

Failure Analysis of Casing–Cement-Formation Systems in Legacy Wells: Implications for Integrity Assessment and Monitoring

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Abstract

While well integrity has been extensively studied for oil and gas wells, few studies examine the impact of high temperature, high pressure conditions characteristic of geothermal wells and the challenges they pose when considering existing defects in the well construction. In this presentation, initial defects are introduced to the cement sheath of an Enhanced Geothermal System via a transient Finite Element thermomechanical simulation to understand the relative impact of different failure mechanisms, including drilling mud contamination, debonding, and casing corrosion. The novelty of the study is to integrate field data with thermomechanical modeling of the cement sheath failure. Unlike prior studies focused on oil and gas wells, the study highlights the influence of unique features of geothermal wells that combine initial cement defects and thermal loading scenarios. The model utilizes temperature time histories from the Utah FORGE well 56-32, in addition to geometry collected from their caliper log. Mohr–Coulomb failure analysis is performed to quantify the fraction of the total simulated volume that experienced failure. In addition, gap sizes are modeled to enable comparison of failure behavior under different conditions.

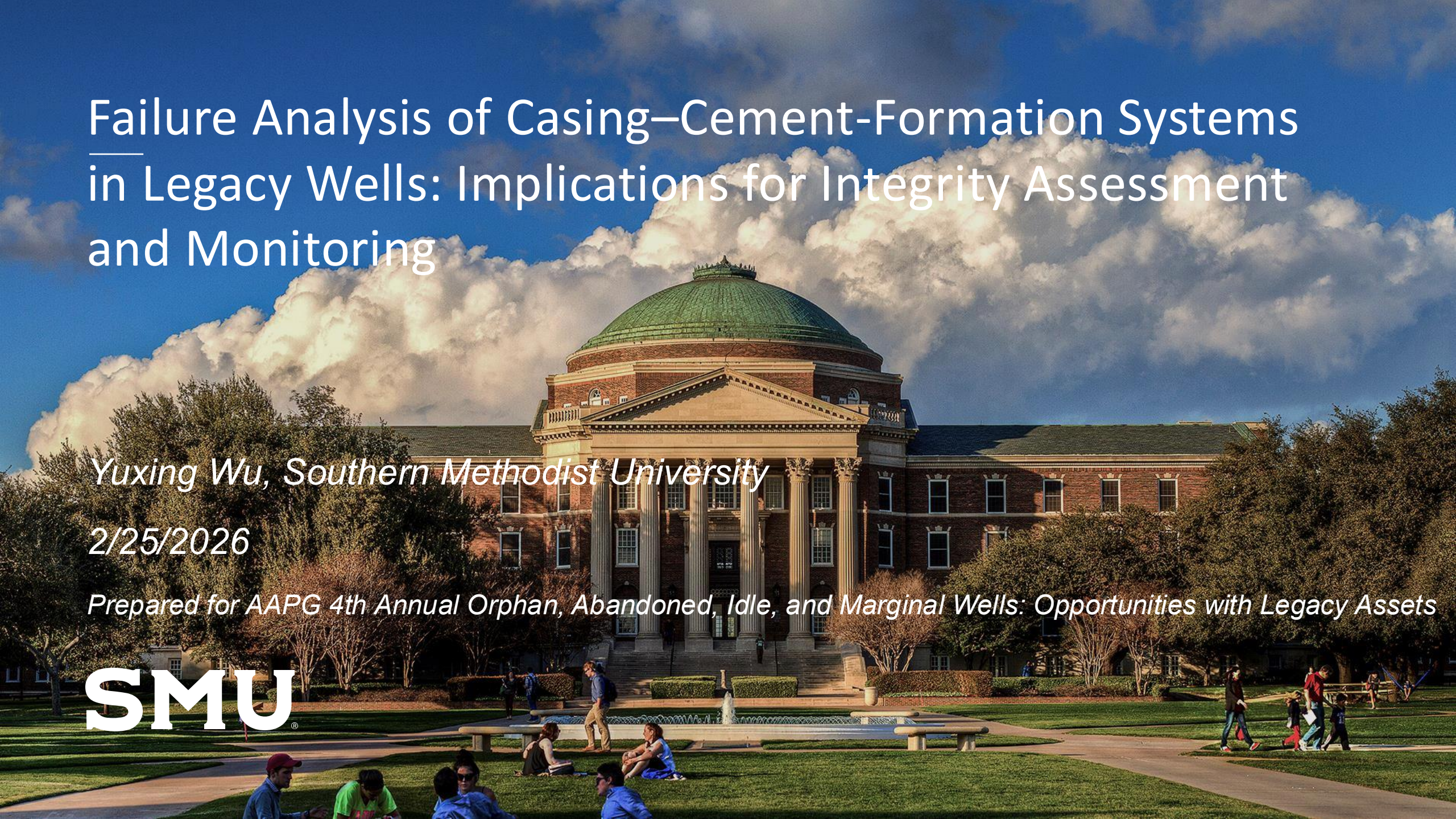
Failure Analysis of Casing–Cement-Formation Systems in Legacy Wells: Implications for Integrity Assessment and Monitoring

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2/25/2026

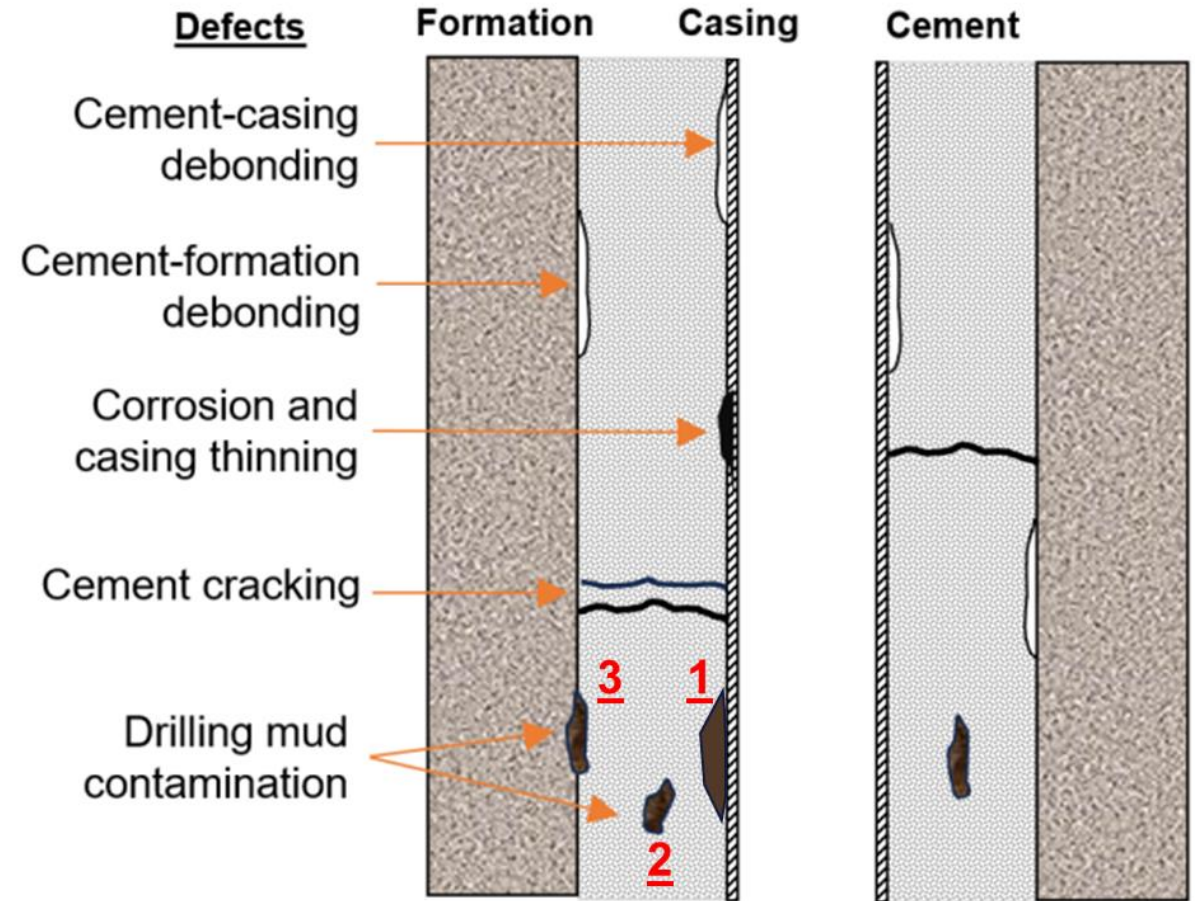
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Introduction & Objectives

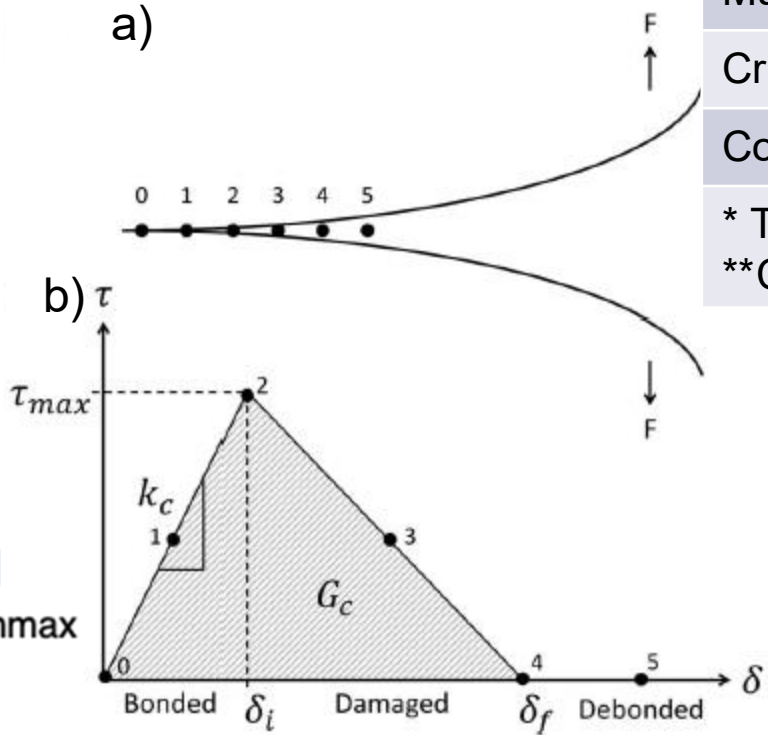
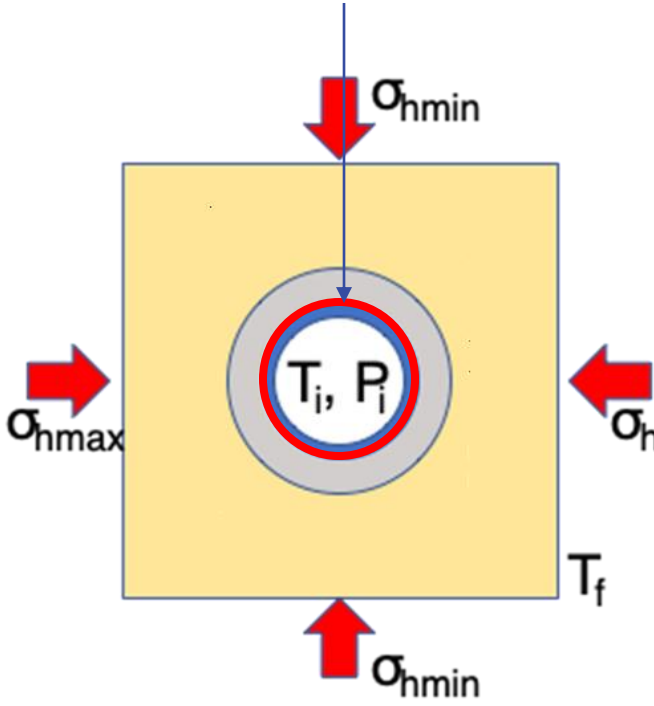
- Most of the legacy wells exceed design life
- Cement degradation:
 - Aging
 - High temperature
 - Corrosion
- 5 common kinds of pathway:
- Objective: Evaluate the effect of cement under different initial defects



Casing-Cement Debonding

- Cohesive zone model

Cohesive zone
(casing-cement bonding)



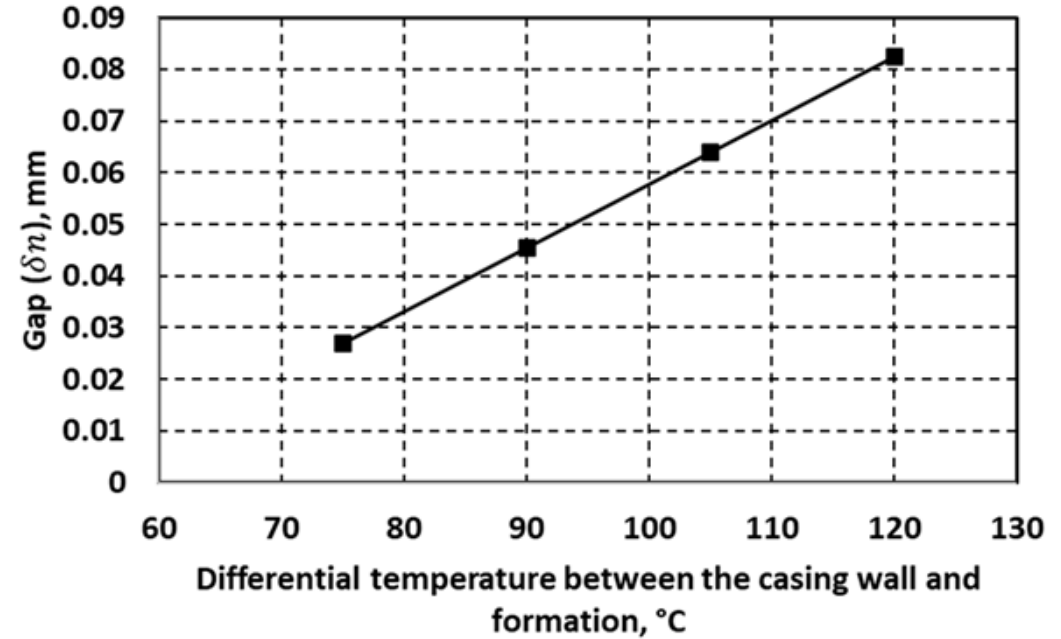
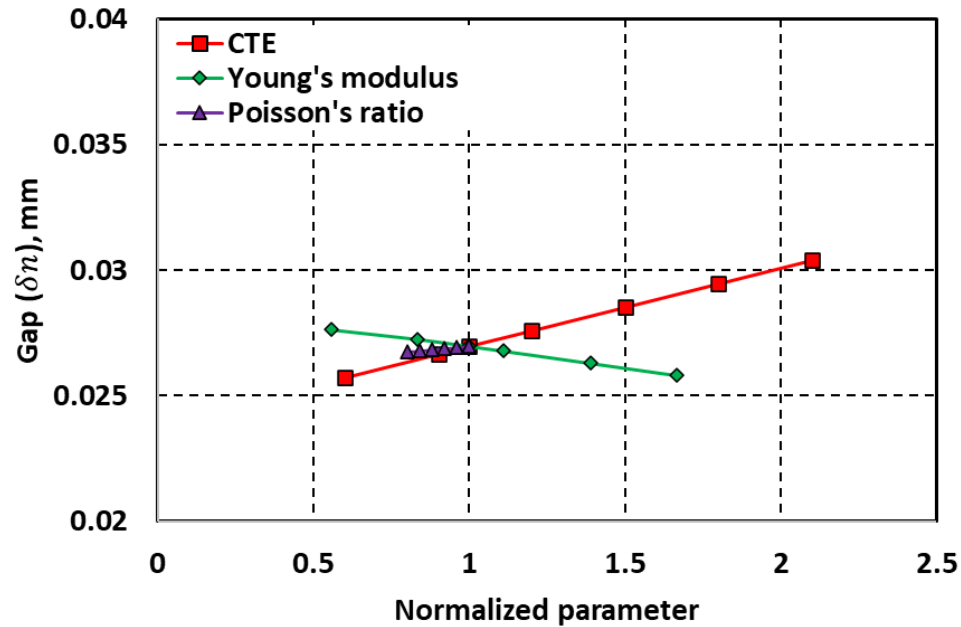
τ : Normal cohesive traction
 δ : Normal displacement jump

| Cohesion zone model properties | Value |
|---|----------------------|
| Maximum normal contact stress*, τ_{max} | 0.5 MPa |
| Critical fracture energy*, G_c | 100 J/m ² |
| Contact stiffness*, K_c | 30,000 |
| * The properties are from Wise & Nygaard, 2023. | |
| **Contact stiffness is from Wang and Dahi Taleghani, 2014 | |

τ_{max} : 500 MPa
 δ_i : 0.01667 mm
 δ_f : 0.4 mm

Bonded when $\delta_n \leq 0.01667$
 Damaged when $0.01667 \leq \delta_n \leq 0.4$
 Debonded when $\delta_n \geq 0.4$

Casing-Cement Debonding Results



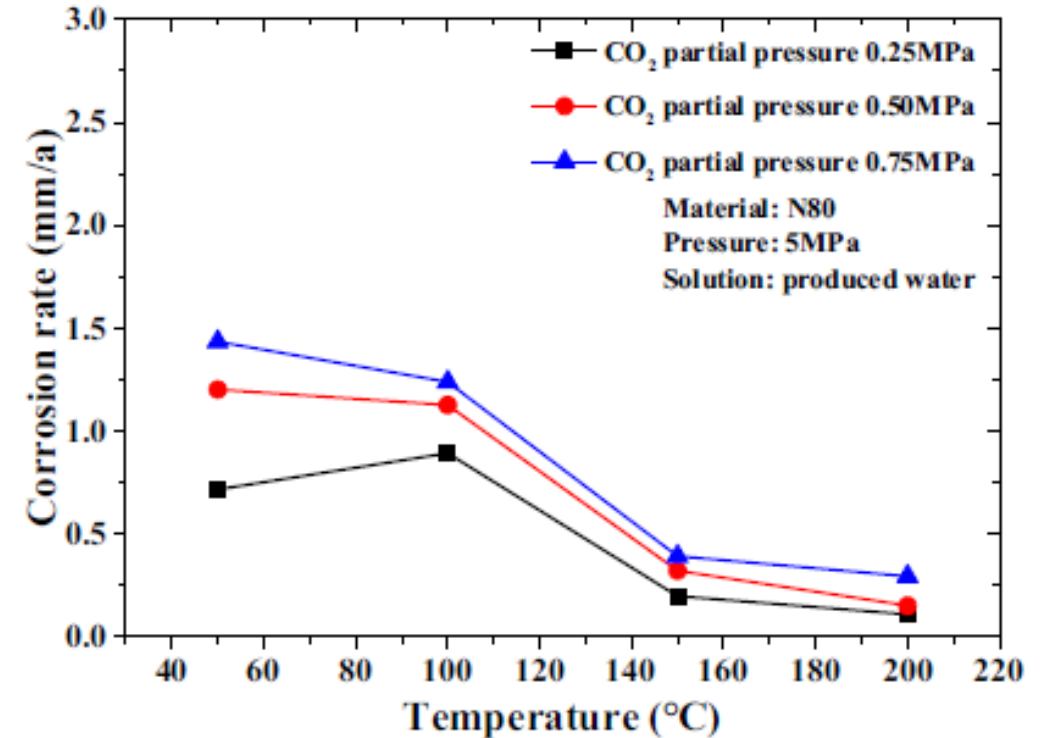
- $0.01667 \leq \delta_n \leq 0.4$. Therefore, in all studied cases, the contact is damaged.
- High CTE results in high shrinkage of the cement, leading to a high δ_n and risk of debonding.
- Higher stiffness helps resist deformation mismatch and maintains contact (too stiff cement could result in cement cracking).
- Poisson's ratio has little influence on the gap in this parameter range.
- With decreasing differential temperature, the δ_n decreases, decreasing the risk of debonding.
- High-accuracy tools are required (i.e., can detect 20 micrometers fractures in this study. Current tools can detect debonding zones, or microannuli, as small as 100-250 micrometers).

Corrosion and Casing Thinning

- Harsh environments in geothermal wells (such as H₂S, CO₂, chloride ions, etc.) result in degradation of the casing.
 - The output model illustrates defect progression and clarifies damage mechanisms
- The corrosion is assumed uniform. No partial corrosion is considered.
 - Equivalent Young's modulus (Chen et al., 2021):

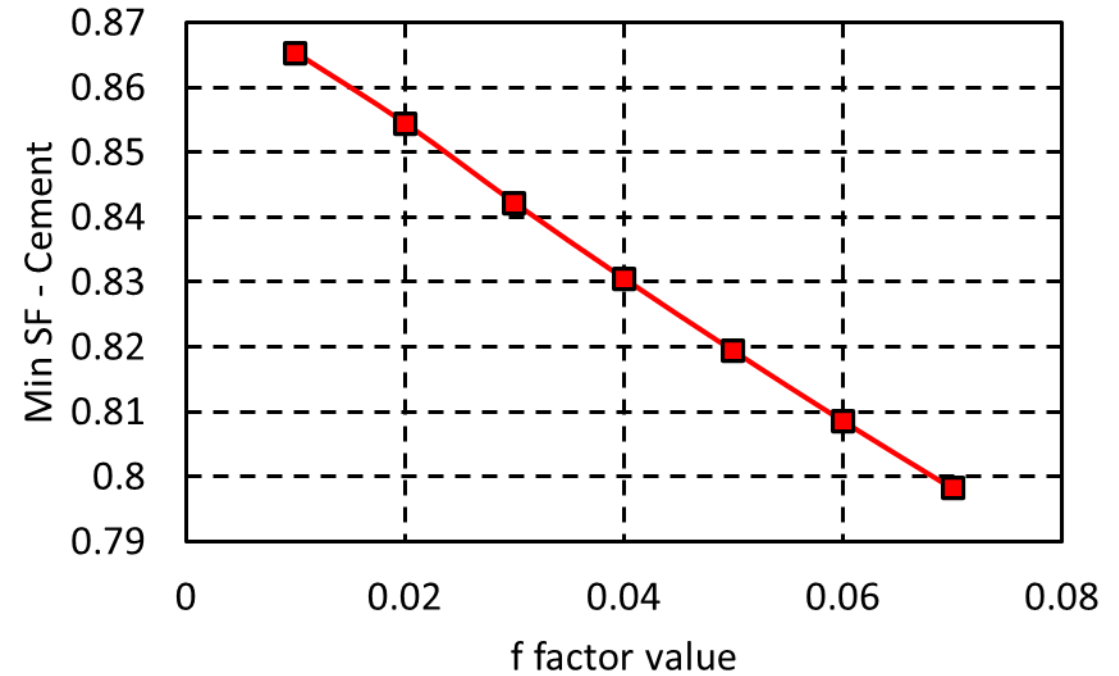
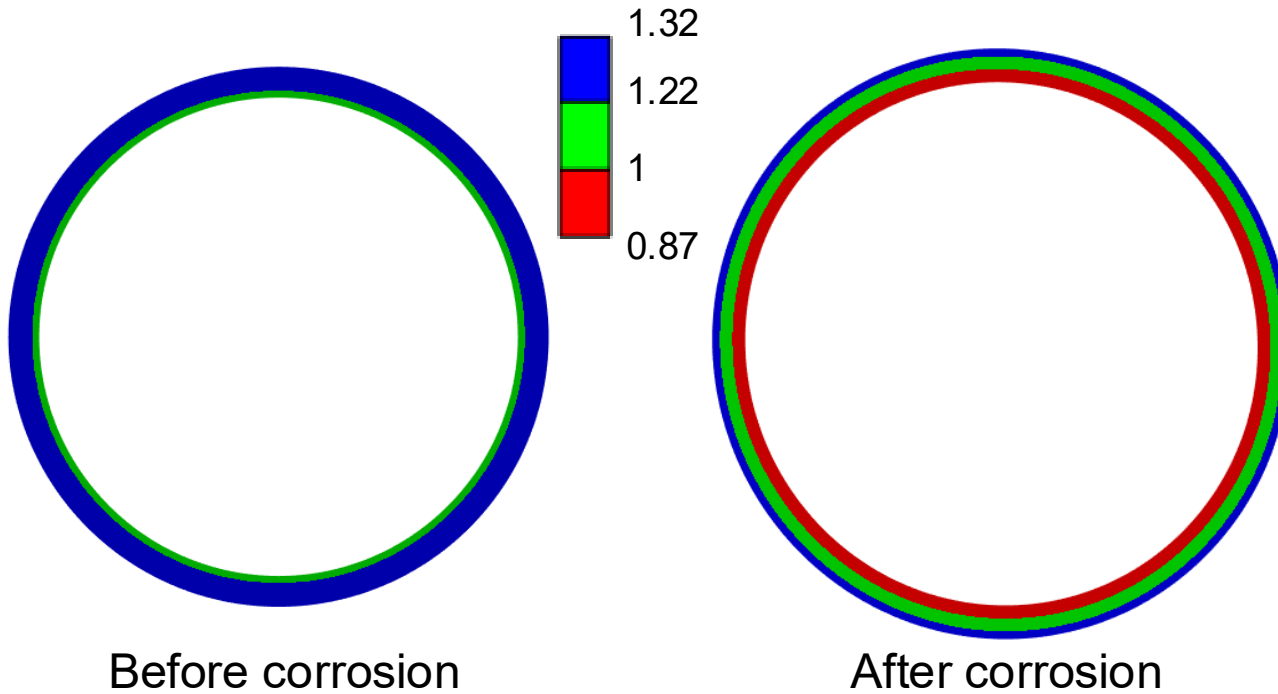
$$\tilde{E} = (1 - 2\nu) \frac{12G_0K_0(1-f)}{4G_0+3K_0f}; f = \frac{m_0}{m_t}$$

- Wall thickness is set to 0.25mm/yr (Cui et al., 2020)



Corrosion and Casing Thinning Results

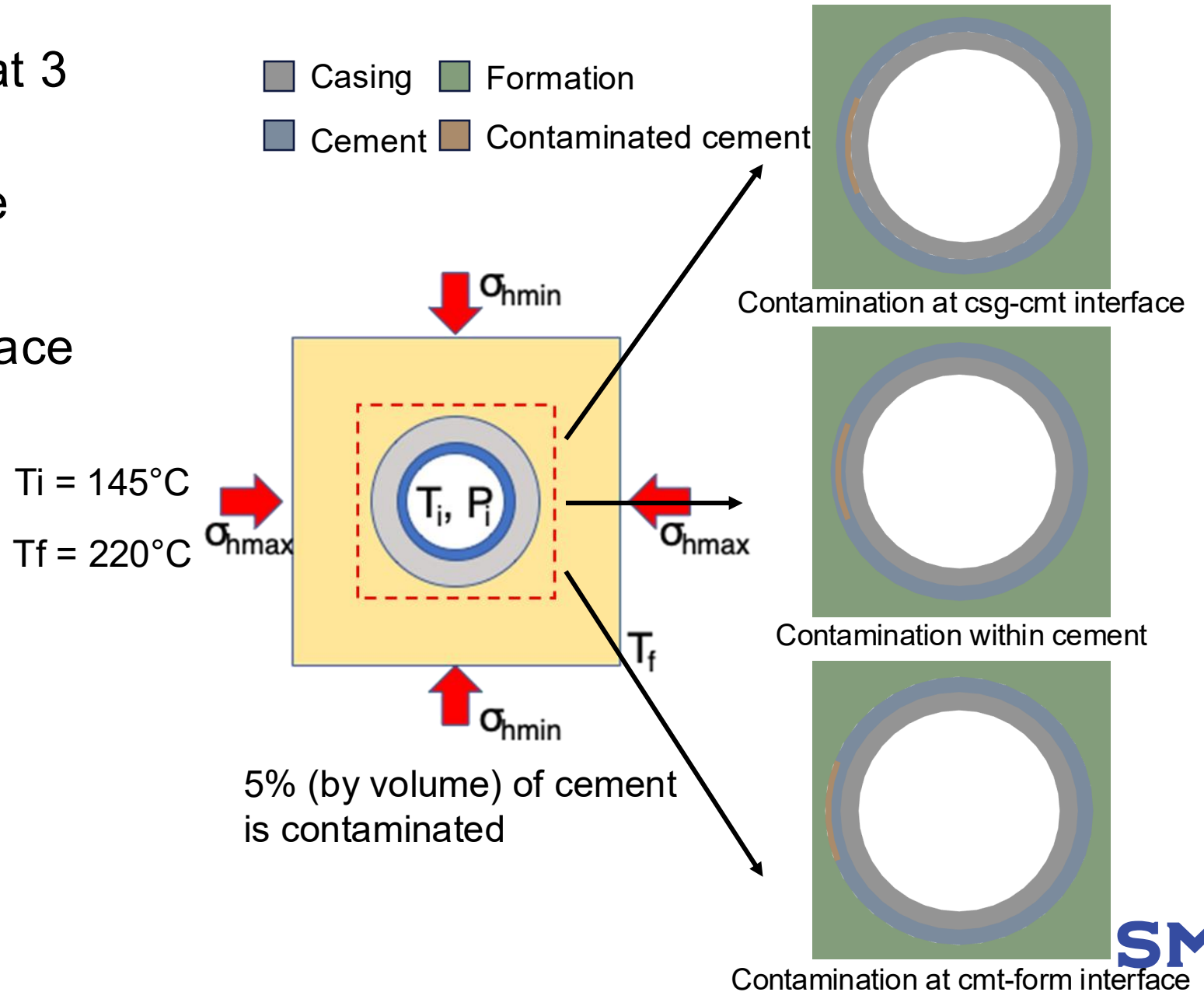
- Base scenario – cement



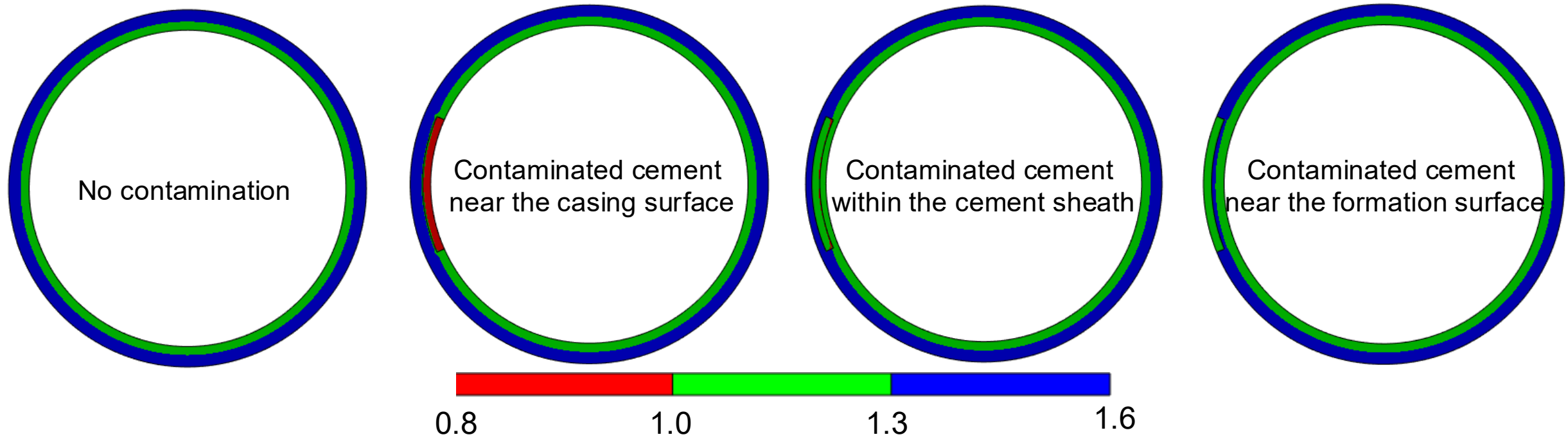
- Failure observed at the internal surface of cement after corrosion.
- f factor significant influence the cement integrity.

Mud Contaminations

- Contaminations occurred at 3 locations are studied:
 - Casing-cement interface
 - Within cement
 - Cement-formation interface

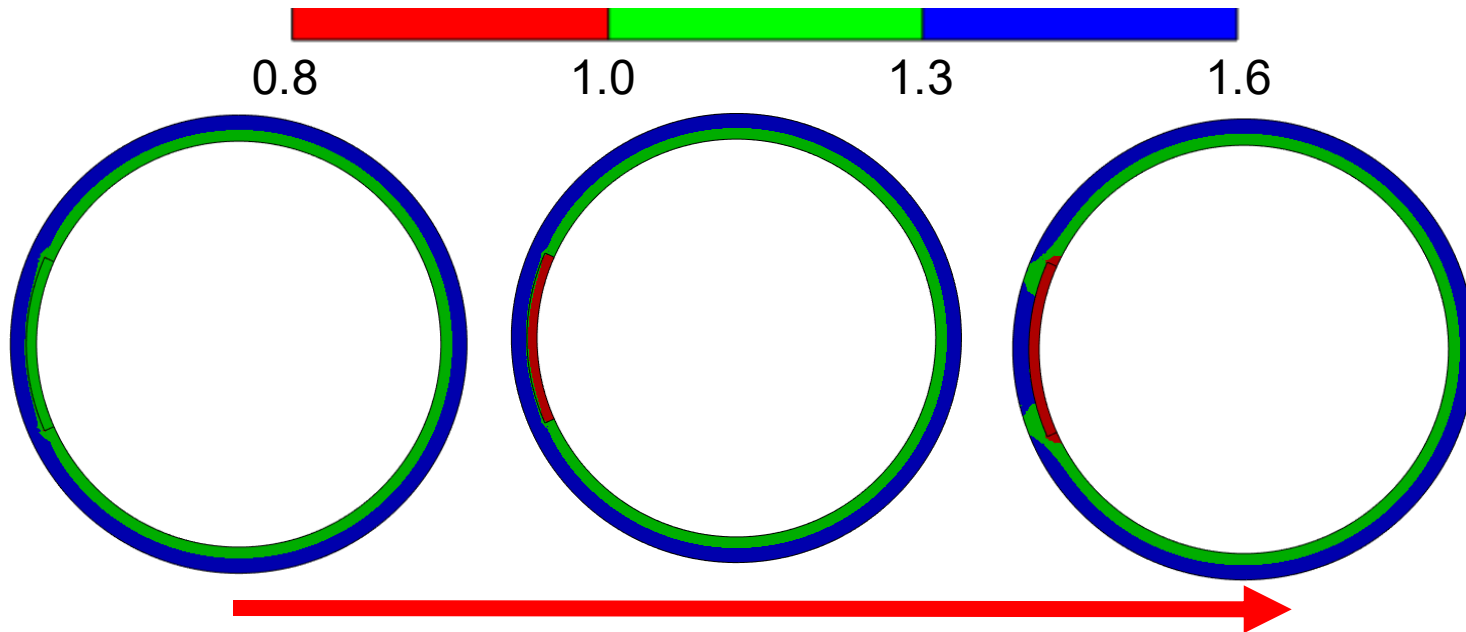


Mud Contamination Results



- The safety factor is evaluated based on the Mohr-Coulomb theory. According to the simulation, shear failure occurs in/around the contaminated cement. Therefore, the well integrity tool should have the ability to detect the shear failure within the cement.

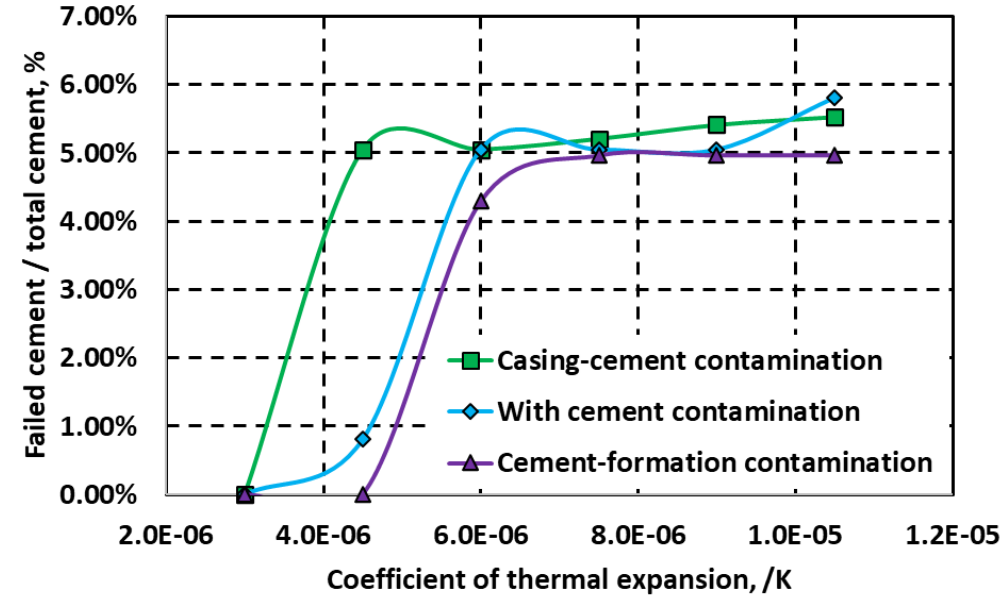
Mud Contamination Results



Coefficient of thermal expansion of contaminated cement increases
 $3E-6/K$ (left); $4.5e-6/K$ (middle); $1.05E-5$ (right)

Casing-cement contamination scenario

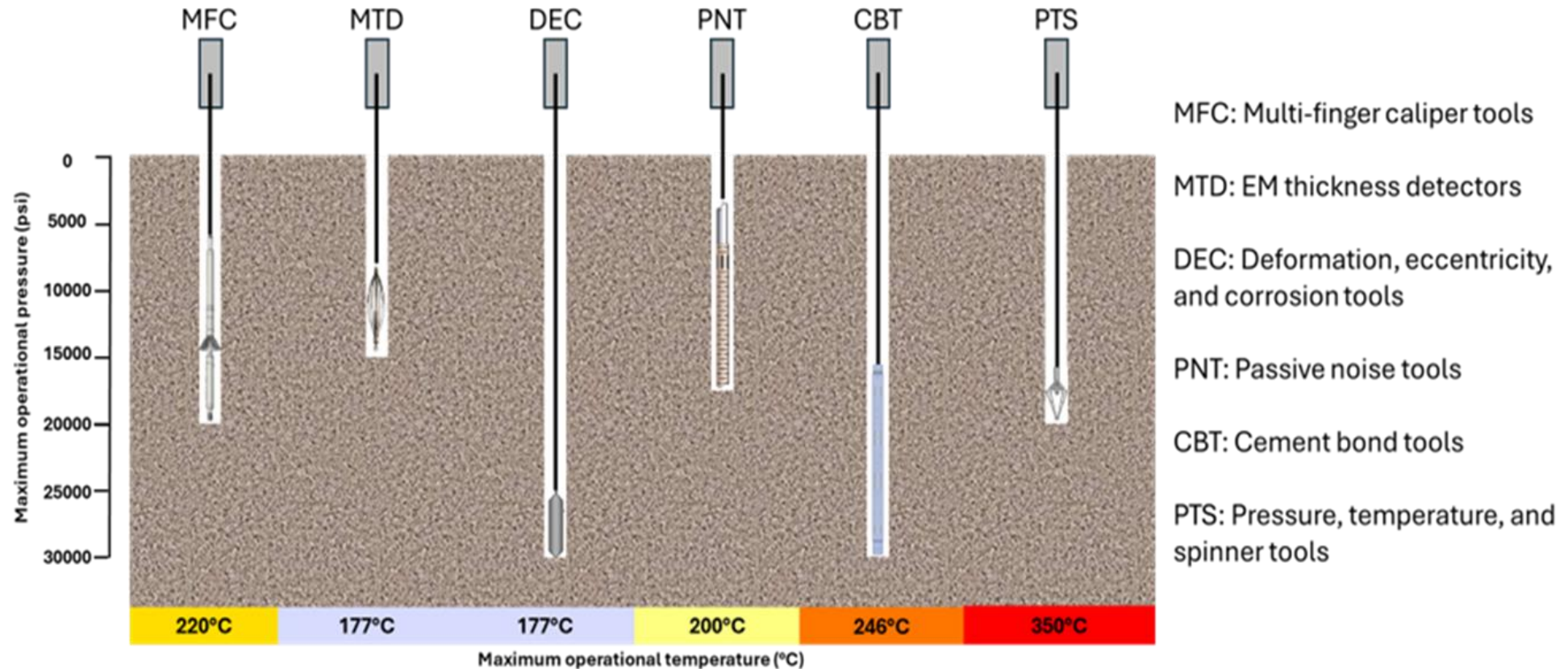
- An increasing CTE results in a high cement failure ratio
- Contaminated cement failed first, then spread to the surrounding areas.



Implication of Monitoring

- Casing-cement debonding:
 - High accurate tool is required (i.e., can detect 20 micrometers fractures in this study. Current tool can detect debonding zones, or microannuli, as small as 100-250 micrometers).
- Corrosion and casing thinning:
 - Detect early-stage casing wall thinning before deformation.
 - Operate reliably under high-temperature, high-corrosion conditions.
- Mud contaminations
 - The tool should have the ability to distinguish which interface is compromised. CBL and VDL only detects the bonding quality.
 - The tool has to detect beyond the casing wall. The cement thickness range for geothermal wells is from 0.375 to 1.5 inches.

Limitations of Current Tools



- Most of tools fail when temperature is higher than 220°C or pressure is higher than 20000 psi.
- Lack of integrated platforms

Conclusions

- The studied defects produce distinct failure signatures and stress concentrations.
- Casing–cement debonding initiates microannulus formation; fractures as small as 20 μm .
- Corrosion and casing thinning influence the stress distribution, accelerating cement failure and debonding.
- Mud contamination alters thermomechanical behaviors. 5% contamination triggers shear failure inside the cement matrix and at interfaces.

Q&A

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