Perforating Basics

How the perforating processes work
Perforating Methods

1. The vast majority of all perforating work is performed with shaped charge or jet perforating charges.

2. Bullet guns – a hardened steel bullet is shot from a short barrel “gun” to penetrate the casing and formation – one of first types of perforators.

3. Abrasive perforating methods – usually a sand/water slurry pumped at high pressures and aimed at the casing wall.

4. Specialty methods – electrical, laser, acid, pressure, mechanical, etc.
A shaped charge for use in a hollow carrier gun. The hole at the rear of the charge accepts the detonating cord.
Big Hole charges in a loading tube prior to loading in a scalloped hollow carrier gun.
A 60 degree phased, hollow steel carrier perforating gun (scalloped) after firing. Note the location of the holes in the scallops and the roundness of the holes. The purpose of the scallops is primarily for containing the burr around the exit hole and preventing scoring in polished bores in packers and profiles. The scallops also reduce the thickness of the gun body through which the charge must penetrate.
Perforator Performance

• How it works – a focused pressure wave is propelled outward from the charge case during firing. The pressure punch, along with the mass of the perforating liner, provides the force necessary to punch through the casing, cement and formation.

• Everything in the path of the jet is forced to the side and compacted.
The following 5 slides are the firing sequence of a shaped perforating charge.
Detonation cord explosion (high order) ignites the charge primer through a small hole in the charge case.
The charge front expands very rapidly – everything in the charge must be symmetrical for the best performance.
As the explosion front of the charge reaches the liner, it will start the process of forming the “jet”.
The liner is deformed and adds mass to the jet, not moving at over 20,000 ft/sec.
Common Gun Phasing

0  180  120  90  60
Factors Affecting Productivity

- Damaged zone diameter
- Openhole diameter
- Crushed zone diameter
- Perforation diameter
- Perforation spacing (dependent on shot density)
- Perforation length

$\phi = \text{phase angle}$
Gun Phasing

• Reason for phasing? – improving contact angle with the formation for the completion or stimulation design.

• Examples
  – 60°, 90°, 120° for fracturing
  – 60° for gravel packing
  – 0° for through-tubing perf addition (common)
  – 180° for orienting perf guns to known frac direction

• Gun phasing may also help reduce sand failures in soft sand formations.
Special Case - Perforation density & phasing for Sand Control

– High shot density and 60° phasing is a common perforating mechanism for high perm formations,

– However, this is probably the worst thing to do in low strength sandstones (leads to extensive shock damage)

– Compromise between flow efficiency & perf stability

  • Low density – higher tunnel velocities (clean up vs. sand face stability)
  • High density and too close
    – rate vs. rock failure
Low shot density perforating

– By shooting at low density and higher phase angle it is possible to avoid overlapping the shock damaged zones of individual perforations.
– The intact rock between perfs stabilizes the rock and prevents massive sand production.
– Fewer perforations, well distributed radially around the wellbore, also have a better chance of attracting sufficient inflow to effectively clean up the tunnels.
Phased perforating

- Maximise vertical spacing between perfs and uniformity of spacing (horizontal spacing >15°)

- Using smaller perforation holes and lower shot density increases perforation spacing

- By adjusting phase angle, the effective perforation spacing (for a given wellbore radius and shot density) can be further increased
  - **Example for 3 3/8” guns, 6spf.**

<table>
<thead>
<tr>
<th>Phasing</th>
<th>Avg Min Perf to Perf</th>
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<tbody>
<tr>
<td>60°</td>
<td>4.32”</td>
</tr>
<tr>
<td>99°</td>
<td>6.62”</td>
</tr>
<tr>
<td>135°</td>
<td>6.63”</td>
</tr>
<tr>
<td>138°</td>
<td>6.67”</td>
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</table>
Perforation density & phasing – BP Magnus example

- Decision to use Stand Alone C&P and live with sand.
- Driver was a need to develop low cost completions capable of low skin / high PI whilst managing sand production.
- Used standard perforating for first 10 years of field life.
- Later, changed from 6 spf / 60 deg phasing, through 6 spf optimally phased (99 deg phasing on the liner) to reduce sand production.
- Moved to using 4 spf / 130 deg phasing with minimal productivity impact.
- Allowed them to considerably increase the critical drawdown & rate prior to sand production.
Perforation charge performance – Deep Penetrating vs Big Hole

A big hole and a deep penetrating charge produced with the same 34 grams of powder.

The BH charge made a 1” diameter entrance hole 8.8” long, while the DP charge produces a 0.55” hole diameter and 17.3” of penetration.
Anatomy of a Perforation

Entrance hole 0.2" to over 1" - loosens some diameter going through casing.

Perf diameter in formation is 0.25" to 0.75", tapering to a point.

Liner, crushed cement and formation debris plug in last 1" or more of perf.

Length = 6" to 24"+ depending on type, size and design of charge; casing properties, formation strength and reservoir pressures.

"loose" sand in bottom of perforation - can cause confusion on sanding rate tests

Hole through cement usually slightly larger than in formation.
What do don't see - loss of permeability

about 1/2"

$k = 50$ to $70\%$ of initial
An estimation of productivity ratio resulting from shot density. **NOTE: this does not consider damage** and all perfs are assumed to be open. (My best estimate is 50% of perfs open – from downhole TV study)
Other factors, such as grain size, porosity, connate fluids and overburden pressures also affect perforation penetration.
Compressive Strength Effect

Source – Larry Behrmann, Schlumberger
Perf Selection

- natural completion - DP usually
- stimulation - BH usually
- weak sands - no pack - DP, Kiss Charge?
- gravel pack - BH
Perforation Density

• Look at flow potential from layers in the well and the intended stimulation design
  – vertical, deviated or horizontal
  – formation variances, layers and bedding planes
  – stimulation designs
  – potential for leveling drawdown along the wellbore
  – total flow rates
  – open perfs vs numbers of perforations
    • about 35% open, more with underbalance (maybe 50%)
Flow convergence towards a slot or hole – can be a very severe restriction, especially in high permeability formations.
Consider the velocity of the fluid as it nears the wellbore – The velocity away from the well is low – the velocity near the well is much higher – turbulence effects????

Viscous drag on gains near the wellbore is much higher.
$\beta = (P - L') N^{3/2} d^{1/2} \alpha^{-5/8} b^{-1}$

$P - L' = \text{penetration beyond damage} = 3, 6, 9, 12, 15, 18 \text{ in.}$

$N = \text{shot density} = 1, 2, 4, 8, 12 \text{ spf}$

$d = \text{perf diam} = 0.31, 0.61, 0.92 \text{ in.}$

$\alpha = \text{anisotropy ratio, } k_h/k_v = 1, 10, 50$

$b = \text{perforating damage} = 1, 1.5, 2.5, 5.5, 10.5$

Larry Behrmann, Schlumberger
Do you really want a cased and perforated completion?

• Why are you running casing and perforating?
• Is there a better way?
• Is an open hole completion an option?
  – High kh reservoirs
  – High deliverability formations, $kh/\mu$
A comparison of two dry gas wells. The B well is a replacement well, drilled 15 meters from the A well. The change was that the B completion was open hole. Note the substantial improvement in production.
Locating high perm streaks

- drilling fluid loss
- sticking points
- gamma-ray? / resistivity?
- depositional environment
- production testing
- FMI
- 3D & 4D

High perm streaks (fractures, large pores, high perm channels) – they may be 100 times higher perm than the rest of the matrix.

They dominate flow capacity!
Problems with locating layers

• The ability to determine existence, boundaries and data on layers depends on the spacing of the logging tool.
• Thin layers can be missed completely.
• Sharp differences in layer properties are often averaged.
Perf Cleanup

• A perforation must be a flow path
  – Restrictions cause both mechanical and turbulent (non darcy) skins

• How to get a flow path
  – Long perfs
  – Remove the crush zone
  – Sufficient number of perforations
  – Open hole completion
Underbalance Used On Tubing Conveyed Perforating In Gas Zones In Sandstone

![Graph showing the relationship between formation permeability, total underbalance, and the effects of acid treatment.](image)

- **Legend**
  - □ Acid did not improve production
  - ● Acid did improve production
  - ○ Problems

- **Axes**
  - Y-axis: Formation permeability (MD)
  - X-axis: Total underbalance (PSI)
Perforating Cleanup

Data from GOM Deep Water Field.

Flow rates in 3, 5, 4 > 25,000 BOPD
Flow rates in 1 & 2 in 12,000 BOPD range.

<table>
<thead>
<tr>
<th>Well</th>
<th>Underbalance, psi</th>
<th>PI (bopd/psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>200</td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>+200</td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>200</td>
<td></td>
</tr>
<tr>
<td>E</td>
<td>200</td>
<td></td>
</tr>
<tr>
<td>D</td>
<td>400</td>
<td></td>
</tr>
</tbody>
</table>

- Surge/bbl?: No
- Flowback: No
- Choke?: Closed

Well C: No
Well A: No
Well B: No
Well E: Yes/40
Well D: Yes/40

30 bbl
Open

3/14/2009
Pressure Response in the Wellbore

The immediate response after firing is a pressure spike followed by a rapid underbalance to a pressure lower than the actual static underbalance. This is dynamic underbalance – a function of gun-refill.
Overbalanced Perfed

Surged Later

Underbalanced & Flowed
Underbalance vs overbalance

• Underbalance best uses
  – high flow capacity formations where perfs may be a choke on flow.
  – natural completions in thinner zones with high reservoir pressures
  – where later operations will be underbalanced
  – competent sandstones (some exceptions; cavities for instance)
  – where the best possible test is needed
Underbalance vs overbalance

• Balanced / Slightly Overbalanced Often Used:
  – Only when the wellbore fluid is non damaging and low particulate.
  – When fracturing – note high overbalance may make breakdown more difficult.
  – When perf tunnels can collapse at the slightest underbalance.
Extreme Overbalance Perforating (EOP) Uses

• Note – EOP is a process that breaks down perfs by high pressures generated by high gas pressures or gas generating charges.

• Where perf breakdown is very difficult or expensive (pumping equipment).

• Where permeability is low (<1 md) and typical perf with underbalance is not effective.

• Where perm is high (k >100 md) and no fracturing planned, but damage bypass is needed.
Unloading Damage After Overbalance

• Lab study on sandstones w/muds
  Unloading damage and restoring permeability required a surge equal to the maximum overbalance
  Low permeability aggravates cleanup - it is the flow rate, not the pressure that causes cleaning
Conveyance Selection

• Depends on what is needed...
  – High underbalance w/flow - TCP
  – Lower underbal to overbal - TCP or E-line
  – Adding Perfs - wireline
  – Deviated
    • long zone - TCP
    • short zone - TCP or coiled tubing
    • short radius - wireline?
The hard, sharp burrs created on the gun must be kept recessed to prevent damage to pipe, coatings and polished bores as the guns are pulled from the well.

If the perfs miss the scallops, it is usually a human-based error in loading or gun component selection.
A close up view of the burr raised on the inside wall of the casing (target plate in this case) after the jet penetrates. The burr height may vary from 0.1” to 0.3” or 2.5 mm to 7.5 mm.

These burrs are particularly damaging to close tolerance equipment such as packers, plugs and other equipment with seals.

The burrs may be best removed by scraping the casing, BUT – potential for formation damage by particle release from the casing wall plugging the perforations, or open hole is sharply reduced.
How Big a Gun?

• The biggest gun you can run **AND** retrieve.
• Problem areas in gun sizes?
  – Multiple strings
  – Washouts (thick cement)
  – Heavy wall and high alloy casing
  – Retrieval (gun swell and bowing)
When guns are fired in a dry environment, gun body swelling potential is increased. Smaller guns are more apt to swell and bow than larger guns due to the limited free body volume and lower bending resistance of small guns.
A model prediction of a multiple string target – this type of completion is often more problematic than shown in models.

Perforating multiple strings is possible but hole diameter diminishes rapidly.
Distance between the steel casing walls and the material in the void space is a major factor in penetration. Test shots are advised.
Notice the area reduction in the perforated hole from the inner string to the outer string.
Note the reduction of hole area from inner to outer string.
The “perforation” produced in this case is too small to be an effective flow path. It probably would scale up quickly.
The cement sheath between the casings. Note that the cement has not been shattered or cracked, even next to the perforation holes. Total shot density is 12 spf (three 4 spf guns were fired). Cement was three days old.
How Many Shots and Shots per Foot?

• Shot density – pipe strength - phasings and longitudinal distance between the holes are most critical.
• Shot density – stimulation – depends on well conditions
• Shot density – flow – look at inflow potential
• Shot density – formation strength – does limiting shots and changing phasing help?
The number of holes, up to about 20 per foot make very little difference in the mechanical crush resistance of casing. Actual casing examples on the left and scale models of L-80 tube on right.
7” N-80 liner w/ 72 drilled ½” holes / foot – note the pattern. This liner retained 80% of the crush resistance compared to unperforated pipe.
High shot capacity is possible – 16 to 27 spf (52 to 88 shots per meter).

**Best Conditions:**

1. Shot separation down the length of gun is >3” (7.5 cm).

2. Guns must be phased – 60° or higher perforating is needed.

3. Cement supported casing is much more resistant to damage.

4. Hollow carrier guns are less damaging than capsule guns.

5. DP charges are much damaging than big hole charges.
When the pipe is not cemented, splits are very likely with capsule guns and high density perforating with carrier guns.
Debris – After Firing

Most gun debris are from charge cases and alignment equipment - and most stays in the gun. However; up to 20% of the debris may escape through the port plugs. This may cause severe problems in sliding sleeve operations and tool sticking in smaller liners.

Average amount of debris released (outside the gun) may be up to 5 lb per foot of 4” gun.
Debris – After Firing

Zinc cased perforating charges reduce the size of the debris released. The released material is also very highly acid soluble. The drawbacks are slightly less performance and a very rare increase in Zinc scales.

Powdered debris causes less problems in wells with sliding sleeves.

Average size of debris after firing a zinc cased charge is less than 200 microns.

Average debris released is 10 lb/ft of four inch guns.
The presence of whole charge cases or very large charge case pieces like this indicate that the gun was detonated low order (bottom) or burned (lower right and right). Neither produced perforations.
Thermal stability of charges is a function of time.

<table>
<thead>
<tr>
<th>Explosive type</th>
<th>1-hr rating</th>
<th>100-hr rating</th>
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<tbody>
<tr>
<td>RDX</td>
<td>340°F [166°C]</td>
<td>240°F [115°C]</td>
</tr>
<tr>
<td>HMX</td>
<td>400°F [204°C]</td>
<td>300°F [149°C]</td>
</tr>
<tr>
<td>HNS</td>
<td>500°F [260°C]</td>
<td>460°F [238°C]</td>
</tr>
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