Perforating Design for HTHP Completion: Rigorous Testing to Maximize Well Productivity

SPE 159920
Optimized Cased and Perforated Completion Designs Through The Use of API RP-19B Laboratory Testing to Maximize Well Productivity

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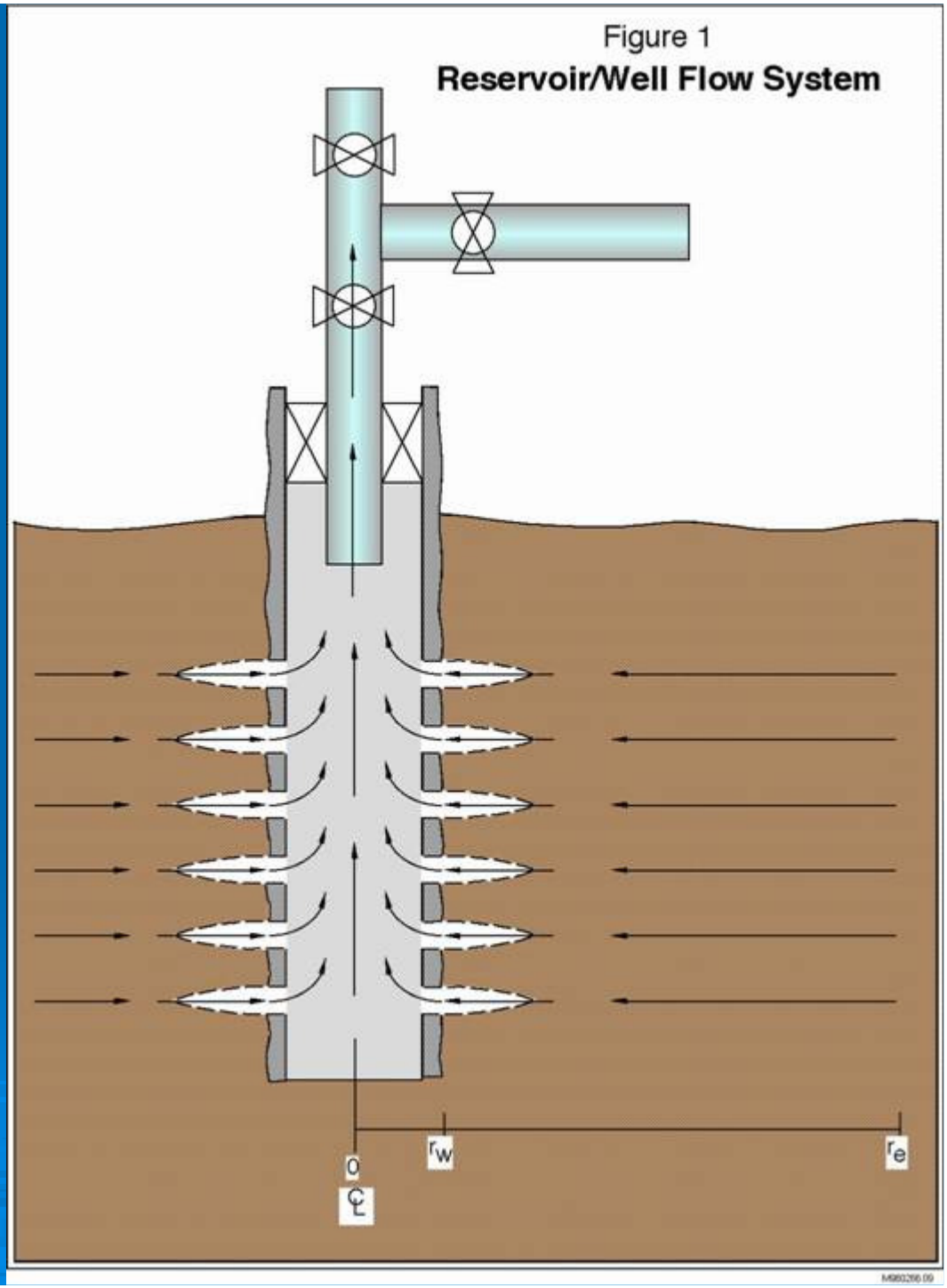
Typical Field Characteristics

- Retrograde gas condensate
- Initial reservoir pressure ~ 11000-12000 psi
- ~ 14,000 ft TVDSS
- 350-375°F - HNS
- Sandstone - Relatively high rock strength
- 20-30 mD Permeability

Proposed Well Configuration

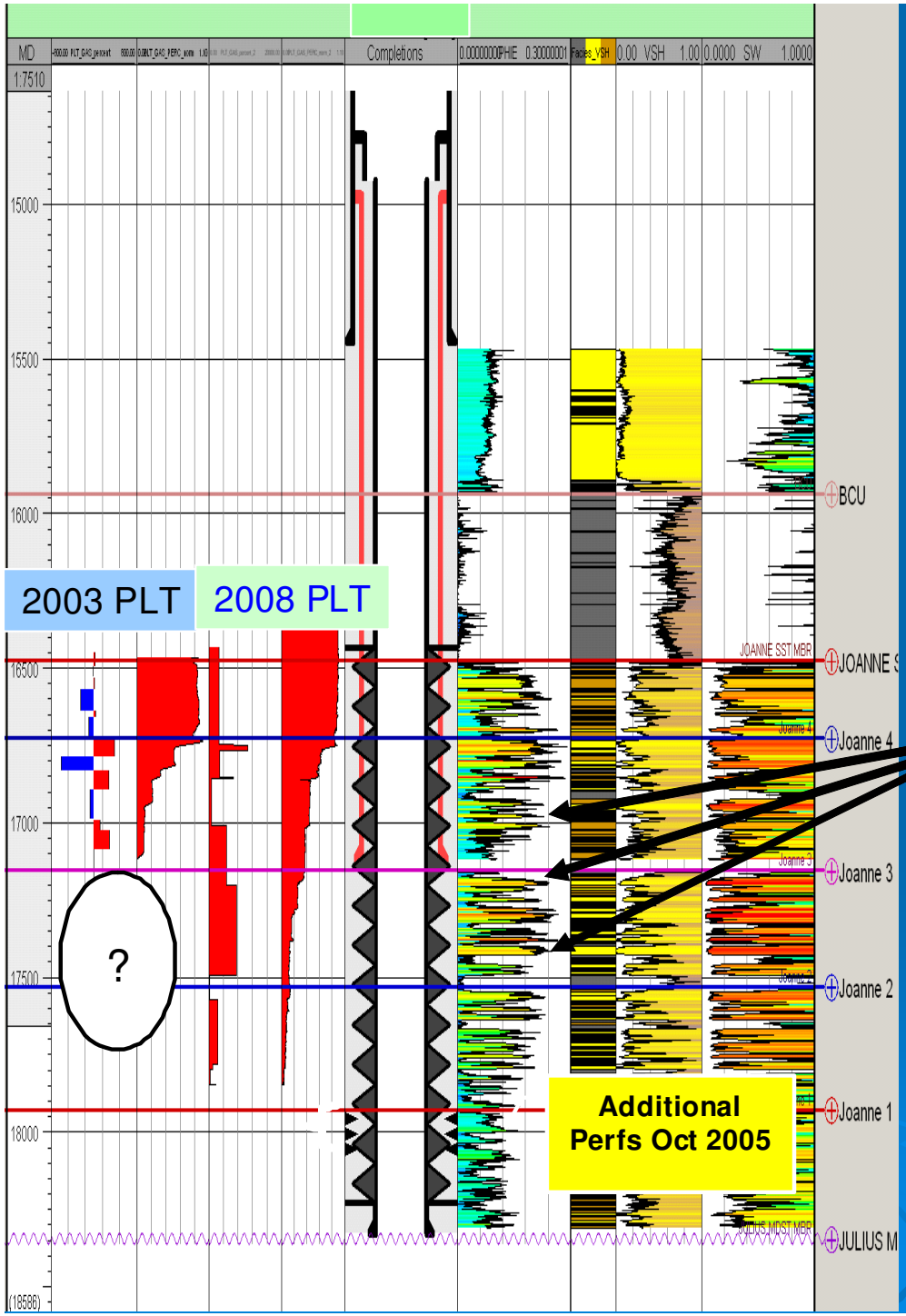
Cased & Perforated Completion



Why are we looking into the perforating process so closely?.....

…….A real world example from a similar field, with similar completion design and similar conditions

Well 4



Initial Perf job:

- Perforated 1000 psi overbalanced in oil based mud
- Poor Well Response from first perf Job Compared to Benchmark well perforated underbalanced

Low PLT Response across High Perm zones

Reperf Job:

- 3 years after first perf job
- UB (live well)
- During the perforating operations the shut-in tubing pressure increased from 3,649 to 5,001 psi.

Perforating Design Goal

- Design perfs to achieve desired skin, the first time!
- Get full production across entire perforated zone

Perforating Requirements

Perforation Geometry:

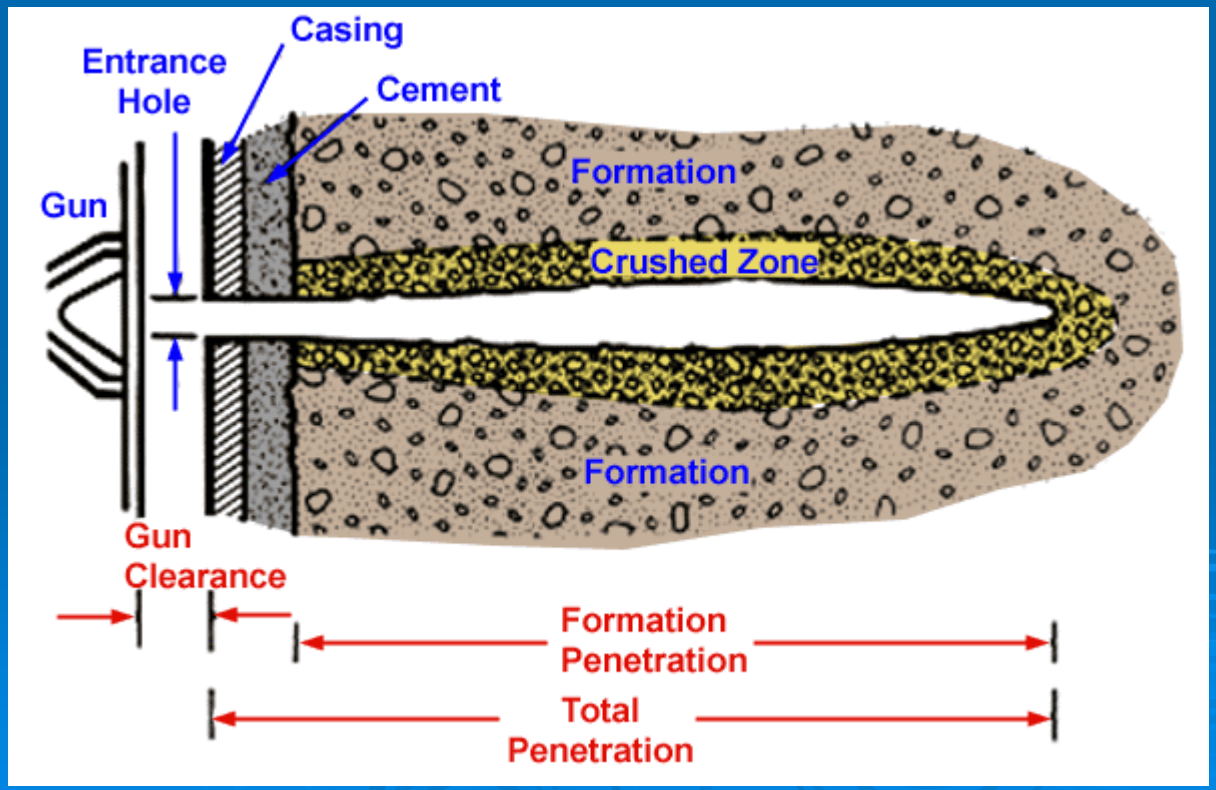
- **Density**
- **Phasing**
- **Diameter**
- **<u>Length</u>**

Perforation Damage:

- **Perforation Fill**
- **Crushed Zone Permeability**

Perforating Requirements

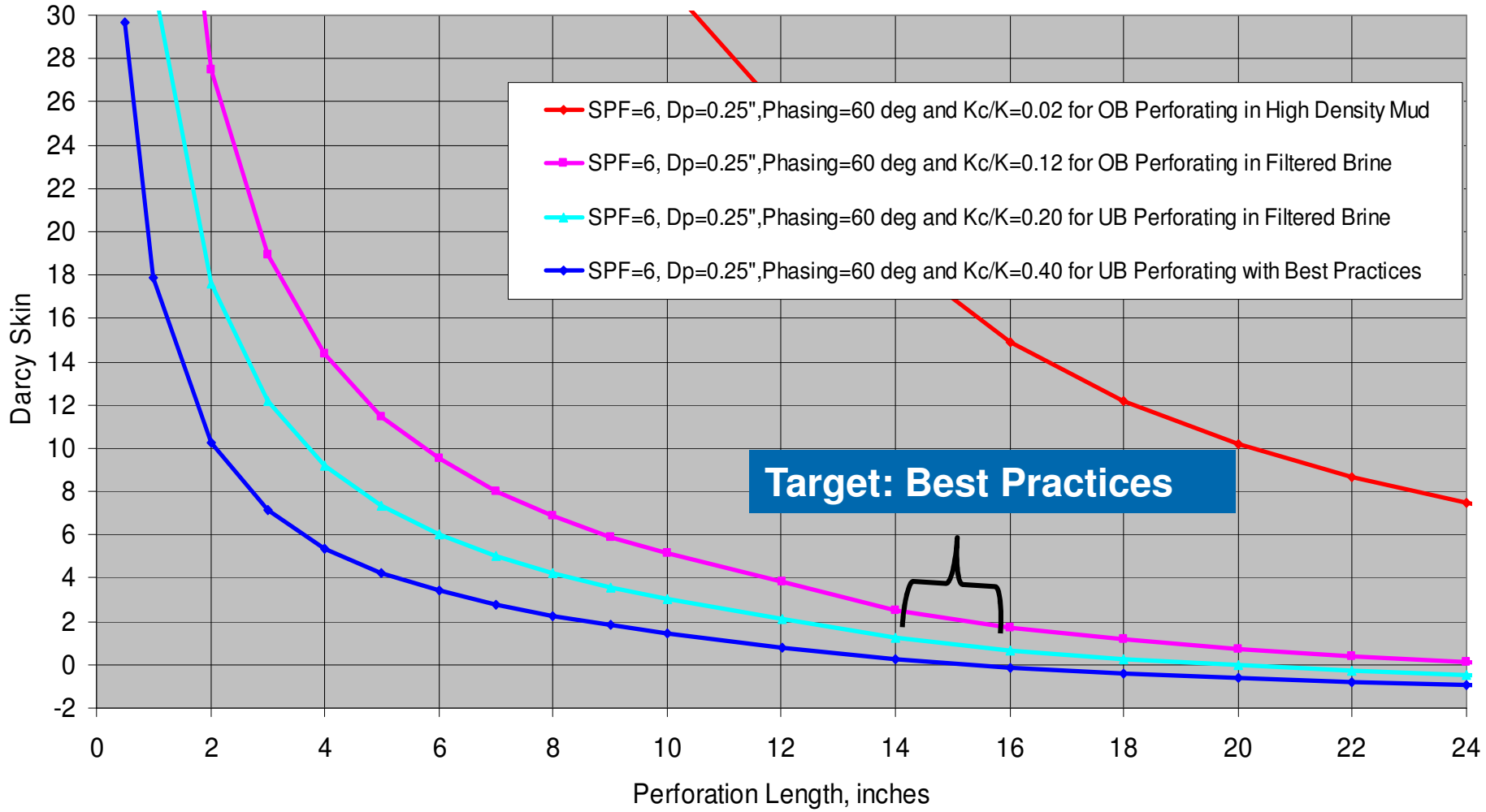
What perforation length do we need?



WHAT PERFORATION LENGTH DO WE NEED?

Evaluation of Perforation Geometry and Damage Effects

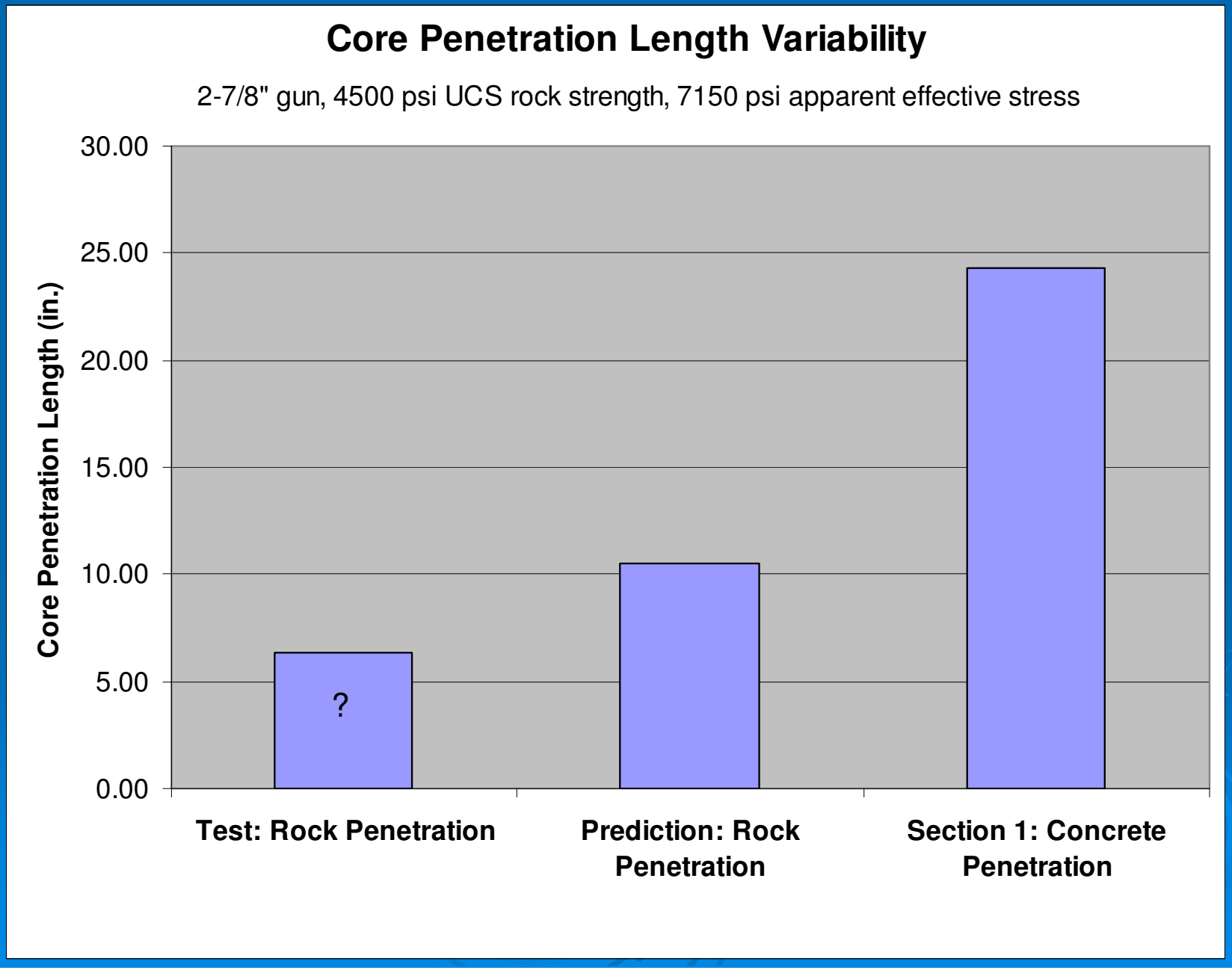
Kh=10 md, Kh/Kv=1, H=500 ft TVT, b=Hp/H=1, Incl=0 deg, Kmf/Kr=0.5, rmf=rw+1 ft and rw=0.354 ft for all cases



Increasing perforation length provides more skin improvement than increasing shot density

5” Lp: 12 spf/6 spf = 1, 5”/10” = 1.5

Beware!


Core Penetration Length Variability
2-7/8" gun, 4500 psi UCS rock strength, 7150 psi apparent effective stress
Core Penetration Length (in.)
30.00
25.00
20.00
15.00
10.00
5.00
0.00
?
Test: Rock Penetration
Prediction: Rock Penetration
Section 1: Concrete Penetration

Perforating Requirements

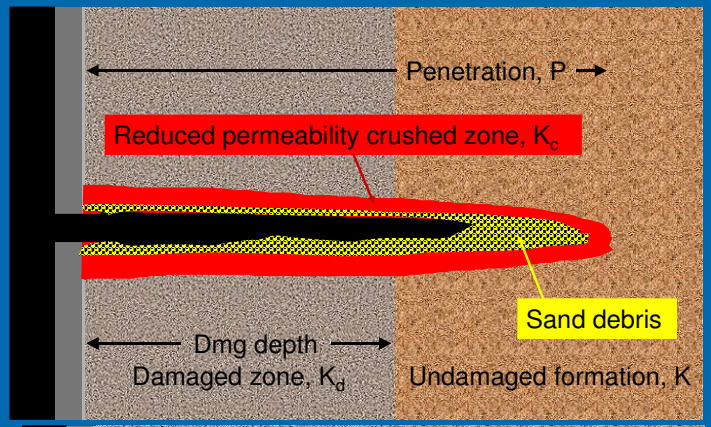
What perforation conditions do we need?

How should we perforate?

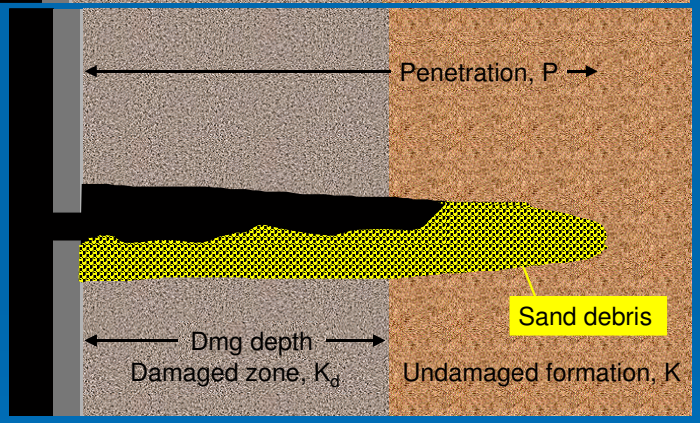
- Overbalanced
- Underbalanced
- In Mud?
- In Brine?

Perforating Damage—Performance

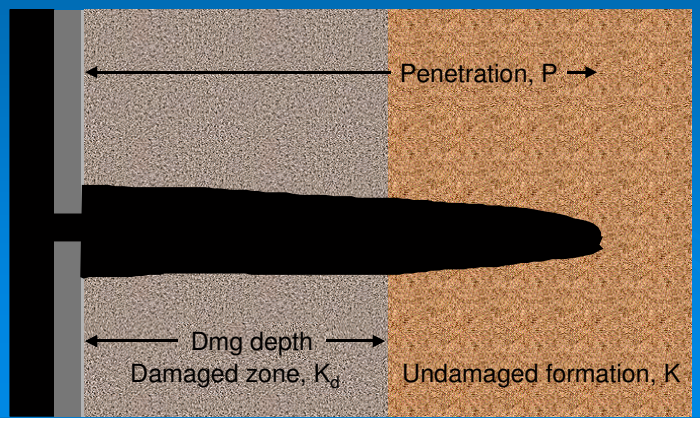
Poor skin

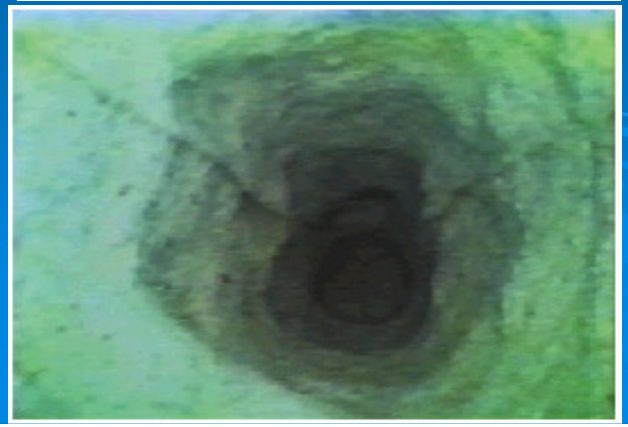


Fair skin



Good skin





Perforation Design: Competing Interests

Best Practice for Completions

- Perforate Underbalanced in filtered brine
- Run as large guns as possible – 3.5”

Best Practice for Operations

- Perforate overbalanced in mud
- Run 2-7/8” gun

Can the Two Competing Interests meet?

Test all Scenarios

1. Flow Tests (skin):

- **Underbalanced**
  - **Static underbalance: 1500 psi**
  - **Dynamic underbalance: 3500 psi**

- **Overbalanced**
  - **500 psi**

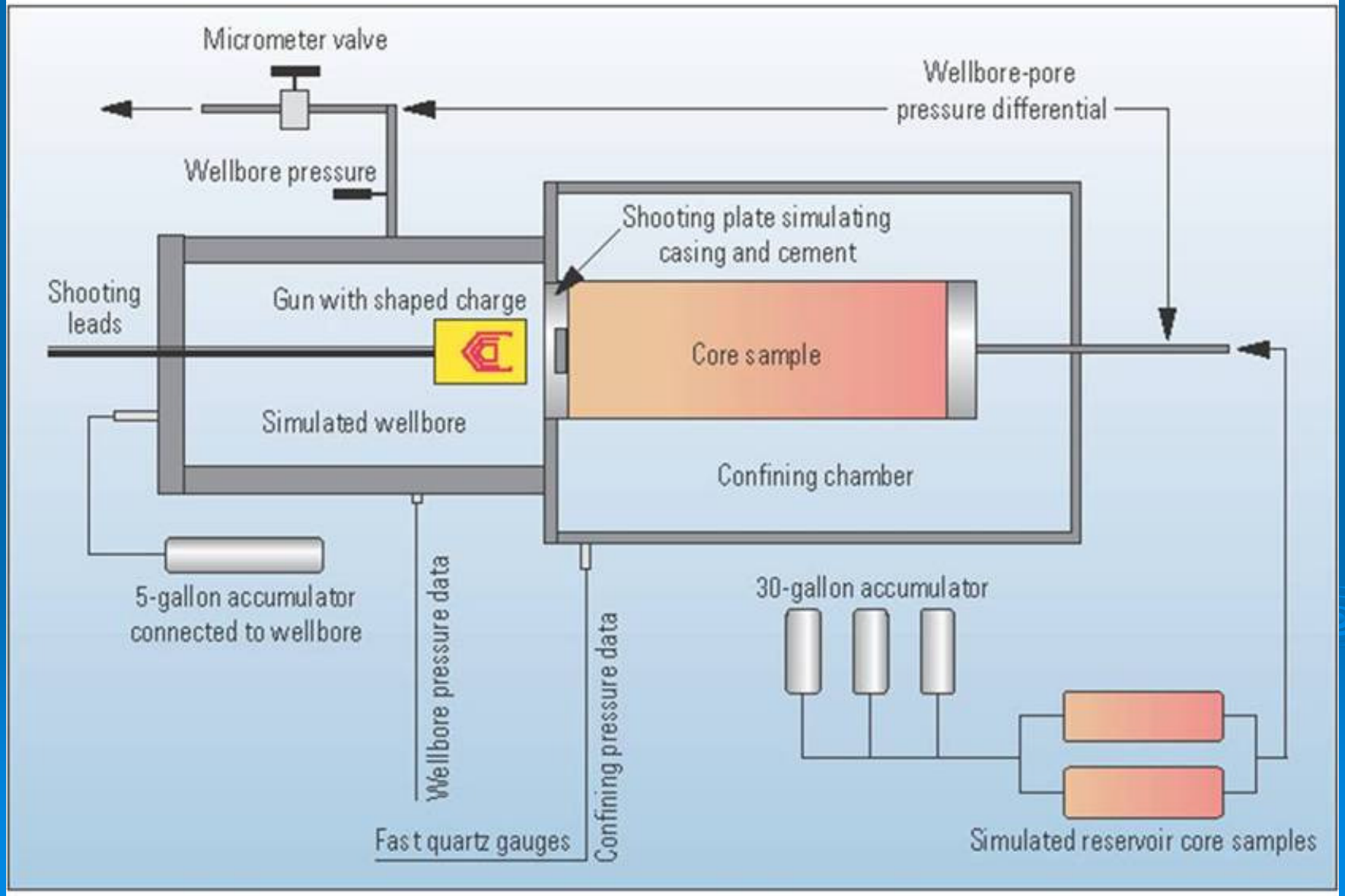
- **In mud (per fluid)**
- **In base oil**
- **3-1/8" gun**

2. Penetration Tests (length)

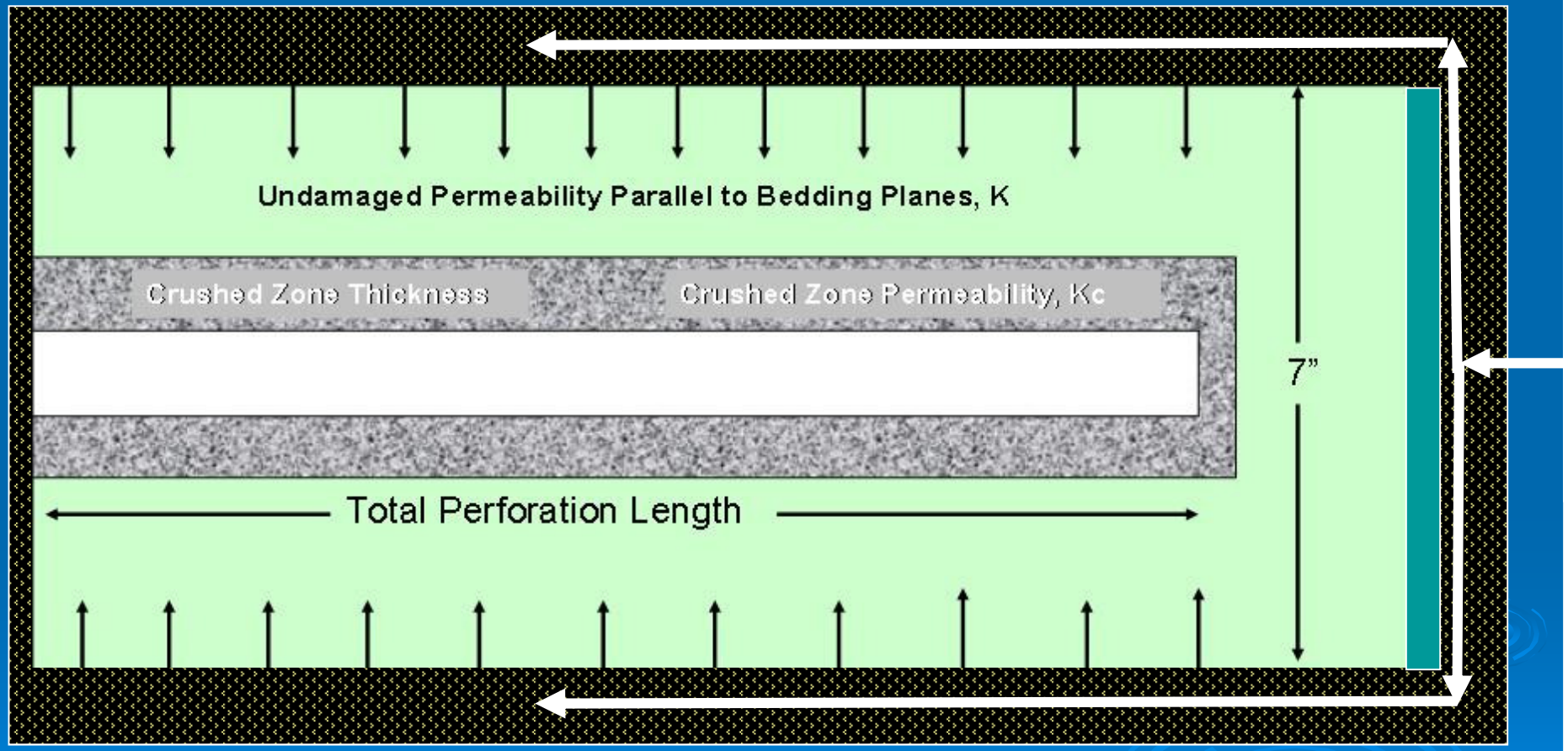
- 2-7/8" gun
- 3-1/8" gun

1. Flow Test

"Section 4"



Crushed Zone Permeability Measurement



Section 4 test not rated for actual conditions

Confinement:	5800 psia (13000 psia)
Pore Pressure:	4500 psia (11700 psia)
Wellbore Pressure:	3000-5000 psia
Temperature:	200°F (350°F)
Core Fluid:	Mineral Spirits (condensate)

Test Scenarios

Scenario A: Shoot overbalanced with mud, no DUB, kill

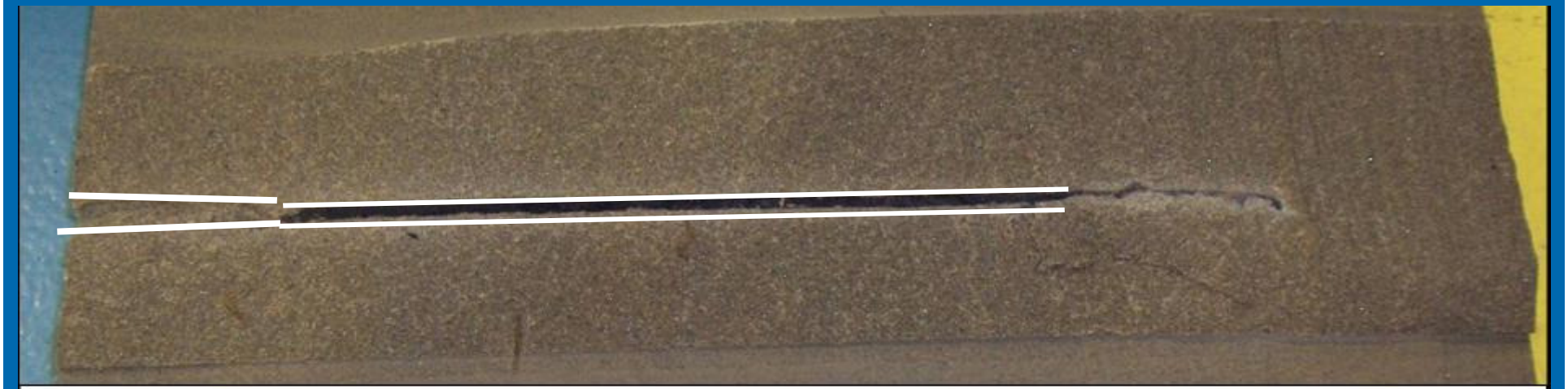
Scenario B: Shoot overbalanced with mud, 3500 psi DUB, kill

Scenario C: Shoot 1500 psi underbalanced in base oil, no DUB

Scenario D: Shoot balanced in base oil, 3500 psi DUB

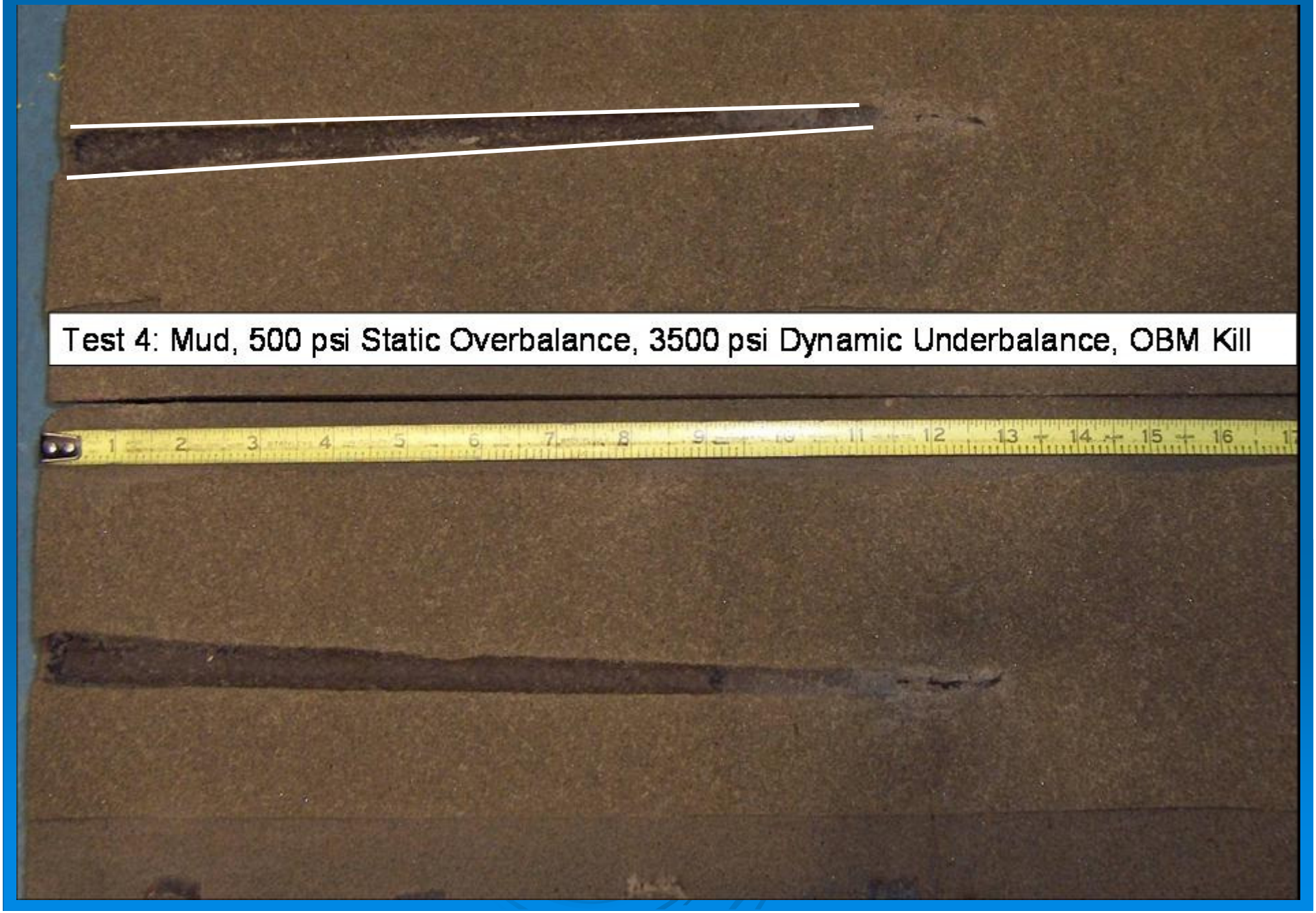
Number of Perforation Tests	Type of Fluid In Wellbore	Static Wellbore Pressure Prior to Perforating	Dynamic Underbalance Applied During Test	Post-Perforation Well Kill Performed
2 Tests	16.5 ppg OBM	500 psi Overbalance	3500 psi Dynamic Underbalance	Kill with OBM/Hold for 72 hrs
2 Tests	7.0 ppg Base Oil	50 psi Underbalance	3500 psi Dynamic Underbalance	Kill with Base Oil/No Hold
1 Test	7.0 ppg Base Oil	1500 psi Underbalance	No Dynamic Underbalance	Kill with Base Oil/No Hold
1 Test	16.5 ppg OBM	500 psi Overbalance	No Dynamic Underbalance	Kill with OBM/Hold for 72 hrs

SECTION 4 TEST PROGRAM RESULTS

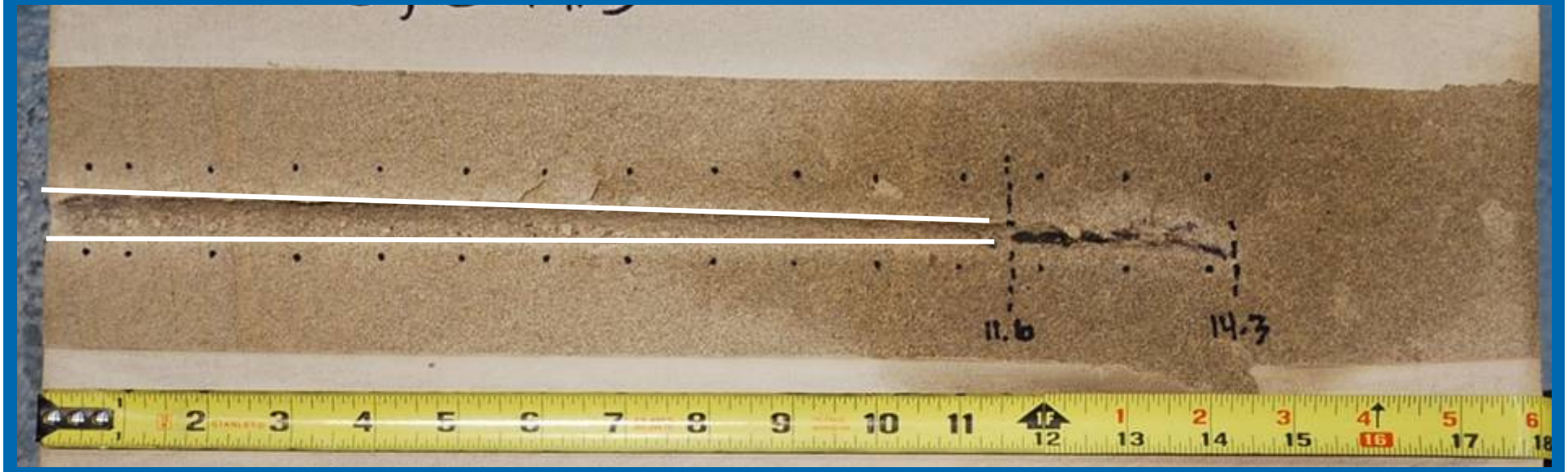


Test 6: Mud, 500 psi Static Overbalance, **no** Dynamic Underbalance, OBM Kill

SECTION 4 TEST PROGRAM RESULTS

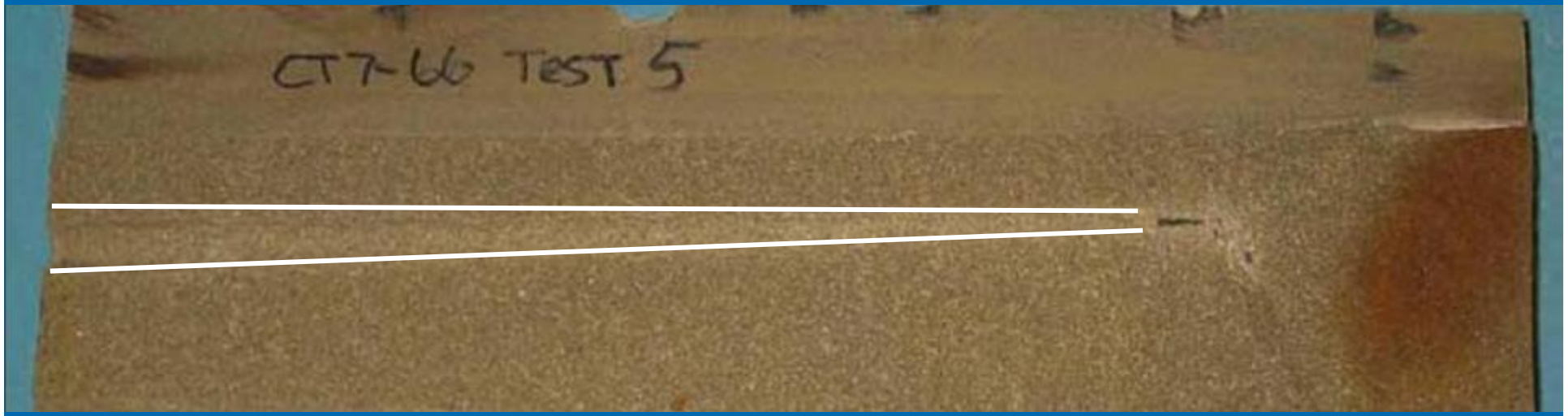


SECTION 4 TEST PROGRAM RESULTS



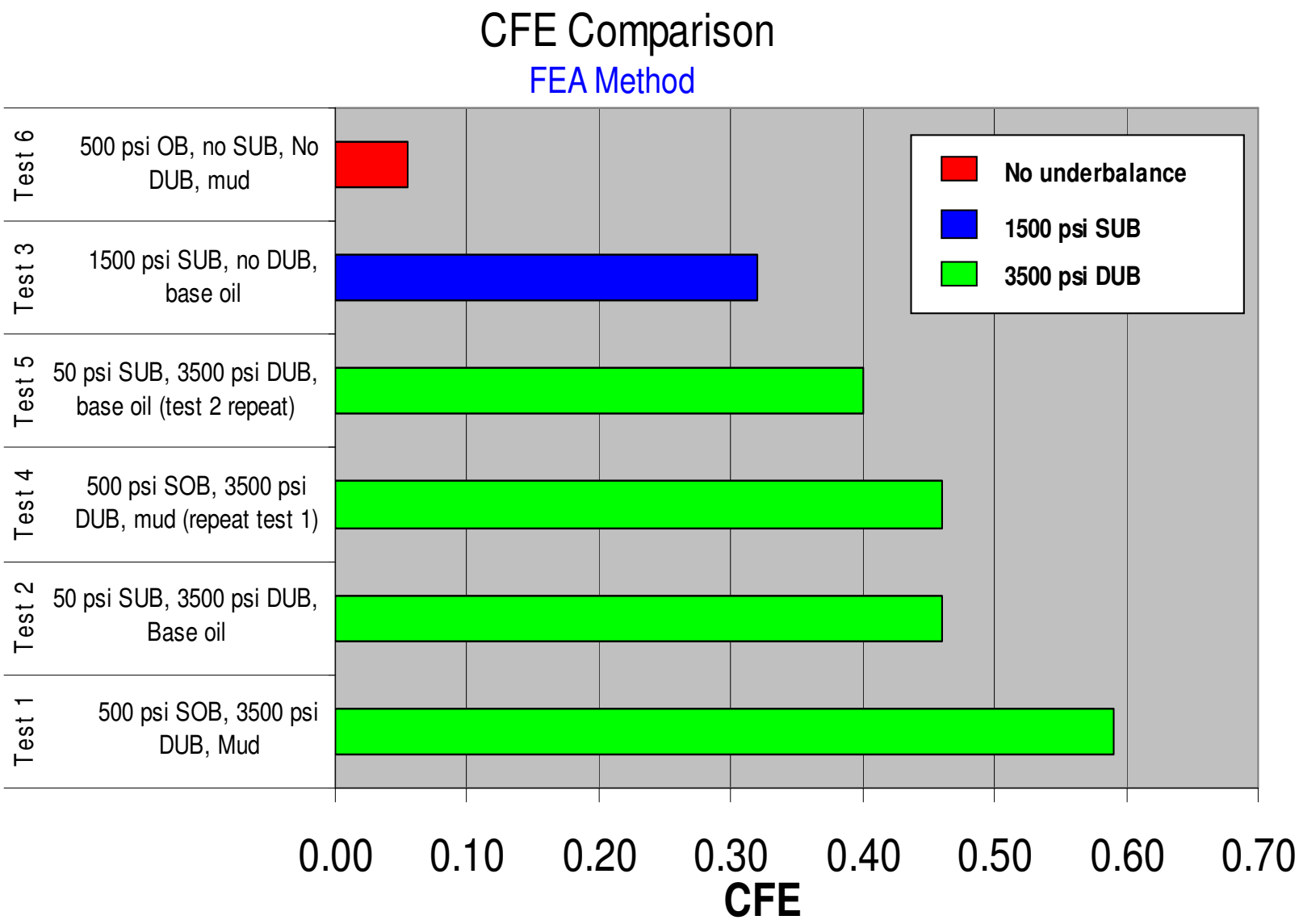
Test 3: Base Oil, 1500 psi Static Underbalance, no Dynamic Underbalance, Base Oil kill

SECTION 4 TEST PROGRAM RESULTS



Test 5: Base Oil, 50 PSI Underbalanced, Dynamic Underbalance, Base Oil kill

SECTION 4 TEST PROGRAM RESULTS



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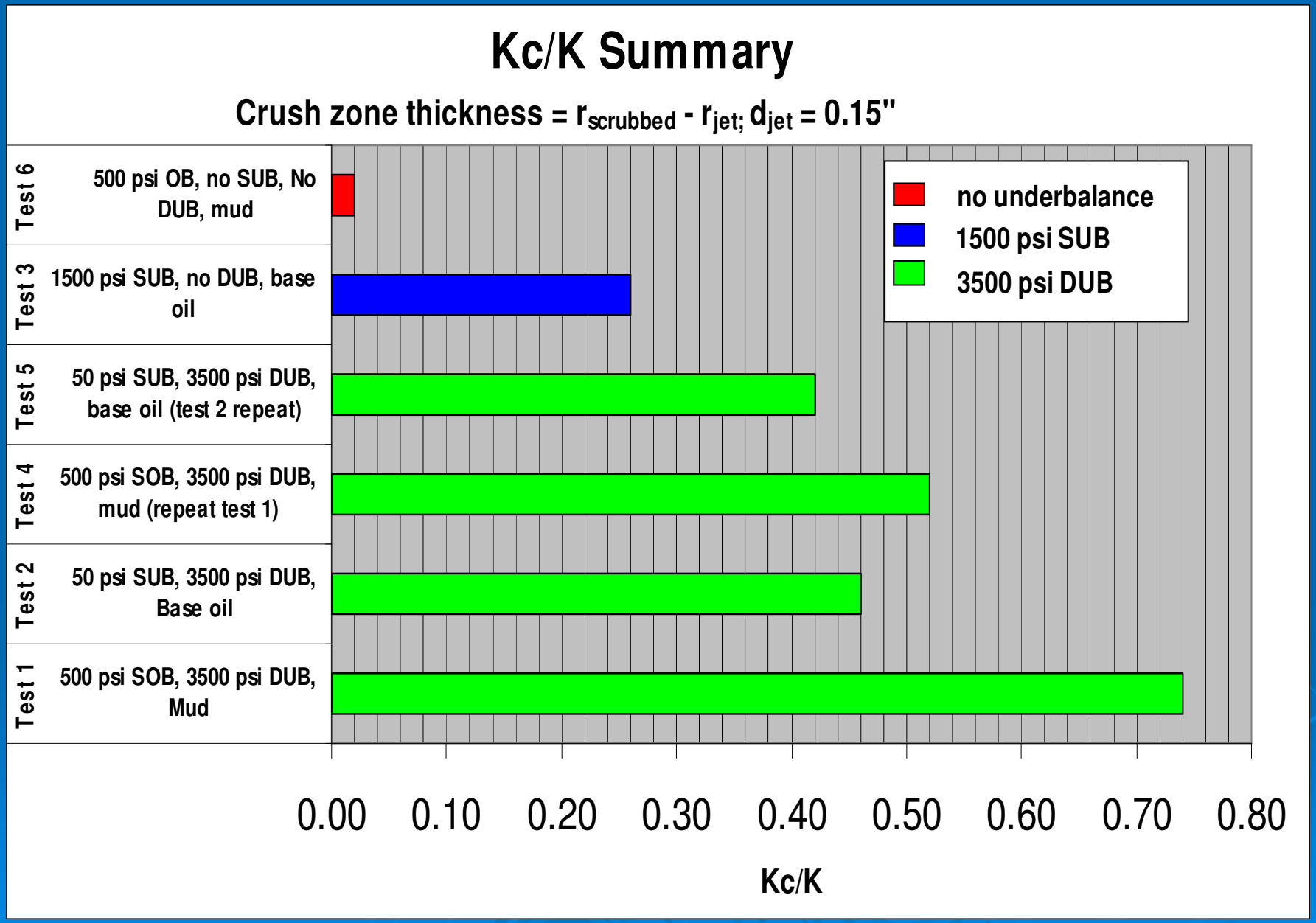


Flow Results

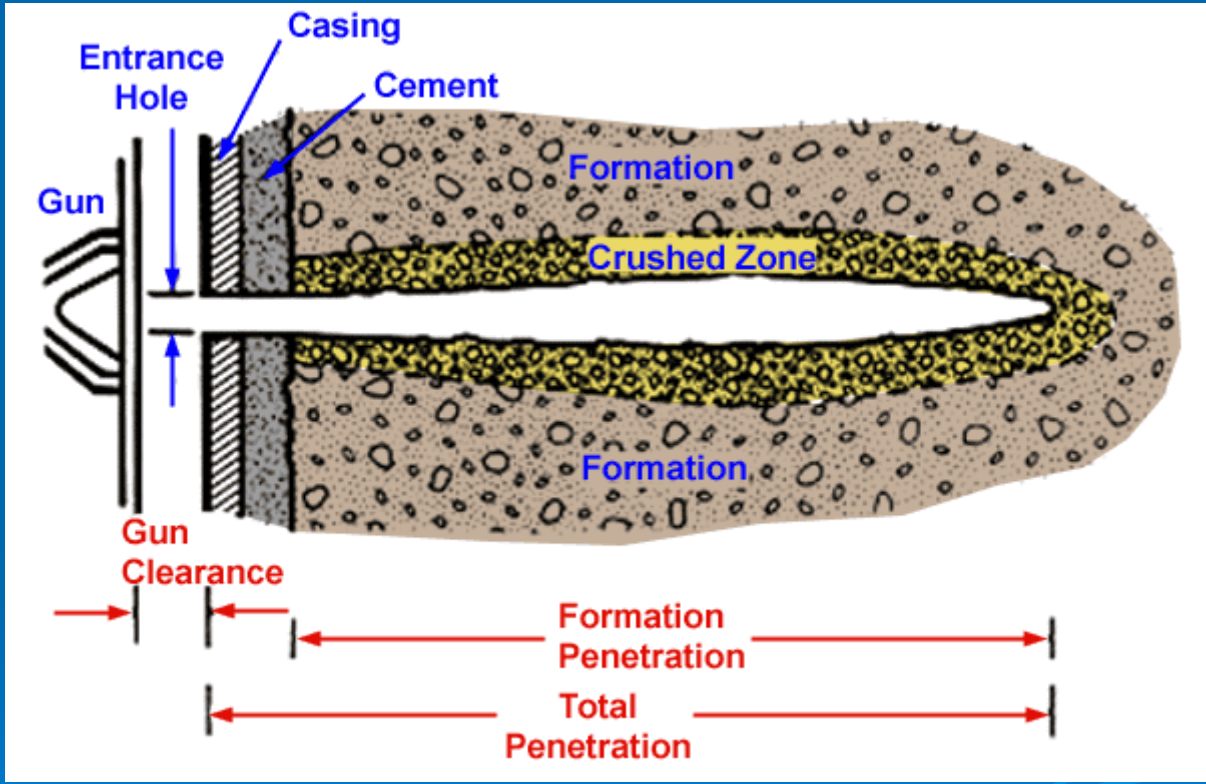
- Perforating in mud without underbalance very bad
  no surprise

- Dynamic underbalance most important
  moderate surprise

- Perforating and killing in mud with dynamic underbalance is OK
  Surprise to us!

Round 1 to Operations

2. Core Penetration Tests



Confirm Actual Penetration with Testing

- Perform tests at realistic conditions
- Compare against predictions
- Select deepest penetrating charge

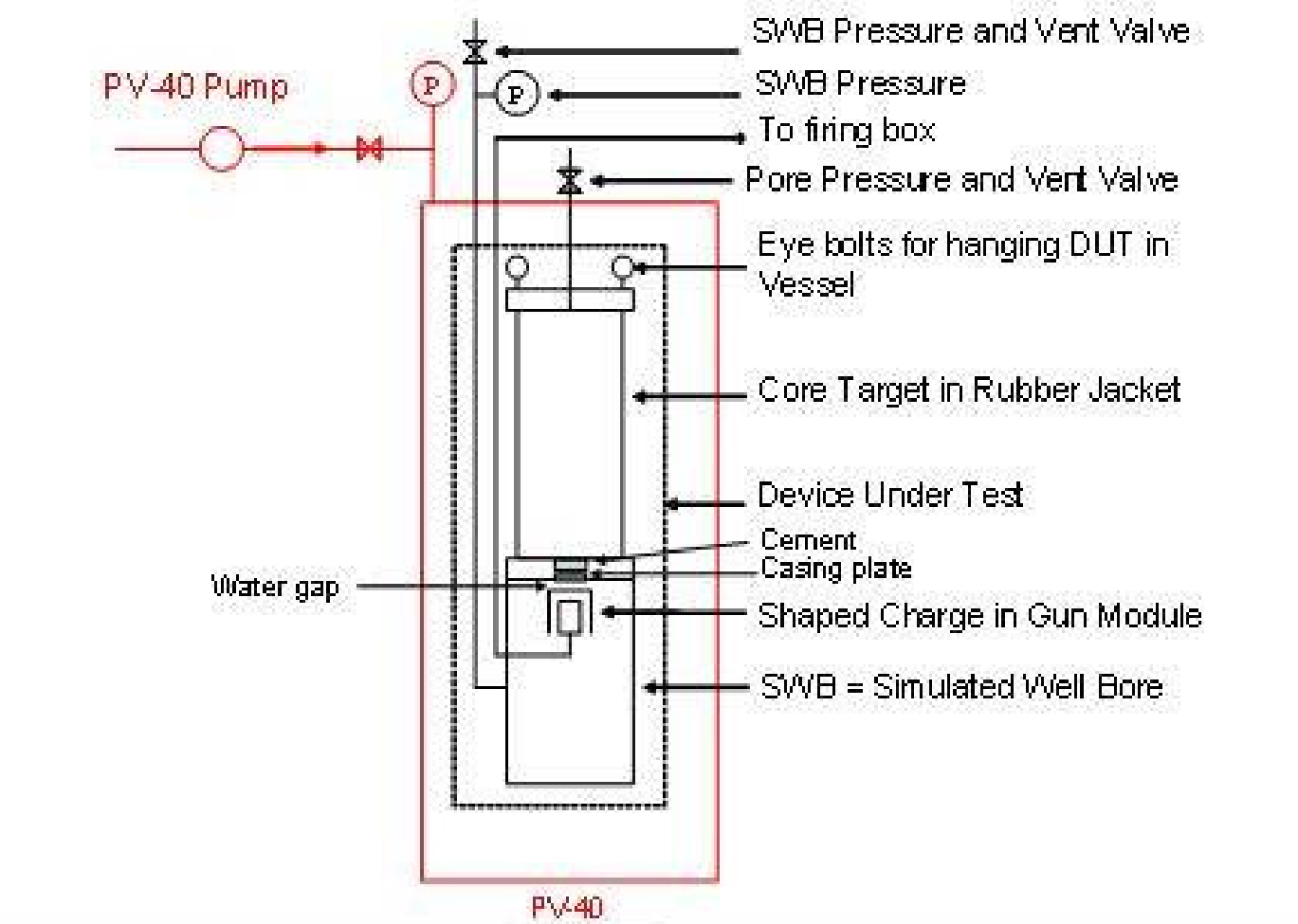
PV-40 MOD'D SECTION 2 TEST SYSTEM DESCRIPTION

Pore Pressure:
11700 psi

Confinement pressure:
13000 psi

Wellbore pressure:
12000 psi

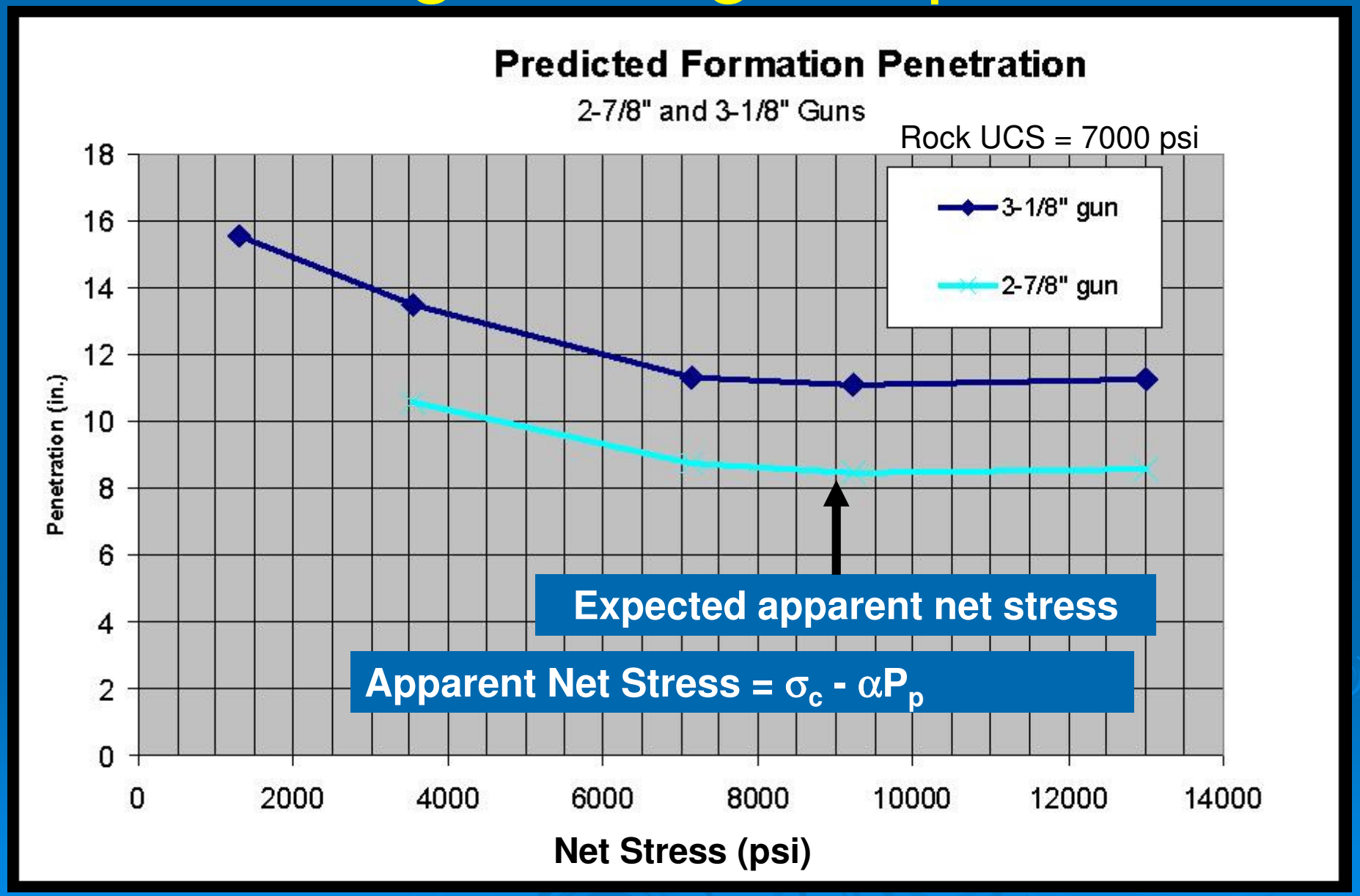
Temperature:
350° F



Net stress: **1300 psi**

Apparent net stress: **~9000 psi**

Perf Length – High Expectations



MODIFIED SECTION 2 TEST PROGRAM RESULTS

Perforation Created By 23 g HNS Charge At HPHT Conditions

SECTION 4 TEST PROGRAM RESULTS

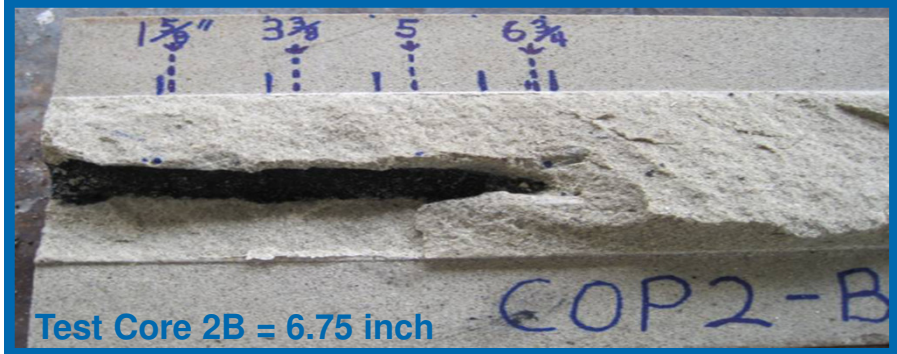
Test 6: Mud, 500 psi Static Overbalance, **no** Dynamic Underbalance, OBM Kill

Apparent net stress = 4400 psi

MODIFIED SECTION 2 TEST PROGRAM RESULTS

Perforation Created By 19 g HNS Charge At HPHT Conditions

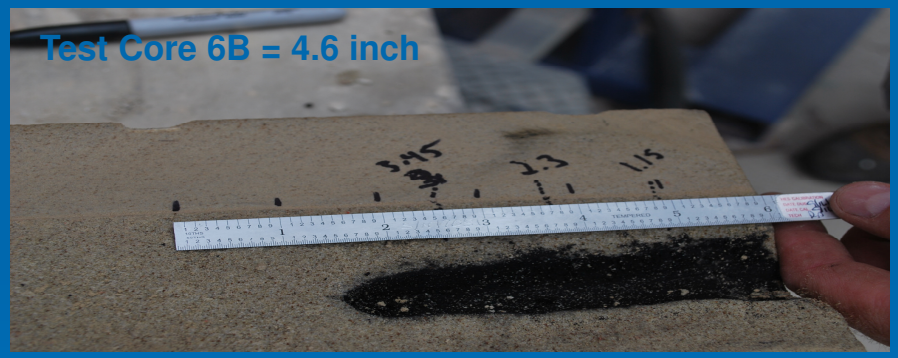
Post Shot - Perf Test Photo's



Test Core 2B = 6.75 inch

Test Core 7T = 5.81 inch

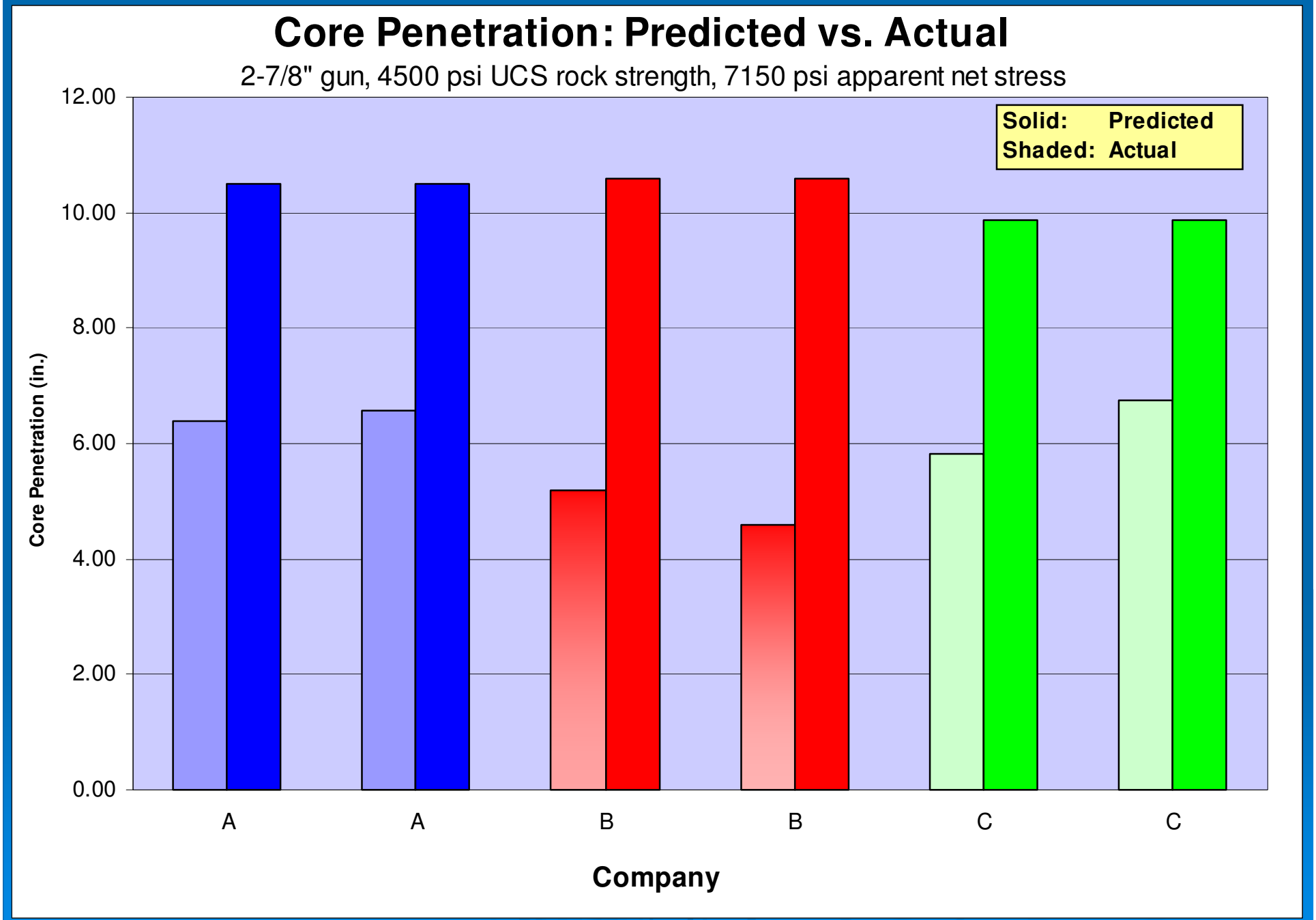
Test Core 3T = 5.2 inch



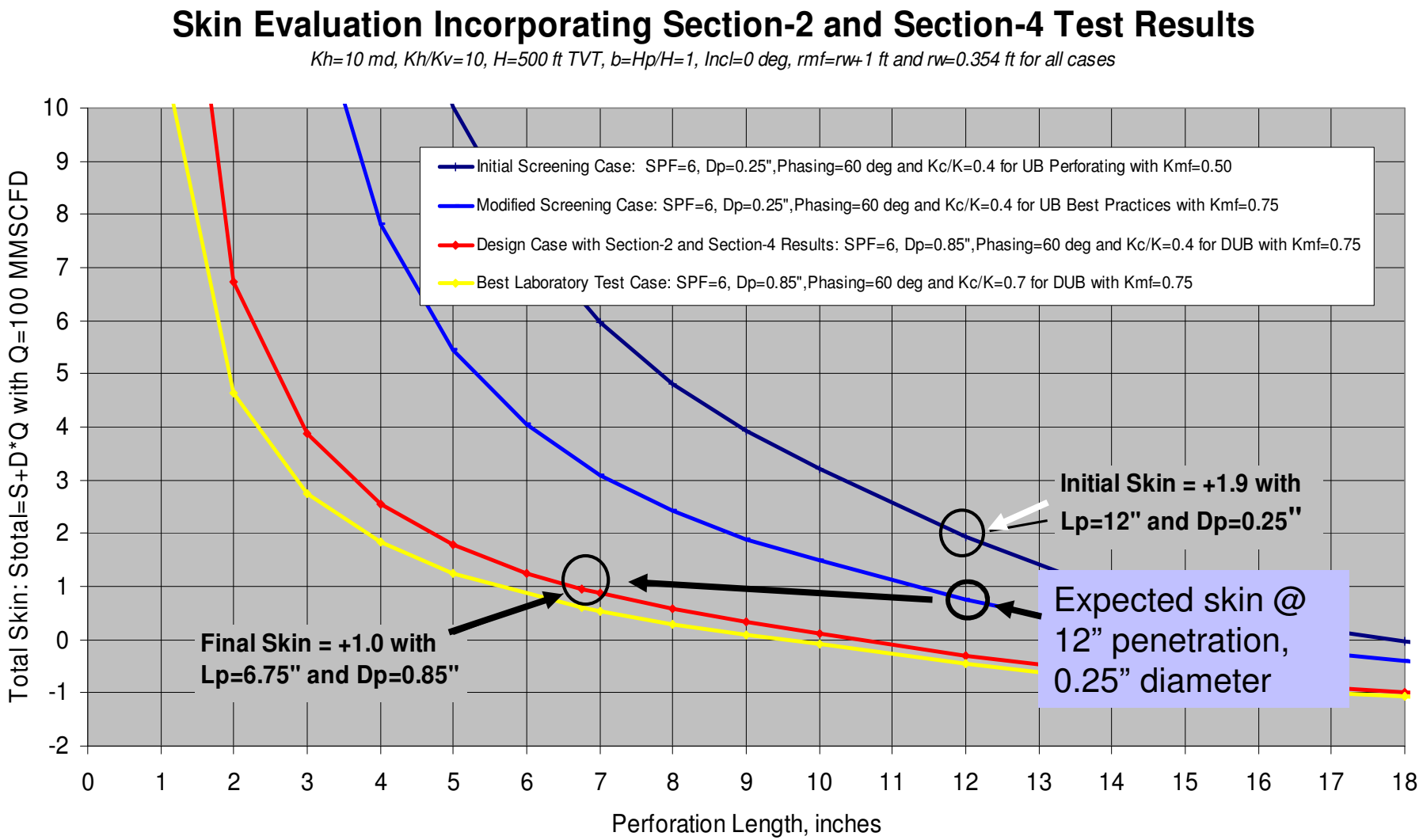
Test Core 6B = 4.6 inch

Test Core 4B = 6.38 inch

Test Core 5T = 6.56 inch


Core Penetration: Predicted vs. Actual
2-7/8" gun, 4500 psi UCS rock strength, 7150 psi apparent net stress
Solid: Predicted
Shaded: Actual
12.00
10.00
8.00
6.00
4.00
2.00
0.00
Core Penetration (in.)
A
A
B
B
C
C
Company

REVISED RESULTS USING SECTION 2 AND 4 RESULTS



Perf Geometry much different than expected, but yields roughly the same skin due to huge diameter (= flow area)

Some things to think about

- Perforation characteristics : - "Carrot Shape" (Short & Dumpy) –
  - Is this an HNS artifact?
  - What effect does the saturating fluid play?
  - Is the carrot shape indicative to the lower rock strength only. What happens in higher rock strength?

Is Short and Fat still acceptable with a low perm mud filtrate invaded zone?

Pushing Testing Further

- How do we encourage the industry to cut larger ID core in actual HPHT rock to advance testing further……..(UK & Norway) are the main user of this HPHT perf technology..
- How do we improve analogue rock selection, is synthetic rock a option? where are we with this technology?
- Testing in Brine. Tests resulted in vastly improved penetration. "Reality" future testing requires accurate saturation of the core to demonstrate if improvement associated with rock saturation.

Pushing Equipment Further

- Gun design for 2 7/8" HPHT Guns (Central Grabben Type Formation use 2 7/8“ due to 5” Tubing /Liners) has **probably** reached its limit. There has to be quantum leap in technology to make any difference and this does not seem to be available today.
- **DUB: Cannot actually measure the event in real time due to limitations of gauge technology (temp) both in the lab and in the field.**

Acknowledgements / Thank You / Questions

The authors wish to thank the management of both ConocoPhillips Company and Schlumberger for permission to publish this work. The authors also wish to thank the PERF Lab engineers and technicians involved in this work for their diligence in performing these tests to ensure meaningful and consistent test results.

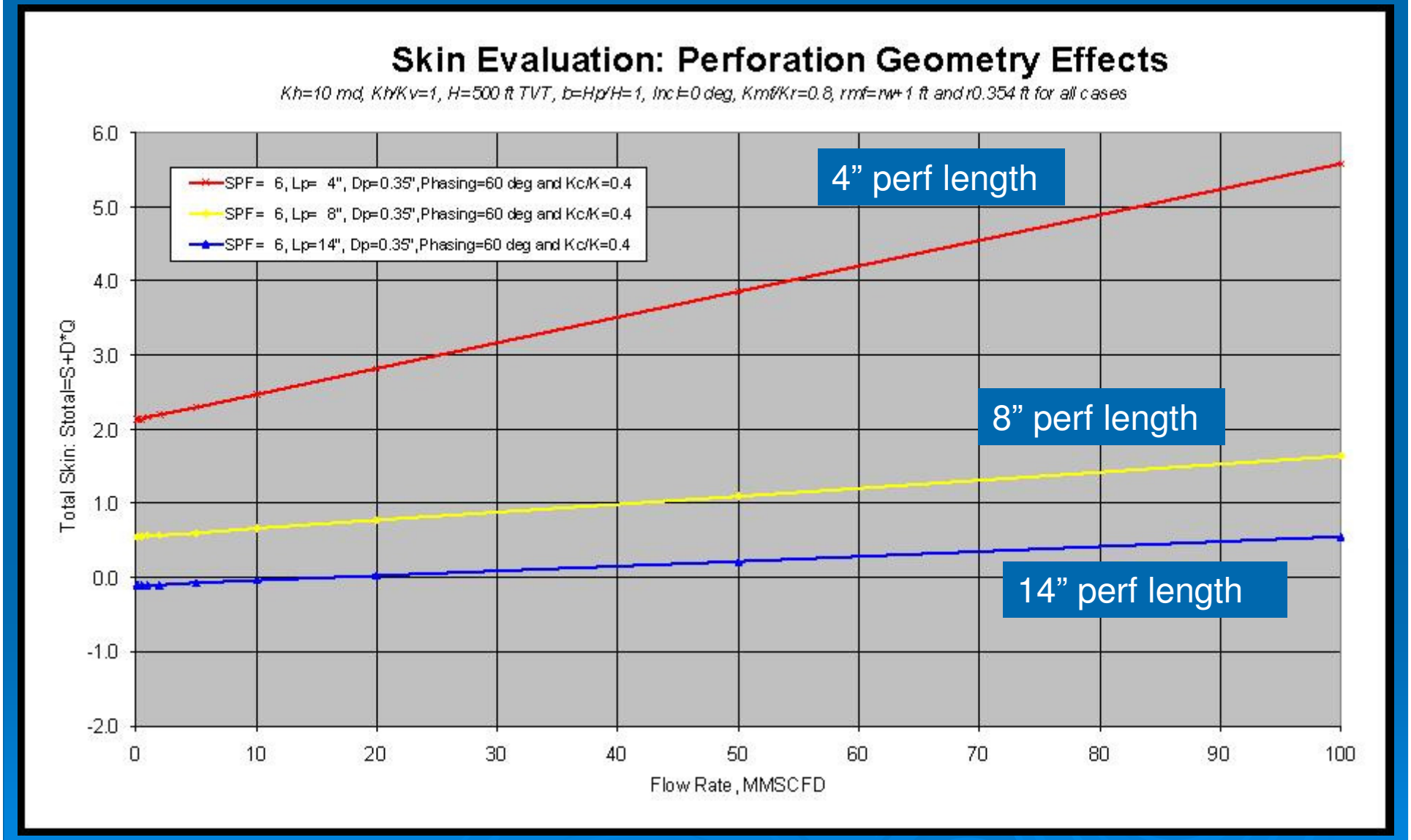
Perf Length Test Results

- Charges shot shorter than expected in HPHT Tests
- Charges had larger perforation diameters in HPHT Tests
- 3-1/8” did not shoot significantly deeper than 2-7/8”, at least settling that argument

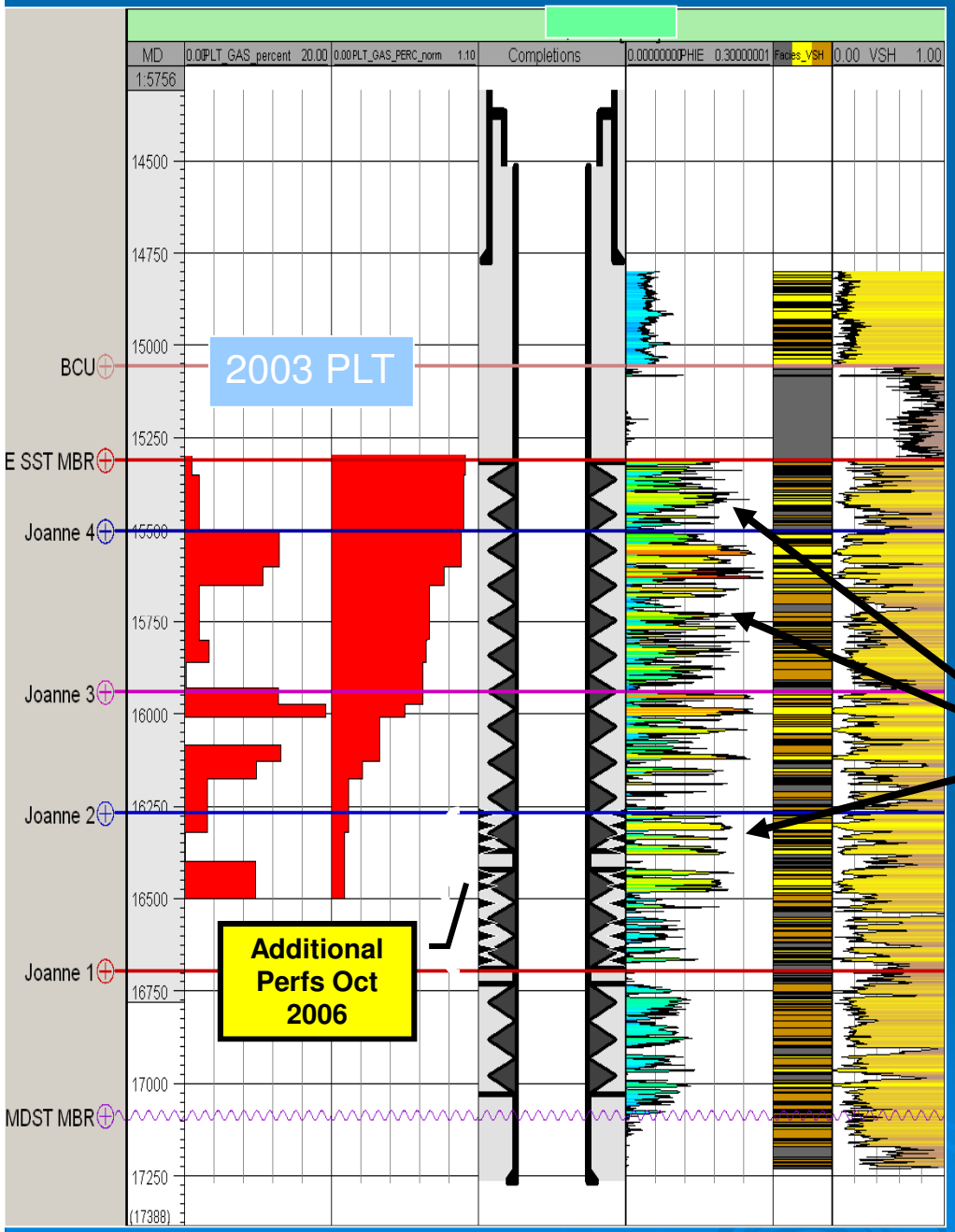
Perf Length Test Results

- Charges shot shorter than expected in HPHT Tests
- Charges had larger perforation diameters in HPHT Tests
- Perf Geometry depended upon saturating fluid (OMS vs brine)
- 3-1/8" did not shoot significantly deeper than 2-7/8", at least settling that argument
- DUB and perf geometry should be sufficient for our skin goals (stay tuned)

Length vs Total Skin



Well 3



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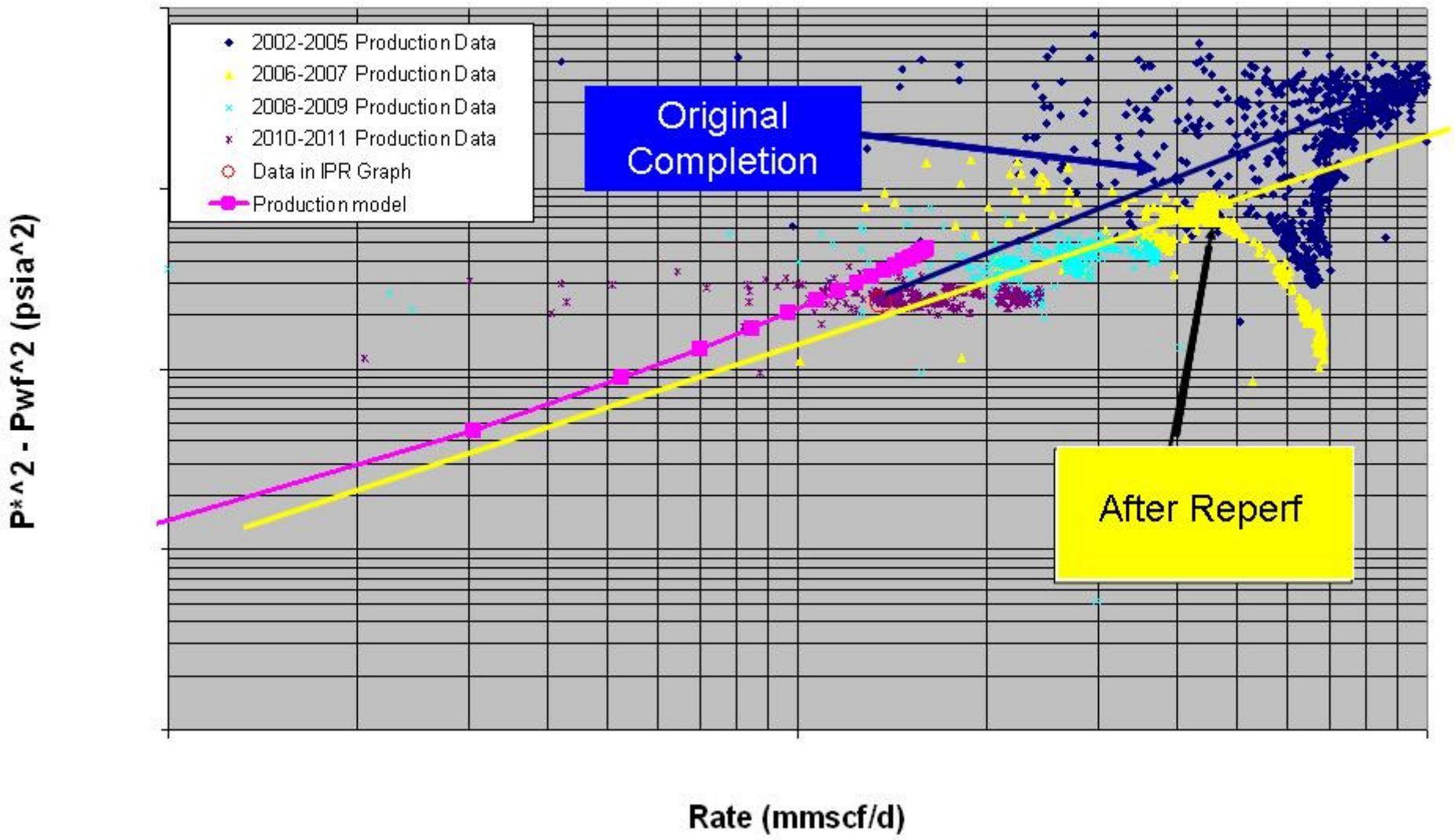
Well 4 Backpressure Plot



Well 3 Backpressure Plot