Flow Modeling Activities: Team Review with Tom Hunter

July 26, 2010 10:00PM CDT
Outline of Report

- Problem Statement
- What is known; what is assumed (as of July 27)
- Review of prior work efforts
- Mass flow estimation opportunities during Shut-in
- Review of 4 computational approaches
- Summary & Assessment
What is Known; What must be assumed

- Known: Limited diagnostics for flow estimation
  - BOP Pressure gauge operational and follows trends
  - Pressure gauges in 3-Ram Capping Stack operating
  - No in-flow temperature measurement capability
  - No direct measurements for possible leaks; to-date, no seismic/sonar quantification of leaks

- **Known: ANYTHING ELSE**

- Assumed: Reservoir depletion of order 2000 psi based on shut-in pressure magnitude

- Assumed: Leakage small (can’t quantify leak rate)

- **Assumed: ANYTHING ELSE**
# History of flow-based estimates of well flow rate prior to Shut-in with 3-Ram Capping Stack

*(See notes, next slide)*

<table>
<thead>
<tr>
<th>Date</th>
<th>Synopsis</th>
<th>Wellhead flow rate (stock bbl/day)</th>
<th>Summary Document</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>5/19/10</td>
<td>4 well scenarios</td>
<td>5000 (specified)</td>
<td>Tri-Lab Pressure Summary</td>
<td></td>
</tr>
<tr>
<td>6/13/10</td>
<td>Video (cut riser)</td>
<td>19,200-46,000</td>
<td>UCSD UW Estimates June 13 (Lasheras)</td>
<td>For Reference/not flow based</td>
</tr>
<tr>
<td>6/15/10</td>
<td>Top Hat 4 fixed flow</td>
<td>72,700-83,000 (baseline, 3 Labs) 51,900-104,900 (max range)</td>
<td>4.2 Flows &amp; Pressures</td>
<td>Uncertainty in skirt flow resistance</td>
</tr>
<tr>
<td>June &amp; July. Various</td>
<td>Flow Variations</td>
<td>50,000 to &gt; 100,000</td>
<td>None</td>
<td>Various attempts to determine total flow from ship flow changes</td>
</tr>
<tr>
<td>7/7/10</td>
<td>Acoustic (fallen riser, no leaks)</td>
<td>18,600-35,700 (0.12m³/s to 0.23m³/s)</td>
<td>Preliminary flow rate calculations using acoustic technologies (Camilli)</td>
<td>For Reference/not flow based</td>
</tr>
<tr>
<td>7/10/10</td>
<td>Well Integrity</td>
<td>0 (shut-in)</td>
<td>7.2 Well Integrity Report</td>
<td>SIWHP range: 8250 – 8750 psi</td>
</tr>
</tbody>
</table>

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6/21/2011
Notes on flow rate modeling history

- **4 Well Scenarios:** Original flow based modeling given four well damage assumptions from BP. All labs made common assumption of 5000 bbl/day flow rate and a fixed BOP pressure. Bottom of well pressure was determined from solution.

- **Video (cut riser):** Results provided via Flow Rate Technical Group during a Science Team conference call. Results done by video analysis. This analysis had three independent cases: flow out fallen riser, flow out kink leaks, flow out cut riser. Only the cut riser results included in the table.

- **Top Hat 4 Fixed Flow:** Tri-Lab effort to calculate total flow rate based on Top Hat 4 leak paths and known surface collection. Great uncertainty in skirt leak path, some uncertainty in pressure measurement inside Top Hat.

- **Flow Variations in Top Hat 4:** Several independent efforts to determine flow rate from known Top Hat & flow rate changes due to shipboard collection rate changes. Generally found that the uncertainties and rate sensitivity made this approach unreliable. Individual attempts by Garwin, Majumdar, Miller, Ratzel.

- **Acoustic:** Results provided via Flow Rate Technical Group during a Science Team conference call. Acoustic analysis of flow out fallen riser, not including kink leaks.

- **Well Integrity:** Tri-Lab effort to determine potential leak rates out of presumed burst disk openings. Model results based on presumed flow rates for open well to define shut-in behavior.

Tri-Lab Assessment – None of methods listed above provide “believable” mass flow results – too many model uncertainties and/or data for quantitative analysis.
Close-in of the 3-Ram Capping Stack provided opportunities for determining mass flow estimates.
Capping Stack Configuration and Pressure Transducer Details

- Bolted onto BOP Manifold on July 13
- Stacking Cap includes 3 Rams. For Shut-in test, top and bottom rams fully open and middle ram closed
- Pressure transducers located between bottom and middle rams
  - ~75 ft above sea floor
  - 2 transducers on single head; signals transmitted acoustically
  - Teledyne Cormon transducer; valid thru 15 kpsi;
  - Transducer accuracy quoted at 0.2% at FS (15psi)
- WHAT ELSE?

6/21/2011
Mass Flow Rate estimates are possible from monitoring flow through the Capping Stack Choke and Kill Line

The shut-in test conducted July 14-15 required flow isolation of both lines
1. During final preparations for test on June 14\textsuperscript{th}, a leak in the choke line required test abort; all flow diverted to kill line
2. Over evening/early morning, some of flow collected by HP1 and Q4000 while choke line was being replaced
3. Prior to shut-in, only the choke line remained open
4. Through the shut-in test, pressures were monitored during CC40 Choke valve closure

Key
- Red = 3” I.D. pipe

Kill side
- Ram #2 (closed)
- 3 1/8” gate valve
- ~30”

Choke side
- Ram #1 (open)
- 3 1/8” gate valve
- 18.75”

Total length of 3” pipe With sweep is 96”
CC 40 Choke valve
6” radius sweep
72”

NOTE: NOT TO SCALE

Top Section of Capping stack.
Pressure gauges mounted to 18-3/4” riser section
Aborted Well Closure on July 14
Different flows through Kill Line during repair

1: Exit Pressure (Pchoke open to sea) ~2178 psi

2: Only kill line open;
Pchoke = 2600 psi +/- 30 psi

3: Kill line open with collection upstream;
Pchoke = 2355 psi +/- 40 psi and recovery from Q4000 and HP1 = 20140 bbl/day +/- 1050 bbl/day

- Well Integrity Test preparations started 7/14 around 1:00 PM
- Early in testing sequence to isolate choke line, a leak was uncovered in the choke line that led to test termination.
- Choke line was isolated by closing valves connecting line to capping stack; only kill line remained open
- Over evening and into early morning while repairs were being made, flow to Q4000 and HP1 was resumed
Kill Line Analyses – Method 1

(Ron to check)

• Analysis Method: Use two flow conditions
  – All flow through the Kill Line
  – Some flow through the Kill valve, some diverted earlier to HP1 and Q4000 collection vessels

• Resulting Model: See derivation

• Assumptions
  – Assumes fluid density does not significantly change (reasonable assumption since 250 psi pressure level change is small compared to 2500 psi base line; But not completely negligible.)
  – Assumes resistance does not significantly change (may be reasonable, but two phase flow can be quite touchy)
  – Assumes total flow from well does not significantly change due to changing sink pressure (an increase in the back pressure by 250 psi can alter the total flow)
  – Any others?
Flow estimates for step change in flow and pressure measurement

(Ron to check)

- Flow through a constant resistance
  \[ \Delta P_1 = kQ^2 \]

- Modify flow rate due to known collection rate change (d)
  \[ \Delta P_2 = k(Q + \delta)^2 \]

- Solve for original flow (Q)

Ron – Please Put in final Eq. here

Note: Required Pressure and collection rate data are obtained from BP and maintained in SharePoint file system
Kill Line Analyses – Method 1 (contd)
(Ron to complete)

• Model Advantages
  – Geometrical effects minimized
  – What else

• Model Limitations/Issues
  – Fill in

• Results
  – Could be a chart and/or tabulations – be sure to add a statement on
    uncertainties, even if currently a WAG

POC – Ron Dykhuizen, Sandia
Kill Line Analyses – Method 2
(Wayne to check/finish)

• Analysis Method: Flow through the Kill Line
  – Model flow restrictions between the pressure gage and exit
  – Use measured Pchoke and known Psea
  – Two cases:
    • Flow only through kill line to exit
    • Some flow through the Kill valve to exit, some diverted earlier to HP1 and Q4000 collection vessels

• Resulting Model: Network Model
• Assumptions
Kill Line Analyses – Method 2 (contd)

(Wayne to check/finish)

- Model Advantages
  - Simple Geometry
  - What else

- Model Limitations/Issues
  - Fill in

- Results
  - Could be a chart and/or tabulations – be sure to add a statement on uncertainties, even if currently a WAG

POC – Wayne Miller, LLNL
Choke Line Analyses – Method 3
Closure Test of July 15
(Curtt to check/finish)

Closure Test of July 15
- Completed repairs to choke line to eliminate leak
- Opened choke line
- Took Q4000 and HP1 collection systems off-line
- Closed valves to kill Line; flow only through choke line
- Closed choke valve in 16 steps (see vgs to follow) to achieve full shut-in; monitored choke pressure

POC – Curttt Ammerman with Multiple modelers – need each to fill in this vg – Art will compile
Choke Line Analyses – Method 3

(Curtt to check/finish)

• Analysis Method: Predict Flow through the Choke Line
  • Model flow restrictions between the pressure gage and exit
  • Use measured Pchoke and known Psea

• Resulting Model: Network Model (may want to lay-out the network model or show a summation equation for the collection of restrictions)

• Assumptions:

POC – Curtt Ammerman with Multiple modelers – need each to fill in this vg – Art will compile
Results from Well Integrity Shut-in Test of July 15

Pressure records available from SharePoint records
**CC40 Choke valve characteristics and choke pressure data for July 15 well integrity shut-in test**

<table>
<thead>
<tr>
<th># Turns</th>
<th>Pchoke**</th>
<th>% Open</th>
<th>Cv</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>2991-3061</td>
<td>100</td>
<td>251</td>
</tr>
<tr>
<td>2</td>
<td>3000-3075</td>
<td>86</td>
<td>250</td>
</tr>
<tr>
<td>2.5</td>
<td>3024-3099</td>
<td>78</td>
<td>240</td>
</tr>
<tr>
<td>3</td>
<td>3061-3140</td>
<td>69</td>
<td>220</td>
</tr>
<tr>
<td>3.5</td>
<td>3155-3230</td>
<td>59</td>
<td>195</td>
</tr>
<tr>
<td>4</td>
<td>3309-3384</td>
<td>50</td>
<td>165</td>
</tr>
<tr>
<td>4.5</td>
<td>3586-3672</td>
<td>41</td>
<td>133</td>
</tr>
<tr>
<td>5</td>
<td>4059-4149</td>
<td>32</td>
<td>103</td>
</tr>
<tr>
<td>5.5</td>
<td>4655-4748</td>
<td>23</td>
<td>76</td>
</tr>
<tr>
<td>6</td>
<td>5502-5602</td>
<td>16</td>
<td>49</td>
</tr>
<tr>
<td>6.5</td>
<td>6113-6220</td>
<td>9</td>
<td>22</td>
</tr>
<tr>
<td>7</td>
<td>6301-6408</td>
<td>5</td>
<td>11</td>
</tr>
<tr>
<td>7.5</td>
<td>6441-6548</td>
<td>2</td>
<td>5</td>
</tr>
<tr>
<td>8</td>
<td>6469-6578</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>8.5</td>
<td>6497-6605</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

** Higher readings on Pchoke to be used in analysis – compared best with sea pressure at elevation prior to test**

Calibration Curve for CC40 Choke Valve
Choke Line Analyses – Method 3 (contd)
(Curtt to check/finish)

• Model Advantages
  – Analyses does not require knowledge of conditions in BOP and Well section
  – Choke line geometrical effects known;
  – What else

• Model Limitations/Issues
  – Fill in

• Results
  – Could be a chart and/or tabulations – be sure to add a statement on uncertainties, even if currently a WAG

POC – Multiple modelers – need each to fill in this vg – Art will compile
Reservoir-to-Sea Analyses – Method 4

- Analysis Method: Flow through the Well, BOP and Capping Stack to Sea
  - Model flow restrictions between the pressure gage and exit
  - Use measured Pchoke and known Psea
  - Two approaches (both described separately):
    - BULLET FROM MORROW
    - BULLET FROM HAVSTAD

- Resulting Models (see next 2 vgs)
General Assumptions/BCs for Method 4

- Reservoir Pressure
  - 10050 psi (depleted)
  - 11850 psi (initial)

- Temperatures
  - 240°F (reservoir)
  - 180°F (exit of choke line)

- Location of exit flow = Assume ~100’ above sea floor (P_{exit} ~ 2180 psi) – IS THIS RIGHT??

- Use higher of pressure records during shut-in
- Use choke valve characteristics
- PI for reservoir (set by analyst)

POC – C. Morrow & M. Havstad
Method 4: Model #1 Description
(Morrow to check/finish)

- Model Description *(could put in network model if have it – in particular, may want to show your BOP network model)*
- Model Assumptions
- Model Uncertainties
Method 4: Model #1 Results
(Morrow to check/finish)

• Charts with a bullet or two at bottom on major take-aways
Method 4: Model #2 Description
(Havstad to check/finish)

- Model Description *(could put in network model if have it)*
- Model Assumptions
- Model Uncertainties
Method 4: Model #2 Results
(Havstad to check/finish)

- Charts with a bullet or two at bottom on major take-aways
### Summary of results from 4 methods for estimating well flow rate

**(to be filled in)**

<table>
<thead>
<tr>
<th>Date</th>
<th>Synopsis</th>
<th>Wellhead flow rate (stock bbl/day)</th>
<th>Major Uncertainties</th>
<th>Other Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Method 1: Pressure Differential Analyses</td>
<td>Kill Line Studies – uses two flow conditions</td>
<td>TBD</td>
<td>TBD</td>
<td>TBD</td>
</tr>
<tr>
<td>Method 2: Flow through Kill Line valve</td>
<td>Computes flow using Pressure at Choke valve and sea pressure through kill line</td>
<td>TBD</td>
<td>TBD</td>
<td>TBD</td>
</tr>
<tr>
<td>Method 3: Flow through Choke Line</td>
<td>Computes flow using Pressure at Choke valve and sea pressure through choke line</td>
<td>TBD</td>
<td>TBD</td>
<td>TBD</td>
</tr>
<tr>
<td>Method 4: Flow from Reservoir to sea</td>
<td>Uses choke and sea pressure and results from first 3 methods - includes flow through BOP and provides estimate for BOP pressure during close-in</td>
<td>TBD</td>
<td>TBD</td>
<td>TBD</td>
</tr>
</tbody>
</table>
Flow Rate Calculation Conclusions

- To Be FILLED IN AFTER RESULTS ASSEMBLED