Damage Processes and Recovery Mechanisms in Long-Term Well Integrity

Bill Carey, Meng Meng, Luke Frash

NETL Well Integrity Workshop: Identifying well integrity research needs for subsurface energy infrastructure

25 May 2021
Topics

• Initial State of Stress in Cement
• Computational Models for Wellbore Integrity
• Self-Sealing Processes in Cement
Cement Initial State of Stress: What is it?

- The stress exerted by the cement against its containing walls
- The stress is unknown because cement evolves from a liquid slurry at hydrostatic stress to a solid which involves consumption of pore fluid and volumetric shrinkage
- This stress controls microannulus formation and cement fracturing
- Requires experimental determination
Cement Initial State of Stress: Why do we care?

• All numerical models of cement performance require this as an initial input
• Essential input to determining adequacy of cement design
  - “Can it handle the imposed stresses”
• Needed to evaluate if past operations damaged the well
• Required to evaluate whether existing design is adequate for future operations (as injector or monitoring well or abandoned well)

Initial state of stress: The key to achieving long-term cement-sheath integrity.
Cement Initial State of Stress: Can it be modified?

- Water/cement ratio
- Expansion agents
- Fluid loss control agents (pore pressure effects)
- Curing agents (retarders)
- Etc.
**Triaxial Cement Evaluation Experimental Facility**

1. Cement is poured into vessel as slurry
2. Constant axial stress is applied
3. Liquid cement has hydrostatic pressure
4. Curing of cement changes the stress state

**Controllable Variables Measurement Objective**

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Field</th>
</tr>
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<tbody>
<tr>
<td>Temperature, $T$</td>
<td>Temperature</td>
</tr>
<tr>
<td>Confining pressure, $P_c$</td>
<td>Horizontal rock stress</td>
</tr>
<tr>
<td>Axial stress, $P_a$</td>
<td>Vertical pressure</td>
</tr>
<tr>
<td>Pore pressure, $P_p$</td>
<td>Pore pressure</td>
</tr>
<tr>
<td>Interface stress, $P_i$</td>
<td>Cement-casing stress</td>
</tr>
<tr>
<td>Time, $t$</td>
<td>Waiting on cement</td>
</tr>
<tr>
<td>Cement Formulation</td>
<td>Cement Formulation</td>
</tr>
</tbody>
</table>

Meng, Frash, Carey et al. (in review) "Cement Stress and Microstructure Evolution During Curing in Semi-rigid High-pressure Environments" Cement and Concrete Research
Interpretation of Cement Hydration in Drained Test

Meng, Frash, Carey et al. (in review)

“Cement Stress and Microstructure Evolution During Curing in Semi-rigid High-pressure Environments” Cement and Concrete Research

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Application of Results to Safe Operating Conditions
Impact of Temperature and Pressure Excursions
via thermoporoelastic calculations

Effect of Initial State of Stress

2 MPa

Effect of Cement Permeability

High Perm

5 MPa

Low Perm

Mechanical Modeling of Well Integrity

- **Common Assumptions** (from Jo and Gray 2010)
  - Elastic materials
  - Concentric, circular well
  - Initially bonded
  - Cohesion/tensile strength
  - Plane strain

- **Model complexity**
  - 2D versus 3D
  - Poroelastic effects
  - Thermal effects
  - Failure mechanisms
  - Plasticity

- **Model types**
  - Finite element
  - Analytical (e.g., Frash and Carey 2019; Meng et al. 2021)

- **Objective**: calculate failure as function of thermal/mechanical stresses

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Experiments, Observations, and Current Understanding of Self-Sealing Processes in Cement

Experiments, Observations, and Current Understanding of Self-Sealing Processes in Cement

Cited work

Experiments

This study: Nguyen et al. (2020) Int. J. Greenh. Gas Control. 100, 103112

Modeling


Experiment Details

- Constant flow (CF) and Constant Pressure (CP) conditions shown
- Use of hydraulic diameter and fluid residence time allows comparison among 9 experiments and 3 models
- Diagram delineates regions that are strongly sealing vs. strongly non-sealing
- Our experiments are primarily in the transitional to non-sealing
- Results allow prediction of fracture sealing conditions

How Much Cement is Needed to Seal a Microannulus?
As function of Pressure Gradient
Research Needs on Cement Self-Sealing

• How best to make use of constant flow-rate experimental data
• What scaling issues exist in going from experiments to wells (length, flow rate, large cross-section flow channels)?
• 3D numerical simulations of fracture sealing
• What limits exist for closing large apertures
• What is the affect of cement formulation? CO\textsubscript{2}-resistant cements?
• Self-sealing under multiphase conditions
Conclusions

• We are just now obtaining data on initial state of stress—much more to understand
• The state of stress is critical to design and analysis of cement performance
• Pore pressure plays a critical role in cement stress
• Excellent infrastructure for well models exist but a great need to validate these simulations, e.g., plastic behavior
• Cement self-sealing has been amply demonstrated but hasn’t quite developed into a predictive tool

Acknowledgements

• Thank you to the organizing committee
• I’d like to acknowledge fruitful discussions with many colleagues on this topic