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Acid Stimulation Challenges and Solutions in Deeper Limestone Reservoirs

Gino Di Lullo

Superior Energy

Society of Petroleum Engineers
Distinguished Lecturer Program
www.spe.org/dl
Overview

• Legacy
• Challenges
• Solutions
• Case History
• Conclusions
Legacy - Actual Stimulation Methods

- Matrix acidizing
- Fracture acidizing
- Closed fracture acidizing
- Competing technology: Horizontal wells
- CTU acidizing
- Acid Constructed Laterals

All Acid Jobs in Carbonates are Successful !!!
But few were Optimally Designed !!!
Legacy - Carbonate Matrix Acidizing

- Radial injection of reactive fluids into the reservoir matrix at below fracturing pressure to dissolve the rock and or mud cake to improve production.

- Removing near wellbore damage
- Enlarging & interconnecting pores
- Increasing original permeability

Source SPE 82260
Legacy – Retarded versus Strong Acid – Radial versus Wormhole

Radial Penetration Versus WormHole
Limestone reacted with 15% HCl

Source SPE 82260
Leaving Path of Increased Permeability- Conductivity

After closure caused by differential etching
Legacy – Acid Fracture Design Criteria

Productivity Ratio versus Dimensionless Conductivity and Penetration Ratios (Square Reservoir)

- After Emulsified Acid- Most Retarded
- After XL Acid-Best Leakoff Control -Cw
- After Gelled – No retardation, Leakoff -Cv
Unrealistic Conductivity Prediction

High Rate Bullheaded Acid & Limited Entry - In a North Sea Field Transient Analyses indicated a 30 ft length average in high leak-off areas while 150 ft average Fracture length in low leak off areas for similar designs.

<table>
<thead>
<tr>
<th>Fract Length Xf ft</th>
<th>Vert. fract. Jvf / Jv</th>
<th>Skin S</th>
<th>Jv/Jv</th>
<th>fwe</th>
<th>fwe/Xf</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>2.07</td>
<td>-4.92</td>
<td>2.75</td>
<td>45.5</td>
<td>.90</td>
</tr>
<tr>
<td>100</td>
<td>2.54</td>
<td>-5.65</td>
<td>3.71</td>
<td>94</td>
<td>.94</td>
</tr>
<tr>
<td>200</td>
<td>3.28</td>
<td>-6.35</td>
<td>5.58</td>
<td>187</td>
<td>.945</td>
</tr>
<tr>
<td>400</td>
<td>4.66</td>
<td>-7.05</td>
<td>10.7</td>
<td>380</td>
<td>.95</td>
</tr>
</tbody>
</table>

20 Acre spacing r_e = 527'  \quad  f_w = 0.33'  
Formation thickness = 20'
Legacy - Vertical Well with Acid built Laterals

Guaranteed Penetration, total accumulated Length the longer the better

Source SPE 103333
Legacy - Multiple Laterals Mara Field

DM-163

CTU Acid Job
Acid Tunneling

BBLs/DAY

04-06 04-06 05-06 06-06 07-06

Water
Oil

Source SPE 103333
Legacy- Treatment Comparison

Carbonate Stimulation Treatment Comparison
400 Gal/ft with 15% HCl

Productivity Index

Stimulated Length, ft

Source SPE 103333
Legacy – Design based on History

Caution: What works for one well ... doesn’t necessarily work for all wells!!!
Challenge in Deeper Carbonate Stimulation

**EFFECT OF TEMPERATURE ON REACTION RATE OF
CALCIUM CARBONATE (MARBLE) AND 15% HYDROCHLORIC
ACID. TEST CONDITIONS: 1000psi PRESSURE, 3–5min.
DURATION, 1:4 AREA–VOLUME RATIO.**
Challenge in Deeper Carbonate Stimulation

Graph showing the rate of 15% HCl spending for varying area-volume ratios (80°F, 1000psi)
Challenges in Matrix – Stimulation

• Divert & Penetrate
  • Treating the complete zone interval equally
  • Limiting-Retarding acid enough to overcome higher temperature & Area : Volume ratio

• Obtaining designed radial penetration or optimized long wormholes
Challenges in Fracture-Stimulation

- Obtain Long Fractures with Reactive Fluids
- Formation Collapse after Closure
- Poor differential-etching
- Lack of fracture Conductivity
Challenge - Replace HCl in Deep Hot Wells

- HCl a Gas not an Acid
  - Volatile, Fumes
- Availability at ~38%
  - Transport, storage
- Carbonate Solubility
  - Chlorides by product
- Corrosive
  - Expensive Inhibition
- Cheap
  - Forms Precipitates
    - Sludge
    - Iron precipitates

1 Barrel 15% HCl dissolves only 1 Gallon of Carbonate
Challenge - Replacing HCl

<table>
<thead>
<tr>
<th>Acid</th>
<th>pK5</th>
<th>pk4</th>
<th>pK3</th>
<th>pK2</th>
<th>pk1</th>
<th>Log K 1:1 Complex</th>
</tr>
</thead>
<tbody>
<tr>
<td>HCl</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>-3</td>
<td></td>
</tr>
<tr>
<td>MSA</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>-1.92</td>
<td></td>
</tr>
<tr>
<td>NTA</td>
<td>9.7</td>
<td>2.5</td>
<td>1.8</td>
<td>1.0</td>
<td></td>
<td>6.40</td>
</tr>
<tr>
<td>DPTA</td>
<td>10.5</td>
<td>8.5</td>
<td>4.3</td>
<td>2.6</td>
<td>1.8</td>
<td>10.80</td>
</tr>
<tr>
<td>EDTA</td>
<td>10.2</td>
<td>6.2</td>
<td>2.7</td>
<td>2.0</td>
<td>1.5</td>
<td>10.70</td>
</tr>
<tr>
<td>Phosphoric</td>
<td>12.3</td>
<td>7.2</td>
<td>2.2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HEDTA</td>
<td>9.8</td>
<td>5.4</td>
<td>2.6</td>
<td></td>
<td></td>
<td>8.40</td>
</tr>
<tr>
<td>HEIDA</td>
<td>8.7</td>
<td>2.2</td>
<td></td>
<td></td>
<td></td>
<td>4.80</td>
</tr>
<tr>
<td>Citric</td>
<td>5.7</td>
<td>4.4</td>
<td>2.9</td>
<td></td>
<td></td>
<td>3.50</td>
</tr>
<tr>
<td>Acetic</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>4.8</td>
<td>0.53</td>
</tr>
<tr>
<td>Carbonic</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>6.4</td>
<td></td>
</tr>
</tbody>
</table>

Acid-Carbonate Effervescent Reaction & Hard to Control
Challenge - Increasing rate to obtain Penetration

- Matrix jobs; increasing the rate help in getting deeper in the formation up to a point
- Fracture jobs; increasing the rate improve leak-off, also increase acid diffusivity but not necessarily differential etching

Source SPE Journal March 98
Challenge - Picking up the right Acid

\[ \pi \frac{dlk}{Q} \]

Da = \frac{\pi dlk}{Q}

Source: SPE Journal March 98
Solution - Viscous-elastic Surfactants

Surfactant monomers

Increase concentration

Above critical micelle conc.

Micelle

Increase concentration

Add certain additives

Worm-like micelle

Surfactant Molecule

Hydrophilic head

Hydrophobic tail

Surfactant molecule contacting oil, water, etc.

Broken upon concentration

3D Gel

Above overlap concentration
Solution - Viscous-elastic Surfactants

LEAKOFF ACID VISCOSITY INCREASE AS CALCIUM CHLORIDE IS FORMED DURING CARBONATE DISSOLUTION
Case History – Typical Treatment
Brazil Post-Salt

Source OTC 22417
Case History – Typical Treatment

<table>
<thead>
<tr>
<th>Each Stage Per zone 170 Bbl</th>
<th>Rate BPM</th>
<th>Fluid</th>
<th>Acid</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre-flush</td>
<td>0.5</td>
<td>HCl-Solvent</td>
<td>15%</td>
</tr>
<tr>
<td>Treatment</td>
<td>0.5</td>
<td>HCl</td>
<td>15%</td>
</tr>
<tr>
<td>Diverter</td>
<td>0.5</td>
<td>Viscoelastic Pill</td>
<td>15%</td>
</tr>
<tr>
<td>Treatment</td>
<td>0.5</td>
<td>HCl</td>
<td>15%</td>
</tr>
<tr>
<td>OverFlush</td>
<td>0.5</td>
<td>Solvent</td>
<td>0</td>
</tr>
<tr>
<td>Flush</td>
<td>0.5</td>
<td>Brine</td>
<td>0</td>
</tr>
</tbody>
</table>

- Expected Production 5 to 6 folds
- Equivalent to 12 gpt (gallons per foot)
- Post Job DST transient result (~ 5.9) skin
- Stabilized Production ~ 2 folds

Source OTC 22417
Case History – Typical Frac with Organic Acid in Venezuela

Source SPE 82211
Case History – Typical Frac with Organic Acid in Venezuela

**Etched width Vs Frac Length**

- 13/9% Acetic/Formic increased volume to match dissolving power of 15% HCl
- 15% HCl

**Acid Dissociation constant and strength**

<table>
<thead>
<tr>
<th>Acid Type</th>
<th>Diss. Constant $K_a$ (mol/l)</th>
<th>Strength of 1 mol/l</th>
<th>pH</th>
<th>$[H^+]$ mol/l</th>
</tr>
</thead>
<tbody>
<tr>
<td>HCl</td>
<td>&gt;&gt;1</td>
<td></td>
<td>0</td>
<td>1.0</td>
</tr>
<tr>
<td>Formic</td>
<td>1.8E-4</td>
<td>1.8</td>
<td>0.016</td>
<td></td>
</tr>
<tr>
<td>Acetic</td>
<td>1.8E-5</td>
<td>2.3</td>
<td>0.005</td>
<td></td>
</tr>
</tbody>
</table>

**Pre & Post Job Production Results**

<table>
<thead>
<tr>
<th>Well</th>
<th>Net Pay ft</th>
<th>Prod Before bopd</th>
<th>Prod. After bopd</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>14</td>
<td>0</td>
<td>1252</td>
</tr>
<tr>
<td>B</td>
<td>22</td>
<td>350</td>
<td>1717</td>
</tr>
<tr>
<td>C</td>
<td>17</td>
<td>0</td>
<td>1940</td>
</tr>
<tr>
<td>D</td>
<td>26</td>
<td>1000</td>
<td>3152</td>
</tr>
<tr>
<td>E</td>
<td>47</td>
<td>1525</td>
<td>4290</td>
</tr>
<tr>
<td>F</td>
<td>22</td>
<td>0</td>
<td>260</td>
</tr>
<tr>
<td>G</td>
<td>16</td>
<td>450</td>
<td>2005</td>
</tr>
<tr>
<td>H</td>
<td>9</td>
<td>0</td>
<td>350</td>
</tr>
<tr>
<td>I</td>
<td>45</td>
<td>0</td>
<td>2485</td>
</tr>
<tr>
<td>J</td>
<td>25</td>
<td>0</td>
<td>882</td>
</tr>
<tr>
<td>K</td>
<td>28</td>
<td>294</td>
<td>2162</td>
</tr>
</tbody>
</table>

Total: 3619 / 20495

~ 700 gal/ft of acid
Alternative Solution – Treating Acid Gelled with Viscoelastic Surfactant

- Bullheaded Acid Treatment

- Continuous use of VS in HCl instead of Diverter Stage
  - Better Diversion, complete zone treatment
  - Better Fluid Loss Control, Longer Fractures
  - Etching pending on Formation’s nature

- No Chemical Acid retardation
- VS Works with HCl, not optimized for other acids
- Still not Optimum!!
Alternative Solution – Treatment
Brazil Pre & Post Salt Reservoirs

- Core Flow Test indicate
  - No worm holes
  - Pore enlargement
  - Homogeneous acid distribution
  - Oil Permeability increased 500 times
  - Acid 10% HCl with 6% VE surfactant
Alternative Solution – Treatment Brazil Pre & Post Salt Reservoirs

Always the bottom zones are pre-treated via CTU with gelled acid and a pulsing jetting device to guarantee bullheaded acid flow reaching the end.

Source SPE 165089
Case History 1 - Vertical Well

- 2450 Bbl 15% Acid with 6% Surfactant
- Equivalent to ~156 Gal/ft
- 1400 Bio Ball Sealers after 490 Bbl
- Pump rate increased to 20 BPM

<table>
<thead>
<tr>
<th>Well Type</th>
<th>Oil Producer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Well Inclination</td>
<td>Vertical</td>
</tr>
<tr>
<td>Rig Type</td>
<td>Semi-Submersible</td>
</tr>
<tr>
<td>Water Depth</td>
<td>4,690 ft</td>
</tr>
<tr>
<td>Last Casing</td>
<td>7”- 32 lbf/ft</td>
</tr>
<tr>
<td>Perforated Interval</td>
<td>14,268 – 14,924 ft</td>
</tr>
<tr>
<td>Perforation Length</td>
<td>656 ft</td>
</tr>
<tr>
<td>Formation</td>
<td>Pre-Salt Carbonate</td>
</tr>
<tr>
<td>Reservoir Permeability</td>
<td>23 mD (14,268 – 14,439 ft)</td>
</tr>
<tr>
<td>Reservoir Pressure</td>
<td>6854 psi</td>
</tr>
<tr>
<td>Reservoir Temperature</td>
<td>255 °F @ 14,353 ft</td>
</tr>
<tr>
<td>Oil Viscosity</td>
<td>0.7 cP</td>
</tr>
<tr>
<td>Oil Grade</td>
<td>31° API</td>
</tr>
<tr>
<td>Workstring</td>
<td>Production String</td>
</tr>
</tbody>
</table>

Source SPE 165089
Case History 2 - Vertical Well

- 2000 Bbl 15% Acid with 6% Surfactant
- Equivalent to ~ 270 Gal/ft
- 1800 Bio Ball Sealers after 200 Bbl
- Pump rate increased to 15 Bpm
- Average Production 6 months test - 12578 BOPD

Source SPE 165089
Case History 3 - Horizontal Well

2335 Bbl 17% HCl with 6% Surfactant
Equivalent to ~ 20 Gal/ft
Pump rate oscillated from 12 to 17 BPM

Source SPE 165089
Conclusions – Deeper Limestone Acidizing Quantum Steps & or Evolution

- Dissolve Rock with acids - higher concentration, organic Acids, Sequestering agents
  - GLDA, Citric Acid
- Alternating pad-acid stages - Use Viscoelastic Surfactants
- Cleaner X-Link Acids - less damaging polymers
- Gelled Organic acids-
  - (Acetic, Formic, EDTA, HEDTA, etc ..)
Conclusions - Everything is Better But we still need to improve!

• **Matrix Treatments**
  • Acid concentration & retardation should be Ramped inversely proportional to radial flow area
  • Acid must be stronger, in situ gelled and retarded
  • Using Ester as pre-flushes is an interesting alternative

• **Acid Fracturing Treatments**
  • Spearhead or Pads should be highly retarded In Situ Acids
  • Avoid Acid dilution - Water, Oils, Gases (Foams & Emulsions)
  • Ramp Acid Retardation

• **Lateral Tunneling**
  • Increase Laterals per elevation
  • Increase Length & Optimize Lateral dissolved diameter
  • New Tool, faster and also applicable in Cased Wells
Your Feedback is Important

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Click on: Section Evaluation