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Modern Perforating Techniques: Key to Unlocking Reservoir Potential

Andy Martin

Schlumberger

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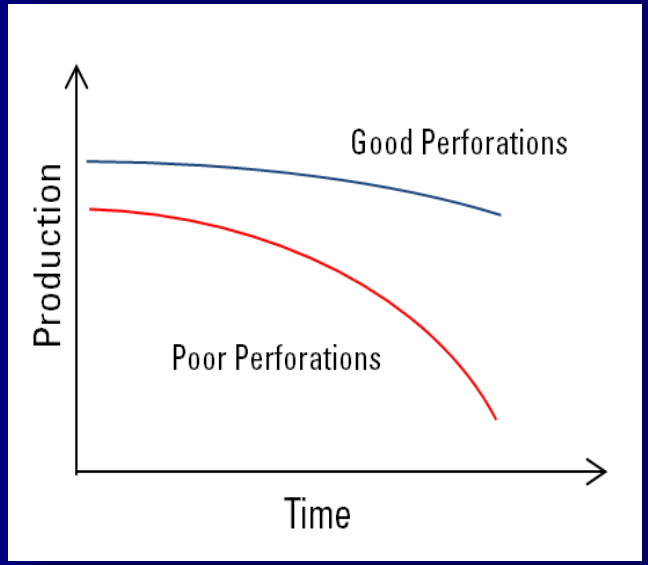
Presentation Outline

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

Shaped charges

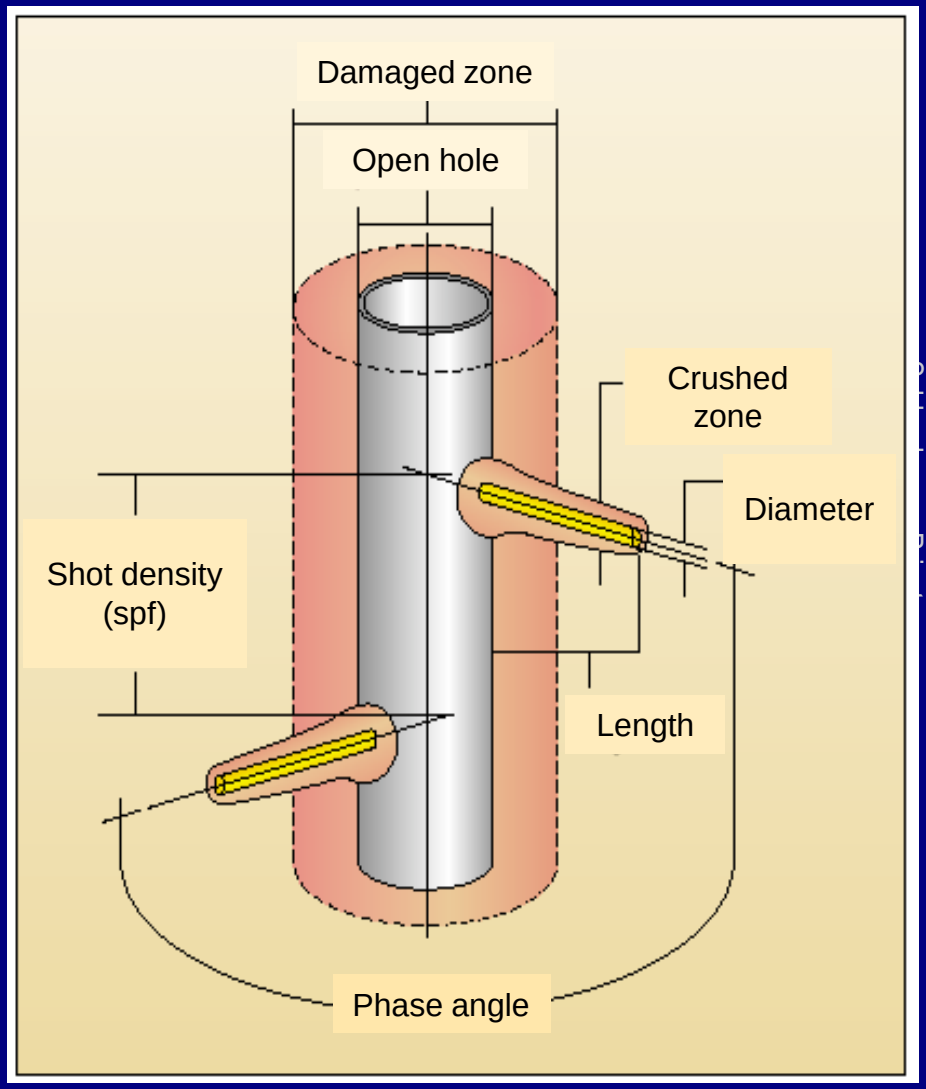
Perforating For Productivity

- 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

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

β = Perforation Efficiency
bc = **Perforation Damage**
N = **Shot Density (spf)**
P = **Perforation Tunnel Length**
D = Average Perforation Tunnel Diameter
α = 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

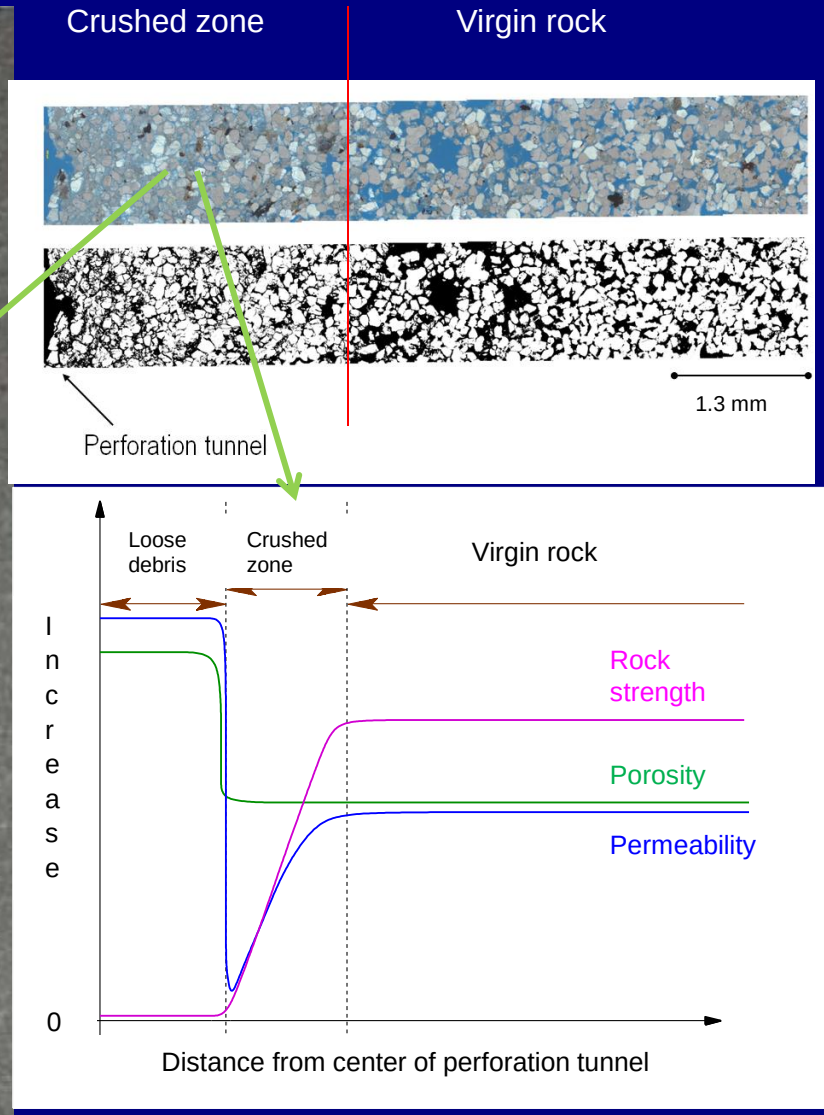
- Perforating crushes rock

Typical Perforation

Ideal Perforation

Crushed Zone

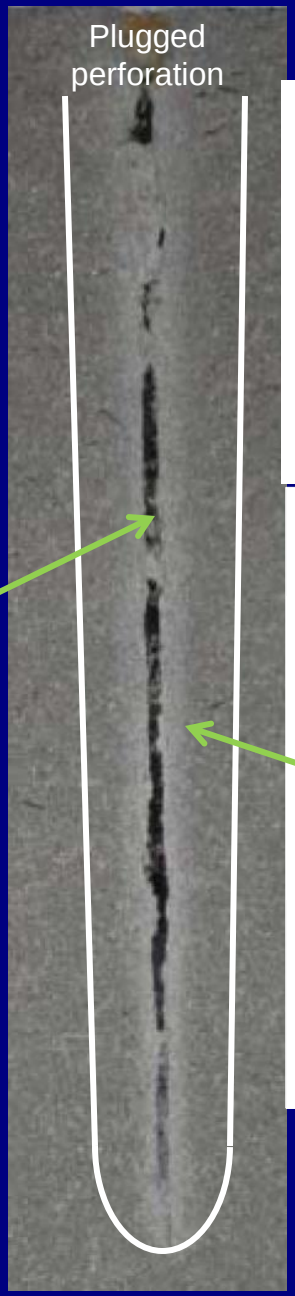
- Reduces production or injection
- Weaker than the virgin rock
- Removed by a sharp drop in pressure

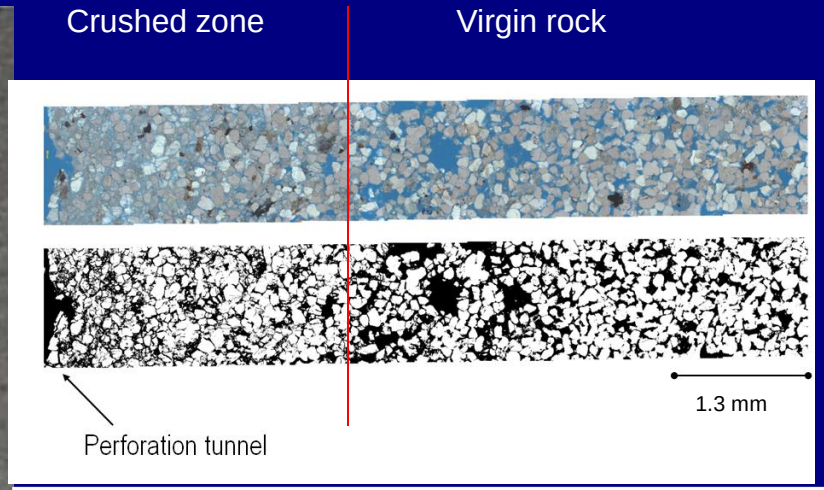


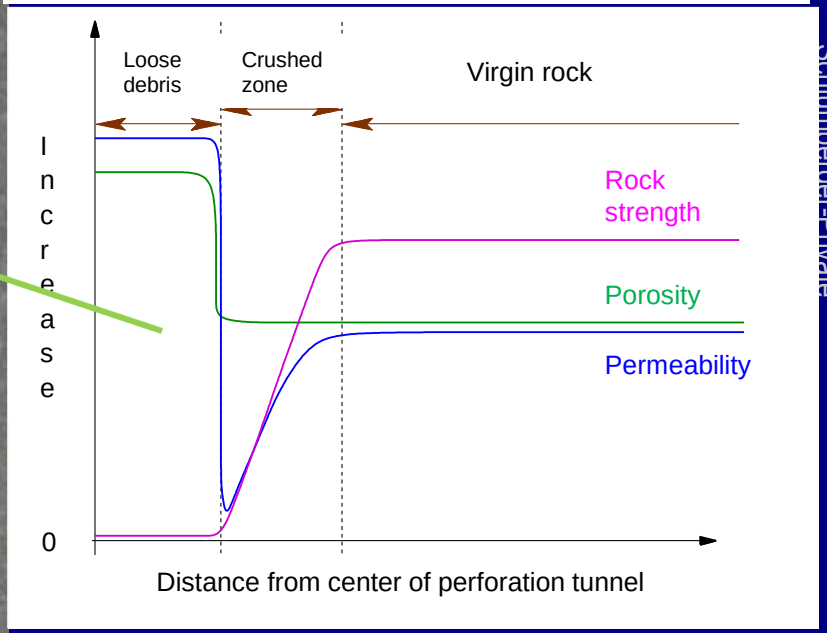
*SPE 122845 “New Fundamental Insights into Perforation Induced Formation Damage” Heiland presented in 2009

Tunnel Debris

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



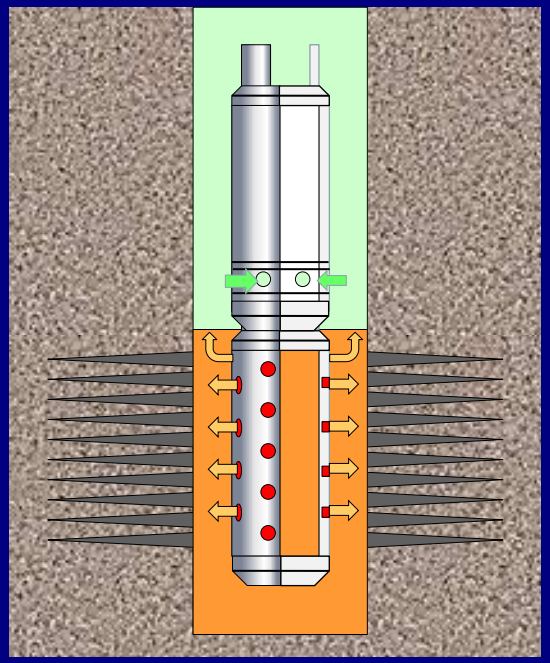




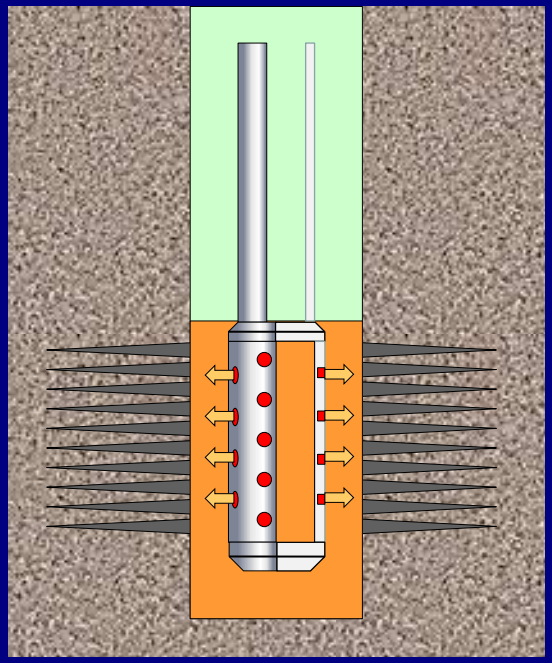
*SPE 122845 “New Fundamental Insights into Perforation Induced Formation Damage” Heiland presented in 2009

Options for Perforation Cleanup

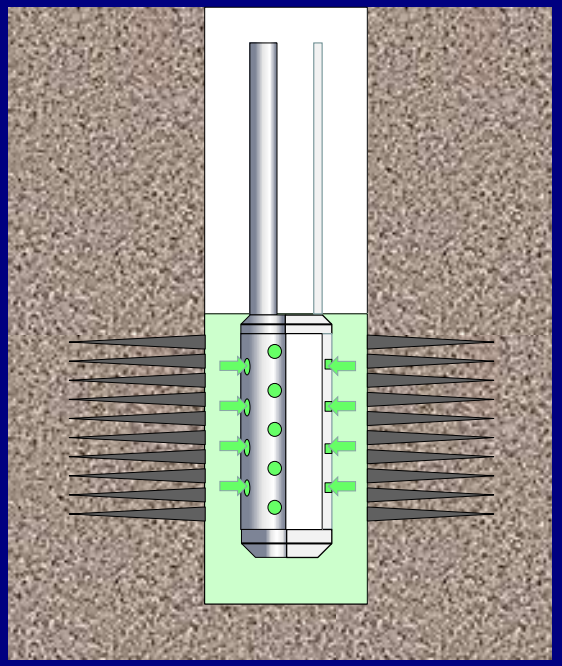
Surging



Static Underbalance

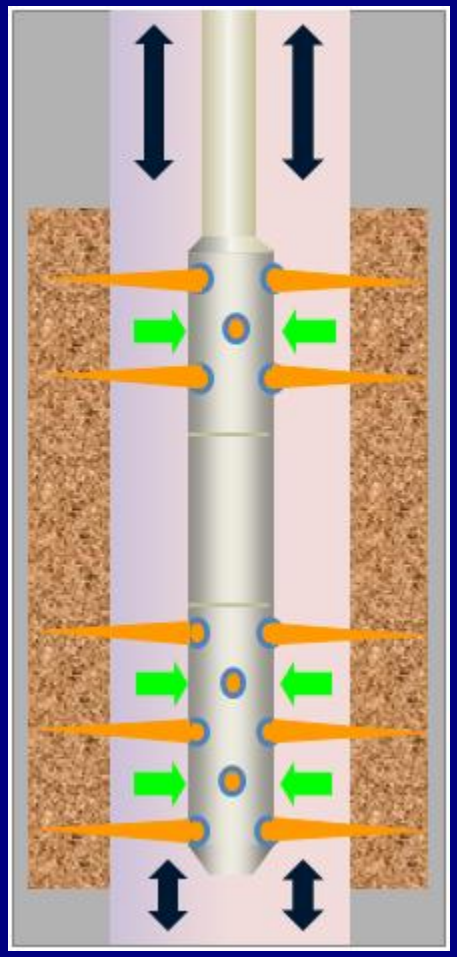


Dynamic Underbalance

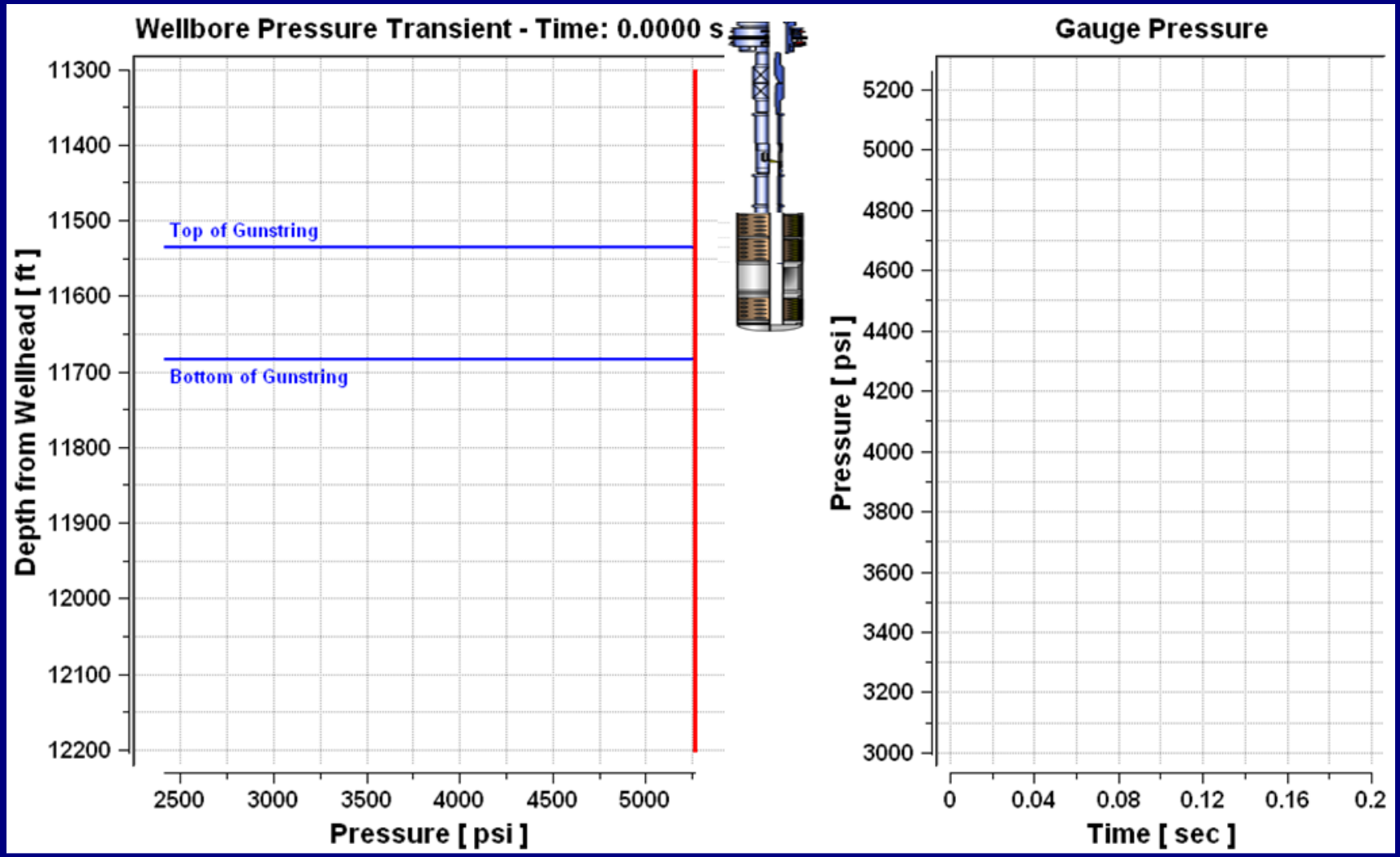


Wellbore Dynamics

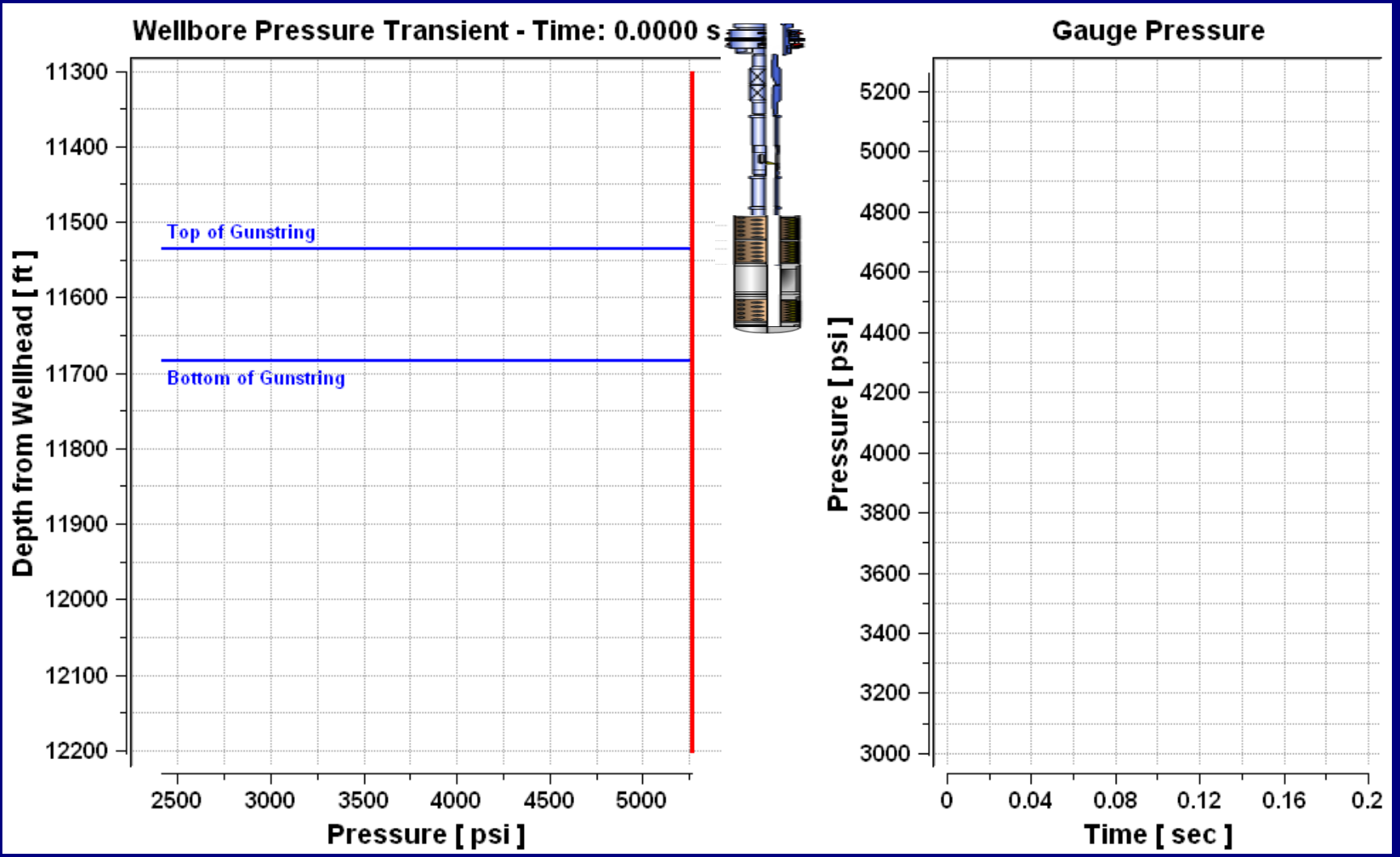
- Guns and spacers act as pressure sinks
- Pressure waves in wellbore
- Waves clean perforations
- Waves also generate shock



Wellbore Dynamics Model

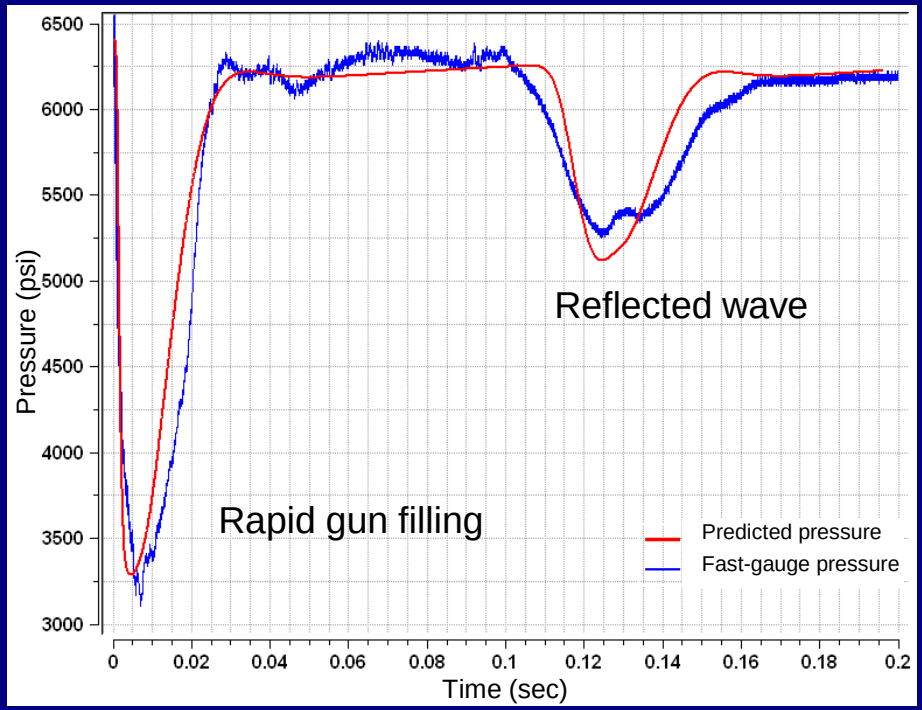


Wellbore Dynamics Model



Measured Data vs Model

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



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

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

API RP19B Section 4 Research Facilities

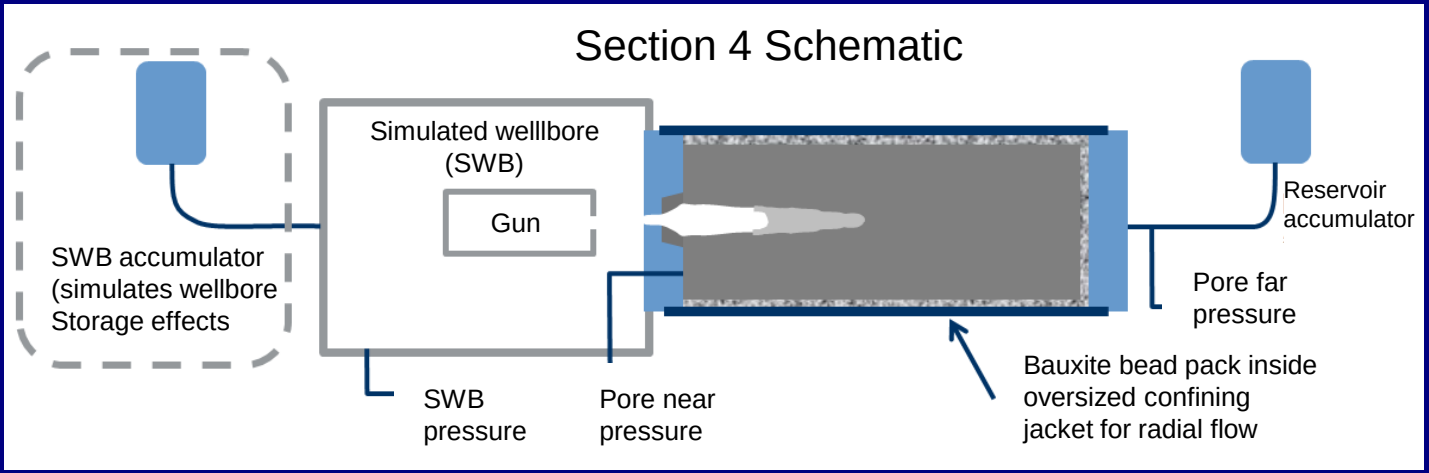
Section 4 Pressure Vessel

Core Flow measurement

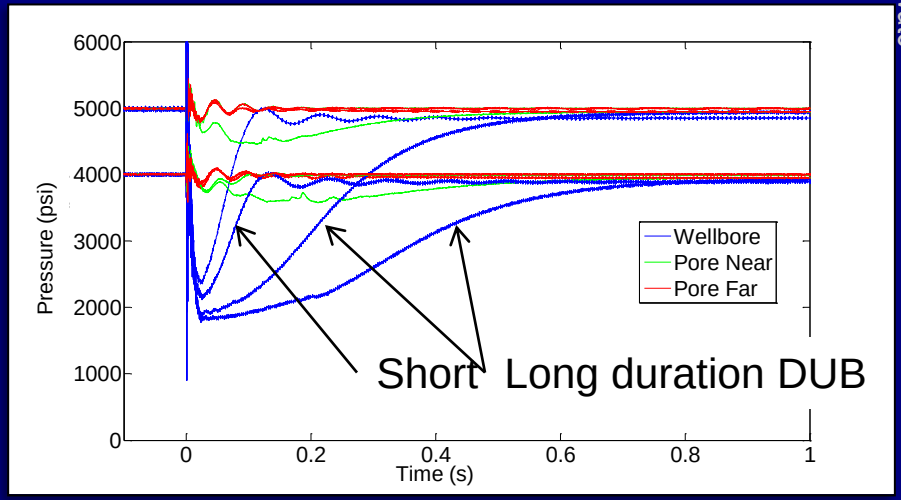
Scratch Tester

Rock UCS measurement

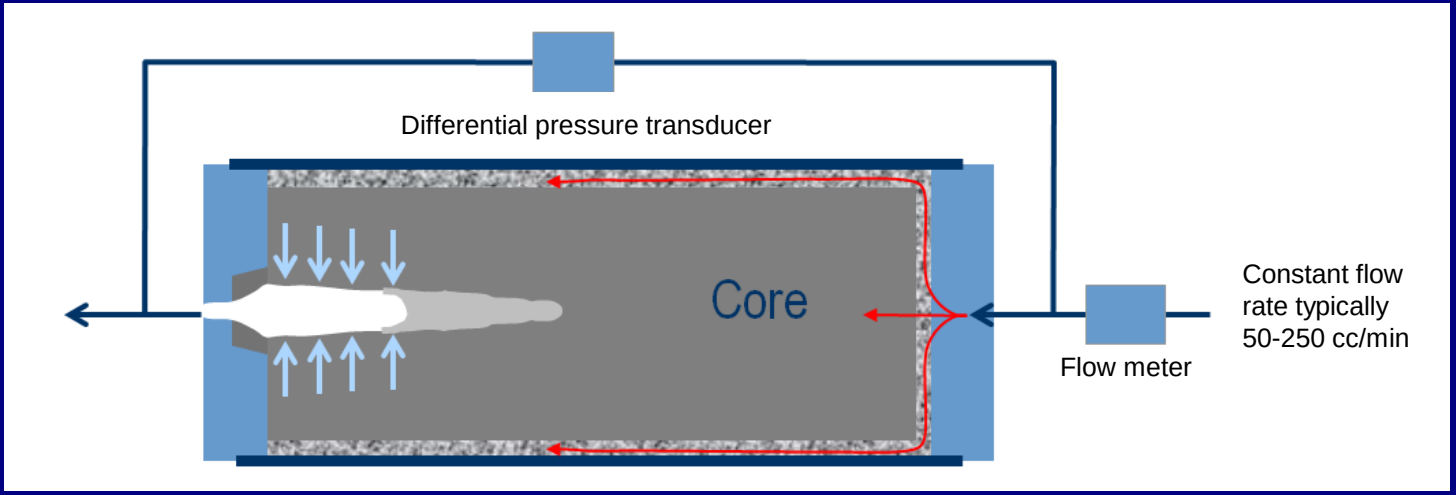
Dynamic Underbalance Experiments



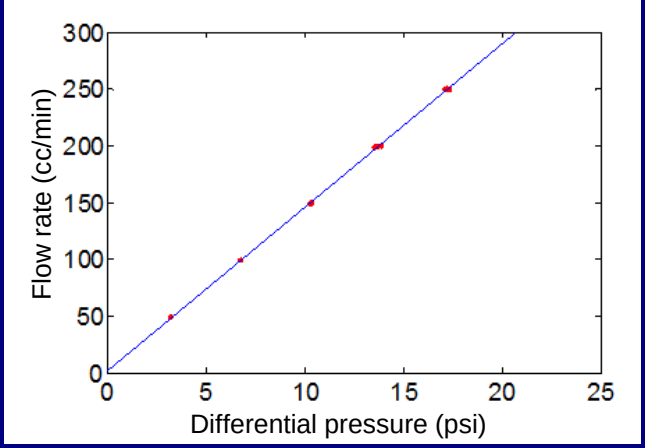
- Simulated Wellbore (SWB) < Gun pressure
- SWB recovery controlled by flow from reservoir and/or SWB accumulators



Flow Measurements

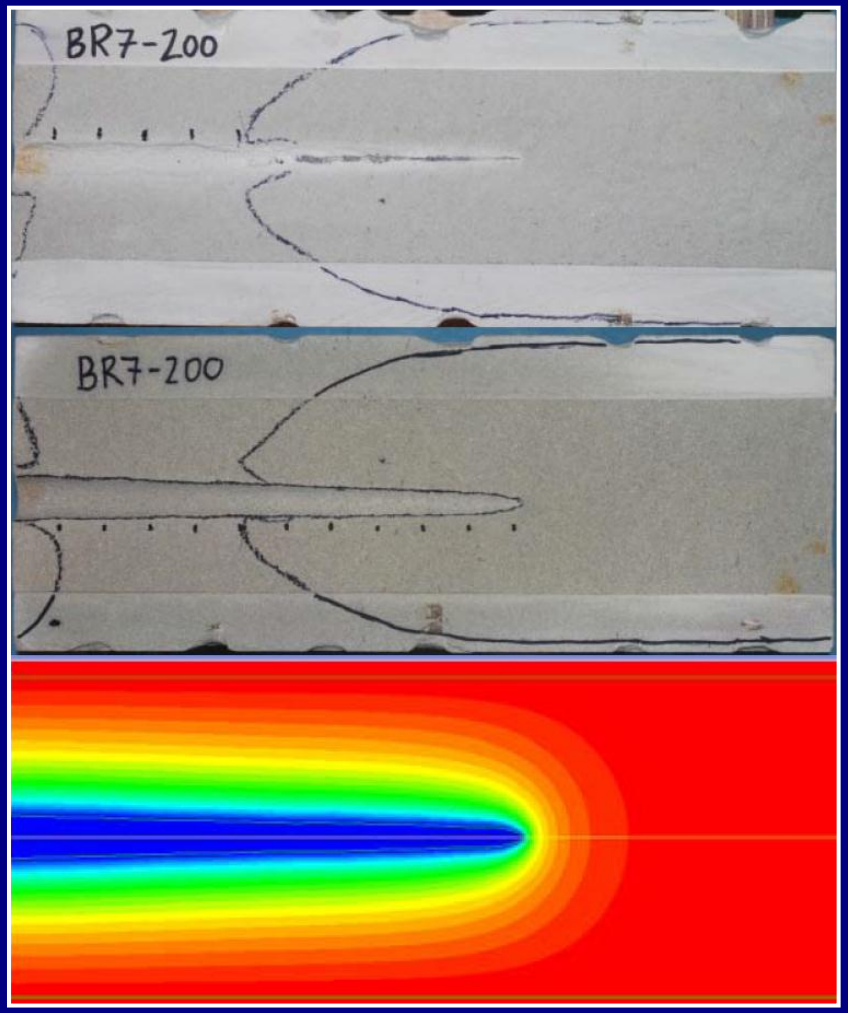


- Stable flow (injection and production)
- PI from slope of differential pressure vs flow rate



Core Flow Efficiency (CFE)

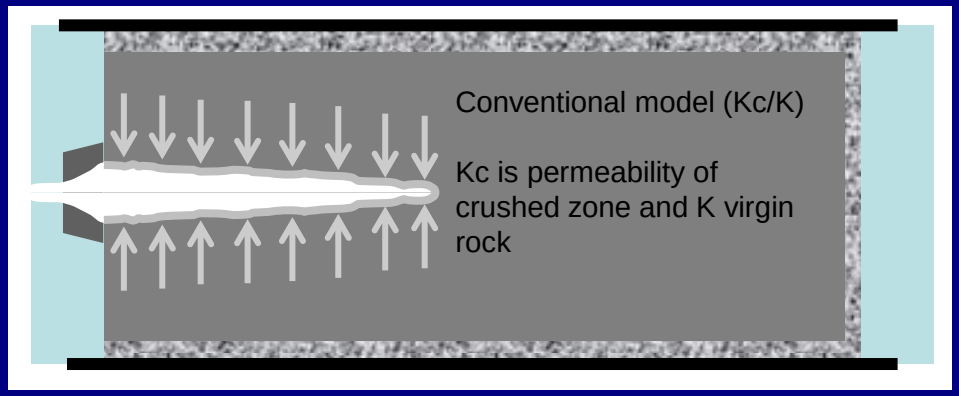
- Ratio measured PI to theoretical PI
- CFE ranges from 0.05 to 1
- Clean perforation tunnel has CFE of 1
- CFE of 0.05 typical of overbalanced perforating



Single Shot Skin Model

- Kc/K model assumes impaired flow along entire length

Kc/K model



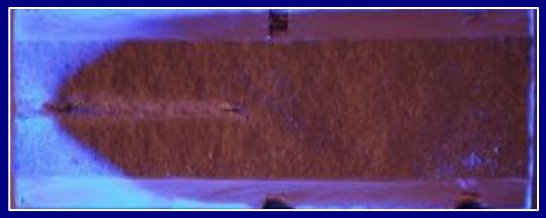
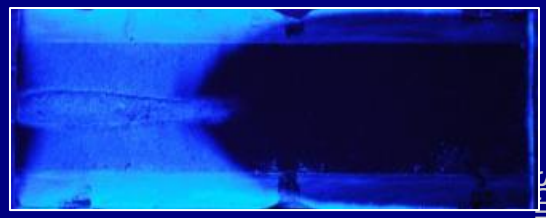
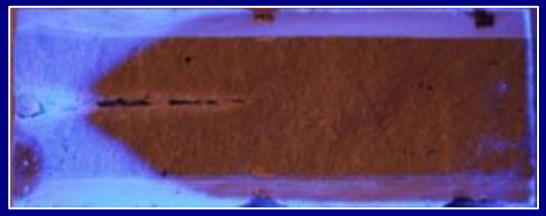
- Lc/L model assumes flow through open tunnel but no flow through plugged tunnel

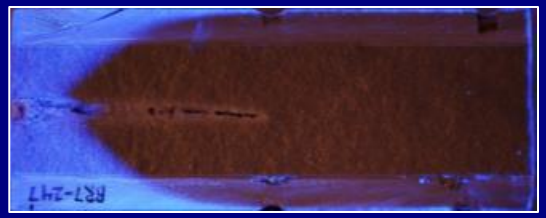
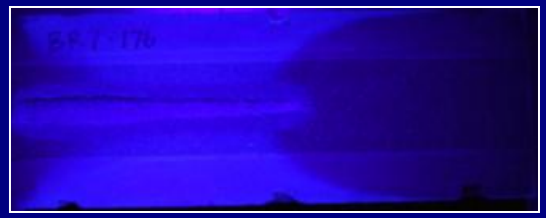
Lc/L model

Flow Visualization Experiments

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

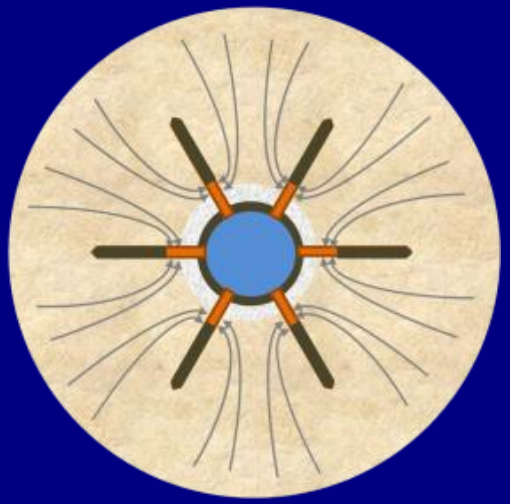
Bright blue region shows fluorescent dye invasion

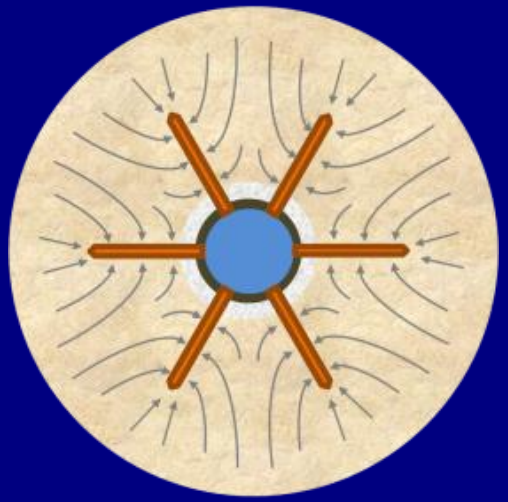



Why is This Important?

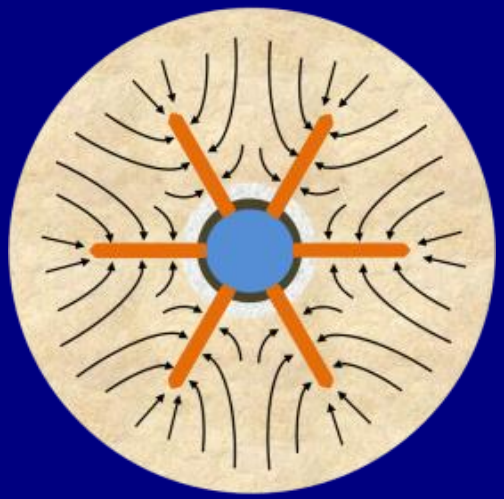
- Kc/K does not predict skin which could lead to the wrong selection of guns or technique
- Lc/L is more realistic and gives more accurate predictions of skin



Partial clean-up
Lc/L model

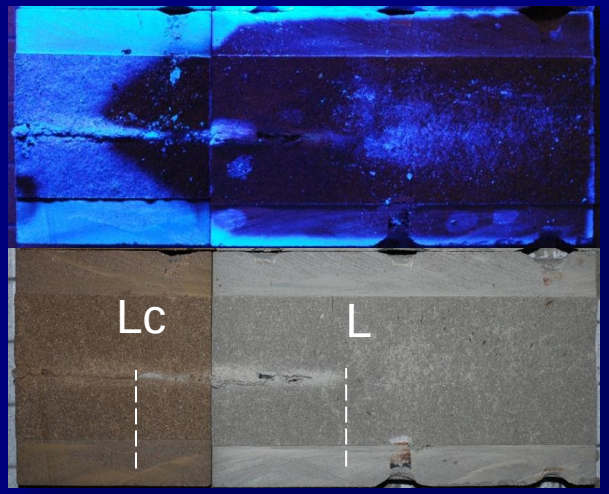


Partial clean-up
Kc/K model



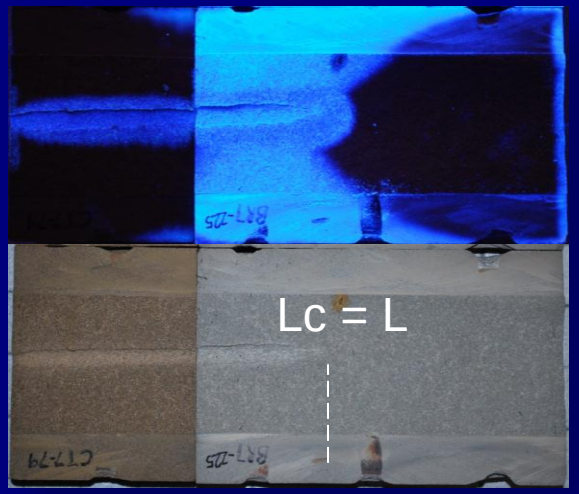
Clean, open tunnel

Deep & Clean Perforations



Drilling damage:
low permeability

Virgin rock:
high permeability

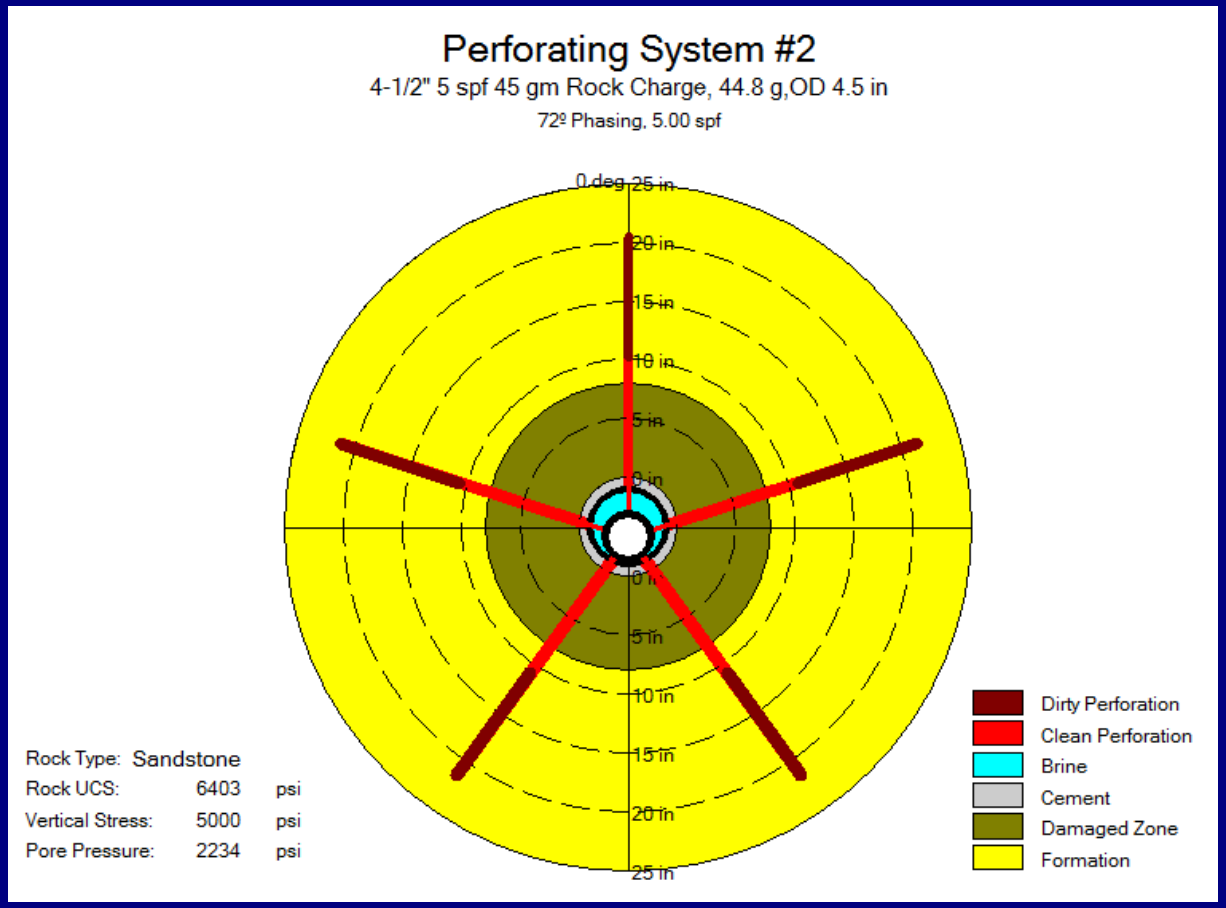


Low
permeability

High
permeability

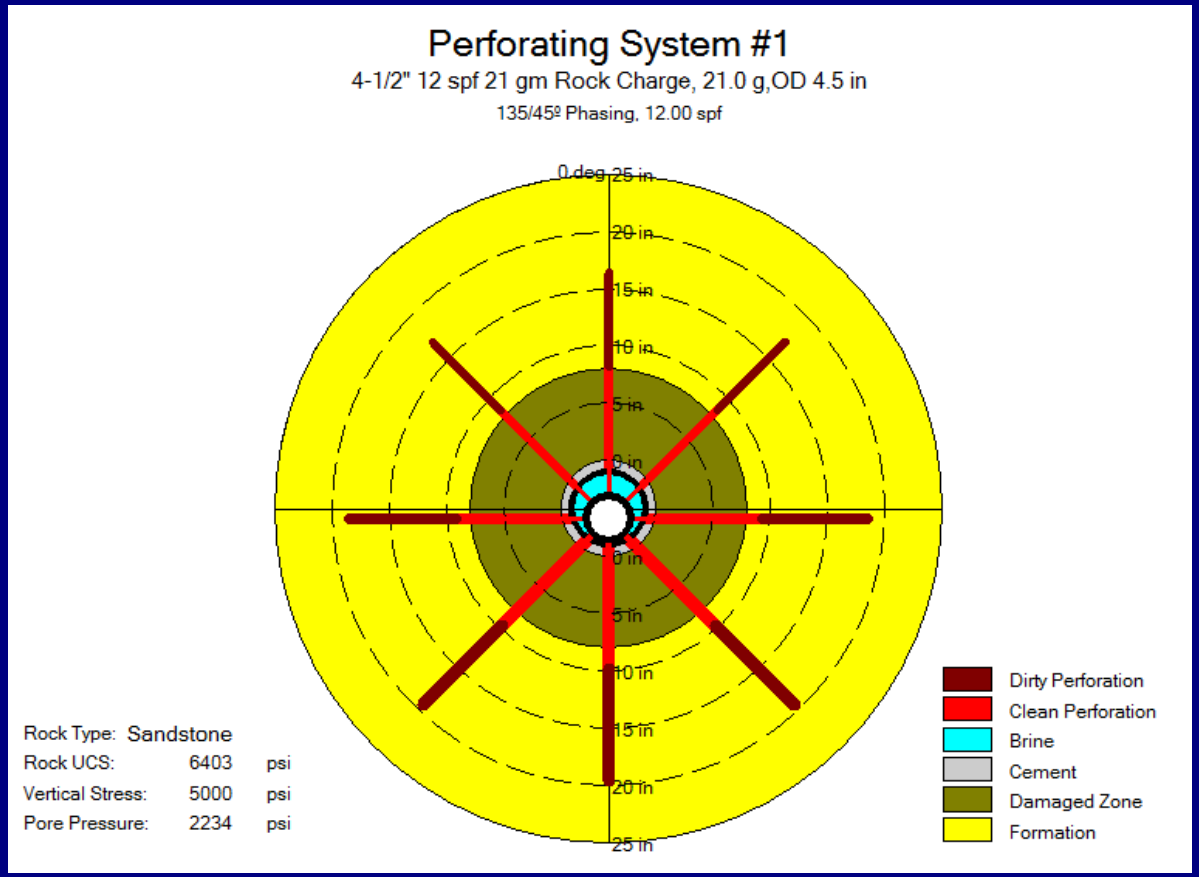
- On the left Lc is short so flow has to go through formation damage simulated by low permeability rock
- On the right the perforation is clean (Lc = L) so flow is through the perforation tunnel avoiding the damage

4 ½” Gun, 5 spf, Large Charge



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

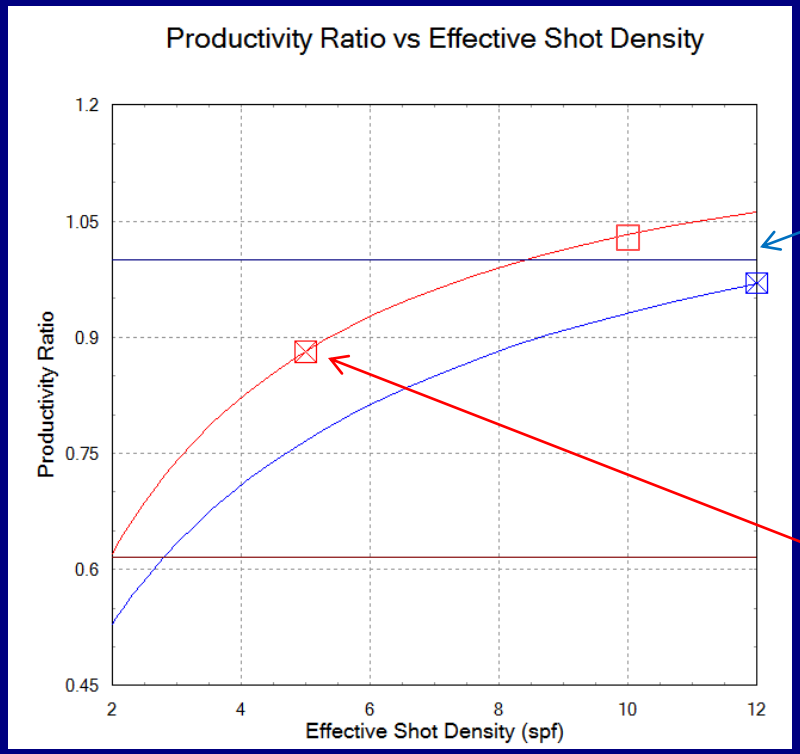
4 ½” Gun, 12 spf, Small Charge

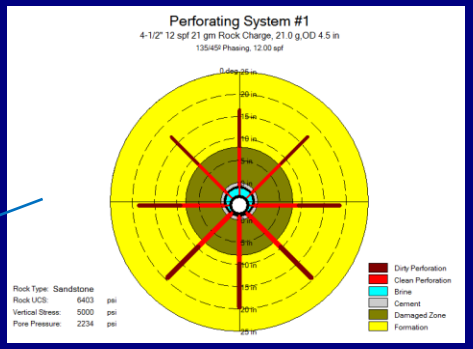


- Penetration with clean tunnel length
- Shooting through the formation damage

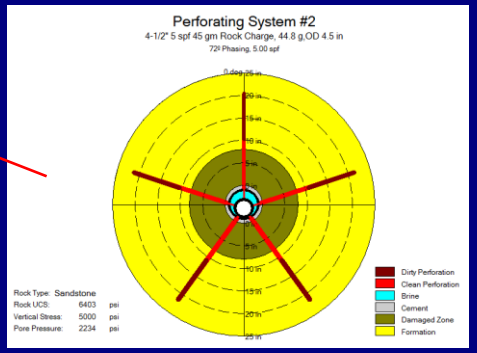
Which system will give the best production?

Shot Density Dominates





12 spf, 135 deg

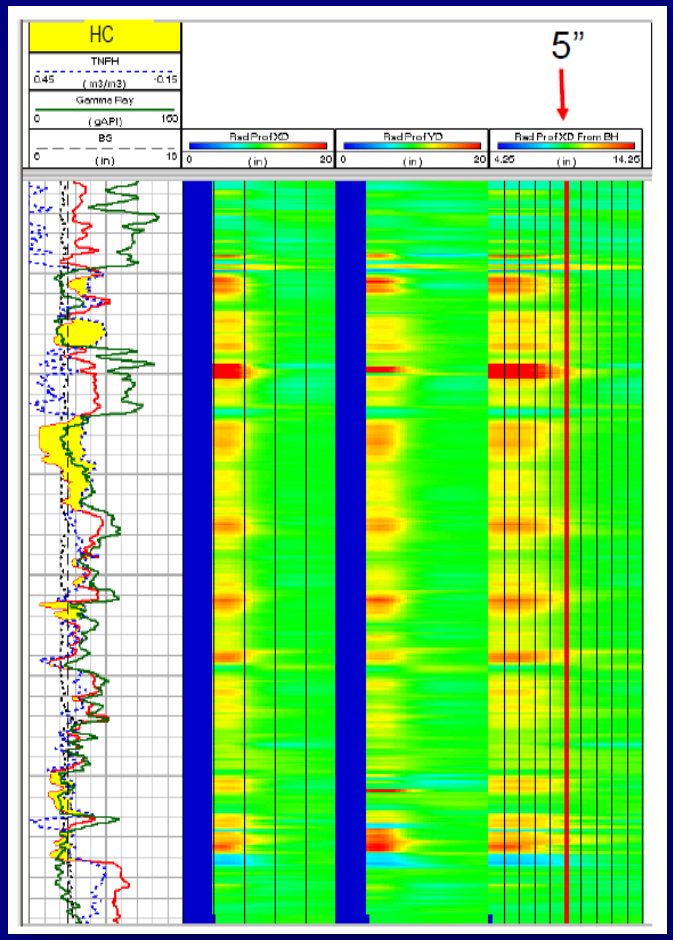


5 spf, 72 deg

- 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

How Deep is Enough?

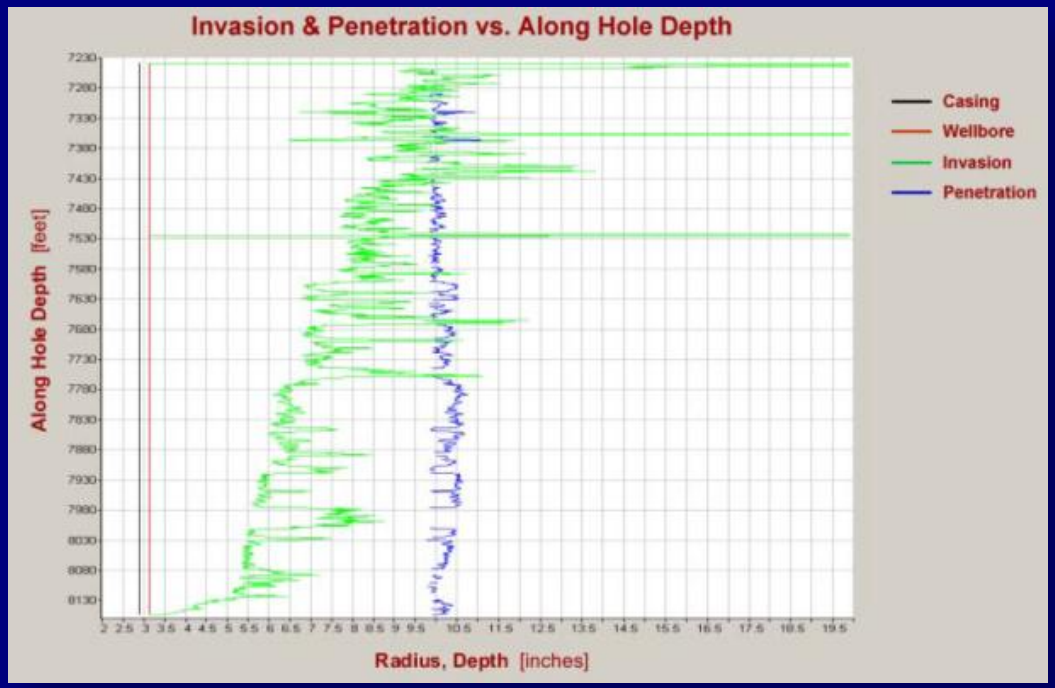
- Sonic radial profiling measures the depth of altered sonic velocities
- Interpreted as damage and low permeability regions
- Shoot about 50% beyond or 8 in. total



*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 ≠ penetration in stressed rock

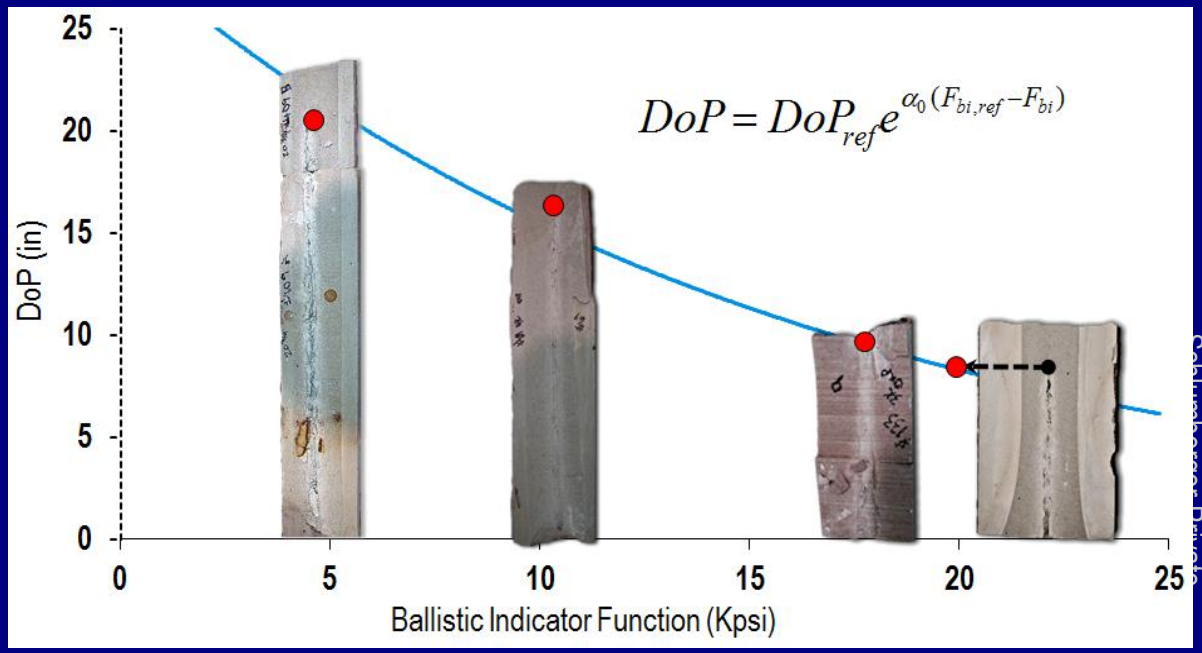


*SPE 101082 “Optimized Perforation—From Black Art to Engineering Software Tool” Bell presented in 2006

- How do we calculate penetration today?

Calculating Penetration

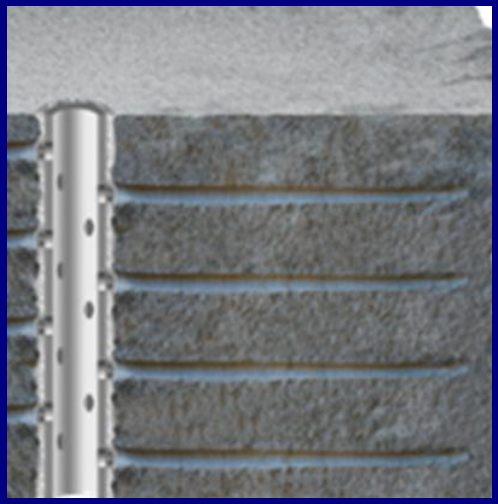
- Depends on target strength or Ballistic Indicator Function* (F_{bi})
- F_{bi} of rock type, strength and confining stress



- Shaped charge characterised across a range of F_{bi}
- Model predicts down hole penetration

*SPE 151846 “Stressed Rock Penetration Depth Correlation” Harvey presented in 2012

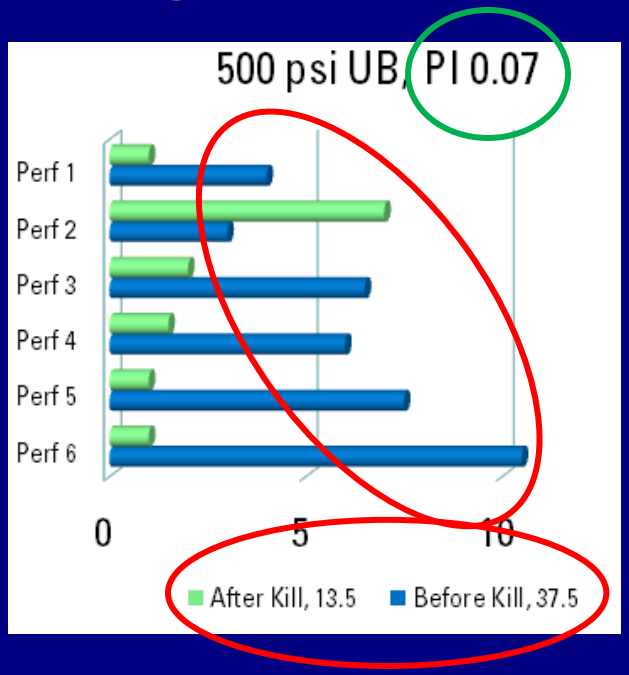
Keeping Perforations Clean

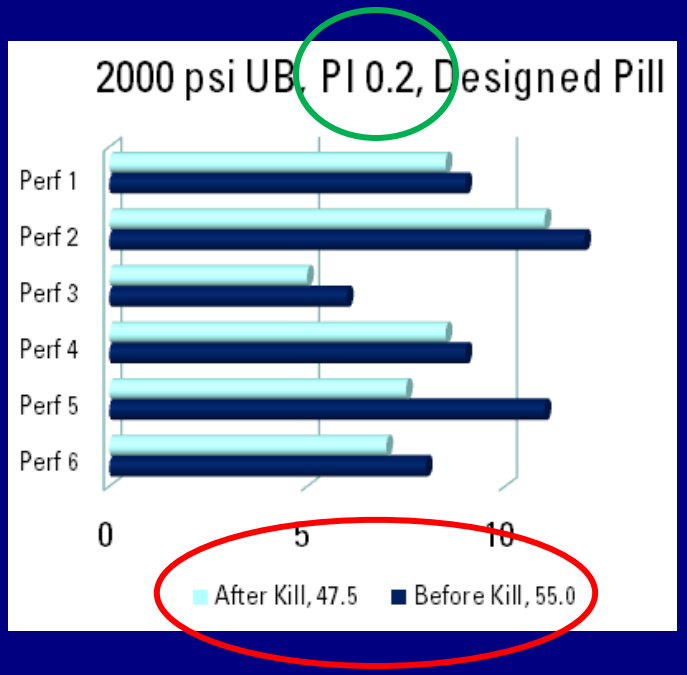


- Tri-axial stress frame experiments*
- Perforate a block of rock under stress with various static underbalance conditions
- Measure flow from each individual perforation

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

Big-Block Experiment Results



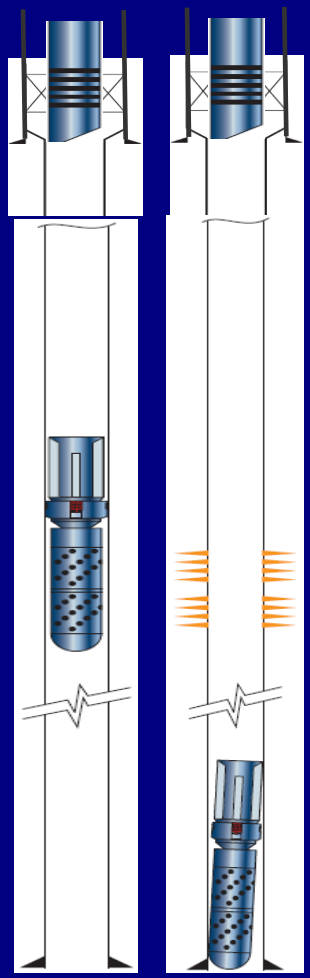


- Large variation in flow from individual perforations
- PI is higher with higher static underbalance
- Killing the well is bad

How to Keep Perforations Clean

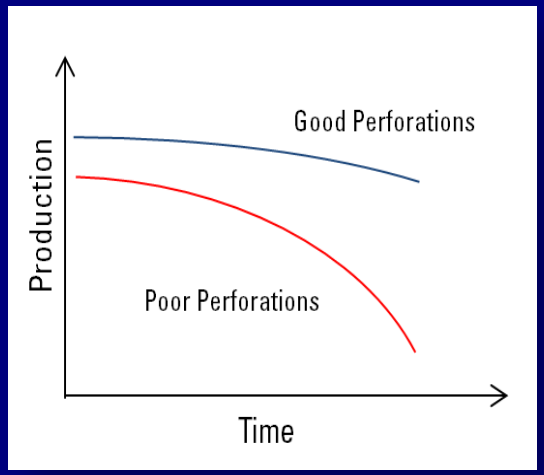
- Do not kill the well. Incompatible fluids can plug perforations and lose production (SPE 28554)
- Drop guns into sump (IPTC 14300, SPE 74351, SPE 28916)
- Recover guns under pressure (SPE 74422, SPE 72134, SPE 38183)
- Use designed kill fluids (SPE 94596)
- Clean up after perforating using implosion chambers (SPE 144080)

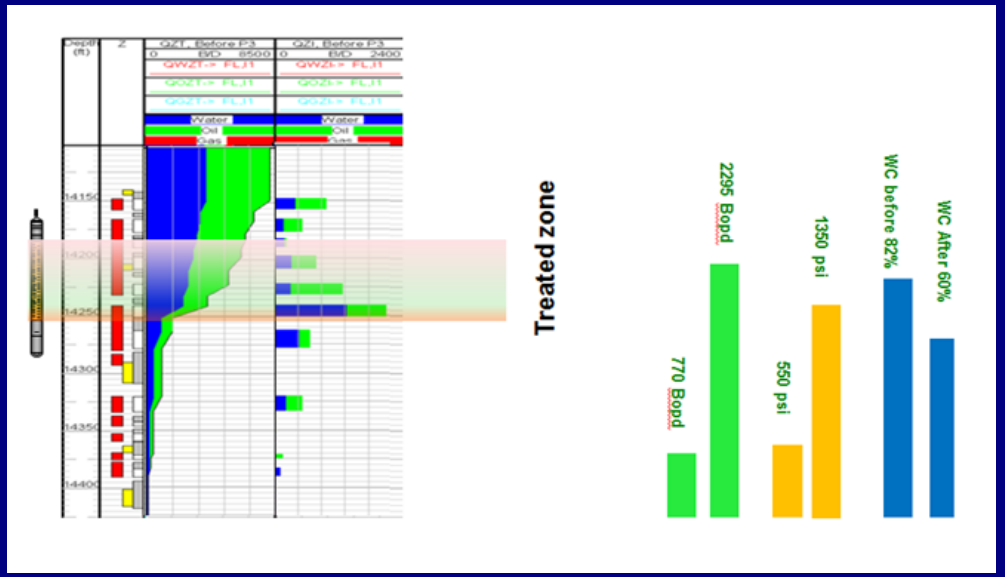
Guns anchored before upper completion run. They automatically drop when detonated.



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

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