Extreme Hard Rock Perforating: Penetration Challenges and Limits

Hanaey Ibrahim

Mohd Shafie Jumaat

Brenden Grove

David Atwood

Schlumberger

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Agenda

1. Introduction
2. Perforating Penetration Model & Challenges
3. The Cores
4. Test Procedure
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Introduction

- Khulud field in Oman has deep vertical 4.5” monobore wells drilled for tight gas. Multi-stage hydraulic fracturing performed.
- Rock strength = ~20,000 psi to ~55,000 psi
- Porosity + ~5%, K = ~1 mD
- Formation breakdown has been a problem.
- SPE-152458 for Khulud: Explosive perforating and abrasive jetting perforating used. Lower breakdown pressure achieved with abrasive jetting by average 1180psi.
- Need to understand explosive perforating performance in very strong rock.

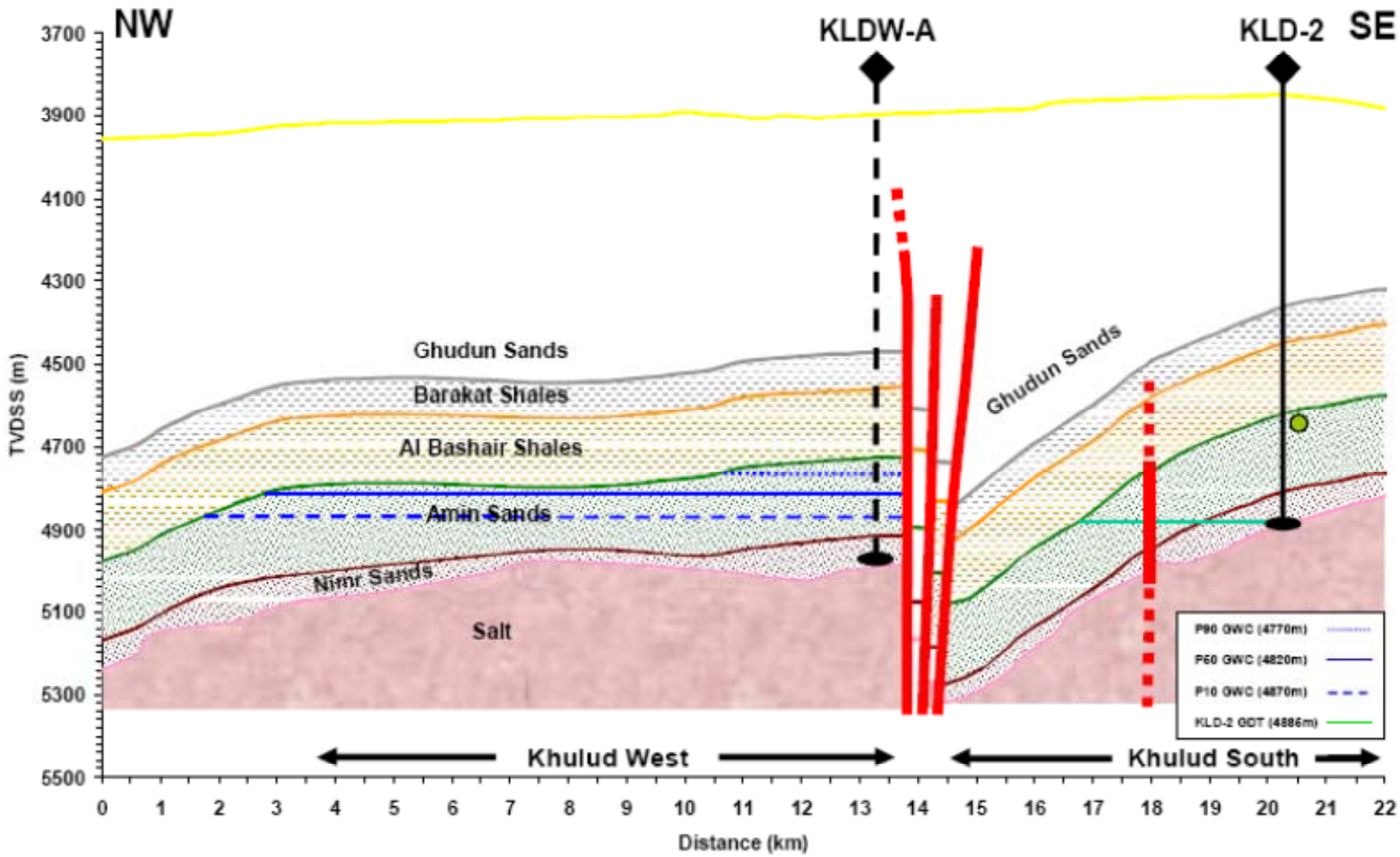


Fig.25: Khulud West preferred structural model and fault-seal concept

Production Casing 9-7/8" 68.9# SM-95S VAM TOP x 9-5/8" 53.5# P-110 VAM TOP SB

Burst Rating: 12,120 psi	Burst Rating: 10,900 psi
Collapse Rating: 11,580 psi	Collapse Rating: 7,930 psi
Drift: 8.375", nom. ID: 8.475"	Drift: 8.379", nom. ID: 8.535"

Production Tubing 4-1/2" 17# SM-13Cr110 VAM TOP
Burst Rating: 16,256 psi
Collapse Rating: 17,009 psi
Drift: 3.615", nom. ID: 3.74"

Top of 7" Liner — 3,991 m — Liner Top Packer ZXP

9-7/8" Casing Shoe @ Base of Gharif — 4,104 m

Drilling Liner 7" 35# SM-95S VAM TOP
Burst Rating: 11,830 psi
Collapse Rating: 11,650 psi
Drift: 5.879", nom. ID: 6.004"

Seal Bore Locator 4-1/2" 17# Inconel 718 VAM TOP 30 ft (min. ID: 3.74", 18 ft up/12 ft down nogo)
Polished Bore Receptacle 30 ft (seal bore ID: 5.000")
Liner Top Packer 4-1/2" ZXP

Top of 4-1/2" Liner — 4,800 m

Production Liner 4-1/2" 17# SM22CR-125 VAM TOP — 4,848 m
Burst Rating: 19,014 psi
Collapse Rating: 19,342 psi
Drift: 3.615", nom. ID: 3.74"

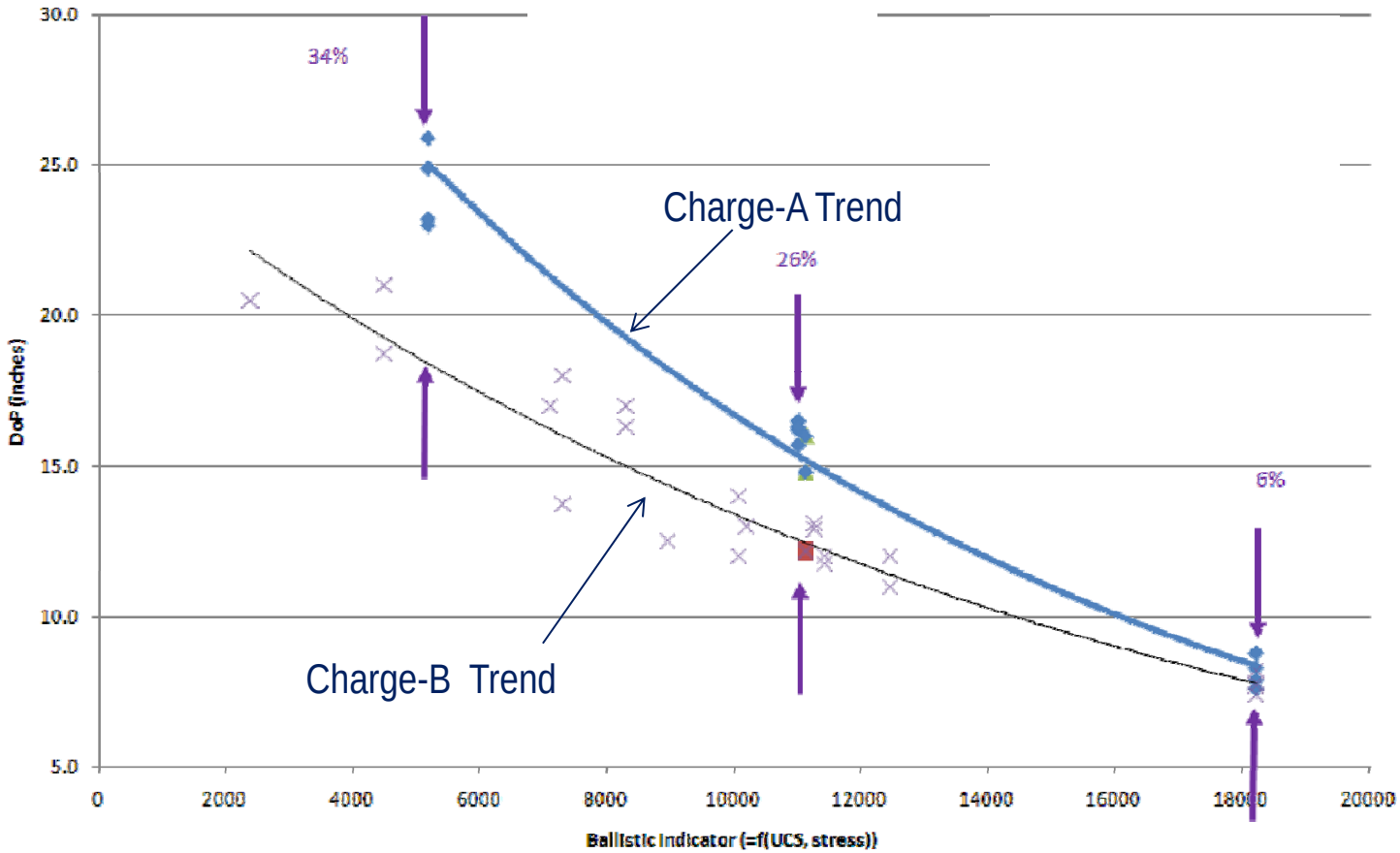
A MIN/ NIMR **16.1 kPa/m**

4,943 m — Wireline perforating guns — Tres: 177.90 °C
2-7/8" [redacted] HMX — Pres: 79000 kPa
(Contingent Coiled Tubing Abrasive Jetting) — p: 2.6 kPa/m

5,201 m

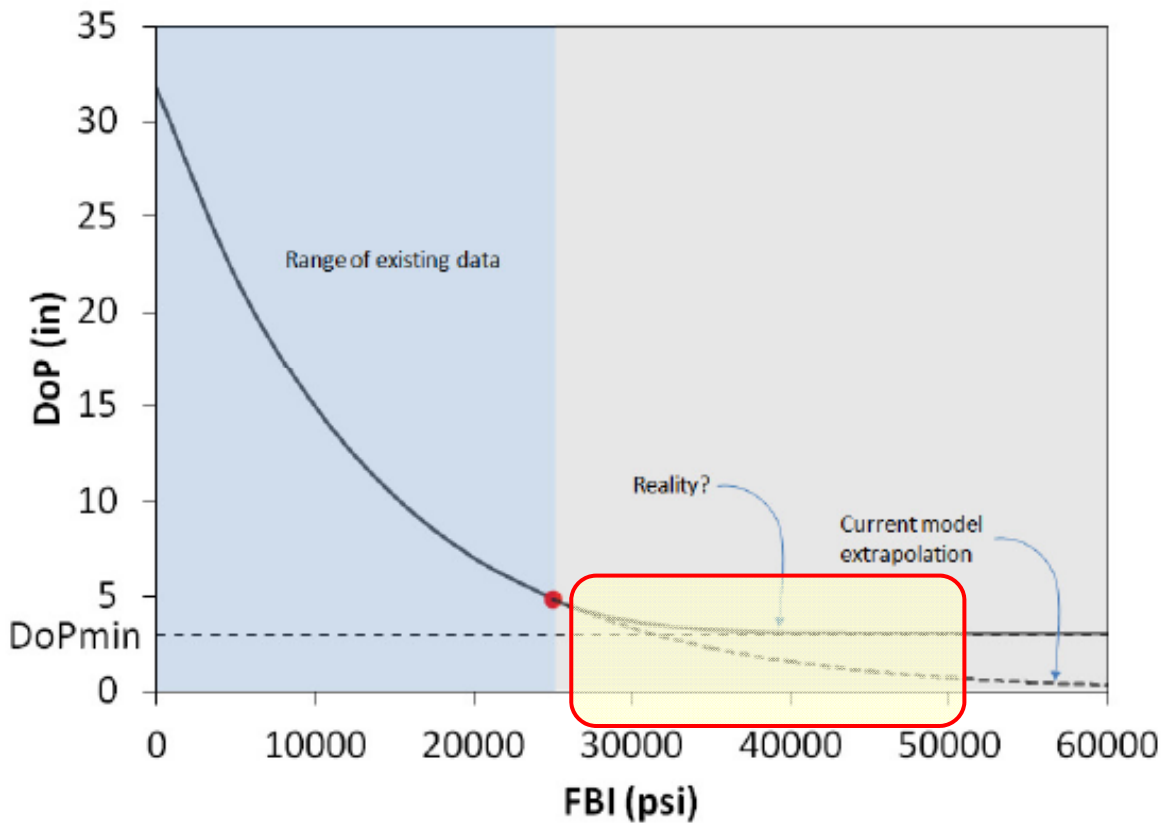
TD 5-7/8" Hole — 5,289 m — T: 188.6 °C

Perforating Modeling & Challenges



- Khulud formations in Oman with UCS in the range 20,000 to 50,000psi .What is the performance ?

Penetration Lower Limit



- To confirm the penetration lower limit (DoPmin) proposed in SPE-151846
- Khulud cores UCS range

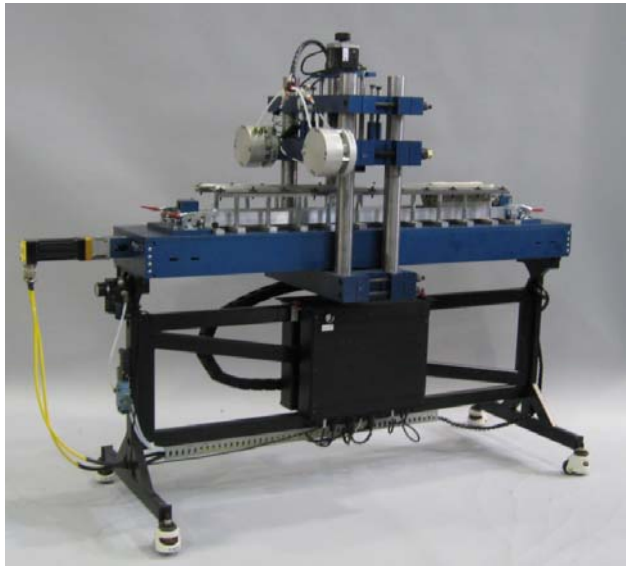
The Cores

- 5 x 1m cores from the following wells were sent to laboratory for perforating shot tests:

Khulud-5			
Box #	Top depth	Bottom depth	Core #
22	4791.16	4792.16	2
35	4831.7	4832.7	3
11	4886.2	4887.2	5

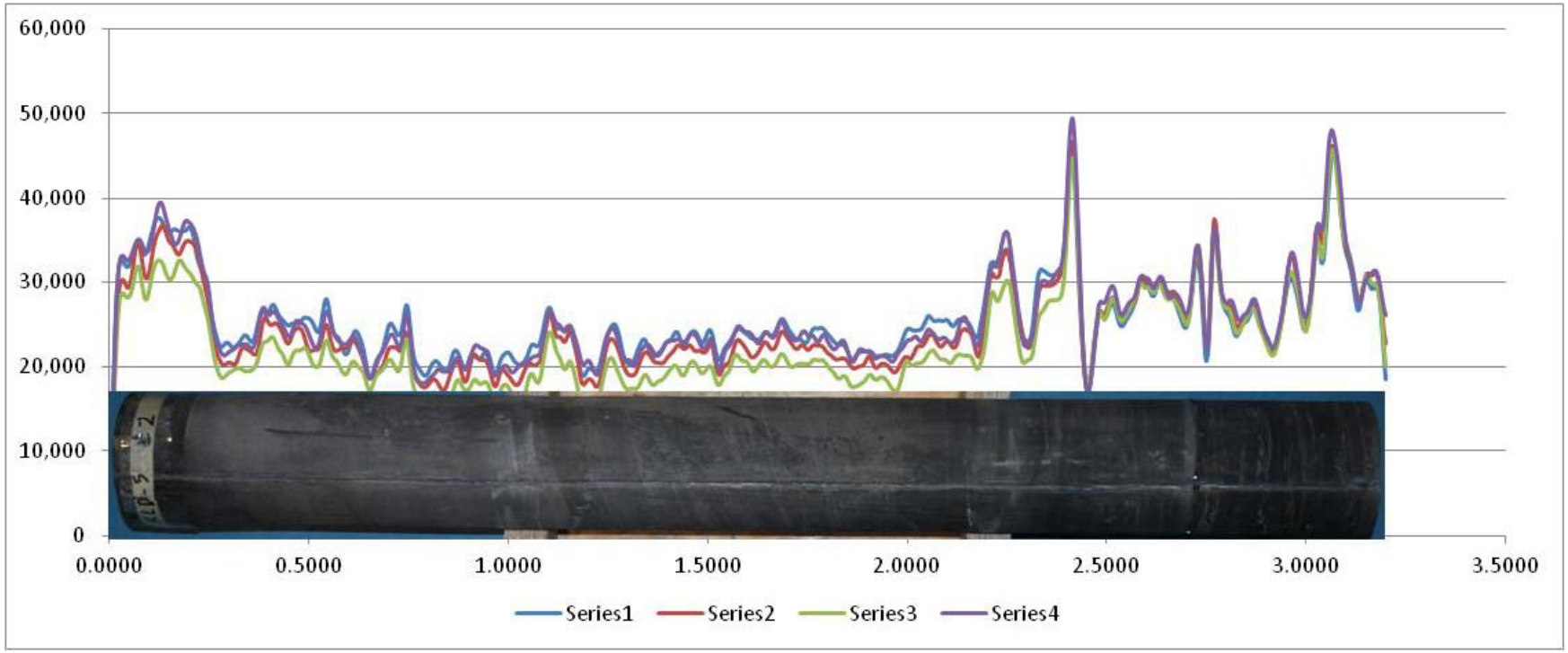
Khulud-6			
Box #	Top depth	Bottom depth	Core #
17	5083.3	5084.3	2
14	5100	5101	3

Test Procedure

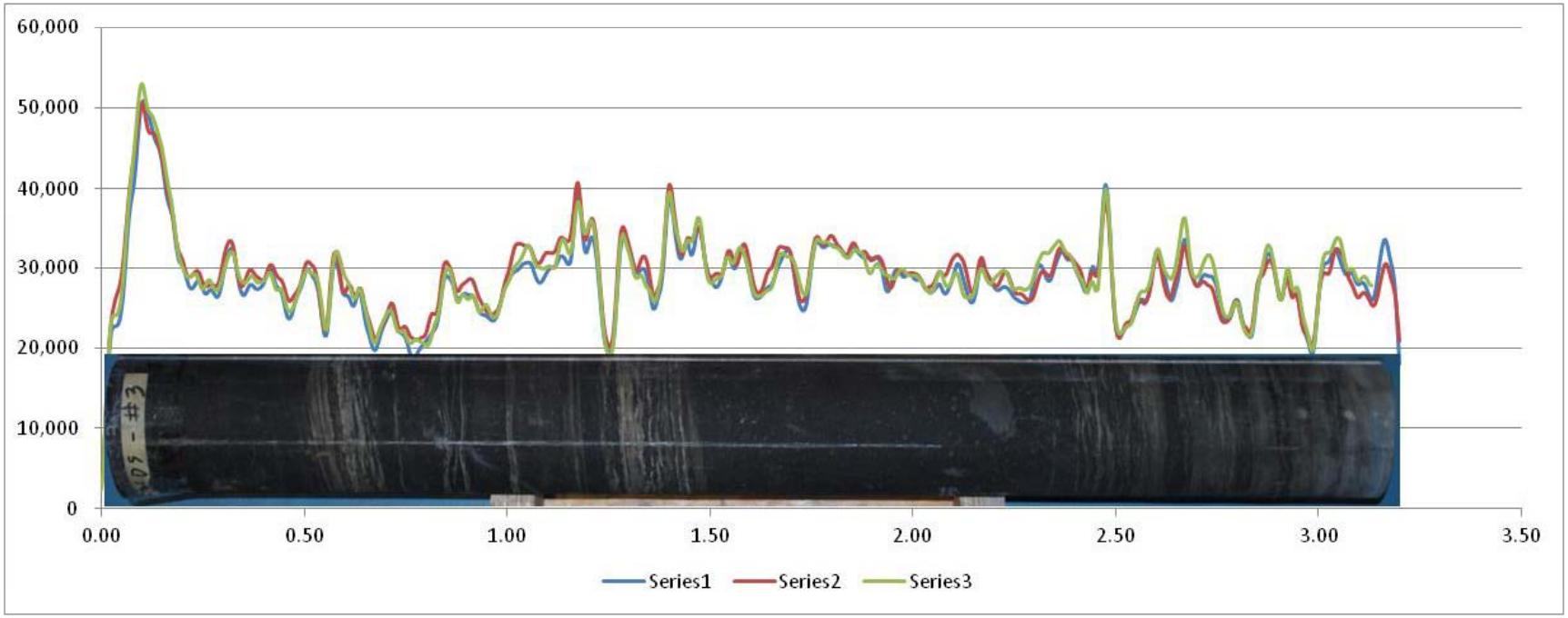


- UCS Scratch Test
- Cut cores into 8” samples based on measured UCS
- Select the samples to use for the proposed explosive charge
- Shoot the samples in API-19B Section 2 Setup
- Retrieve the shot core, cut and measure the penetration

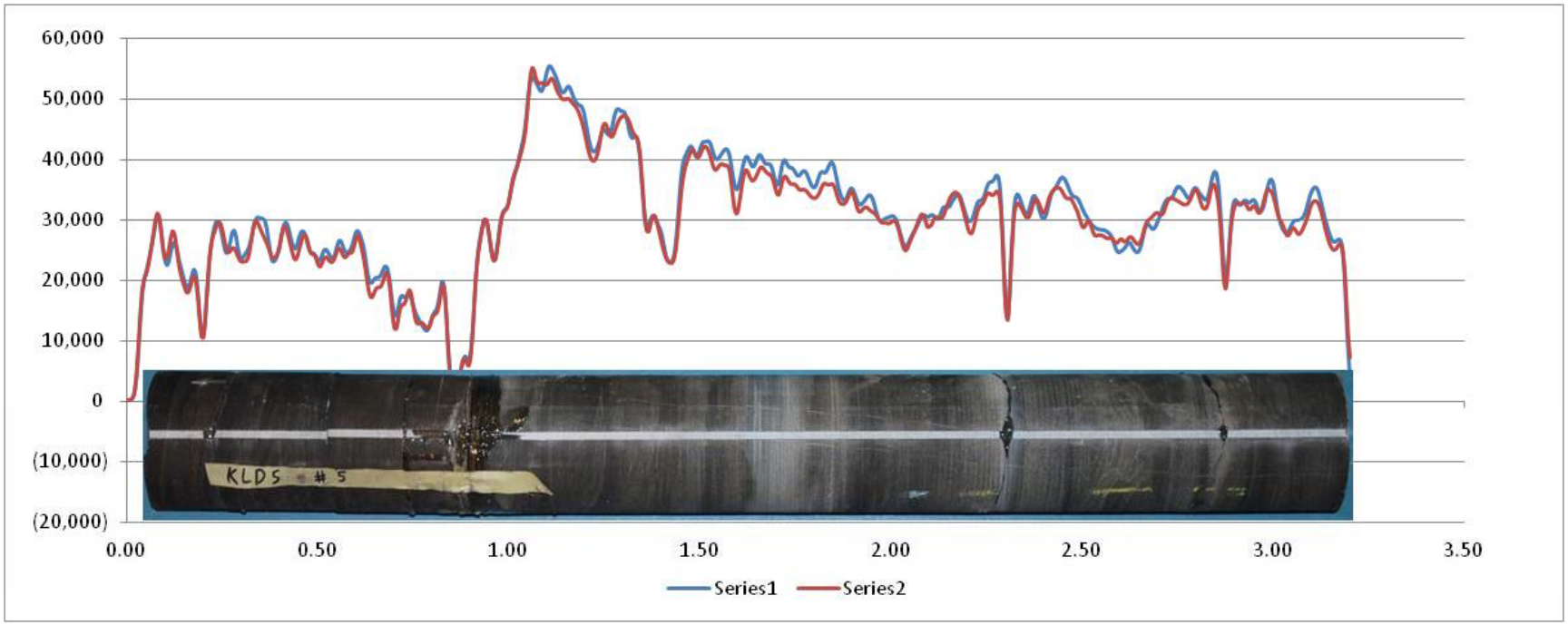
UCS Scratch Test Result (Core 5-2)



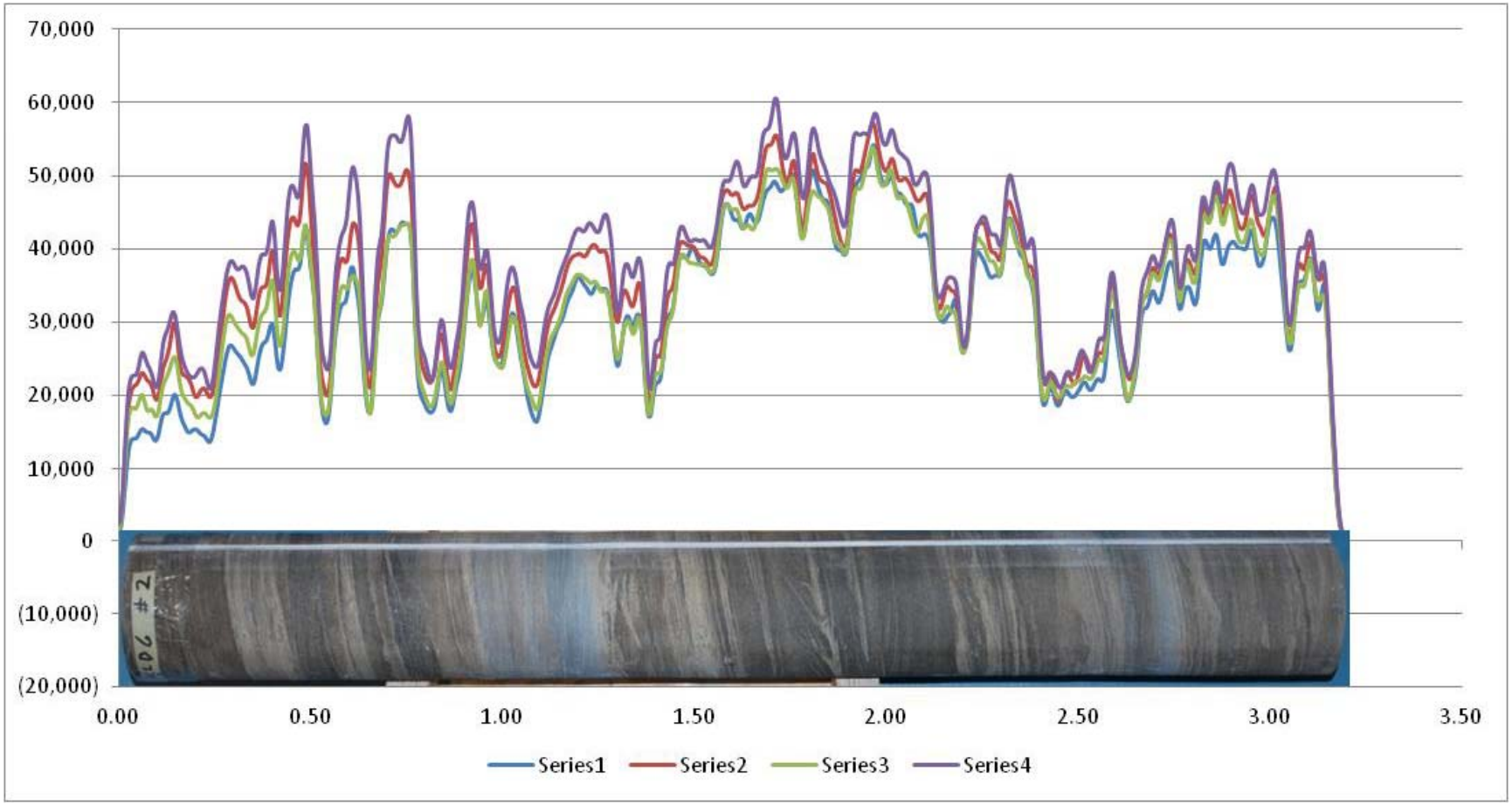
UCS Scratch Test Result (Core 5-3)



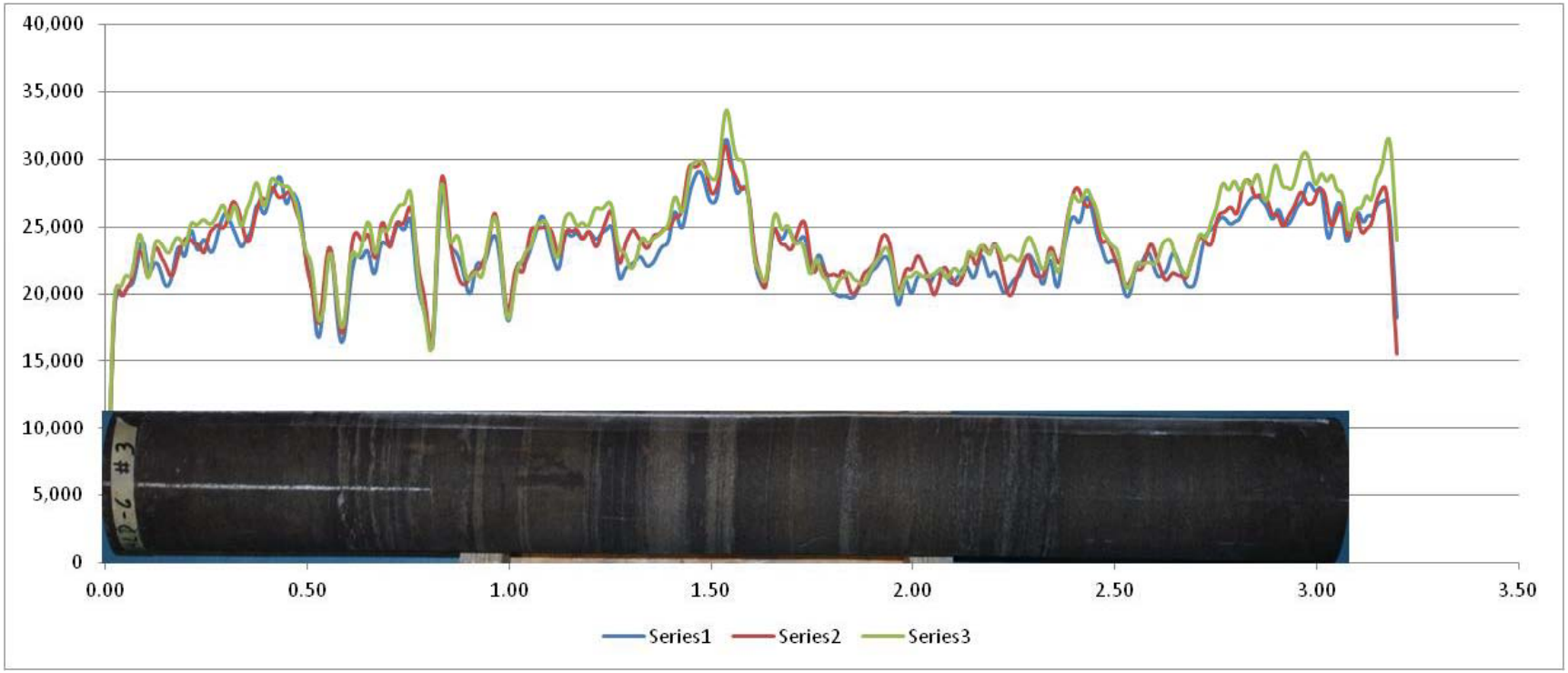
UCS Scratch Test Result (Core 5-5)



UCS Scratch Test Result (Core 6-2)



UCS Scratch Test Result (Core 6-3)



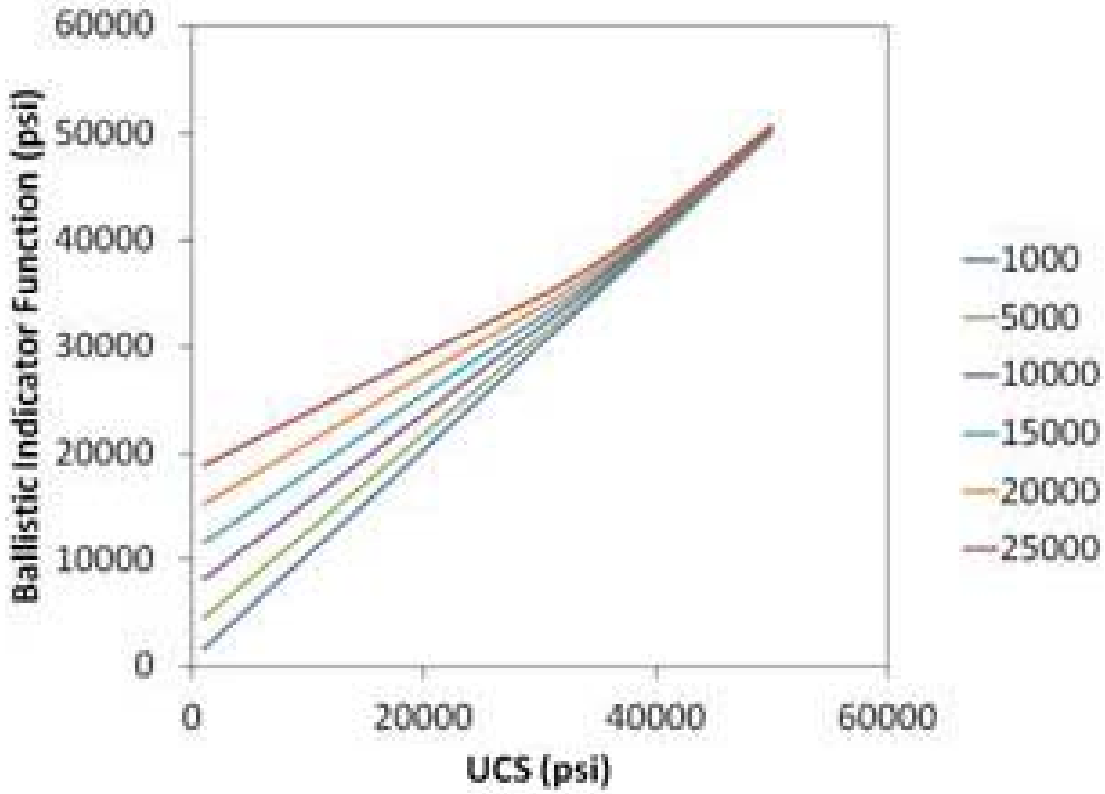
UCS Scratch Test vs UCS Core Plug Test

Plug UCS Vs. Scratch UCS

Sample ID	Taken From Core #	Dry Bulk Density	Effective Compressive Strength	Quasi-Static Young's Modulus	Quasi-Static Poisson's Ratio	Approximate Scratch UCS From Same Location
P-P-1	KHDL 5-5	2.660	31520	5817500	0.26	30 ksi to 34 ksi
P-P-2	KHDL 5-5	2.654	28920	5701700	0.35	
P-PL-1	KHDL 5-5	2.653	24410	5761600	0.14	30 ksi to 34 ksi
P-PL-2	KHDL 5-5	2.660	26505	5096600	0.16	
S-P-1	KHDL 5-2	2.591	32345	5624100	0.22	30 ksi to 40 ksi
S-P-2	KHDL 5-2	2.585	29450	5925000	0.25	
S-PL-1	KHDL 5-2	2.551	27880	6033100	0.31	30 ksi to 40 ksi
S-PL-2	KHDL 5-2	2.593	31325	5488300	0.25	
U-P-1	KHDL 6-2	2.594	22275	3504500	0.21	25 ksi to 31 ksi
U-P-2	KHDL 6-2	2.599	29380	5088600	0.09	
U-PL-1	KHDL 6-2	2.594	24805	4816800	0.30	25 ksi to 30 ksi
U-PL-2	KHDL 6-2	2.599	37510	5999000	0.20	35 ksi to 42 ksi
V-P-1	KHDL 6-3	2.610	32535	5617300	0.21	28 ksi
V-PL-1	KHDL 6-3	2.594	32330	5249600	0.21	25 ksi to 29 ksi
Z-P-1	KHDL 5-3	2.614	(Note 1)	(Note 1)	(Note 1)	53 ksi
Z-PL-1	KHDL 5-3	2.620	52360	8536400	0.13	

(1) This sample "failed" the UCS test apparatus being used, when the sample exploded at a load that would indicate a UCS in excess of 60 ksi.

F_{bi} from UCS and Stress (SPE-151846)



- UCS range from the cores for the tests: 20,000 to 50,000psi

Cores Segmentation

Test Setup

- API-19B Section 2 Test
- Apply 10,000 radial and confinement stress
- 0 pore pressure with residual pore fluid
- Standard end-cap with cement sheath
- Standard gun carrier with scallop and 0.5” water standoff

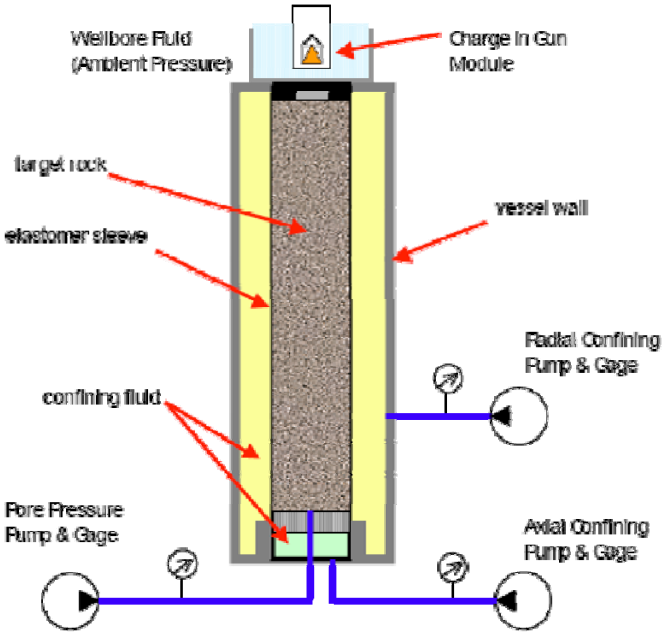


Fig. 9. Pressure vessel schematic

The Tests

- 2-7/8” guns Charge-A

The Tests

- 2-7/8” gun charge-B

The Tests

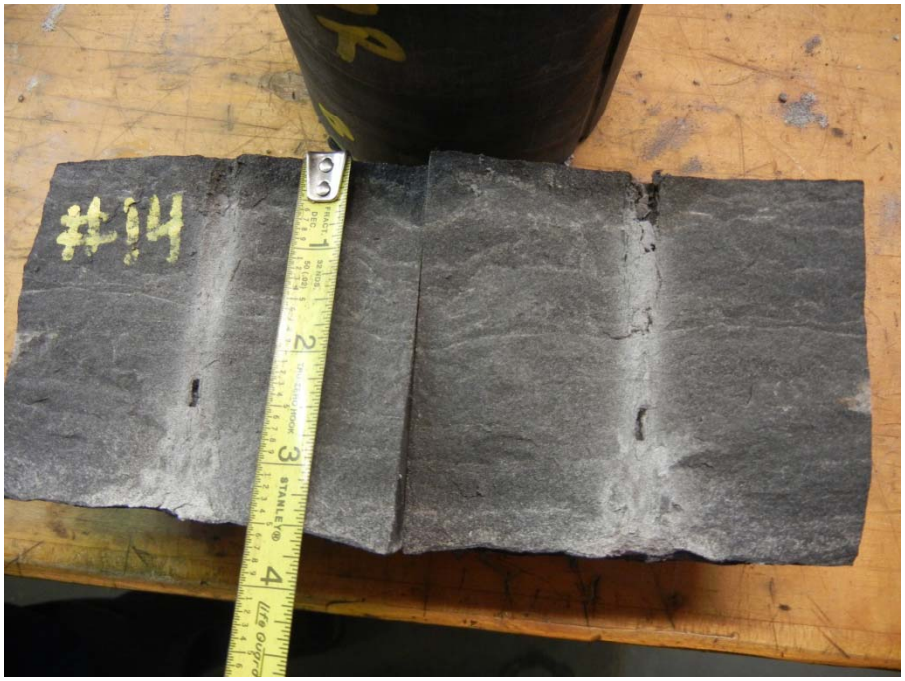
- 3.5” gun Charge-C

The Tests

- 3-3/8” gun charge-D

The Tests

- 2” gun charge-E

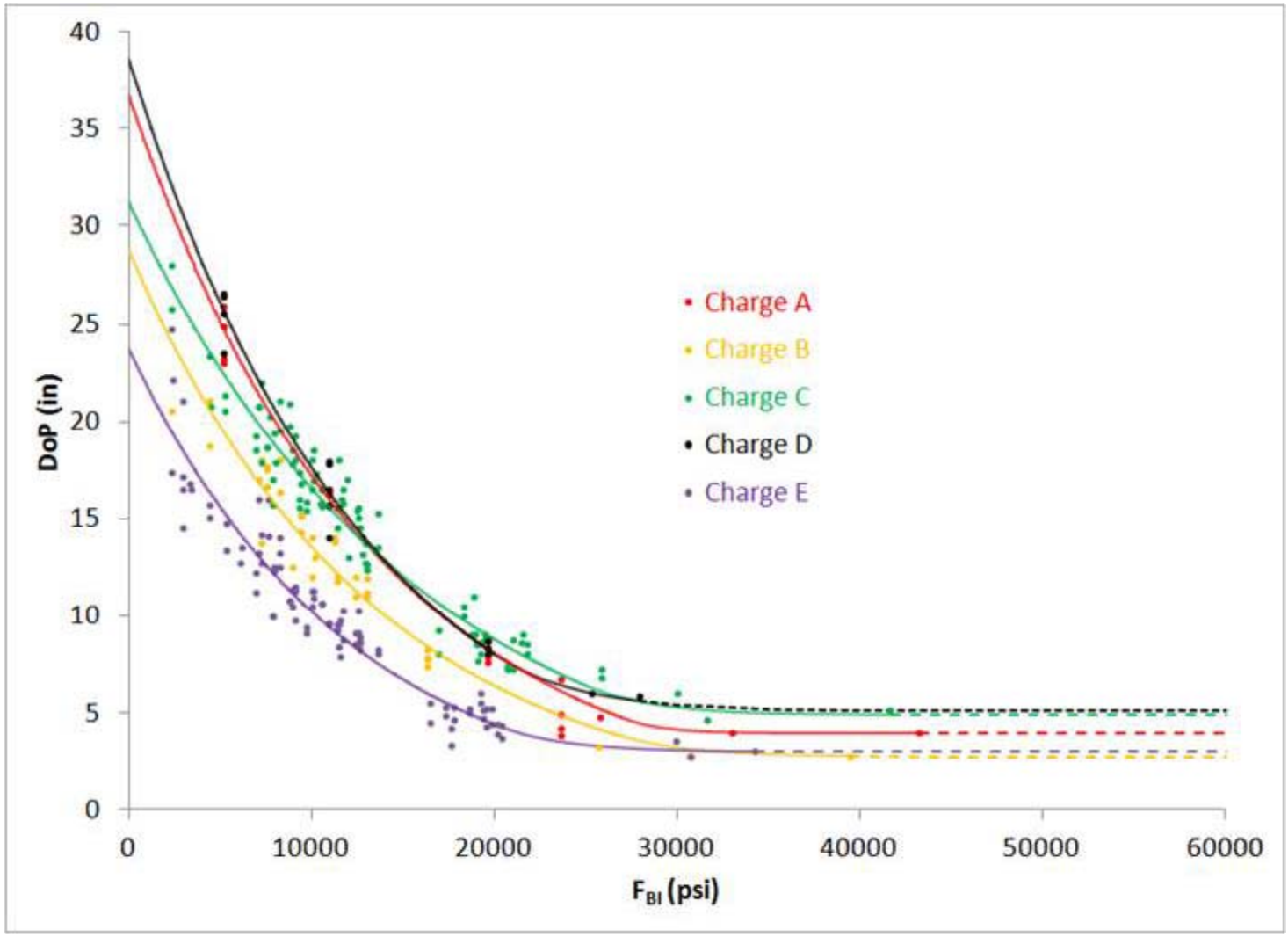


Test Results

Test Number	Sample ID Number	Source Well Core	Scratch UCS Over Perforated Interval	Shaped Charge To Shoot	Water Clearance	Rock Penetration	Comments
1	One	KLD5-2	22.6 ksi	2-7/8" Charge-A	0.5	4.75	T to B
2	Nine	KLD5-5	42.7 ksi	2-7/8" Charge-A	0.5	4.00	T to B
3	Six	KLD5-3	31.4 ksi	2-7/8" Charge-A	0.5	4.00	B to T
4	Three	KLD5-2	22.5 ksi	2-7/8" Charge-B	0.5	3.25	T to B
5	Ten	KLD5-5	38.7 ksi	2-7/8" Charge-B	0.5	2.75	T to B
6	Seven	KLD5-3	28.7 ksi	2-7/8" Charge-B	0.5	2.75	T to B
7	Eighteen	KLD6-2	29.7 ksi	3.5" Charge-C	0.5	4.62	T to B
8	Five	KLD5-3	27.7 ksi	3.5" Charge-C	0.5	6.00	T to B
9	Seventeen	KLD6-2	41.0 ksi	3.5" Charge-C	0.5	5.12	T to B
10	Seven (back end)	KLD5-5	28.6 ksi	2" Charge-E	0.5	2.75	T to B; using remains of core from Test 6
11	Ten (back end)	KLD5-3	32.8 ksi	2" Charge-E	0.5	3.00	B to T; using remains of core from Test 5
12	Thirteen	KLD6-3	22.0 ksi	3-3/8" Charge-D	0.5	6.00	B to T
13	Fourteen	KLD6-3	25.2 ksi	3-3/8" Charge-D	0.5	5.88	B to T
14	Four	KLD5-2	27.6 ksi	2" Charge-E	0.5	3.50	T to B

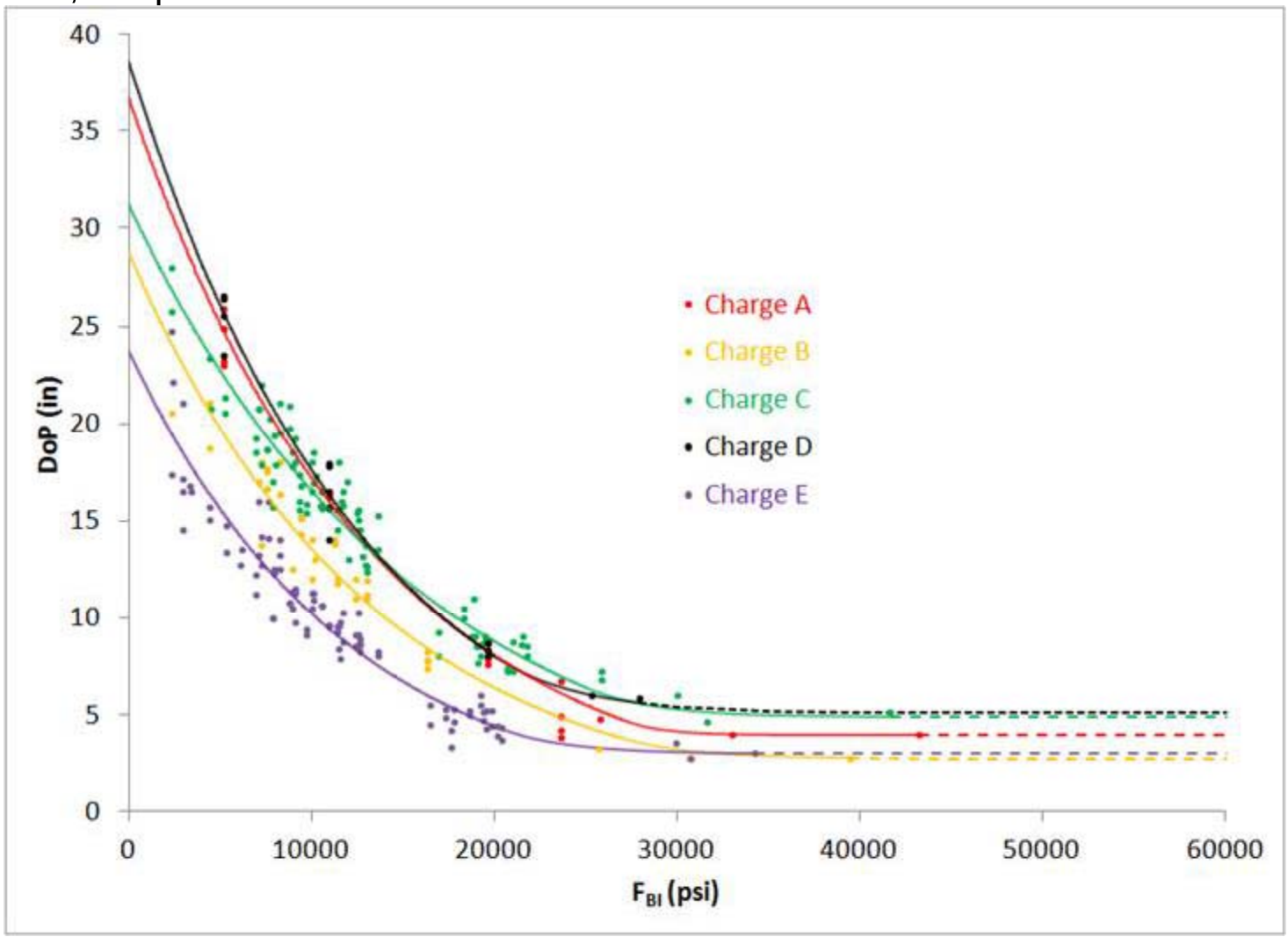
Observation-1

- The penetration does not diminish towards zero, confirming the asymptote (DoPmin)



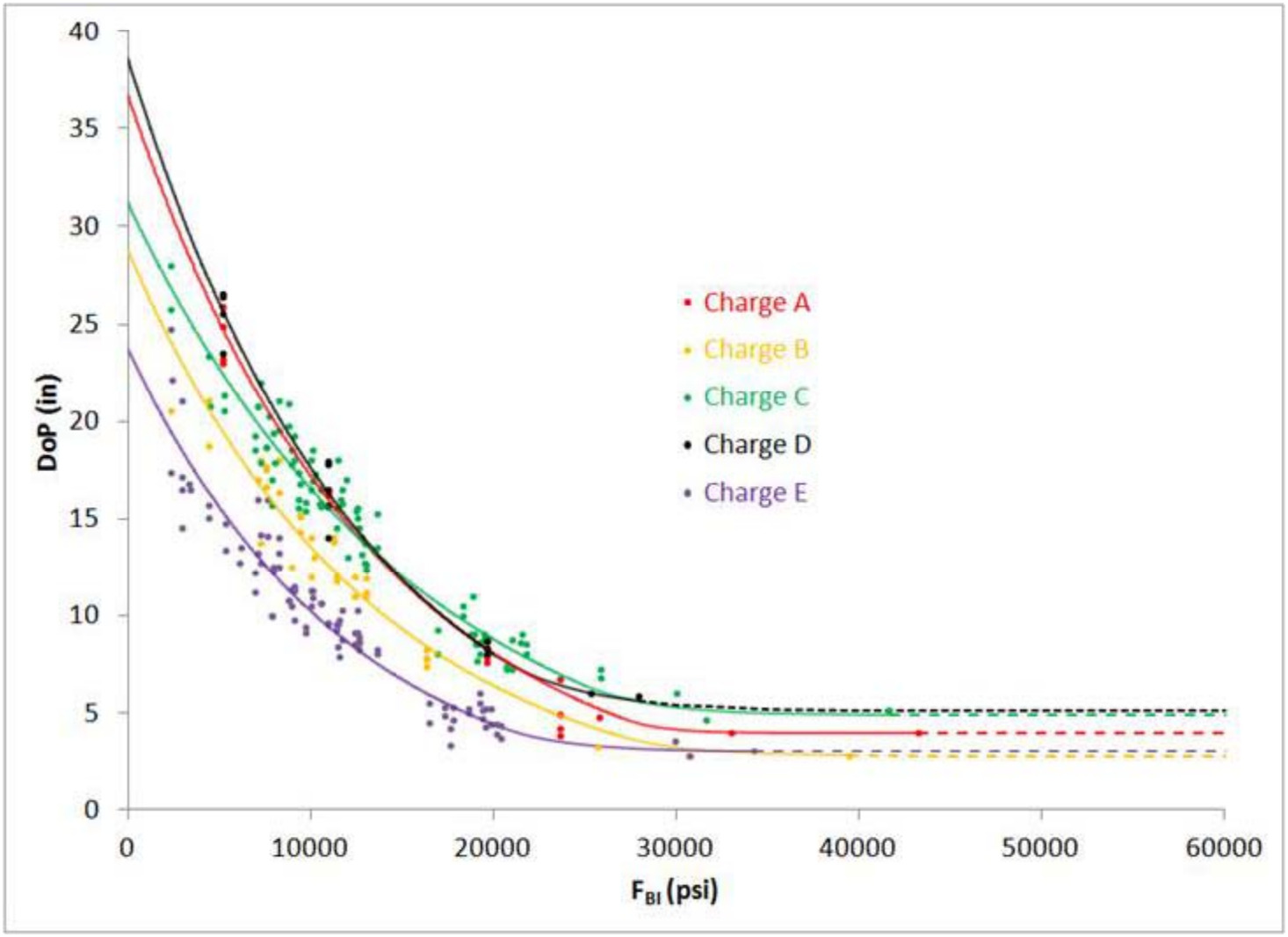
Observation-2

- Crossover of Charge-A vs Charge-B based on extrapolation of experimental data at UCS<20,000 psi does not occur.



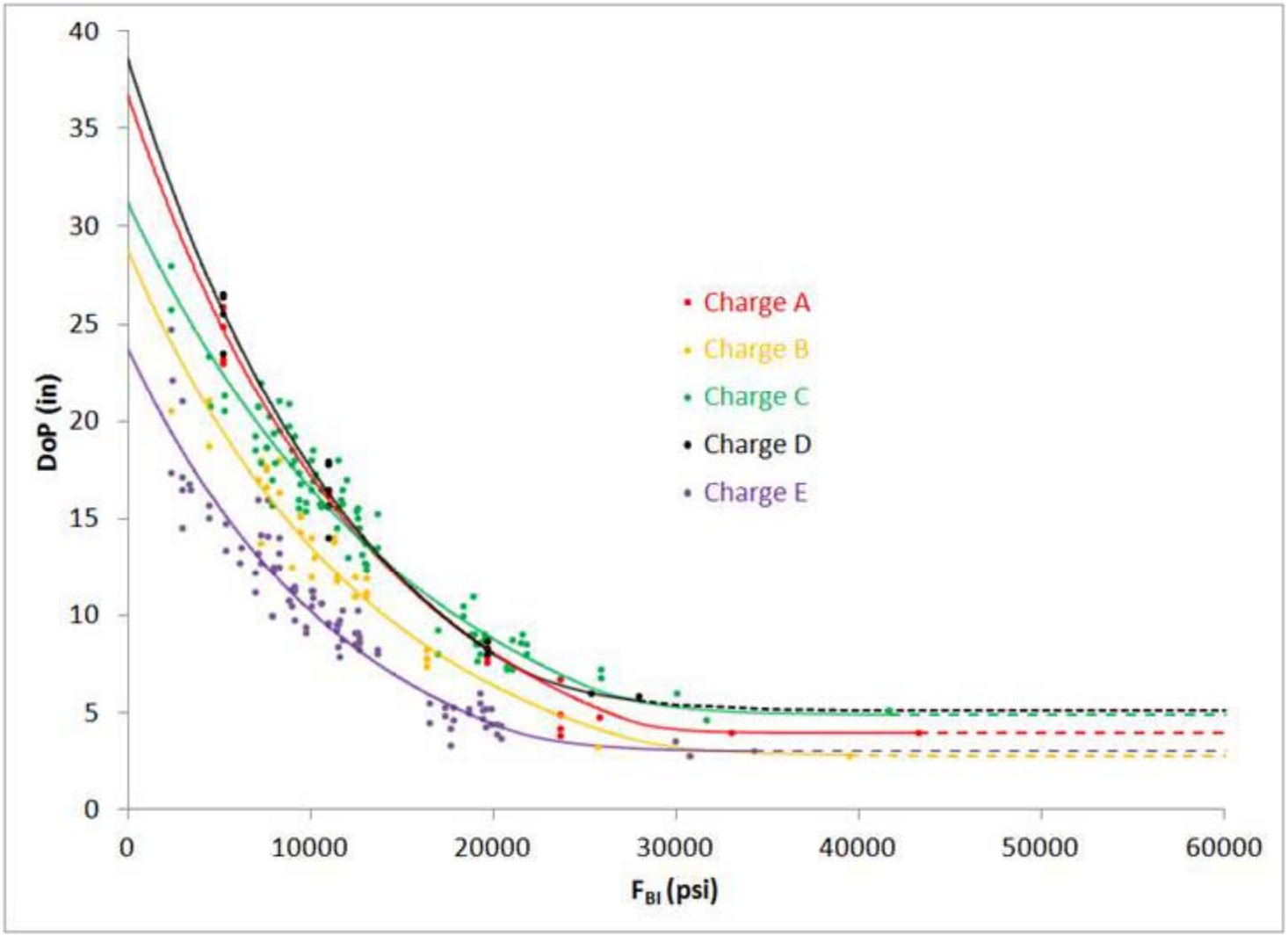
Observation-3

- 3-3/8” gun Charge-D matches the performance of 3.5” gun Charge-C at high UCS.



Observation-4

- 2” gun Charge-E matches the performance of 2-7/8” gun Charge-B at high UCS.



Way Forward

- Charge-A has deeper penetration than Charge-B in the test:
  - For hydraulic fracturing in Khulud field: trial will be done in 3 wells to see if that is beneficial.
- Based on these characterization, these 5 charges can be selected for Khulud (completion size) and other fields depending on:
  - Rock strength
  - Application (normal unstimulated completion or pre-stimulation perforating)
- PDO Charge A trials:
  - Two wells have been perforated using Charge A and production logging interpretation is on going for evaluation.
  - Third well will be perforated this week using charges A and B followed by acid stimulation and PLT to measure charge A performance.