SPE DISTINGUISHED LECTURER SERIES

is funded principally
through a grant of the

SPE FOUNDATION

The Society gratefully acknowledges
those companies that support the program
by allowing their professionals
to participate as Lecturers.

And special thanks to The American Institute of Mining, Metallurgical,
and Petroleum Engineers (AIME) for their contribution to the program.
Engineer Your Gas-Condensate Systems, Reservoir to Sales Meter

Shah Kabir
Chevron Energy Technology Company

SPE 95531, 95528, 89753, 89754, 100384
Presentation Outline

- Reserves & Consumption of Natural Gas
- Useful Correlations for RF and Gas Cycling
- Simple Simulator: Well Count
- Coupled Modeling w/Economics: Pipe Size
- Real-Time Reservoir Management
- Concluding Remarks
Distribution of Proved Natural Gas Reserves (%) in 2004

Natural Gas Production (billion cubic metres), 1970-2004

Source: UNCTAD based, June 2005
Consumption Per Capita By Country, Tonnes Oil Equivalent

Source: UNCTAD based, June 2005
Estimating Gas & Liquid Recovery Factors
Phase Diagram of Retrograde Condensate Fluid

- **Liquid**
- **Critical Point**
- **Undersaturated**
- **A**
- **A Saturated**
- **B**
- **Retrograde**
- **Stock tank**
- **Gas**

Pressure vs. Temperature diagram showing:
- % liquid
- Temperature at atmospheric pressure ($T_{atm}$)
- Temperature at reservoir pressure ($T_{res}$)
Condensate Banking & Role of $N_c$

$N_c = \mu v / \sigma$

(after Kamath, JPT, April 2007)
Gas RF: Low-Perm, Low-Yield Scenario

Effect of Perforated Length

10 md, 45 STB/MMscf

Gas Rate (MMscf/d)

Gas Rate (MMscf/d)

Effect of Skin

(after SPE 95531, 2005)
Gas Recovery Correlated to Five Variables

\[ RF = 46.682 + 0.585*\text{Perm} - 0.091*\text{Yield} - 1.448*\text{Skin} + 42.51*\text{Perf Int} \]
\[ - 0.00135*\text{Perm}^2 + 0.003772*\text{Perm}*\text{Skin} \ldots \]

(after SPE 95531, 2005)
Effect of Yield and Permeability on Gas RF

RF = 57.605 + 0.16*Perm - 0.014*Yield – 0.00014*Perm² - 0.000146*Yield²

(after SPE 95531, 2005)
To Cycle or Not to Cycle

Up-dip Producer

Down-dip Injector

(after SPE 95531, 2005)
Recovery Factor Correlation to Evaluate Potential Cycling Candidates

RF = 0.459 – 0.00067*Yield – 0.00004*Perm - 0.355*VRR – 0.028*PID + 0.277*VRR*PID

Observed Cond. RF

Predicted Cond. RF

R^2 = 0.9874

(after SPE 95531, 2005)
Incremental Condensate RF in Cycling

Inc. RF (%) = 8.532 - 0.0057*Perm - 37.14*VRR - 3.44*PID + 28.52*VRR*PID

(after SPE 95531, 2005)
Summary

- Condensate Banking Impairs Gas Recovery
  - Impairment Severe for Low-Perm, High-Yield Systems
  - Completion Issues Important in Low-Perm Systems

- In Gas Cycling, Liquid Recovery Improves When
  - VRR > 75%
  - PID > 2.5 km

- Appropriate Correlations Presented for Initial Assessment of G-C Systems
Estimating Well Count & Pipe Diameter
Gas Supply Network for an LNG Plant

- Well Count
- Pipe Dia

(15-km ‘O’ Flowline)

(5-km ‘F’ Flowline)

(Separator)

Well

Reservoir

(after SPE 95528, 2005; SPEREE, June 2007)
Homogeneous Model’s Performance in Gas/Condensate Wells

\[ p_{wfH} = 0.9952 \ p_{wfm} \]

\[ R^2 = 0.9936 \]

167 Tests

Compared with measured values, computed values are within ±10% of the measured values.

(after SPE 89754, SPEPO, Feb. 2006)
Comparison of MB & FD Solutions

$q_c$ or $q_w$
STB/D

$q_g$
MMscf/D

Date
1/14/04 10/10/06 7/6/09 4/1/12 12/27/14

(after SPE 95528, 2005; SPERE, June 2007)
Results From DST & Volumetric Analyses

<table>
<thead>
<tr>
<th>OGIP Ratio</th>
<th>k (md)</th>
<th>h (ft)</th>
<th>s</th>
<th>D (D/Mscf)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5,115</td>
<td>67</td>
<td>187</td>
<td>0.097</td>
</tr>
<tr>
<td>1.16</td>
<td>2,770</td>
<td>30</td>
<td>30</td>
<td>0.0112</td>
</tr>
</tbody>
</table>

(after SPE 89753, SPEREEN, Feb. 2006)
Performance Comparison of Completion Scenarios

Completion Scenarios:
- 1.1
- 3.2
- 4.4
- 22.2

Cumulative Gas (Bscf):
- 16
- 18
- 20
- 22

Cumulative Cond (MSTB):
- 16
- 18
- 20
- 22

Completion kh Ratio (M-6/M-7):
- 1.1
- 3.2
- 4.4
- 22.2

(after SPE 89753, SPEREE, Feb. 2006)
Discounted Income Comparison

Discounted Gas Income

<table>
<thead>
<tr>
<th></th>
<th>Intelligent</th>
<th>SPC</th>
<th>Conventional</th>
</tr>
</thead>
<tbody>
<tr>
<td>Million$</td>
<td>75</td>
<td>74</td>
<td>73</td>
</tr>
</tbody>
</table>

Discounted Liquid Income

<table>
<thead>
<tr>
<th></th>
<th>Intelligent</th>
<th>SPC</th>
<th>Conventional</th>
</tr>
</thead>
<tbody>
<tr>
<td>Million$</td>
<td>177</td>
<td>176</td>
<td>175</td>
</tr>
</tbody>
</table>

Depletion Time

<table>
<thead>
<tr>
<th></th>
<th>Intelligent</th>
<th>SPC</th>
<th>Conventional</th>
</tr>
</thead>
<tbody>
<tr>
<td>Year</td>
<td>12</td>
<td>6</td>
<td>0</td>
</tr>
</tbody>
</table>

(after SPE 89753, SPEREE, Feb. 2006)
Essence of a Simple Simulator

Single-Reservoir, Single-Well, Spreadsheet-Based Simulator

- Gas Properties Correlations: Gas Viscosity, $B_g$, Z-factor, etc
- Material-Balance Model
- Wellbore Model for Homogeneous Flow

Input
- Fluid Properties
- Reservoir Properties
- Completion Details
- Production Constraints
- Economic Scenario

Computations
- Material Balance
- Wellbore Model
- Economic Evaluation

Output
- Rate Forecast
- Cum Production
- Res Pressure Forecast
- NPV

(after SPE 95528, 2005; SPEREE, June 2007)
# Template for a Deterministic Run

<table>
<thead>
<tr>
<th></th>
<th>M-6</th>
<th>M-7</th>
<th>R-1</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Reservoir/Fluid Variables</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>OGIP (Bscf)</td>
<td>306</td>
<td>238</td>
<td>586</td>
</tr>
<tr>
<td>Initial Pressure (psia)</td>
<td>5,800</td>
<td>5,800</td>
<td>5,800</td>
</tr>
<tr>
<td>Reservoir Temperature (F)</td>
<td>241</td>
<td>241</td>
<td>241</td>
</tr>
<tr>
<td>Gas Gravity (-)</td>
<td>0.68</td>
<td>0.68</td>
<td>0.68</td>
</tr>
<tr>
<td>Reservoir Permeability (md)</td>
<td>6,646</td>
<td>2,894</td>
<td>151</td>
</tr>
<tr>
<td>Net Pay (ft)</td>
<td>150</td>
<td>150</td>
<td>200</td>
</tr>
<tr>
<td><strong>Reservoir Geometry/ Wellbore</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Area (acres)</td>
<td>930</td>
<td>930</td>
<td>1,620</td>
</tr>
<tr>
<td>Shape factor</td>
<td>30.88</td>
<td>30.88</td>
<td>30.88</td>
</tr>
<tr>
<td>Skin</td>
<td>20</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>Non-Darcy Coefficient (D/Mscf)</td>
<td>0.00097</td>
<td>0.00097</td>
<td>0.00047</td>
</tr>
<tr>
<td>Wellbore Radius (ft)</td>
<td>0.25</td>
<td>0.25</td>
<td>0.25</td>
</tr>
<tr>
<td><strong>Production Constraints</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Imposed Constant Rate (MMscf/D)</td>
<td>140</td>
<td>140</td>
<td>145</td>
</tr>
<tr>
<td><strong>Wellbore Model Variables</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tubing Inside Diameter (in)</td>
<td>4.95</td>
<td>4.95</td>
<td>4.95</td>
</tr>
<tr>
<td>Wellhead Pressure (psig)</td>
<td>1,000</td>
<td>1,000</td>
<td>1,000</td>
</tr>
<tr>
<td>Wellhead Temperature (F)</td>
<td>80</td>
<td>80</td>
<td>80</td>
</tr>
<tr>
<td>Well depth (ft)</td>
<td>10,000</td>
<td>12,000</td>
<td>10,000</td>
</tr>
<tr>
<td>Pipe roughness ratio</td>
<td>0.0018</td>
<td>0.0018</td>
<td>0.0018</td>
</tr>
</tbody>
</table>
Deterministic Cumulative Production

Base Production
(1 Well in Each Reservoir)

Cumulative Production MMscf

Time, days

2nd Well

M-7
M-6
R-1

(after SPE 95528, 2005; SPERE, June 2007)
Deterministic NPV for Assessing Well Count

NPV ($MM)

- M-6 w/o 2nd well
- M-6
- M-7 w/o 2nd well
- M-7
- R-1

Determined by: SPE 95528, 2005; SPERE, June 2007
Well

Uncertainty at well location set to zero

Depth Surface From P-50 $V_{avg}$

Velocity-Model-derived Depth Uncertainty

Realizations of Depth Surface

100 top depth surfaces of M-6 Sand

(after SPE 95528, 2005; SPERE, June 2007)
Probability Distribution of OGIP in M-6 Sand

(after SPE 95528, 2005; SPEREE, June 2007)
Probabilistic NPV for Each Reservoir

Cum Probability fraction

NPV, MM$

M-7
M-6
R-1

(after SPE 95528, 2005; SPERE, June 2007)
Modeling Multiple Reservoirs w/Uncertainties
Discerning Pipe ID

15-km ‘O’ Flowline

5-km ‘F’ Flowline

Separator

Well
Reservoir

(after SPE 95528, 2005; SPERE, June 2007)
Decision Management System

Production Profile
- Material Balance
- Volumetric Uncertainty
- Fluid Yield Uncertainty

Surface Network
- Well & Surface Network
- ‘F’ Pipeline ID
- ‘O’ Pipeline ID

Economics
- Spreadsheet
- CAPEX
- OPEX

(Graphics)

$NPV
DPI

(after SPE 95528, 2005; SPERE, June 2007)
Cum Gas Shows Delivery Certainty

Cum Gas Tscf

Days

0 1000 2000 3000 4000 5000

0 0.5 1.5 2.5

(after SPE 95528, 2005; SPEREE, June 2007)
Cum Liquid Shows Uncertainty Spread

(after SPE 95528, 2005; SPERE, June 2007)
CDF’s of Various Pipe Combinations
500 LH Sampling

<table>
<thead>
<tr>
<th>Diff DPI</th>
<th>16/16</th>
<th>7</th>
<th>9</th>
<th>11</th>
</tr>
</thead>
<tbody>
<tr>
<td>-0.01</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.01</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(after SPE 95528, 2005; SPEREE, June 2007)
Assessing Reservoir Compartmentalization Issue
Diagnosing Reservoir Performance

Infinite-Acting
Plateau Period
Pseudosteady-State

\( p_{wf} \)

\( q \)

(time)

(after SPE 100384, 2006)
Seismic Map Shows Barriers
Deepwater Gas/Condensate Field: FE–2

Are Wells #1 and #4 Separated From Well #3?

This fault probably seals, but only to this point? #4
This fault probably doesn’t extend beyond this point

#3
Shale-filled channel

Possible flow barrier

Net Thickness scale

(after SPE 100384, 2006)
Compartments Evident From Well Behavior

Field Example–2

$P_{wf} = 911.23e^{0.0191q}$

(after SPE 100384, 2006)
Concluding Remarks

• Need for Additional Wells Screened w/Unbiased Tool

• CRWS Modeling When Combined w/Economics Allows
  > Handling Uncertainty in Many Variables
  > Understanding Importance of Decision Variable

• Commingled Completion Feasible When Res Volumes Similar

• Reservoir Compartmentalization Question Answered by Monitoring Pressure and Rate