SPE DISTINGUISHED LECTURER SERIES

is funded principally
through a grant of the

SPE FOUNDATION

The Society gratefully acknowledges
those companies that support the program
by allowing their professionals
to participate as Lecturers.

And special thanks to The American Institute of Mining, Metallurgical,
and Petroleum Engineers (AIME) for their contribution to the program.
The Art and Practice of Acid Placement and Diversion: History, Present State, and Future

Distinguished Lecturer Series
2004 – 2005

Leonard J. Kalfayan
BJ Services
Tomball, TX
USA
Two Reasons Why Acid Treatments Fail

- Acid-removable damage is not present
- If it is present it is not fully contacted
  - Acid does not go where it needs to go

To ensure success …

→ Select viable candidates
→ Implement treatment placement
→ Simplify treatment design
# Standard Sandstone Acidizing Procedure

<table>
<thead>
<tr>
<th>Step</th>
<th>Description</th>
<th>Volume Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Tubing pickling stage</td>
<td></td>
</tr>
<tr>
<td>2.</td>
<td>Solvent pre-treatment</td>
<td>10-50 gal/ft</td>
</tr>
<tr>
<td>3.</td>
<td>Acid preflush (HCl / organic acid)</td>
<td>10-250 gal/ft</td>
</tr>
<tr>
<td>4.</td>
<td>Main acid stage (HF solution)</td>
<td>20-250 gal/ft</td>
</tr>
<tr>
<td>5.</td>
<td>Overflush stage (HCl / organic acid / NH₄Cl)</td>
<td>10-250 gal/ft</td>
</tr>
<tr>
<td>6.</td>
<td>Diverter stage</td>
<td></td>
</tr>
<tr>
<td>7.</td>
<td>Repeat steps 2–6 (as necessary)</td>
<td></td>
</tr>
<tr>
<td>8.</td>
<td>Repeat steps 2–5</td>
<td></td>
</tr>
<tr>
<td>9.</td>
<td>Final displacement stage (NH₄Cl / diesel)</td>
<td>tubing volume +</td>
</tr>
</tbody>
</table>


**Simplified Sandstone Acidizing Procedure**

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Injectable non-acid tubing pickling stage</td>
</tr>
<tr>
<td>2.</td>
<td>Acid (HF) system *</td>
</tr>
<tr>
<td>3.</td>
<td>Displacement</td>
</tr>
</tbody>
</table>

* Mechanically placed; on-the-fly diversion; self-diverting fluid
Brief Acidizing History
1895 – two patents (Standard Oil – Ohio)
  - Frasch patent – HCl
  - Van Dyke patent – H$_2$SO$_4$

Used 30-40% HCl

Prolific response … but …

No acidizing for the next 30 years
Frasch Patent Ahead of Its Time

- Need to “press” acid into formation
- Long channels can be formed
- Advantageous to displace acid into rock
- Need for corrosion protection
- Need for a “rubber packer” to isolate the formation to be treated with acid
Acidizing History

- **1928**
  - Used corrosion inhibitor from steel industry (circa 1845)

- **1932**
  - Dow and Pure Oil – acidized limestone (Michigan)
  - Arsenic corrosion inhibitor used

- Led to creation of commercial acidizing industry
Acidizing History

1933
- First HF acid treatment in sandstone
- Result: Sand production

1936
- Chemical diversion introduced (soap solutions)

1939
- Introduction of Mud Acid (12% HCl-3% HF)
- Sandstone acidizing remained unpopular through 1950s

1960s
- Tapered (staged) acid treatments introduced
After 110 Years of Acidizing

- Periods of advancement … and periods of stagnation
- Great successes … and very little tolerance of failures
- Limited appreciation of its value
- Resistance to cost has persisted
- Resistance to new ideas and methods
- Now … at the onset of a new period of advancement
World Hydrocarbon Production

- Deepwater development 8%
- Green fields (newer development) 22%
- Brown fields (mature fields) 70%
  - 35-37% recovery
  - Matrix stimulation (acid) and water control crucial
  - Treatment placement crucial
  - Field-wide treatment approach necessary
Acid Placement

Methods

- Bullhead injection (MAPDIR Method)
- Mechanical placement
- Chemical diversion
Acid Injection
Heterogeneous Interval
Maintain maximum pressure differential ... maximum rate as skin is removed

\[ dP = p_{iw} - p_e = 141.2 \, q_i \, B \mu/kh \left[ (\ln r_e / r_w) + s \right] \]

Maximum matrix injection rate may not be enough
Mechanical Placement
Chemical Diversion

Maximize Coverage ...
Minimize Volumes
Packer Systems

- Earliest mechanical method
- Can select any desired area
- Easier to set in monobores
- Generally multiple set

Types
- Cup type packers
- Mechanical packers
- Inflatable packers

Can apply 1,000s of psi differential pressure
Ball Sealers

- **Evolution**
  - Sinkers (1950s)
  - Later – buoyant; floaters

- **Shut off area taking fluid**
  - Flow to perforation must be sufficient
  - Requires ball to first seal, then be removed
Jetting

- Evolution
  - Coiled tubing and nozzles
  - Sophisticated configurations

- Can Select any area

- Most completions

- Rotary action required
  - For perforation coverage
  - For screen or open hole coverage
Goal: Equalize acid injection rate per unit area (Q/A) across the interval targets

- Temporarily block paths of least resistance
- Divert acid to untreated (damaged) zones
Evolution
Chemical Diversion

1936 → Soap solutions, then …
   - CaCl₂ brine (heavier than acid)
   - Cellophane flakes
   - Oil-external emulsions
   - Chicken feed

1950s → Removable materials
   - Naphthalene (moth balls)
   - Crushed limestone
   - Oyster shells
   - Perlite
   - Gilsonite
   - Sodium tetraborate
   - Paraformaldehyde

Eventually replaced by rock salt
Evolution
Chemical Diversion (cont’d)

1960s to 1970s → Degradable materials
with HF acid
• Benzoic acid flakes
• Benzoate salt solutions
• Molded wax particulates
• Polymer gels

1980s to 1990s →
• Oil-soluble resins (OSR)
• Foam
• Combinations
• Refinements

Now →
• Benzoic acid forms
• Foam
• Surfactant gels
# Current Chemical Diverters

<table>
<thead>
<tr>
<th>Diverter</th>
<th>Temp Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Graded rock salt</td>
<td>any T</td>
</tr>
<tr>
<td>Wax particulates</td>
<td>&lt;180 °F</td>
</tr>
<tr>
<td>Water-selective resin</td>
<td>200 °F</td>
</tr>
<tr>
<td>Benzoic acid flakes; benzoate salt solutions</td>
<td>250 °F</td>
</tr>
<tr>
<td>Polymer gels</td>
<td>Varies</td>
</tr>
<tr>
<td>Gas-in-water emulsion (foam)</td>
<td>&gt;300 °F</td>
</tr>
<tr>
<td>Gilsonite</td>
<td>330 °F</td>
</tr>
<tr>
<td>Surfactant-based gels</td>
<td>325 °F</td>
</tr>
</tbody>
</table>

**Needs:** Reliable high temperature diverter; gas well diverter
In Situ Acid Diversion
Also Important

Sandstone Acidizing

Enhanced with mild systems ... moderated reaction
Self-diverting Acid – Carbonate Matrix
28% HCl VES Gels – 150 °F

VES Acid 1
Effective self-diversion

VES Acid 2
Limited self-diversion
Surfactant-gelled Carbonate Matrix Acidizing Fluid

Viscosity Development
Spending 28% HCl + 4% VES

Viscosity (cP) vs. % HCl (calculated)
Delayed Crosslinked Polymer-gelled Carbonate Fracture Acidizing Fluid

![Viscosity Profiles - 180° F](image)

- **0 gpt delayer**
- **2 gpt delayer**
- **4 gpt delayer**

Viscosity Profiles - 180° F

- Time (min)
- Viscosity 40sec-1 (cp)
Acid Placement & Diversion Examples
Carbonate Fracture Acidizing

- West Texas horizontal gas wells – 180 °F
- Limited entry completion – perforated liner
- Previous method: Pad – acid (gelled)
  - Average initial response – 2-3 mmscfd
  - Average 150-day decline – 53%
- New method: Delayed x-linked gelled acid
  - Delayed viscosity – high injection rate – 133 bpm
  - Post-acid frac production rate (IP) – 5.2 mmscfd
  - 150-day decline – 12%
## Sandstone Acidizing – Horizontal GP

HF Acid – CT / Rotating Nozzle

<table>
<thead>
<tr>
<th>Well</th>
<th>Production Rate (BOPD) Before</th>
<th>Production Rate (BOPD) After</th>
<th>Water Cut (%) Before</th>
<th>Water Cut (%) After</th>
</tr>
</thead>
<tbody>
<tr>
<td>Well A</td>
<td>175</td>
<td>883</td>
<td>98</td>
<td>89</td>
</tr>
<tr>
<td>Well B</td>
<td>16</td>
<td>318</td>
<td>97</td>
<td>24</td>
</tr>
<tr>
<td>Well C</td>
<td>98</td>
<td>366</td>
<td>93</td>
<td>95</td>
</tr>
<tr>
<td>Well D</td>
<td>862</td>
<td>1613</td>
<td>65</td>
<td>68</td>
</tr>
</tbody>
</table>

- Used low acid strength – HF formulation
- 20 gal/ft vs. 100-150 gal/ft acid previously
- Oil preferentially treated – reducing water cut
Mild HF System – CT / Rotating Nozzle Method
Injection Well Matrix Stimulation

SPE 90815: McClatchie, Garner, Yurkanin
Mechanical Placement
Future

- **Coiled tubing (CT) methods**
  - Nozzle tools – focused lower volume treatment
  - Concentric coiled tubing (CCT) – multiple annuli
  - Diagnostics

- **Multi-zone completion and isolation systems**
  - Selective stimulation
  - Anticipation of future treatments
Chemical Diversion
Future

- Simplified treatments → single acid stage
- Self-diverting fluids
- Combined acid stimulation and water control
- Surfactant technologies
Acid Placement Role in Mature Field Exploitation

- Field-wide treatment campaigns
- Simplified selective treatments
- Candidate wells previously avoided
  - Long vertical completions
  - Horizontal completions
  - Multiple zones
  - Open–hole completions
  - High temperature formations
  - High water cut wells
### Acid Program Economics
**Hypothetical 10-well Example**

**Oil Price per barrel**: $40.00

**Gas Price per MCF**: $6.00

**Water Cost per barrel**: $0.50

<table>
<thead>
<tr>
<th>10-well Monthly Production - Bullheaded Treatments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Month</td>
</tr>
<tr>
<td>-------</td>
</tr>
<tr>
<td>Before</td>
</tr>
<tr>
<td>1</td>
</tr>
<tr>
<td>2</td>
</tr>
<tr>
<td>3</td>
</tr>
<tr>
<td>4</td>
</tr>
<tr>
<td>5</td>
</tr>
<tr>
<td>6</td>
</tr>
<tr>
<td></td>
</tr>
</tbody>
</table>

**25% increase**
60 to 75 bopd
100 to 125 mcfd
5%/mo decline

$25,000 per well job cost
## Acid Program Economics

**Hypothetical 10-well Example**

<table>
<thead>
<tr>
<th>Oil Price per barrel</th>
<th>$40.00</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gas Price per MCF</td>
<td>$6.00</td>
</tr>
<tr>
<td>Water Cost per barrel</td>
<td>$0.50</td>
</tr>
</tbody>
</table>

### 10-well Monthly Production - Bullheaded Treatments

<table>
<thead>
<tr>
<th>Month</th>
<th>BOPM</th>
<th>MCF/M</th>
<th>BWPM</th>
<th>Water Cut</th>
<th>Net Oil $000</th>
<th>Net Gas $000</th>
<th>Net Water $000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Before</td>
<td>18000</td>
<td>30000</td>
<td>342000</td>
<td>95.0%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>22500</td>
<td>37500</td>
<td>427500</td>
<td>95.0%</td>
<td>180</td>
<td>45</td>
<td>(43)</td>
</tr>
<tr>
<td>2</td>
<td>21375</td>
<td>35625</td>
<td>427928</td>
<td>95.2%</td>
<td>171</td>
<td>43</td>
<td>(43)</td>
</tr>
<tr>
<td>3</td>
<td>20306</td>
<td>33844</td>
<td>428355</td>
<td>95.5%</td>
<td>162</td>
<td>41</td>
<td>(43)</td>
</tr>
<tr>
<td>4</td>
<td>228784</td>
<td>428784</td>
<td></td>
<td>95.7%</td>
<td>154</td>
<td>39</td>
<td>(43)</td>
</tr>
<tr>
<td>5</td>
<td>429213</td>
<td>429642</td>
<td></td>
<td>95.9%</td>
<td>147</td>
<td>37</td>
<td>(43)</td>
</tr>
<tr>
<td>6</td>
<td>429642</td>
<td>429642</td>
<td></td>
<td>96.1%</td>
<td>139</td>
<td>35</td>
<td>(43)</td>
</tr>
<tr>
<td>7</td>
<td>238</td>
<td>238</td>
<td>429642</td>
<td>96.1%</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Net: 954, 238 (257)

### Net Value ($000): **685**

- **$25,000 per well job cost**
- **25% increase**
- **60 to 75 bopd**
- **100 to 125 mcf**
- **5%/mo decline**
### Acid Program Economics

**Hypothetical 10-well Example**

<table>
<thead>
<tr>
<th></th>
<th>Oil Price per barrel</th>
<th>$40.00</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gas Price per MCF</td>
<td></td>
<td>$6.00</td>
</tr>
<tr>
<td>Water Cost per barrel</td>
<td></td>
<td>$0.50</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>10-well Monthly Production - Placed Treatments</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Month</strong></td>
</tr>
<tr>
<td>----------</td>
</tr>
<tr>
<td>Before</td>
</tr>
<tr>
<td>1</td>
</tr>
<tr>
<td>2</td>
</tr>
<tr>
<td>3</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Total</td>
</tr>
</tbody>
</table>

Additional 10% increase
3%/mo decline
4% decrease

$100,000 per well job cost (4x)
**Acid Program Economics**

*Hypothetical 10-well Example*

<table>
<thead>
<tr>
<th></th>
<th>Oil Price per barrel</th>
<th>$40.00</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gas Price per MCF</td>
<td>$6.00</td>
<td></td>
</tr>
<tr>
<td>Water Cost per barrel</td>
<td>$0.50</td>
<td></td>
</tr>
</tbody>
</table>

### 10-well Monthly Production - Placed Treatments

<table>
<thead>
<tr>
<th>Month</th>
<th>BOPM</th>
<th>MCF/M</th>
<th>BWPM</th>
<th>Water Cut</th>
<th>Net Oil $000</th>
<th>Net Gas $000</th>
<th>Net Water $000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Before</td>
<td>18000</td>
<td>30000</td>
<td>342000</td>
<td>95.0%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>24750</td>
<td>41250</td>
<td>250250</td>
<td>91.0%</td>
<td>270</td>
<td>68</td>
<td>46</td>
</tr>
<tr>
<td>2</td>
<td>24008</td>
<td>40013</td>
<td>245740</td>
<td>91.1%</td>
<td>276</td>
<td>69</td>
<td>48</td>
</tr>
<tr>
<td>3</td>
<td>23257</td>
<td>38812</td>
<td>241341</td>
<td>91.2%</td>
<td>282</td>
<td>70</td>
<td>51</td>
</tr>
<tr>
<td>4</td>
<td>22589</td>
<td>37648</td>
<td>237051</td>
<td>91.3%</td>
<td>286</td>
<td>72</td>
<td>53</td>
</tr>
<tr>
<td>5</td>
<td>21911</td>
<td>36518</td>
<td>232868</td>
<td>91.4%</td>
<td>290</td>
<td>72</td>
<td>55</td>
</tr>
<tr>
<td>6</td>
<td>21254</td>
<td>35423</td>
<td>228789</td>
<td>91.5%</td>
<td>293</td>
<td>73</td>
<td>57</td>
</tr>
<tr>
<td>Total</td>
<td>1,697</td>
<td>424</td>
<td>311</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Net Value ($000)**: 1,432

- **Additional 10% increase**
- **4% decrease**
- **3%/mo decline**

**$100,000 per well job cost (4x)**
The Art and Practice of Acid Placement and Diversion: History, Present State, and Future

Distinguished Lecturer Series
2004 – 2005

Leonard J. Kalfayan
BJ Services
Tomball, TX
USA