SAND2017-5149C

Predicting Structural Relaxation in a Glass-to-Metal Seal Connector: How Does Long-Term Storage Affect Performance?

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May 23rd, 2017

Sandia National Laboratories

Exceptional service in the national interest

12^{th} Pacific Rim Conference on Ceramic and Glass Technology

Waikoloa, HI, May 21-26th, 2017

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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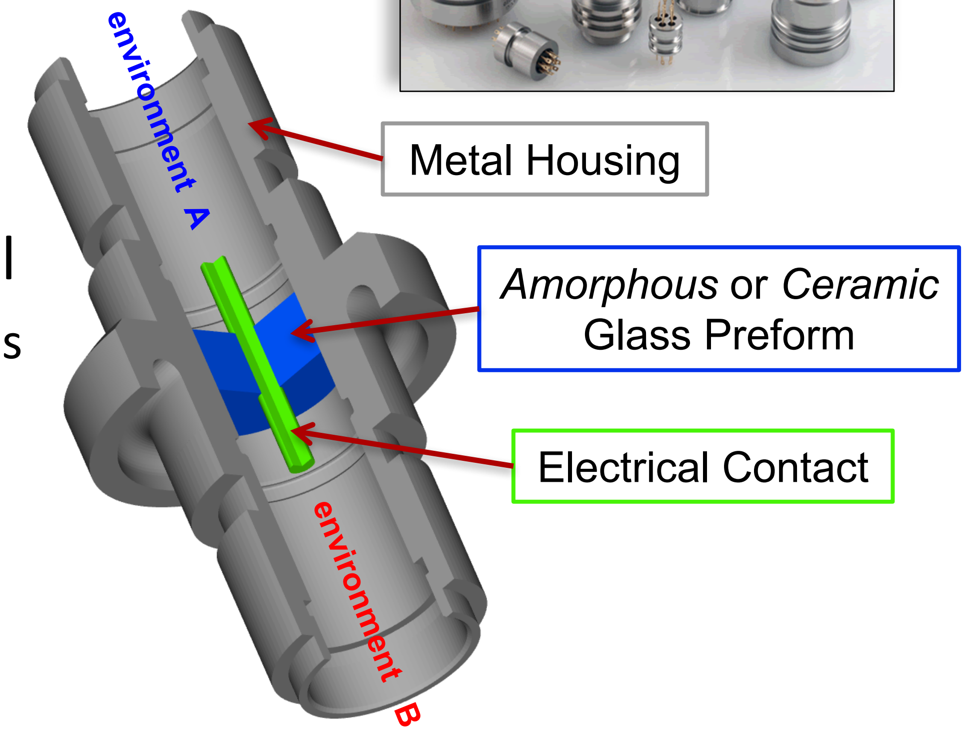
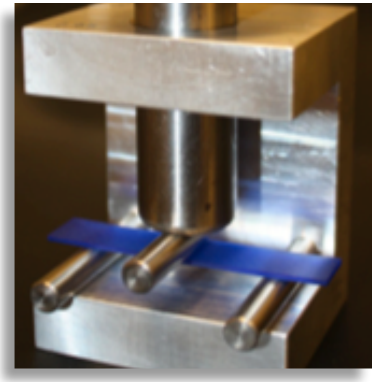
What is a hermetic connector?

- Barrier to gas/liquid transfer between environments.
  - Allow electrical transmission
- Designed for extreme conditions
  - Thermal
  - Pressure
  - Shock/vibration
- Compression glass-to-metal seal
  - Housing CTE >> Glass/Contact CTEs
  - Plastic deformation of metals
  - Long term residual stress in glass



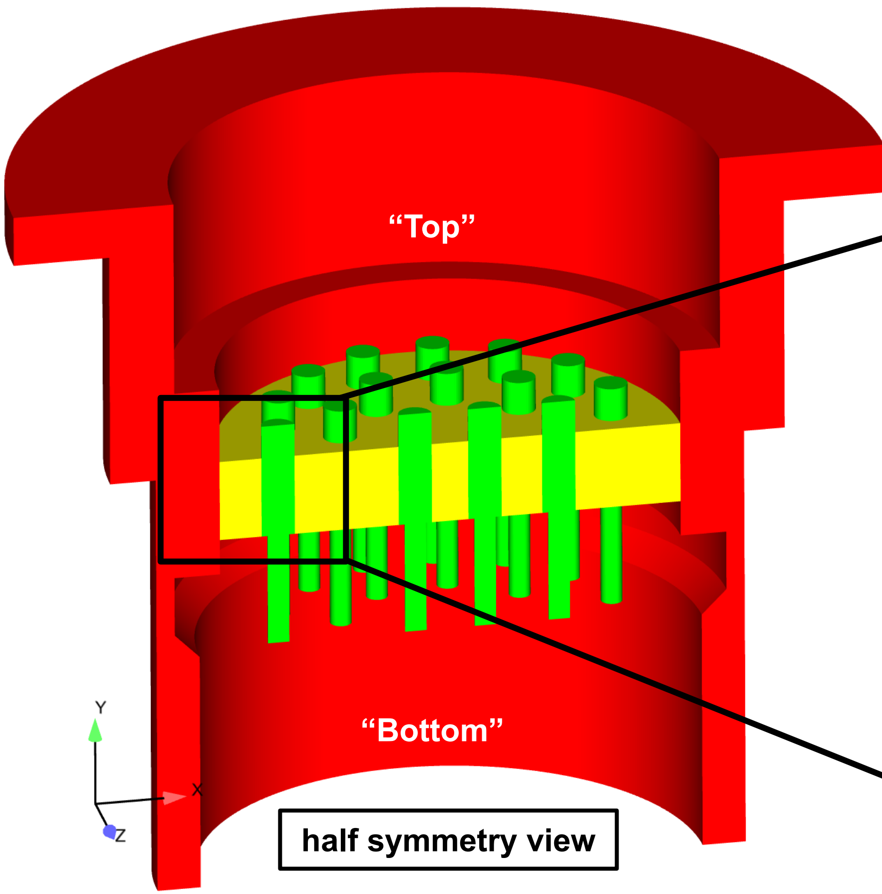
Why Do We Care About Long Term Performance?

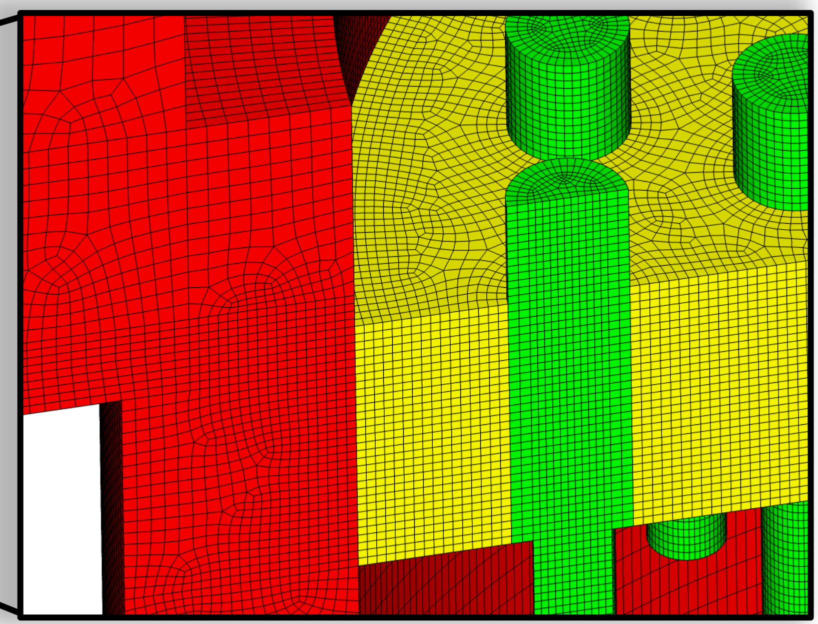
- Connectors must remain hermetic for many years.
  - Once installed, difficult/impossible to replace.
  - Hermetic failure of a connector may fail entire systems.
- Testing parts years after manufacturing is not always possible.
  - Produce extra parts to sit on shelf, test fielded connectors, etc.
  - Want to know NOW if design needs a *re*-design.
- Recent 3-pt bend tests on glass coupons showed measureable creep at room temperature after 6 months.
  - ***Can glass aging effect residual stress at longer times?***



Hermetic Seal FEA Model

RED – 304L Shell
YELLOW – Inorganic sealing glass
GREEN – Alloy 52 Pins





compression seal
- 304L: 17 ppm / °C
- Glass: 10-11 ppm / °C
- Alloy 52: 10-11 ppm / °C

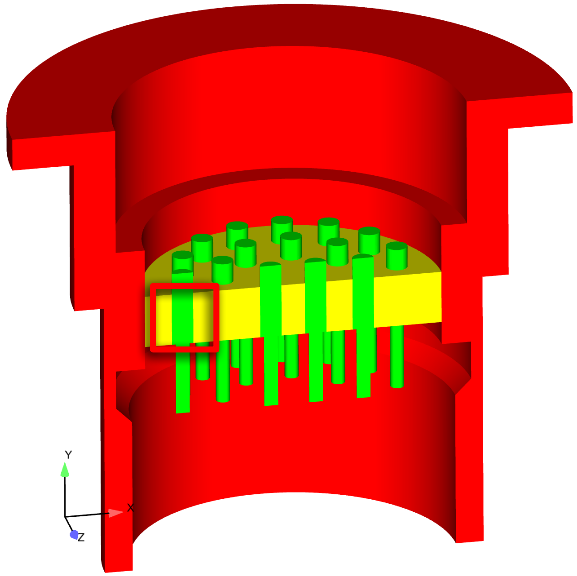
- no glass menisci or pin details
- simplified shell (no threads, rounds, chamfers)
- contiguously meshed interfaces
- uniform temperature boundary condition

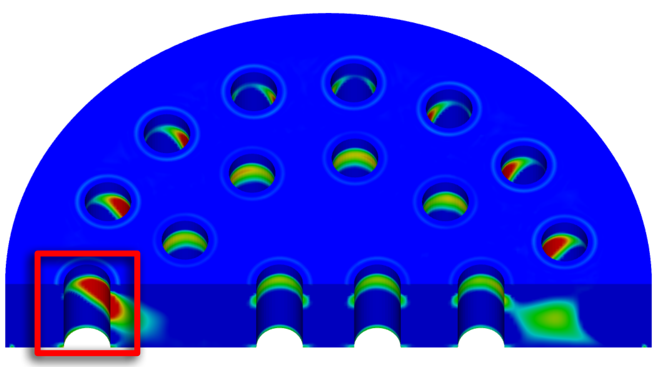
Material Constitutive Models

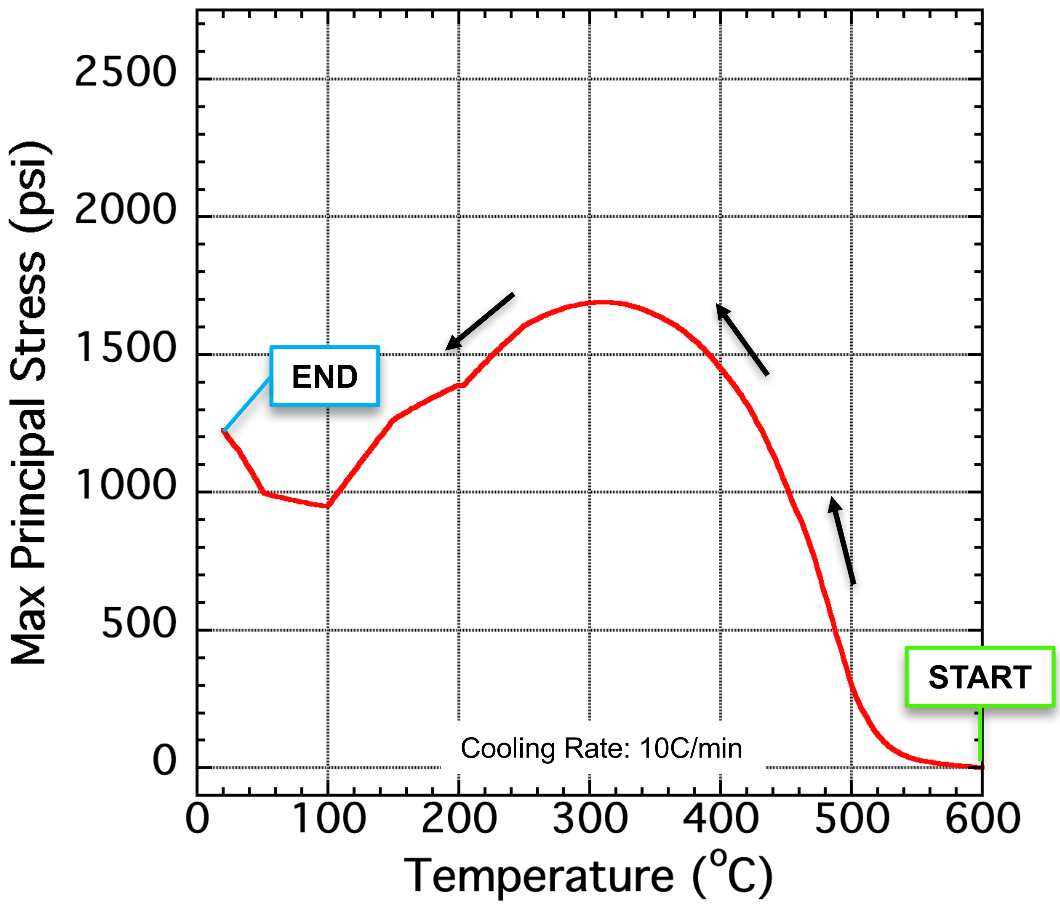
- Inorganic sealing glass, alkali–barium–silicate (viscoelastic)
  - Simplified Potential Energy Clock (SPEC) Model [1]
  - Predicts behavior of thermorheologically simple materials
    - Thermosets [2], thermoplastics, elastomers, and inorganic glasses [3]
    - stress relaxation, physical aging, creep
- 304L (viscoplastic)
  - Bammann, Chiesa, Johnson (BCJ) Model [4]
  - Rate/temperature dependent yield, hardening, and post yield creep
- Alloy 52 Contacts (elastic-plastic)
  - Temperature dependent yield and hardening (not rate dependent)

1. Adolf, Douglas B., Chambers, Robert S., Neidigk, Matthew A., "A simplified potential energy clock model for glassy polymers." *Elsevier Polymer* 50 (2009): 4257-4269.
2. Adolf, Douglas B., Chambers, Robert S., Caruthers, James M., "Extensive validation of a thermodynamically consistent, nonlinear viscoelastic model for glassy polymers." *Elsevier Polymer* 45 (2004): 4599-4621.
3. Chambers, Robert S., Tandon, Rajan, Stavig, Mark E., "Characterization and calibration of a viscoelastic simplified potential energy clock model for inorganic glasses." *Elsevier Journal of Non-Crystalline Solids* 432 (2016): 545-555.
4. Bammann, D. J., M. L. Chiesa and G. C. Johnson, "Modeling Large Deformation and Failure in Manufacturing Processes," Proceedings of the 19th International Congress of Theoretical and Applied Mechanics, ed. T. Tatsumi, E. Watanabe and T. Kambe, pp. 359-376, Elsevier Science Publishers, Amsterdam, 1997

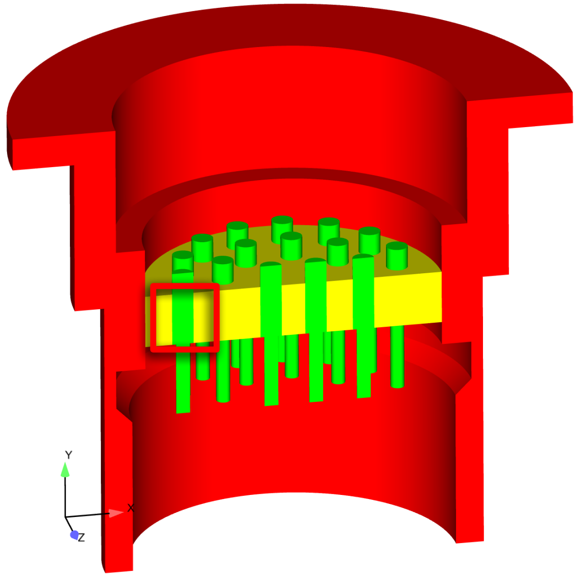
Manufacturing of Compression Seal

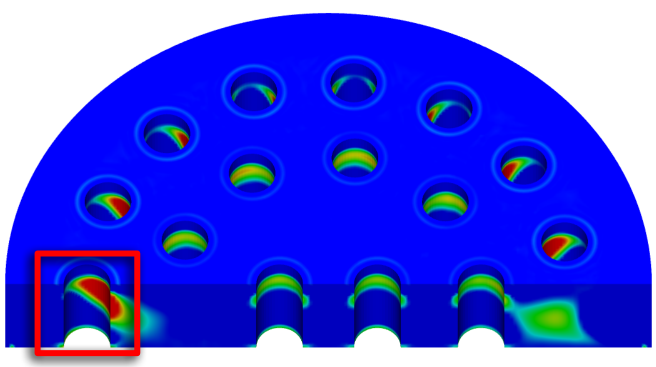


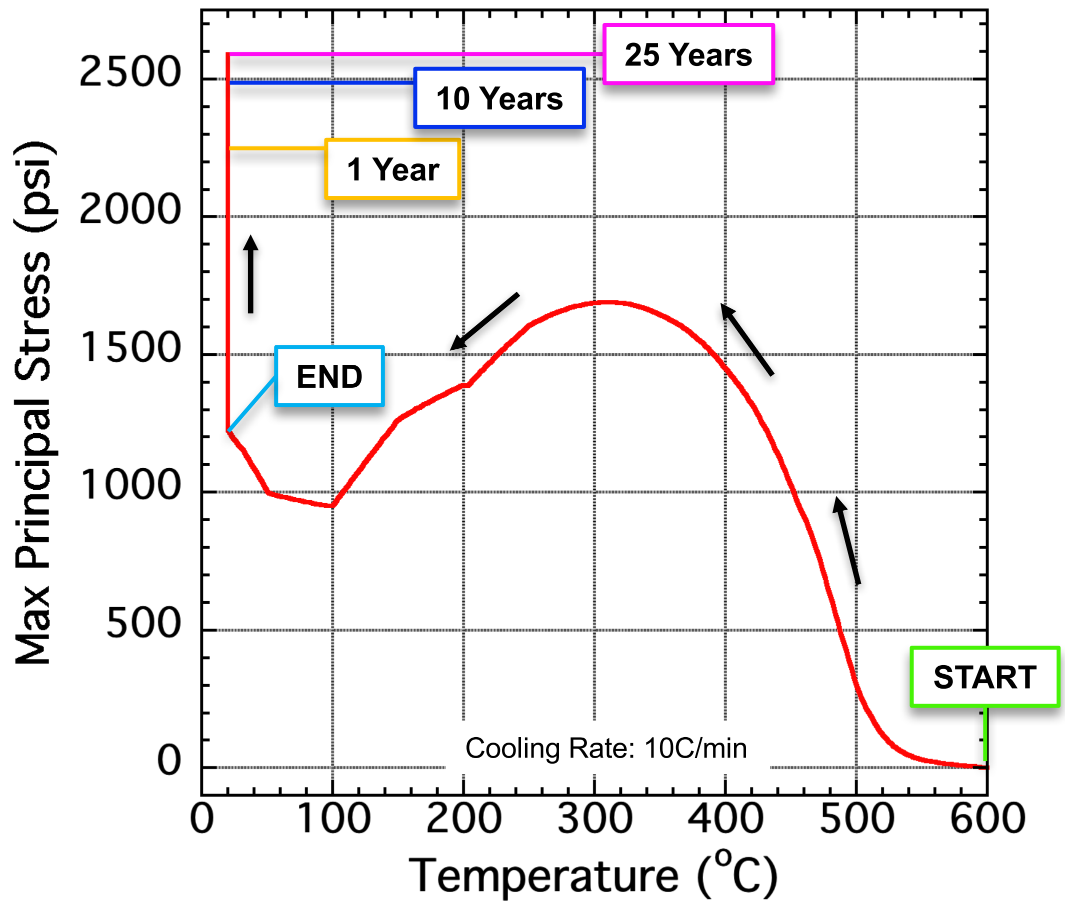




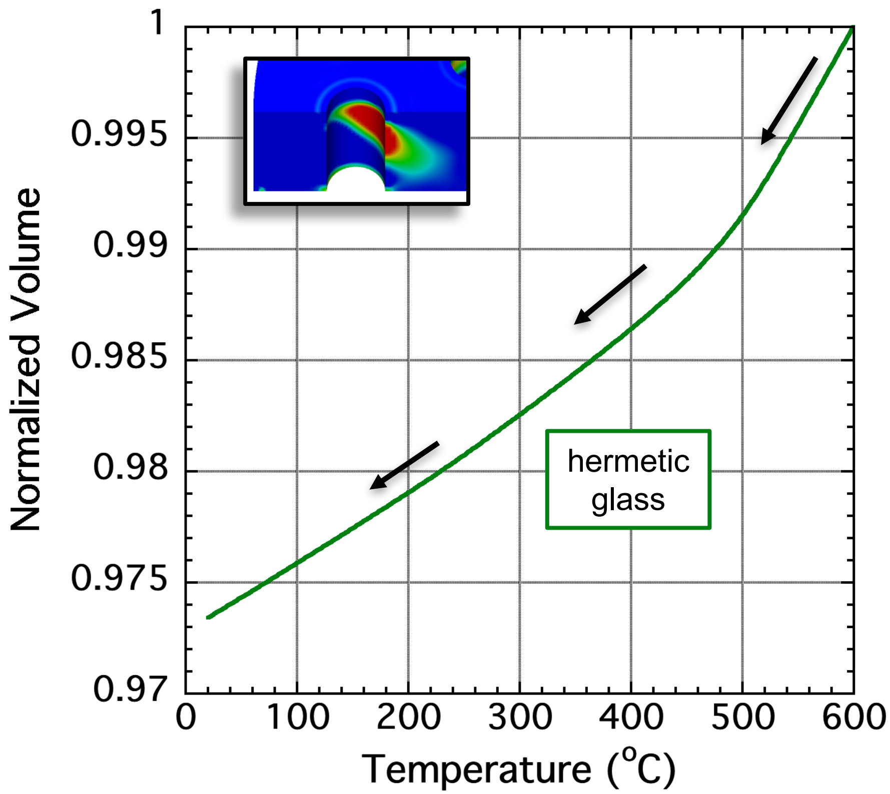
Aging of Compression Seal





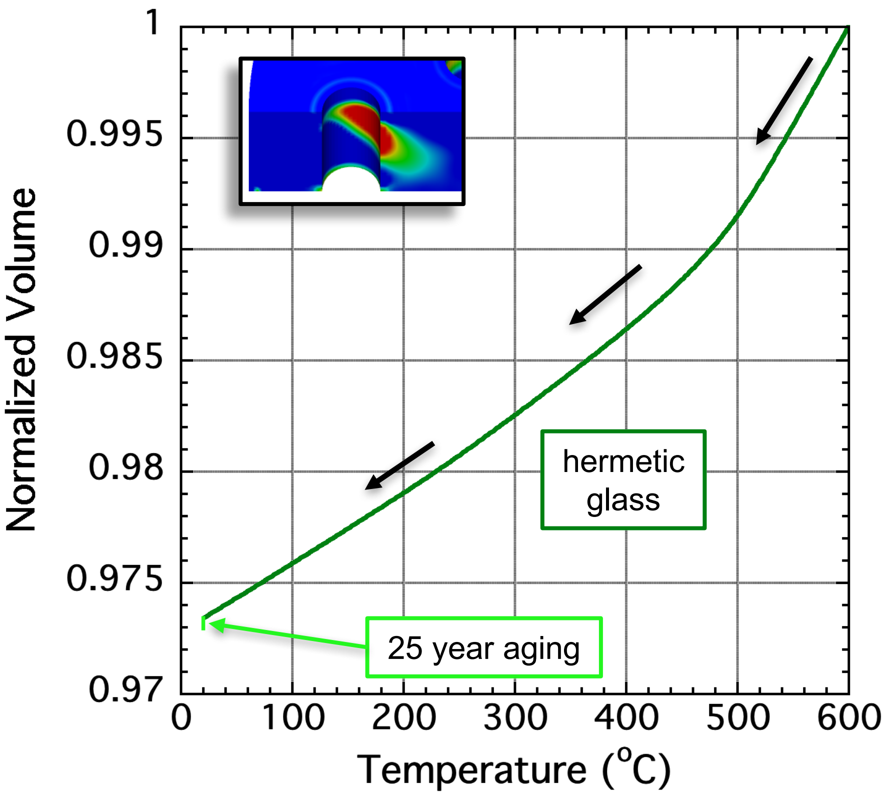


Structural Relaxation During Aging



*Cooling Rate: 10C/min

Structural Relaxation During Aging



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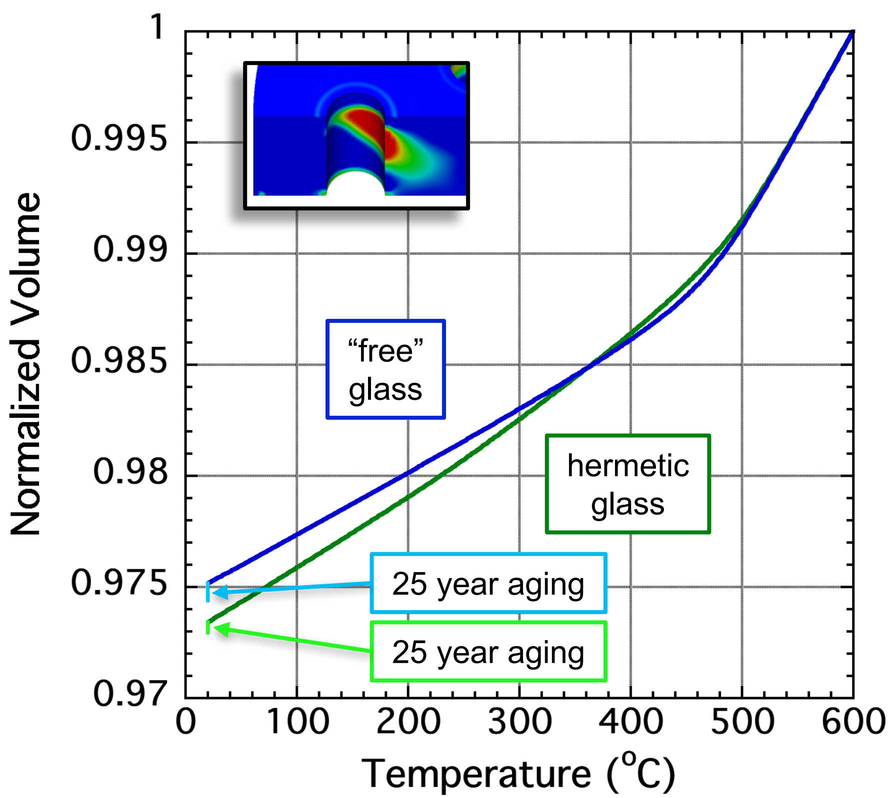

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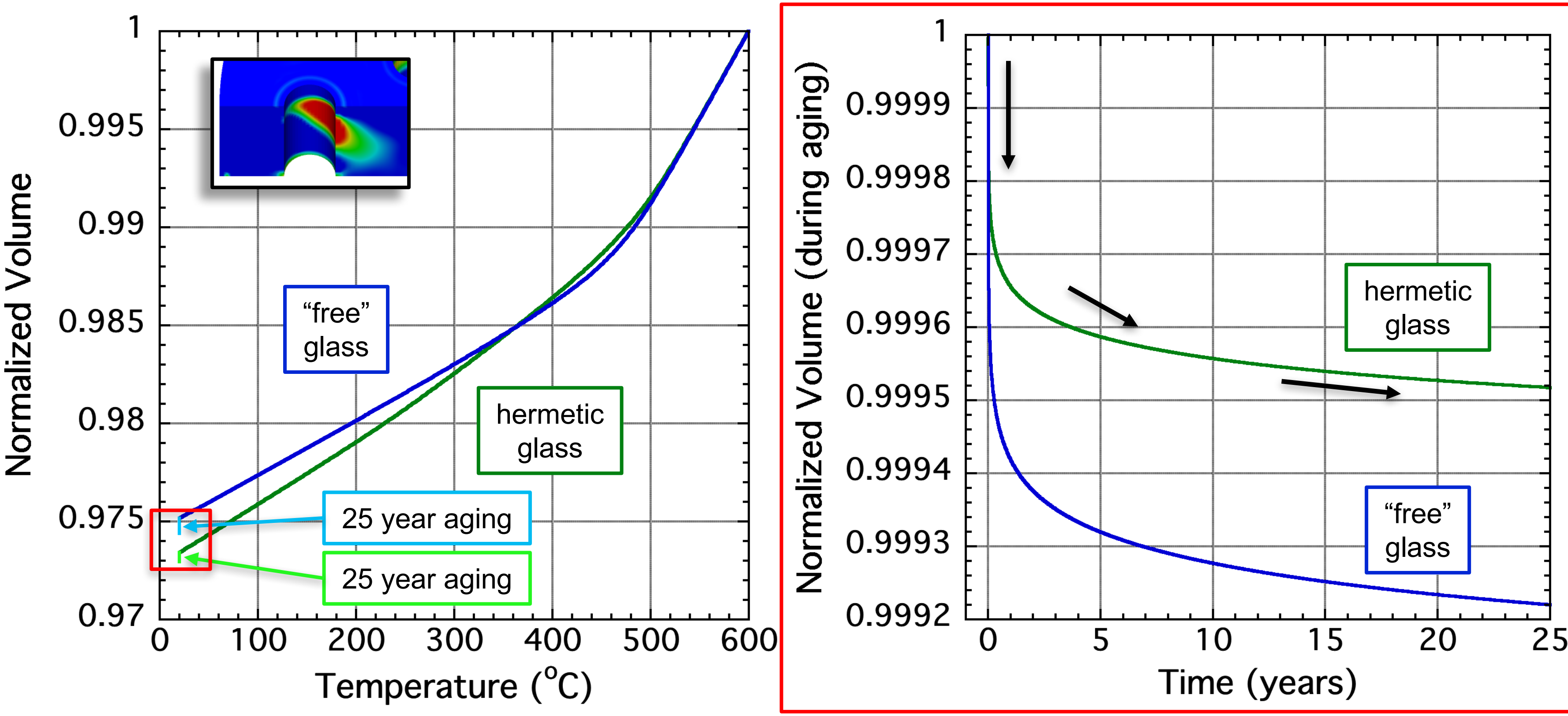

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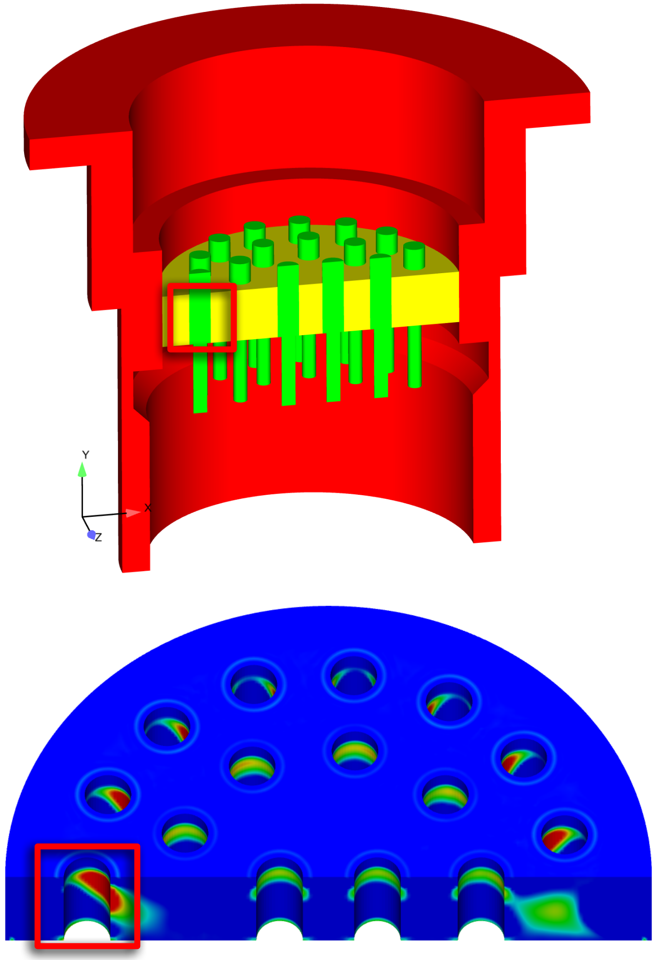
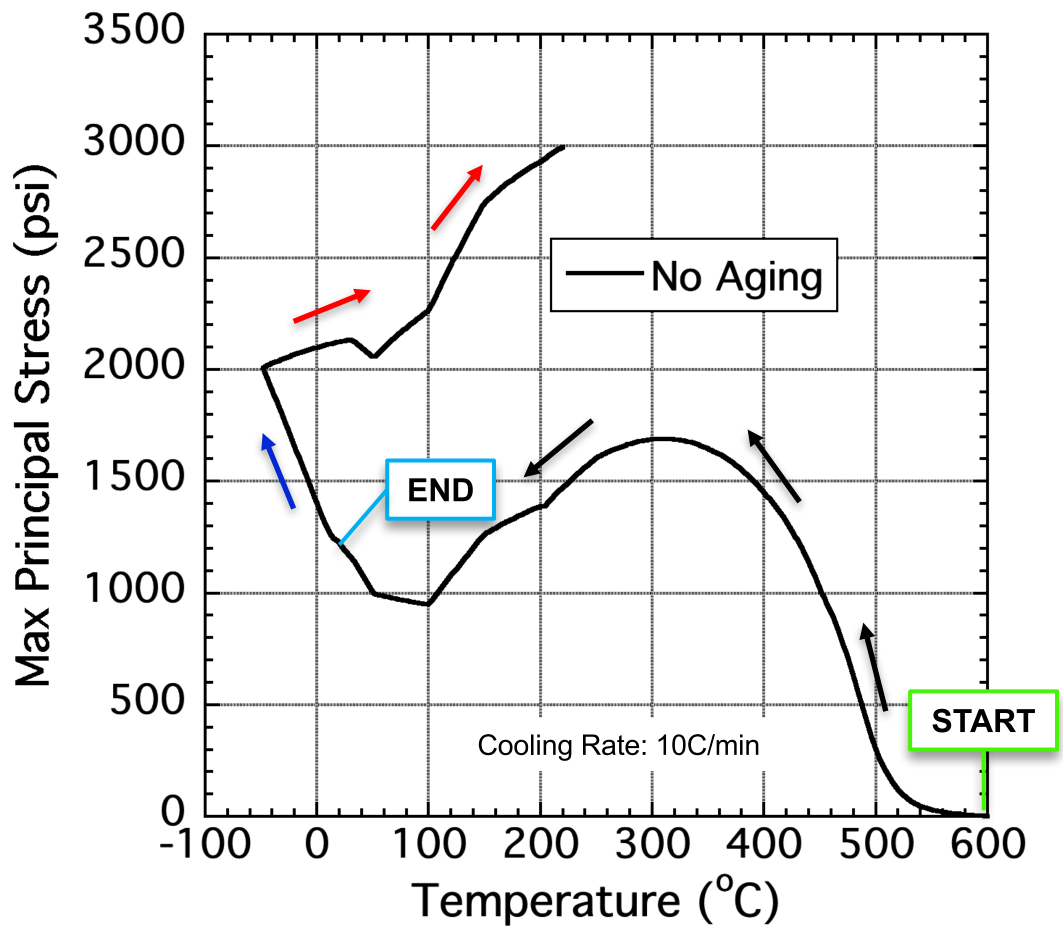
Residual Stress Due to Complex Thermal Histories





3 °C/min thermal cycle: -50 °C → 220 ° C

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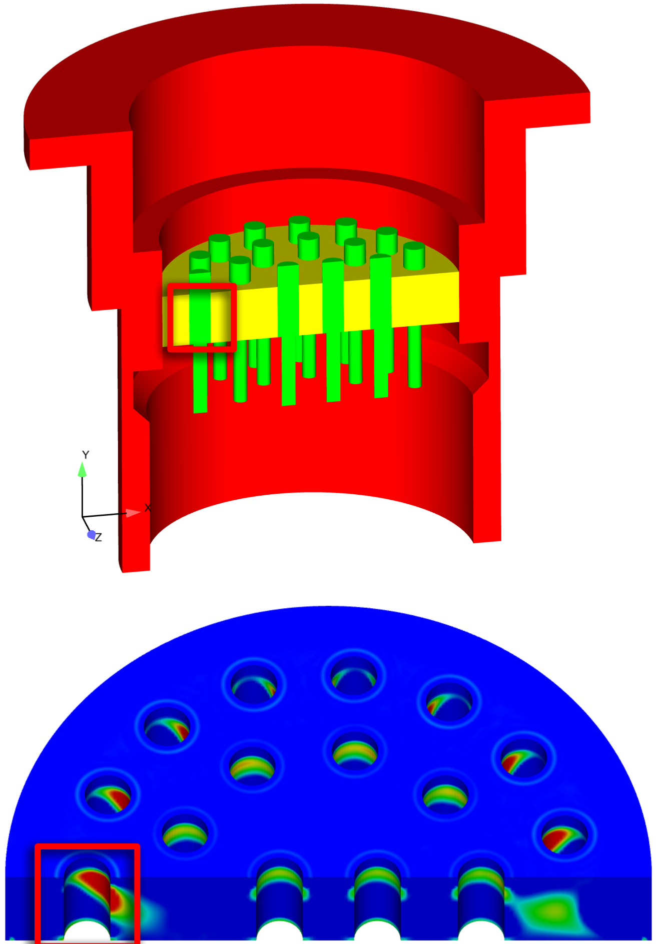

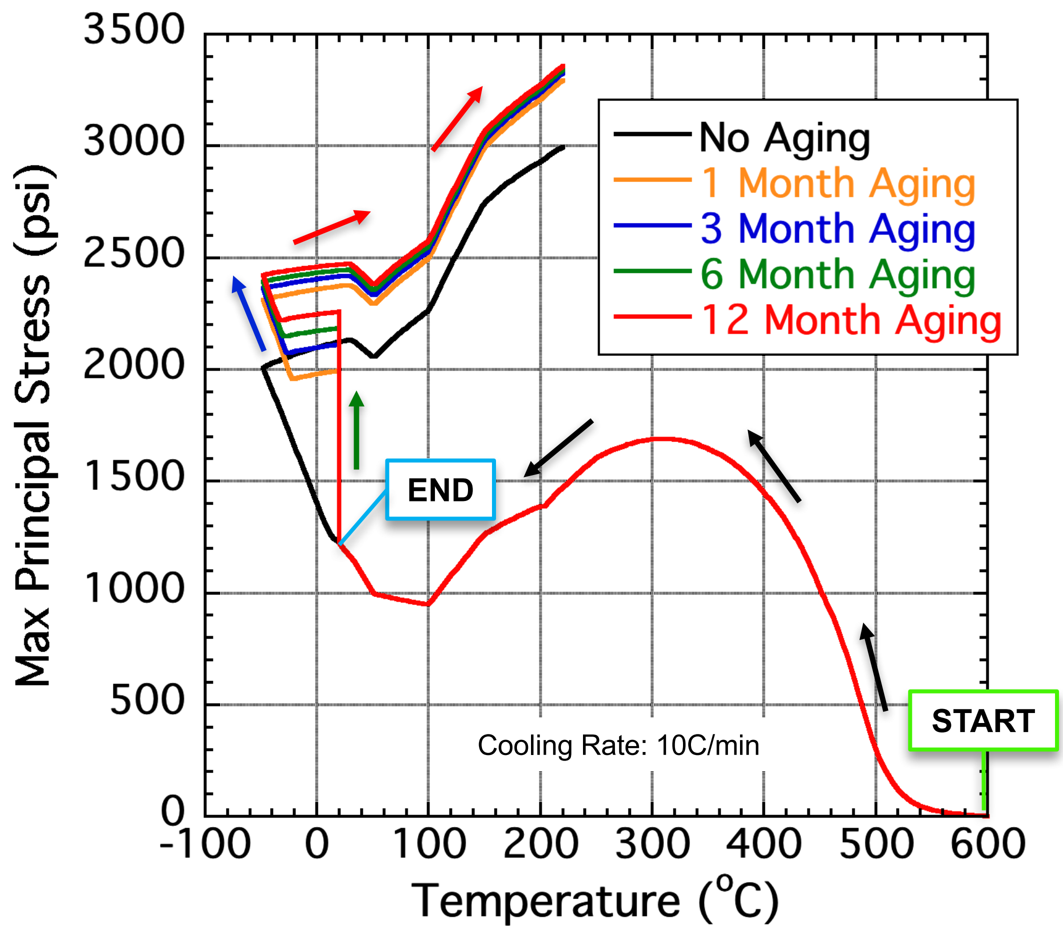

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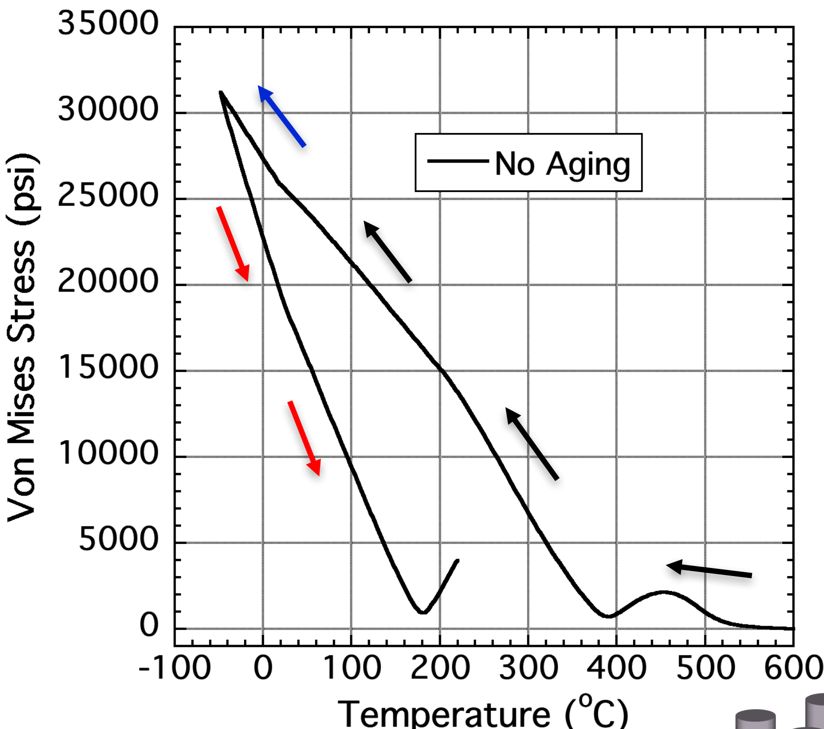

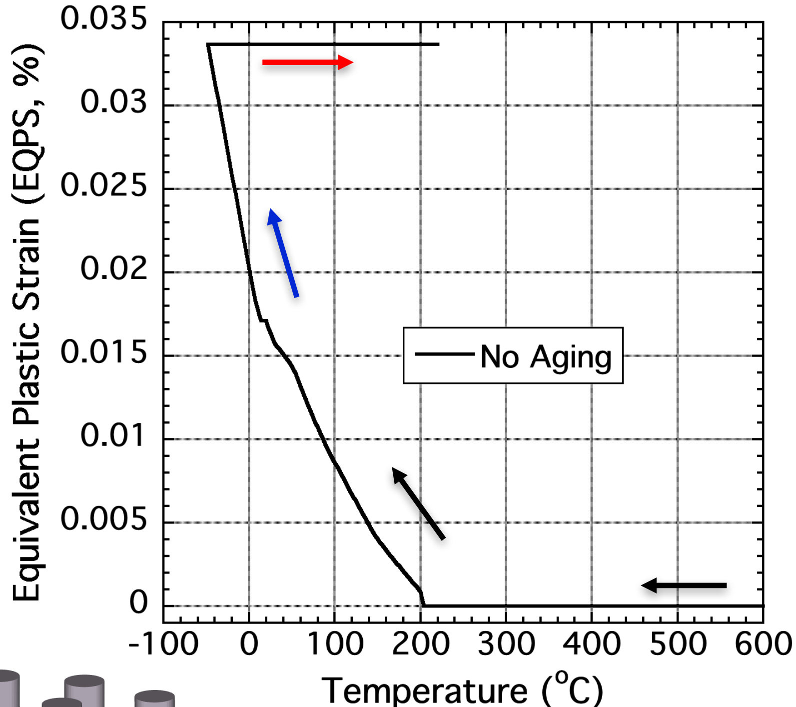

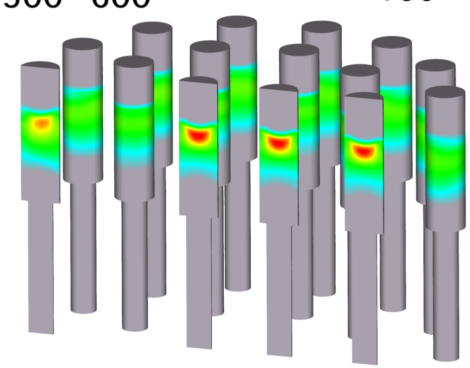

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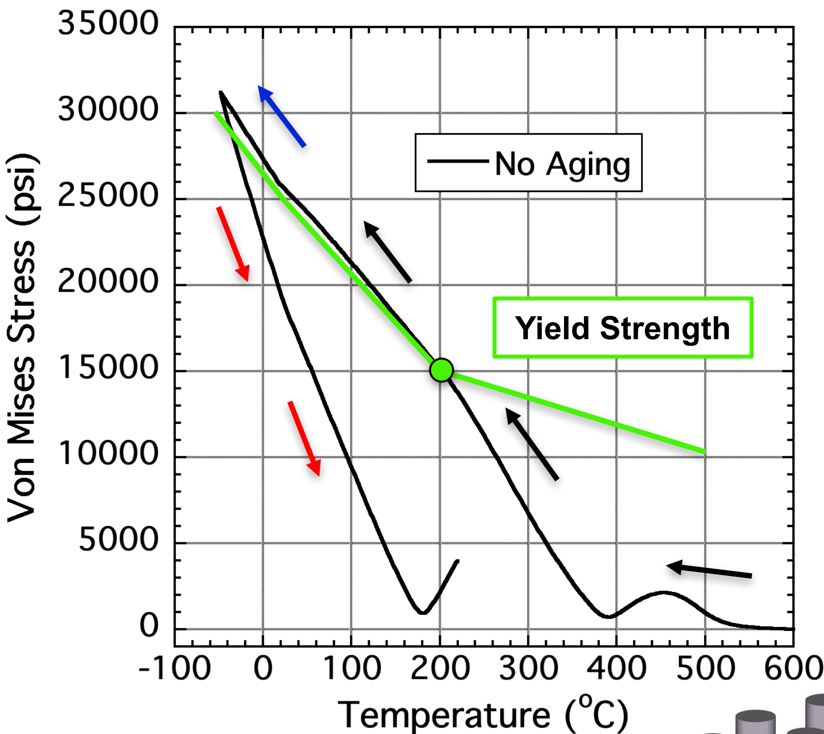

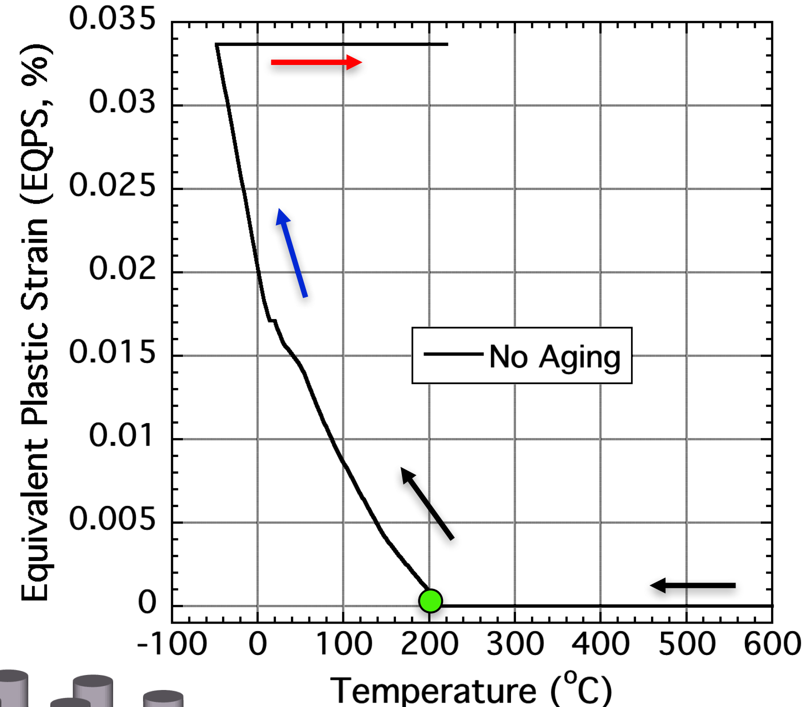

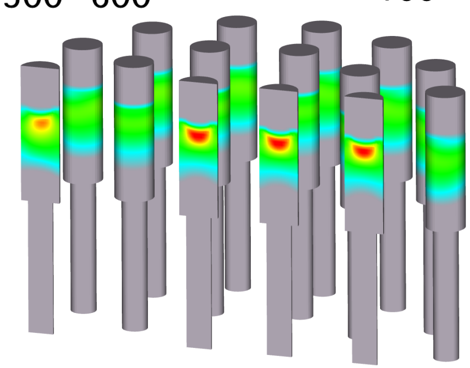

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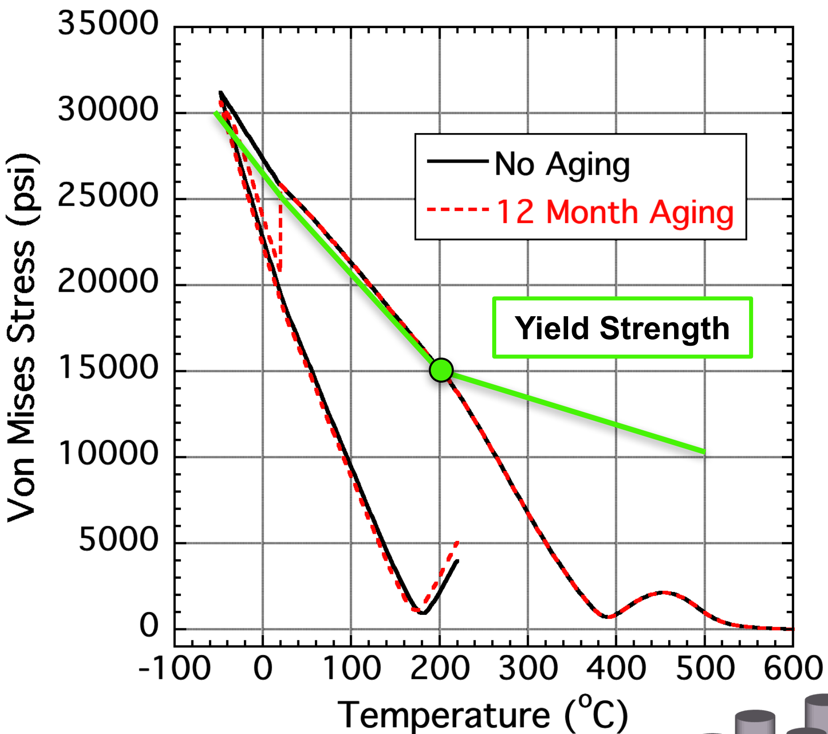
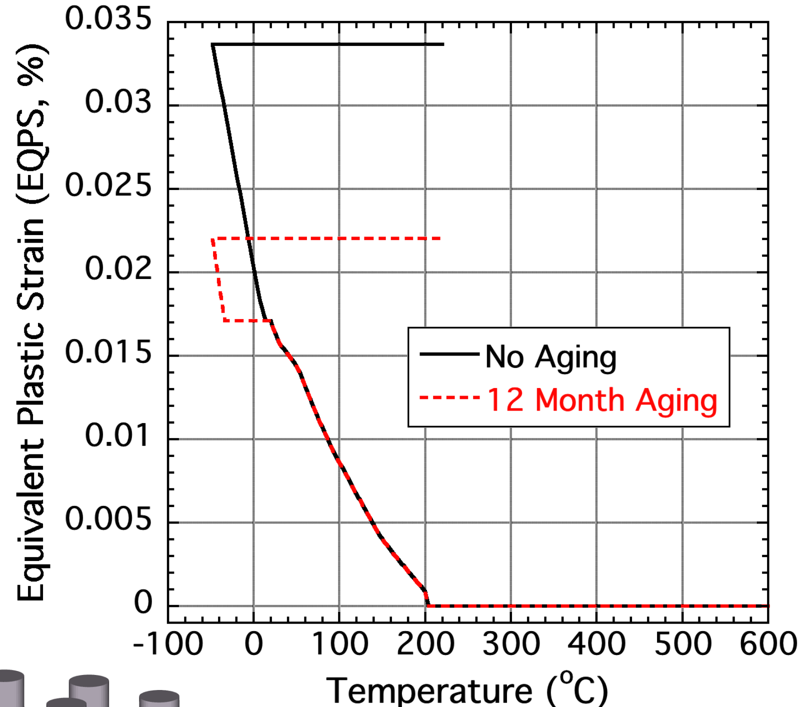
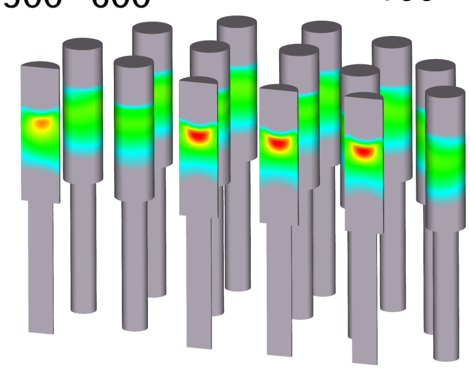






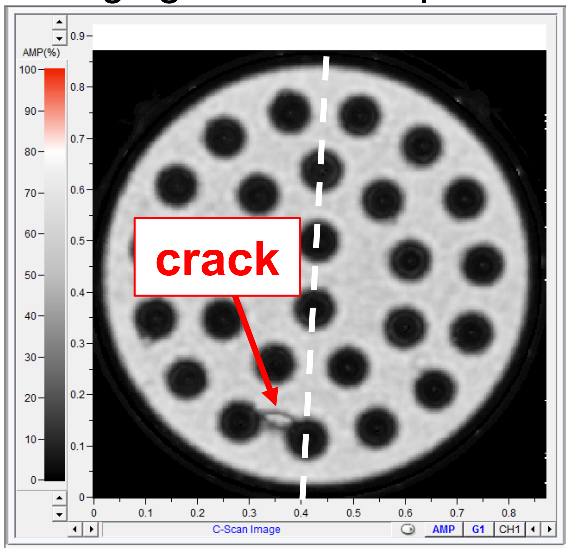
Contact Plastic Strain

Aging Testing

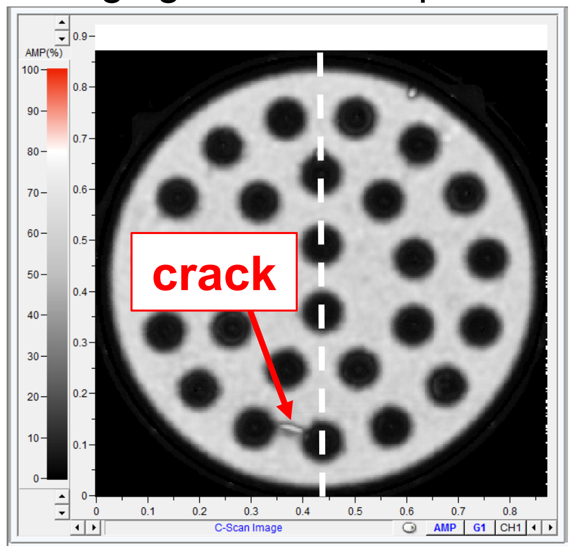
- 10 connectors tested after receiving from supplier
  - Approximately 2 days after manufacturing
- 10 connectors tested 6 months after receiving
- 10 cycles, then ultrasonic scan through glass thickness
  1. -50 °C → 150 °C
  2. -50 °C → 180 °C
  3. -50 °C → 200 °C
  4. -50 °C → 220 °C (oven low/high limits)
- 10/10 connectors tested shortly after receiving did not crack after all thermal cycles.
- 7/10 shells tested 6 months after receiving did not crack after the cycles.
  - **3/10 cracked after the -50 °C → 220 °C thermal cycles.**

Ultra Sound after 220 °C cycle

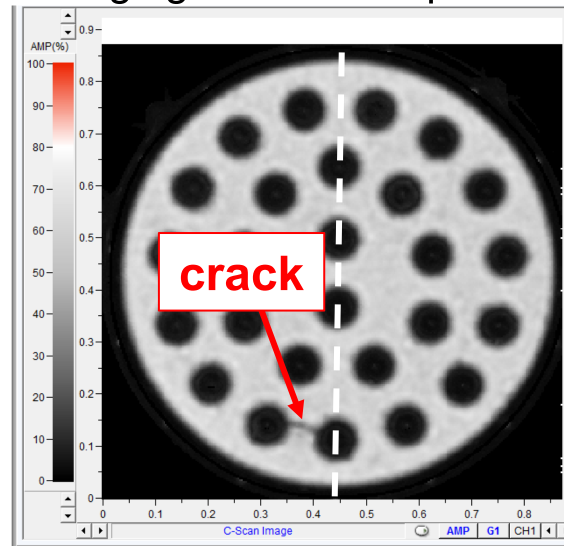
Imaging at Crack Depth #1

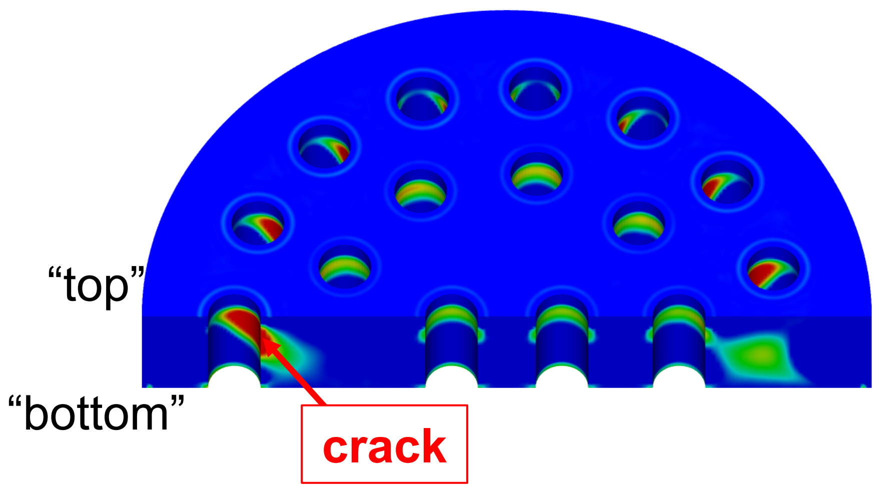


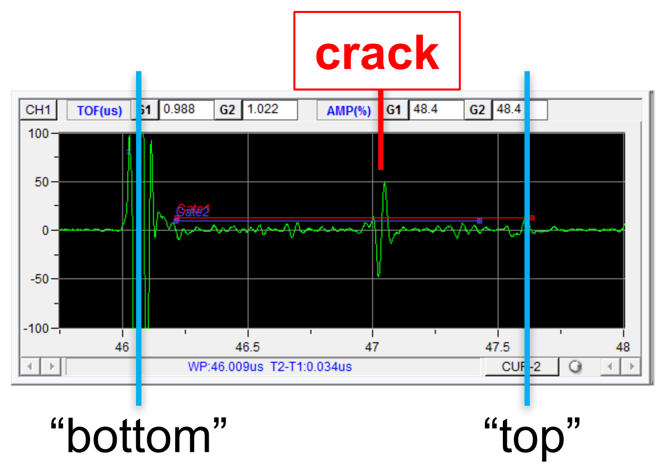
Imaging at Crack Depth #2



Imaging at Crack Depth #3







Conclusion

- Glass structural relaxation is predicted to occur far below T_g.
- FEA predictions and data suggest that even short amounts of time may be changing the stress state of the hermetic seal.
  - May stabilize quickly…application dependent? TBD!
- Competing effects (glass relaxation and metal plasticity) make for a non-intuitive residual stress after aging.
- More experiments are necessary to validate long term aging predictions of the SPEC model.
  - FEA can help determine what experiments will be most useful.
- FEA model predicted the location of crack initiation.
  - Still working on a failure metric.

QUESTIONS?

References

1. Adolf, Douglas B., Chambers, Robert S., Neidigk, Matthew A., "A simplified potential energy clock model for glassy polymers." *Elsevier Polymer* 50 (2009): 4257-4269.
2. Adolf, Douglas B., Chambers, Robert S., Caruthers, James M., "Extensive validation of a thermodynamically consistent, nonlinear viscoelastic model for glassy polymers." *Elsevier Polymer* 45 (2004): 4599-4621.
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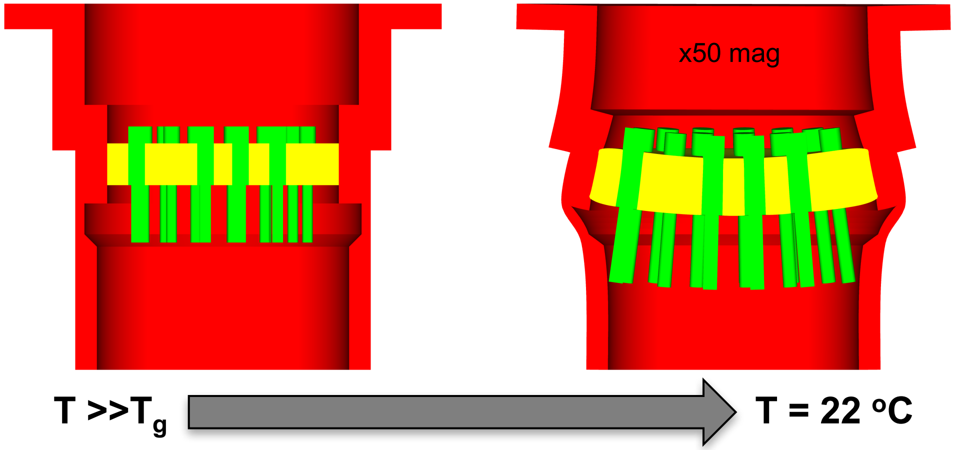
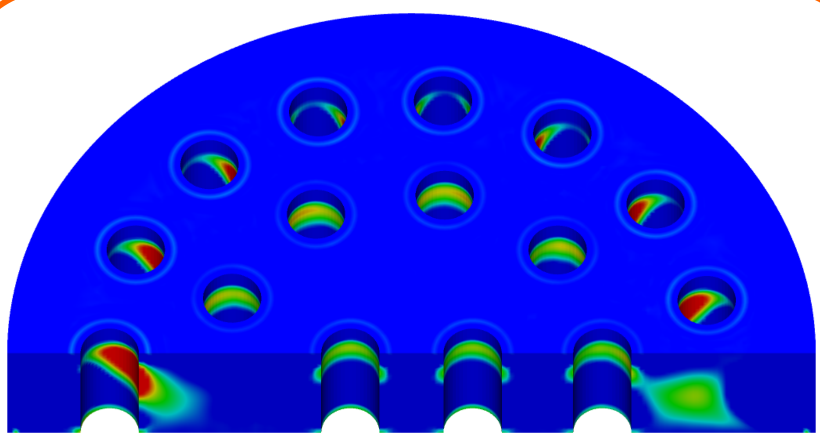
BACKUP SLIDES

Residual Stress from Sealing Process

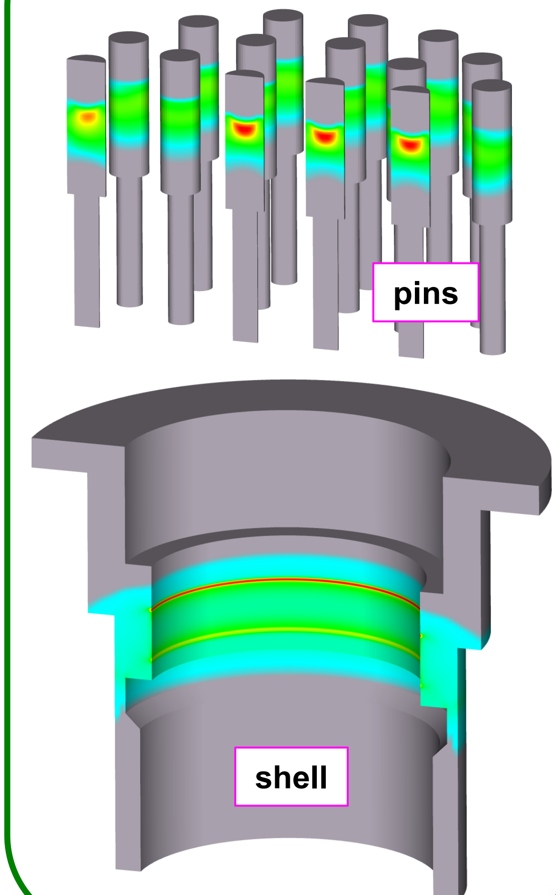
compression during cool down



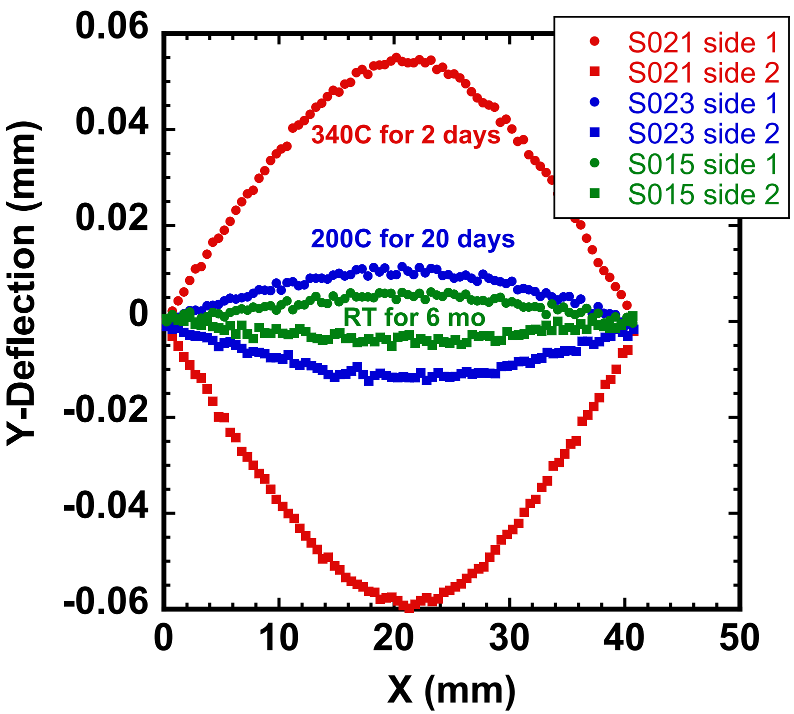


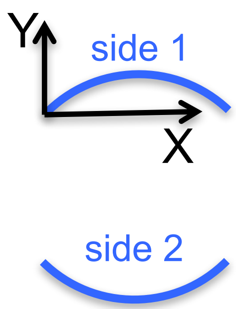
residual tensile stress

plastic strain in metals



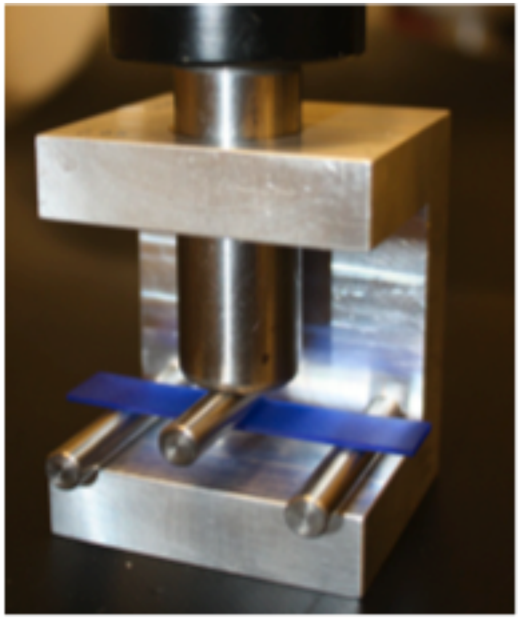
Glass Creep at Room Temperature





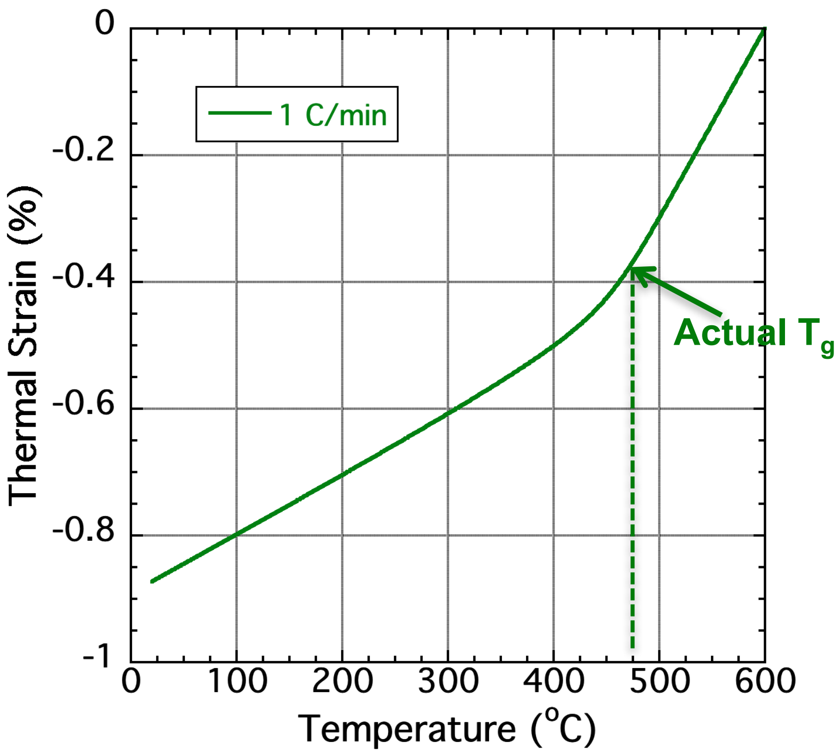
T (°C)	Stress (psi)
340	3500
200	3500
20	4000

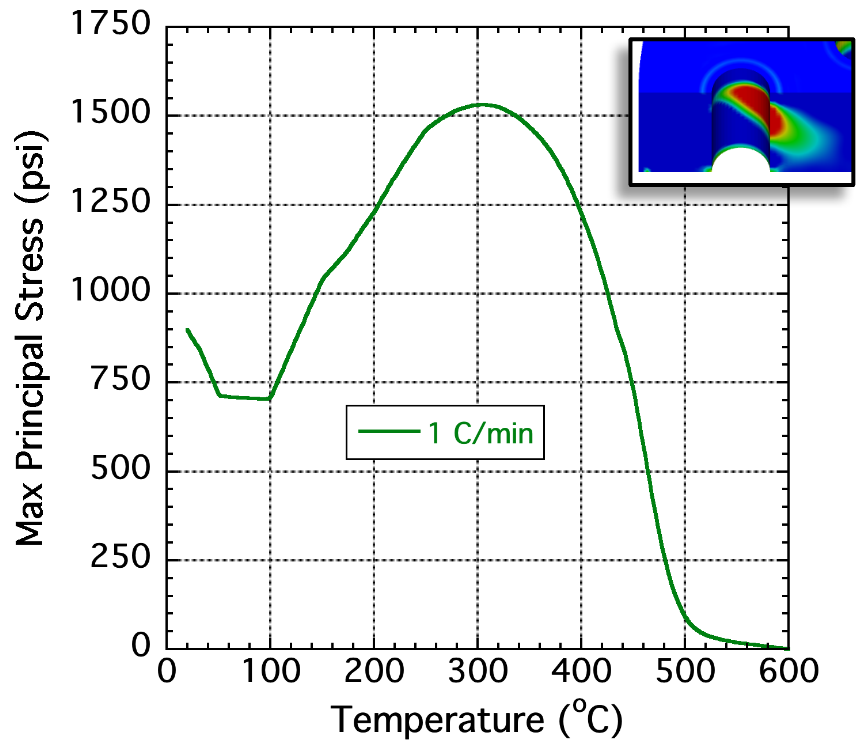
3-Pnt Bending Test
Creep Under Dead Load



. . . . Measurable creep 440°C below glass transition…
So what happens over long periods of time?

History Dependent Predictions





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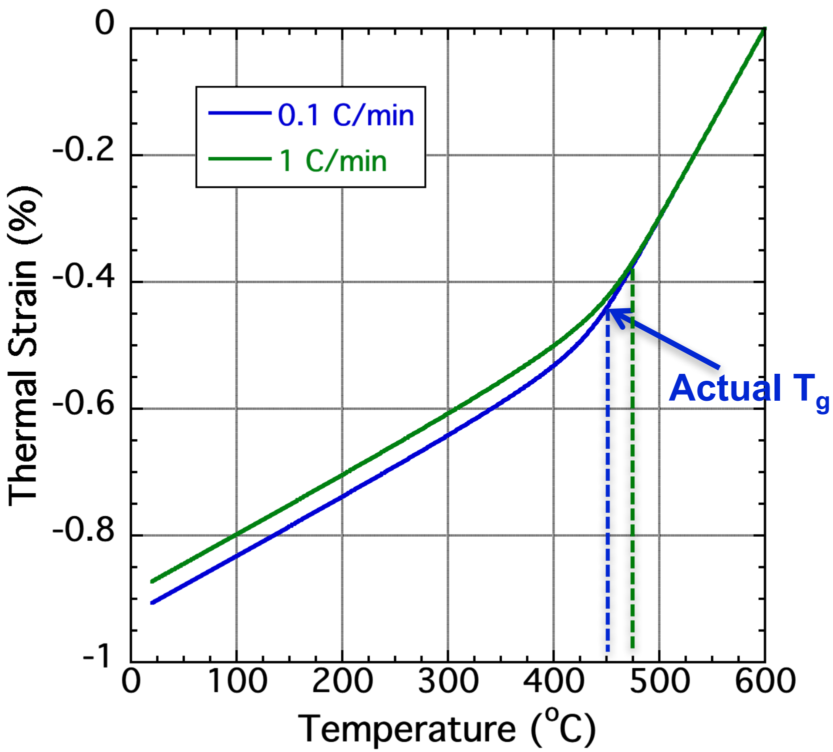

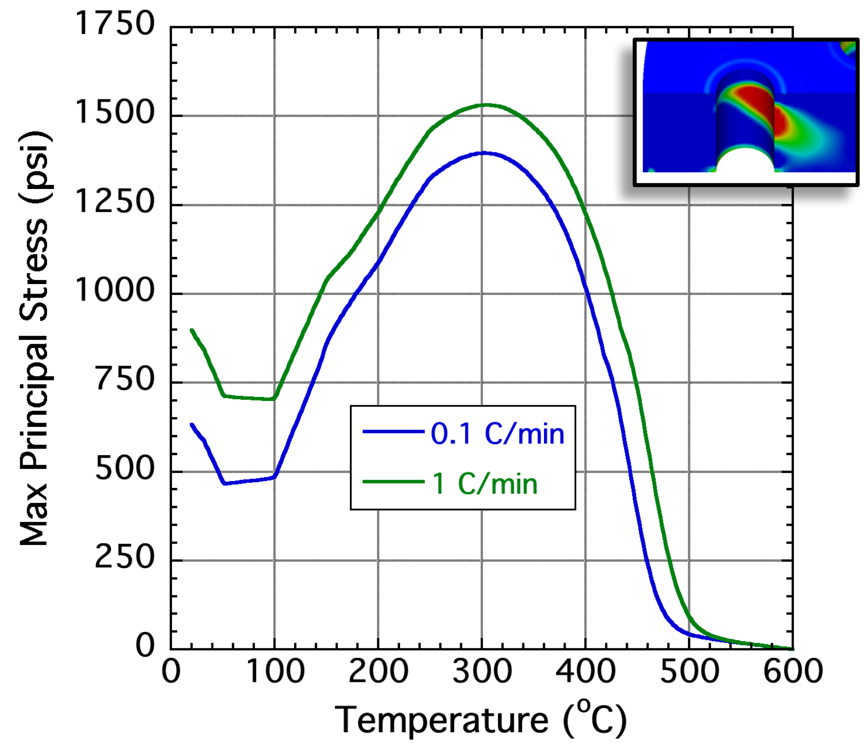

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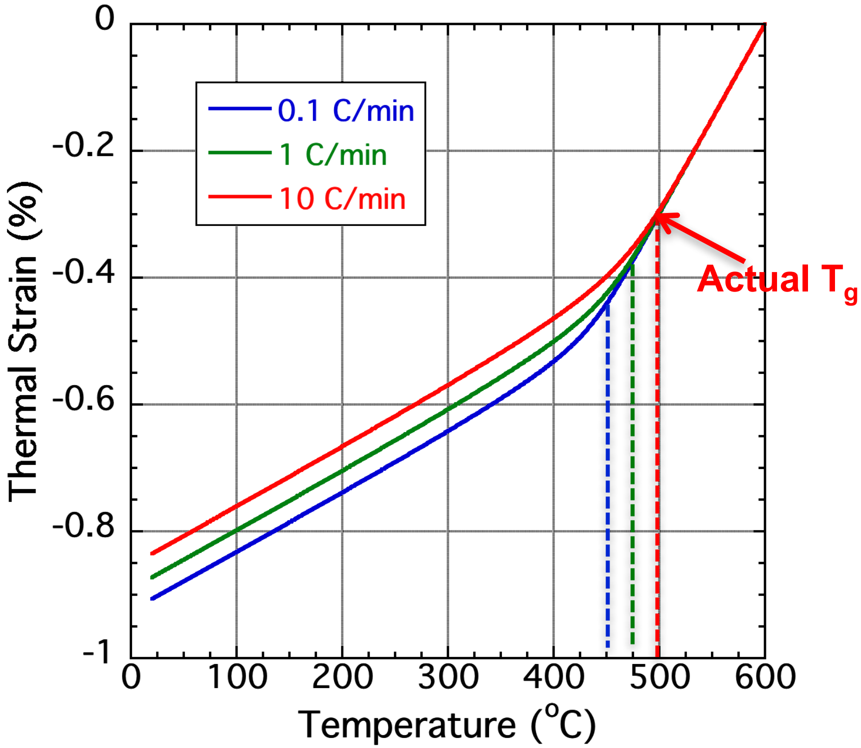
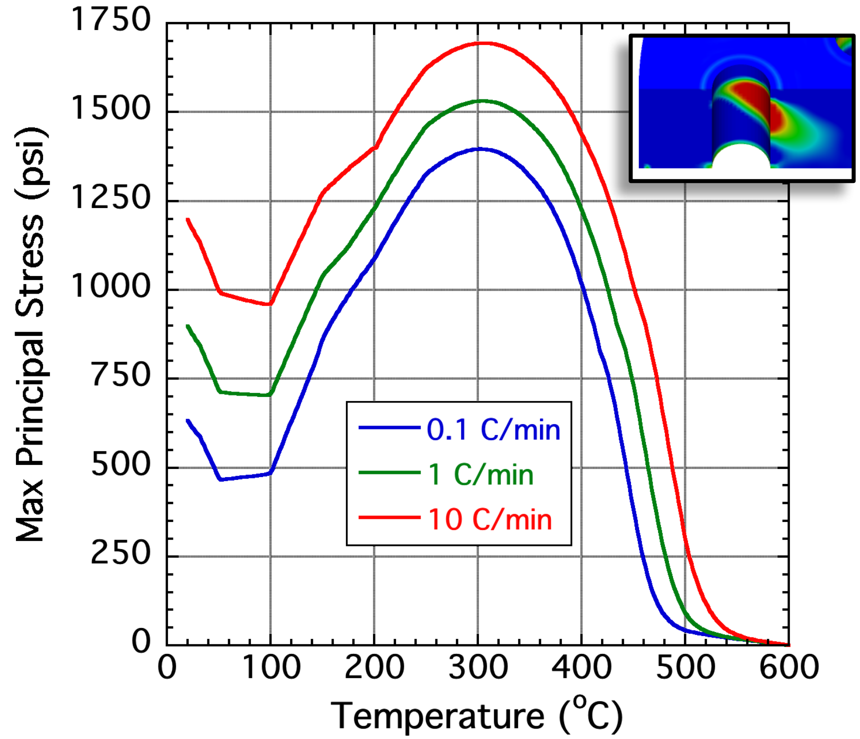
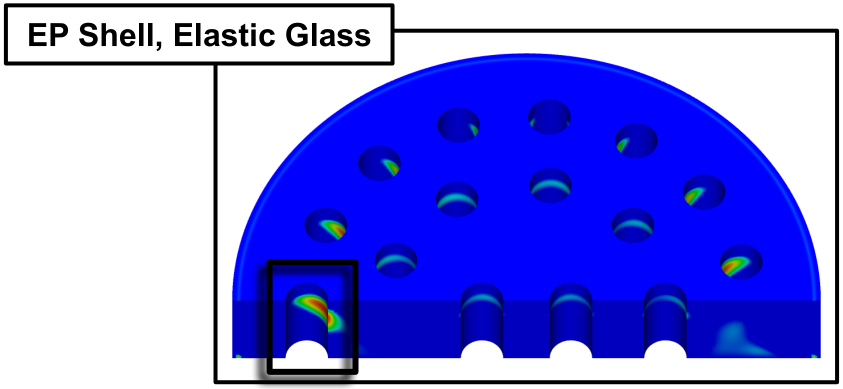
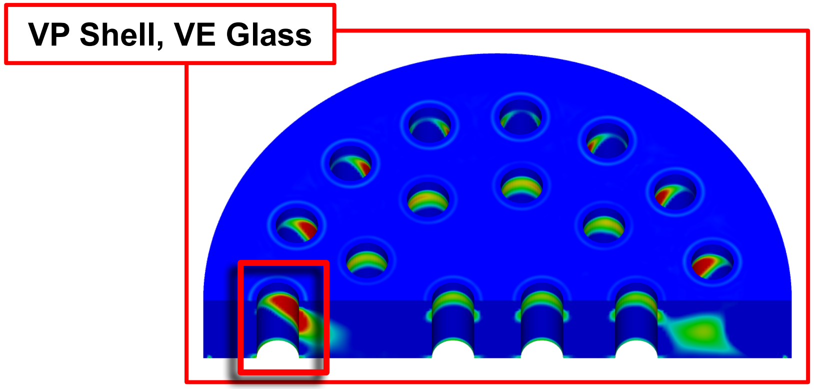
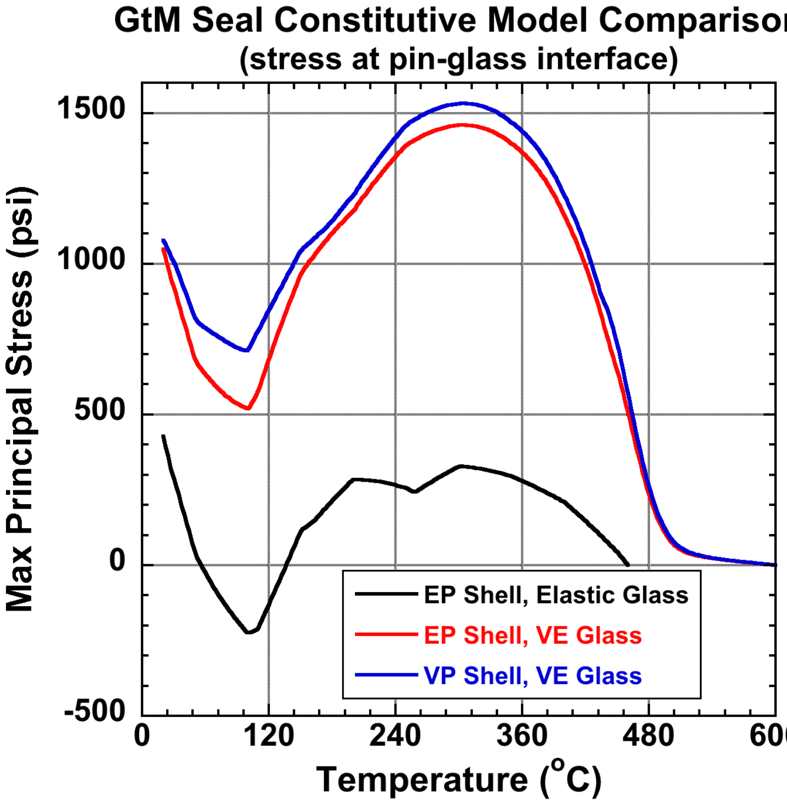




Constitutive Model Comparison







*1 °C/min cooling rate