Impact of Thermal Stress on Wellbore Integrity

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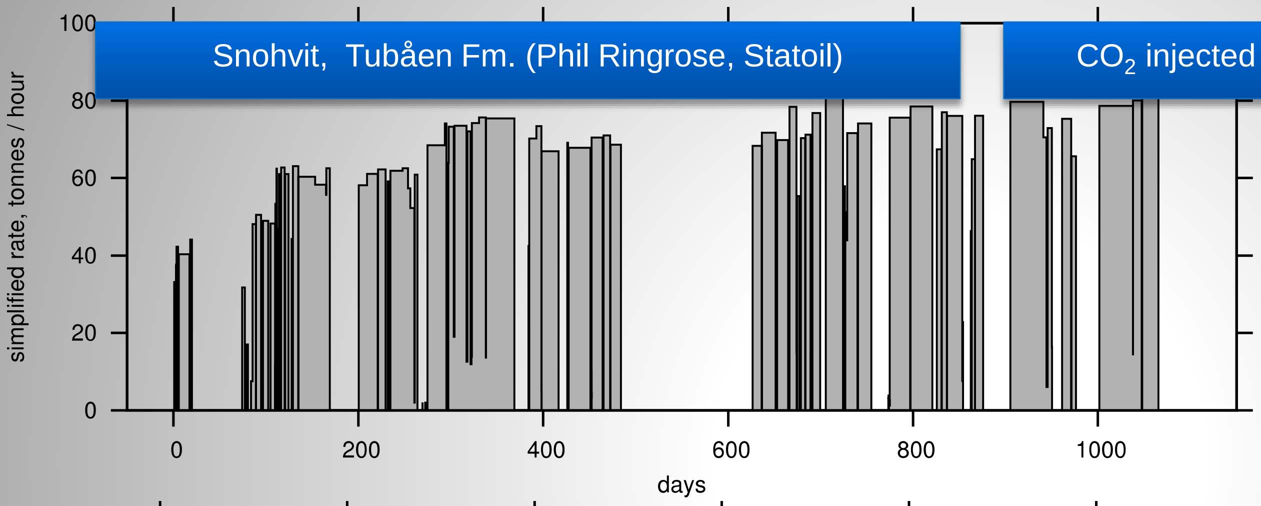
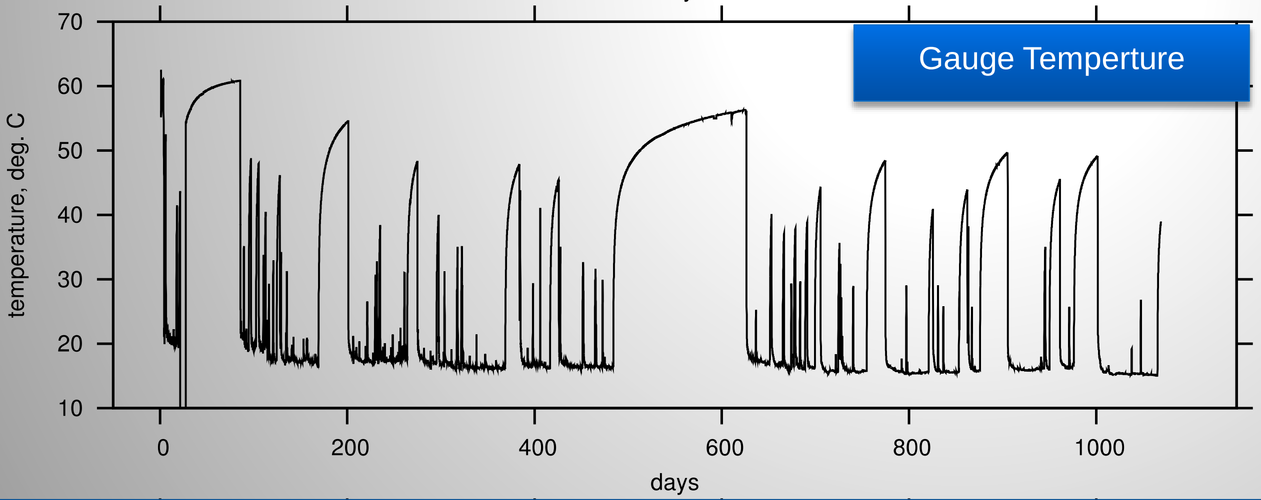
Impact of thermal stresses caused by injection of cold CO_2 into warmer storage reservoirs on wellbore integrity

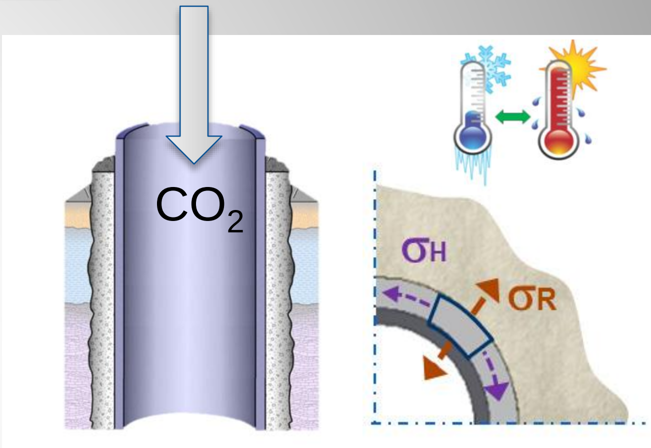


Snohvit, Tubåen Fm. (Phil Ringrose, Statoil)

CO_2 injected



Gauge Temperture



Thermal mismatch between the formation and the injected CO_2 is a potential source of leakage risk

(Malin Torsater, BigCCS, 2015)

Data from Snohvit CO_2 storage project (White et al., 2014)

Project Objective

Assess the impact of thermal stresses caused by injection of CO_2 into storage reservoirs

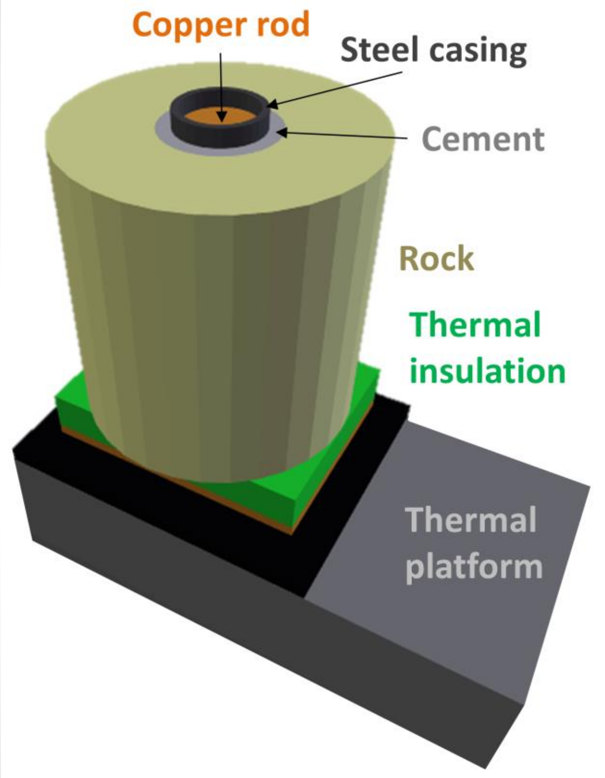
- What is the extent of damage during thermal cycling operations?
- How the thermally induced stresses vary with variation of cooling/heating rates?
- Where the fractures are more likely to appear during thermal cycling operations?
- How to translate the experimental and simulation results into field scale?

Program Goals and Benefits

- This project develops and validates geomechanical computational tools needed to avoid wellbore failure during CO_2 injection.
- Approach
  - GEOS - multi-scale, multi-physics simulator developed at LLNL
  - Wellbore Integrity
    - Update key physics to bound the impact of thermal stresses on well integrity (Completed)
    - Constrain simulations against thermal cycling experiments conducted by SINTEF (Focus of this talk)
    - Apply model to physical conditions reflecting CO_2 operations (Future work)
- Success is defined as determining temperature ranges that yield minimum damage in the wellbore.

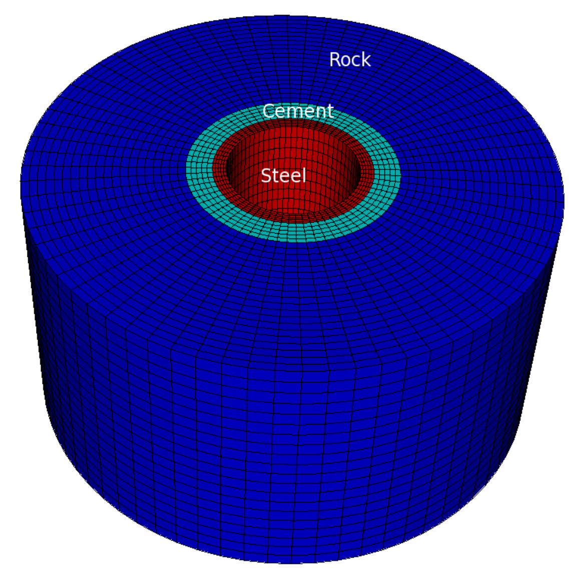
Experimental Setup

SINTEF Thermal cycling setup with liquid nitrogen tank and heating/cooling stage



Technical drawing of the thermal platform
Sample length = 20 cm, diameter = 20 cm

Simulation Specifications



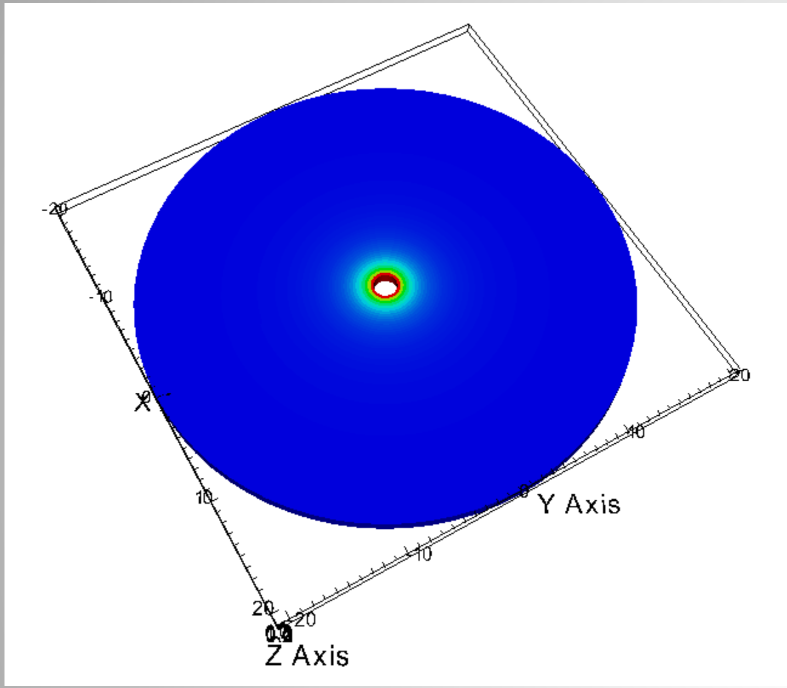
- Thermal and Linear Elastic Solvers

- Variable Temperature at inner radius
- Constant Temperature at outer radius
- Temperature range = -50 – 80 °C
- Heating or cooling rate = 1.0 – 2 °C/min

- Fail Strength
  - Steel-Cement interface = 1.0 Mpa
  - Cement-Rock interface = 1.5 MPa

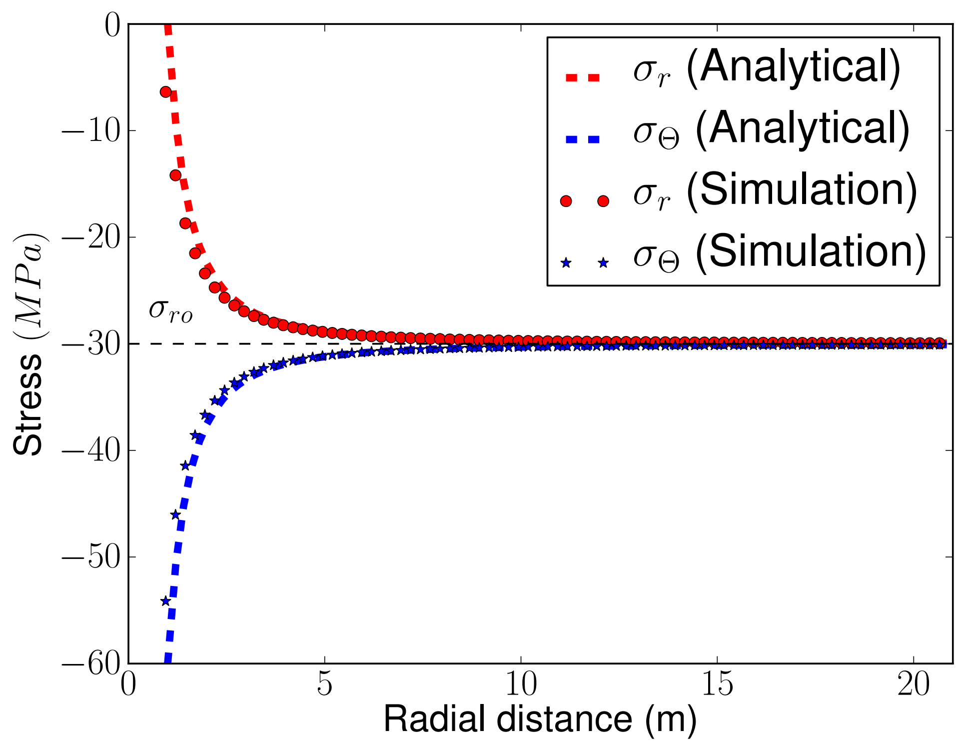
Properties/ Material	Steel	Cement	Rock
Density (kg/m^3)	8000	2300	2500
Thermal Exp. Coeff (m/(mK))	12.0×10^{-6}	7.9×10^{-6}	10.0×10^{-6}
Thermal Conductivity (W/m/K)	50	1	2.1
Specific Heat (J/kg/K)	450	1600	2000
Tensile Strength (MPa)	200	2	6
Fracture Toughness (Mpa.m$^{1/2}$)	40	1	2.5

Code validation: Stress concentration near the wellbore region



$$\sigma_r = \frac{R_\mathrm{o}^2\sigma_{r\mathrm{o}} - R_\mathrm{w}^2 p_\mathrm{w}}{R_\mathrm{o}^2 - R_\mathrm{w}^2} - \frac{R_\mathrm{o}^2}{R_\mathrm{o}^2 - R_\mathrm{w}^2}\frac{R_\mathrm{w}^2}{r^2}(\sigma_{r\mathrm{o}} - p_\mathrm{w})$$

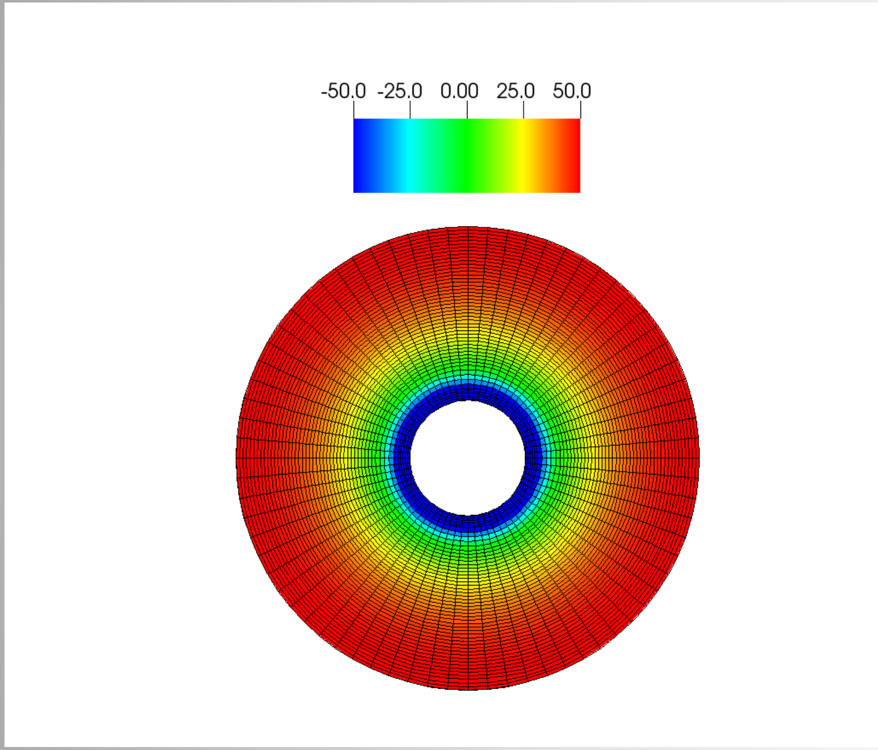
$$\sigma_\theta = \frac{R_\mathrm{o}^2\sigma_{r\mathrm{o}} - R_\mathrm{w}^2 p_\mathrm{w}}{R_\mathrm{o}^2 - R_\mathrm{w}^2} + \frac{R_\mathrm{o}^2}{R_\mathrm{o}^2 - R_\mathrm{w}^2}\frac{R_\mathrm{w}^2}{r^2}(\sigma_{r\mathrm{o}} - p_\mathrm{w})$$

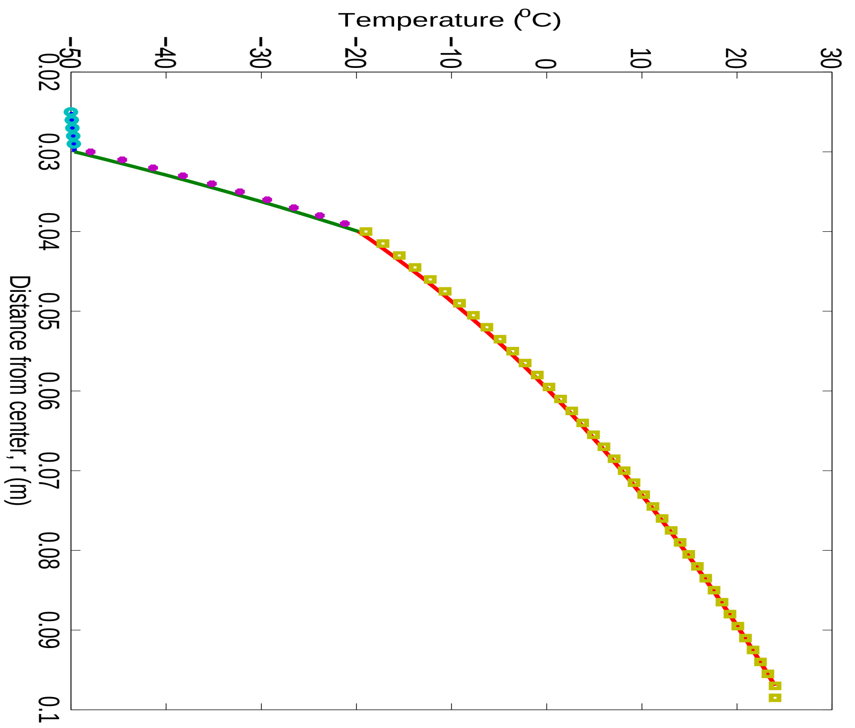


-Ve = Compressive stress
+Ve = Tensile stress

Stresses in hollow cylinder assuming plane strain condition

Code validation: Temperature variation across multiple materials



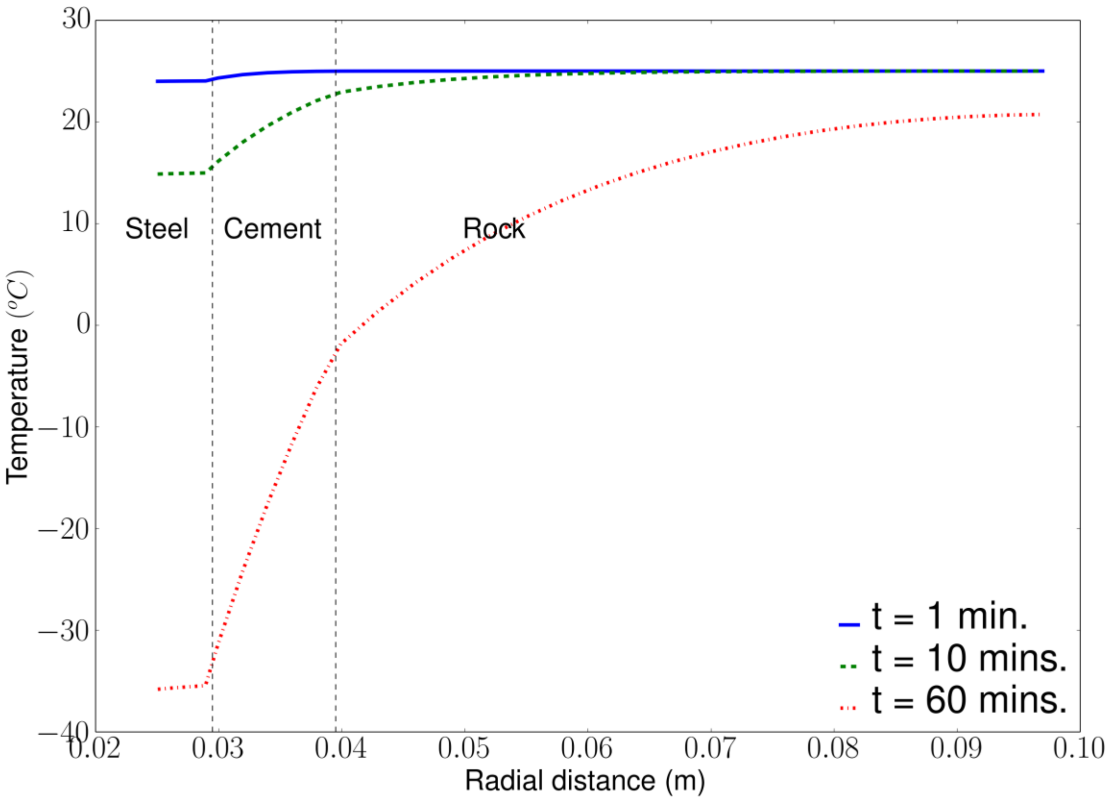


Markers : Numerical solution
Solid lines : Analytical solution

Steady state temperature distribution in a cylindrical disk with constant temperature boundary conditions

Temperature profile during Cooling

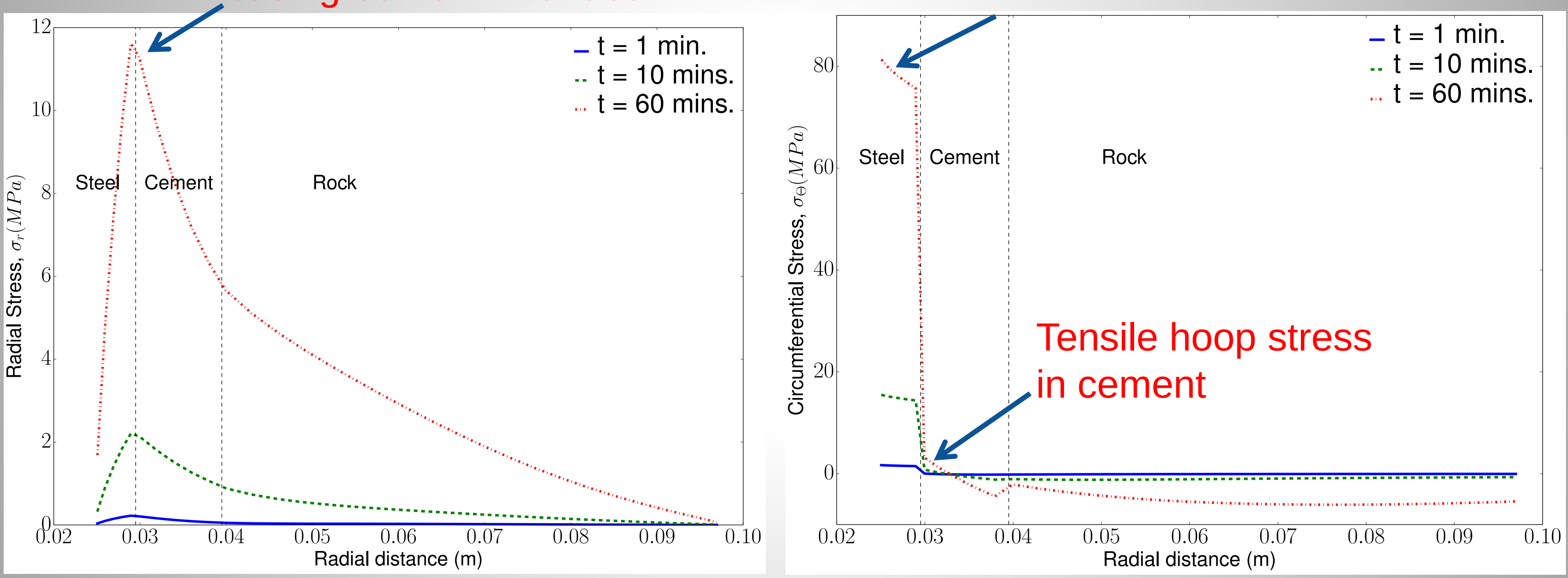
Cooling rate = 1 ^{o}C/min



Temperature (left) variations with time

Radial Stress and Hoop Stress during Cooling

Cooling rate = 1 °C/min



High tensile radial stress at casing-cement interface

High tensile hoop stress in casing

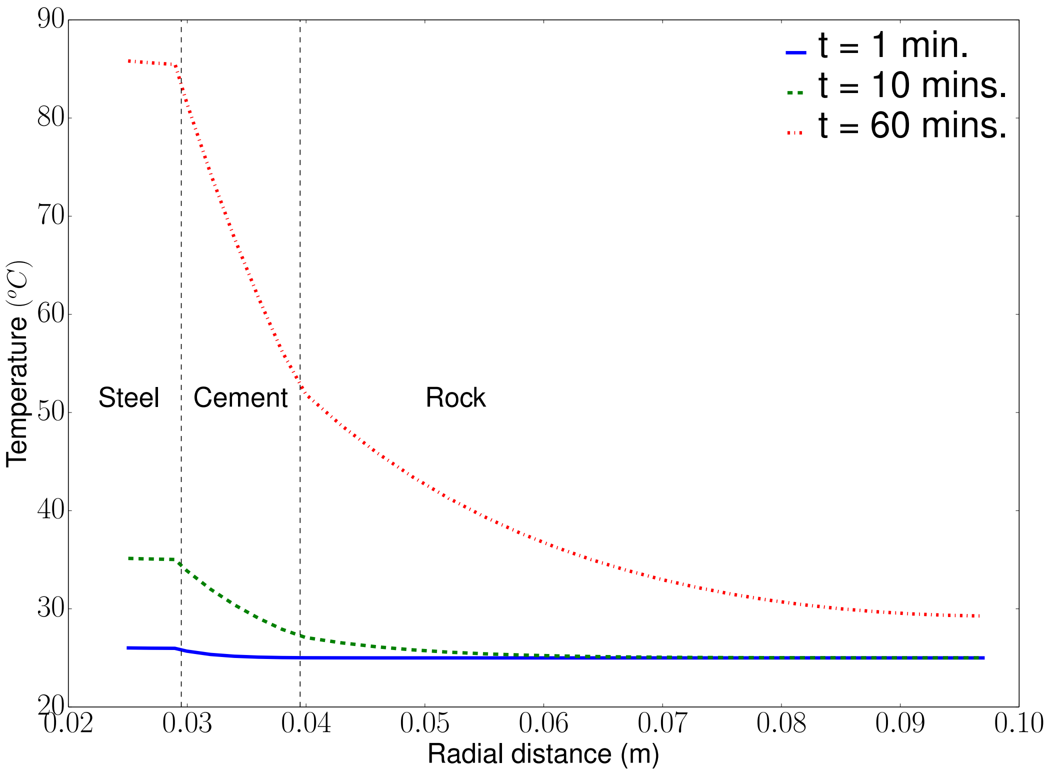
Tensile hoop stress in cement

Thermal Stress: $\sigma_T = \frac{E\alpha}{1-2\nu}(T - T_0)$

Radial stress (left) and hoop stress (right) variations with time

Temperature profile during Heating

Heating rate = 1 ^{o}C/min

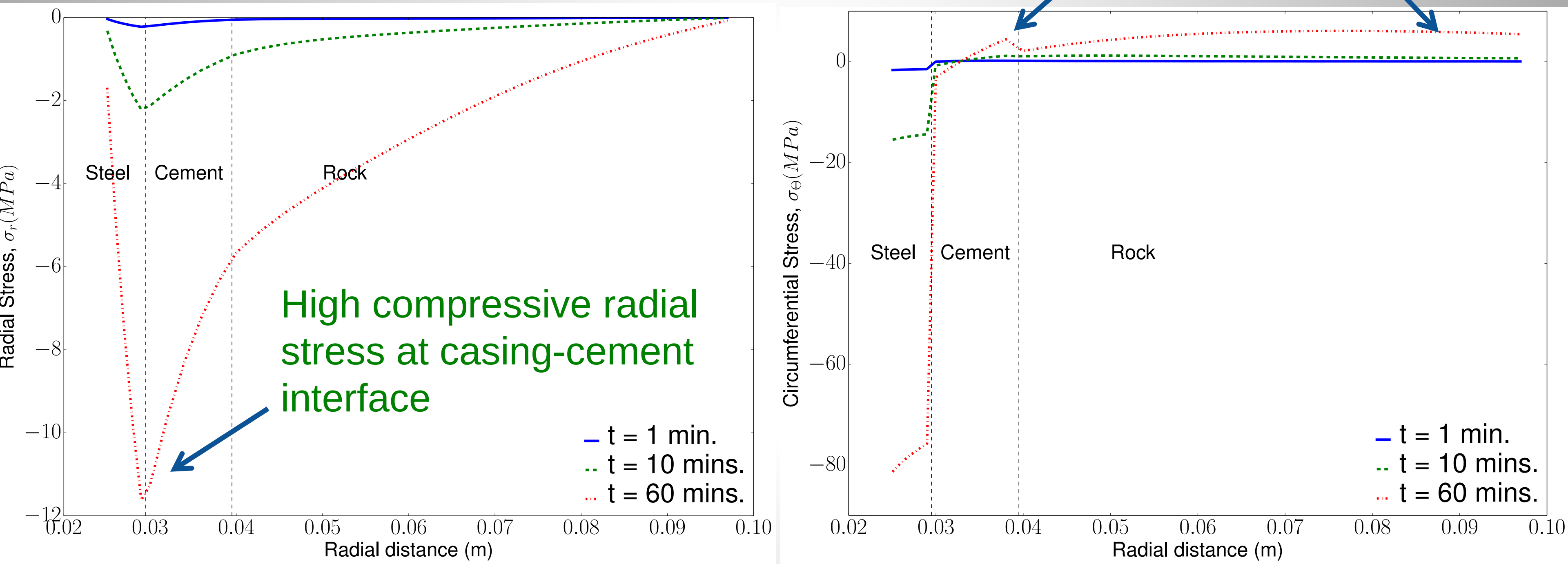


Temperature (left) variations with time

Radial stress and Hoop stress in during Heating

Heating rate = 1 ^{o}C/min

Tensile hoop stress near cement-rock interface and inside rock

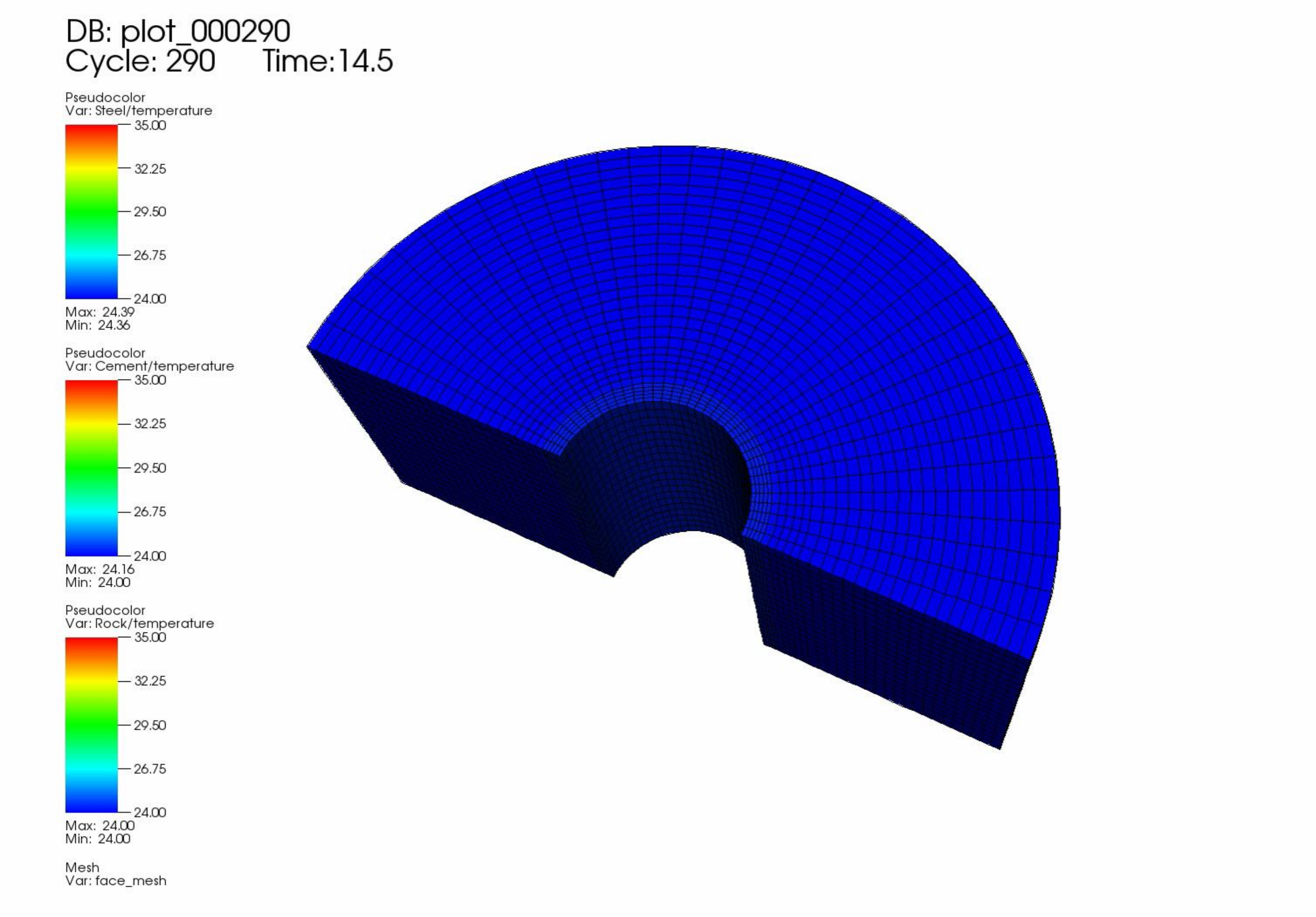


High compressive radial stress at casing-cement interface

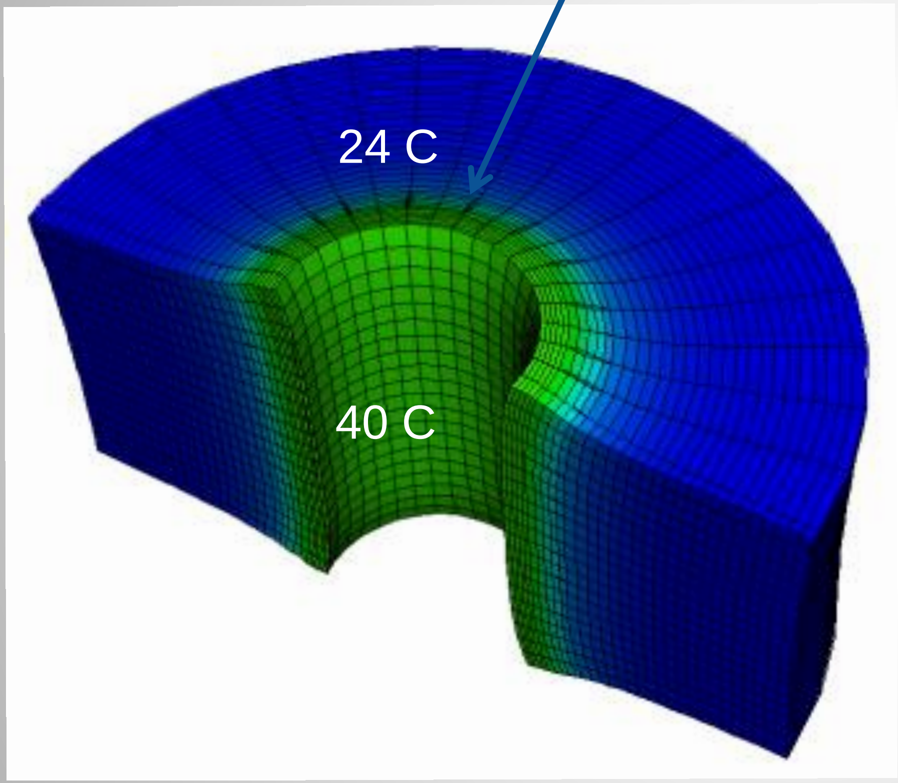
Thermal Stress: $\sigma_T = \frac{E\alpha}{1-2\nu}(T - T_0)$

Radial stress (left) and Hoop stress (right) variations with time

Radial crack initiation during heating



During heating –
Thermal expansion causes radial cracks


Temperature contours

Radial cracks due to high hoop stress


Fracture propagation

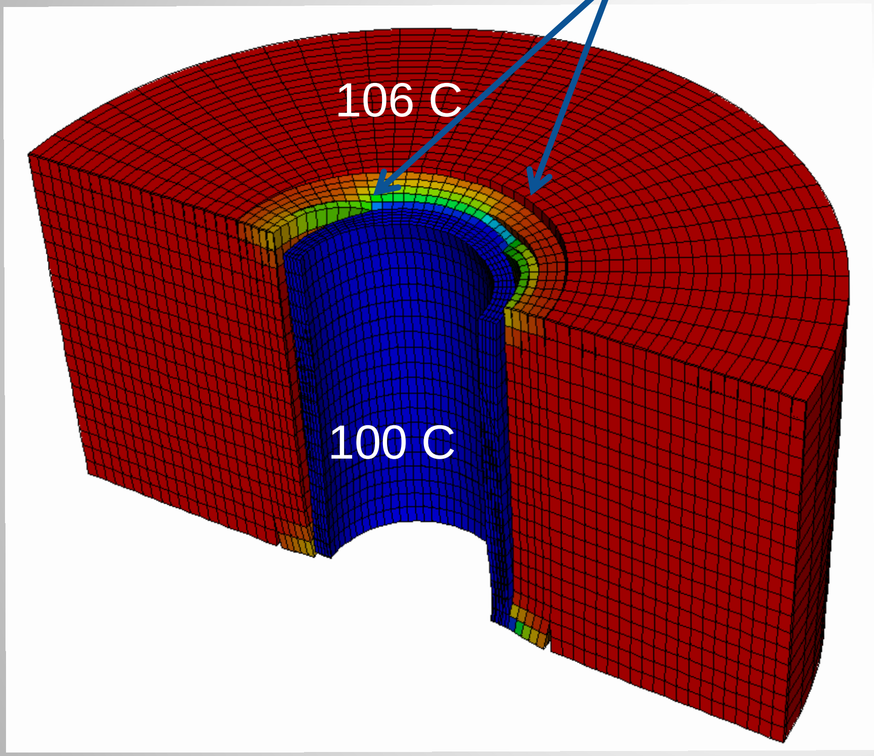
Heating rate = 1.8 °C/min.
Displacement 1000x magnified
Fracture width = 5-10 micro meter

Adding confining pressure slows/ prevents fracture propagation

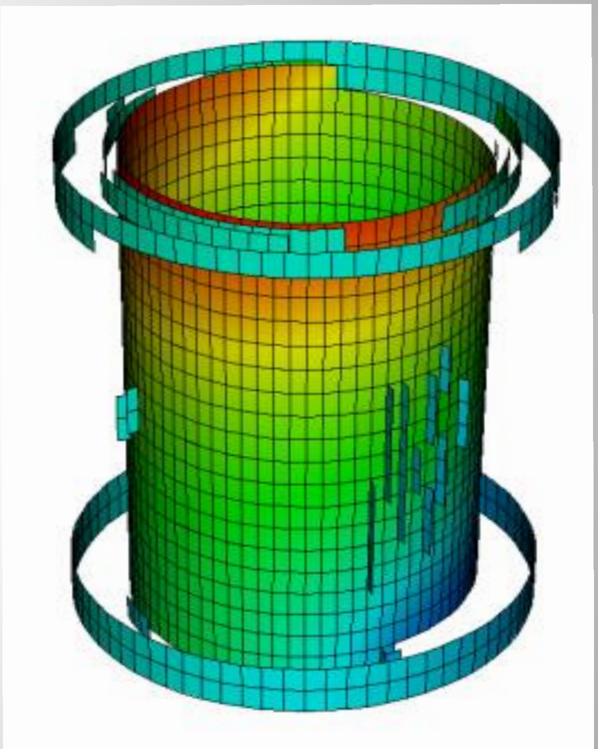
During cooling –
Thermal contraction causes interfacial debonding

Temperature contours

Interfacial debonding
due to high radial stress



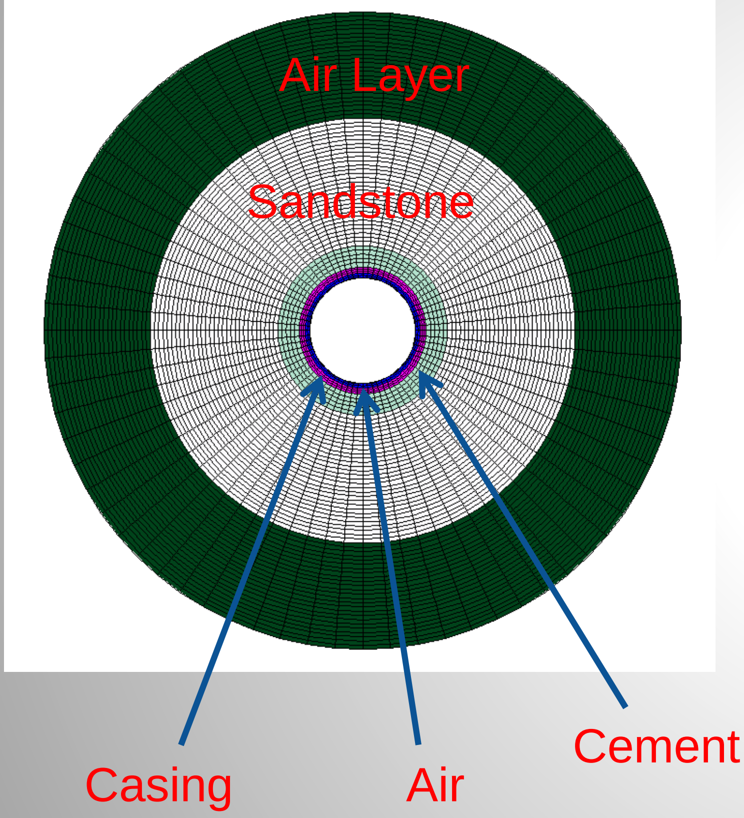
Fracture propagation

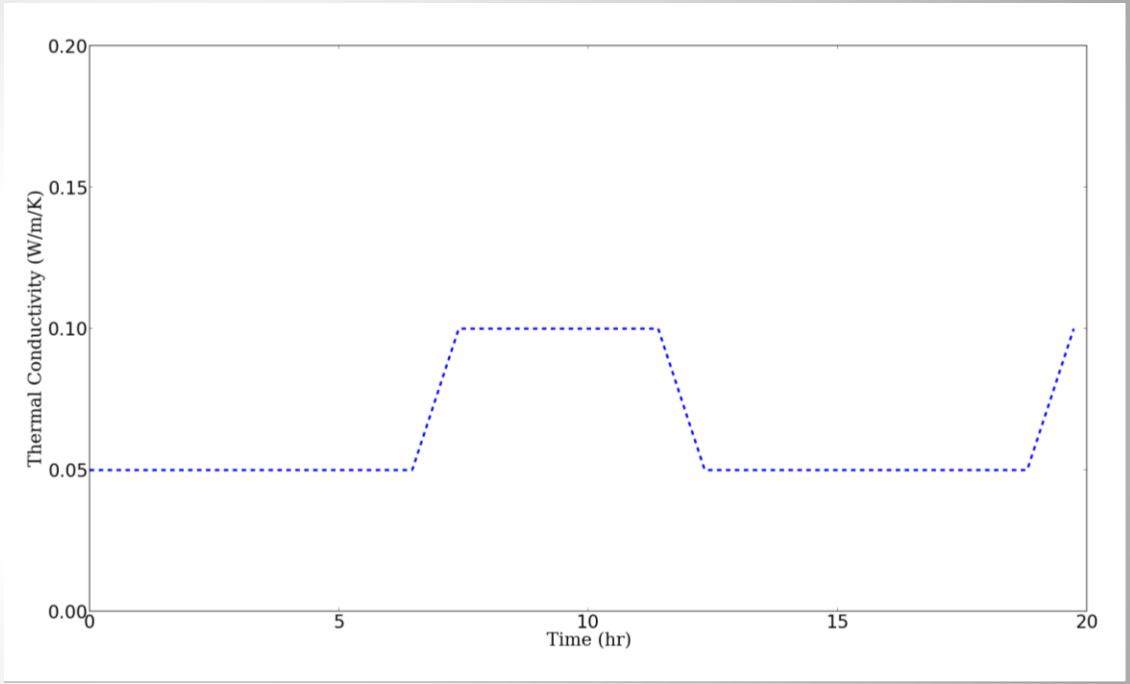


Cooling rate = 1.8 ºC/min.
Displacement 1000x magnified
Fracture width = 10-20 micro meter

Adding confining pressure slows/prevents fracture propagation

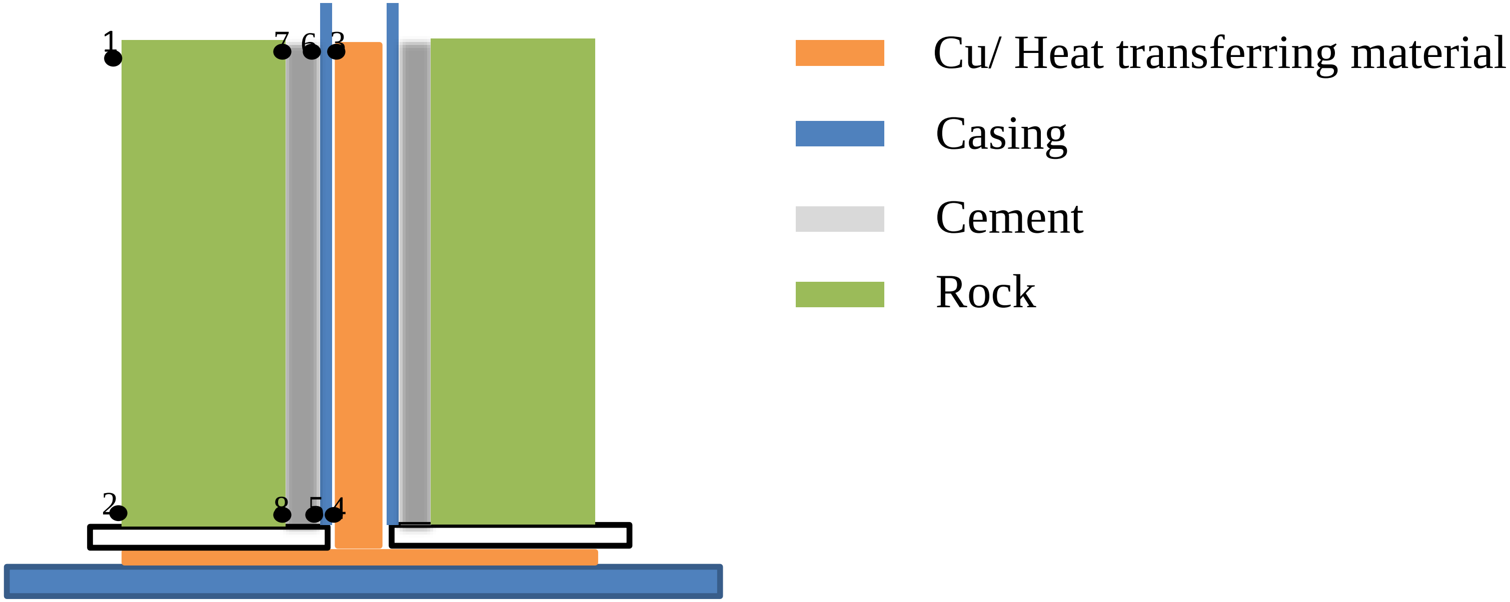
Modeling of the Experiment



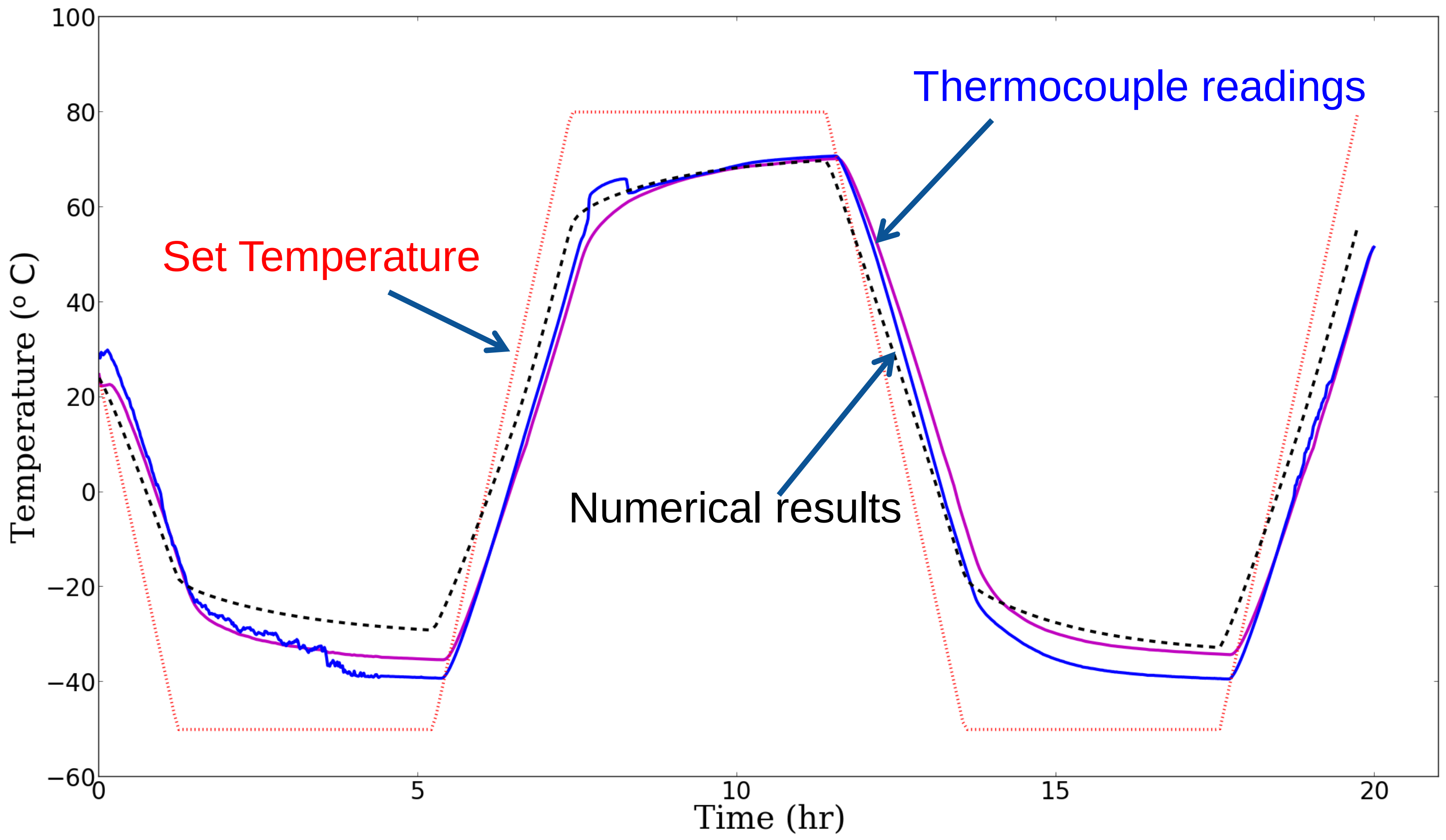


Variable thermal conductivity used between copper and casing

Schematic of Experiment: Thermocouple positions

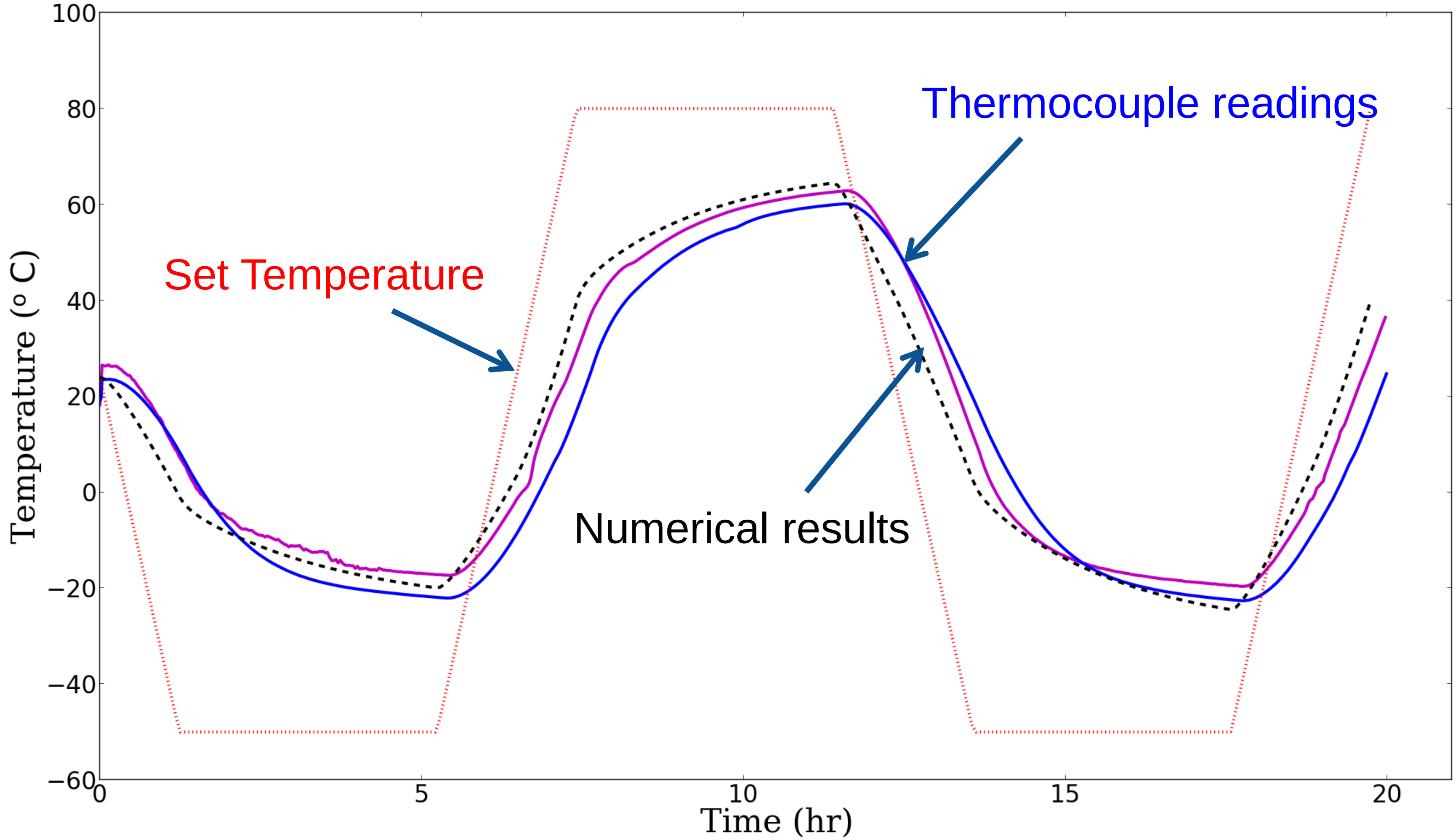


Copper-Casing Interface Temperature



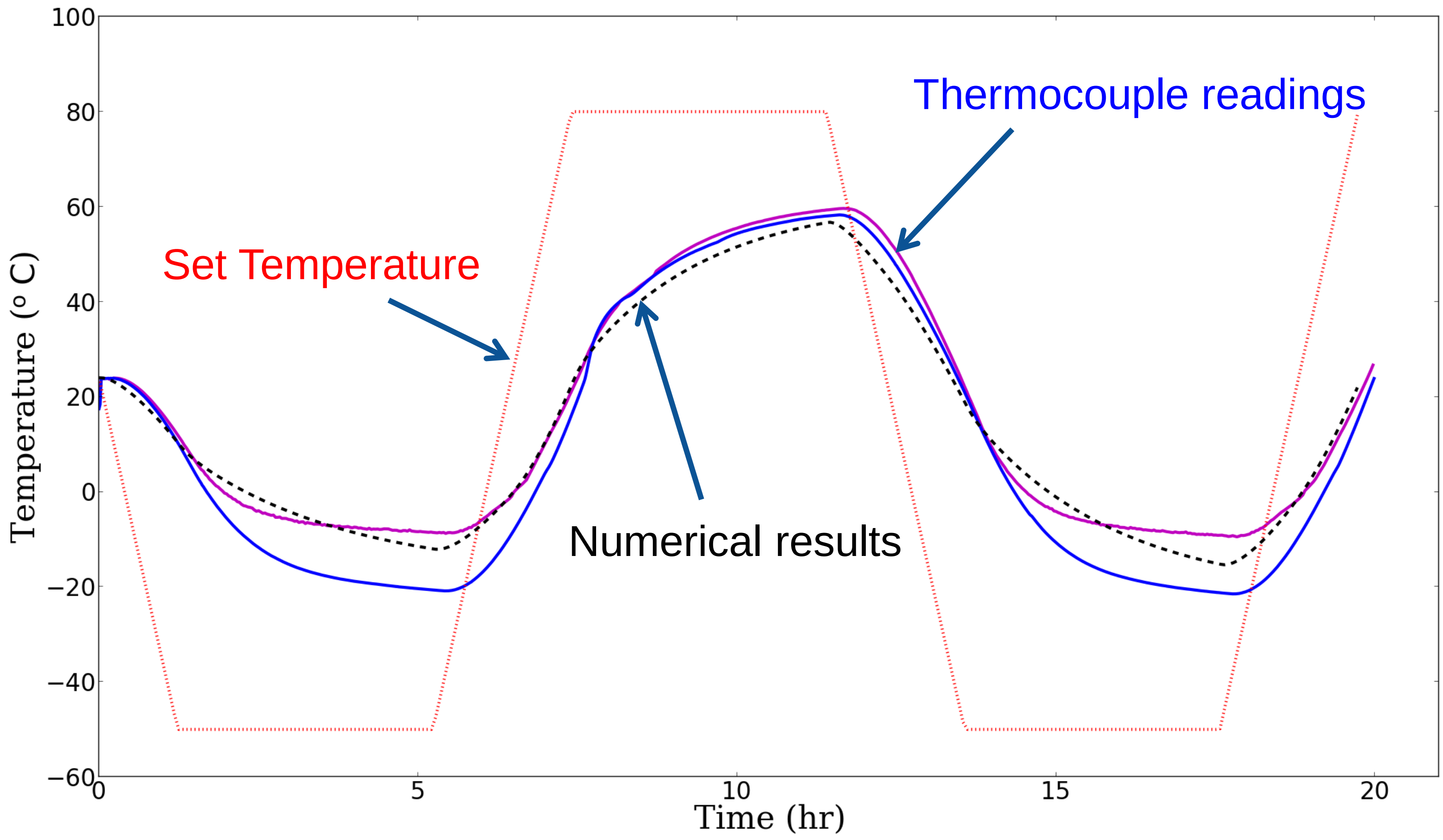
Good agreement with experimental data

Cement-Casing Interface Temperature



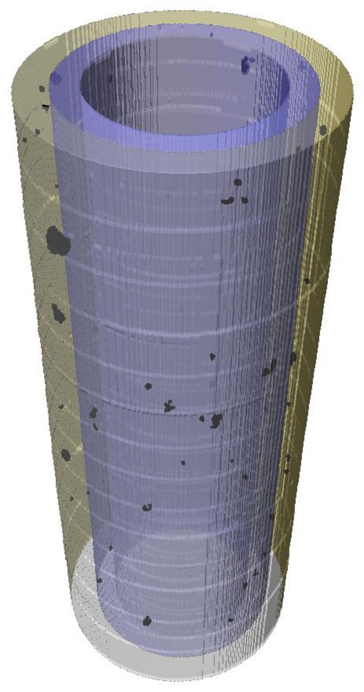
Good agreement with experimental data

Cement-Rock Interface Temperature

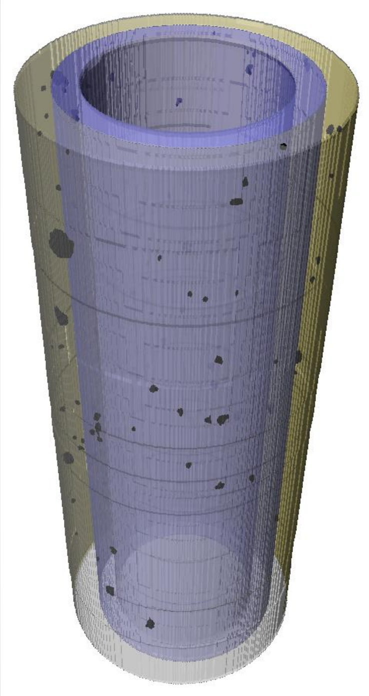


Good agreement with experimental data

CT scan results did not show any visible crack



Before (Cycle = 0)



After (Cycle = 20)

Voids within cement – gray
cement – transparent yellow
casing – transparent blue

- Resolution of CT Scan: 150-200 micro meter in XY (horizontal) and 1 mm in Z (vertical) direction
- The material properties, especially the tensile strength and modulus of elasticity, might be different
- The CT scan was conducted at room temperature
- De Andrea et al. (2014) and Albwai et al. (2014) experimentally showed that pre-existing cracks can extend upon thermal cycling

Summary and Future Work

- Radial cracks are likely to occur in cement and/or rock during heating while debonding is likely to occur in cement/casing or cement/rock interfaces during cooling.
- Confinement reduces the tensile stresses and delays/prevents the initiation of fracture.
- Modeled SINTEF Experiments: Good agreement was found between the thermocouple readings and the numerical temperature profiles.
- No visible crack was detected during the experiment. However, numerical simulations showed possibility of failure due to the thermal cycling operations.
- Specifying the in-situ stress state for field scale simulations (on-going work as part of NRAP Phase 2).
- Predict acceptable temperature ranges for safe injection and storage of CO_2 (part of NRAP Phase 2).

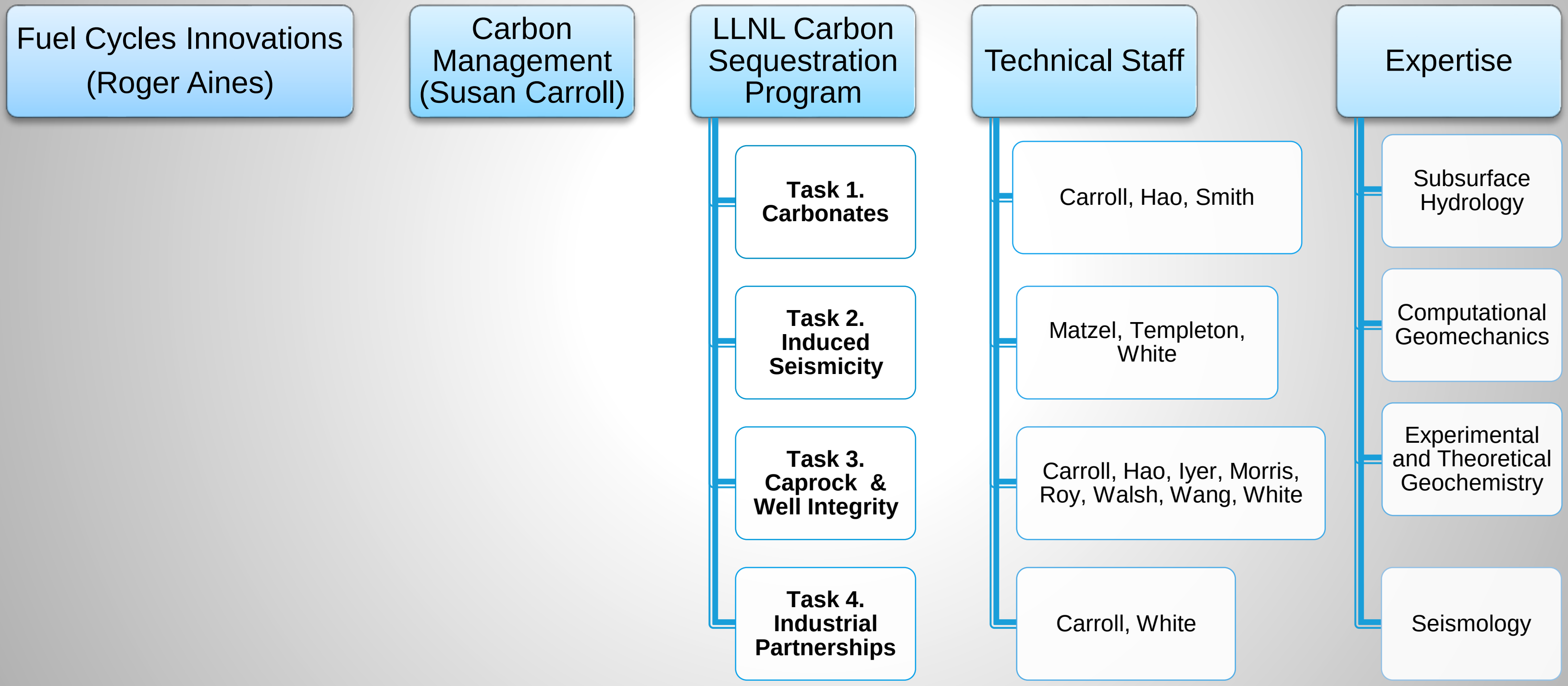
Synergy Opportunities

- Collaboration with SINTEF Petroleum Research
  - Provides detailed experimental data to constrain models

- Joint publications: ARMA, GHGT

Appendix

FEW0191



Fuel Cycles Innovations (Roger Aines)

Carbon Management (Susan Carroll)

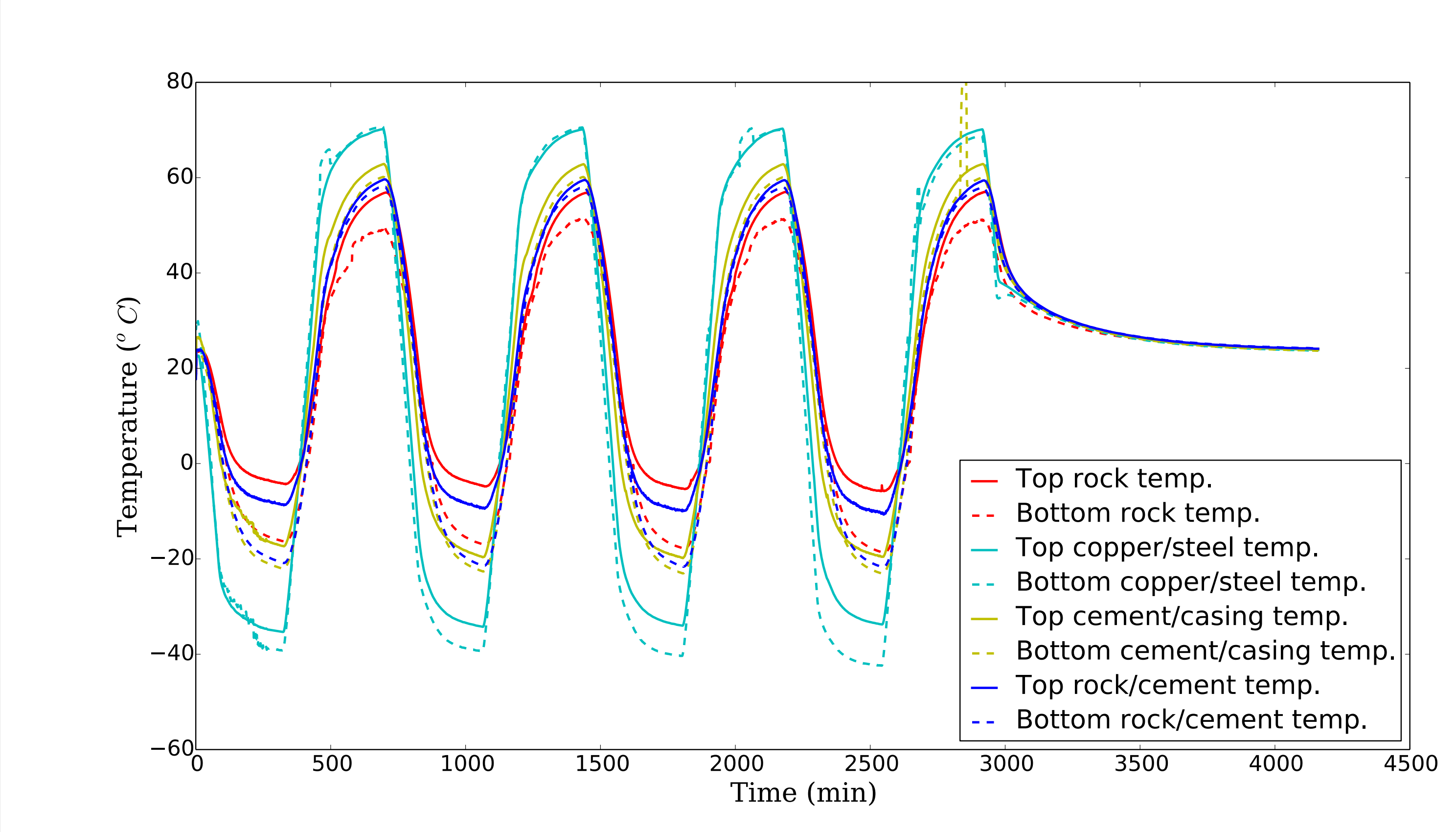
LLNL Carbon Sequestration Program	Technical Staff	Expertise
Task 1. Carbonates	Carroll, Hao, Smith	Subsurface Hydrology
Task 2. Induced Seismicity	Matzel, Templeton, White	Computational Geomechanics
Task 3. Caprock & Well Integrity	Carroll, Hao, Iyer, Morris, Roy, Walsh, Wang, White	Experimental and Theoretical Geochemistry
Task 4. Industrial Partnerships	Carroll, White	Seismology

Project Timeline for FEW0191

Task	Milestone Description*	Project Duration	Start : Oct 1, 2014					End: Sept 30, 2017						Planned Start Date	Planned End Date	Actual Start Date	Actual End Date	Comment (notes, explanation of deviation from plan)
		Project Year (PY) 1				PY 2				PY 3								
		Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11	Q12					
1.1	Calibrate Reactive Transport Model	🟥	🟥	🟥	🟥	🟥	🟥 x							1-Oct-14	30-Mar-15			
1.2	Calibrate NMR Permeability Estimates	🟥	🟥	🟥	🟥	🟥	🟥 x							1-Oct-14	30-Mar-15			
1.3	Scale Reactive Transport Simulations from the core to reservoir scale				🟥	🟥	🟥	🟥	🟥	🟥	🟥 x			1-Jul-15	28-Feb-17			
1.4	Write topical report on CO2 storage potential in carbonate rocks									🟥	🟥	🟥	🟥 x	1-Dec-16	30-Sep-17			
2.1	Algorithm development and testing	🟨	🟨	🟨	🟨 x									1-Oct-14	30-Sep-15			
2.2	Array design and monitoring recommendations					🟨	🟨	🟨	🟨 x					1-Oct-15	30-Sep-16			
2.3	Toolset usability and deployment									🟨	🟨	🟨	🟨 x	1-Oct-16	30-Sep-17			
3.1	Analysis of monitoring and characterization data available from the In Salah Carbon Sequestration Project	🟩	🟩	🟩	🟩 x									1-Dec-14	30-Sep-15			
3.2	Wellbore model development	🟩	🟩	🟩	🟩 x									1-Oct-14	30-Sep-15			
3.3	Analysis of the full-scale wellbore integrity experiments			🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩 x			1-Mar-14	28-Feb-17			
3.4	Refining simulation tools for sharing with industrial partners									🟩	🟩	🟩	🟩 x	1-Oct-16	30-Sep-17			
4.1	Engage with industrial partnerships	🟧	🟧 x											1-Oct-14	28-Feb-15			Future tasks pending discussions with industrial partners
4.2	Develop work scope with industrial partners			🟧	🟧 x									1-Mar-14	30-Sep-15			

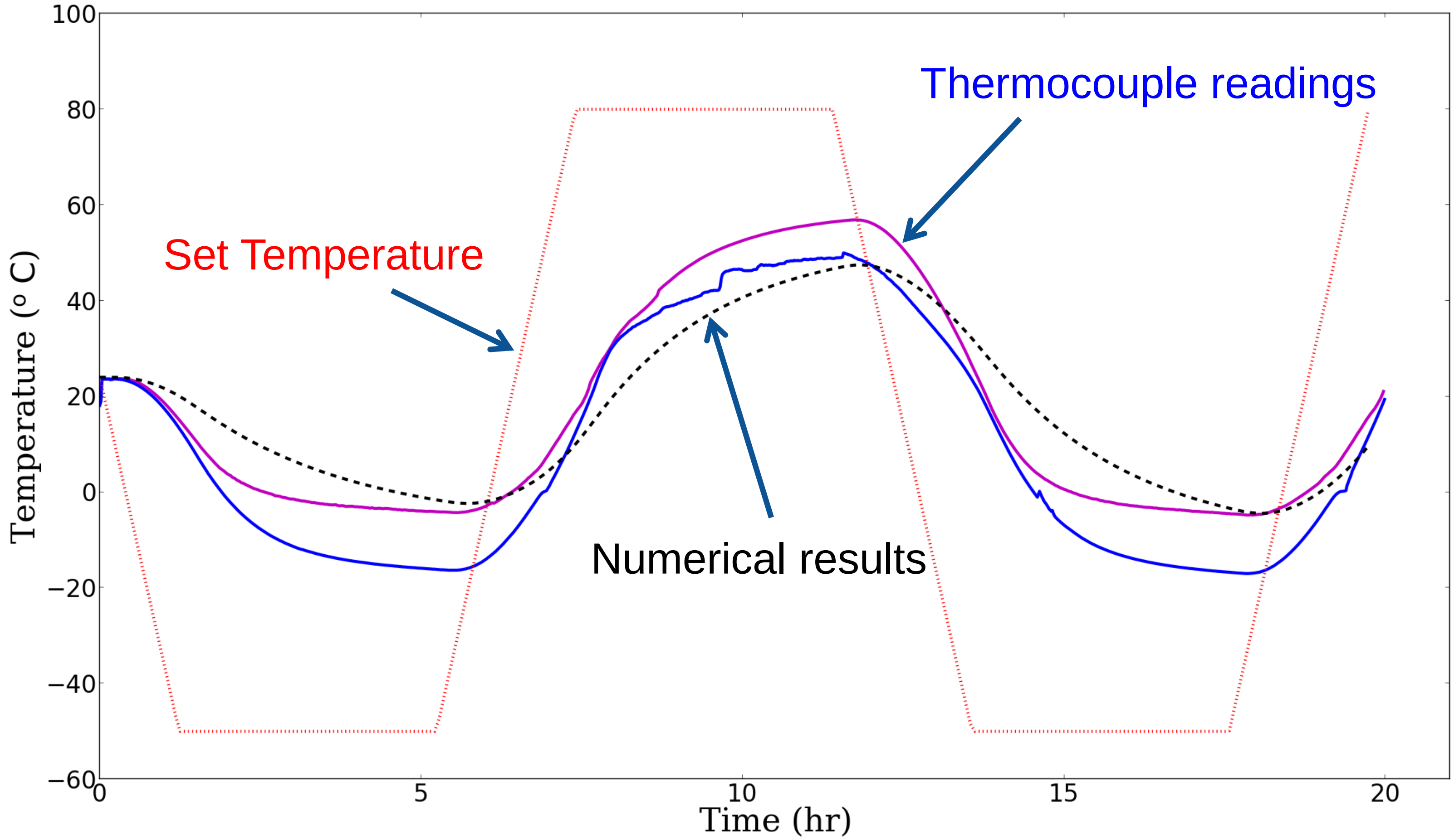
* No fewer than two (2) milestones shall be identified per calendar year per task

Temperature profiles from experiment



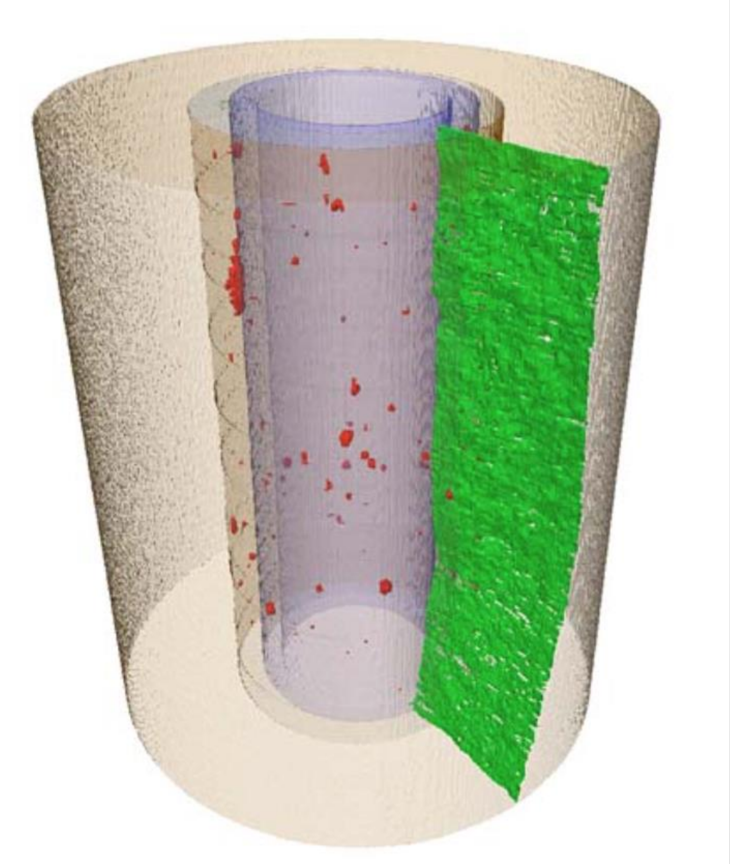
Dashed lines represent bottom thermocouple readings
Solid lines represent top thermocouple readings

Comparison with experimental data

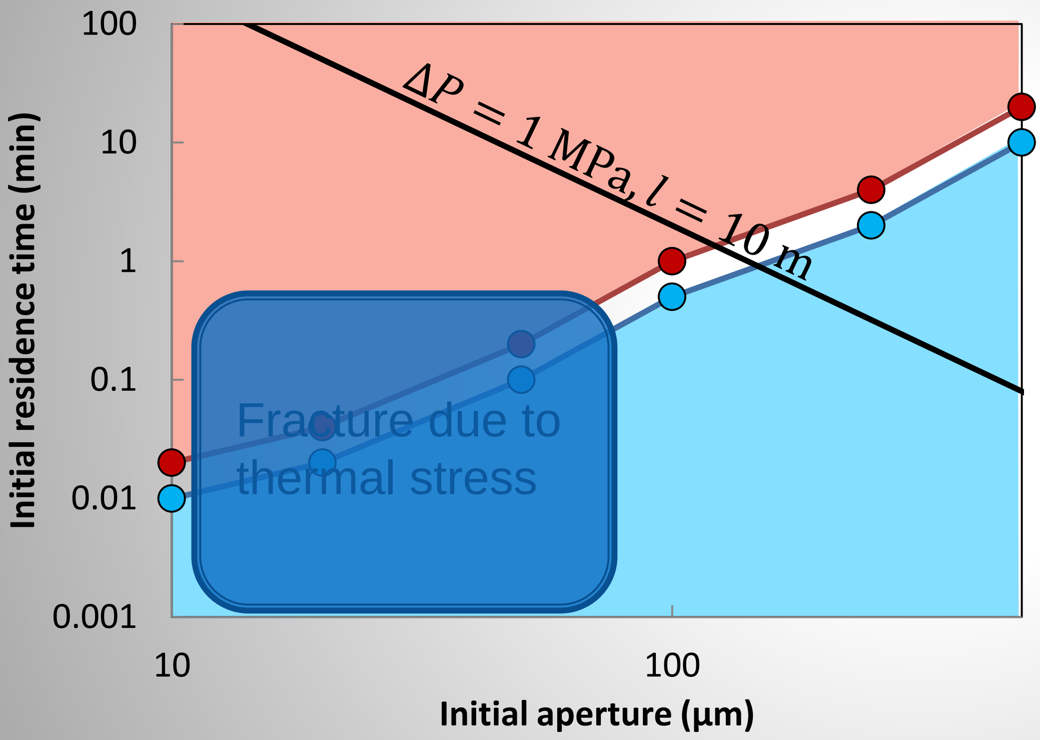


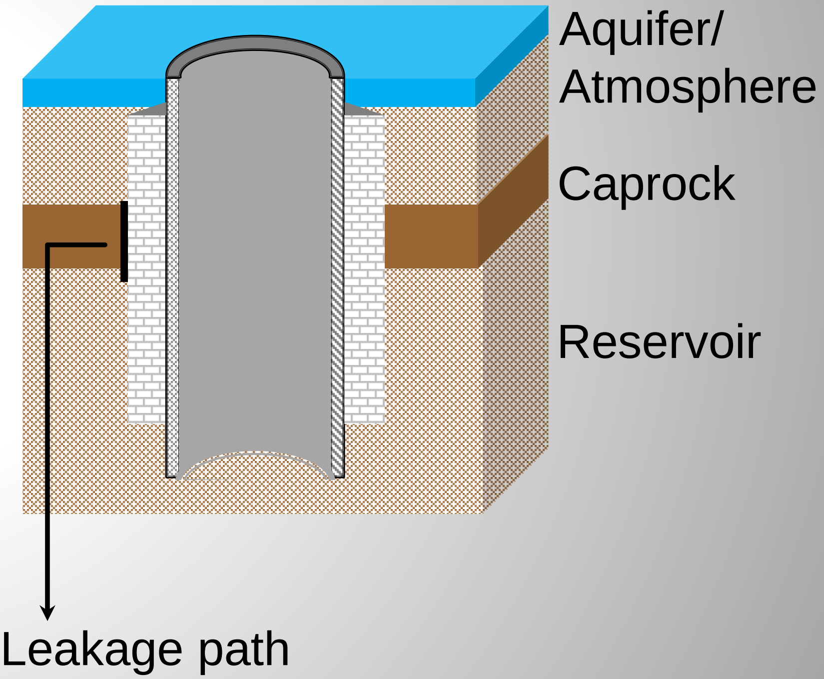
Outer Rock temperature

Extreme cooling



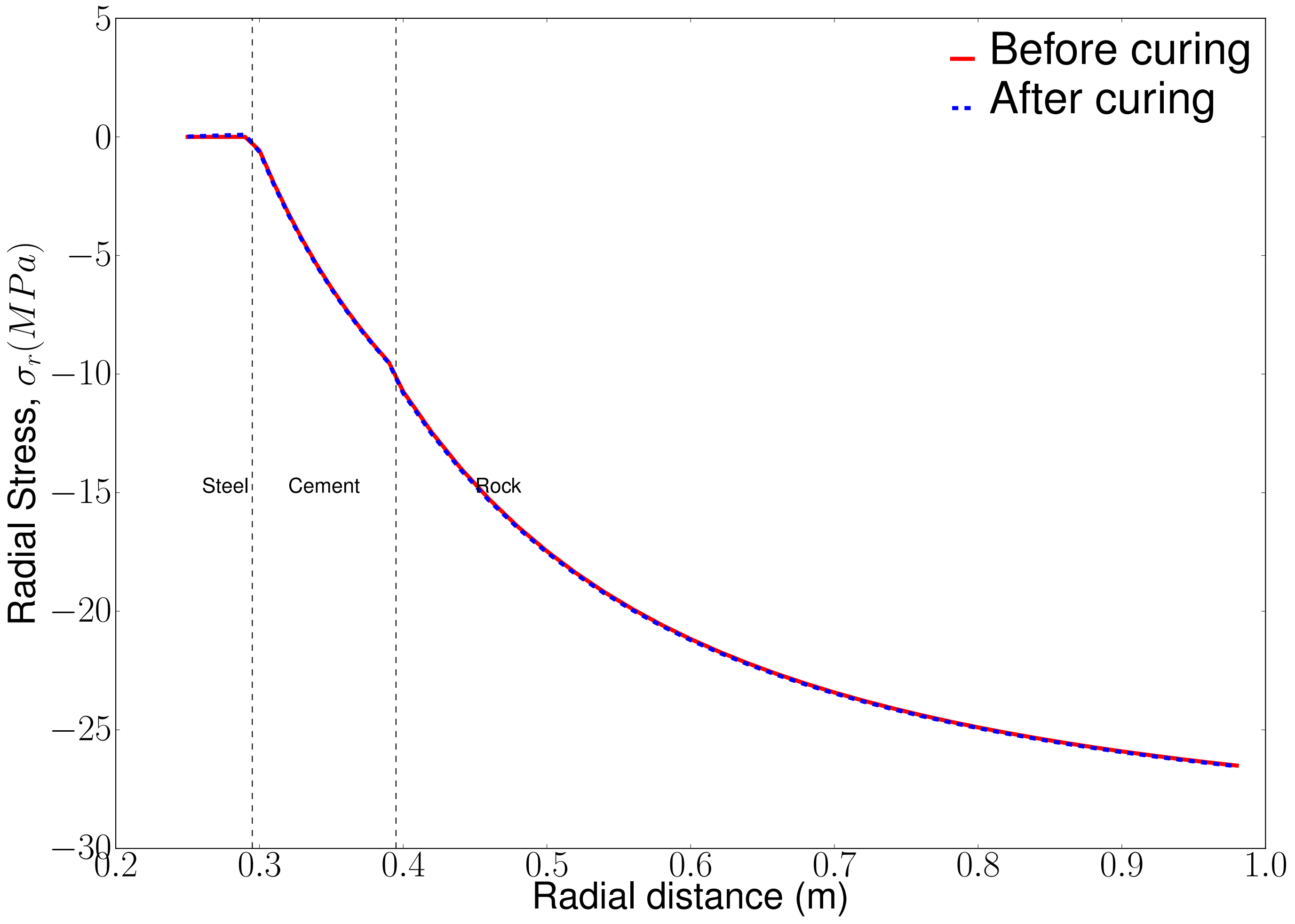
Operating conditions can be overlaid on the sealing map to guide risk assessment





Courtesy: Jaisree Iyer et al. (2016)

Effect of cement hardening: No Expansion of Cement



Effect of cement hardening:
1% Expansion of Cement