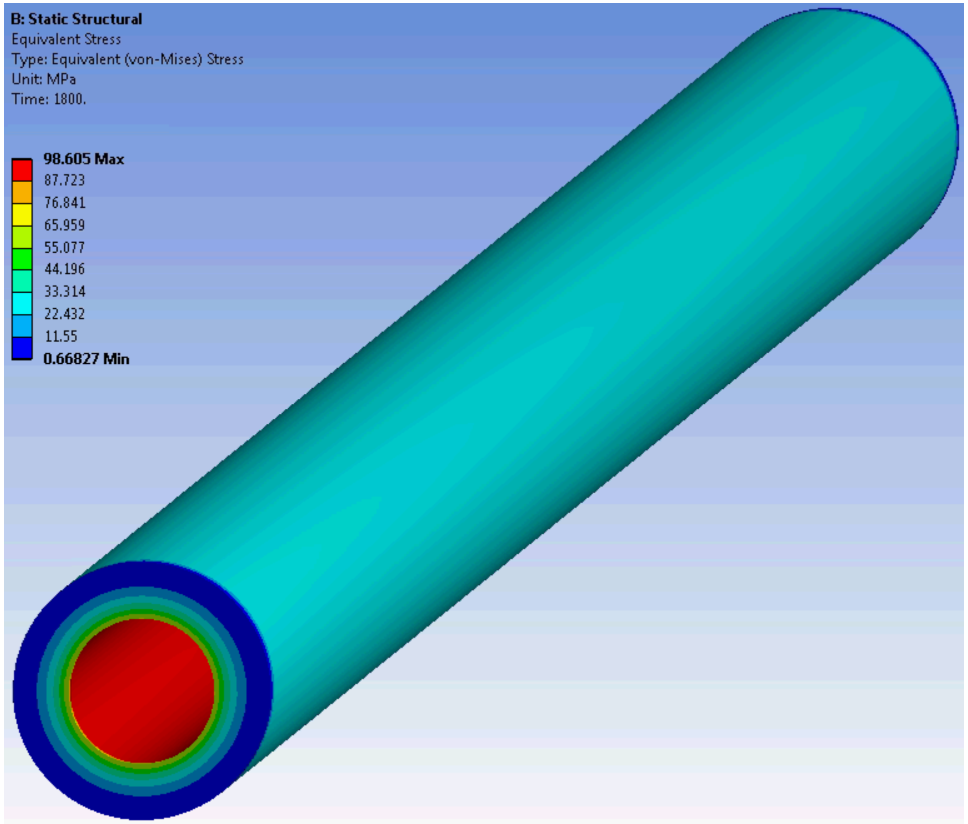
- The procedure followed was presented by Neises et al. [2] which focuses on the development of an analytical model using the pressurized cylinder equations. The calculated stress components throughout the tube are calculated analytically. Each component is composed of the mechanical and thermal stresses which are resulting stresses from the pressure and thermal load respectively. The results obtained from the analytical models were then used to build a finite element analysis (FEA) structural model using ANSYS Mechanical.

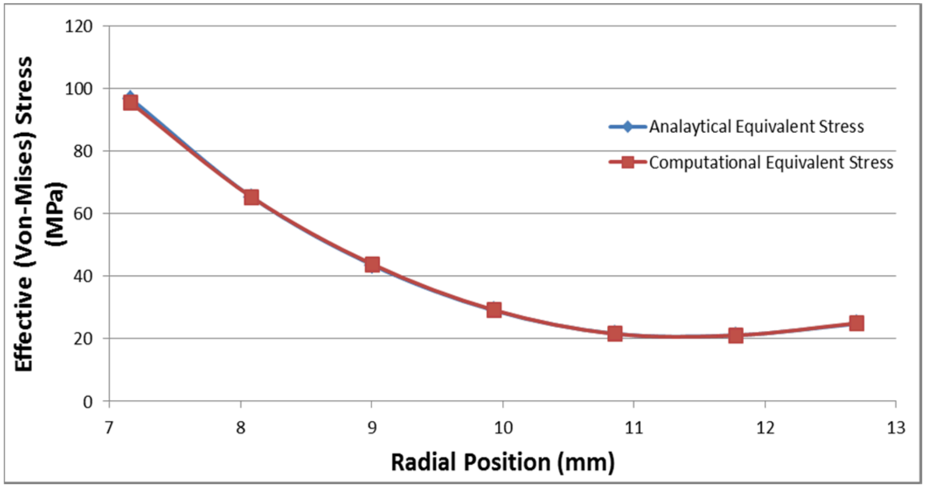
Static Stress Analysis (Case 1)



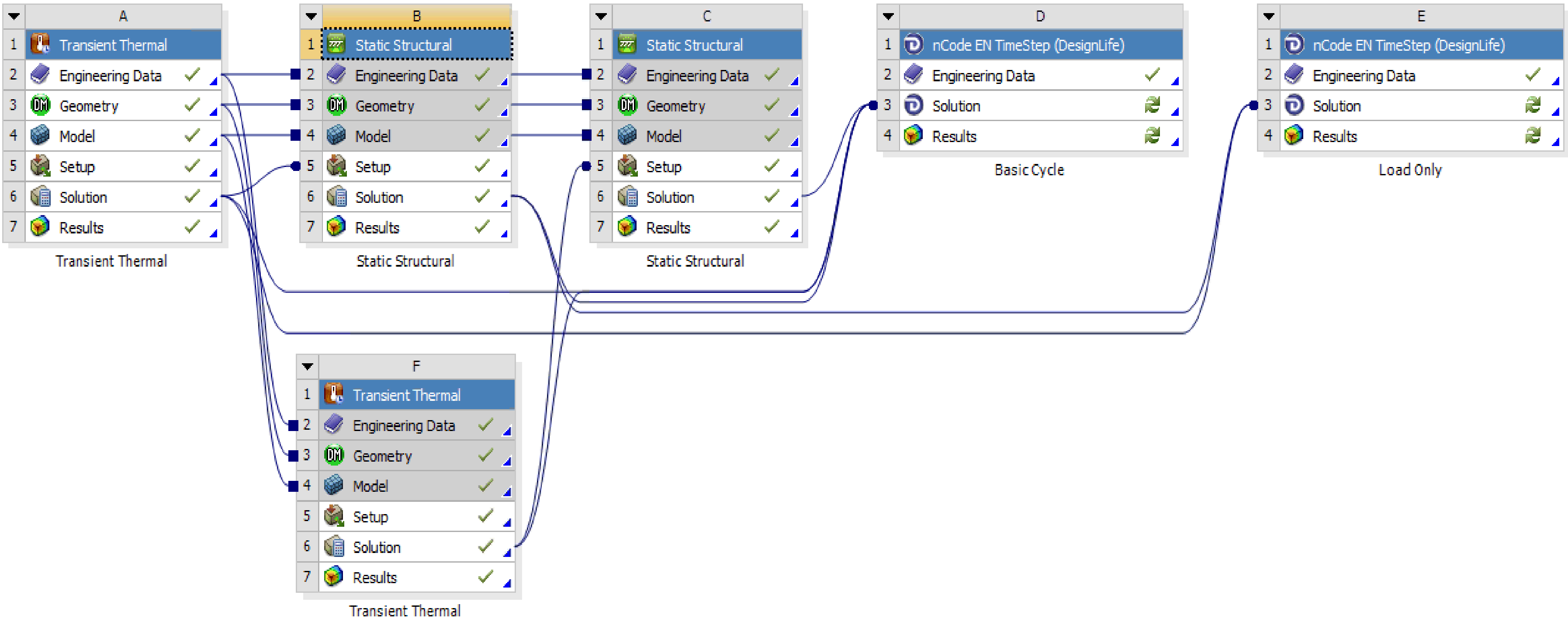


Static Stress Analysis (Case 1)





Mechanical to nCode Link



Creep Modeling

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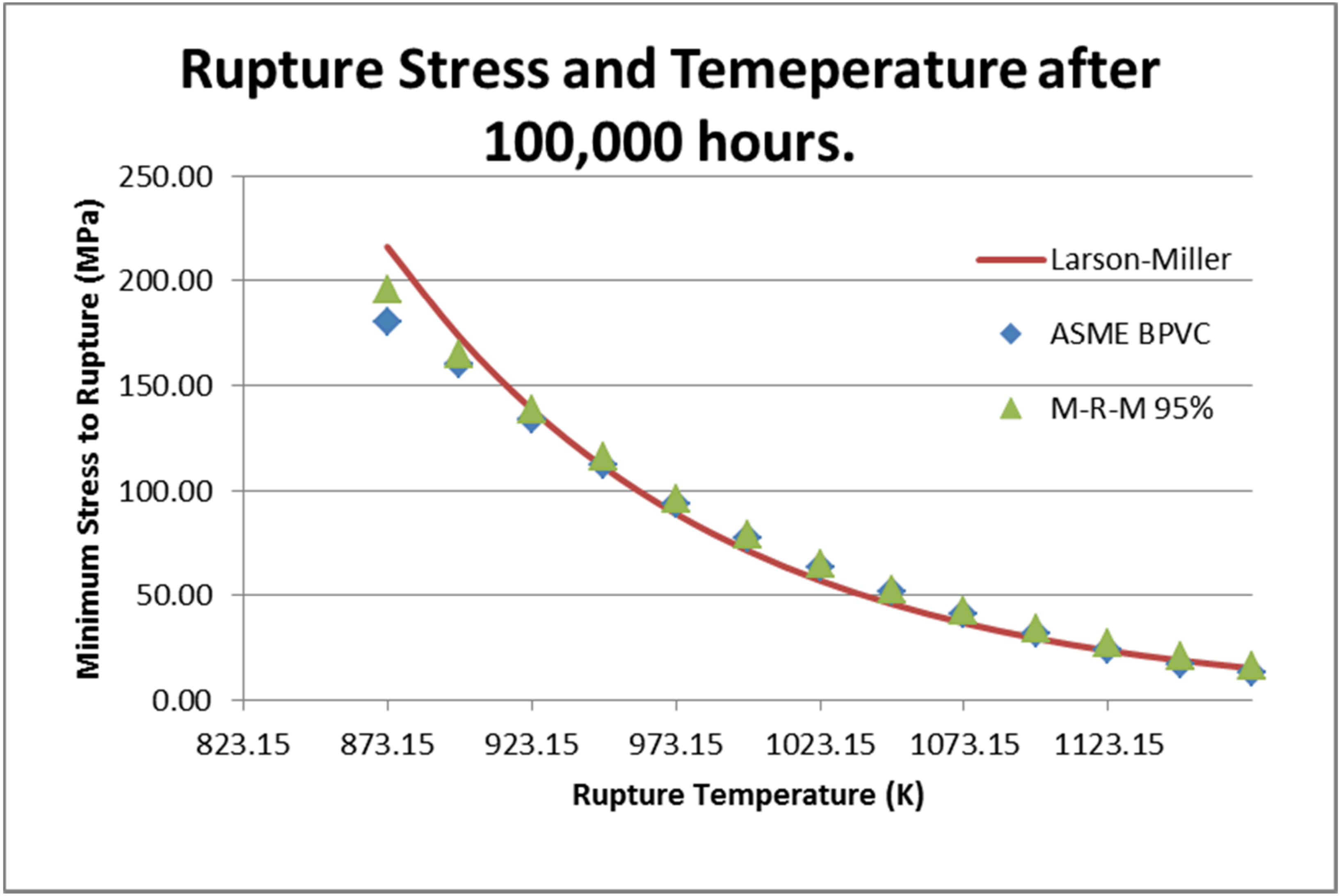
- The Larson-Miller coefficients were obtained from the curve-fit generated from the ASME BPVC stress tables (Section II).
- Eno et al. [5] published the Mendelson-Roberts-Manson (M-R-M) model, that claims to be better than the commonly used Larson-Miller, to extrapolate the rupture time of a material.
- The Larson-Miller model is used in nCode Design Life to evaluate the remaining life and damage accumulated at every node.

$$\log(t) = \beta_0 + \beta_1 \frac{1}{T} + \beta_2 \log(\sigma) + \beta_3 \log(\sigma) \frac{1}{T}$$

Method	β_0	β_1	β_2	β_3
M-R-M_95%	-26.64	44158	4.72	-11337
Larson-Miller	20	36967.5	0	-6483

Creep Modeling



Fatigue Modeling

- Fatigue Modeling
  - For the fatigue modeling, the material cyclic properties were estimated using the modified universal slopes (Muralidharan) method since it is more conservative than the one proposed by Manson.
  - The Strain-Life equation below was used to develop Strain-Life curves for nCode.

$$\frac{\varepsilon_{Tot}}{2} = \frac{\varepsilon_E}{2} + \frac{\varepsilon_P}{2} = \sigma_f'(2N)^B + \varepsilon_f(2N)^C$$

Variable		
Yield Strength	Sy (MPa)	Refer to Properties
Ultimate Tensile Strength	Su (MPa)	Refer to Properties
Young's Modulus	E (GPa)	Refer to Properties
Axial Fatigue Strength Coefficient	σf' (MPa)	$0.623 * \mathrm{Su}^{0.823} * \mathrm{E}^{0.168}$
Axial Fatigue Strength Exponent	B	-0.09
Fracture Ductility	εf	$1.375\text{-}125\ {}^{\mathrm{Su}}/_{E}$
Axial Fatigue Ductility Coefficient	εf'	$0.0196 * \varepsilon\mathrm{f}^{\,0.155} * ({}^{\mathrm{Su}}/_{E})^{-0.53}$
Axial Fatigue Ductility Exponent	C	-0.56
Cyclic Strain Hardening Exponent	n'	0.2

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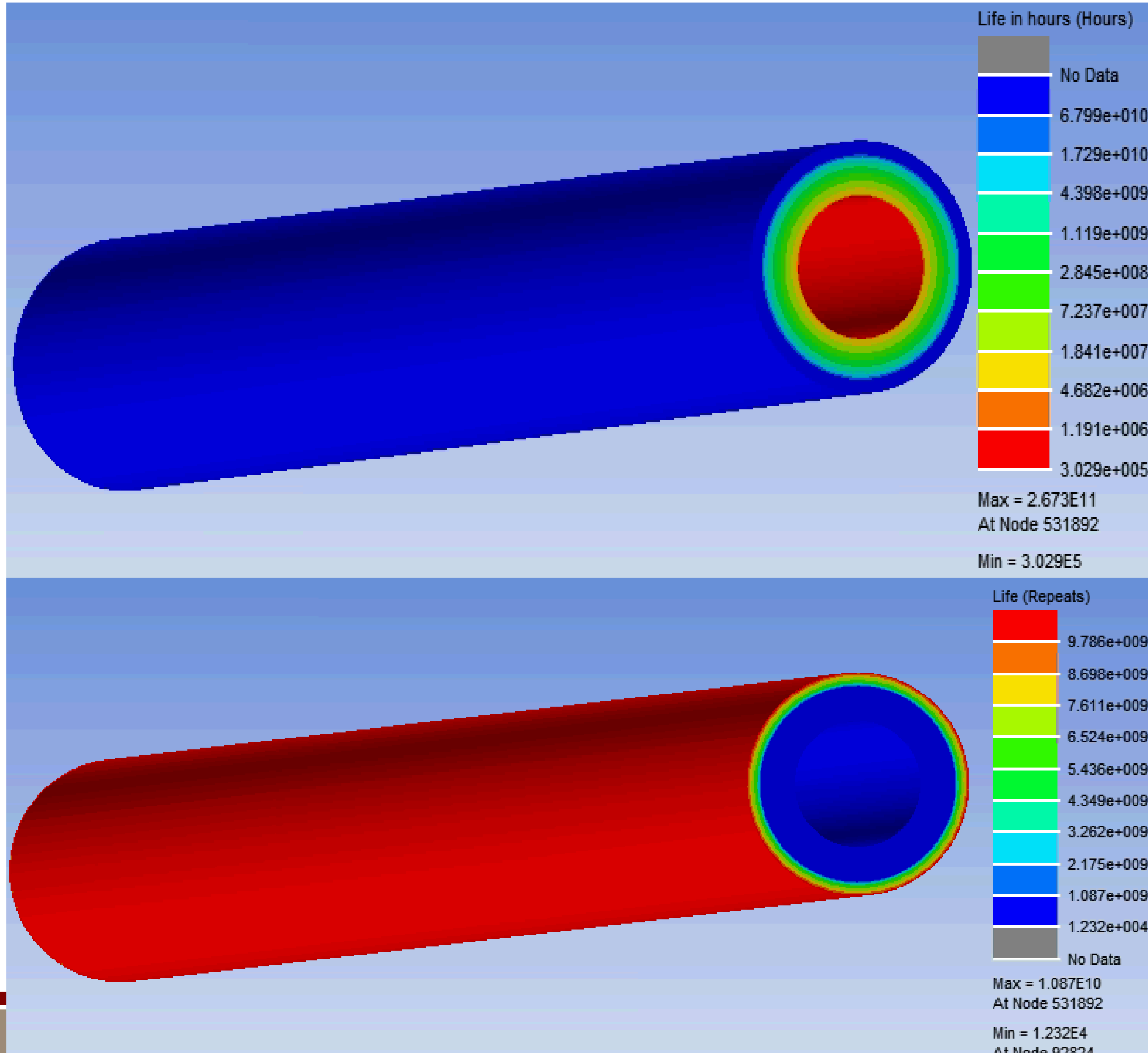
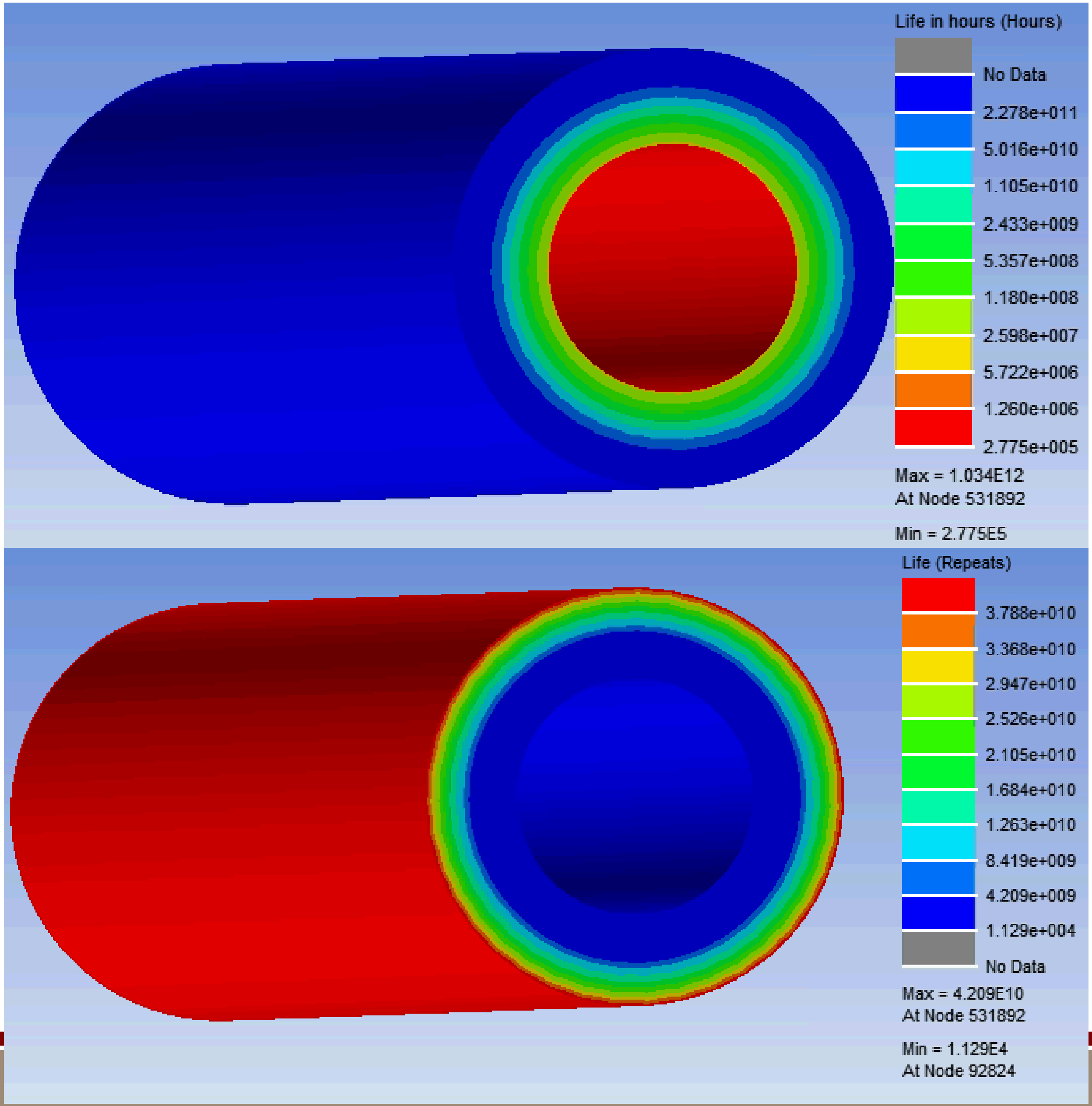
Creep-Fatigue Results (Case 1)



Creep-Fatigue Results (Case 2)



Creep Results

	Analytical allowable creep rupture time (hrs.)	nCode allowable creep rupture time (hrs.)
Load Only	$1.151x10^5$	$1.268x10^5$
Basic Cycle	$2.761x10^5$	$3.029x10^5$

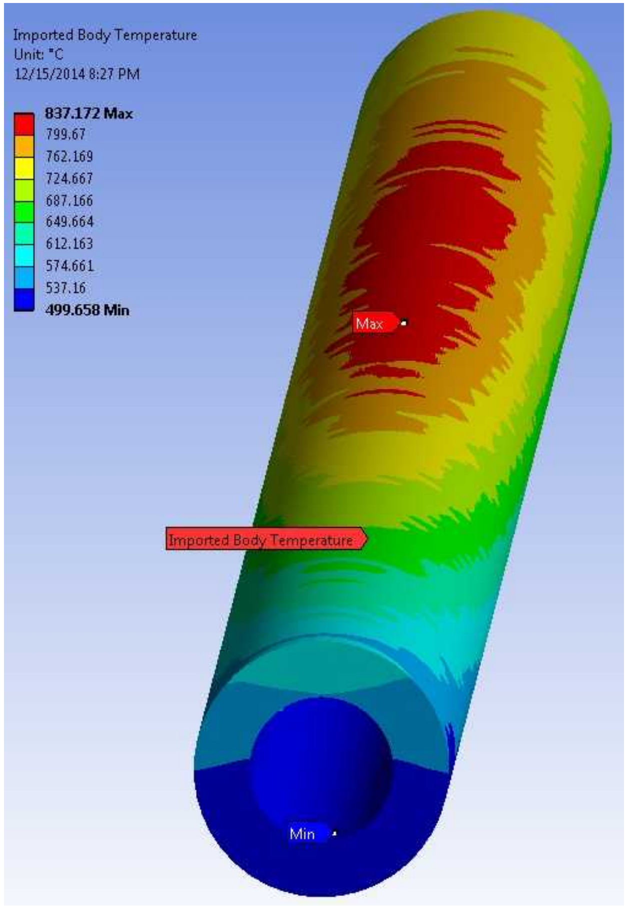
Life in hours calculated analytically and compared to the values obtained in nCode for case 1.

	Analytical allowable creep rupture time (hrs.)	nCode allowable creep rupture time (hrs.)
Load Only	$1.155x10^5$	$1.162x10^5$
Basic Cycle	$2.772x10^5$	$2.775x10^5$

Life in hours calculated analytically and compared to the values obtained in nCode for case 2.

Nonaxisymmetric Creep-Fatigue Modeling

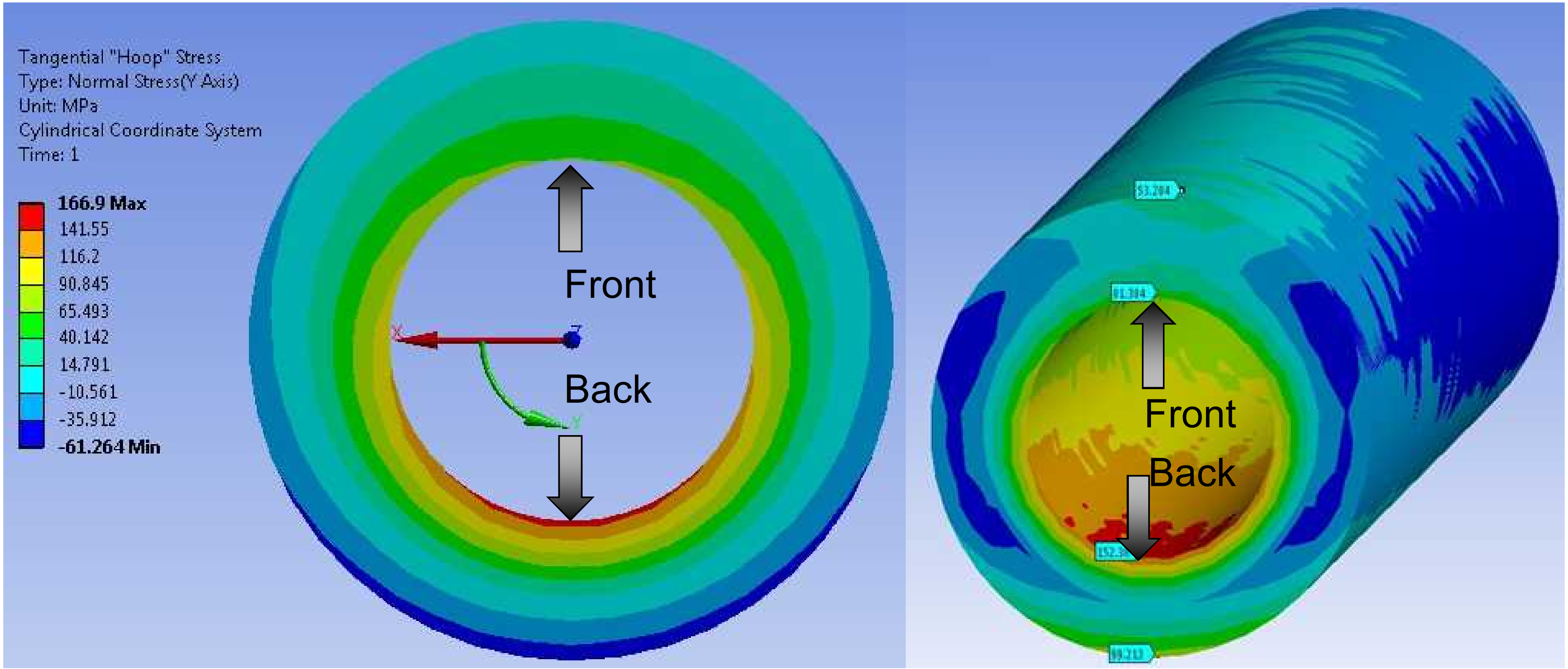
Applied Heat-Flux



Temperature distribution along the tube for ~700 kW/m^2 irradiance (Case 2).

Temperature distribution along the tube with a cross-sectional cut along the region with highest temperature (Case 2).

Creep-Fatigue Results



Point of interest	Temperature (K)	Equivalent Stress (MPa)
Front	993.15	81.15
Back	863.15	152.4

Analytical Creep-Fatigue Results

Point of interest	Allowable creep rupture time (Inner Wall) (hrs.) T_d	Creep Damage (Inner Wall) t/T_d	Fatigue Damage (Inner Wall) n/N_d	Total Damage (Inner Wall) D
Front	109,525	0.913	0.1	**1.013**
Back	1.246×10^7	0.008	0.1	**0.108**

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Conclusions

- By completing this work, the possibility of a high temperature and high pressure supercritical carbon dioxide has been confirmed.
- The static structural FEA was validated using the analytical formulations presented. As a result, a more complex thermal-structural FEA was performed. This method allows the designer to focus on the weaker sections of the receiver and adjust accordingly to the concentration levels that the receiver will be exposed to. This new method of coupling will help to estimate the life of the new generation of solar thermal receiver.

Conclusions

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- Currently, there are no other published studies analogous to this one for solar thermal receivers. This work will serve as reference for future design and evaluation of future direct and indirect tubular receivers.
- This methodology is geometry independent, so any type of structures could be analyzed by applying the corresponding boundary conditions and constraining the analyses appropriately.

Future Work

- Since Fluent results cannot be coupled to nCode, we have been looking into adding a script on ANSYS Structural to evaluate creep and fatigue directly. This could be done since the creep and fatigue are evaluated using the nodal information (i.e. temperature, stress etc..) directly.
- Complete the design of the receiver using headers.

Reference

- 1. **Dostal V.**, "A supercritical carbon dioxide cycle for next generation nuclear reactors," PhD Thesis, Nuclear Engineering, (2004) Massachusetts Institute of Technology.
- 2. **T. W. Neises, M. J. Wagner, A. K. Gray**, *Structural Design Considerations for Tubular Power Tower Receivers operating at 650 C,* Proceedings of the 8th International Conference on Energy Sustainability (ES2014), Boston, MA, June 30th – July 2nd 2014, ASME Paper No. 6603.
- 3. **X. Chen, M. a. Sokolov, S. Sham, D. L. Erdman III, J. T. Busby, K. Mo, and J. F. Stubbins**, *Experimental and modeling results of creep–fatigue life of Inconel 617 and Haynes 230 at 850° C.*, J. Nucl. Mater. vol. 432, no. 1–3, pp. 94–101, Jan. 2013.
- 5. **Eno, D. R., Young, G. A., and Sham, T.-L.**, 2008, *A Unified View of Engineering Creep Parameters*, Proceedings of ASME Pressure Vessels and Piping Division Conference (PVP2008), Chicago, July 27–31, ASME Paper No. 61129, pp. 777–792.
- 6. **J. D. Ortega, S. D. Khivsara, J. M. Christian, J. E. Yellowhair, C. K. Ho**, *Coupled Optical-Thermal-Fluid Modeling of a Directly Heated Tubular Solar Receiver for Supercritical CO2 Brayton Cycle,* Proceedings of the 9th International Conference on Energy Sustainability (ES2015), San Diego,CA, June 28th – July 2nd 2015


ANY QUESTIONS ?