Advanced Modeling of Perforating System Performance

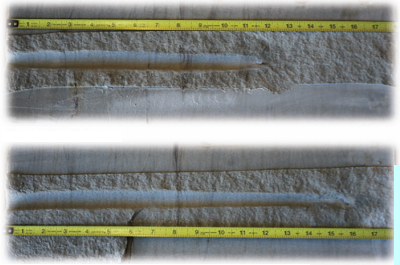
Brenden Grove, Jeremy Harvey, Lang Zhan, Carlos Bauman, Andy Martin

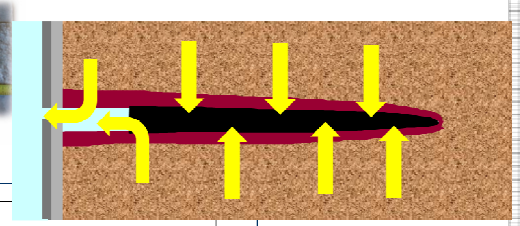
Schlumberger

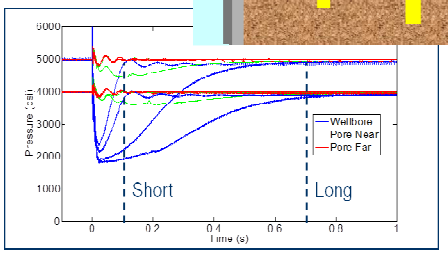
Advanced Modeling of Perforating System Performance

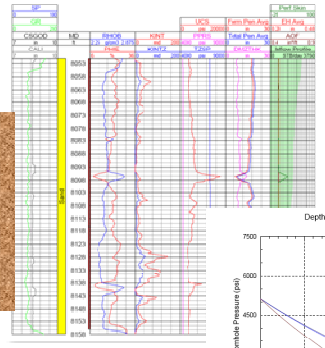
Why Perforate?

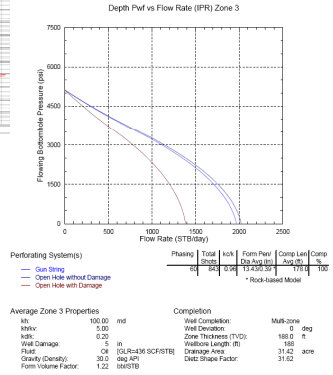
- Penetration
- Cleanup
- Inflow Performance
- Gun Shock



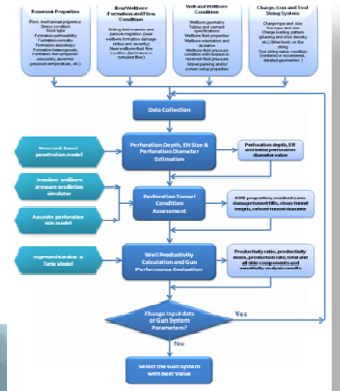


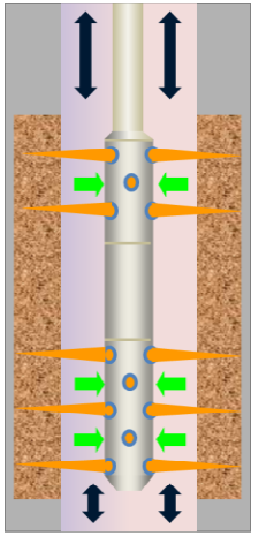






Integrated Workflow for Job Design



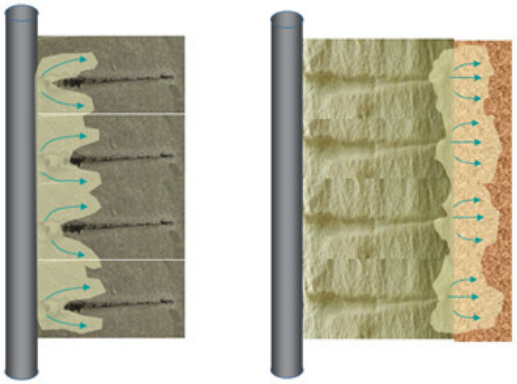


Why Perforate?

- Perforating is a fundamental part of any well completion
- It provides the connection between wellbore and virgin reservoir rock
- It provides the conduit for processes such as hydraulic fracturing or acid stimulation
- The success of a gravel pack completion strongly depends on perforating parameters

Perforating Connects Wellbore to Virgin Reservoir

Matrix Acid Treatment

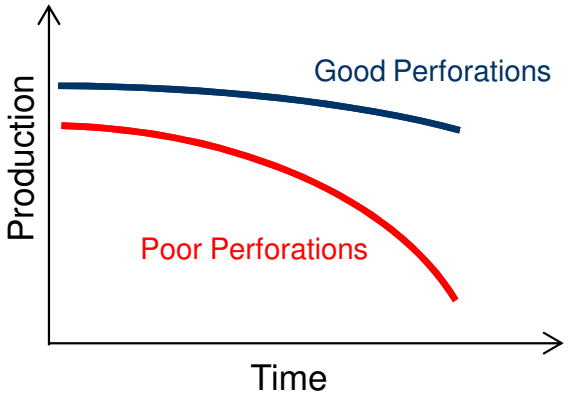


Bad Perforations vs Good Perforations

Additional Benefits of Good Perforating Practices

- Operational efficiency improves such as reduced cleanup periods during a well test or reduced N_2 or completion fluid requirements to fire guns
- Deep, clean perforations prolong the life of a well by reducing near-wellbore pressure drop
- High pressure drop leads to many well problems: scale and aspheltene buildup, fines migration or condensate banking, water coning or production below bubble point

Scale Deposit

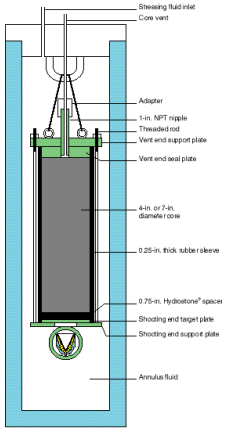


Modeling a Perforated Completion – 4 Stages

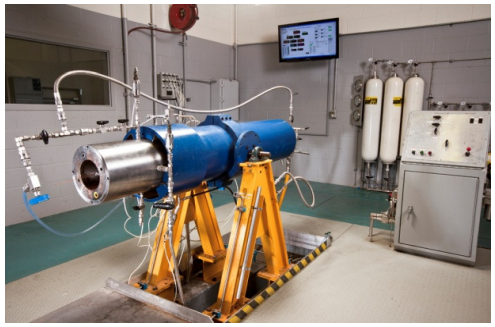
- Stage 1: Gathering Data
- Stage 2: Perforation Tunnel Geometry Estimation
- Stage 3: Perforation Tunnel Condition
- Stage 4: Inflow Performance Estimation
- Stage 5: Wellbore & Completion Effects

How Do We Choose the Best?

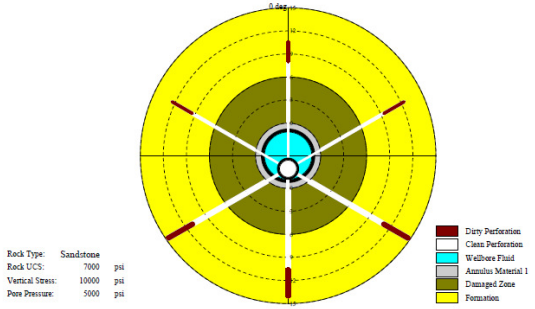
- Section 2 Penetration Tests in Stressed Rock



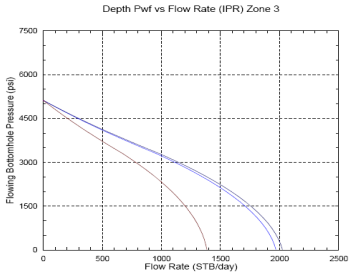
- Section 4 Flow Efficiency Tests in Stressed Rock



- Model



Angle (deg)	Clearance (in)	Total Pen * (in)	Form Pen * (in)	Form Dia (in)	Cag EH Dia (in)
0	3.38	11.69	10.53	0.41	0.20
60	2.17	13.88	12.72	0.49	0.23
120	0.48	16.11	14.96	0.84	0.40
180	0.00	15.10	13.95	0.76	0.36
240	0.48	16.11	14.96	0.84	0.40
300	2.17	13.88	12.72	0.49	0.23
Average	1.45	14.46	13.30	0.65	0.31
				AOF (in2/ft)	0.43844 at 6.00 spf



Perforating System(s)
- Gun String
- Open Hole without Damage
- Open Hole with Damage

Phasing	Total Shots	kc/k	Form Pen/ Dia Avg (in)	Comp Len Avg (ft)	Comp %
60	843	0.98	13.43/0.39 *	178.0	100

* Rock-based Model

Average Zone 3 Properties

kh:	100.00	md
kh/kv:	5.00	
kd/k:	0.20	
Well Damage:	5	in
Fluid:	Oil	[GLR=436 SCF/STB]
Gravity (Density):	30.0	deg API
Form Volume Factor:	1.22	bbl/STB

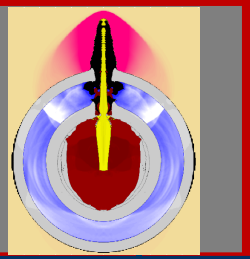
Completion

Well Completion:	Multi-zone	
Well Deviation:	0	deg
Zone Thickness (TVD):	188.0	ft
Wellbore Length: (ft)	188	
Drainage Area:	31.42	acre
Dietz Shape Factor:	31.62	

Perforation Time Scales

Charge detonation

Perforation tunnel (& initial damage) created



10^{-7} 10^{-6} 10^{-5} 10^{-4}

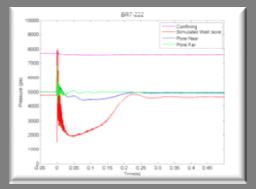
Jet Formation

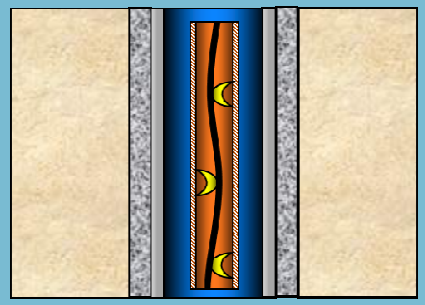
Pressure inside the gun varies widely, in both time and space (shocks subsiding, gun internal pressure decaying and reaching spatial equilibrium)

Gun-wellbore-formation interactions

Wellbore dynamics

Perforation cleanup





Time (sec)

10^{-2} 10^{-1} 10^{0} 10^{1} 10^{2}

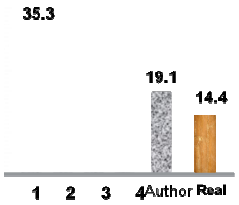
Reservoir response

Fluid column response

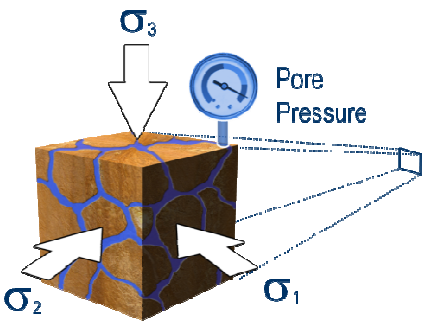
Hardware & completion response

gun internal has reached spatial equilibrium, begins to "see" and interact with wellbore

Road to a Comprehensive Rock-Based Penetration Model



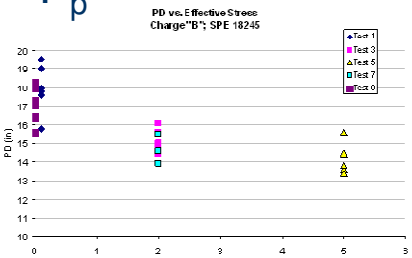
- Getting Away from Concrete
- >1,000 Experiments in Stressed Rock
- Formation effects
  - Weak to strong rocks tested
  - Largest ever range of stresses: 1,000 to 20,000 psi (~70 to 1,400 bar)
  - Pore pressure influence
  - Range of rock types
- Charge effects
  - Different families of charges used
  - Carrier and capsule charges



From *Effective* stress to *Ballistic* stress

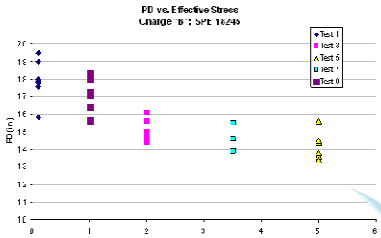
DoP=f(effective stress)

$P_{eff} = P_c - P_p$



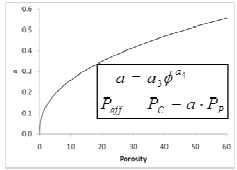
Ballistic pore pressure coefficient (bppc) "a"

$P_{ball}=P_c-\underline{a}\times P_p$; a~0.5



DoP=f(ballistic stress)

bppc is a rock property



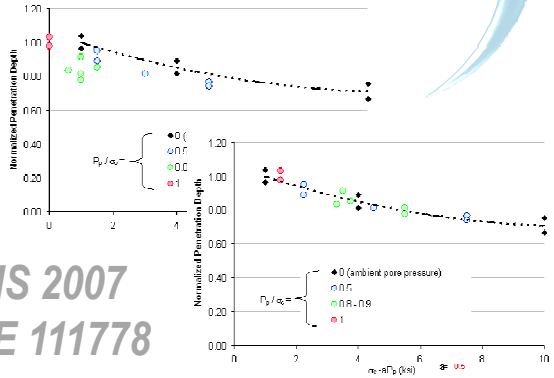
•*SPE 151846*

1980

2000

1990

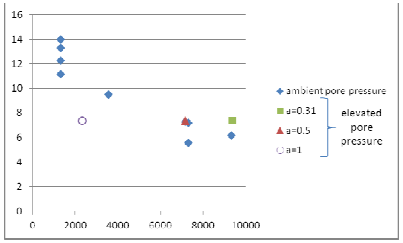
2010



•*HVIS 2007*

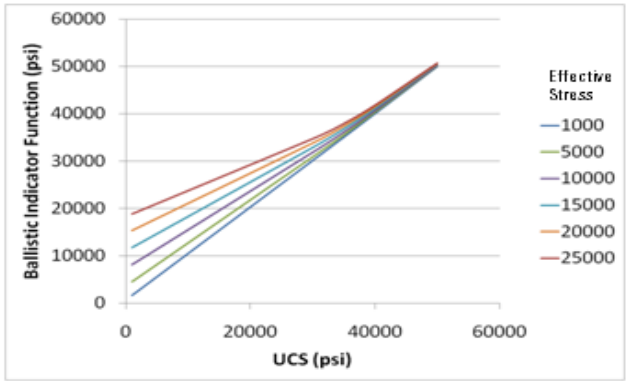
•*SPE 111778*

Confirmed at higher stresses

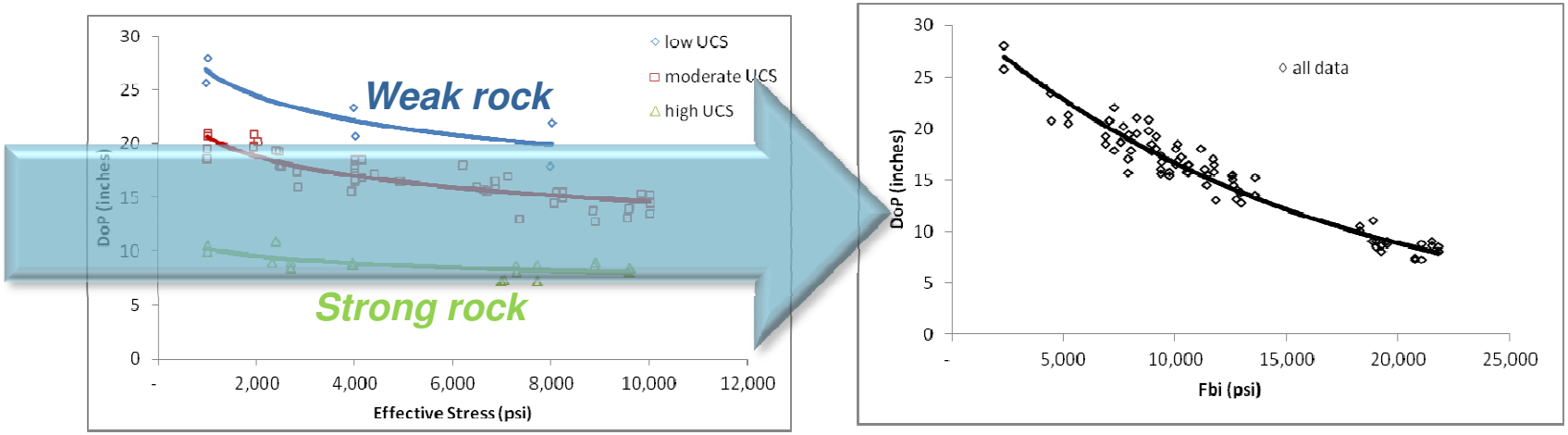


Single Formation Parameter: *Ballistic Indicator Function*

- Formation characterized by a single term
  - F_{bi} combines UCS and ballistic stress
- High UCS rocks have less dependence on stress



$$F_{BI} = UCS + F_1 P_{eff}$$

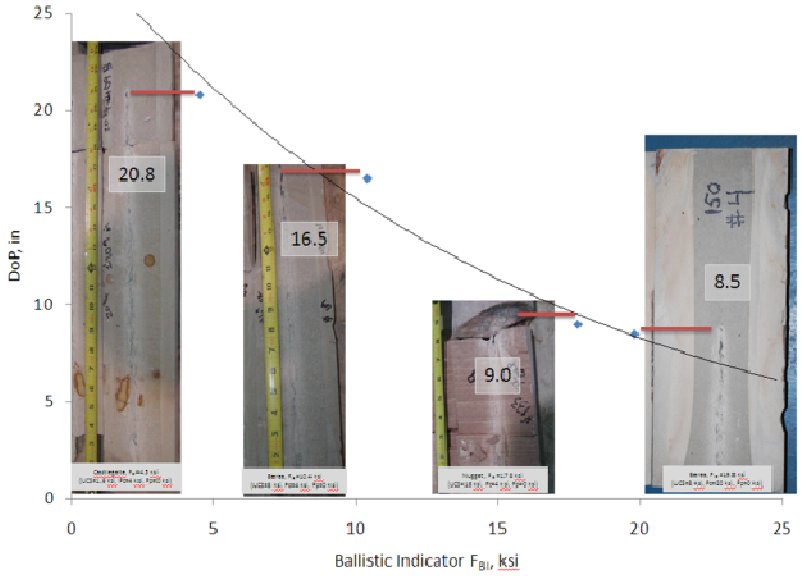


Before Fbi: Multiple performance curves for single charge

With Fbi: collapse to a single curve

Penetration Model – Formation Effects

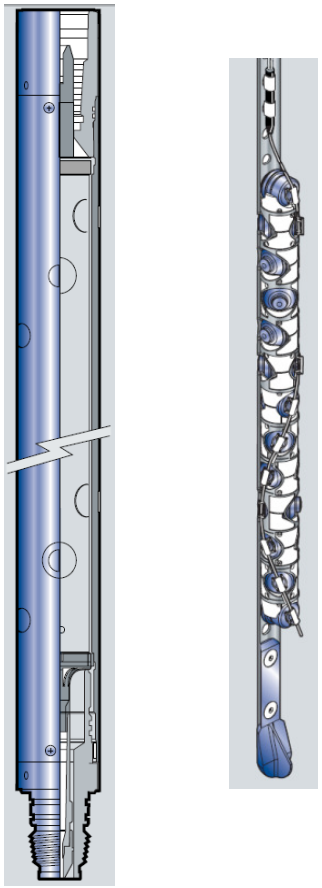
- Penetration decreases exponentially with increasing Fbi



$$DoP = DoP_{ref} e^{\alpha_0 (F_{bi,ref} - F_{bi})}$$

Universal behavior

- Carrier & capsule systems
- 2” to 4-1/2” gun sizes



Penetration Model – Charge Effects

- Significance of having two parameters
  - 1st parameter (DoP_{ref}), gives general indication of how "high" the curve is
  - 2nd parameter (α_0) is related to charge optimization (i.e. for "hard" vs. for "soft" targets)

$$DoP = DoP_{ref} e^{\alpha_0 (F_{bi,ref} - F_{bi})}$$

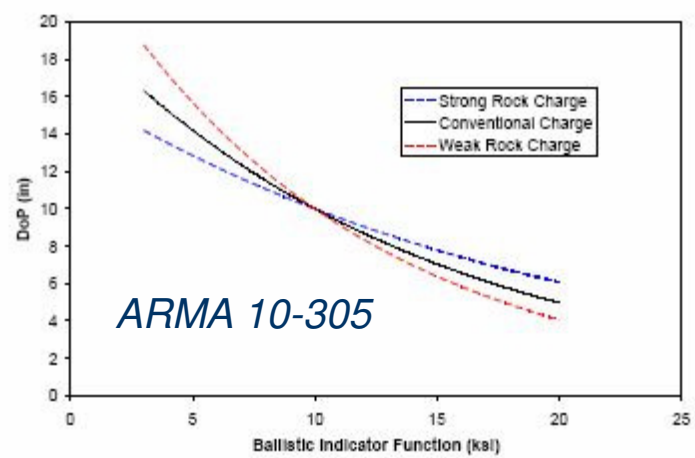
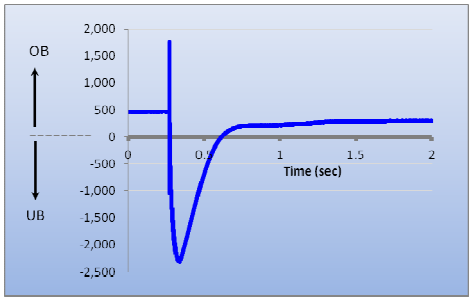


Figure 10 – Implications of charge optimization

Road to a Dynamic Underbalance Perforation Cleanup Model

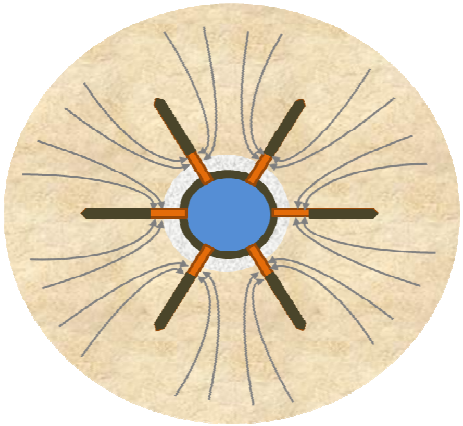
- Static UB known since at least early 1950's
  - Used successfully (though not always with consistent results) for 5-6 decades
  - First cleanup models not until 1980's
- Dynamic UB phenomena reported 2001
  - Extensively proven effective in field (multiple environments)
  - Additional laboratory studies through mid-2000s to better understand the physics
  - Extensive laboratory program launched late 2000's



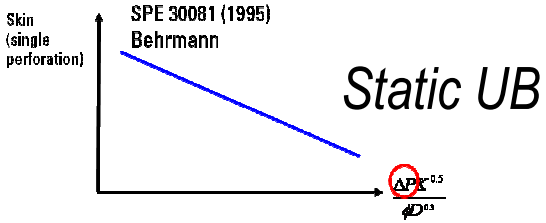
Much more complicated than penetration

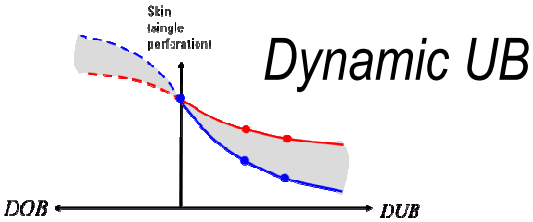
Dynamic Underbalance Cleanup More Complicated Than Penetration Depth

- Perforation cleanup deals with at least 2 main elements
  - How efficiently does perf flow? (Q/dP)
  - Where does flow come from?



- DUB perforation cleanup is dictated by
  - Wellbore pressure transients *
  - Formation properties



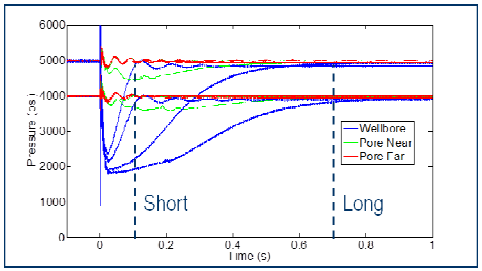


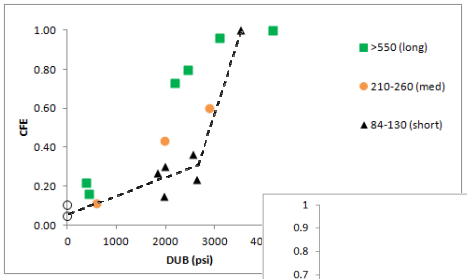
•*Multiple parameters (magnitude, recovery duration, rate)*
•*Understanding & controlling wellbore pressure transients*

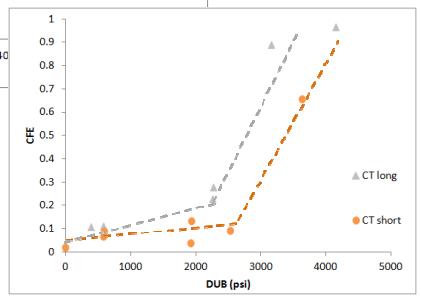
Dynamic Underbalance Perforation Cleanup Model

Status

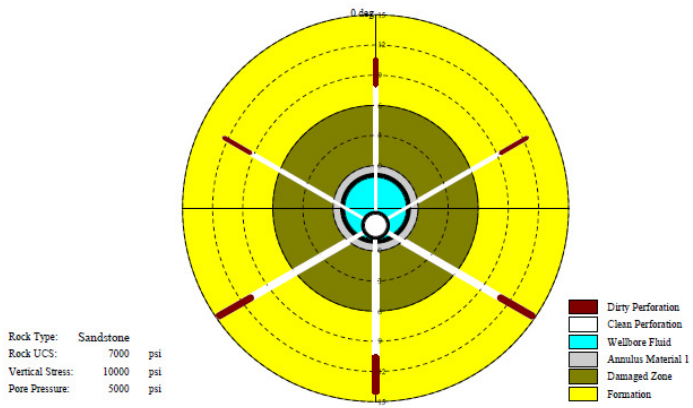
- Model developed
- Considers wellbore pressure transients and formation properties
- Implemented into inflow simulator







EWAPS 12-8



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Average	1.45	14.46	13.30	0.65	0.31
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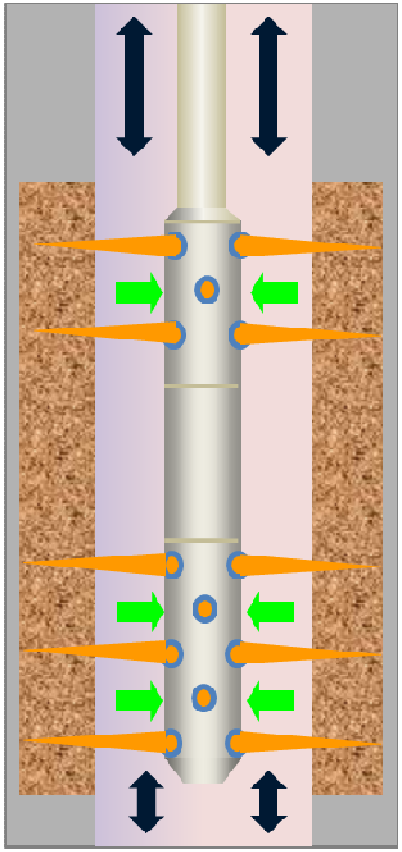
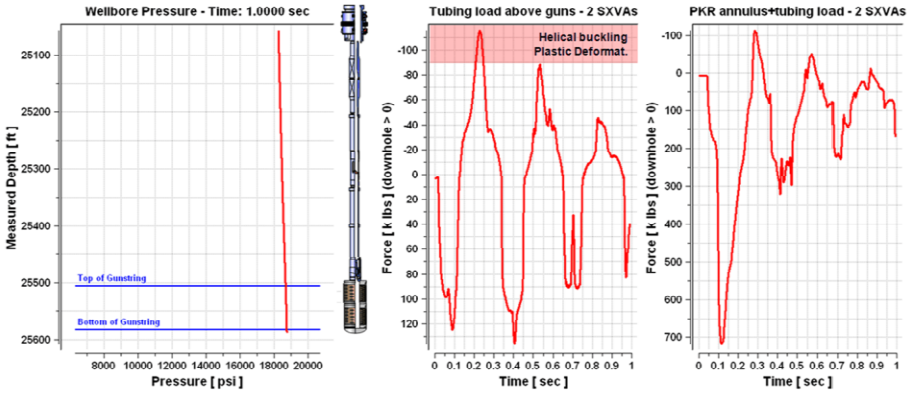
at 6.00 spf

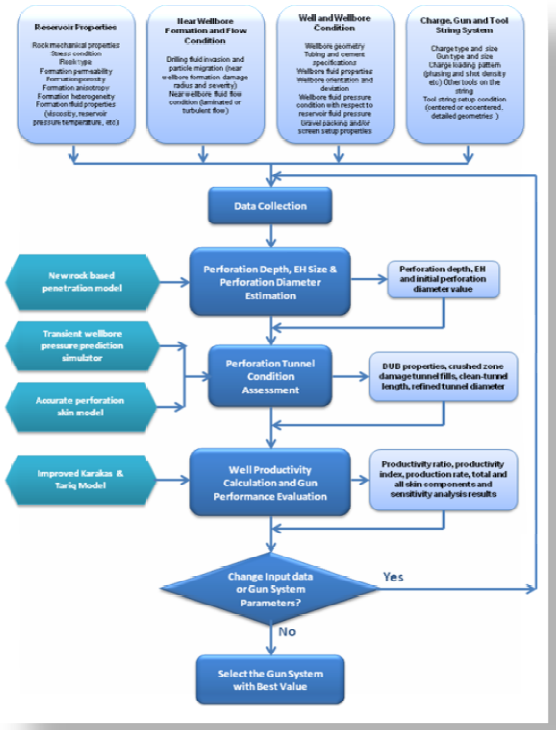
Gun Shock Model



- Gun system acts as a pressure source/sink generating pressure waves in the wellbore
- Pressure waves acting on cross-sectional area changes produce gun shock loads
- Model predicts interactions among gun, wellbore, reservoir, and completion hardware

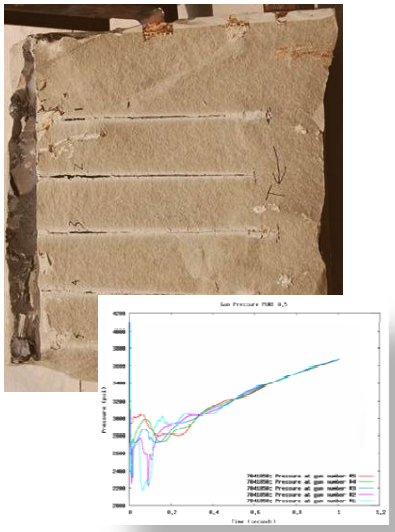


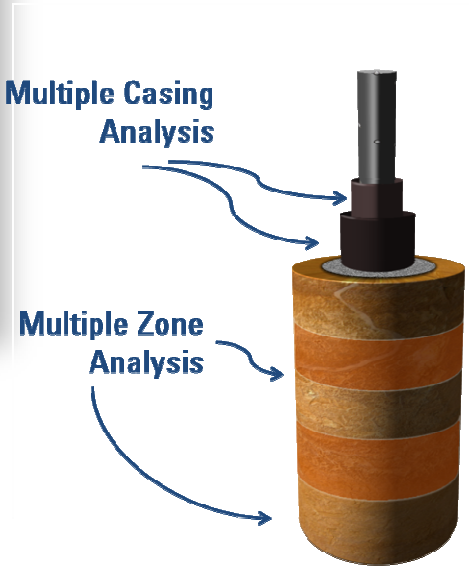
Workflow for Predicting Perforating System Performance

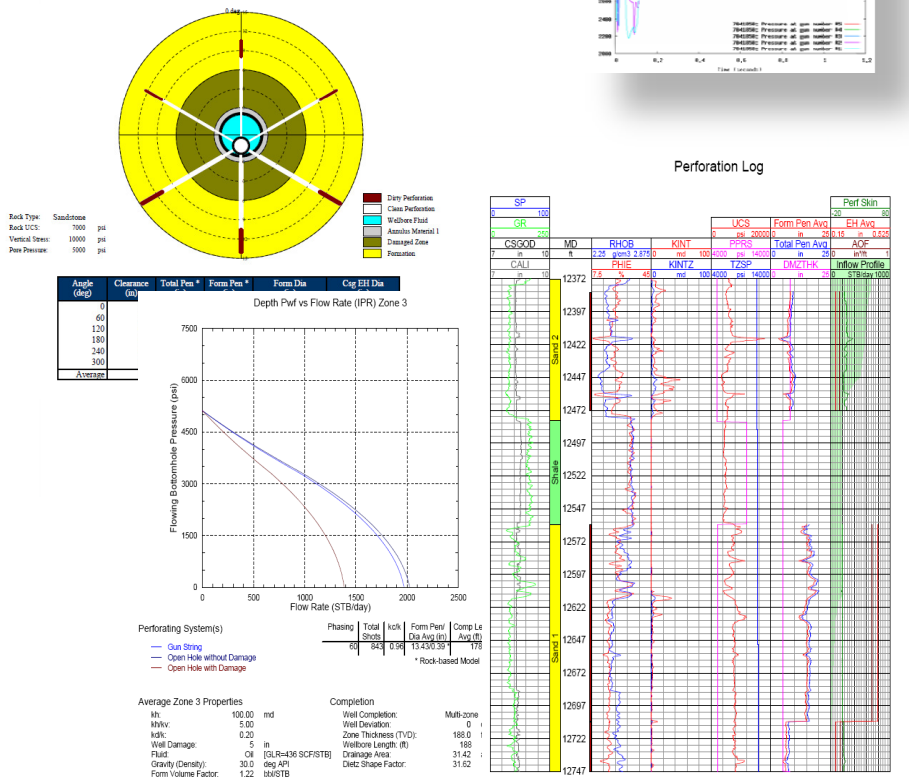


SPE 151800

- Rock based penetration model
- Wellbore dynamics prediction
- DUB cleanup model
- Inflow prediction (net and per-zone)







Summary

- Shaped charges should be characterized in stressed rock, not concrete
- Perforation cleanup dependant on shot-time wellbore dynamics, formation properties, wellbore fluids
- Gunshock depends on gun/wellbore/formation interactions
- Accurate models for penetration depth, cleanup, and gun shock phenomena are essential for reliable estimation of well performance and operational risk

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Thank You

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