Basic Production Engineering and Well Performance

Dr. Hemanta Mukherjee
iPoint LLC
Westminster, CO. 80031
January 2011
Texts and References


5. James P. Brill and Hemanta Mukherjee: Multiphase Flow In Wells, SPE Monograph Volume 17, SPE Dallas, TX (1977) 5.
Drilling Rig
Well Performance Analysis

- Also called Production System Analysis
- Essential for optimized production from wells
- Essential Component of Reservoir Management
Reservoir Management

- Reservoir Definition/Characterization
  - Geology / Geophysics
  - Surface Seismics

- Reservoir Performance
  - Exploratory and Development Wells
  - Well Data - logs, cores, well tests, VSPs etc
  - Well Performance and Issues:
    - Optimum Completion
    - Well Surveillance
      - Stimulation, Artificial Lift, Pressure Maintenance
      - Secondary and Tertiary Recovery etc
Oil and Gas Field Management

Three Levels

- **Field Level**:
  - Specifications: Rates (GOR, FW), Pressures etc
  - Constraints: Rates, GOR, FW, Pressures etc

- **Group Level**:
  - Specifications: Rates (GOR, FW), Pressures, Solids etc
  - Constraints: Rates, GOR, FW, Pressures etc

- **Well Level**:
  - Specifications: Rates (GOR, FW), Pressures, Solids etc
  - Constraints: All specified Parameters
Why Manage Reservoirs?

- Earnings and Investment Appraisal
  - Revenue Projections --- Oil & Gas Price
- Investment Decisions Based on Revenue
- Overall Development Strategy
  - Primary Recovery / Artificial Lift
  - Secondary Recovery
  - Tertiary Recovery
  - Possible Environmental Impact
Engineering Tools Used

- Formation Evaluation - Geological Information, Rock and Fluid Properties
- Reservoir Simulator
  - Prediction
  - History Matching
- Well Performance and Completion Simulators
  - Management of a Reservoir at the Well Level
Historical Preview

- W.E. Gilbert (1944, 1954) of Shell
  - Flowing and Gas Lift Well Performance (Concept)
- Problems
  - Computers
  - Lack of understanding of MultiPhase Flow in Pipes and Piping Components
  - Poettman and Carpenter (1952) - Oil & Gas Flow in Vertical Pipes
Historical Preview (Contd.)

- Revolution in Computer Technology (1960s)
- H. D. Beggs and J. P. Brill (1973) - Gas-Liquid Flow in Inclined Pipes
  - Systems Analysis
Objectives and Importance

- Optimization of Oil & Gas Well Performance
- Minimization of unnecessary Well Costs
  - Optimum Tubing size
  - Optimum Separator Pressure
  - Optimum Completion
    - Perforation: Shot Density, Tunnel Length, Phasing etc
    - Stimulation
      - Fracturing: Half Length, Conductivity
      - Matrix Treatments: Acid, Solvents, Scale Removal etc
Objectives and Importance (Contd.)

- Optimization of Artificial Lift
- Prediction and Control of Unacceptable Production Conditions
  - Slugging or Surging
    - Slug Catchers
    - Velocity strings
  - Liquid Loading
    - Velocity Strings, Plunger Lift
  - Control of Undesired - Water and Gas
Economic Impact

- Maximization of Return on Investment (ROI)
- Net Present Value (NPV) Considerations
Typical Production System with Nodes

<table>
<thead>
<tr>
<th>Node</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Pr Reservoir</td>
</tr>
<tr>
<td>2</td>
<td>Pwfs - Sand face</td>
</tr>
<tr>
<td>3</td>
<td>Pwf - bottom hole/wellbore</td>
</tr>
<tr>
<td>4</td>
<td>Restriction</td>
</tr>
<tr>
<td>5</td>
<td>Safety Valve</td>
</tr>
<tr>
<td>6</td>
<td>Wellhead</td>
</tr>
<tr>
<td>7</td>
<td>Surface Choke</td>
</tr>
<tr>
<td>8</td>
<td>psep - Separator</td>
</tr>
</tbody>
</table>

Gas Sales
Stock Tank

Pressure Regulator
Valve
What is a Node?

- Any point in the well
- Rate into the node = Rate out of the node
- Only one pressure exists at the node
Simple Production System

- Choke
- Flowline
- Vertical or Inclined Tubing
- Gas Sales
- Separator
- Stock Tank
- Reservoir
- Completion
Possible Pressure Losses in Production System

\[ \Delta \text{P1} = (\text{Pr} - \text{Pwfs}) = \text{Loss in Porus Medium} \]
\[ \Delta \text{P2} = (\text{Pwfs} - \text{Pwf}) = \text{Loss across Completion} \]
\[ \Delta \text{P3} = (\text{PUR} - \text{PDR}) = \text{Loss across Restriction} \]
\[ \Delta \text{P4} = (\text{PUSV} - \text{PDSV}) = \text{Loss across Safety Valve} \]
\[ \Delta \text{P5} = (\text{Pwh} - \text{PDSC}) = \text{Loss across Surface Choke} \]
\[ \Delta \text{P6} = (\text{PDSC} - \text{Psep}) = \text{Loss in Flowline} \]
\[ \Delta \text{P7} = (\text{Pwf} - \text{Pwh}) = \text{Total Loss in Tubing} \]
\[ \Delta \text{P8} = (\text{Pwh} - \text{Psep}) = \text{Total Loss in Flowline} \]
Pressure Balance

\[ p_{wf} = p_{sep} + \Delta p_h + \left( \Delta p_{fl} + \Delta p_t + \Delta p_{ch} \right)_f + \Delta p_{acc} \]

Subscripts:

- sep = Separator
- h = Hydrostatic
- fl = Flow Line
- t = Tubing
- acc = Acceleration
Tubing gradients
Gradient Curves

WHP = 200 psi

Rate = 2000 bpd
27/8”; 350 API; 200°F

<table>
<thead>
<tr>
<th>Pressure, psig</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inflow</td>
</tr>
<tr>
<td>(1) 100.0</td>
</tr>
<tr>
<td>(2) 200.0</td>
</tr>
<tr>
<td>(3) 400.0</td>
</tr>
<tr>
<td>(4) 1500.0</td>
</tr>
<tr>
<td>(5) 3000.0</td>
</tr>
</tbody>
</table>

Reg: Authorized User - Dowell Schlumberger
Fig. 6.3 A Typical Tubing Intake Curve for Producing Wells.
Units

\( q_o = \text{oil rate, bopd} \)
\( r_e = \text{reservoir radius, ft} \)

\( q_g = \text{gas rate, Mscf/D} \)
\( r_e = \text{reservoir radius, ft} \)
Darcy’s Law (Liquid): PSS

\[ q_o = 7.08 \times 10^{-3} \, kh \frac{(p_r - p_{wf})}{\mu_o B_o \left[ \ln \left( \frac{r_e}{r_w} \right) - \frac{3}{4} + S \right]} \]

\[ PI = \frac{q}{p_r - p_{wf}} = \frac{7.08 \times 10^{-3} \, kh \left[ \ln \left( \frac{r_e}{r_w} \right) - \frac{3}{4} + S \right]}{\mu_o B_o} \]
Skin Effect

\[ S_T = S_{\text{drill}} + S_{\text{cement}} + S_{\text{perfs}} + S_{\text{gp}} + Dq + S(\text{time}) + S_{\text{pseudo+etc}} \]

\[ S_{\text{drill}} = S_{\text{inv}} + \text{Drilling Induced Skin} \]
Skin Effect

• Alternative treatment of Skin Effect is “effective wellbore radius” (Matthews and Russel), the radius which makes the pressure drop in an ideal reservoir equal to that of an actual reservoir with Skin:

\[ r_w' = r_w e^{-S} \]

• This is equivalent to Hawkins with \( k_{\text{Skin}} = \infty \)
• For Skin = 0, \( r_w' = r_w \)
• For Skin > 0, \( r_w' < r_w \)
• For Skin < 0, \( r_w' > r_w \)
Skin Effect

For Infinite Conductivity Vertical Fracture,
Apparent $r_w = x_f / 2$

For Finite Cond. Vert. Fracture: Prat’s correlation

$$S = \ln \left( \frac{2 \ r_w}{x_f} \right)$$

Equivalent to a Negative Skin
Skin Effect

- Added pressure difference due to Skin effect
- $k$ around well can be damaged by well drilling process, by frac, acid or perfs. To accommodate for this, Van Everdingen defined and area of infinitesimal size around the wellbore
- For (+) Skin - OK
- For (-) Skin - difficult physical interpretation
- Hawkins defined Skin of finite radius $r_{\text{Skin}}$ with $k_{\text{Skin}}$:

$$S = \left( \frac{k}{k_{\text{Skin}}} - 1 \right) \ln \frac{r_{\text{Skin}}}{r_w}$$

- Unfortunately, there is no unique $r_{\text{Skin}}, k_{\text{Skin}}$ for any $S$
Inflow Performance Relationship (IPR)

Rate, \( q \) (STB/D)

\( p_r \)

\( p_{wf} \) (psia)

Darcy’s Law (Liquid)

AOFP
Productivity Index (J)

Darcy’s Law (Liquid)

\[ J = 1.22 \text{ STBO/psi-D} \]

\[ \text{AOFP} = 3,672 \text{ STBO/D} \]
Jone's IPR

\[ p_r - p_{wf} = aq^2 + bq \]

**Where,**

\[ a = \frac{2.30 \times 10^{-14} \beta B_o}{h_p r_w} \]

\[ b = \frac{\mu_o B_o \left[ \ln \left( 0.472 \left( \frac{r_e}{r_w} \right) \right) + S \right]}{7.08 \times 10^{-3} k h} \]

\[ \beta = \frac{2.33 \times 10^{10}}{k^{1.201}} \]
IPR Type – Phase Envelope

A Black Oil
B Composite
C Wet Gas
D Dry Gas
E Solution Gas

Bubble Point Curve
Dew Point Curve

Temperature (°R)
Pressure (psia)

X pr
O pwf
Δ Wellhead
Vogel’s IPR (Oil Below Bubble Point)

\[ q_o = q_{o \text{max}} \left[ 1 - 0.2 \frac{p_{wf}}{p_r} - 0.8 \left( \frac{p_{wf}}{p_r} \right)^2 \right] \]
Vogel’s IPR (Composite Reservoir)

\[ q_o = q_b + \left( \frac{PI \ast p_b}{1.8} \right) \left[ 1 - 0.2 \frac{p_{wf}}{p_b} - 0.8 \left( \frac{p_{wf}}{p_b} \right)^2 \right] \]
Darcy’s Law (Gas): PSS

\[ q_g = 703 \times 10^{-6} \, kh \left( \frac{\left( p_r^2 - p_{wf}^2 \right)}{\mu_g T Z \left( \ln \left( \frac{r_e}{r_w} \right) - \frac{3}{4} + S \right)} \right) \]
Darcy’s Law (Gas)

\[ q_g = \frac{kh}{1424} \frac{(p_r^2 - p_{wf}^2)}{\mu_g TZ \left( \ln \left( \frac{r_e}{r_w} \right) - \frac{3}{4} + S \right)} \]
Jone’s IPR (Gas)

\[ p_r^2 - p_{wf}^2 = a q^2 + b q \]

\[ a = \frac{3.16 \times 10^{-12} \beta \gamma_g T \!Z}{h_p r_w} \]

\[ b = \frac{1.424 \times 10^{-3} \mu_g T \!Z \ln \left( 0.472 \frac{r_e}{r_w} \right) + S}{kh} \]
Back Pressure Equation

\[ q_g = c \left( P_r - P_{wf} \right)^n \]

Where,

\[ c = \frac{703 \times 10^{-6} kh}{\mu_g TZ \left[ \ln \left( \frac{r_e}{r_w} \right) - \frac{3}{4} + S \right]} \], \quad 0.5 < n < 1
Liquid vs Two Phase or Gas IPR

Darcy’s Law (Liquid)

Two-Phase Gas/Oil
-- Vogel
-- Fetkovitch

Single-Phase Gas
-- Darcy’s Law

\( p_r \)

\( p_{wf} \) (psia)

Rate, \( q_{sc} \)

AOFP
### Shape Factors in Darcy Equation

<table>
<thead>
<tr>
<th>SYSTEM</th>
<th>X</th>
</tr>
</thead>
<tbody>
<tr>
<td>.</td>
<td>$\frac{r_e}{r_w}$</td>
</tr>
<tr>
<td>-</td>
<td>$0.571A^{1/2}/r_w$</td>
</tr>
<tr>
<td>-</td>
<td>$0.565A^{1/2}/r_w$</td>
</tr>
<tr>
<td>-</td>
<td>$0.604A^{1/2}/r_w$</td>
</tr>
<tr>
<td>- 60</td>
<td>$0.610A^{1/2}/r_w$</td>
</tr>
<tr>
<td>1/3</td>
<td>$0.678A^{1/2}/r_w$</td>
</tr>
<tr>
<td>2</td>
<td>$0.668A^{1/2}/r_w$</td>
</tr>
<tr>
<td>4</td>
<td>$1.368A^{1/2}/r_w$</td>
</tr>
<tr>
<td>5</td>
<td>$2.066A^{1/2}/r_w$</td>
</tr>
<tr>
<td>1</td>
<td>$0.884A^{1/2}/r_w$</td>
</tr>
<tr>
<td>.</td>
<td>$1.485A^{1/2}/r_w$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>SYSTEM</th>
<th>X</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>$0.966A^{1/2}/r_w$</td>
</tr>
<tr>
<td>1</td>
<td>$1.44A^{1/2}/r_w$</td>
</tr>
<tr>
<td>4</td>
<td>$2.206A^{1/2}/r_w$</td>
</tr>
<tr>
<td>4</td>
<td>$1.925A^{1/2}/r_w$</td>
</tr>
<tr>
<td>4</td>
<td>$6.59A^{1/2}/r_w$</td>
</tr>
<tr>
<td>4</td>
<td>$9.36A^{1/2}/r_w$</td>
</tr>
<tr>
<td>1</td>
<td>$1.724A^{1/2}/r_w$</td>
</tr>
<tr>
<td>2</td>
<td>$1.794A^{1/2}/r_w$</td>
</tr>
<tr>
<td>2</td>
<td>$4.072A^{1/2}/r_w$</td>
</tr>
<tr>
<td>2</td>
<td>$9.523A^{1/2}/r_w$</td>
</tr>
<tr>
<td>1</td>
<td>$10.135A^{1/2}/r_w$</td>
</tr>
</tbody>
</table>
Transient IPR – Hydraulically Fractured Well
Transient IPR
Infinite Homogeneous Reservoir

\[ q_o = \frac{k_o h (p_r - p_{wf})}{162.6 \mu_o B_o \left[ \log \left( \frac{k_o}{\phi \mu_o C_t r_w^2} \right) - 3.23 + 0.87 s \right] + \log(t)} \]

Valid upto

\[ t_{pss} = 948 \frac{\phi \mu_o c_t r_e^2}{k_o}, \text{ hr} \]
Transient IPRs

![Graph showing transient IPRs with pressure in psi on the y-axis and producing rate in STB/D on the x-axis. The graph includes lines for 365 days, 30 days, 10 days, and 5 days.]
Horizontal Well
Vertical Well Drainage Model

\[ h \]

\[ 2r_w \]

\[ r_{ev} \]
Horizontal IPR - Joshi

\[ q = \frac{2\pi k h (p_r - p_{wf})}{\mu B \left[ \ln \left( a + \sqrt{a^2 - \left(\frac{L}{2}\right)^2} \right) \left( \frac{L}{2} \right) \right]^3 + \frac{\beta h}{L} \ln \left( \frac{\beta h}{2r_w} \right) } \]

\[ \beta = (k_h/k_v)^{0.5} \]

\[ a = \left( \frac{L}{2} \right) \left[ 0.5 + 0.25 + \left( \frac{2r_{eh}}{L} \right)^4 \right]^{0.5} \]

for \( L > \beta h \), \( 0.5L < 0.9r_{eh} \)
Horizontal Well IPR (Joshi)

\[ q_o = \frac{7.08 \times 10^{-3} k_{oh} h (p_r - p_{wf})}{\mu_o B_o \left\{ \ln \left[ a + \sqrt{a^2 - \left(\frac{L}{2}\right)^2} \right] \right\} + \frac{h I_{ani}}{L} \ln \left( \frac{h I_{ani}}{2 r_w} \right)} \]
Horizontal Well IPR

\[ q_o \equiv \frac{7.08 \times 10^{-3} k_{oh} h (p_r - p_{wf})}{\mu_o B_o \ln \left( \frac{a + \sqrt{a^2 - \left( \frac{L}{2} \right)^2}}{\frac{L}{2}} \right) + \frac{h I_{ani}}{L} \ln \left( \frac{h I_{ani}}{r_w (I_{ani} + 1)} \right)} \]
Horizontal Well IPR (Gas): PSS

\[ q_g \equiv \frac{7.04 \times 10^{-4} k_{gh} h (\bar{p}_r - p_{wf})}{\mu_g Z T \ln \left[ \frac{a + \sqrt{a^2 - \left(\frac{L}{2}\right)^2}}{L} \right] + \frac{h I_{ani}}{L} \ln \left( \frac{h I_{ani}}{r_w (I_{ani} + 1)} - 0.75 + Dq_g \right)} \]
Horizontal Drainage Model
Horizontal Well - Flow Components
Flow Regimes in Horizontal Wells

(a) Early-time radial
(b) Intermediate-time linear
(c) Late-time pseudo-radial (intermediate)
(d) Late-time linear (pseudo steady state)
SPE 69700 : Example of Gull Wing, Crows Feet and Fishbone Multilaterals

LM19 Pad
53,827 ft Drilled
43,693 Net pay (81%)
4 Multilateral wells

LM17 Pad
108,833 ft Drilled
81,555 Net pay (75%)
4 Multilateral wells

LM19 & LM17
Pads
Well Performance

![Graph showing well performance over time. The graph compares average rate per well (BOPD/Well) for 94 single horizontal wells and 19 multi-lateral wells. The data is synchronized over 12 months.]
A typical systems graph

\[ p_r \]

\[ p_{wf} \] (psi)

Rate
\( P_{wf} \) (psi)

\( \Delta p \)

(A)

(B)

(C)

\( p_r \)

\( q_o \)

\( q_{pump} \)

Rate
Nodal Analysis

Improve Reservoir Performance by:
- Horiz./ Lat. well
- Acid
- Fracture
- Perforate
- Add pay

Improve Plumbing Performance by:
- Change tubing,
- Artificial lift,
- Scale removal
- Water Control

Graph showing pressure and flow rate with performance gap and existing performance.
**Production Gap**

**Parameters Affecting Performance:**
- PVT
- Darcy's Law
- Physical Description
- Impact
- Perfs
- Sand Control
- Acid/Skin
- Zone Isolation
- Tubing & Flowlines
- Traps
- Restrictions
- Erosional Velocity
- Lift System Problems
- ESP (CAMCO)

**Services Needed to Define Unknown Reservoir Parameters:**
- PTA / RST
- PL
- DPS
- SPAN / PL
- RST
- USI
- Calipers / CCL
- USI
- PL
- PL / Data Pump

**Remedial Actions / Solutions:**
- Perforation
- Stimulation - Frac/Acid
- Squeeze Cem.- Isolation
- Laterals
- Reperforate
- Gravel Pack
- Squeeze Cementing
- Acidizing
- Acidizing
- Scale Removal (CT)
- CT Completion
- Velocity String
Injection Wells

- Mathematically injection is equivalent to negative production
- Darcy’s Law becomes,

\[
q_w(bwpd) = 7.08 \times 10^{-3} \ k h \left( p_{wf} - p_r \right) \mu_w B_w \left( \ln \left( \frac{r_e}{r_w} \right) - \frac{3}{4} + S \right)
\]
Completion

- Perforation
  - McLeod Model
- Gravel Pack
  - Jones, Blount and Glaze Model
Most Oil and Gas wells are cased and cemented.

These wells are perforated with Shaped charges:
- Pressure on Target: $5 \times 10^6$ psi
- Jet Velocity: 20,000 ft/sec

API Specifications of penetration and hole dia. are available.

- Assumes each tunnel to have a compacted zone of reduced permeability around it experiences radial flow around it
- Impact of shaped charge creates the compacted zone
Perforation Model (oil)

\[ p_{wfs} - p_{wf} = aq^2 + bq = \Delta p \]

\[
\Delta p = \left[ 2.30 \times 10^{-14} \beta B_o^2 \rho \left( \frac{1}{r_p} - \frac{1}{r_c} \right) \right] \frac{L_p^2}{q^2} + \left[ \mu_o B_o \left( \frac{\ln r_c}{r_p} \right) \right] q \]

\[
\beta = \frac{2.33 \times 10^{10}}{k_p^{1.201}}
\]
Perforation Model (gas)

\[ p^2_{\text{wfs}} - p^2_{\text{wf}} = aq^2 + bq \]

\[
\begin{align*}
\beta &= \frac{2.33 \times 10^{10}}{k^{1.201}} \\
&= \frac{3.16 \times 10^{-12} \beta \gamma g \varepsilon T Z \left( \frac{1}{r_p} - \frac{1}{r_c} \right)}{L_p^2} q^2 + \frac{1.424 \times 10^3 \mu T Z \left( \ln \frac{r_c}{r_p} \right)}{k_p L_p} q
\end{align*}
\]
Gravel Pack Model

- Cross section of a Gravel Packed Well
- Shows Casing, Gravel Pack, Screen, Perforated inner liner and the perforation tunnel
- The flow path from the reservoir into the well is also shown
Gravel Pack Model (oil)

\[ p_{wfs} - p_{wf} = aq^2 + bq \]

\[ \Delta p = \frac{9.08 \times 10^{-13} \beta B_0^2 \rho L}{A^2} q^2 + \frac{\mu B_0 L}{1.127 \times 10^{-3} k_g A} q \]

\[ \beta = \frac{1.47 \times 10^7}{k_g^{0.55}} \]
Gravel Pack Model (gas)

\[ p_{\text{wfs}}^2 - p_{\text{wf}}^2 = aq^2 + bq \]

\[
p_{\text{wfs}}^2 - p_{\text{wf}}^2 = \frac{1.247 \times 10^{-10} \beta \gamma_g T Z L}{A^2} q^2 + \frac{8.93 \times 10^3 \mu T Z L}{k_g A} q
\]

\[
\beta = \frac{1.47 \times 10^7}{k_g^{0.55}}
\]
Perform Example

- Water injection well
- Vertical well
Gas Lift System

- Depth (ft)
- Pressure (psig)
- Tubing Gradient
- Casing Gradient
- Dead Well
- IPR
- Rate (STB/O/D)
- $p_{wh}$
- $p_c$
- $p_{wf}$
- $q_o$
- $p_r$
- $\Delta p$
Pumped System

- Depth (ft)
- Pressure (psig)
- Rate (STBO/D)
- $p_{wh}$
- $q_o$
- $p_{wf}$
- Tubing Gradient
- Dead Well Pressure
- Pump Intake Pressure
- Pump Discharge Pressure
- $\Delta p_{pump}$
- IPR
- $p_r$
Gas Well Loading

Low PI Gas wells producing with low gas velocity often fail to unload any liquids or condensates - resulting in accumulation of liquids in the wellbore. This phenomena eventually curtails the Gas velocity further and results in gas Well Loading.

**Diagnostic**: Systems Plot – intersection of IPR curve in the unstable part of the intake Curve.
Criteria for Gas Well Unloading

“Gas flow rate at every point in the Tubing has to exceed the critical gas flow rate”
Critical Gas Flow Rate (MMScf/D) at any point in the flow conduit,

\[ q_{gC} = 3.06 \rho \frac{A}{T_z} \]

Where,

\[ V_t = 1.59 \left[ \frac{\sigma (\rho_L - \rho_g)}{\rho_g^2} \right]^{1/4} \]

Units: MMScf/d; psia; ft/sec; °R; dynes/cm; lbm/ft³
Remedial Measures

- Intermittent Gaslift
- Soap Bars ??
- Plunger Lift
- Velocity String to reduce tubing diameter to increase gas velocity
Erosion – A real Production Problem
Erosional Velocity

\[ v_e = \frac{C}{\sqrt{\rho}} \]

\( C = 300 \) for Liquid impinging on Steel and erosion at 10 mils/year

Units: ft/sec and lbm/ ft\(^3\).
Concept of Equivalent Stagnation Length

Stagnation Zone

Tee

Elbow

Equivalent Stagnation Length

\[ v_f = v - \frac{x}{L} \]

Particle Initial Position

Linear Fluid Velocity

\[ v_f = v - \frac{x}{L} \]
Salama and Venkatesh

\[ h = 496920 \left( \frac{q_{sd} \cdot v_p^2}{T \cdot d^2} \right) \]

- \( h \): penetration rate in Elbow, mil/yr
- 1 mil = .001 in. or .0254 mm
- \( q_{sd} \): sand production rate, ft\(^3\)/D
- \( V_p \): particle impact velocity, ft/sec
- \( T \): elbow metal hardness, psi (Ref. 37)
- \( d \): elbow diameter, in
Erosional Velocity - Elbow

\[ v_e = 1.73 \frac{d}{\sqrt{q_{sd}}} \]

Assume:

\[ T = 1.55 \times 10^5 \text{ psi} \]
\[ h = 10 \text{ mils/yr} \]
Geothermal and Hydrothermal Gradients in different environments.

- Permafrost
- Marine Environment
- Earth’s Crust

Temperature vs. Depth

- Thermal Gradient
- Hydrate Formation Temp.
- Hydrate Zone

Seabed
Hydrates and Scales

• Clathrate Hydrates – Solids

• Scales

  • Organic : Wax and Asphalts
  • Inorganic : Sulphates, Chlorides, carbonates

• Mobile Formation Fines
Hydrate Phase Envelope
Tubing and Casing patches

Reasons:
- To patch holes, corroded or weaker parts
- To remediate water or gas leakage
- To patch perforations that are water or gas invaded
  - provided cement integrity is not a problem
- To isolate zones that are not productive
- To protect parts of tubing and casing from surface damage
PatchFlex**

- Flexible composite cylinder
  - run on electric wireline
  - inflated downhole
  - set flush against casing
- In-situ polymerization technology
  - resin polymerized by heat
- Pressure resistant inner lining
- Excellent mechanical and chemical properties
## Screening Criteria for Optimum Completion Type:

<table>
<thead>
<tr>
<th>Completion</th>
<th>Formation Type</th>
<th>Permeability</th>
<th>Zone</th>
<th>Anisotropy</th>
<th>Coning</th>
<th>Nearby water or gas zone</th>
<th>Naturally Fractured Reservoirs</th>
<th>Heavy Oil</th>
<th>Low Sh h</th>
</tr>
</thead>
<tbody>
<tr>
<td>Open Hole</td>
<td>Consolidated</td>
<td>Low</td>
<td>Thin</td>
<td>Thick</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cased Hole</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>√</td>
<td></td>
<td></td>
<td></td>
<td>√</td>
</tr>
<tr>
<td>Vertical Well</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Horizontal Well</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>√</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Deviated Well</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fractured Well</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sand Control</td>
<td></td>
<td>X</td>
<td>√</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>


5. James P. Brill and Hemanta Mukherjee: Multiphase Flow In Wells, SPE Monograph Volume 17, SPE Dallas, TX (1977) 5.
Horizontal Completion Potential

- These two Sands are above thick water Zones
- These two sands are ideal for future Horizontal well completion
- 7304’-7350’ Low Resistivity Production – very good producer

Log of GOM#70
Sands 27 and 26 are 20’ and 28’ thick respectively
Darcy’s Law
(Inflow Performance for Single Phase Fluid, IPR)

\[ q = \frac{0.00708 \, kh \, (p_r - p_{wf})}{\mu \, \beta \, \{ \ln \left( \frac{r_e}{r_w} \right) - 0.75 + S \} } \]

Completion efficiency is manifested in the Skin Value (S)
Horizontal Well Applications

- Thin Zones – Difficult to Fracture Effectively
- High vertical permeability
- Zones with bottom water
- Higher Vertical Permeability than Radial Perm.
  - Naturally Fractured Reservoirs e.g. Rospo Mare field, Italy
    (Total- Old Elf publications in early 1980s)
- Drilling Access – Pad Drilling, Island to offshore location etc (Example: Sakhalin Island)