Quantification of wellbore leakage risk using non-destructive borehole logging techniques

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U.S. Department of Energy
National Energy Technology Laboratory
Carbon Storage R&D Project Review Meeting
Developing the Technologies and Infrastructure for CCS
August 20-22, 2013
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- J. William Carey, Los Alamos National Lab,
- Mike Celia, Princeton University,
- Nikita Chugunov, Schlumberger-Doll Research,
- Sarah Gasda, Uni Research
- Susan Hovorka, University of Texas as Austin (GCCC, BEG)
- T.S. Ramakrishnan, Schlumberger-Doll Research,
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- James Wang, Princeton University

- Denbury Onshore
- Rocky Mountain Oilfield Testing Center
Presentation Outline

- Benefits to the program
- Project overview
- Summary
- Accomplishments
- Appendix
Benefit to the Program

• Develop and validate technologies to ensure 99 percent storage permanence.
  – This research project is developing methods to estimate the permeability of potential leakage pathways in a well between casing and the formation. This technology will provide an improved understanding of well leakage pathways and well leakage risk. This technology contributes to the Carbon Storage Program’s effort of ensuring 99 percent CO₂ storage permanence (Goal).
Project Overview: Goals and Objectives

- Investigate methods to establish average flow parameters (porosity/permeability/mobility) from individual material properties measurements and defects in a well.
- Investigate correlation between field flow-property data and cement logs – used to establish flow-properties of well materials and well features using cement mapping tools.
- Establish a method that uses the flow-property model to analyze the statistical uncertainties associated with individual well leakage to provide basis for risk calculation uncertainty.
Project Wells (MS, 2013)

1945
68 yrs
Potential Avenues for Leakage

LEGEND
- Cement
- Formation
- Drilling mud
- Well casing
- Open casing
- Migrating CO₂
Create Flow Property Maps from Cement Maps

Log and Lab Measurements → Flow Property Map

Plug into:

\[
k = \frac{d^2}{32b} \frac{\Delta V_L}{V_{L0}}
\]

\[
p = \frac{1}{b} \left(1 - \frac{V_L}{V_{L0}}\right)
\]

\[
b = 15 \frac{1 - v_0}{7 - 5v_0}
\]

\[
E = \text{Young’s Modulus}
\]

\[
V_L = \text{longitudinal acoustic velocity}
\]

\[
d = \text{capillary tube diameter}
\]

\[
\nu = \text{Poisson’s Ration}
\]

\[
\rho = \text{Porosity}
\]

Note: the subscript 0 denotes 0-porosity cement
Data Collection

- **Logging Tools**
  - Isolation Scanner* cement evaluation service
  - SCMT* slim cement mapping tool

- **Testing and Sampling Tools**
  - CHDT* cased hole dynamics tester
  - MDT* modular formation dynamics tester
  - MSCT* mechanical sidewall coring tool
Well Logging and Sampling

- Perforation for VIT test
- CHDT Sample Point
- Fluid Sample Point
- Point permeability measurement
- Sidewall Core Sample
- VIT Interval
- Wellbore and casing walls
- Well Cement
- Geologic Formation
Well Sampling – CHDT
CHDT Analysis

\[ k = 125 \ \mu D \]

**Curve Fit Results**
- **Fit Type:** least squares fit
- Coefficient values ± one standard deviation:
  - \( y_0 = 1824.7 \pm 0.497 \)
  - \( A = -856.69 \pm 0.873 \)
  - \( \tau = 138.71 \pm 0.345 \)
- **Constant:** \( X_0 = 5224 \)

**Graph Details**
- **X-Axis:** Time, sec
- **Y-Axis:** Pressure, psi
- **Legend:**
  - Quartz Gauge Pressure (○)
  - Fit (–)

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*Note: The diagram shows a graph with pressure values increasing over time, illustrating the CHDT analysis with a specific permeability value.*
Well Testing – MDT

Flow path

MDT measurement point
Perforated zone

Upper packer
Perforated zone
MDT measurement
Pressure equalization line

Lower packer
Best-fit model results to VIT data from the 46-TPX-10 (left) and CC1 (right) wells.

- Shown (in red) are the measured MRPA data in blue and the model results obtained from parameter estimation. The 95% confidence in the best-fit solution is bracketed by the dotted red lines.
Sidewall Cores

CC1 1111.9 m (3648 ft)

46-TPX-10 1220.7 m (4005 ft)

CC1 1051.6 m (3450 ft)

46-TPX-10 1223.8 m (4015 ft)

CC1 960.1 m (3150 ft)
Permeability vs. porosity for cement samples

- CC1 Cement Samples
- 43-TPX-10 Cement Samples
- 46-TPX-10 Cement Samples
Permeability

Comparison of cement sample and VIT permeability

Permeability (mD)

- CC1 910.4 m (2987 ft)
- CC1 VIT 908.3 - 911.4 m (2980 - 2990 ft)
- 46-TPX-10 1220.7 m (4005 ft)
- 46-TPX-10 VIT 1222.2 - 1225.3 m (4010 - 4020 ft)
## Lab Cements

*TerraTek* rock mechanics and core analysis services

<table>
<thead>
<tr>
<th>Well</th>
<th>Unique number</th>
<th>Sample Number</th>
<th>Pressure (psi)</th>
<th>Temperature (°F)</th>
<th>W/C</th>
<th>Density (PPG)</th>
<th>Cement</th>
<th>Length (mm)</th>
<th>Diameter (mm)</th>
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<tbody>
<tr>
<td>Industry Well 1</td>
<td>9</td>
<td>IW1-14.9PPG-3</td>
<td>475</td>
<td>89</td>
<td>0.5</td>
<td>14.9</td>
<td>35/65</td>
<td>95.5</td>
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<td>35/65</td>
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<td>89</td>
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<td>13.65</td>
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<td>26</td>
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<td>89</td>
<td>0.7</td>
<td>13.65</td>
<td>35/65</td>
<td>98</td>
<td>26</td>
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<td>89</td>
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<td>IW1-12.8PPG-3</td>
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<td>475</td>
<td>89</td>
<td>1.1</td>
<td>12.18</td>
<td>35/65</td>
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<tr>
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<td>IW1-12.18PPG-2</td>
<td>475</td>
<td>89</td>
<td>1.1</td>
<td>12.18</td>
<td>35/65</td>
<td>91</td>
<td>26</td>
</tr>
</tbody>
</table>
CC1 Field Porosity Data and Estimates

\[ p = \frac{1}{b} \left( 1 - \frac{V_L}{V_{L0}} \right) \]

<table>
<thead>
<tr>
<th>Material</th>
<th>Sample Depth (ft)</th>
<th>Ambient Porosity</th>
<th>( V_L ) (P-Wave Velocity) (ft/s)</th>
<th>Estimated Porosity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement</td>
<td>2260</td>
<td>0.654</td>
<td>7333</td>
<td>0.654</td>
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<td>Cement</td>
<td>2410</td>
<td>0.6417</td>
<td>7582</td>
<td>0.630</td>
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<td>Cement</td>
<td>2987</td>
<td>0.6334</td>
<td>7980</td>
<td>0.591</td>
</tr>
<tr>
<td>Cement</td>
<td>2995</td>
<td>0.6635</td>
<td>6971</td>
<td>0.690</td>
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<tr>
<td>Cement</td>
<td>3648</td>
<td>0.5568</td>
<td>7812</td>
<td>0.607</td>
</tr>
</tbody>
</table>

**Dried samples**

\[ - = 0.11 L \]

**Constants**

\[
\begin{array}{l}
V_{L0} = 14003 \\
b = 0.7277
\end{array}
\]
Permeability Estimates

43-TPX-10 Permeability vs P-wave Velocity

- Estimated k Dried
- Measured k
- Estimated K, As Received
- Lab sample 7A estimate
- Lab Sample Measured Data
- Max and Min Estimates (pore dia)
- Max and Min Estimates (P-Wave)
Density Functions
Summary

– Log results, taken in conjunction with the lab measurements, indicate that interfaces and/or problems with cement placement due to eccentricity provide preferential flow paths for fluids, which can increase the effective permeability of the barrier several orders of magnitude above the permeability of intact cement.

– The results of the maps created using logging tools indicating that the cement condition and bond are generally good, identify a need for more research to understand how logs can be used to predict effective well permeabilities such as those measured by the VITs in this study.

– The next steps are to collect and analyze logs, cores, and samples at Ella G Lees 7 and incorporate them into the project (In progress). And use the PDFs and CDF to study risk assessment techniques in old wells.
Accomplishments to Date

- Samples, tests, and logs in 6 old wells
- Modeling of point permeability measurement
- Modeling of the VIT measurements
- Modeling of cement permeability using ultrasonic log data
- Development of methods to create CDFs and PDFs
Appendix

– These slides will not be discussed during the presentation, **but are mandatory**
Bibliography

To date, no manuscripts have been submitted for peer review. However, The following conference proceedings from the project are available:

