ارامكو السعودية
Saudi Aramco

Engineered Perforating Charges Designed for Proppant Frac Stimulation

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HALLIBURTON

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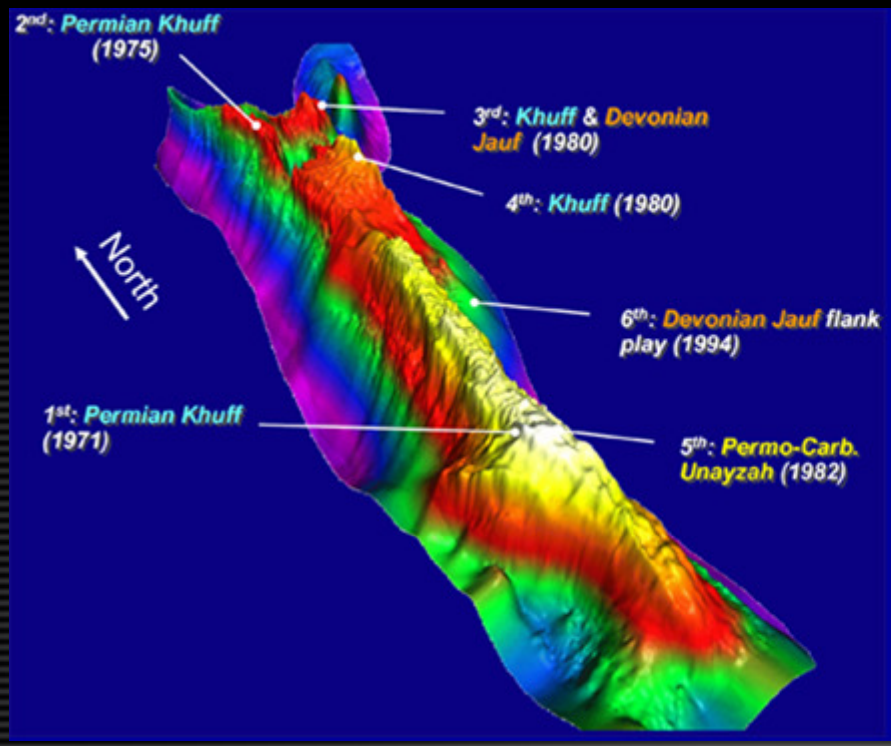
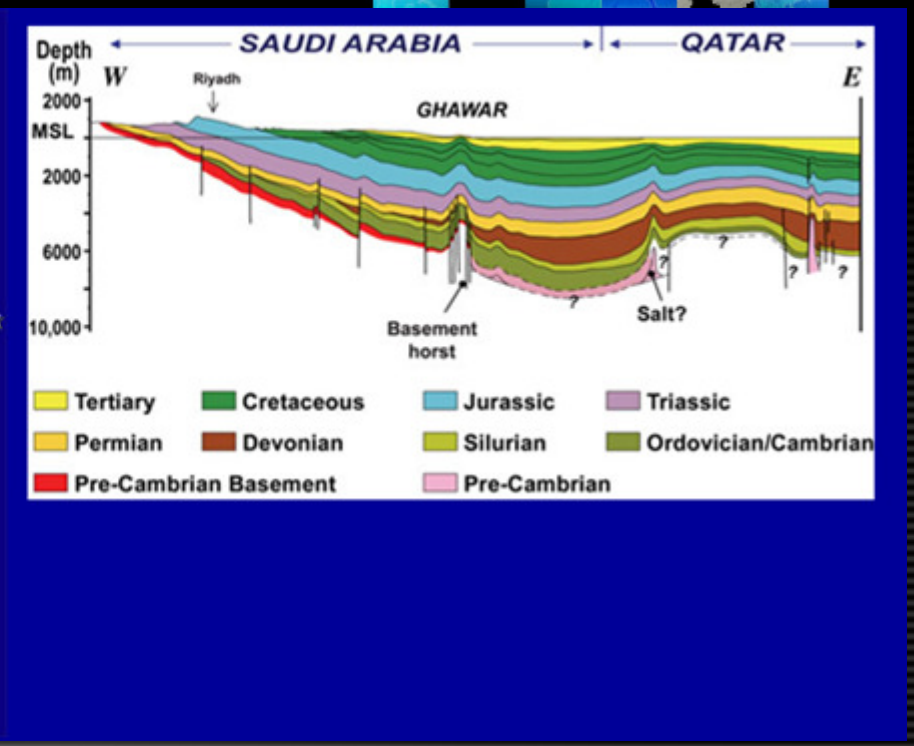
Background (Ghawar Gas Field)





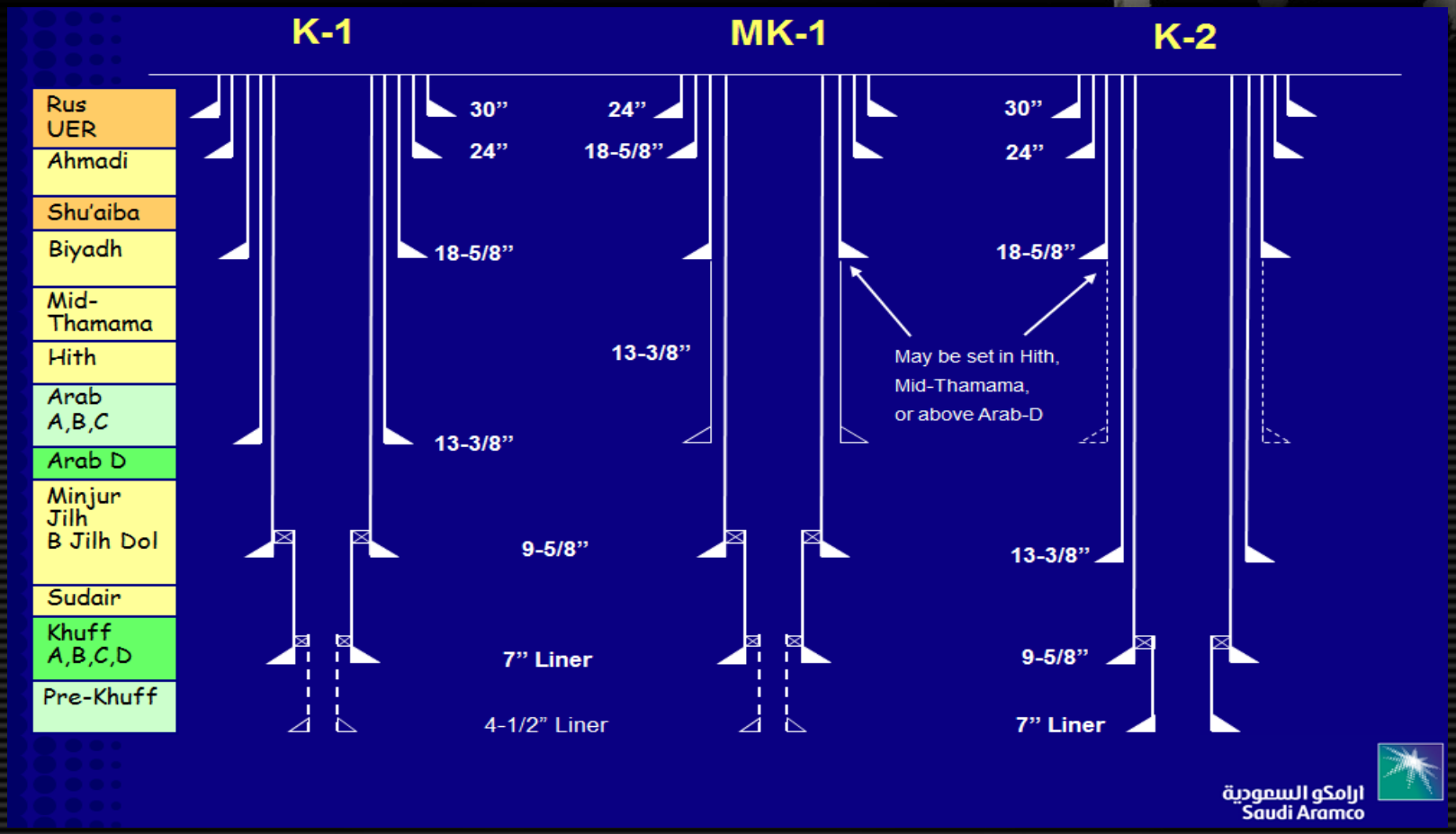
Depth increases going to the North (reduction in CGR)
Temperature increases going to the North (BHT = 340 deg F)
Stress increases going to the flanks/North (1.1 psi/ft)

Background (Ghawar Pre-Khuff)

- Sandstone formations at 15,000 ft
- CO_2 = 4% (Pre-Khuff gas Wells)
- Static BHT = 330 deg F
- SIWHP ranges from 6,500 to 7,100 psig
- Pickup tension from 2,100 to 3,200 lbs
- 20 to 40 ft guns – tool weight = 450 to 600 lbs
- S shape well profiles – requires use of ART
- 3.688” restrictive nipple
- H_2S = average of 5% (Khuff gas wells)
- Limitations of oriented perforating in S shape wells

Justification

- K2 Gas Well - Saudi Aramco standard in 2005

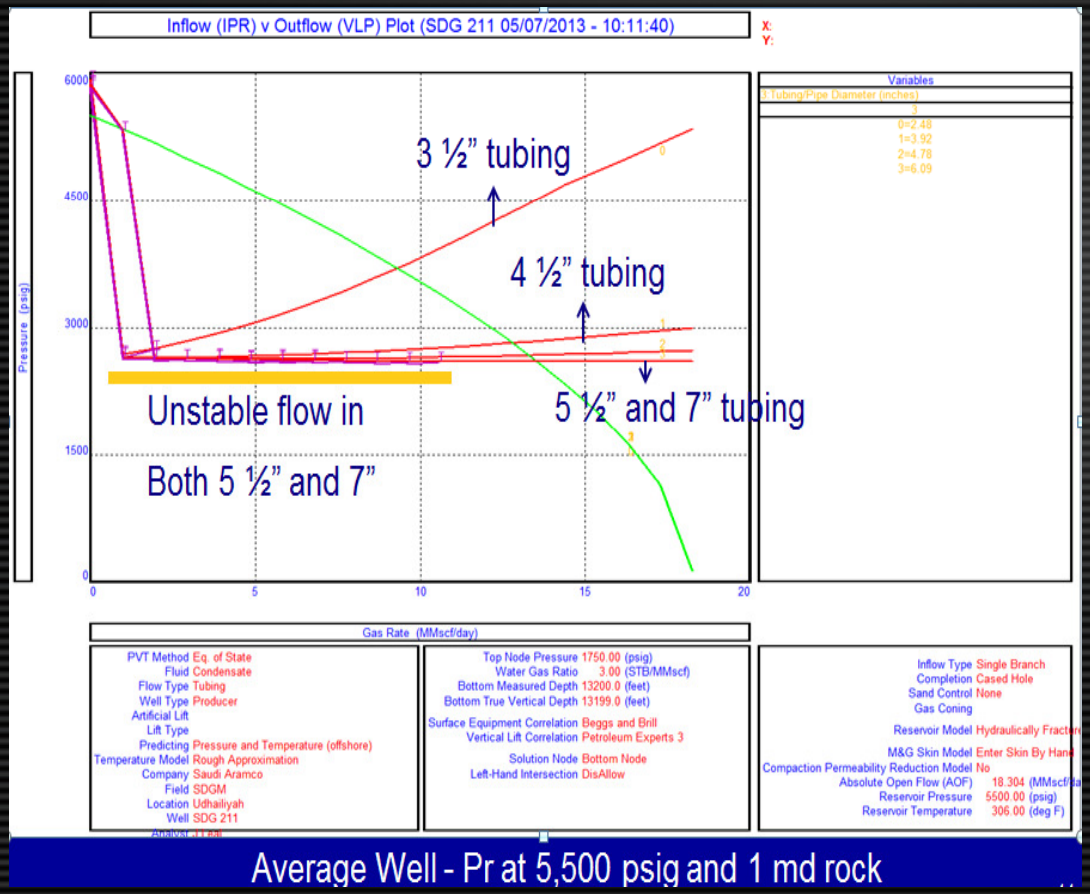


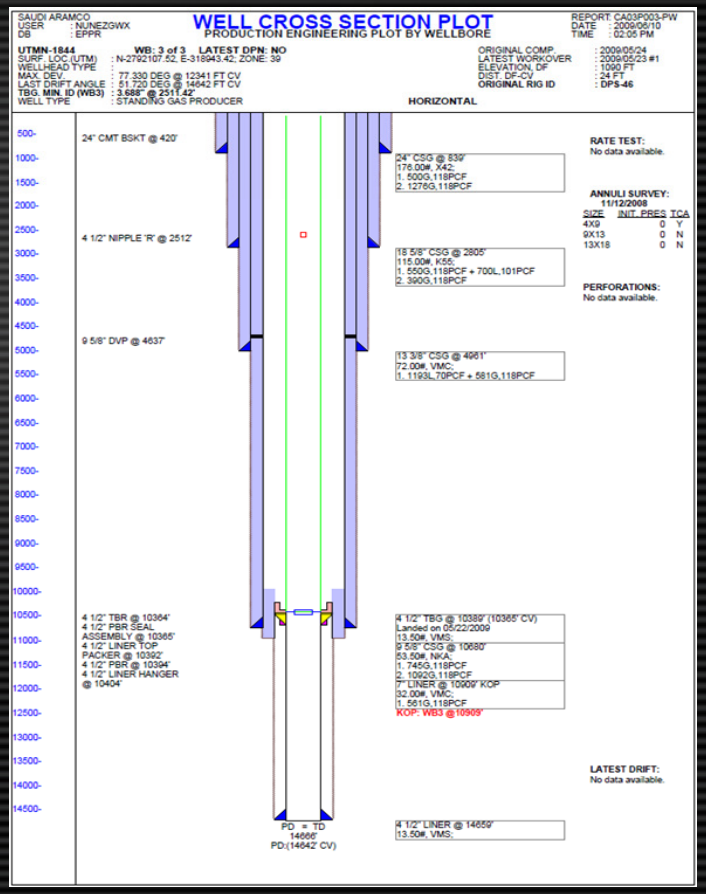
- Main disadvantages - restrictive tubing condition and limited 2-7/8" charge penetration (into 7" liner)

New 4 ½” Monobore Approach (2009)

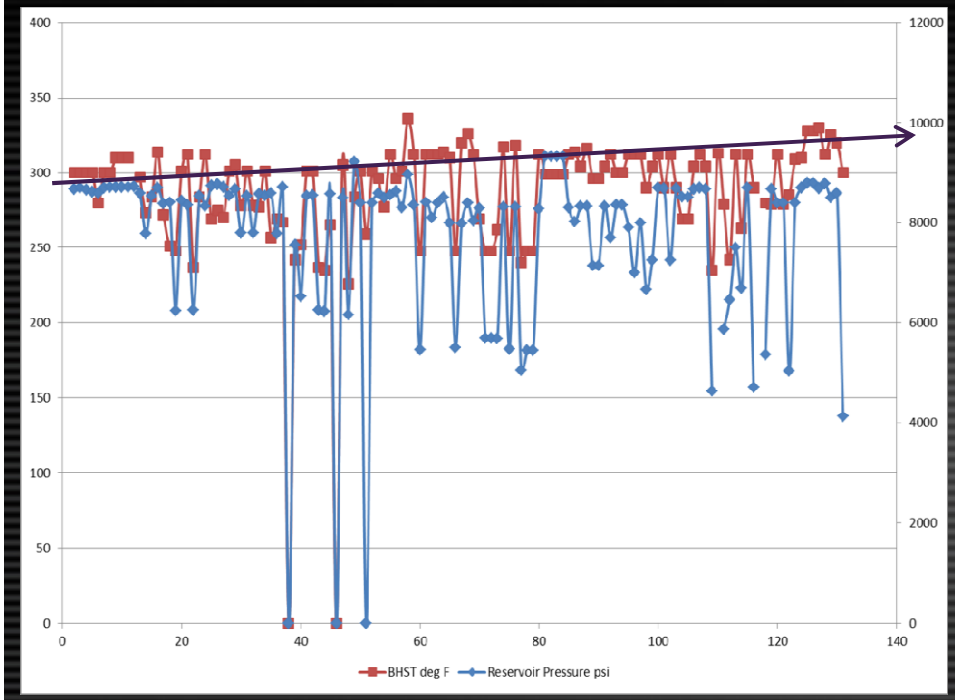
- 4 ½”, 13.5 ppf, high collapse connection (3.688” nipple)
- 4 1/2” monobore completion - 5 to 25 MMSCFD

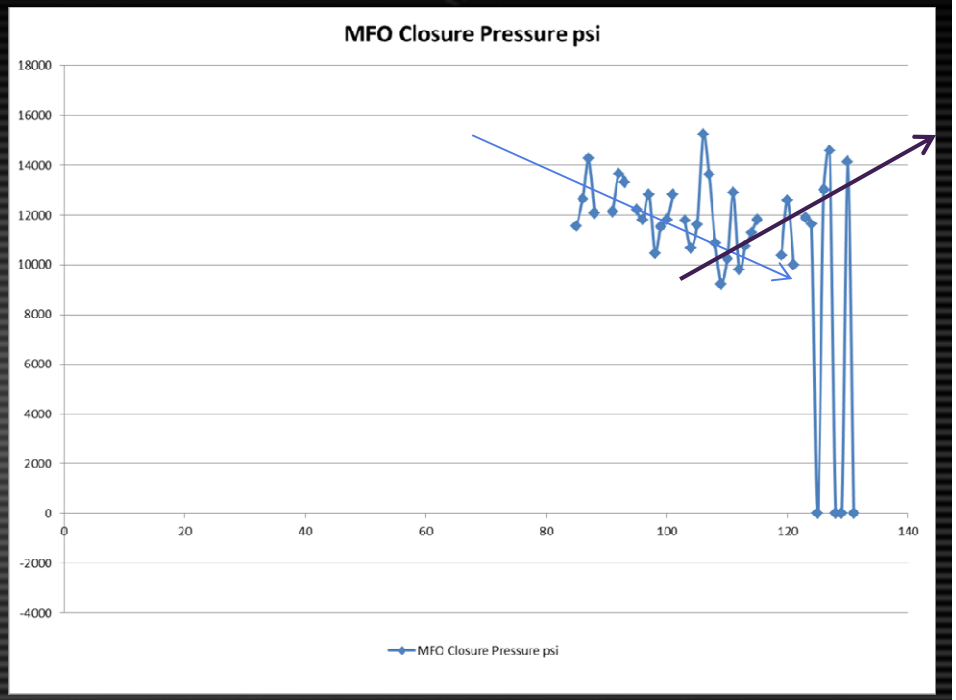
(Saudi Aramco Operative Conditions)





Pre-Khuff Development (past 3 years)





Increasing temp with depth

1.65 deg F/100 ft

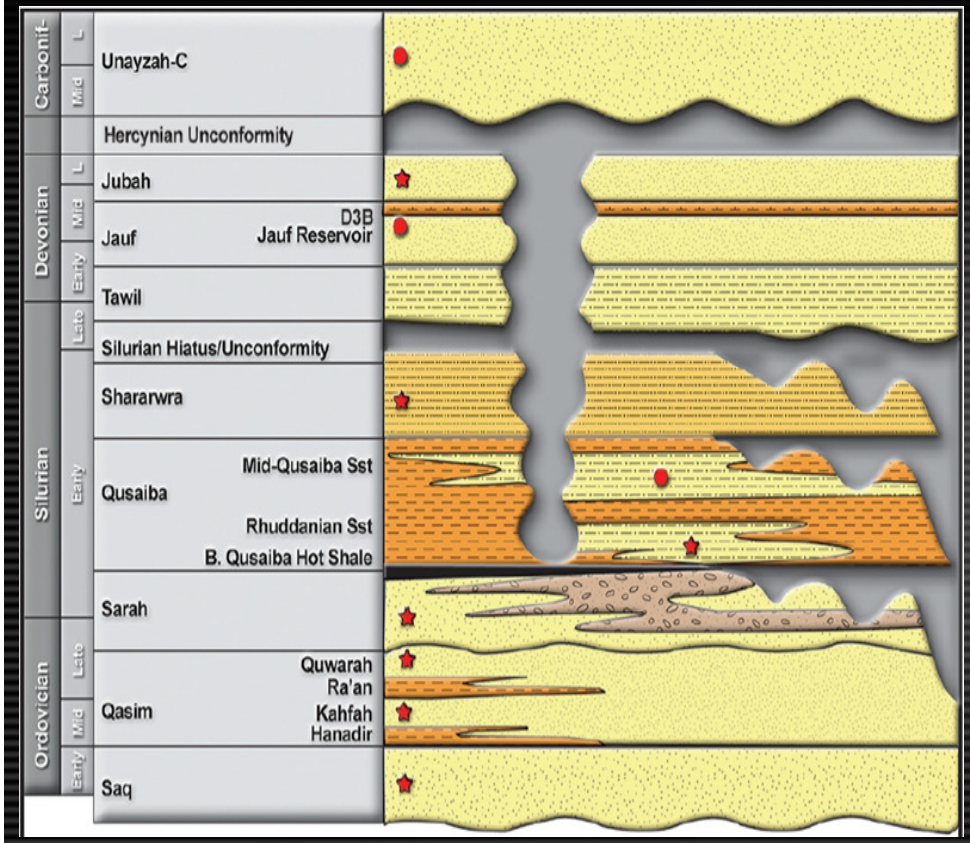
Increased rock stress

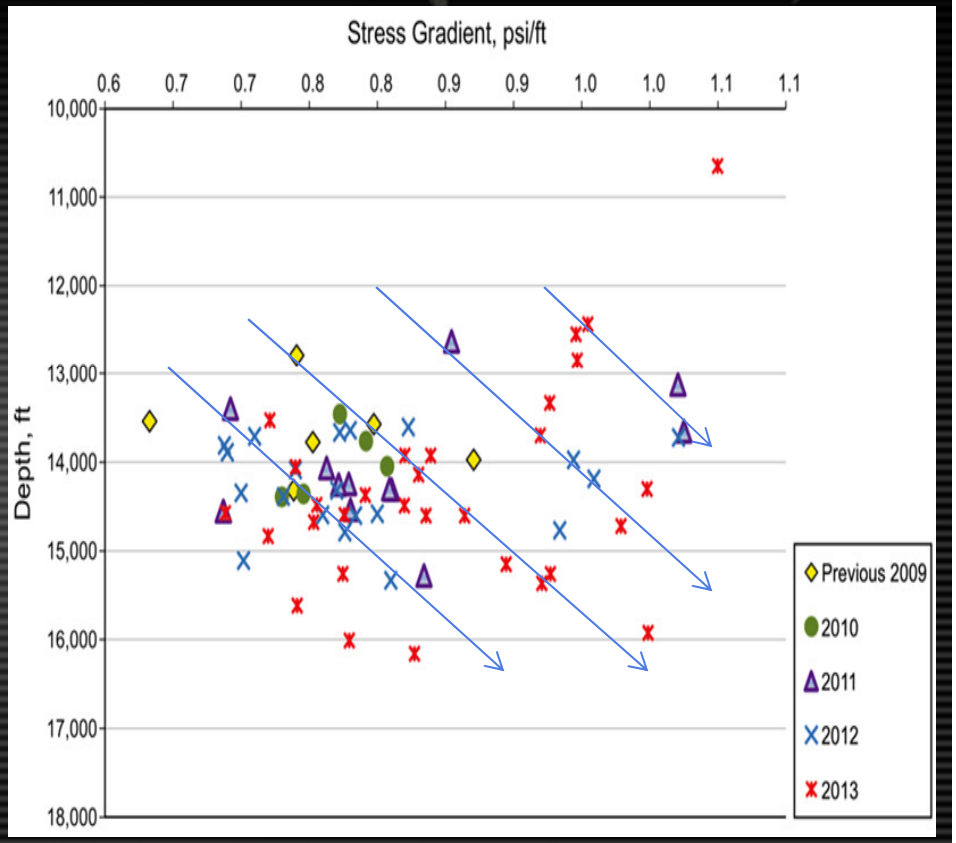
New Pre-Khuff development in Lower Jauf, Sarah, Tawil, Qusaiba Formations

Main Challenge (Increase Gun Size)

- OD changes considering maximum swell
  - max swell - 3.219”, avg 3.19” (hydrostatic pressure > 4500 psi)
  - minimum well restrictions (3.688” nipple profile)
- Increased tool weight
  - wireline strength to move tools at working depth
  - margin for over pull if tools become stuck
- Increased shock via higher weight charges with larger gun
  - maximum gun length
  - successfully used 30 ft guns with 7/32’s and 5/16’s corrosive resistant cables

Main Challenge (New Stress)



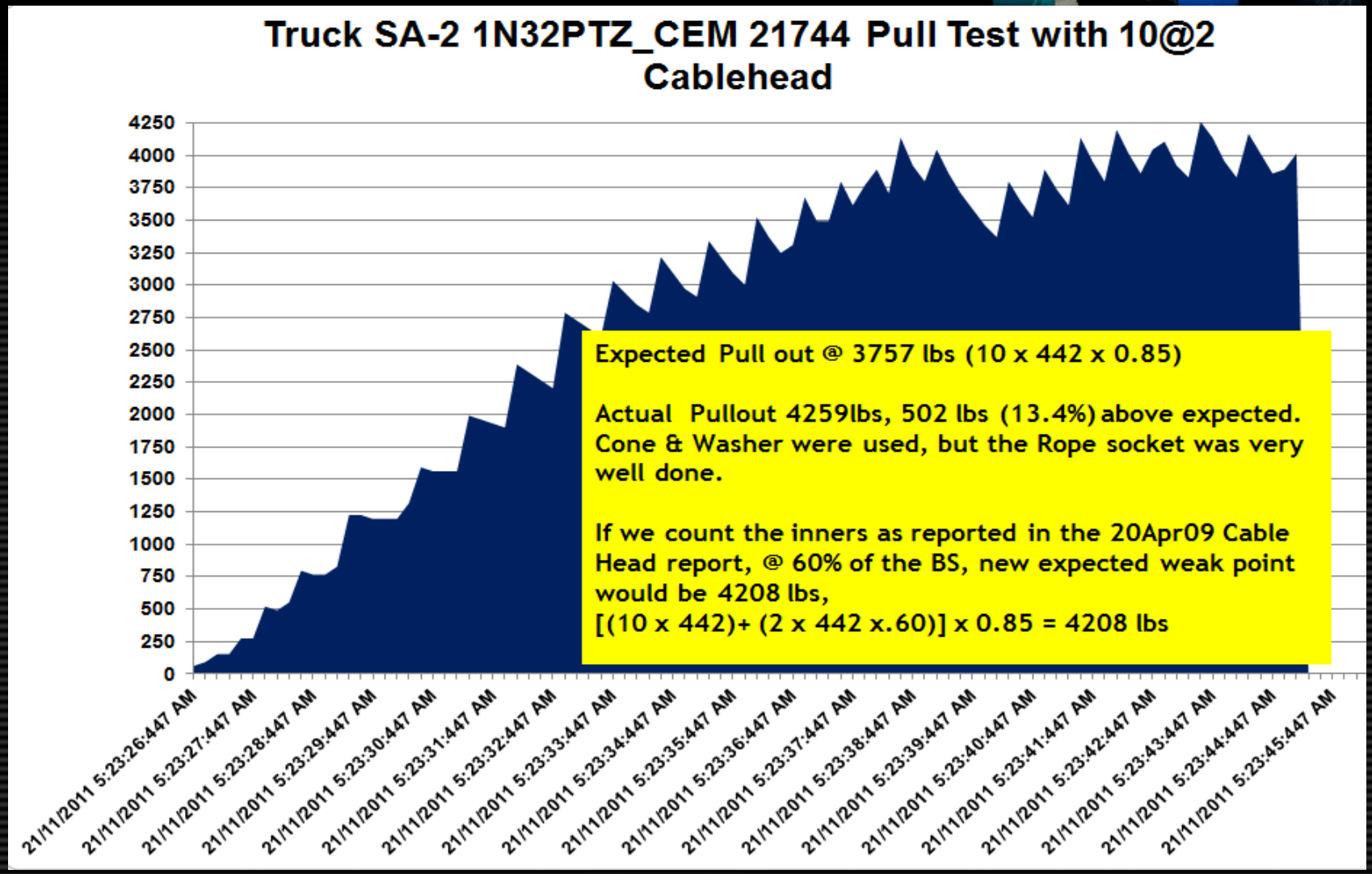


Increased Rock Stress after strike new Pre-Khuff Reservoirs (Tawil, Qusaiba, Sarah)

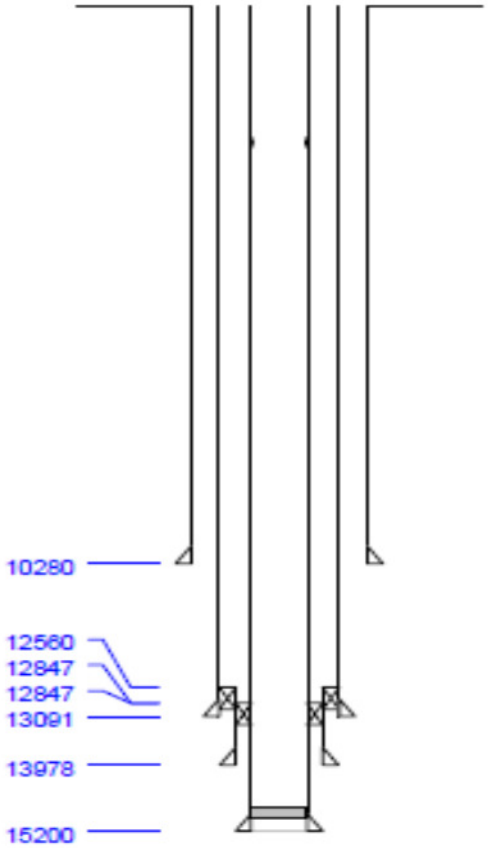
Additional Implications

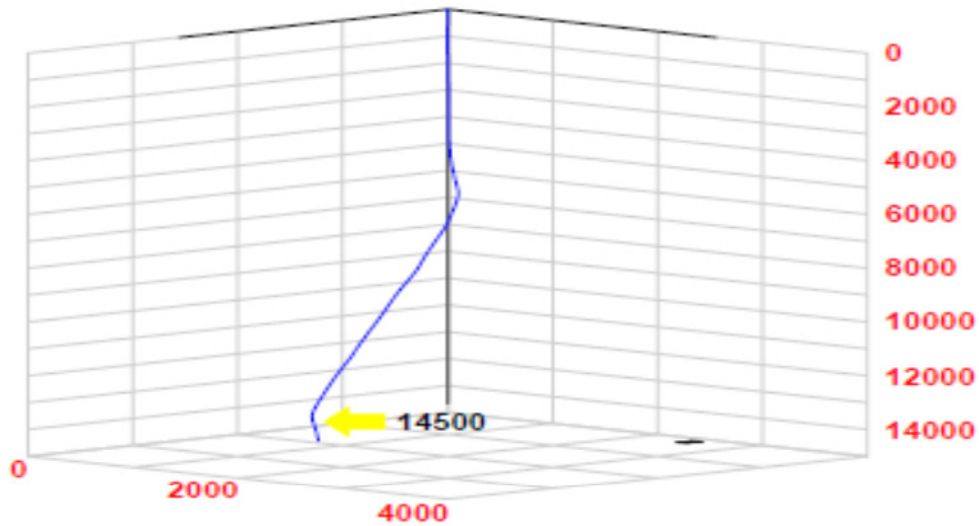
- 1. Hydraulic grease injection
- 2. Cable selection (4800# at 50%)
- 3. Grease selection (winter and summer)
- 4. ART (release tool) – S shape wellbore
- 5. Well modeling (Cerberus)
- 6. Methanol use (hydrates)
- 7. Charges design (for prop frac)
- 8. Stimulation design (rate and pressure)
- 9. Sand control (oriented perforating)

Cable Head Test



Increased Margin with 5/16” Cable



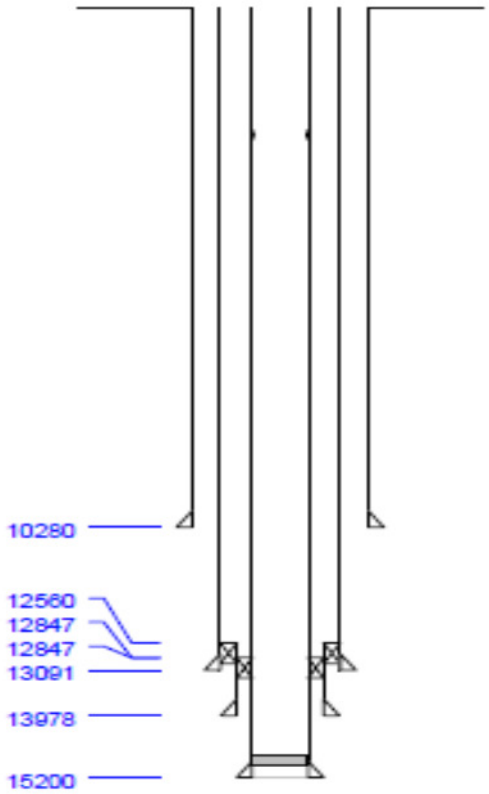


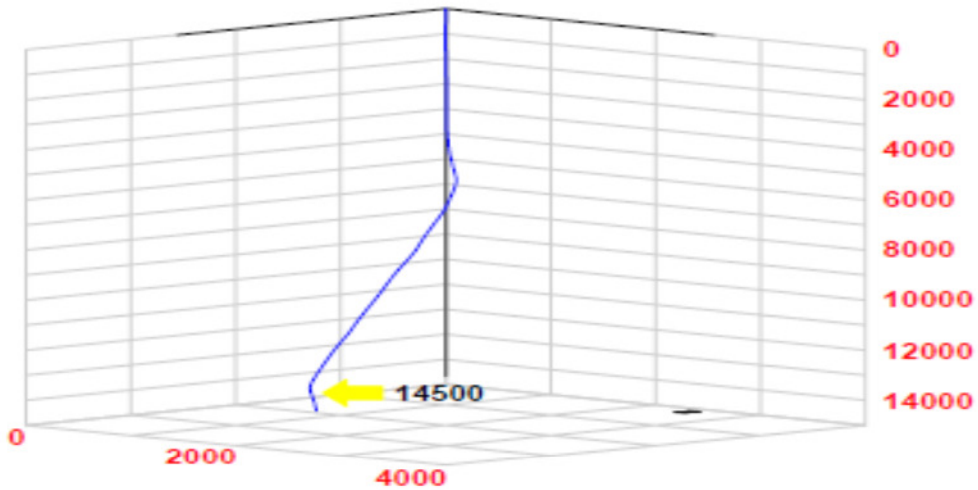
Well name :	Well A
Total depth :	15200 ft
Max inclination :	26.3° at 8716 ft
Max DLS :	36.206 °/100ft at 14900 ft
Min ID :	3.688 in at 2520 ft
WHP :	2500 psi

This maximum overpull (limited by the weak point) is 121% of the toolstring weight in air. The recommended minimum is 150%. The absolute minimum is 75%.

* Job not possible with 7/32’s cable

Increased Margin with Release Tool



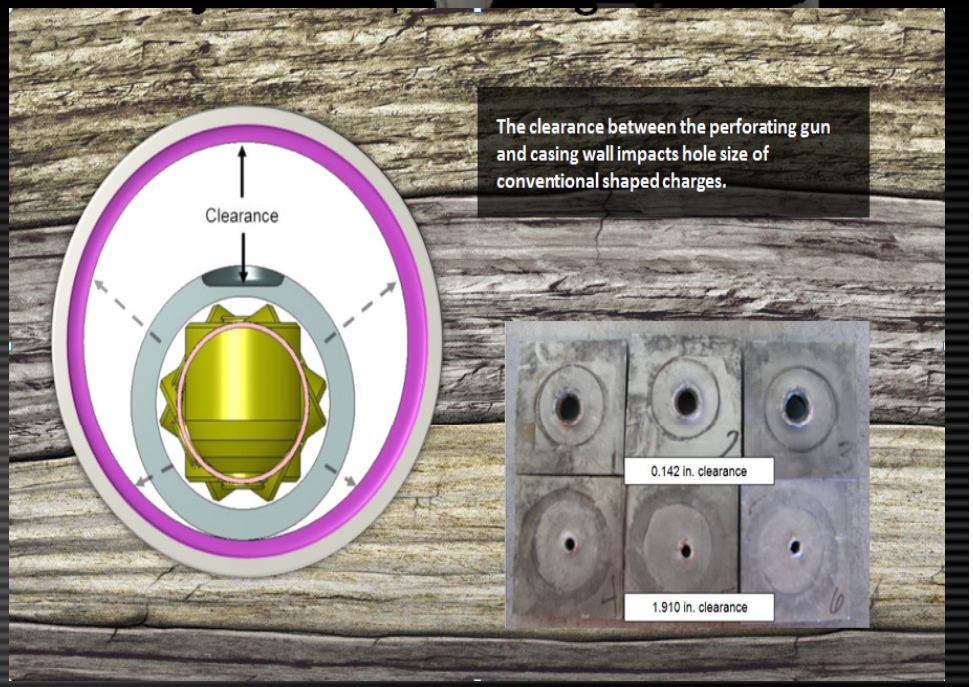


Well name :	Well A
Total depth :	15200 ft
Max inclination :	26.3° at 8716 ft
Max DLS :	36.206 °/100ft at 14900 ft
Min ID :	3.688 in at 2520 ft
WHP :	2500 psi

This maximum overpull is 234% of the toolstring weight in air.
The recommended minimum is 150%. The absolute minimum is 75%.

* Job Performed with 5/16 1N32PTZ-S77 and Addressable Release Tool

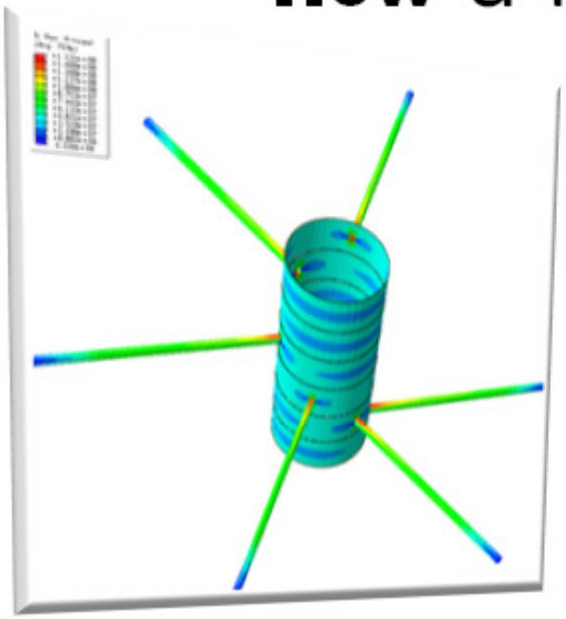
Decision Made for 3 1/8” Engineered Charge

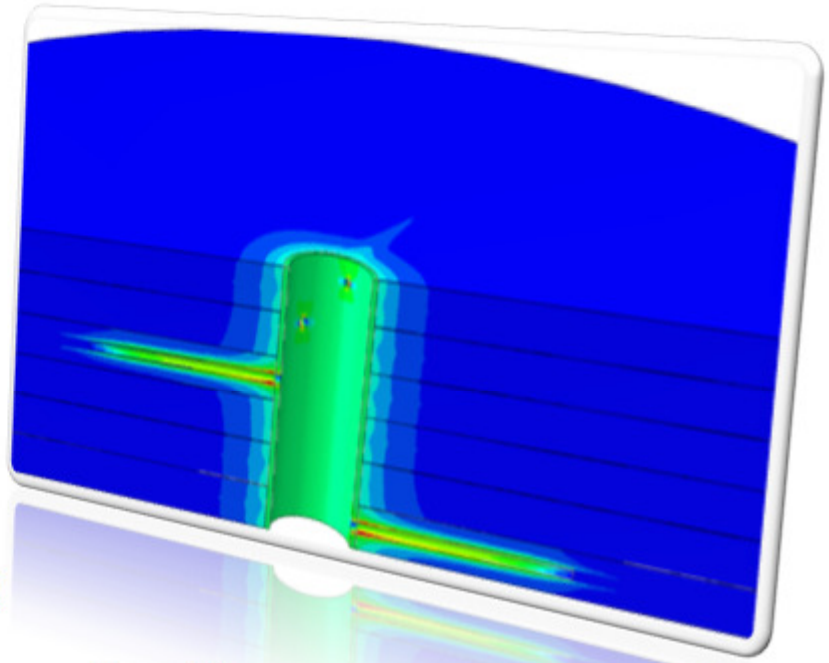


1. Retrievable in 4 ½” tubing and 3.688 R nipple
2. Targeting increased entrance hole size and reduced perforation friction
3. Targeting reduction of breakdown pressure and increased rate
4. Minimize early screen-out
5. Maximize fluid and proppant distribution

Frac Orientation Benefit

How a Frac Charge works.





$\sigma_1 = T_{fail}$

SPE 159085

$\sigma_1 = Kp$

$p_{bd} = T_{fail}/K$

- Larger casing-hole diameter reduces breakdown pressure
- Ensures larger hole-size is in contact with preferred fracture plane
- Contact with fracture plane minimizes near-wellbore tortuosity

Benefits (SRT and SDT – reach 40 BPM)

SDT

Perf and Near-Wellbore Friction - F8

Entry Friction versus Time

	Time (min)	Rate #1 (bpm)	Rate #2 (bpm)	Near-Wellbore Friction (psi)	Perf. Friction (psi)	Perf. Coef. Mult.	Perfs Open (effective)
1	248.48	22.32	0.00	559	3036.84	328.37	4.41
2	0.00	0.00	0.00	0	0.00	1.00	0.00
3	0.00	0.00	0.00	0	0.00	1.00	0.00
4	0.00	0.00	0.00	0	0.00	1.00	0.00
5	0.00	0.00	0.00	0	0.00	1.00	0.00
6	0.00	0.00	0.00	0	0.00	1.00	0.00
7	0.00	0.00	0.00	0	0.00	1.00	0.00
8	0.00	0.00	0.00	0	0.00	1.00	0.00

Perforation Data

	Top MD (ft)	Bot MD (ft)	# Perfs	Diam (in)
1	14,385	14,390	80	0.400
2	14,510	14,515	80	0.400
3	14,680	14,685	80	0.400
4	0	0	0	0.000
5	0	0	0	0.000
6	0	0	0	0.000
7	0	0	0	0.000
8	0	0	0	0.000
9	0	0	0	0.000

Perforation Pressure Drop Model: Default Fracpro Model

Use Cramer's Perf Erosion Model

Wellbore Friction
Fluid: SH20
Friction Multiplier: 0.50

Rate Step-Down Test Analyser

Previous Test | Curr Test: 1 | Next Test

	Time (min)	Rate #1 (bpm)	Rate #2 (bpm)	Change in Friction (psi)
1	248.20	22.31	17.28	407
2	248.42	17.27	12.19	1,423
3	248.63	12.19	7.13	1,167
4	248.76	7.14	0.00	600
5	0.00	0.00	0.00	0

Note: Flow rate needs to go all the way to zero.

Display Step-Down Plot | New Step-Down Analysis

Step-Down Friction Analysis

	Estimated Value
Total Friction Power B	1.55
Total Friction Coeff K	32.19
Perf Friction Coeff K	6.10
NWB Friction Coeff K	118.34
Effective Perfs Open	4.41
Perf Friction (psi)	3,037
NWB Friction (psi)	559
Max Flow Rate (bpm)	22.32

Display Step-Down Results Plot

Next

reatment #1 | Fracture Analysis

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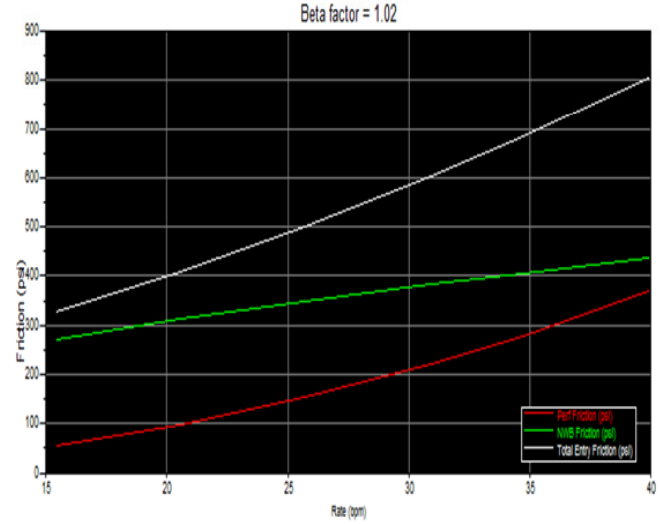
Total Frict = 5,189 psi.
Perf Frict = 3,037 psi.
NW Frict = 559 psi

Step Down Analysis Results

Effective Perfs:	34.60	Beta Factor:	1.02
Pipe Friction, psi:	2231	Entry Friction, psi:	804
Perf Friction, psi:	368	NWB Friction, psi:	436
Entry Coeff:	18.39	Perf Coeff:	0.23
NWB Coeff:	68.95		

Step	Rate (bpm)	Pressure (psi)	Pipe Frict (psi)	Entry Frict (psi)	Perf Frict (psi)	NWB Frict (psi)
1	39.93	10148	2231	804	368	436
2	34.73	9539	1744	685	278	406
3	30.92	9137	1411	604	221	383
4	25.70	8646	995	502	152	350
5	20.56	8190	654	410	98	313
6	15.41	7793	379	325	55	271

Pressure vs Rate
Beta factor = 1.02



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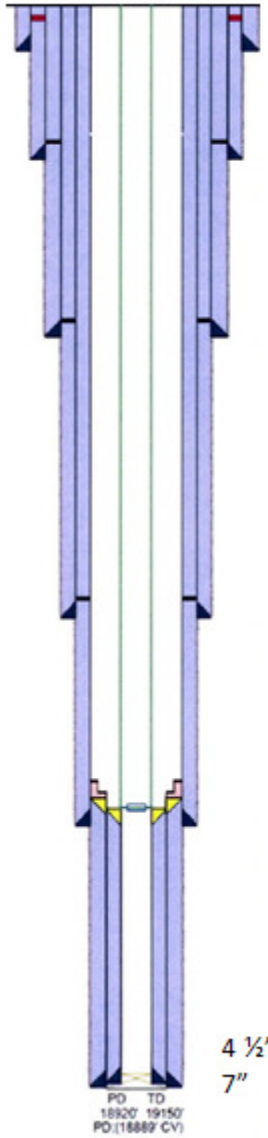
Before – 24 BPM

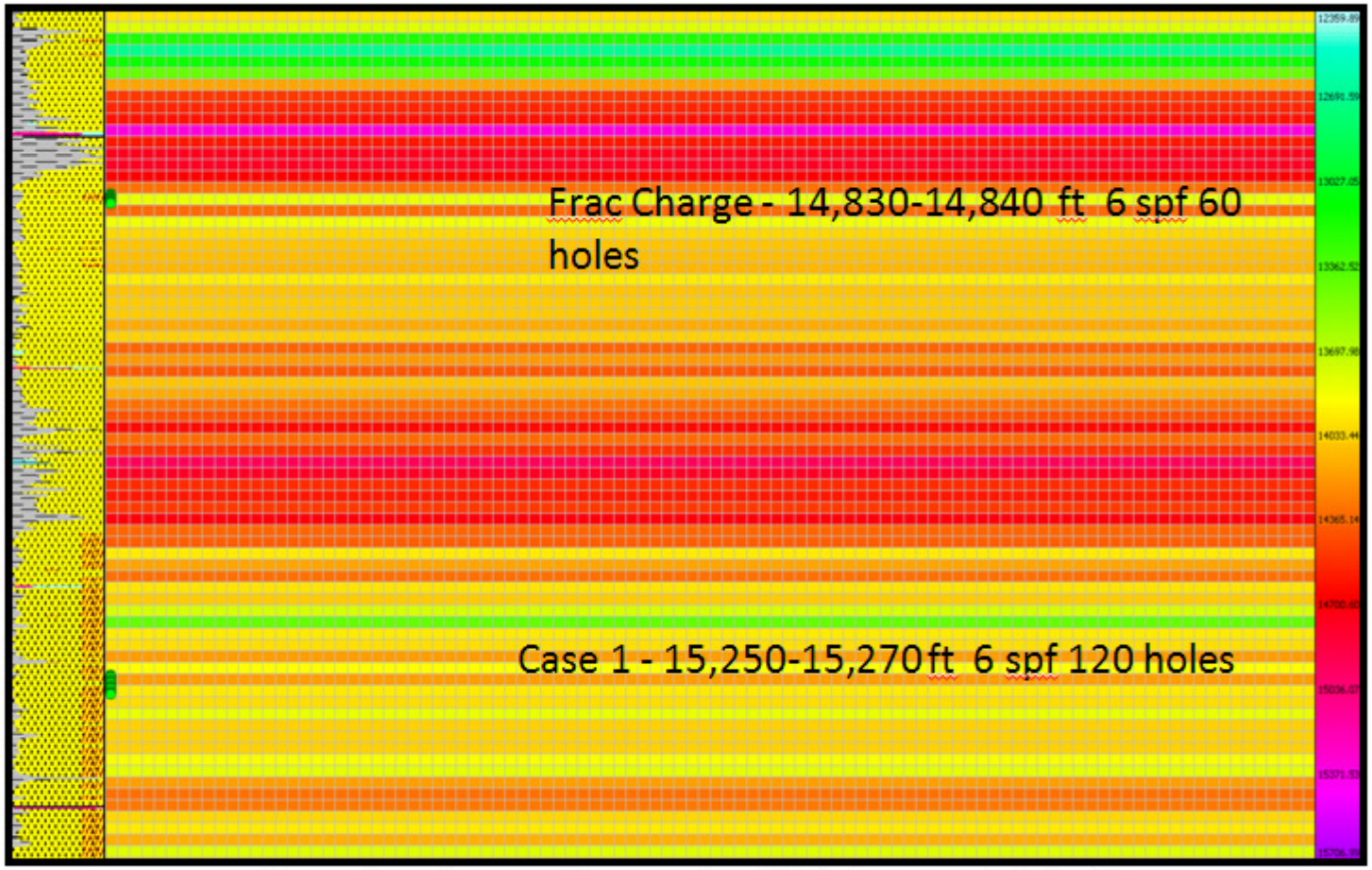
After – reach 40 BPM

Case Study (Pre-Khuff Evaluation)



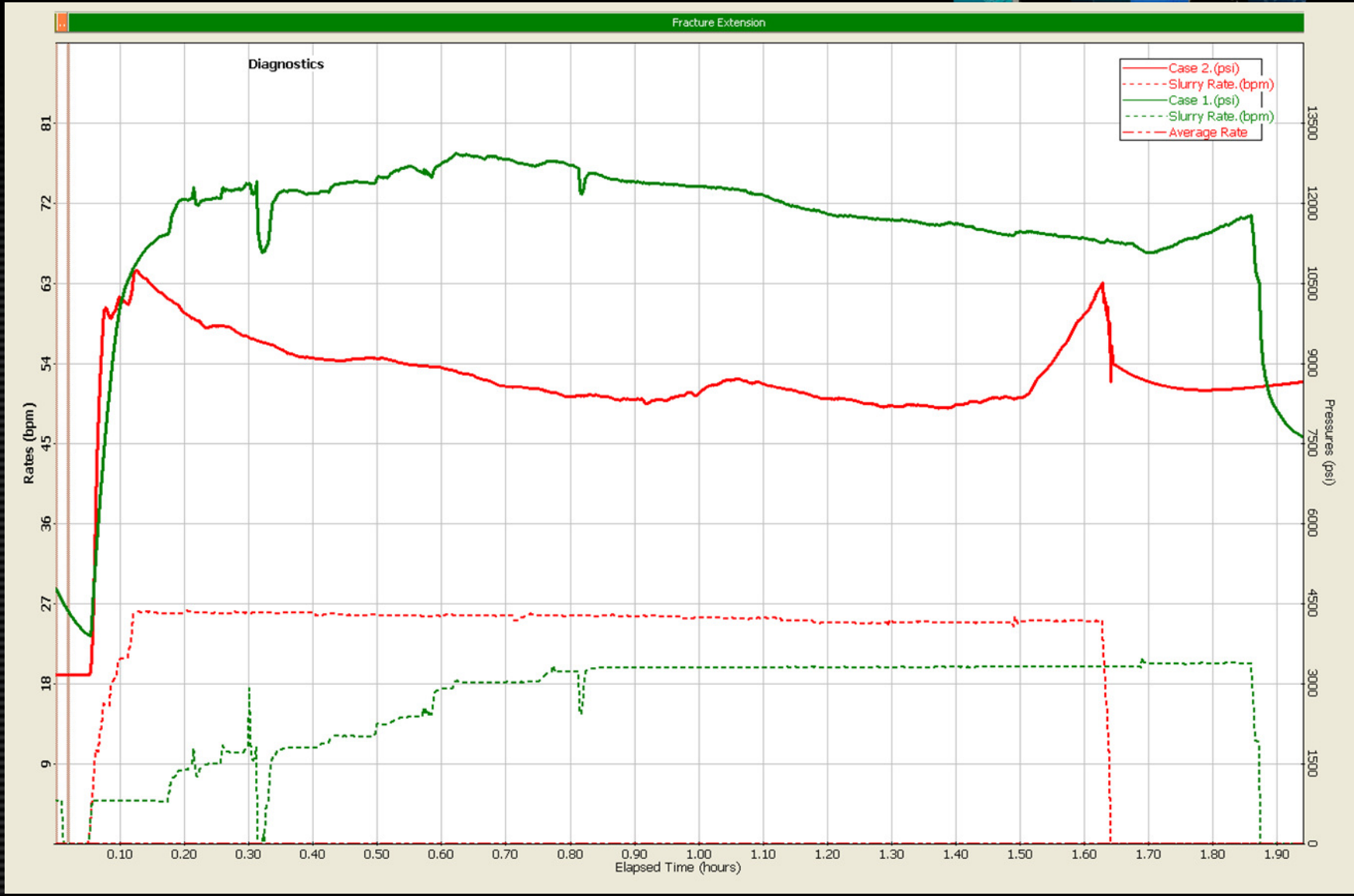
4 ½" Liner 15.20# Q12
7" Liner 35.0 # Q12

Stresses Distribution Grid

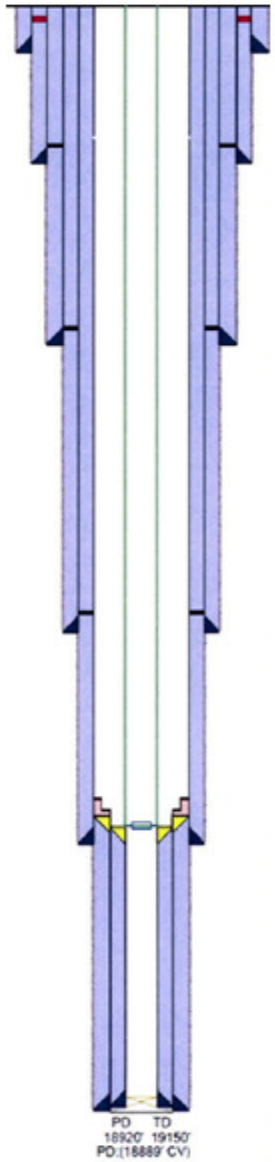


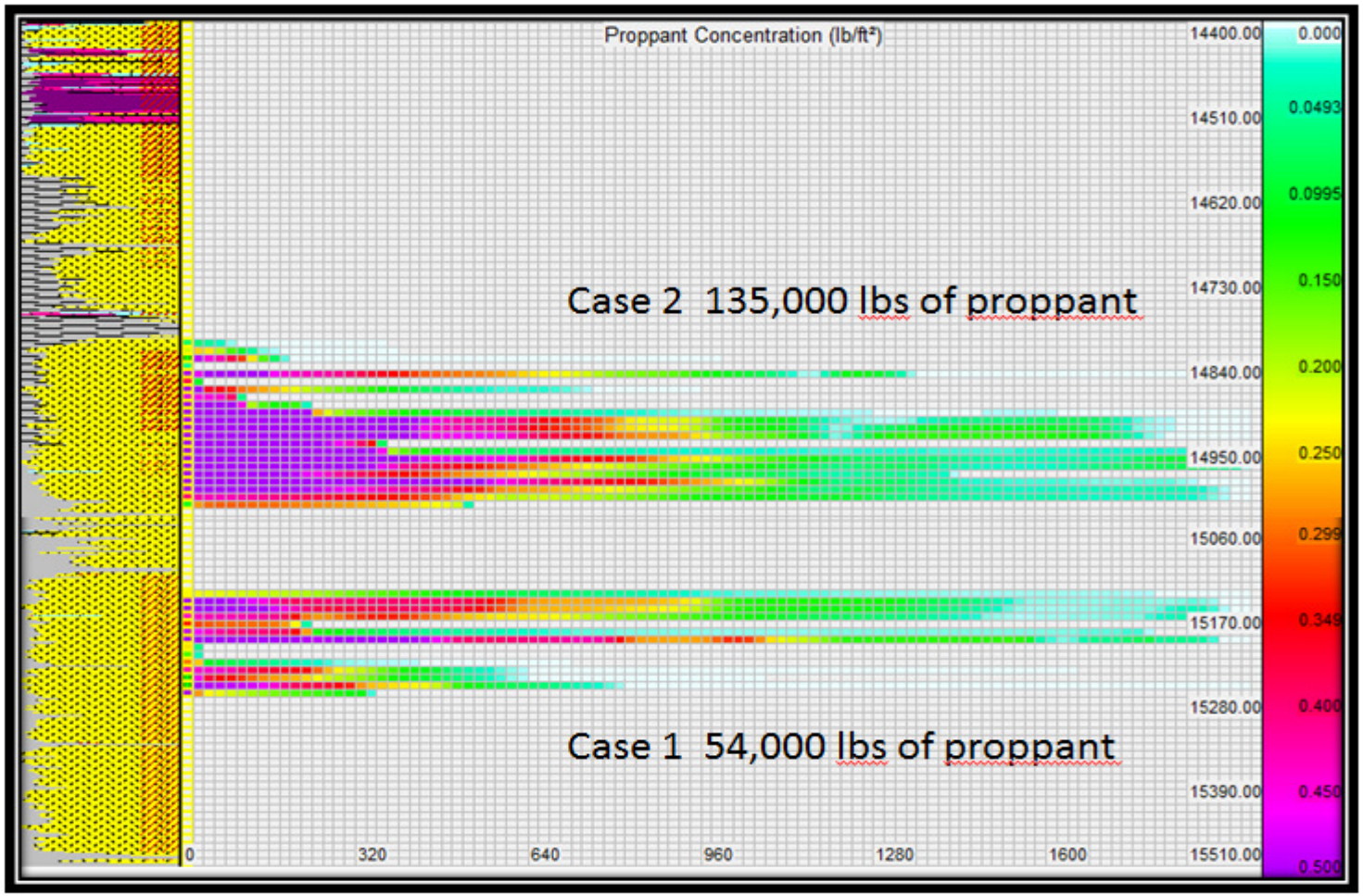
Deep Sandstone Formation High Stresses Tight Gas
First Interval perforated with a 3 3/8" Deep Penetration
Second Interval perforated with the Engineered Charge

Comparing Results – Proppant Frac



Comparing Results – Frac Placement

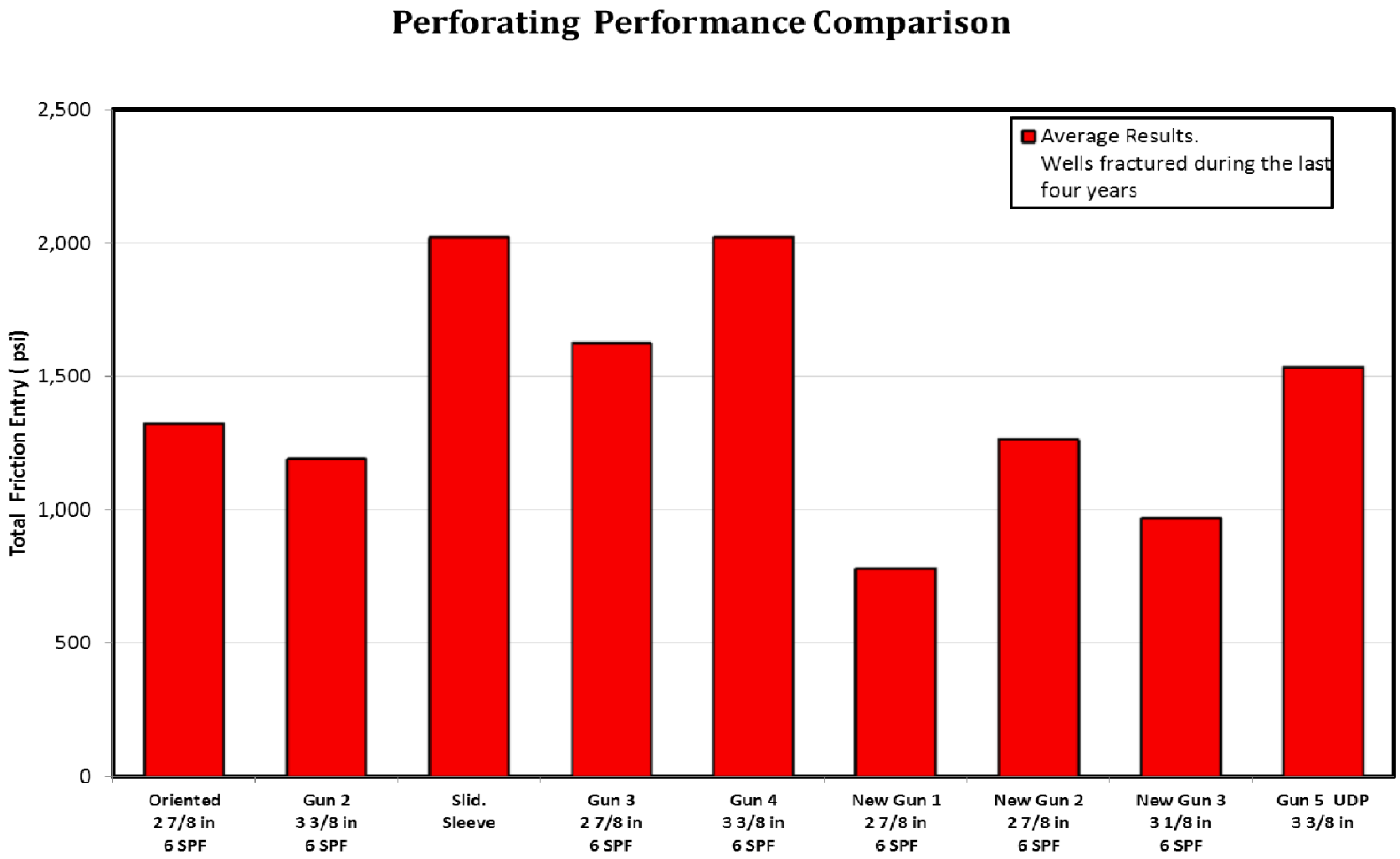




4 ½" Liner 15.20# Q12

7" Liner 35.0 # Q12

Comparing Results – Gun Performance



Conclusions

1. Successful implementation for 3 1/8” Engineered Charge for consistent entry hole approach with 4 ½” monobore
2. Reduction of treating pressures ranging from 800 to 1,100 psig
3. Increased injection rate – avg 6 BPM, 36 BPM (normalized 30 ft)
4. Average NWB friction values are lower than other perforating methods resulting in reduced likelihood of early screen-out
5. No operational issue while deploying/retrieving 3 1/8” spent gun


Thank You