Modern Perforating Techniques: Key to Unlocking Reservoir Potential

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Presentation Outline

- Introduction: Perforating for Productivity
- Perforation Clean-up
- Increasing Shot Density
- Increasing Penetration
- Keeping Perforations Clean
- Summary

Shaped charges
Perforating For Productivity

- Connects well to reservoir
- 45 million shaped charges shot per year
- Perforating sub-optimal in 95% of operations
- 20% to 50% production lost
- Modern techniques unlock a reservoir’s full potential
A Review of Fundamentals

- Semi-analytic model*
- Gun/shaped charge: length, diameter, shot density (spf), phase angle
- Damage: near wellbore, perforation
- Recent modifications: accurate penetration model, accurate clean up model

*SPE 18247 “Semi-analytical Productivity Models for Perforated Completions” Karakas and Tariq presented in 1988
Simplification of Karakas and Tariq

\[ \beta = (P - L)N^{3/2}D^{1/2} \alpha^{-5/8} bc^{-1} \]

- \( \beta \) = Perforation Efficiency
- \( b \) = Perforation Damage
- \( N \) = Shot Density (spf)
- \( P \) = Perforation Tunnel Length
- \( D \) = Average Perforation Tunnel Diameter
- \( \alpha \) = Formation Permeability Anisotropy Ratio
- \( L \) = Formation Damage Depth

*SPE 38148 “A Simple Method for Estimating Well Productivity”
Brooks presented in 1997
Simplification of Karakas and Tariq

\[ \beta = (P - L)N^{3/2}D^{1/2} \alpha^{-5/8}bc^{-1} \]

- Clean perforations \( bc \) : Static Underbalance (SUB), Dynamic Underbalance (DUB)
- Increase shot density \( N \) : Higher spf guns; Double Shoot
- Shoot beyond formation damage \( P - L \) : Deeper Penetrating Shaped Charges
Obtaining Clean Perforations

- Perforating crushes rock

**Typical Perforation**

**Ideal Perforation**
Crushed Zone

- Reduces production or injection
- Weaker than the virgin rock
- Removed by a sharp drop in pressure

*SPE 122845 “New Fundamental Insights into Perforation Induced Formation Damage” Heiland presented in 2009
Tunnel Debris

- Reduces injection rates
- Loose, weak material
- Removed by surge flow

*SPE 122845 “New Fundamental Insights into Perforation Induced Formation Damage” Heiland presented in 2009
Options for Perforation Cleanup

- Surging
- Static Underbalance
- Dynamic Underbalance
Wellbore Dynamics

- Guns and spacers act as pressure sinks
- Pressure waves in wellbore
- Waves clean perforations
- Waves also generate shock
Wellbore Dynamics Model

Wellbore Pressure Transient - Time: 0.0000 s

- Top of Gunstring
- Bottom of Gunstring

Gauge Pressure

Pressure [psi]

Time [sec]
Wellbore Dynamics Model

Wellbore Pressure Transient - Time: 0.0000 s

Depth from Wellhead [ft]
- Top of Gunstring:
- Bottom of Gunstring:

Pressure [psi]
- 2500 to 5000

Time [sec]
- 0 to 0.2

Gauge Pressure
- 3000 to 5200

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Measured Data vs Model

- Implosion chamber*
- Fast recording pressure gauge
- Pressure amplitude and time match
- Second pressure drop is reflection from a plug

How do we link this pressure response to perforation clean up?

*SPE 144080 “Controlled Well Implosions Show that Not All Damage is Bad—A New Technique to Increase Production from Damaged Wells” Busaidy presented in 2011
API RP19B Section 4 Research Facilities

Section 4 Pressure Vessel
Core Flow measurement

Scratch Tester
Rock UCS measurement
Dynamic Underbalance Experiments

- Simulated Wellbore (SWB) < Gun pressure
- SWB recovery controlled by flow from reservoir and/or SWB accumulators
Flow Measurements

- Stable flow (injection and production)
- PI from slope of differential pressure vs flow rate
Core Flow Efficiency (CFE)

- Ratio measured PI to theoretical PI
- CFE ranges from 0.05 to 1
- Clean perforation tunnel has CFE of 1
- CFE of 0.05 typical of overbalanced perforating
Single Shot Skin Model

Kc/K model

- Kc/K model assumes impaired flow along entire length

Lc/L model

- Lc/L model assumes flow through open tunnel but no flow through plugged tunnel

Conventional model (Kc/K)

Lc is permeability of crushed zone and K virgin rock

New model (Lc/L)

Lc is the clean tunnel length and L the total tunnel length
Flow Visualization Experiments

- Fluid only flows into clean perforation tunnel
- Lc/L is a better model of perforation clean-up

Bright blue region shows fluorescent dye invasion
Why is This Important?

• Kc/K does not predict skin which could lead to the wrong selection of guns or technique

• Lc/L is more realistic and gives more accurate predictions of skin

Partial clean-up Lc/L model

Partial clean-up Kc/K model

Clean, open tunnel
Deep & Clean Perforations

- On the left Lc is short so flow has to go through formation damage simulated by low permeability rock.

- On the right the perforation is clean (Lc = L) so flow is through the perforation tunnel avoiding the damage.
4 ½” Gun, 5 spf, Large Charge

- Penetration with clean tunnel length
- Shooting through the formation damage

Perforating System #2

Rock Type: Sandstone
Rock UCS: 6403 psi
Vertical Stress: 5000 psi
Pore Pressure: 2234 psi

Legend:
- Dirty Perforation
- Clean Perforation
- Brine
- Cement
- Damaged Zone
- Formation
4 ½” Gun, 12 spf, Small Charge

- Penetration with clean tunnel length
- Shooting through the formation damage

Which system will give the best production?
Shot Density Dominates

- Penetration with the smaller charge is less, but the productivity is higher.
- Shoot the 5 spf system twice, to get higher productivity and more than 12 spf system.

Productivity Ratio vs Effective Shot Density

12 spf, 135 deg

5 spf, 72 deg
How Deep is Enough?

- Sonic radial profiling measures the depth of altered sonic velocities
- Interpreted as damage and low permeability regions
- Shoot about 50% beyond or 8 in. total

*SPE 112862 “Dipole Radial Profiling and Geomechanics fro New Wellbore Alteration Detection to Improve Productivity in a Matured Field” Subbiah presented in 2008
How Deep is Enough?

• Shell estimate invasion along the well and want to perforate beyond the invaded zone

• API section 1 concrete penetration $\neq$ penetration in stressed rock

How do we calculate penetration today?

*SPE 101082 “Optimized Perforation—From Black Art to Engineering Software Tool” Bell presented in 2006
Calculating Penetration

- Depends on target strength or Ballistic Indicator Function* \((F_{bi})\)
- \(F_{bi}\) of rock type, strength and confining stress
- Shaped charge characterised across a range of \(F_{bi}\)
- Model predicts down hole penetration

\[
DoP = DoP_{ref} e^{\alpha_0 (F_{bi,ref} - F_{bi})}
\]
Keeping Perforations Clean

- Tri-axial stress frame experiments*
- Perforate a block of rock under stress with various static underbalance conditions
- Measure flow from each individual perforation

*SPE 28554 “Block Tests Model the New Wellbore in a Perforated Sandstone” Mason presented in 1994
Big-Block Experiment Results

- Large variation in flow from individual perforations
- PI is higher with higher static underbalance
- Killing the well is bad
How to Keep Perforations Clean

• Do not kill the well. Incompatible fluids can plug perforations and lose production (SPE 28554)

• Drop guns into sump (IPTC 14300, SPE 74351, SPE 28916)

• Recover guns under pressure (SPE 74422, SPE 72134, SPE 38183)

• Use designed kill fluids (SPE 94596)

• Clean up after perforating using implosion chambers (SPE 144080)
Summary

- Perforating provides the connection between the well and the reservoir
- By using the techniques discussed in this presentation we should be able to unlock the full potential of reservoirs resulting in more production

*SPE 144080 “Controlled Well Implosions Show that Not All Damage is Bad—A New Technique to Increase Production from Damaged Wells” Busaidy presented in 2011