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SPE Distinguished Lecturer Series

HYDRAULIC FRACTURING
RESTIMULATION

Steve Wolhart
Pinnacle Technologies
Acknowledgements

Gas Research Institute (GRI) for sponsoring this project

• Project Team
  – Advanced Resources International
  – Ely & Associates
  – Intelligent Solutions
  – Pinnacle Technologies
  – Schlumberger Dowell
  – Schlumberger Holditch-RT
  – Stim-Lab

• Operating Companies
  – Barrett Resources (Williams Production)
  – Enron Oil & Gas (EOG Resources)
  – Mitchell Energy (Devon Energy)
  – UPRC (Anadarko)
Presentation Outline

• Introduction
  – Key Questions
  – Basic Concepts

• Restimulation Background
  – Industry Interviews
  – Literature Review

• GRI Restimulation Program
  – Candidate Selection Methodology
  – Case Histories

• Conclusions
Key Questions

Is there a natural gas resource base that can be economically captured via restimulation?

What is the nature of the resource?

What is industry’s experience with gas-well restimulation?

What are the technical obstacles?

Should restimulation be part of your development plan?
**Restimulation – Candidate Identification**

**Definition:** An underperforming well is one that is not performing up to its productive potential as governed by in-situ reservoir properties.

**Implication:** To identify underperforming wells, performance must be separated into reservoir and completion components.
Causes of Well Underperformance

Ineffective/Problematic Initial Completion
- Design
- Execution
- Lack of Data
- Damage

Pressure Depletion Changes the Stress Field
- Frac Geometry Changes
- Refrac Reorientation
- Longer Fracs

Formation Damage During Production Operation
- Workover Fluid Incompatible
- Scale Buildup
- Proppant Pack Degradation

Well Underperformance

Technology Evolution
- New Technology
Restim Background

- GRI Industry Survey (U.S. Only)
  - 89 Interviews: Operators, Service Companies & Consultants
  - Literature Review: 50 Published Case Studies & 15 Detailed Case Histories

- Refracs are a small fraction of total U.S. fracture-stimulation activity
  - 20,000 to 30,000 total frac jobs/year
  - 450 to 750 refracs/year

- Most restim decisions made without detailed reservoir & completion analysis
  - Simple production comparisons - frac poor well near the good well
In general, there is a very negative perception of restimulation by industry

Survey Quotes

“Remediation doesn’t work. These are poor reservoirs with poor recovery, poor economics.”

“Don’t do any refracs. If a well doesn’t perform, we assume it’s a poor formation.”

“We had a bad experience in the Eighties with the results of refracs.”

“It is usually better to abandon the well.”
However...

• There are a number of plays with active restimulation programs:
  – Codell/Niobrara, Denver-Julesburg Basin
  – Antrim Shale, Michigan Basin
  – Fruitland Coal, San Juan Basin
  – Pottsville Coal, Black Warrior Basin
... with Documented Restimulation Success

<table>
<thead>
<tr>
<th>Region</th>
<th>Avg. Incr. Recovery (Bcf)</th>
<th>Average Restim Cost ($000)</th>
<th>Average Cost of Incr. ($/Mcf)</th>
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<tbody>
<tr>
<td>Mid-Continent (6)</td>
<td>2.03</td>
<td>155</td>
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<tr>
<td>South Texas (2)</td>
<td>1.30</td>
<td>158</td>
<td>0.12</td>
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<td>Rockies (8)</td>
<td>1.97</td>
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<td>0.42</td>
<td>15</td>
<td>0.04</td>
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<td>Other (4)</td>
<td>0.48</td>
<td>134</td>
<td>0.28</td>
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Key: Required Intensive Candidate Selection & Treatment Design Effort
General Observations from the Interview & Literature Study

- Operators are reluctant to restim good wells
- Production data alone is used to select candidates
  - Detailed performance assessments are rarely conducted
- Restim results are frequently disappointing
  - Restim is perceived as high risk/marginal return
  - Variable and unreliable restim outcomes
- Resource constraints (manpower, capital, etc.) limit ability to analyze
- There have been areas of significant restimulation success
Components of GRI Restimulation Project

• Analytic
  – Candidate selection methods - Develop efficient selection methodology
    • Production Statistics, Production Data Analysis & Virtual Intelligence
    • Benchtop Study
  – Short-term/low-cost verification testing
  – Laboratory testing
  – Treatment schemes

• Field Demonstrations
  – Four Sites:
    • Green River Basin (Frontier Formation)
    • Piceance Basin (Williams Fork Formation)
    • East Texas Basin (Cotton Valley Formation)
    • Ft. Worth Basin (Barnett Shale Formation)
Candidate Selection Methodologies

- **Production Statistics**
  - Limited, easily-obtained (public) data
  - No data interpretation
  - Production trend mapping

- **Virtual Intelligence**
  - Detailed well data
  - No data interpretation
  - Neural nets, genetic algorithms & fuzzy logic
  - Pattern recognition – subtle relationships

- **Production Data Analysis**
  - Moderate data requirements
  - Considerable data interpretation
  - Type curve analysis
Production Statistics

- Compare production performance of each well to nearby offsets using several production indicators
- Look for underperforming wells relative to offsets
Virtual Intelligence (VI)

- Pattern recognition – discover subtle relationships between data
- Computer tools to mimic human mind
  - Neural networks, genetic algorithms & fuzzy logic
- Tools allow
  - Adaptive learning (neural nets)
  - Intelligent optimization (genetic algorithms)
  - Computing with words (fuzzy logic)
Virtual Intelligence (VI)

- Pattern recognition – discover subtle relationships between data
- Computer tools to mimic human mind
  - Neural networks, genetic algorithms & fuzzy logic
- Tools allow
  - Adaptive learning (neural nets)
  - Intelligent optimization (genetic algorithms)
  - Computing with words (fuzzy logic)
VI – Three Step Process

Artificial Neural Nets
- Build a Well Performance Model for the Field

Genetic Algorithms
- Identify controllable (fluid type, sand concentration, etc.) and uncontrollable (pay thickness, porosity) parameters
- Optimize controllable parameters – successful practices

Fuzzy Logic
- Decision tool
  - Using engineering expertise to identify key parameters
- Do not have to be precise in value (fuzzy & qualitative)
- Incorporate with steps 1 and 2

Most Virtual Intelligence work to date in E&P is just artificial neural nets
1. Monthly Production & Pressure Histories
   - Identify operating pressure changes
   - Identify added zones
   - Identify workovers, shutdowns

2. Log-Derived Data Per Operator’s Cut-Off(s)
   - Net thickness
   - Net porosity
   - Net water saturation

3. Other
   - Initial reservoir pressure
   - Gas gravity and reservoir temperature
   - Discern field practices

Type-Curves

Dimensionless Rate, \( q_d \)

Dimensionless Time, \( T_d X_f \)

Results

- Permeability \( X_f \)
- Drainage Area
- Production Forecast
- Predicted Pressure vs. Time
Comparison - Data and Interpretation Requirements

Data Requirements

Interpretation Requirements

Production Statistics

Virtual Intelligence

Type Curves

Time, Cost Increases
7 total layers (4 reservoir, 3 inter-zone seals), all laterally continuous
- 16,000 total acres: ~8km x 8 km (26,400 feet x 26,400 feet)
- 49,392 total gridblocks, 84 x 84 x 7 (28,224 active)
- Depth to top layer: 2721 m to 2843 m (8,928 to 9,328 feet)
- 122 meters of relief (400 feet of relief)
- Gently dipping NE to SW at 6°
- No faults
- Original datum pressure of 27,600 kPA, 9.73 kPa/m (4,000 psi, 0.43 psi/ft.)
- Original datum temperature of 93 °C (200 °F)
- Single phase gas (0.7 S.G.), no water saturation
Benchtop Study

• Type curves provided the best candidate selections
  – 85% efficiency benchtop study
  – Quantitative predictions of incremental production were not always accurate however
    • Oversimplifies well & reservoir conditions

• Virtual intelligence also provided good results
  – 83% efficiency benchtop study
    • Best results in our field tests
  – Can lead to insights into “performance drivers”
  – Lacks analytic rigor
Benchtop Study

• Production statistics worked poorly for benchtop study
  – Less efficient at candidate identification than random selection
    • Doesn’t separate reservoir and completion components well
  – Production Statistics best used in simpler reservoirs
Case Histories

Ineffective/Problematic Initial Completion
- Design
- Execution
- Lack of Data
- Damage

Pressure Depletion Changes the Stress Field
- Frac Geometry Changes
- Refrac Reorientation
- Longer Fracs

Formation Damage During Production Operation
- Workover Fluid Incompatible
- Scale Buildup
- Proppant Pack Degradation

Well Underperformance

Technology Evolution
- New Technology
Location of Field Test Sites

Green River Basin
- Big Piney/LaBarge Producing Complex
- Frontier Formation
- EOG Resources

Piceance Basin
- Grand Valley/Parachute/Rulison Fields
- Williams Fork Formation
- Barrett Resources

Ft. Worth Basin
- Barnett Shale
- Mitchell Energy

East Texas Basin
- Carthage Field
- Cotton Valley Sandstone
- Anadarko
Case History – EOG Resources, Frontier Formation

Frontier Type Log

1st (Kf1)

2nd (Kf2)

3rd (Kf3)

• 2nd Frontier
  • Pay Distributed among 5 Benches (gross 130 meters, 400 ft)

• Variable Reservoir Parameters:
  – 1B: fluvial channels
  – 2, 3B: marine shoreface
  – 4B: fluvial, coastal plain
  – 5B: mixed fluvial / marginal marine

• Production Commingled with Other Fms

• 2370 m (7350')

• 2500 m (7750')
Case History – EOG Resources, Frontier Formation

Detail Review

- Started with ~270 wells in database
- Candidate selection with all three techniques
- Perform detailed review of all available data on top 50 wells
- Rated wells from 1 - 50 with respect to potential candidates
- Reviewed with EOG
- Selected restimulation candidates (4 restims)
  - Three - small fracs, untreated zones
  - One – unbroken gel
Case History – EOG Resources, Frontier Formation

Field Results

Pre-Restim Rate (Mcfd)

Post-Restim Rate (Mcfd)

GRB 45-12

NLB 57-33

GRB 27-14

WSC 20-09

Could not pump job as designed

Poor load fluid recovery

2830 m³/d 5660 m³/d 8490 m³/d

2830 m³/d 5660 m³/d 8490 m³/d

8490 m³/d 11,320 m³/d 14,150 m³/d

5660 m³/d 2830 m³/d

Poor load fluid recovery
Case History – East Texas

Green River Basin
- Big Piney/LaBarge Producing Complex
- Frontier Formation
- EOG Resources

Piceance Basin
- Grand Valley/Parachute/ Rulison Fields
- Williams Fork Formation
- Barrett Resources

Ft. Worth Basin
- Barnett Shale
- Mitchell Energy

East Texas Basin
- Carthage Field
- Cotton Valley Sandstone
- Anadarko
Case History – Anadarko, Cotton Valley

CGU 19-13 - Cotton Valley Section

- Thick, Layered and Low Perm
- Stacked sands
- Poor well-to-well correlation
- Utilized a Wide Variety of Completion & Stimulation Procedures
- Pay & perfs?
- Zonal Coverage?

Travis Peak/Cotton Valley Transition

B-Lime

Upper Cotton Valley (UCV)

C-Lime

Taylor

Stage 1

2740 m

2890 m

3020 m

3080 m

3130 m

Stage 2

Stage 3

8000

8100

8200

8300

8400

8500

8600

8700

8800

8900

9000

9100

9200

9300

9400

9500

9600
Case History – Anadarko, Cotton Valley

Detailed Analysis

Evaluated ~ 300 wells with all three selection techniques

• Top 15 for each method had detailed analysis

All wells had large numbers of perfs over long intervals

• Poor zonal coverage and low conductivity

Two categories of wells

• Category I: Very stable delayed crosslink fracs with little or no breaker
• Category II: Low gel concentration poor proppant transport fluids
Ten candidates were proposed for waterfrac/gel cleanup treatment – performed three restims

- **Objectives**
  - Polymer cleanout
  - Stimulate new zones with ball sealers for diversion
  - CO$_2$ in later portion of each frac to assist in water cleanup

- **Pull tubing and isolate the Taylor interval**

- **Treat the intervals**
  - Single-stage, water, KCl, friction reducer, breaker, proppant, ball sealers, and CO$_2$

- **Volume of proposed treatment approximately the same as previous fracs**
### CGU 3-8 Production & Tracer Logs

<table>
<thead>
<tr>
<th>Depth (feet)</th>
<th>Gt API 2000</th>
<th>Perforation</th>
<th>Flow Rate MCFD</th>
<th>QGas MCFD</th>
<th>QWater BFPD</th>
<th>QpGas MCFD</th>
<th>QpWater BFPD</th>
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<td>0</td>
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<td>130</td>
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<td>9400</td>
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<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

**Depth Values:**
- 2755 m
- 2990 m
Case History – Anadarko, Cotton Valley

Field Results

![Graph showing field results with points for CGU 10-7, CGU 3-8, and CGU 15-8.]
Location of Field Test Sites

Green River Basin
- Big Piney/LaBarge Producing Complex
- Frontier Formation
- EOG Resources

Piceance Basin
- Grand Valley/Parachute/Rulison Fields
- Williams Fork Formation
- Barrett Resources

Ft. Worth Basin
- Barnett Shale
- Mitchell Energy

East Texas Basin
- Carthage Field
- Cotton Valley Sandstone
- Anadarko
Case History – Barrett Resources, Williams Fork Formation

- Average Gross Thickness 550 to 800 meters (1700’ - 2400’)
- Discontinuous, stacked sands
- 20-40 stacked pays
  - Small lenses
- Completion issues
  - Pay & perfs
  - Frac stages
  - Sand volumes
Case History – Barrett Resources, Williams Fork

**Prepare Short List of Potential Candidates**

- Started with ~300 wells in database
- Candidate selection with all three techniques
- Selected 40+ wells
  - Detailed well study
- Reduced to 20 wells
- Reviewed with Barrett
- Selected restimulation candidates
  - Small fracs, untreated perfs
Case History – Barrett Resources, Williams Fork

Langstaff #1 Tracer Scan
Case History – Barrett Resources, Williams Fork

Field Results

Pre-Restim Rate (Mcfd) vs. Post-Restim Rate (Mcfd)

- Langstaff #1: 2830 m³/d, 5660 m³/d, 8490 m³/d
- RMV 55-20: 11,320 m³/d, 14,150 m³/d, 5660 m³/d, 2830 m³/d
Case Histories

- Ineffective/Problematic Initial Completion
  - Design
  - Execution
  - Lack of Data
  - Damage

- Pressure Depletion Changes the Stress Field
  - Frac Geometry Changes
  - Refrac Reorientation
  - Longer Fracs

- Formation Damage During Production Operation
  - Workover Fluid Incompatible
  - Scale Buildup
  - Proppant Pack Degradation

- Well Underperformance

- Technology Evolution
  - New Technology
Case History - Mitchell Energy, Barnett Shale

Refrac Reorientation

Concept: Frac Geometry Changes With Depletion
Refrac Drains Untapped Reservoir
Case History – Mitchell Energy, Barnett Shale

Wells ‘A’ & ‘B’ Log-log Rate Plots

- 283 m³/d
- 2830 m³/d
- 28,300 m³/d
- 283,000 m³/d

Production rate, Mscf/d

Time, days
Case History – Mitchell Energy, Barnett Shale

Well ‘A’ Surface Tiltmeter Results

Initial azimuth N40E
Case History – Mitchell Energy, Barnett Shale

Well ‘A’ Rate Match Plot

Gas Rate, Mscf/d

Date

24-Jul-98  28-Aug-99  01-Oct-00

22,640 m³/d
7075 m³/d
1415 m³/d
Case History – Mitchell Energy, Barnett Shale

Well ‘B’ Rate Plot

- 5660 m³/d
- 28,300 m³/d

Mscf/d

- Refrac

date

2-Jan-00 3-Mar-00 3-May-00 3-Jul-00 2-Sep-00

200 400 600 800 1000 1200 1400
Case History – Mitchell Energy, Barnett Shale

Refrac Reorientation Conclusions

• Two Refrac Treatments
  – Good production increases
  – Oblique reorientation measured (research focus)
• Mitchell has active refrac program
• Refrac Treatments Viable On Suitable Tight Gas Wells
• Technology Applicable To Suitable Oil Wells
# Economic Results
*(does not include Mitchell wells)*

<table>
<thead>
<tr>
<th>Site</th>
<th>Well</th>
<th>Date</th>
<th>Incr. Reserves (MMcf)</th>
<th>Frac Cost</th>
<th>Reserve Cost ($/Mcf)</th>
<th>Successful</th>
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<tbody>
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<td>$87,000</td>
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<td>(186)</td>
<td>$87,000</td>
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<tr>
<td>GRB</td>
<td>NLB 57-33</td>
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<tr>
<td>GRB</td>
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<tr>
<td>PB</td>
<td>Lan 1</td>
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<td>PB</td>
<td>RMV 55-20</td>
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</table>
Conclusions
Identifying Areas to Study for Restimulation Potential

• **Under-performing completions**
  – Reservoir Complexity & Variability
    • Unconventional, naturally fractured, tight gas, etc.
  – Completion Complexity
    • Multiple zones
    • Thick gross intervals
    • Advanced stimulation & variation in frac designs
  – Performance
    • Cums & EURS seem low
    • Infill drilling success
    • Refrac success (but not followed-up)

• **Frac geometry changes (reorientation or longer frac length)**
  – Good initial stimulation
  – Moderate difference in max/min horizontal stresses
Conclusions
Treatment Design Considerations

• Identify cause of well underperformance and design treatment accordingly

• Treatments for GRI Project
  – Trended away from heavy gelled fluids
  – Moved to ungelled water, simpler fluids
  – Gas assist to aid clean-up
  – Single-stage treatments (economical) with diversion (ensure zonal coverage)
Conclusions

• Single Selection Technique Remains Elusive
  – Virtual Intelligence and Type Curves Offer the Best Results
  – Select method based on reservoir

• Case Histories Show Restimulation Potential
  – Despite negative industry perception

• Restim Can Add Reserves Inexpensively – Infrastructure Already in Place
  • Well & Production System

• Should Consider Restimulation as Part of Field Development Plan
Contact Information

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