Optimizing Wellbore Integrity in Well Construction

Jim Kirksey
Well Engineering Manager
Schlumberger Carbon Services
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1. General Observations
   Cementing over time

2. Zonal Isolation
   Cement from Placement to Abandonment

3. Cement Design
   Accounting for the unknowns

3. Looking forward
Evolution - Cementing

- **Early AD**: Clays, Quicklime, Pozzolans
- **1824**: Portland Cement Patent
- **1906**: Portland Cement used in Oil Well
- **1917**: Oil Well Cements Commonly Available
- **1948**: API Code 32 “API Code for Testing Cements Used in Oil Wells
- **1956**: API Recommended Practice 10B - Tables
- **1980**: Basic Mechanism for annular fluid flow defined
- **1983**: Gas Migration Design tools
- **1988**: Computerized Cement Simulation
- **1993**: Basic Placement Simulators
- **2000**: Mud Removal Simulations
- **2005**: Poro-Mechanical Models
- **2010**: API Standard 65 Part 2
- **2012**: Drilling Final Rule, Draft of API 90, Norsok D010, others

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**Table E.1 — Casing well simulation tests**

<table>
<thead>
<tr>
<th>Depth (ft)</th>
<th>Temperature (°F)</th>
<th>Temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100 ft</td>
<td>40</td>
<td>50</td>
</tr>
<tr>
<td>200 ft</td>
<td>80</td>
<td>30</td>
</tr>
<tr>
<td>300 ft</td>
<td>120</td>
<td>45</td>
</tr>
<tr>
<td>400 ft</td>
<td>160</td>
<td>70</td>
</tr>
<tr>
<td>500 ft</td>
<td>200</td>
<td>90</td>
</tr>
<tr>
<td>600 ft</td>
<td>240</td>
<td>110</td>
</tr>
</tbody>
</table>

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**Figure 1 — Schematic of cement placement in a wellbore**

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**Figure 2 — Typical cement job in an oil well**

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**Figure 3 — Cementation in a gas well**
Cementing Fundamentals

Types of jobs: Surface, Intermediate, Long String, Liner, Squeeze, Plug

Additives: Thick, Thin, Heavy, Light, Low fluid loss, Expanding, Temperature degradation, (Better cementing through chemistry)

Placement: Slow, Fast, In Between

Simulators: Flow Loops, Temperature, U-tube, Placement,

Jewelry and Control lines: Will become common DHG, DTS, DAS

Regulations: Post Deepwater Horizon, Gasland, Shale gas expansion, CO$_2$ Sequestration the world is changing

Wellbore Integrity will become more and more an issue
Well Cementing is simply the displacement by cement of the drilling fluid in the well casing-open hole annulus, so why are there failures?

1. Execution
   Equipment, people
2. Incomplete Mud Removal (Design)
3. Flow after placement (Design)
4. Inappropriate slurry (Design)
Cementing Failures

Equipment and People
1. Poor selection; inappropriate supplier
2. Equipment failure: Maintenance, catastrophic, rig related
3. People failure: Training and competency, human error, lack of planning, QA/QC process

Design Failures
Not so simple, let’s take a look
Zonal Isolation

From Placement to Abandonment
Mud Removal - Centralization

- **Stand-off**: measure for centralization
- **100%**: casing in the middle of the hole
- **0%**: casing touching one side of the hole

- Flow prefers wide side.
- Major influence on mud removal efficiency

- **Standoff < 75% almost always guarantees a bad cement job**
Mud Removal - Laminar or Turbulent Flow?

Laminar Flow

- Streamline flow, no mingling of parallel layers.
- Flow velocity at solid surface is zero
- Highest flow velocity furthest from surface
- Only shear stress acts at the surface

**NEED **HIGH RHEOLOGY FLUIDS!!!

Turbulent Flow

- Eddies are random in size and direction
- Average direction is the mean flow
- Incident and Shear forces act at the surface

**NEED **LOW RHEOLOGY FLUIDS
Cementing Design – Turbulence

Minimum Turbulent Rate for Cement - 9 5/8” Casing in 12 ¼ OH

- Guage Hole
- 50% Excess
Cementing Design – What if?

Turbulent Flow Regime

_Hole Size is Bigger Than Expected_
- Won’t Be Turbulent – Mud Channel

_Formation Weaker Than Expected_
- Can’t Slow Down – Losses

_Problems Reaching Desired Rate_
- Won’t Be Turbulent – Mud Channel

Laminar Flow Regime

- Probably OK

- Slow Down

- Probably OK

Slurry and Spacer Design Critical to be based on actual well conditions !!!!!!!
Designing a Cement Job

• Check for an efficient mud removal to prevent mud \textit{channeling} and to ensure good \textit{zonal isolation}
  
  Ensure a flat interface between fluids
  Avoid stationary mud around the annulus
  Ensure good wall cleaning

• Optimize fluid properties (density, viscosity hierarchy)
• Optimize the pumping rate/velocity, yield stress and PV
• On the way down: Mechanical plugs
• Optimize casing centralization
• Optimize pre-flushes contact time, volume, velocity and flow rate
Mud Removal – Density-Viscosity Hierarchy (Ryan et al. 1992)

Slurry density/viscosity > Spacer density/viscosity > Mud density/viscosity

- Flattens fluid interface and improves interface stability.
- Minimum density difference of 10%.
- Best spacer density halfway between mud and slurry density.
- Less effective in highly deviated sections
- Counterproductive in pipe – Use Wiper Plugs
1-D Laminar Flow Design Criteria (SPE 24977) 1992

2-D Computational Fluid Dynamics (SPE 68959) 2002

Future will be Integrated Model 2014
Rheology, Geometry, Temperature
Zonal Isolation – Cement Phases

1. **Placement**
   - Liquid
   - Minutes
   - 

2. **During Set**
   - Semi Solid
   - Hours → Days
   - Mud Removal
     1. Centralisation
     2. Rheology
     3. Density
   - Fluid Migration
     1. CSGS
     2. Additives

3. **Post-set**
   - Solid
   - Months → Years
   - Mechanical Properties
     1. Compressive Strength
     2. Youngs’ Modulus
Gas Migration – Critical Static Gel Strength

- Initial Hydrostatic Pressure
- Gas Migration
- Critical Static Gel Strength
- Bottom Hole Pressure
- Reservoir Pressure
- Cement Static Gel Strength
- After this point fluid can invade
  - Hydrostatic > Pore
  - Hydrostatic < Pore
  - Cement Set
  - CSGS
  - Reservoir Pressure
  - Cement Set

Time

Bottom Hole Pressure

Cement Static Gel Strength
Fluid Migration – Critical Static Gel Strength

\[ CSGS = \frac{OBP \times 300 \times D_{\text{eff}}}{L} \]

**Definitions:**

- **OBP**  Overbalance Pressure
- **300**  Conversion Factor
- **L**    Length of Cement Column
- **\( D_{\text{eff}} \)**  Effective Diameter
- **\( D_{\text{OH}} \)**  Open Hole Diameter
- **\( D_{\text{C}} \)**  Casing Diameter

\[ D_{\text{eff}} = D_{\text{OH}} - D_{\text{C}} \]
Fluid Migration – Slurry Design

1. Faster liquid to Solid Transition
   - Dispersants
   - Antigelling agents

2. Prevent Downhole Pressure Loss
   - Foamed cement
   - Downhole gas generation

3. Reduce Permeability of Semi Solid Cement
   - Latex
   - Microsilica
Gas Migration – Industry Solution

- Identify Mechanism of Invasion *(SPE 11982)*
  - C. 1980

- Invasion Risk Software *(SPE18622)*
  - C. 1989

- Slurry Design for High Risk Zones *(SPE 17258)*
  - C. 1988
Zonal Isolation – Cement Phases

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     - 1. CSGS
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3. **Post-set**
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   - Mechanical Properties
     - 1. Compressive Strength??
     - 2. Youngs’ Modulus
Why Mechanical Analysis?

A well is a stressful environment

- Production/Injection
- Temperature changes in upper casings during production/injection
- Pressure changes: drilling, production, injection
- Permanent well abandonment
- Formation changes/tectonic activity
- Well completion/perforation/stimulation
Stresses on the Cement Sheath

Tensile cracks
- Wellbore pressure increase
- Wellbore temperature increase
- Cement shrinkage

De-bonding steel/cement interface
- Wellbore pressure decrease
- Temperature decrease
- Casing movement
- Cement expansion

De-bonding cement/rock interface
- Formation stress decrease
- Wellbore pressure decrease
- Hydraulic fracturing
- Cement shrinkage

Potential Results
- Loss of Well Integrity
- Sustained Casing Pressures
- Collapsed Casing
Cement Mechanical Failure

- Pressure or Temperature Increase
- Soft Formation
- Casing
- Cement

Diagram showing a cylindrical structure with cracks and labels indicating the points of failure due to pressure or temperature increase, as well as the involvement of soft formation and casing.
Work Goes on to Improve Cement Slurries

Understanding of Nano/Microstructure of set cements enables our capabilities to create next generation of materials

- First Result: Solution to Coarsening Effect in HPHT cement has potential for HO and Geothermal applications
- Composite materials (Organic-Inorganic) = (Elasticity-Strength) -> Self Sealing

Expanding cement combined to Poro-Mechanical Model -> Sealing Properties

Slurries designed for specific purpose (CO₂ Resistance)

Better understanding of the temperature/pressure profile of setting cement
Well Cementing Design

Accounting for the unknowns
Simulation

Flow Loops 1940s  *First indication of the importance of mud removal*
Circulating Temperature equations
U – tube simulator 1970s
1-D Flow simulation 1980
Gas Migration late 1980s
2-D Simulators 1990
2-D Computational Fluid Dynamics 2001
Building the complete model 2013  *Still trying to understand mud removal*

*It’s all the unknowns that are hard to simulate*
Effects of Ovality on Zonal Isolation

Caliper

Zone of Interest

Channeled Cement

Cement Evaluation Logs
Quantitative Assessment of Ovality/Washout

Outside hole (OH) diameter = 8 3/4-in bit
Casing diameter = 7 in
Average rugosity = 5/8 to 3/4 in

- Annular volume per foot:
  - 8 3/4-in OH = 0.0268 bbl/ft
  - 9 3/8-in OH = 0.0378 bbl/ft
  - 9 1/2-in OH = 0.0401 bbl/ft

- Annular volume per 20-ft interval:
  - 8 3/4-in OH = 0.536 bbl
  - 9 3/8-in OH = 0.756 bbl + 41%
  - 9 1/2-in OH = 0.802 bbl + 50%
Conventional Free-Standing Model

Using single arm caliper or assuming gauge hole
Utilizing OH Caliper to Optimize Design

Using multi-arm caliper
Cement Design Flow Path

Roles:
- Cementing Engineer
- Drilling Engineer
- Petrophysicist
- Wireline Engineer
- Project Coordinator
- Lab Engineer

Initial Cement Design

- WL Log
- LWD Data
- Caliper Processing

Real-Time (RT) Iterative Updates to Cement Job Design

- Conventional Lab Testing
- Contamination Tests

Final Cement Job Design and Centralizer Arrangement

- Drilling Adjustments
- CBL*/USI* or Isolation Scanner*

Cement Job Execution

- RT Survey
- RT Caliper
- RT Petrophysics

Post job Evaluation of Cement Execution

- Final Results of Cement Isolation

Cement Properties Report

Client Review
Integrated Solution to Zonal Isolation

Results when integrating all known information into the cementing design
1. Work remains in understanding cement placement including circulating temperature
2. Instrumentation external to casing will help in improving the above
3. Research in molecular and nano technologies will improve slurry robustness
4. Regulations will only become stricter with more oversight
5. Greater accountability for both operators and service providers
Questions?