Mechanical Integrity Testing Workshop

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Technical Advisor’s Halliburton
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Safety Moment!

• With wild swings in Temperatures about to start happening this time of year.

• Keep your tire pressure within the recommended range for your vehicle.
Agenda

• Introduction to Open Hole Logging
• Primary Cementing 101
• Interpreting Cement Evaluation Tools
• Remedial Cementing 101
• Casing Inspection 101
• New Technologies
Introduction to Open Hole Logging
Electric Well Logging

- The practice of making a detailed record of the geologic formations penetrated by a borehole.
  - Usually Continuous but can be Stationary
  - Includes Testing and Sampling Services
Open Hole Logs, What Information Do We Want To get. Everything!
What we usually get!
Effective Porosity
Volume of Rock Matrix
Volume of Shale
Volume of Hydrocarbons
Volume of Water

Traditional Rock - Shale Model (with Hydrocarbons)

Volume_{Total} = V_{RM} + V_{SH} + V_{W} + V_{HC}
Open Hole Borehole Conditions

- $h$: Bed Thickness
- $h_{mc}$: Mudcake Thickness
- $d_i$: Diameter of invasion (step profile)
- $d_h$: Borehole Diameter
- $d_{zf}$: Diameter of Flushed Zone
- $d_{zt}$: Diameter of Transition Zone

- $R_m$: Mud Resistivity
- $R_{mc}$: Mudcake Resistivity
- $R_{mf}$: Mud Filtrate Resistivity
- $R_s$: Adjacent Bed Resistivity
- $R_t$: True Resistivity
- $R_{xo}$: Flushed Zone Resistivity
- $R_w$: Formation Water Resistivity

- $S_h$: Hydrocarbon Saturation
- $S_o$: Water Saturation
- $S_{wo}$: Flushed Zone Water Saturation
- $S_{rt}$: Residual Hydrocarbon Saturation
Gamma Ray

[Diagram showing a rock matrix and a shale block with an arrow indicating the path of a gamma ray.]
Gamma Ray Detection

- Passive Detection
  - Geiger-Mueller Detectors
  - Scintillation Detectors
    - Detect Naturally Occurring Gamma Ray
GR Environmental Corrections

- Corrections
  - Borehole Diameter
  - Mud Weight
  - Washout
  - Standoff
  - Tool Position
Gamma Ray
Neutron Apparent Porosity

Energy Decay of Neutrons

Porosity Determination
Neutron Limestone Porosity versus Porosity

DSN-II
Density Apparent Porosity
Sonic Apparent Porosity

- Measures Sound Travel Time
  - $\Delta T_c$ is Delta Time for P-wave
  - $\Delta T_s$ is Delta Time for S-wave

$$\phi_{Sonic} = \frac{\Delta t_{Log} - \Delta t_{Matrix}}{\Delta t_{Fluid} - \Delta t_{Matrix}}$$
Resistivity

- Matrix material High resistivity
- Oil High resistivity
- Gas High resistivity
- Formation waters Usually Low resistivity
- Water-based mud filtrate can be Low or High resistivity
- Oil-based mud filtrate High resistivity
- Resistivity
  - Hydrocarbon Indicator
  - Invasion Indicator
  - Shale Indicator
- $R_t$
  - Environmentally Corrected Deep Resistivity
Formation Dip, Imaging, etc.
Micro Imager
Circumferential Acoustic Scanning
If There is a Problem Production Engineering Will Fix It!

1. **DOES IT MOVE?**
   - No
     - Should it?
       - No
         - No Problem
       - Yes
         - No Problem
   - Yes
     - Should it?
       - Yes
         - No Problem
       - No
Oil and Gas Well Cementing Reasons

- Restrict fluid movement between formations
  - Manage formation pressures
  - Seal off zones (i.e. water, thief, producing)
- Bond and support the casing
  - Protect from corrosion
  - Protect from shock loads

Source: Society of Petroleum Engineers, Cementing Monograph Volume 4, 1990
Cement History

- Egypt
  - Plaster of Paris (CaSO₄ + Heat)
- Greece
  - Lime (CaCO₃ + Heat)
- Roman Empire
  - Pozzolam-lime reactions
- England
  - Natural Cement (1756)
  - Portland Cement (1824)
- United States
  - Portland Cement (1872)
Raw Materials

• Calcareous Material – Source of lime (CaCO₃)
  • Limestone, Chalk, Coral, Cement Rock, Marble, Seashells
    • 70 to 80%

• Argillaceous Material – Source of silica (SiO₂)
  • Clay, Sand, Shale, Fly Ash, Volcanic Ash, Blast furnace slag
    • 20 to 30%

• Gypsum (CaSO₄·2H₂O)
# Chemical Compounds in Portland Cement

<table>
<thead>
<tr>
<th>Compound</th>
<th>Formula</th>
<th>Standard Designation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tricalcium aluminate</td>
<td>$3\text{CaO} \cdot \text{Al}_2\text{O}_3$</td>
<td>$\text{C}_3\text{A}$</td>
</tr>
<tr>
<td>Tricalcium silicate</td>
<td>$3\text{CaO} \cdot \text{SiO}_2$</td>
<td>$\text{C}_3\text{S}$</td>
</tr>
<tr>
<td>B-dicalcium silicate</td>
<td>$3\text{CaO} \cdot \text{SiO}_2$</td>
<td>$\text{C}_2\text{S}$</td>
</tr>
<tr>
<td>Tetracalcium aluminoferrite</td>
<td>$3\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot \text{Fe}_2\text{O}_3$</td>
<td>$\text{C}_4\text{AF}$</td>
</tr>
</tbody>
</table>
## API Classifications of Cements

<table>
<thead>
<tr>
<th>API Classification</th>
<th>Mixing Water (gal/sk)</th>
<th>Well Depth (feet)</th>
<th>Static Temp (°F)</th>
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</thead>
<tbody>
<tr>
<td>A (Portland)</td>
<td>5.2</td>
<td>0 – 6000</td>
<td>80 – 170</td>
</tr>
<tr>
<td>B (Portland)</td>
<td>5.2</td>
<td>0 – 6000</td>
<td>80 – 170</td>
</tr>
<tr>
<td>C (High Early Strength)</td>
<td>6.3</td>
<td>0 – 6000</td>
<td>80 – 170</td>
</tr>
<tr>
<td>D (Retarded)</td>
<td>4.3</td>
<td>6,000 – 12,000</td>
<td>170 – 260</td>
</tr>
<tr>
<td>E (Retarded)</td>
<td>4.3</td>
<td>6,000 – 12,000</td>
<td>170 – 260</td>
</tr>
<tr>
<td>F (Retarded)</td>
<td>4.5</td>
<td>10,000 – 16,000</td>
<td>230 – 320</td>
</tr>
<tr>
<td>G (Basic)</td>
<td>5.0</td>
<td>0 – 8,000</td>
<td>80 – 200</td>
</tr>
<tr>
<td>H (Basic)</td>
<td>4.3</td>
<td>0 – 8,000</td>
<td>80 – 200</td>
</tr>
<tr>
<td>J</td>
<td>4.9</td>
<td>12,000 – 16,000</td>
<td>260 – 330</td>
</tr>
</tbody>
</table>
Slurry Additives

• Accelerators
• Retarders
• Fluid Loss
• Dispersants
• Light Weight
• Heavy Weight
• Defoamers
• Lost Circulation
• Free Water
• Bond Improving
Purpose of Cementing

• Zonal Isolation
  • Well Control
  • Protects the environment
  • Prevents blowouts
• Casing protection against
  • Corrosion
  • Drilling Shocks
  • Burst/Collapse
• Strengthen Casing
• Plug/Abandonment
Material Storage

- Bulk Silos
- Sacks/Pallets
Scale and Blending

- Cement and additives are measured by weight
- Scale Tanks have scales to monitor tank weight
- Bend tanks used as “Mixing pots”
Admix Hopper

- The additives that are not stored in bulk are added to the scale tank threw the admix hopper.

- Material dumped via bag directly into hopper.

- Uses vacuum to move materials over to the scale tank.
Control System

- Entire process controlled from one station
- PLC Controlled – fully automated
- Air Compressors
  - one to pressure up the tanks
  - one to pull vacuum
  - a high pressure compressor to open and close valves
Process Layout

Scale Tank

Blending Tank #1

Blend Tank #2

Storage Tanks

Admix Hopper

Waste Tank

Bulk Tank
Loading Procedure
The 1/3, 1/2, 1/3, 1/2, 1/3 Loading Method

“Sandwich”

Bulk
Additives
Bulk
Additives
Bulk
Cement Placement: Process Basics

- High-rate mixer blends cement, water and chemicals into a slurry
- The slurry is pumped down through steel casing, then up through the annulus
Cement Placement: Process Details

- Plug separates cement slurry from the well fluids to keep it from being contaminated.
- Like a squeegee, plug helps displace the cement, forcing it cleanly through casing.

Society of Petroleum Engineers, Cementing Monograph Volume 4, 1990
Equipment
Interpreting Cement Evaluation Tools
Common Terms

- Formation
- Mud
- Casing
- Cement
- Channels
- Free Pipe
- Cement to Pipe Bond
- Cement to Formation Bond
- Microannulus
- Formation
- Casing
Cement Bond Types and Tools

• Two basic cement bonds
  • Pipe to cement bond
  • Cement to formation bond

• Two basic types of cement evaluation tools
  • Sonic
    • Conventional cement bond log (CBL)
      • Cement to formation bond
      • Cement to casing bond
    • Modified CBLs for expanded casing to cement evaluation.
  • Ultrasonic
    • Casing to cement bond and Casing Inspection
Standard Cement Bond Tools

• Cement Bond Log (CBL)
  • Circumferential averaged bond
  • Cement-to-Pipe bond
    • Amplitude
    • Attenuation
    • Acoustic waveform
  • Cement-to-Formation
    • Acoustic waveform

• Radial Bond Log
  • Amplitude
Cement Bond Log (CBL)

- Single transmitter
- Two receivers
- Circumferential averaged data
  - Omni-directional transmitter and receivers
  - No indication of radial continuity of bonding or channels

Physics of measurement
- Transmitted energy
- No practical mud weight limitation
Cement Bond Log (CBL) Measurements

• Data from the 3 foot receiver
  • Pipe amplitude
  • Attenuation
  • Transit time or travel time

• Data from the 5 foot receiver
  • Waveform data
Compressional Wave P-Waves

- The only mechanism of acoustic energy transport in gases and liquids.
Shear Wave S-Waves

- Common mechanism of energy transport for ridged bodies and for surfaces
Transmitter

MUD/FLUID 189-208 μsec/ft

CASING 57 μsec/ft

CEMENT 100 μsec/ft

FORMATION 40-140 μsec/ft

COMPOSITE
Amplitude and Travel Time

- **Attenuation**
  - Inversely proportional to Amplitude
  - How fast the signal will die out
    - Low Attenuation = lack of cement
    - High Attenuation = cement
Amplitude

• Measured at one receiver 3 feet away from the transmitter

• Indication of pipe to cement bond

• Used in determination of cement bond index

\[ BI = \frac{\log(A_{fp}) - \log(A_{ls})}{\log(A_{fp}) - \log(A_{100\%})} \quad \quad BI_{\text{linear}} = \frac{(A_{fp} - A_{ls})}{(A_{fp} - A_{100\%})} \]

BI = bond index
Afp = free pipe amplitude
Als = the measured amplitude
A100% = what is considered to be 100% bonding
### Typical Amplitude and Travel Time Readings

<table>
<thead>
<tr>
<th>CASING SIZE (in)</th>
<th>CASING WEIGHT (lb/ft)</th>
<th>TRAVEL TIME (μs)</th>
<th>AMPLITUDE (mV)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>1-11/16&quot; TOOL</td>
<td>3-5/8&quot; TOOL</td>
</tr>
<tr>
<td>4-1/2</td>
<td>9.5</td>
<td>252</td>
<td>233</td>
</tr>
<tr>
<td></td>
<td>11.6</td>
<td>250</td>
<td>232</td>
</tr>
<tr>
<td></td>
<td>13.5</td>
<td>249</td>
<td>230</td>
</tr>
<tr>
<td>5</td>
<td>15.0</td>
<td>257</td>
<td>238</td>
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<td></td>
<td>18.0</td>
<td>255</td>
<td>236</td>
</tr>
<tr>
<td></td>
<td>20.3</td>
<td>253</td>
<td>235</td>
</tr>
<tr>
<td>5-1/2</td>
<td>15.5</td>
<td>266</td>
<td>248</td>
</tr>
<tr>
<td></td>
<td>17.0</td>
<td>265</td>
<td>247</td>
</tr>
<tr>
<td></td>
<td>20.0</td>
<td>264</td>
<td>245</td>
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<tr>
<td></td>
<td>23.0</td>
<td>262</td>
<td>243</td>
</tr>
<tr>
<td>7</td>
<td>23.0</td>
<td>291</td>
<td>271</td>
</tr>
<tr>
<td></td>
<td>26.0</td>
<td>289</td>
<td>270</td>
</tr>
<tr>
<td></td>
<td>29.0</td>
<td>288</td>
<td>268</td>
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<td>32.0</td>
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<td>284</td>
<td>265</td>
</tr>
<tr>
<td></td>
<td>38.0</td>
<td>283</td>
<td>264</td>
</tr>
<tr>
<td>7-5/8</td>
<td>26.4</td>
<td>301</td>
<td>281</td>
</tr>
<tr>
<td></td>
<td>29.7</td>
<td>299</td>
<td>280</td>
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<tr>
<td></td>
<td>33.7</td>
<td>297</td>
<td>278</td>
</tr>
<tr>
<td></td>
<td>39.0</td>
<td>295</td>
<td>276</td>
</tr>
<tr>
<td>9-5/8</td>
<td>40.0</td>
<td>333</td>
<td>313</td>
</tr>
<tr>
<td></td>
<td>43.5</td>
<td>332</td>
<td>311</td>
</tr>
<tr>
<td></td>
<td>47.0</td>
<td>330</td>
<td>310</td>
</tr>
<tr>
<td></td>
<td>53.5</td>
<td>328</td>
<td>309</td>
</tr>
<tr>
<td>10-3/4</td>
<td>40.5</td>
<td>354</td>
<td>333</td>
</tr>
<tr>
<td></td>
<td>45.5</td>
<td>352</td>
<td>332</td>
</tr>
<tr>
<td></td>
<td>51.0</td>
<td>350</td>
<td>330</td>
</tr>
<tr>
<td></td>
<td>55.5</td>
<td>349</td>
<td>328</td>
</tr>
</tbody>
</table>
Waveform Data

• Provides the basic data for evaluating the quality of the cement sheath

• Delineate cemented from non-cemented sections by interpreting waveforms of acoustic signals

• Horizontal measurement is in time
Wellbore and Waveform Response
Traditional CBL Waveform Displays

- CBL Waveform
- Clipped Travel Time
- MicroSeismicGram (MSG) or Variable Density Log (VDL)
Free Pipe

- Travel time indicates free pipe and good centralization

- High amplitude = free pipe
- Strong casing arrival = free pipe
- Straight WMSG waveforms = free pipe
- Visible chevrons at collars = free pipe
Free to Bonded Pipe

<table>
<thead>
<tr>
<th>GAMMA RAY</th>
<th>TRAVEL TIME</th>
<th>AMPLITUDE</th>
<th>AMPLIFIED AMPLITUDE</th>
<th>CBL WAVEFORM</th>
</tr>
</thead>
<tbody>
<tr>
<td>200</td>
<td>300</td>
<td>0</td>
<td>10</td>
<td>-20</td>
</tr>
</tbody>
</table>

WMSG waveforms = some cement all the way from pipe to formation

Lower amplitude = Some cemented pipe

Weaker casing arrival = some cement around pipe
Excellent Cement Bond

- Amplified amplitude = cemented pipe
- Very weak casing arrival = Good cement around pipe
- WMSG waveforms = cement all the way from pipe to formation
- Changes in waveform response correspond to changes in gamma ray, indicating good cement all the way to the formation
Radial Bond Log

- CBL with an additional sectored receivers
- Provides information on radial continuity of bonding or channels
- Depending upon the above
  - Sectors roughly 2 feet from source
  - 3 ft from source
- Six radial amplitude measurements for 1 11/16” tool.
- Eight radial amplitude measurements for larger tool 3 1/8” tool.
- Some tools have relative bearing sensor
  - High side and low side of hole determination
Radial Bond Tool Waveforms
Radial Bond Log

• With the higher frequency of the radial bond tool, changes in the cement are indicated by changes in the waveform amplitude.

Black and White indicate high amplitudes.

Lower amplitudes colors indicating cement.

Amplitude Image from 8 Segmented Amp. Readings.

Min, MAX, AVE Amp from 8 Segmented Amp. Readings.

Bonded Pipe.
Advanced Cement Bond Tools
Rotating Ultrasonic Transducers

• CAST-F, CAST-M, USIT
  • Cement and casing inspection
    • Azimuthal cement-to-pipe bond
    • Casing inspection
      • Casing internal radius
      • Casing thickness
  • Extensive horizontal coverage
    • 100% horizontal coverage (CAST-F, CAST-M)
    • 36, 72, or 100 Measurements Per Depth (USIT, CAST-V)
Ultra Sonic Cement Evaluation Tools

• Physics of Measurement

• Reflected Ultrasonic energy
  • Two way travel time
    • Casing radius
  • Amplitude of reflected waveforms
    • Casing inspection
  • Frequency of reflected waveforms
    • Casing thickness
  • Evaluation of reflected waveforms
    • Cement evaluation

• Mud weight and type limitation
  • Solids weighting material attenuates the ultrasonic signal
  • Signal attenuation in OBM ≈ 14-16 ppg.
Ultrasonic Wave Propagation
Impedance Values

\[ Z = \rho \times V \]

\[ Z = (\rho_{ppg}/\Delta T_{\mu sec/ft}) \times 36.5 \]
# Impedance Values

<table>
<thead>
<tr>
<th>Material</th>
<th>$V_p$ (km/s)</th>
<th>$V_s$ (km/s)</th>
<th>$\rho_b$ (gm/cc)</th>
<th>$Z$ (MRayls)</th>
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</thead>
<tbody>
<tr>
<td>Fresh water</td>
<td>1.52</td>
<td>0</td>
<td>1.00</td>
<td>1.52</td>
</tr>
<tr>
<td>Salt water (200 Kppm)</td>
<td>1.74</td>
<td>0</td>
<td>1.14</td>
<td>1.98</td>
</tr>
<tr>
<td>Diesel oil</td>
<td>1.25</td>
<td>0</td>
<td>0.80</td>
<td>1.00</td>
</tr>
<tr>
<td>Mineral oil</td>
<td>1.45</td>
<td>0</td>
<td>0.83</td>
<td>1.2</td>
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<tr>
<td>Free gas (mostly methane)</td>
<td>0.38</td>
<td>0</td>
<td>0.001</td>
<td>0.1</td>
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<tr>
<td>Water-based drilling fluid (8 lb/gal)</td>
<td>1.44</td>
<td>0</td>
<td>0.96</td>
<td>1.38</td>
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<tr>
<td>Water-based drilling fluid (16 lb/gal)</td>
<td>1.40</td>
<td>0</td>
<td>1.92</td>
<td>2.69</td>
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<tr>
<td>Oil-based drilling fluid (8 lb/gal)</td>
<td>1.34</td>
<td>0</td>
<td>0.96</td>
<td>1.29</td>
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<tr>
<td>Oil-based drilling fluid (16 lb/gal)</td>
<td>1.20</td>
<td>0</td>
<td>1.92</td>
<td>2.30</td>
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<tr>
<td>10% Porosity sandstone</td>
<td>4.66</td>
<td>2.91</td>
<td>2.49</td>
<td>11.60</td>
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<tr>
<td>30% Unconsolidated sands</td>
<td>3.31</td>
<td>1.94</td>
<td>2.16</td>
<td>6.42</td>
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<tr>
<td>10% Porosity limestone</td>
<td>4.91</td>
<td>2.73</td>
<td>2.54</td>
<td>12.47</td>
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<td>10% Porosity dolomite</td>
<td>5.24</td>
<td>3.06</td>
<td>2.68</td>
<td>14.04</td>
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<tr>
<td>Class H cement (12 lb/gal)</td>
<td>3.1</td>
<td>1.8</td>
<td>1.55</td>
<td>4.8</td>
</tr>
<tr>
<td>Class H cement (16.6 lb/gal)</td>
<td>3.20</td>
<td>1.90</td>
<td>1.94</td>
<td>6.21</td>
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<tr>
<td>Lightweight cement (9 lb/gal)</td>
<td>3.10</td>
<td>1.80</td>
<td>1.55</td>
<td>4.81</td>
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<tr>
<td>Steel</td>
<td>5.90</td>
<td>3.23</td>
<td>7.70</td>
<td>45.43</td>
</tr>
</tbody>
</table>
CAST and CBL

Map indicates free pipe

Channel

WMSG indicates some cement from casing to formation
Bonded Pipe
Cement Evaluation Theory (*ART)

• CBL, Sonic
  • Amplitude
    • High indicates free pipe
    • Low indicates cement
  • Waveform
    • High activity indicates cement
    • Low activity (railroad tracks) indicates free pipe

• Ultrasonic Tools
  • Impedance
    • High impedance indicates cement
    • Low impedance indicates free pipe
Quality Control for Cement Evaluation Tools

• All tools need to be very well centralized

• Each tool will have traces that will relate to QC

• Environmental Effects on Logs
  • Thin cement sheaths
  • Microannulus
  • Borehole shape
  • Fast formations
  • Cement curing time

• Garbage in = Garbage Out
Tool Decentralization Effects
for 1-11/16" CBL Tool
Attenuation Rate vs. Cement Thickness

![Graph showing the relationship between Attenuation Rate (Db/ft) and Cement Thickness (inches).]
Which Cement Evaluation Log is Correct?
The CBL or Scanner?
Both! Cement Sheath IS Very Thin.

Chevron Pattern from First String of Casing

Chevron Pattern from Second String of Casing

Must Have Acoustic Coupling = Cement
<table>
<thead>
<tr>
<th>ECTY</th>
<th>GAMMA</th>
<th>AVZ</th>
<th>DZAVG</th>
<th>AMPLIFIED AMPLITUDE 0</th>
<th>AMPLITUDE 0</th>
<th>CBL WAVEFORM</th>
<th>TOTAL CBL WAVEFORM</th>
<th>IMPEDANCE IMAGE</th>
<th>DERIVATIVE IMAGE</th>
<th>CEMENT IMAGE</th>
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<tr>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>FCBI 0</td>
<td>70</td>
<td>WMSG</td>
<td>WMSGT</td>
<td>ZP</td>
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<td>FCEMBI 1</td>
<td>0</td>
<td></td>
<td></td>
<td></td>
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</tbody>
</table>

ACE Analysis
Radial Bond Microannulus

Changes in wmsg, amplitude image, amplitude, with pressure increase = microannulus
Microannulus 0 and 500 psi

Changes in wmsg, travel time, amplitude with pressure increase = microannulus

Large change in the pipe arrival indicates better bonding suggesting a microannulus
Caliper and Bonding
Fast Formations

When the waveform goes thru the formation faster than thru the pipe it is called fast formation response. On the wmsg the formation signal comes before the casing signal.

Is it a problem?

Should not be, indicates cement is contacting both the casing and formation, thus indicating good bond.
Cement Curing
Collar Responses

<table>
<thead>
<tr>
<th>GAMMA</th>
<th>AMPLIFIED AMPLITUDE</th>
<th>CBL WAVEFORM</th>
<th>CBL DERIVITIVE OR VARIANCE</th>
<th>CBL TOTAL</th>
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<td>0</td>
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<td>0</td>
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</tbody>
</table>

Free Pipe

Free to Bonded Pipe

Microannulus
Foamed Cement 8lb/gal
Remedial 101
Problem Determination

- Why are we squeezing
- Shut off water or gas
- Abandon zone
- Temporarily seal off zone
- Injection Profile Modification
Problem Determination

- Why are we Squeezing
- Repair channel
- Isolate prior to perforating
- Insufficient top of cement
- Repair casing leak
Problem Determination

- Do we need to squeeze now or wait?
- Cost Considerations
- Equipment
- Time Delays
- Well Construction Plans
- Cost
Problem Determination

- What criteria should we use for determining the need to do a squeeze job?
  - Sonic evaluation logs
  - Primary cement job design
  - Primary cement job performance
    - Flow rate
    - Centralization
    - Mud Properties
    - Lost returns during job
  - Experience
  - Offset well data
Problem Determination

- Will a squeeze job do what we want it to do?
- All channels will be filled with some fluid or mud cake
- Mud must be displaced from channels for squeeze to be effective
- Most channels cannot receive cement under squeeze pressure
Squeeze Cementing Myths
Myth – Cement Slurry Enters the Formation Matrix

- Cement average particle size 20-50 microns
- > 2000 md formation permeability required

Fact –
Cement particles are too large to enter the matrix of most formations
Myth – Squeeze Cementing Produces a Horizontal Pancake of Cement

Fact

- Fracture orientation is normally vertical rather than horizontal
- Fracture may be an angle to the wellbore in deviated wells
Tri-Axial Loading of Rocks

- Fracture orientation is perpendicular to the least principle stress
- Least principle stress is normally horizontal
- Most induced fractures are vertical
Myth – All Perforations are Open During Injection

Fact

- Perforations may be partially plugged
- Injection pressure of perforations varies
- Cement will take the path of least resistance
Myth – High Final Squeeze Pressure is Necessary

Fact

- Final Squeeze Pressure Does not Need to Equal Future Working Pressure (Why?)
- Squeeze Pressure is Applied Across Node Before Cement Develops Compressive Strength
- Fracture May be Created
- Productivity May Be Damaged
- High Pressure Does not Insure Placement in Desired Location
SQUEEZE TECHNIQUES
Squeeze Techniques

- Pressure to Squeeze
  - High Pressure Squeeze
  - Low Pressure Squeeze

- Pumping Techniques
  - Hesitation Squeeze
  - Running or Walking Squeeze

- Placement Techniques
  - Squeeze Packer
  - Bradenhead (Including Coiled Tubing)
High Pressure Squeeze

Surface Pressure
  +
Displacement Fluid Hydrostatic
  +
Cement Slurry Hydrostatic
  =
Total Bottom Hole Pressure
  Greater Than
Formation Fracture Pressure
Low Pressure Squeeze

Surface Pressure
+ Displacement Fluid Hydrostatic
+ Cement Slurry Hydrostatic
= Total Bottom Hole Pressure

Less Than
Formation Fracture Pressure
Low Pressure Squeeze

Existing Cement Sheath

Cement From Squeeze Job
Squeeze Techniques

- Pressure to Squeeze
  - High Pressure Squeeze
  - Low Pressure Squeeze

- Pumping Techniques
  - Hesitation Squeeze
  - Running or Walking Squeeze

- Placement Techniques
  - Squeeze Packer
  - Bradenhead (Including Coiled Tubing)
Hesitation Squeeze

- Pressure Limit
- Slurry Placement Complete
- Pressure to Test Squeeze
- Cement Entering Formation
- Pumps Stopped Intermittently
- Mixing and Displacing Cement
- Press. Bleed Off to Check Backflow
“Running/Walking” Squeeze

Diagram showing the pressure behavior over time during a squeeze operation. Key points include:
- Mixing and Displacing Cement
- Cement Entering Formation
- Pressure Limit
- Slurry Placement Complete
- Pressure to Test Squeeze
- Press. Bleed Off to Check Backflow
Squeeze Techniques

- Pressure to Squeeze
  - High Pressure Squeeze
  - Low Pressure Squeeze

- Pumping Techniques
  - Hesitation Squeeze
  - Running or Walking Squeeze

- Placement Techniques
  - Squeeze Packer
  - Bradenhead (Including Coiled Tubing)
Squeeze Packer Method

- Retrievable or drillable squeeze packer set above injection point
- Isolates casing above packer from squeeze pressure
- Higher squeeze pressure possible
- Annular pressure can be applied
Bradenhead Method

- Spot cement across squeeze interval
- Pull workstring above cement top
- Close BOP/Bradenhead & reverse tubing clean
- Apply squeeze pressure

Disadvantages
- Casing exposed to squeeze pressure
- Limited squeeze pressure

Advantages
- Cost reduction
- Wash cement out of casing
Coiled Tubing Method

- Form of Bradenhead
- Inside Production Tubing
- Higher Pressure Possible
- Improved control of slurry placement
Squeeze Slurry Design
Squeeze Slurry Design Considerations

- Application Temperature
  - API Squeeze BHCT
  - Other factors
- Thickening Time
- Fluid Loss Control
  - HP vs. LP Squeeze applications
  - Multiple perforations
- Static Gel Strength
- Spacers
Fluid Loss Control vs. Filter Cake

1000 cc - Neat Cement Slurry

300 cc Fluid Loss Slurry

75 cc Fluid loss Slurry

25 cc Fluid Loss Slurry
Ultra-Fine Cement

- Penetration into small leaks, gravel packs, etc.
- Casing Leaks where there is low injection rate
- Behaves like Portland cement
- Average particle size around 10 micron
Tool Selection

- Squeeze Packers
  - Drillable
    - Cast Iron
    - Composite
  - Retrievable
Tool Location

- Set in cemented casing when possible
- Close to interval to minimize cement drill-out
- Adequate distance from perfs for staging volume
- Displace tubing volume before staging
- Safe distance from perfs to prevent casing collapse
Job Execution

- Well preparation
  - Well fluid circulated and balanced
  - Perforations open
- Pressure test surface treating lines, work-string, and tools to maximum expected pressure
- Use clean workover fluids for injection
Squeeze Applications
Block Squeeze

- Performed to isolate zone
- Perforate & squeeze below zone
- Perforate & squeeze above zone
- Drill out & test
- Difficult to remove trapped fluid/mud
- Avoid Fracturing
- Questionable practice
Circulation Squeeze

- “Suicide Squeeze”
- Drillable tool set between perforations
- Circulation path back into casing above
- Improved channel cleaning
- Possibility of sticking
- Possibility of casing collapse
Abandonment Squeeze

- Retainer set high to meet regulatory plugging requirements
- Perform low pressure squeeze through retainer
- Sting out & dump cement on top of retainer
Channels

- Channel must be clear of mud
- Allow production to clean channel if possible
- Clean channel with acid or chemical wash
- Perform low pressure squeeze
- Inject into production perfs or adjacent to problem zone
Unwanted Production

- Water coning from below
- Gas cap production due to depletion
- Channels
- Vertical fractures
  - Natural
  - Created
  - High vertical permeability
Corrosion Holes

- Often occur above cement top
- May require multiple stages
- Caution with tools due to weak or enlarged casing
- New holes can be created during squeeze
- Use low pressure squeeze
Casing Split

- Often occurs above cement top
- May require multiple stages
- Caution with tools due to restrictions or enlarged casing
- Split length may increase during squeeze
- Use low pressure squeeze
Liner Top

- Poor mud displacement during primary cement job
- No cement returns to liner top
  - Solids bridging
  - Losses due to high ECD
  - Planned Tack & Squeeze
Re-Cementing

- Raise the top of cement
- Displacement plug method
- Packer method (drillable)
- Circulate to surface to condition/clean annulus
- Use large volumes of flush/spacer
- Mod/Low fluid loss cement
- Casing collapse possible with packer method

Displacement Plug  Packer
Fractured or Vugular Zones

- Multiple stages likely
- Lead or first stage
  - Lost circulation material
  - High fluid loss cement
  - Thixotropic cement
  - Foam cement
  - Quick setting cement
  - Reactive pre-flushes
- Second stage
  - Low fluid loss cement
Long Perforated Interval

- Difficult to inject into all perforations at once
  - Acid wash optional
- As perforations are squeezed others will take fluid
- Low pressure squeeze
- Low fluid loss, extended TTT, low/slow SGS
- Ball sealers optional
- Spot cement across entire interval with Coiled Tubing or tailpipe
Collar Leaks

- Often extremely low injection rate
- Treatment systems
  - Internally catalyzed treatments
  - Microfine cement
  - Resin
Casing Inspection 101
Multi-Finger Caliper TOOLS

24 finger MFC — 1.75” to 4.5” range
Finger Spacing 0.229” to 0.589”

40 finger MFC — 3.0” to 7.5” range
Finger Spacing 0.236” to 0.589”

60 finger MFC — 4.5” to 9 5/8” range
Finger Spacing 0.236” to 0.504”

80 finger MFC — 8.5” to 16” range
Finger Spacing 0.334” to 0.628”
COMPARING VIDEO & MFC DATA

Crushed Casing (not the same well)
SCALE DEPOSITION & REMEDIAL WORK

Hole in tubing

Lower Limit of scale cleanup job

Section view of scale precipitation
Casing Inspection Ultrasonic Scanners
CASE Post Processing

<table>
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<tr>
<th>GR</th>
<th>ECCEN</th>
<th>OVAL</th>
<th>AVTHIKN</th>
<th>MXTHIKN</th>
<th>AVRADN</th>
<th>MXRADN</th>
<th>PRADN</th>
<th>THKPN</th>
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<table>
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<th>THKPN PIPE THICKNESS NORMALIZED</th>
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<tbody>
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DIAGRAM
FASTCASE
7 inch liner

There is a single (large) hole with thin wall areas adjacent to the hole
CAST-M 4 ½”
Casing Inspection

<table>
<thead>
<tr>
<th>Layer</th>
<th>Event Description</th>
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<tbody>
<tr>
<td></td>
<td>Collar leak</td>
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<tr>
<td></td>
<td>Casing Swelling from Capsule Perforating Guns</td>
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<tr>
<td></td>
<td>Damage from Milling Packer</td>
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</table>
FIGURE 10. A CAST 3-D reconstruction of a cased hole downhole assembly in a horizontal well with a close up of a sliding sleeve seen in the closed position.
Slotted liner damage as seen by CAST™ in casing inspection mode
Lost Circulation Challenges

- Lost circulation is the biggest non-productive cost in the industry today
  - 10-30% of all drilling NPT attributable to losses and wellbore instability
- Lost circulation occurs from:
  - Highly permeable formations
  - Naturally fractured formations
  - Cavernous formations
  - Induced fractures
- Resulting in:
  - Anything from seepage to total losses
BridgeMaker™ II Lost Circulation Material
What is BridgeMaker™ II Lost Circulation Material?

- A special pre-blended LCM designed for use in spacers, but works equally well in cement
- Bridges across a broad range of fracture widths
- Carefully composed for optimum performance and suspension for spacer and cementing fluids
- Tested for problem-free pumping though float equipment
- Environmentally Friendly - North Sea compliant
Cementing New Technology
BridgeMaker™ II Lost Circulation Material – Properties

- **Physical Properties**
  - Blend SG = 1.71
  - Bulk Density 0.49-0.65 SG (31-40 lb/ft³)

- **Temperature Limits**
  - Upper limit 347°F (175°C) **short term** (4 – 6 hours)
  - Upper limit 302°F (150°C) **medium term**

- **Recommended Loading**
  - Add 30-80 kg/m³ or 10-28 lb/bbl for primary cementing operations

- **Bridging Capabilities**
  - Easily plugs fracture widths up to 1000µ at 1000 psi ΔP deposit pressure
  - At higher concentration plugs 1500µ at 1000 psi ΔP deposit pressure
  - Lower deposit pressure allows better plugging
  - Can withstand at least 1500 psi ΔP once deposited

- **Secondary Effects**
  - Moderate effect on fluid viscosity – can establish correction factor
  - No impact on wettability
Performance tested in LCM test cell (modified to handle coarse materials)
- Slotted disks
- Instant pressure application (N2 over floating piston)
- Room temperature
- Record spurt loss and time

Disks used for the testing:

- 500µ flat disk
- 1000µ flat disk
- 1500µ flat disk
- 1000µ -1500µ V-slot disk
What if I want to use as LCM for stopping losses?
When mixed in 1.60 SG TSE+ maximum concentration is
- ±260 kg/m³
- ±91 lb/bbl
Suspends well in fluids with viscosity
- Econolite™ Additive – liquid
- Unweighted spacers
- Needs filler material to plug properly

Example – use with no filler:
80 kg/m³ in TSE+ 1.06 SG
- Spurt loss 268 ml
Flow 1.45 SG lead slurry after, no fluid loss control
- Spurt loss 8 ml
Tuned Defense Cement Spacer
CUSTOMER CHALLENGE

Defending the wellbore from lost circulation while cementing
Next-generation adjustable rheology cement spacer with lost circulation capabilities to maintain wellbore stability

- Achieve planned top of cement
- Effective mud displacement
- Enable a dependable barrier to maximize production

Eliminate Seepage
Prevent severe losses
What do you want from a cement spacer?

Tuned® Spacer Portfolio
- Industry leading spacer systems system for over 22 years
- Used in over 11,000 cement jobs per year

The Industry’s best cement spacer just got better.

Tuned® Defense™
Cement Spacer
What Makes Tuned® Defense™ Cement Spacer Unique?

Seepage to partial loss control

Optimized fluid rheology helps improve mud displacement

Ability to reduce seepage and achieve top of cement
What Makes Tuned® Defense™ Cement Spacer Unique?

Up to Severe Loss Control

- Optimized fluid rheology helps improve mud displacement
- Ability to plug fractures and prevent losses when tailored with BridgeMaker™ II LCM
Tuned® Defense™ Cement Spacer Technical Capabilities

- Up to 325°F*
- Up to 19 ppg density
- Non-damaging to the formation
- Able to seal pores up to 500 microns
- Combines with BridgeMaker™ II LCM to plug fractures up to 3000 microns

* DefenseMod™ 325 Additive may be used above 300°F
Tuned® Defense™ Cement Spacer Test Procedures

A spacer’s ability to control losses can be tested and verified.

- Fluid Loss Cell
  - Same apparatus used for API Fluid Loss testing
  - 250 micron screen (60 mesh)
  - 1000 psi pressure

- Particle Plugging Apparatus (PPA)
  - Common apparatus in drilling fluid labs
  - 500 to 3000 micron slots
  - 1000 psi pressure
Tuned® Defense™ Cement Spacer Demonstration

Conventional Spacer **without** loss control

Tuned® Defense™ Cement Spacer **with** loss control
Tuned® Defense™ Cement Spacer
Operational Benefits

- Increase confidence in achieving top of cement
- Avoid remediation
- Minimize non-productive time
- Lower overall operating costs
Tuned® Defense™ Cement Spacer Potential Applications

- Permeable or fractured formations
- Narrow pore pressure/frac gradient margins
- Fields with history of losses
- Areas with strict top of cement requirements
SentinelCem™ Cement
What is SentinelCem™ Cement?

- **What It Is:**
  - A Dependable Barrier for Losses that uses Chemistry rather than Physical Mechanisms (LCM)
  - A highly-thixotropic cement slurry with Low Solids Content and High Yield
  - Acid Soluble System

- **What It Does:**
  - Can cure Total Lost Circulation
  - Can be pumped through the drilling BHA
  - Enables deeper formation penetration

- **What It Means:**
  - Minimizes risks of cost overruns and NPT
  - Allows Operator to continue drilling ahead
  - Enables access to deeper reservoirs previously inaccessible
Why SentinelCem™ Cement?

**Features**
- Lightweight slurry density 10 ppg
- Low percentage of solids ~10% by volume, ~20% by weight
- Rapidly gels when pumping is stopped, yet becomes pumpable again when shear is returned.
- Acid soluble

**Benefits**
- Reduced hydrostatic on weak formations
- Allows for pumping through the Drilling BHA
- Maximum penetration into the loss zone maximizes the chance of success to cure the losses
- Can be used in production reservoirs
Case Study:
SentinelCem™ Cement Placed Using the BHA Solves Total Lost Circulation

Operator Challenge
- Over 500 bbls/hour of Total Losses were experienced during drilling in the Llanos Basin in Colombia.

Solution
- SentinelCem™ cement due to the shear-rate dependent rheology.
- Low viscosity during pumping enabled placement via drilling BHA.
- Rig-time was reduced by avoiding additional trips.

Results
- Circulation was re-established on three different wells with total losses.
- Avoided the need for remediation.
- Operator saved $250,000 (USD) per well in rig time and mud recovery.
Tailoring SentinelCem™ Cement Designs

- SentinelCem™ cement is a low complexity slurry
- Low sensitivity to mild changes in BHCT
- All standard API lab testing applies

Additional Considerations

- Use FYSA to measure rheology
- Always perform On-Off-On Thickening Time tests
SentinelCem™ Cement – Highly Thixotropic Behaviour

- When pumping stops, slurry gels rapidly.
- When pumping continues, the slurry re-establishes liquid form
SentinelCem™ Cement – Highly Thixotropic Behaviour

- When kept under continuous shear, SentinelCem™ cement can be pumpable for >24 hours
Electromagnetic Pipe Xaminer
## Electromagnetic Pipe Xaminer® V (EPX™ V) Performance Specifications

<table>
<thead>
<tr>
<th>General Tool Specifications</th>
<th>English</th>
<th>Metric</th>
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<tbody>
<tr>
<td>Tool Length</td>
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<td>Maximum Pressure</td>
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<td>Maximum Temperature</td>
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<td>176°C</td>
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<td>Maximum First Tubular OD for Maximum Resolution</td>
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<td>Maximum First Tubular OD</td>
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<td>Thickness Measurement Accuracy and Detection</td>
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<td>1st Pipe Defect Detection</td>
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<tr>
<td>1st Pipe (2 strings) Accuracy</td>
<td>2% or 0.015 in,</td>
<td>2% or .38 mm</td>
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<tr>
<td>Total Metal Thickness 1.2” (3cs)</td>
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<td>Total Metal Thickness 1.8” (4cs)</td>
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Full-Resolution Array Optimization for Overlapping Defects

- Overlapping defects in pipes 4 and 5
ACX ( Array Noise Tool )
Beamforming

Tubing  Casing  Casing

Leak – Acoustic Source

Hydrophone Array

Time

Received Acoustic Array Signals

Beamforming

Vertical and Radial Leak Location

Single Array Output Signal

Principal Component Analysis

Signal Features
Tubing and Casing
Gas-Lift Mandrel Leak

- Radial Pick
  » Clear indication
  » Maximum deviation at depth of leak is 70°
Fiber Optics use for Cement Evaluation

- Warm drilling Fluid in annulus was pushed upward
- Cool cement flowed downward in casing
- Heat effect by cement curing
- End of Intermediate casing
Temperature Increase from Cement Curing

Temperature Increase between TOC and Intermediate casing is enhanced because the exothermic heat released by cement curing dissipated slower in this zone.
PACERS
Peak Analysis of CBL Waveform
Radial Segmented
PACE (Peak Analysis for Cement Evaluation)

• The new technique uses the peaks and troughs of the waveform for analysis and a derivative process is used to determine the peaks and troughs.

• When the derivative changes sign is the peak or trough of that waveform, and the value of the waveform will be called a peak.

• This provides an automatic method of picking both the positive and negative peaks of the entire waveform.
CBL Waveforms
CBL Peaks
Stacked Absolute Value of the CBL Peaks
PACE (Peak Analysis for Cement Evaluation)
Segmented Radial Shells

- Taking each region from each segmented PACE it is possible to create Shells1 – Shells 4
- The average amplitude reading from each Segmented PACE is used and interpolated to the next reading allowing an image to be created
  - If a RB curve is available all regions will be corrected
- Shell 1 is nearest to the wellbore while Shell 4 is further away
PACER Shell
Peak Analysis of CBL Waveform
Radial Segmented
Who to Contact, Where to get more information

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