The Society of Petroleum Evaluation Engineers
SPEE Denver Chapter announces its January Luncheon Meeting.
(Members and Guests are cordially invited to attend.)

Friday, January 19, 2018

Dr. Bob Barree
President, Barree & Associates, LLP

Will be speaking on:
Interference in Horizontal Well Developments
LUNCHEON STARTS AT 11:30 A.M.
(A plated lunch will be served.)
PRESENTATION BEGINS AT NOON

The Denver Athletic Club
4th Floor, Ballroom
1325 Glenarm Place (14th and Glenarm) Denver CO 80204
Parking flat rate $7.00 on space available basis

Cost: $25.00 per Person
(Credit Card, Cash or Check made out to ‘SPEE Denver Chapter’)

Sponsored in part by Entero Corporation, makers of
Mosaic, a comprehensive software application for reserves management,
petroleum economics, and decline analysis www.entero.com

Please RSVP by Noon Wednesday, January 17, 2018

RSVP and simultaneously pay by credit card online at:
https://secure.spee.org/civicrm/event/info?reset=1&id=173
Abstract: Most unconventional reservoirs are developed with pad drilling of multiple, closely spaced horizontal wells which are then fracture stimulated with closely spaced fracture initiation points. These wells, fractures, and fields are subject to several sources of interference during the drilling, completion, and production phases of development. This talk discusses various forms of interference and their impact on economic development and resource recovery.

Speaker Bio: Robert (Bob) D. Baree (PhD., P.E.) is president and principal investigator of Barree & Associates. Previously Dr. Barree was a Senior Technical Consultant at Marathon's Petroleum Technology Center. He has been involved in the development of hydraulic fracture design simulators and fracture diagnostic procedures for nearly 40 years, and is the author of more than 70 technical publications. He has served as SPE Distinguished Lecturer on the topic of new philosophies in hydraulic fracturing, and has served on many technical committees for SPE annual and regional meetings, Applied Technology Workshops, and Forum Series. He is a registered Professional Engineer in the State of Colorado and holds degrees in Petroleum Engineering (B.S.) from the Pennsylvania State University and Colorado School of Mines (PhD).

About SPEE: SPE was formed in 1962 as a professional, non-profit organization bringing together specialists in the evaluation of petroleum and natural gas properties. SPE continues today to be strongly committed to providing educational and other services to its members and to the oil and gas industry, and to promoting the profession of petroleum evaluation engineering.

For additional information, please contact:
Mike Flanigan
2018 Vice Chairman / Program Chairman SPEE Denver Chapter
Mike.Flanigan@USBank.com
303-585-4214

For event registration issues, please contact:
Mike White
mwhite@ResoluteEnergy.com
303-573-4886 Ext. 1450
Interference in Horizontal Well Stimulation

R. D. Barree
Barree & Associates LLC
Interference:
From Merriam-Webster

Definition of INTERFERENCE

• 1a : the act or process of interfering  
  b : something that interferes : OBSTRUCTION

• 2: the mutual effect on meeting of two wave trains (as of light or sound) that constitutes alternating areas of increased and decreased amplitude (such as light and dark lines or louder and softer sound)

• 3a : the legal blocking of an opponent in football to make way for the ballcarrier  
  b : the illegal hindering of an opponent in sports

• 4: partial or complete inhibition or sometimes facilitation of other genetic crossovers in the vicinity of a chromosomal locus where a preceding crossover has occurred

• 5a : confusion of a received radio signal due to the presence of noise (such as atmospherics) or signals from two or more transmitters on a single frequency  
  b : something that produces such confusion

• 6: the disturbing effect of new learning on the performance of previously learned behavior with which it is inconsistent
Interference for Us

- Fracture-to-facture stress interference in a stage
- Stress shadow interference between multiple stages in one well
- Stress interference between multiple wells with multiple stages (zipper fracs, “wine-rack” stacks, parent-child interactions)
- Production transient interference between fractures and frac stages (frac spacing)
- Production transient interference between wells (well spacing, parent-child effects, depletion)
Stress Interference

Fracs spaced far enough apart

Interference between stages
Fracture Stress Shadow

\[
\sigma = \frac{3 \times 144 \times P}{2\pi Z^t}
\]

\[
\sigma = \frac{wE}{12Z^t}
\]
Stress and Strain Projected
Non-Parallel Fractures

Blue arrows indicate stress/strain transmitted to offset frac planes. Red arrows show stress vectors that do not impact offset fracs.
Induced Fiber-Optic Strain

- Fiber outside casing
- Blue: Compression
- Red: Extension
- Stress shadow
- Pumps shut off
- Relaxation
- New fracture opening
- Ball Seat
- Fractures closing

$X_i > 1500'$
$1000'$

URTeC 2670034, 2017
ConocoPhillips
Interference of Oblique Fractures
Proppant Distribution Based on DAS/DTS for 14 Stages
Interference for Us

• Fracture-to-facture stress interference in a stage
• Stress shadow interference between multiple stages in one well
• Stress interference between multiple wells with multiple stages (zipper fracs, “wine-rack” stacks, parent-child interactions)
• Production transient interference between fractures and frac stages (frac spacing)
• Production transient interference between wells (well spacing, parent-child effects, depletion)
Well-to-Well Stress Interference

Wells frac’d sequentially from east to west
Sequential Fracture Interference

Well B
Frac'd First

Well A Frac'd
Second with Interference from Well B

Well A is 880' Offset from B

Well A is 100' Above Well B
Parent-Child Effects: Frac a New Well Offsetting an Older Producing Well

330 ft Offset
Fracs Offsetting Depleted Well
Interference for Us

• Fracture-to-facture stress interference in a stage
• Stress shadow interference between multiple stages in one well
• Stress interference between multiple wells with multiple stages (zipper fracs, “wine-rack” stacks, parent-child interactions)
• Production transient interference between fractures and frac stages (frac spacing)
• Production transient interference between wells (well spacing, parent-child effects, depletion)
Assumed Fracture Linear Flow Model (Wattenberger, et al)

No flow beyond ends of “effective” fractures. Linear flow is normal to all fracture faces. Fractures are very long and perm is very low, so interference time is long.
Analysis Using Linear Flow Model

For multiple fractures (N), $h = h^*N$ and $A$ is area per frac.

Time to “fracture” interference = 1600 days.

<table>
<thead>
<tr>
<th></th>
<th>Analysis</th>
<th>Model</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>$x_f \sqrt{k}$ (ft-md$^{1/2}$)</td>
<td>41.43</td>
<td>41.41</td>
<td>0.0%</td>
</tr>
<tr>
<td>$A$ (acre)</td>
<td>27.30</td>
<td>25.25</td>
<td>8.1%</td>
</tr>
<tr>
<td>$s$</td>
<td>0.43</td>
<td>0.50</td>
<td>19.1%</td>
</tr>
</tbody>
</table>

For $x_f \sqrt{k}$, the equation is:

$$x_f \sqrt{k} = \frac{200.8107T}{mh} \sqrt{\frac{1}{(\Phi \mu C_t)_i}}.$$

And for $A$:

$$A = \frac{90.3648T}{mh} \frac{1}{(\Phi \mu C_t)_i} \sqrt{t_{elf}}.$$

And for $s'$:

$$s' = \frac{bkh}{1.417E3T}.$$
Fractures appear to interfere quickly to form a continuous pressure sink that leads to linear flow from into the composite well-fracture system.
Evaluation of “Linear Flow” Models:
5000’ Lateral, 10 Fracs

---

**Inner Boundary:** Infinite Conductivity Fracture

**Outer Boundary:** Rectangular

- **Reservoir Pressure** ($P_i$): 5000
- **Reservoir Temperature** ($T$): 212
- **Thickness** ($h$): 500
- **Permeability** ($k$): 0.001
- **Porosity** ($\phi$): 0.06
- **Area** ($A$): 10
- **Half length** ($X_f$): 35
- **Skin** ($Skin$): 0
- **Fracture Conductivity** ($k_{wfr}$): 1000
- **Wellbore Storage** ($C$): 0
- **Aspect Ratio** ($L/W$): 4
- **Channel Width** ($ft$): 1500
- **Well X-Offset** ($X_{off}$): 0.5
- **Well Y-Offset** ($Y_{off}$): 0.5
- **Wellbore Radius** ($R_w$): 0.354
- **Vertical/Horizontal Perm** ($K_v/K_h$): 0.01
- **Horizontal Well Length** ($L_h$): 5000
- **Vertical Position** ($Z_{wd}$): 0.5
- **Specific Gravity** ($\gamma_d$): 0.65
- **Initial Water Saturation** ($S_{wi}$): 0.35
- **Water Compressibility** ($c_w$): 3.00E-06
- **Formation Compressibility** ($c_f$): 8.11E-06
- **Carbon Dioxide** ($CO_2$): 0
- **Nitrogen** ($N_2$): 0
- **Hydrogen Sulphide** ($H_2S$): 0
- **Wellhead Temperature** ($WHT$): 80
- **Measured Depth** ($L$): 11000
- **Pipe Roughness** ($\varepsilon$): 0.0006
- **Pipe Diameter** ($d$): 4.778
- **Condensate API** ($API$): 55
- **Diameter Perfs** ($dp$): 4.892

---

**Volumetric OGIP = 2.21 BCF**

---

Channel = 330.0 ft Length = 1320.0 ft
Linear Flow Plot for 10 Frac Case

spacing = 333.56 and Skin' = 1.09

Note: skin has no real meaning

Model Inputs
Xf = 35
h = 50
A/frac = 10
A = 100
k = 0.001
Nf = 10

Assumed Input Model Geometry

Channel = 330.0 ft Length = 1320.0 ft

© 2018
Comparison of Production Analysis with Increased Frac Density: 5000’ Lateral, 30 Fracs

30 Transverse 35 ft (inf) fracs

Infinite Conductivity Fracture

Rectangular

Reservoir Pressure: $P_i = 5000$
Reservoir Temperature: $T = 212$
Thickness: $h = 1500$
Permeability: $k = 0.001$
Porosity: $\phi = 0.06$
Area: $A = 5.38$
Half length: $X_f = 35$
Skin: $\text{Skin} = 0$
Fracture Conductivity: $k_{wf} = 1000$
Wellbore Storage: $C = 0$
Aspect Ratio: $L/W = 7$
Channel Width: $ft = 1500$
Well X-Offset: $X_{off} = 0.5$
Well Y-Offset: $Y_{off} = 0.5$
Wellbore Radius: $R_w = 0.354$
Vertical/Horizontal Perm: $K_v/K_h = 0.01$
Horizontal Well Length: $L_h = 5000$
Vertical Postion: $Z_{wd} = 0.5$
Specific Gravity: $\gamma_g = 0.65$
Initial Water Saturation: $S_{wi} = 0.35$
Water Compressibility: $c_w = 3.00E-06$
Formation Compressibility: $c_f = 8.11E-06$
Carbon Dioxide: $CO_2 = 0$
Nitrogen: $N_2 = 0$
Hydrogen Sulphide: $H_2S = 0$
Wellhead Temperature: $WHT = 80$
Measured Depth: $L = 11000$
Pipe Roughness: $\epsilon = 0.0006$
Pipe Diameter: $d = 4.778$
Condensate API: $\text{API} = 55$
Diameter Perfs: $dp = 4.892$

Volumetric OGIP = 3.57 BCF

Channel = 183.0 ft Length = 1280.8 ft
Linear Flow Plot for 30 Frac Case

spacing = 180.11 and Skin’ = 0.54

Note: skin has no real meaning

Model Inputs
Xf = 35
h = 50
A/frac = 5.38
A = 161.4
k = 0.001
Nf = 30

(Frac Spacing)          (Well Spacing)
≈ 183/2                      ≈1280/2

Channel = 183.0 ft Length = 1280.8 ft
Comparison of Radius of investigation for Radial and (Initially) Linear Flow

Depth of investigation at various times in days (log scale):
(a) from FMM with analytic solution for radial flow superimposed (black lines)
(b) from FMM for a vertical well with an infinite conductivity fracture or horizontal well with interfering fractures.
Transient Radius of Investigation (Oil Reservoir)

Radius of Investigation (ft) = 0.15875 \sqrt{\frac{kt}{\phi \mu c_t}}

- time, t in days
- permeability, k in millidarcy
- porosity, \( \phi \)
- viscosity, \( \mu \) in cp
- total compressibility, \( c_t \) in 1/psi

Reserv. Porosity: 0.08 fraction
Resv. Viscosity: 0.5 cp
Total Compressibility: 2.25E-05 1/psi

System Perm, md
- 0.0001
- 0.0005
- 0.001
- 0.005
- 0.01
- 0.05
- 0.1

© 2018 B&A Bureau & Associates
Effective Drainage Area
(Assumes 1:1 Aspect, Oil Reservoir)

<table>
<thead>
<tr>
<th>Drainage Area Contacted, acres</th>
</tr>
</thead>
<tbody>
<tr>
<td>100,000</td>
</tr>
<tr>
<td>10,000</td>
</tr>
<tr>
<td>1,000</td>
</tr>
<tr>
<td>100</td>
</tr>
<tr>
<td>10</td>
</tr>
<tr>
<td>1</td>
</tr>
<tr>
<td>0.1</td>
</tr>
</tbody>
</table>
Well Spacing Constraints on Area
Production Analysis Example

- Depth = 10000 ft
- Pressure = 8000 psi
- Porosity = 0.05
- Sw = 0.35
- Net H = 50 feet
- Perm 1 = 0.01 md (.5 md-ft)
- Perm 2 = 0.0001 md (0.005 md-ft)
- Area 1 = 20 acres
- Area 2 = ? acres
- Xf = 150 feet
- WHFP = 300 psi (3.992” ID Casing)
- BHST = 240F
Decline Analysis on 180 Days, $b=1.7$

After M. J. Fetkovitch, 1973

Rate Vs. Time
Possible EUR Estimates with Hyperbolic Decline \((b>1)\)

<table>
<thead>
<tr>
<th>Decline Exponent (b)</th>
<th>1.7</th>
</tr>
</thead>
<tbody>
<tr>
<td>EUR</td>
<td>10.998 BCF</td>
</tr>
<tr>
<td>Abandonment Rate</td>
<td>1 Mscf/day</td>
</tr>
<tr>
<td>Terminal Decline</td>
<td>0 %</td>
</tr>
</tbody>
</table>

- No terminal exponential decline or abandonment rate

<table>
<thead>
<tr>
<th>Decline Exponent (b)</th>
<th>1.7</th>
</tr>
</thead>
<tbody>
<tr>
<td>EUR</td>
<td>0.933 BCF</td>
</tr>
<tr>
<td>Abandonment Rate</td>
<td>1 Mscf/day</td>
</tr>
<tr>
<td>Terminal Decline</td>
<td>6 %</td>
</tr>
</tbody>
</table>

- Using 6% terminal exponential decline

<table>
<thead>
<tr>
<th>Decline Exponent (b)</th>
<th>1.7</th>
</tr>
</thead>
<tbody>
<tr>
<td>EUR</td>
<td>0.662 BCF</td>
</tr>
<tr>
<td>Abandonment Rate</td>
<td>50 Mscf/day</td>
</tr>
<tr>
<td>Terminal Decline</td>
<td>0 %</td>
</tr>
</tbody>
</table>

- Using reasonable minimum economic rate
Example Type-Curve (1 year)

Case 2

<table>
<thead>
<tr>
<th>Inner Boundary</th>
<th>Infinite Conductivity Fracture</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outer Boundary</td>
<td>Rectangular</td>
</tr>
<tr>
<td>Reservoir Pressure</td>
<td>$P_i$ = 8000</td>
</tr>
<tr>
<td>Reservoir Temperature</td>
<td>$T$ = 240</td>
</tr>
<tr>
<td>Thickness</td>
<td>$h$ = 50</td>
</tr>
<tr>
<td>Permeability</td>
<td>$k$ = 0.01</td>
</tr>
<tr>
<td>Porosity</td>
<td>$\phi$ = 0.05</td>
</tr>
<tr>
<td>Area</td>
<td>$A$ = 20</td>
</tr>
<tr>
<td>Half length</td>
<td>$X_f$ = 160</td>
</tr>
<tr>
<td>Skin</td>
<td>$\text{Skin}$ = 0</td>
</tr>
<tr>
<td>Fracture Conductivity</td>
<td>$k_{wf}$ = 50</td>
</tr>
<tr>
<td>Wellbore Storage</td>
<td>$C$ = 0</td>
</tr>
<tr>
<td>Aspect Ratio</td>
<td>$L/W$ = 3.5</td>
</tr>
<tr>
<td>Channel Width</td>
<td>$\text{ft}$ = 480</td>
</tr>
<tr>
<td>Well X-Offset</td>
<td>$X_{off}$ = 0.5</td>
</tr>
<tr>
<td>Well Y-Offset</td>
<td>$Y_{off}$ = 0.5</td>
</tr>
<tr>
<td>Wellbore Radius</td>
<td>$R_w$ = 0.354</td>
</tr>
<tr>
<td>Vertical/Horizontal Perm</td>
<td>$K_v/K_h$ = 0.01</td>
</tr>
<tr>
<td>Horizontal Well Length</td>
<td>$L_h$ = 5000</td>
</tr>
<tr>
<td>Vertical Postion</td>
<td>$Z_{wd}$ = 0.5</td>
</tr>
<tr>
<td>Specific Gravity</td>
<td>$\gamma_g$ = 0.65</td>
</tr>
<tr>
<td>Initial Water Saturation</td>
<td>$S_{wi}$ = 0.35</td>
</tr>
<tr>
<td>Water Compressibility</td>
<td>$c_w$ = 3.00E-06</td>
</tr>
<tr>
<td>Formation Compressibility</td>
<td>$c_f$ = 6.78E-06</td>
</tr>
<tr>
<td>Carbon Dioxide</td>
<td>CO2 = 0</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>N2 = 0</td>
</tr>
<tr>
<td>Hydrogen Sulphide</td>
<td>H2S = 0</td>
</tr>
<tr>
<td>Wellhead Temperature</td>
<td>WHT = 80</td>
</tr>
<tr>
<td>Measured Depth</td>
<td>L = 10000</td>
</tr>
<tr>
<td>Pipe Roughness</td>
<td>$\varepsilon$ = 0.0023</td>
</tr>
<tr>
<td>Pipe Diameter</td>
<td>d = 3.992</td>
</tr>
<tr>
<td>Condensate API</td>
<td>API = 55</td>
</tr>
<tr>
<td>Diameter Perfs</td>
<td>dp = 3.992</td>
</tr>
</tbody>
</table>

Volumetric OGIP = 0.46 BCF

Channel = 498.9 ft Length = 1746.2 ft

© 2018 B&F Barbe & Associates
Example Flowing Material Balance Plot (1 year)

Gas in Place = 0.45 BCF - Equivalent Area 19.63 acres - L/W ratio 3.52 - Case 2

First Boundary
Last Boundary

Time (days) $T_a$

$M/P/Q$

© 2018 B&A Barree & Associates
Decline Curve on 10 years Production

Decline becomes volumetric after 5-7 years

After M. J. Fetkovitch, 1973
10 year Decline Adjusted to b = 0.7

Decline Exponent b 0.7
EUR 0.561 BCF
Abandonment Rate 1 Mscf/day
Terminal Decline 0 %

Decline Exponent b 0.7
EUR 0.348 BCF
Abandonment Rate 50 Mscf/day
Terminal Decline 6 %
Production Analysis Example:
What was really there? (2.8 BCF)

- Depth = 10000 ft
- Pressure = 8000 psi
- Porosity = 0.05
- Sw = 0.35
- Net H = 50 feet
- Perm 1 = 0.01 md (.5 md-ft)
- Perm 2 = 0.0001 md (0.005 md-ft)
- Area 1 = 20 acres (0.46 BCF OGIP)
- Area 2 = 100 acres (2.3 BCF OGIP)
- Xf = 150 feet
- WHFP = 300 psi (3.992” ID Casing)
- BHST = 240F
Example Production Decline (50 years)

- Cum Gas = 0.57 BCF
- ~1/2 Slope: Transient Flow
- ~1 Slope: Boundary Influence

Graph showing time in days on the x-axis and rate in MSCF/day on the y-axis.
Example of Log-Log Diagnostic Plot for Bakken Oil Well

Thirty Year Oil Forecast

- 1/2 Slope

- 1 Slope

Dial Oil Rate, Bopd

Time, Days

© 2018 B&A Bureau & Associates
Overall Analysis of Time to Boundary Influenced Flow in Bakken

Bakken Study Wells
Time to Unit Slope

Probability

Time, Months

975 Wells
In Conclusion...

• Closely spaced perf clusters may accelerate early production, but there is a physical limit past which fractures will tend to annihilate one another.
• Stress interference affects fracture geometry, asymmetry, and growth direction allowing fracs to be steered constructively or destructively.
• Fracturing offsets to partially depleted wells leads to frac hits, well bashing, and loss of reserves.
• Stimulated reservoir volumes larger than well spacing [probably] have minimal impact on actual reserves.
• Estimating EUR from early production (even a year) can be fruitless and deceiving.
• Is the industry “spending money like a drunken sailor”?  

Not to disparage drunken sailors...

“Most of [my pay] goes for likker and wimmen. The rest I spend foolishly”

-A U.S. sailor in China, 1920’s
The Quarterly Journal of Military History
Summer 2013, Volume 25, Number 4

Even drunken sailors can weigh and set priorities.
Thank you!

Questions?