Reactive® Perforating:
The New Ballistic Frontier That's Revolutionizing Well Completions

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GEODynamics
Engineered Perforating Solutions

Outline

- Introduction
  - Six Steps to Getting Perforating Wrong
  - The Reactive Materials Revolution
- Reactive Perforating
  - Laboratory Evaluation
  - Field Applications
  - Untapped Opportunities
  - Learnings & Successes
- Concluding Remarks

See also: SPE 122174

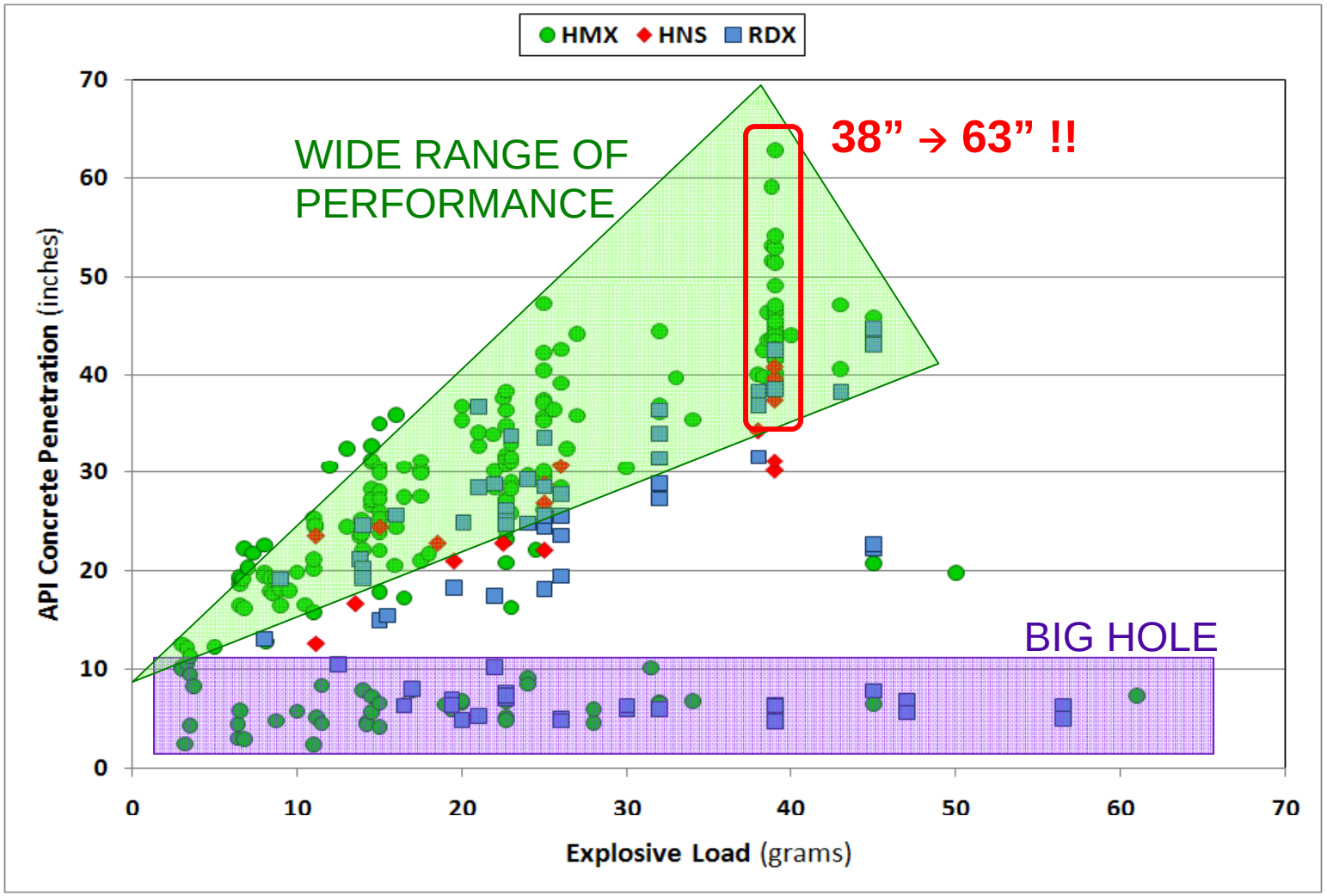
Six Steps to Getting Perforating Wrong

1. Pay it Too Little Attention
2. Assume All Perforating Systems are Equal
3. Focus Only on Penetration
4. Over-Simplify the Target
5. Apply Brute Force
6. Accept Under-performance

The Last, Little Step…

- On average, perforation accounts for less than 10% of the total well budget … often <1%
- Modern perforating systems are >98% reliable
  - "Failures" are due to human error & safety features
- According to a 2008 survey, 75% of operators rely on service providers to design their perforation jobs. Fewer than 50% claim to have a "company expert" on perforating.
- A hole is just a hole, right? Wrong!

All Systems are Not Created Equal



Your Reservoir is Not Made of Concrete

- >98% of perforators are optimized for deep penetration into a cement target at surface conditions – not stressed rock
- Cement penetration does not translate linearly to rock penetration
- Require tunnel quality as well as penetration
- Tests in concrete tell us nothing about tunnel quality, especially under downhole conditions
- Only flow testing using natural rock under representative conditions can reliably determine the best system for a particular application

Select Your System With Care

	Penetration - Charge A	Penetration – Charge B	Estimated Depth of Formation Damage
API Penetration	62.9 inches	38.8 inches	12 inches
Penetration into Stressed Rock	16.3 inches	10.2 inches	12 inches

Optimization for a specific stressed rock application can yield 10-20% improvement in penetration and flow performance.

Average In = [At Best] Average Out

- Most wellbore models take average reservoir properties as input values
- Designing a perforating system for average permeability and rock strength will result in:
  - Failure to shoot past invasion damage in some zones
  - Failure to clean up many tunnels
  - Bias towards better-quality intervals
- Off-the-shelf systems are designed for a simple one-casing + concrete target
  - Take care when asking them to do more!
  - Would you take your family saloon off-road?

Brute Force and Ignorance

- Underbalance only cleans tunnels in combination with permeability
  - Low or variable permeability = low efficiency
  - Dynamic underbalance may sometimes help
- Acid will treat clean tunnels first and can only dissolve acid-soluble debris
- "Driller's mentality" … if it doesn't work, hit it with a bigger hammer
  - Cost, complexity … and collateral damage

Houston, We Don't Have a Problem

- Perforation under-performance is **built into** many operators' expectations for well performance!
  - Best well in the field is assumed to be perfect
  - Acid stimulation included as standard procedure
  - Sacrifice shot density to achieve dynamic underbalance
- Well program only specifies penetration … service company supplies lowest cost solution … performance remains mediocre
  - No incentive for introduction of new technology
- No-one gets fired for meeting expectations

Six Steps to Getting Perforating **Right**

1. Pay it Lots of Attention … **Engineer It!**
2. Select the **Best System** for the Task
3. Focus on Penetration & **Quality** (Cleanup)
4. Design the **System** for the Target
5. Apply **Technology** to Solve Challenges
6. Maximize performance of **every well**

Technology

The Reactive Materials Revolution

Introduction • Reactive Materials

Over the past 20 years, **reactive materials** have revolutionized the ballistic industries.

Reactive materials are combinations of materials that are normally stable, but, when subjected to sudden shock -- such as striking a target -- release a large amount of energy.

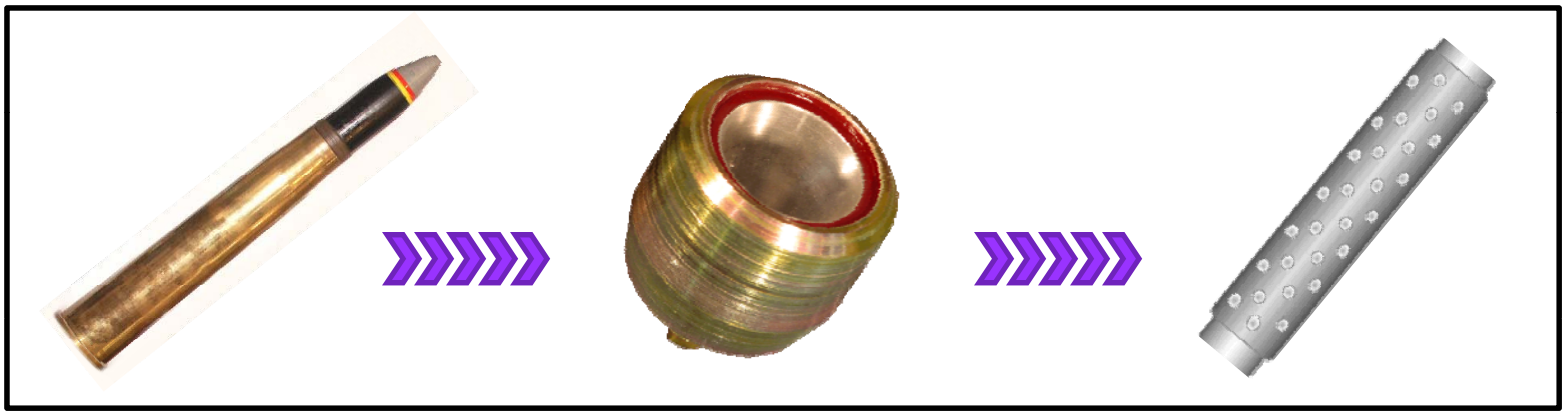
The Pentagon has quietly been working on a new arsenal of advanced weaponry that replaces metal casings with "reactive materials," normally harmless matter that combines to release explosive amounts of energy on impact.

Objective • Enhance Performance

- Objective:
  - Turn structural elements of a ballistic device into active, performance-enhancing components
- Required Characteristics:
  - Common, easy-to-handle precursors
  - Stable during normal operations
  - Reactivity triggered by extreme stimulus
  - Highly energetic, rapid reaction
  - Enhance functional performance of the device
  - Maintain established mechanical performance

Proven Military Technology

Proven military technology is now being translated into **oilfield applications**.



There will also be civilian spin-offs. In fact, British defense research company Qinetiq has already patented a reactive material-shaped charge liner for oil-well perforators under the name Connex:

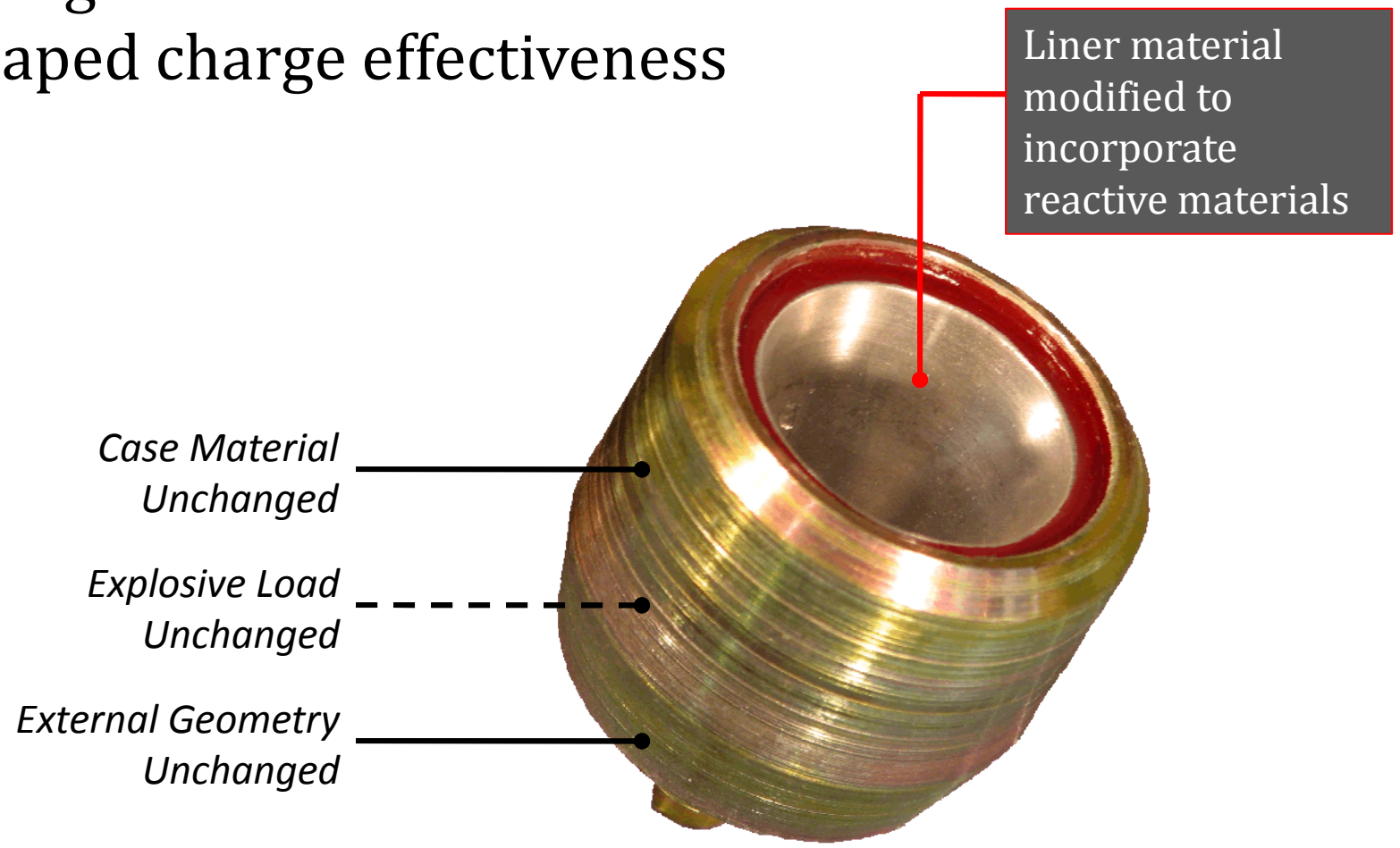
(wired.com)

Introduction

Reactive Perforating

Reactive Materials in Perforating

Using reactive materials to enhance shaped charge effectiveness



Reactive Perforating • Overview

- Generate secondary reaction between charge liner materials, triggered by detonation pressure
- Commercial charges use intermetallic reaction between liner components
  - Intense exothermic reaction
  - Heats tunnel volume & near-tunnel pore space
  - Generates acute pressure spike
  - Breaks up and expels debris from tunnel
- Independent of rock material and wellbore fluids
- Effect occurs in each tunnel, independently
- Clean tunnels without requiring underbalance

Validation

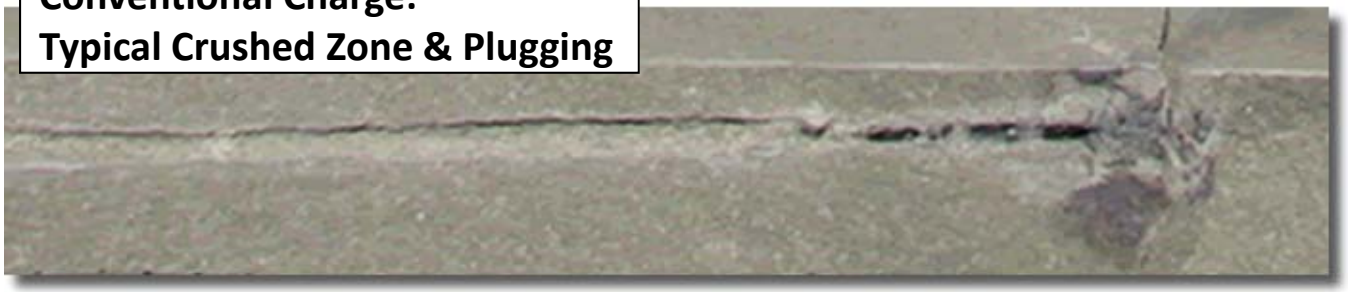
Laboratory Evaluation

Laboratory Evaluation

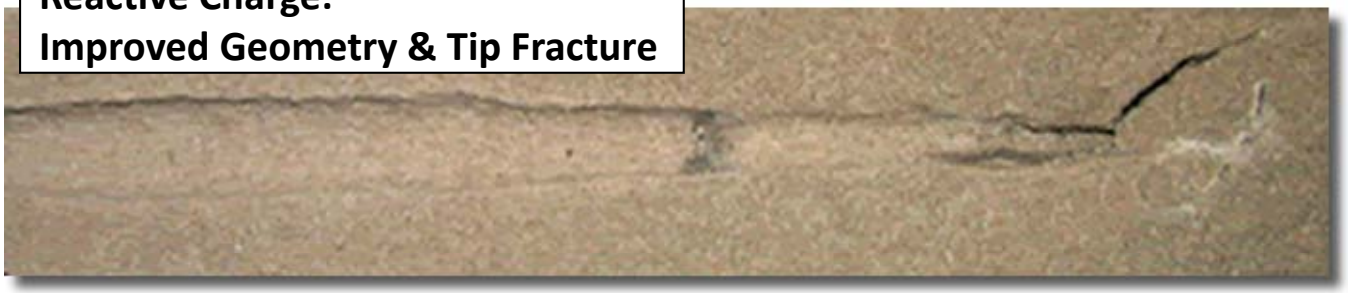
- More than 1,000 stressed rock test shots
  - "In the spirit of" API RP 19-B, Sections 2 & 4
  - Sandstones, carbonates, others
  - Wide range of stress states & configurations
- Comparative testing to conventional charges
- Evaluating:
  - Perforation geometry and clean-up
  - Relative flow performance (Section 4 type tests only)

Tunnel Quality Comparison

Conventional Charge:
Typical Crushed Zone & Plugging



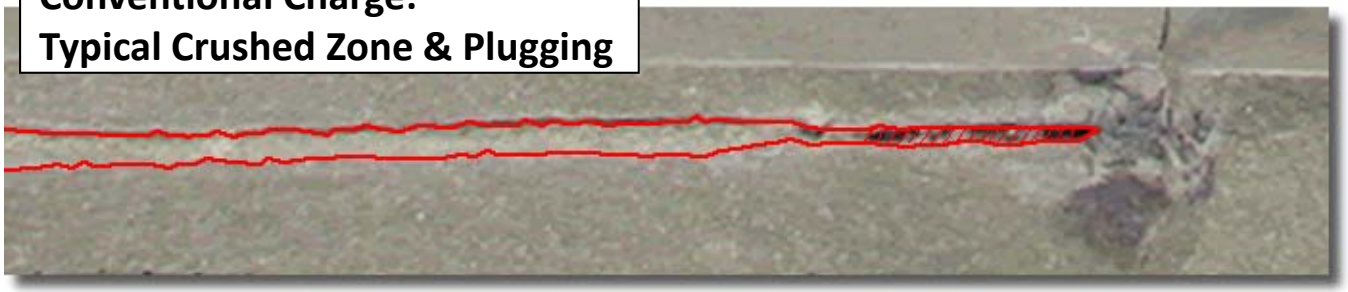
Reactive Charge:
Improved Geometry & Tip Fracture



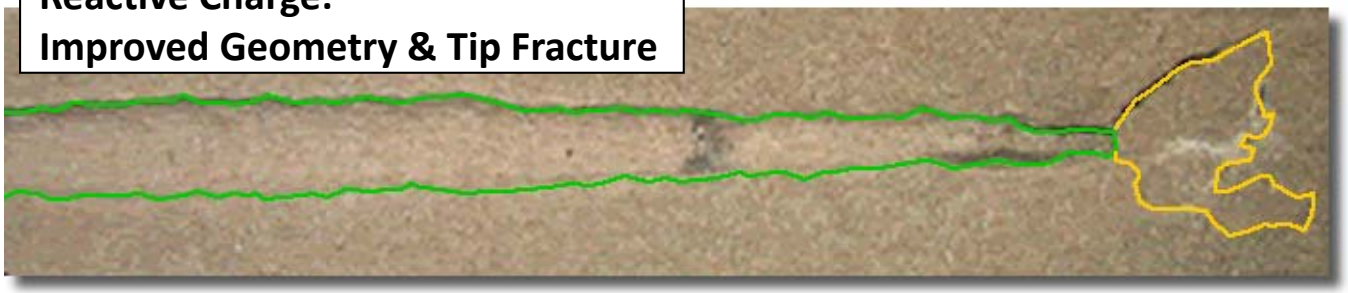
8,000psi, 160mD Sandstone, 25g Charges, 2000psi Effective Stress, 250psi UB

From Drinking Straw to Garden Hosepipe

Conventional Charge:
Typical Crushed Zone & Plugging



Reactive Charge:
Improved Geometry & Tip Fracture

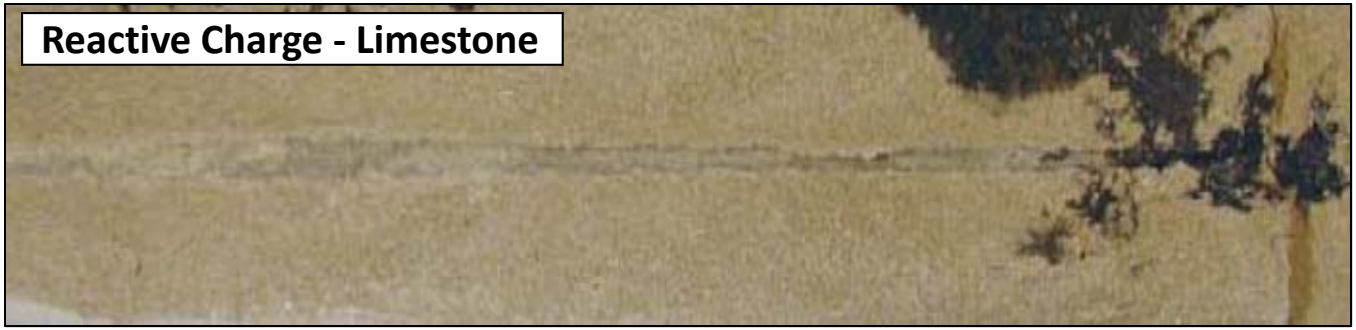


8,000psi, 160mD Sandstone, 25g Charges, 2000psi Effective Stress, 250psi UB

More Challenging Target

7,500psi, 0.05mD Sandstone, 23g Charges, 5000 psi Effective Stress, Balanced

Different Lithologies



Spectacular Lab Results

Charge	Rock	Effective Stress	UB	Δ Clear Tunnel	Δ Lab Productivity
22.7g	11,000psi SSt	4,000psi	1500psi	**+216%**	S2 Test
39g	11,000psi SSt	5,000psi	Balanced	**+82%**	S2 Test
25g	5,000psi SSt	3,000psi	Balanced	**+235%**	**+25%**
25g	7,000psi SSt	4,000psi	500psi	**+80%**	**+28%**
6.8g	10,000psi SSt	4,000psi	Balanced	**+35%**	S2 Test

Even Better News: Lab tests are highly conservative. Significantly greater productivity improvements are being reported in the field!

Laboratory Evaluation • Observations

- Improved geometry and flow performance measured across wide range of conditions
  - Reactive charge preferred in almost every situation
  - Impossible to test every set of conditions encountered in the field (years of work)
- Current work focused on:
  - Client specific conditions
  - Acidization of carbonates after reactive perforating
  - Optimization of reactive materials for different applications … a whole new area for investigation

Proof in Action

FIELD APPLICATIONS

Field Applications • Overview

- Reactive perforators applicable wherever conventional premium DP is in use
  - Shoot and produce
  - Re-perforation
  - Prior to stimulation
  - Limited entry
- 18+ months since first sales … just beginning to ‘extract’ data from end users
  - Design + Deploy + Evaluate + Sustain = 12-24 months

Field Applications • Shoot and Produce

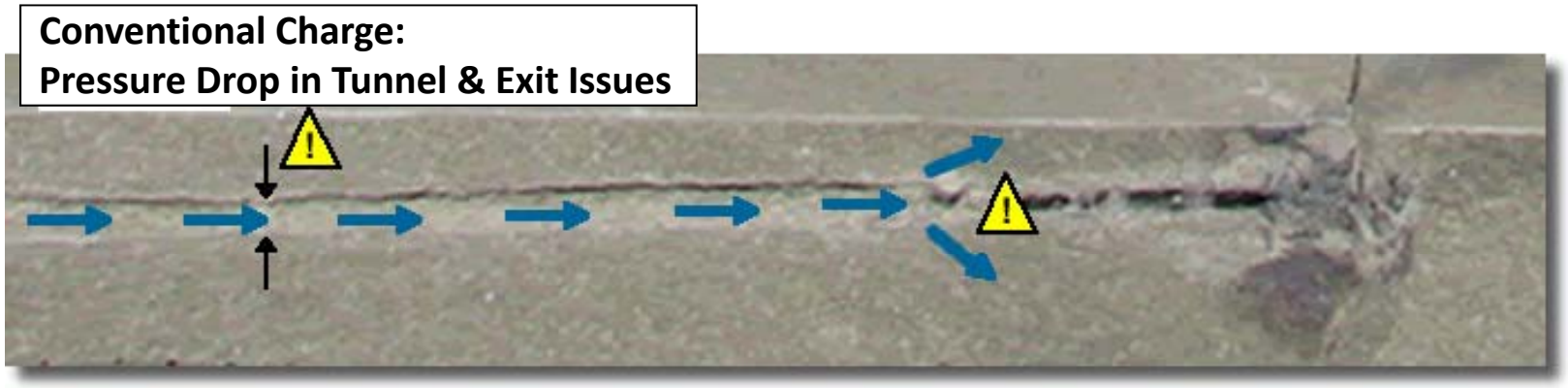
- Wells in which no stimulation is required
- Success = increased productivity
- Bonus = reduced cost, complexity, risk
  - Eliminate underbalance, release rig (TCP to W/L)
- Examples:
  - **Thailand** • NuCoastal reports +50% initial productivity based on performance of appraisal wells perforated with premium system
  - North Sea • Equivalent productivity with 1 run vs. 3 runs

Field Applications • Re-Perforation

- Generally a tough task for perforators
  - Effective stress increases as reservoir pressure drops
  - Hard to apply underbalance with open perforations etc.
- Success = increased productivity
- Examples:
  - UK • 30x productivity after re-perforation (best in field)
  - USA • 10x productivity … more than 2x the increase seen re-perforating offset wells with conventional systems
  - USA • 10x increase in gas well production after re-perforation … already shot twice with premium DP system

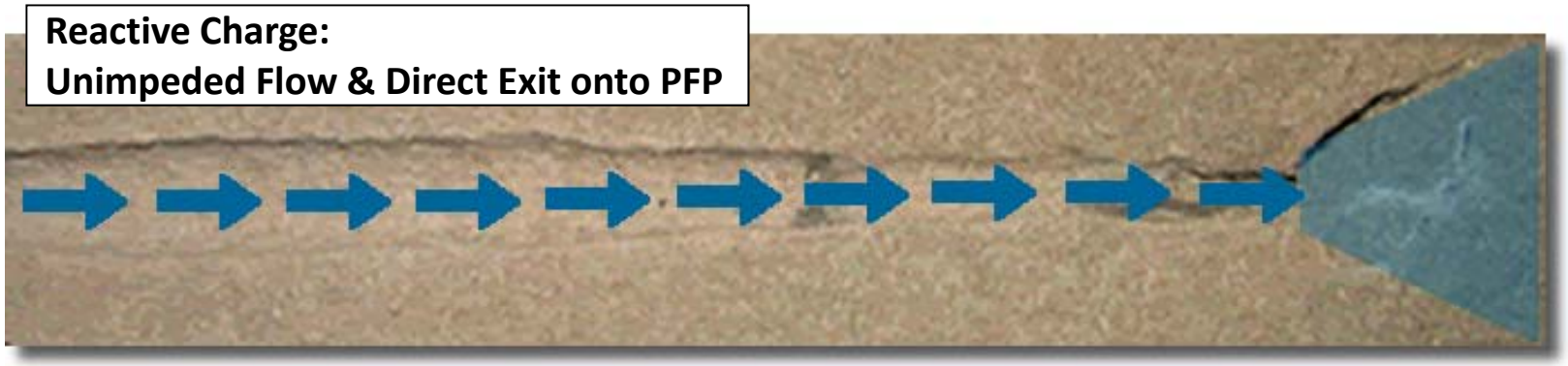
Field Applications • Prior to Stimulation

- Stimulation after conventional perforating impeded by narrow/plugged tunnels



Field Applications • Prior to Stimulation

- Reactive perforator yields clean tunnel and tip fracture that eliminates stress cage effect



- Up to 70% reduction in fracture initiation pressure, and negligible tortuosity

Field Applications • Prior to Stimulation

- Success = reduced pressure, increased rate, improved reliability
- Bonus = eliminate acid, avoid cleanouts
- Examples:
  - USA • 30-70% reduction in fracture initiation pressure
  - Canada • Reduced perforation friction, negligible tortuosity, eliminate need for acid spear
  - Pakistan • 3x productivity increase over previous best in field well
  - USA • 30% increase in initial productivity as result of 10% increase in treating rate at same pump pressure

Field Applications • Limited Entry

- Success = consistent, predictable outflow area for injectant distribution along wellbore
- Bonus = eliminate rig-based breakdowns
- Examples:
  - Canada • Controlled EHD perforator for steam injection
  - Oman • Controlled EHD perforator under development for steam injection – assurance of clean tunnels will eliminate current practice of breaking down each set of holes using straddle packer assembly on drill pipe

Field Applications • Unconsolidated Rock

- Success = reduce TSS at same/higher rate due to greater number of open tunnels and reduced flow velocity in each tunnel
- Example:
  - Oman • Well produced 2x gross liquids of comparable offsets (unfortunately mostly water…) but only 10% of the field average sand rate

Upcoming/Untapped Opportunities

- Injection Wells • Expect higher injectivity, improved injection profile, and slower injectivity decline
- Acid stimulation of carbonates • Lab work in progress to demonstrate single dominant wormhole
- Tractor conveyed re-perforation • Do not require underbalance to achieve clean tunnels
- Exposed systems • Capsule charge for through-tubing work (to be introduced by end 2009)
- Reactive Big Hole • Under investigation…

(Almost done…)

Learnings, Successes and Conclusions

Key Learnings & Successes

- Do not 'pigeonhole' reactive perforating
  - Benefits realized across a wide range of well types, lithologies, and operations
  - Value add in vast majority of DP applications
- Value proposition = "no brainer"
  - Incremental perforating cost easily recovered by improving well productivity &/or reducing costs
- Understand what's wrong with the patient
  - Can cure sick wells but cannot revive dead wells
  - Expectation management

Key Learnings & Successes

- Lab testing greatly accelerates learning
  - Reactive perforating is still in its infancy … lots to learn
  - Care translating lab results to field
- Greatest benefit may not be well performance
  - Reduced rig time (e.g. fewer runs, TCP to W/L)
  - Reduced equipment (e.g. smaller frac spread)
  - Reduced chemical & service charges
  - Reduced non-productive time (e.g. reliable breakdown)
  - Lower solids production, fewer cleanouts

Conclusions

- Reactive materials are the state-of-the-art in ballistics … first military, now oilfield
- New class of reactive shaped charges finding wide applicability and success
- Many more applications still to come … just scratching the surface of what is possible
- Economic justification for reactive perforators is highly compelling

Thank You! Any Questions?

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