# SPE-API Technical Luncheon: "Developing an Early-Warning System for Well/Reservoir Problems"

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**NEW ORLEANS, LA**
**AUGUST 17, 2010**

# Outline

- Background: Data Acquisition & Processing
  - Data Measurement, Transfer and Visualization
  - Virtual Rate Measurement
- The Wellbore-Completion-Reservoir System
  - PVT
  - Heat Loading & Thermal Modeling
  - Inflow Modeling
- Analysis/Evaluation Tools
  - PTA, RTA, Decline Analysis, p/z
  - Nodal Analysis
  - Reservoir Simulation

# Outline II

- Creating an On-line Well Monitoring package
  - Take a batch process and make it continuous
  - The Hard Parts in More Detail
    - Wellbore Thermal and PVT Modeling
    - Completion Model
    - Reservoir Model (WaveX Reservoir Model)
    - Don't Forget the Coupled Effects
  - Need to have a Closed Solution for Well Bore and Reservoir
  - Effective Transient & Regime Recognition
  - Combine steady-state and transient effects into same system of eqns
  - Include Internal Checks for Validity

# Outline III

- Examples of RT Process
- Conclusions

# Data Acquisition: Instrumentation

- What do I really need to measure accurately?
  - Wellhead Pressure
  - Wellhead Temperature (Thermowell)
  - Flow Rates of Oil, Gas & Water
    - Multiphase Meters, Venturi Meters, Turbine Meters
    - Sep T & P
    - Choke Setting
    - Virtual Rate Measurement (VRM)
  - Bottomhole Pressure
  - Bottomhole Temperature
  - Distributed Temperature
  - NOTE: Last 3 not required for gas wells (still nice to have)

# Data Acquisition: Pressure Gauges

- What to ask your gauge supplier:
  - What is the resolution (digital) or “effective resolution” for Scada gauges?
  - How many bits in the A/D converter?
    - (Needs to be >14 for 1 psi resolution)
  - How quickly can it sample or be polled?
  - Is it thermally compensated? How much temperature change is required to cause the pressure to change 1 psi?
  - Does the gauge measure and export its internal temperature?
  - How susceptible is the gauge to plugging?

# A/D Conversion: Scada/DCS

## Resolution based on Scale and A/D Conversion

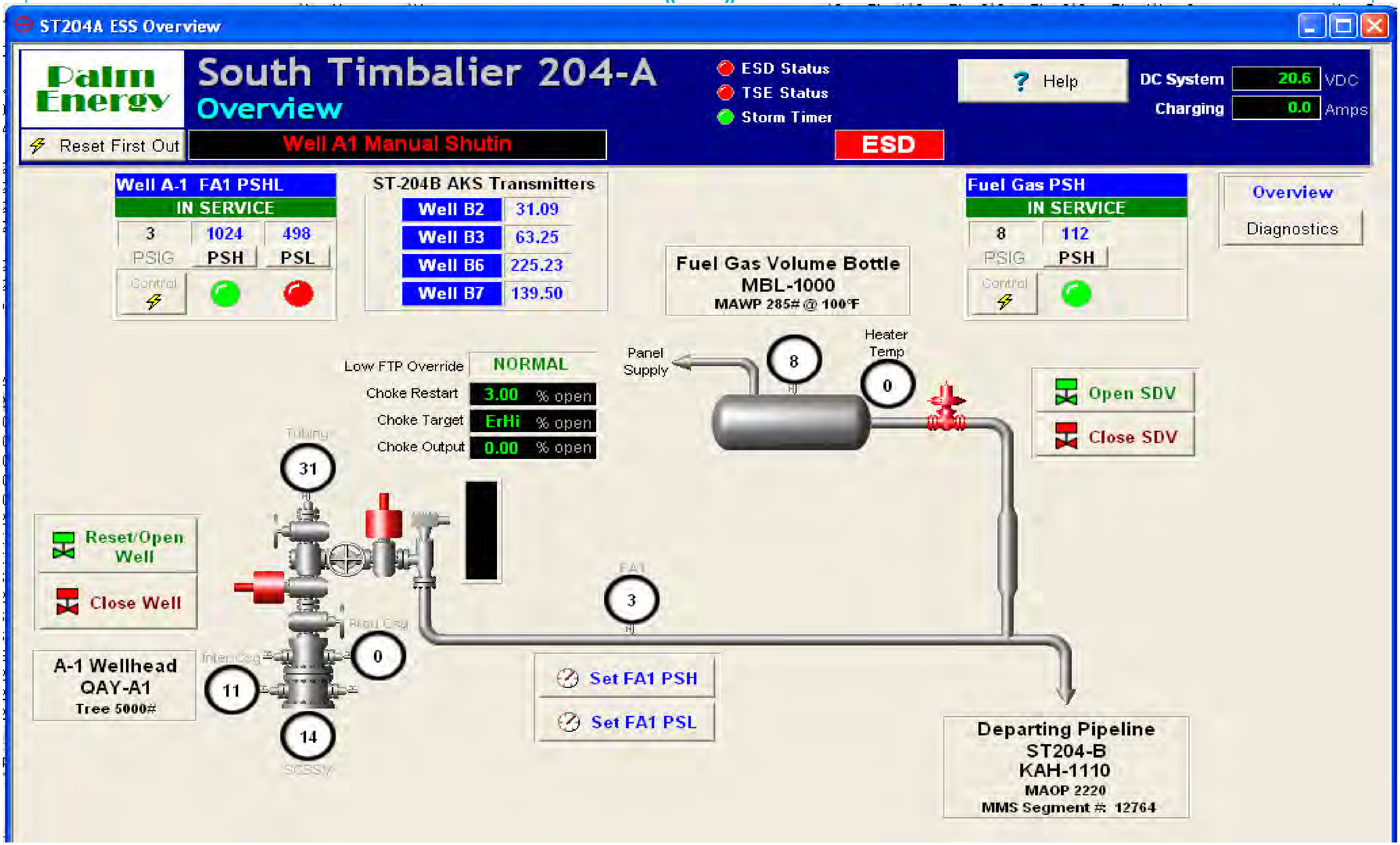
| | Resolution per bit (Bar) | | | | |
|---|---|---|---|---|---|
| Range (bar) | 8 | 12 | 14 | 18 | 24 |
| 0-200 | 0.78125 | 0.048828 | 0.012207 | 0.000763 | 1.19E-05 |
| 0-400 | 1.5625 | 0.097656 | 0.024414 | 0.001526 | 2.38E-05 |
| 0-700 | 2.734375 | 0.170898 | 0.042725 | 0.00267 | 4.17E-05 |
| 0-1000 | 3.90625 | 0.244141 | 0.061035 | 0.003815 | 5.96E-05 |

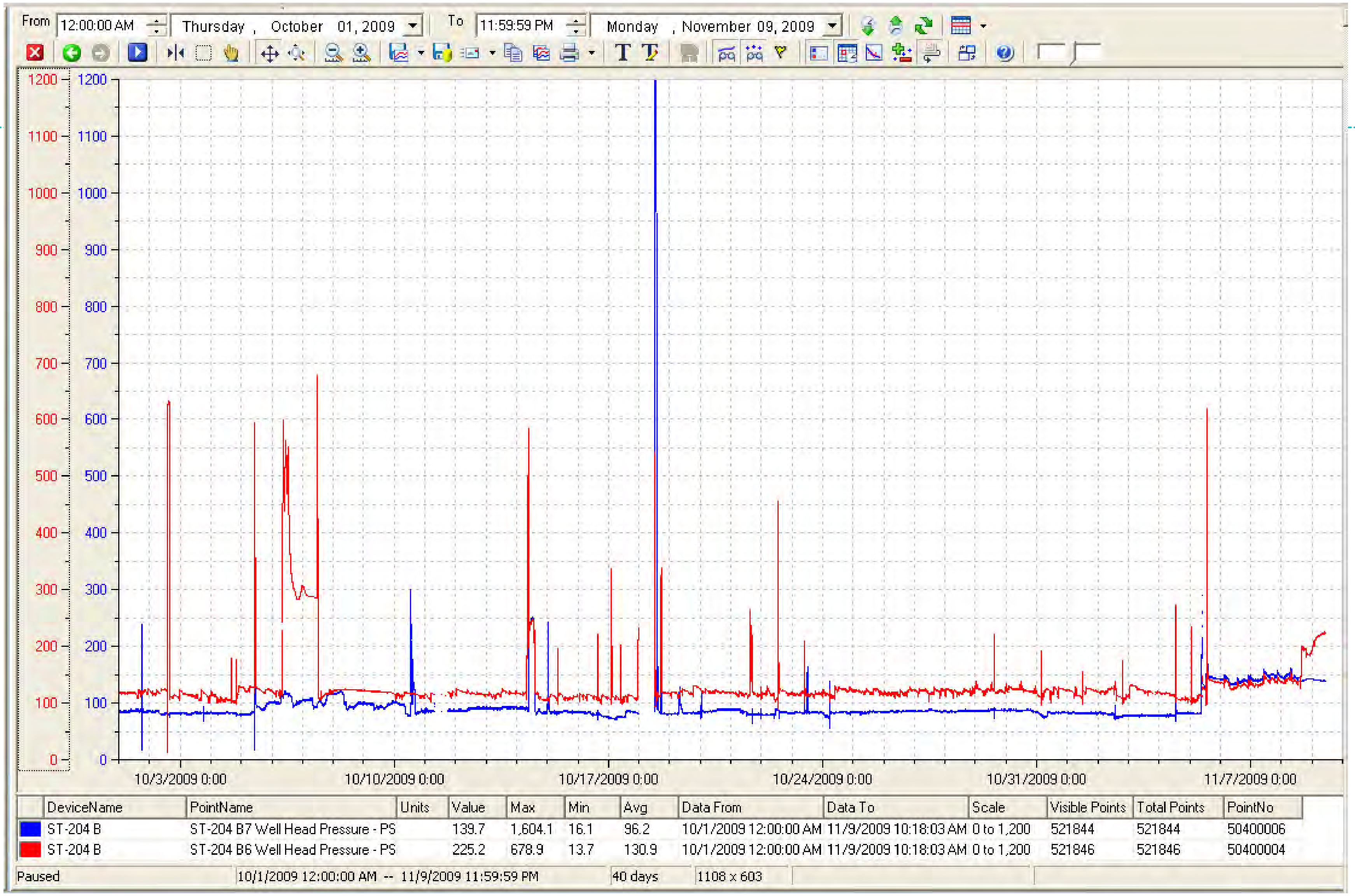
# Data Transfer: Don’t Lose Resolution!

- Before it gets to you, Your Data is likely to pass through:
  - One or two A/D converters
  - An I/O card on the Control Panel
  - Dead-band filters
  - Signal filters
  - Archive filters

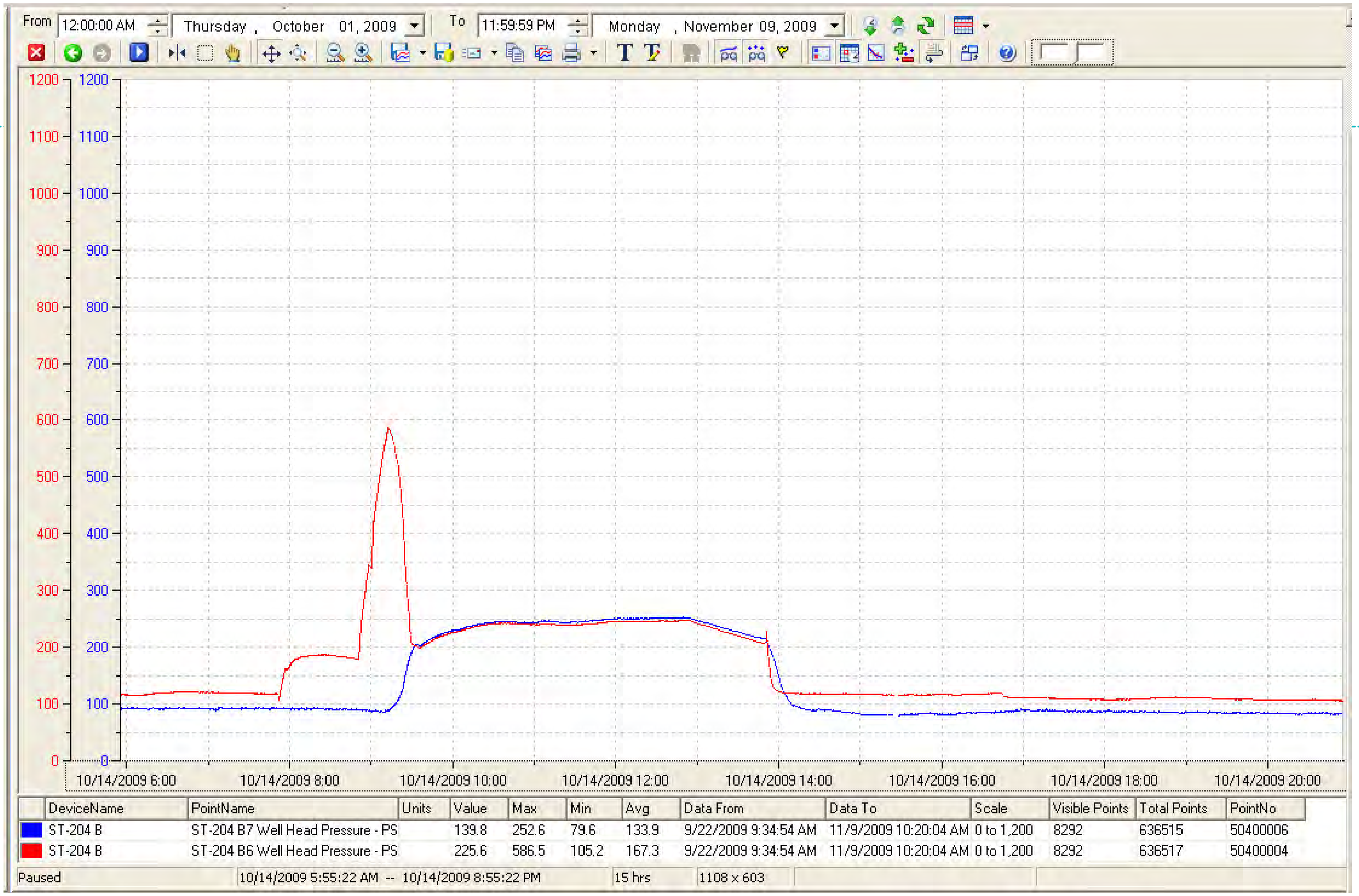
- You can lose sampling resolution and instrument resolution at any point along the way

# Data Visualization






| | DeviceName | PointName | Units | Value | Max | Min | Avg | Data From | Data To | Scale | Visible Points | Total Points | PointNo |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | ST-204 B | ST-204 B7 Well Head Pressure - PS | | 139.7 | 1,604.1 | 16.1 | 96.2 | 10/1/2009 12:00:00 AM | 11/9/2009 10:18:03 AM | 0 to 1,200 | 521844 | 521844 | 50400006 |
| | ST-204 B | ST-204 B6 Well Head Pressure - PS | | 225.2 | 678.9 | 13.7 | 130.9 | 10/1/2009 12:00:00 AM | 11/9/2009 10:18:03 AM | 0 to 1,200 | 521846 | 521846 | 50400004 |

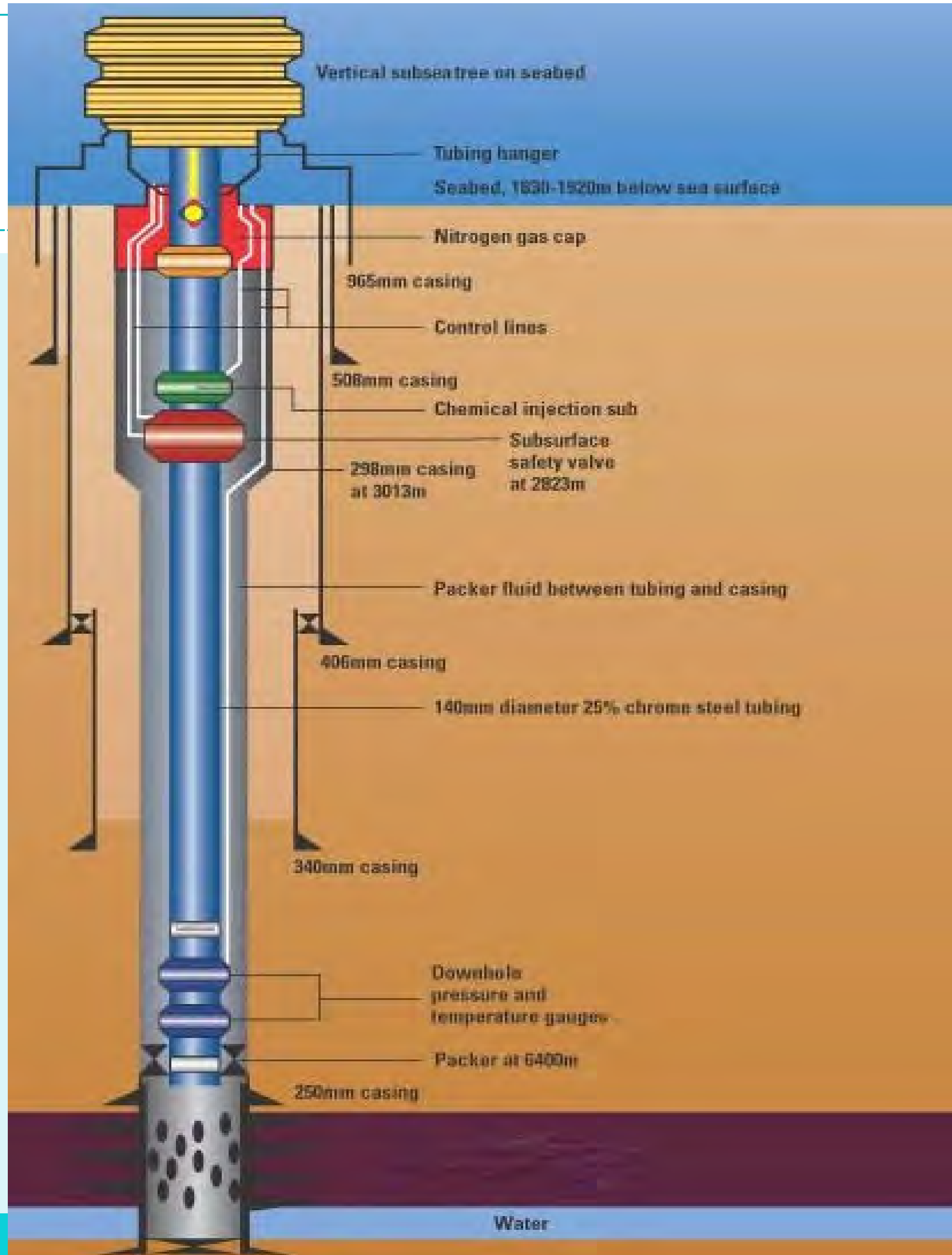



| DeviceName | PointName | Units | Value | Max | Min | Avg | Data From | Data To | Scale | Visible Points | Total Points | PointNo |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ST-204 B | ST-204 B7 Well Head Pressure - PS | | 139.8 | 252.6 | 79.6 | 133.9 | 9/22/2009 9:34:54 AM | 11/9/2009 10:20:04 AM | 0 to 1,200 | 8292 | 636515 | 50400006 |
| ST-204 B | ST-204 B6 Well Head Pressure - PS | | 225.6 | 586.5 | 105.2 | 167.3 | 9/22/2009 9:34:54 AM | 11/9/2009 10:20:04 AM | 0 to 1,200 | 8292 | 636517 | 50400004 |

# Virtual Rate Measurement

- Used for Scenarios where there is not continuous rate measurement
- Common Instances:
  - Use productivity and periodic test sep rates
  - Use choke settings and DPs
  - Use WHT and Heat Loading model
  - Allocation by Difference (Platform)
  - Sonic

# The Wellbore-Completion-Reservoir System



Vertical subseatree on seabed
Tubing hanger
Seabed, 1830-1920m below sea surface
Nitrogen gas cap
965mm casing
Control lines
508mm casing
Chemical injection sub
Subsurface
safety valve
at 2823m
298mm casing
at 3013m
Packer fluid between tubing and casing
406mm casing
140mm diameter 25% chrome steel tubing
340mm casing
Downhole
pressure and
temperature gauges
Packer at 6400m
250mm casing
Water

# Governing Physics Laws & Rules

- Flow in Pipe (Well Bore)
  - 1st Law of Thermo (Mechanical Energy Balance)
  - Fluid Mixing Rules
  - Continuity
- Flow in Reservoir
  - 1st Law of Thermo
  - 2nd Law of Thermo (Power Dissipation Seeks Equilibrium)
  - Darcy's Law (porous media)
  - Radial Coordinates: Flow is Radially Constrained
- Flow in Completion & Near-Well Region
  - Conflicts resolved between Radial Flow and Well Geometry
  - Common Solution is to employ a "skin" factor

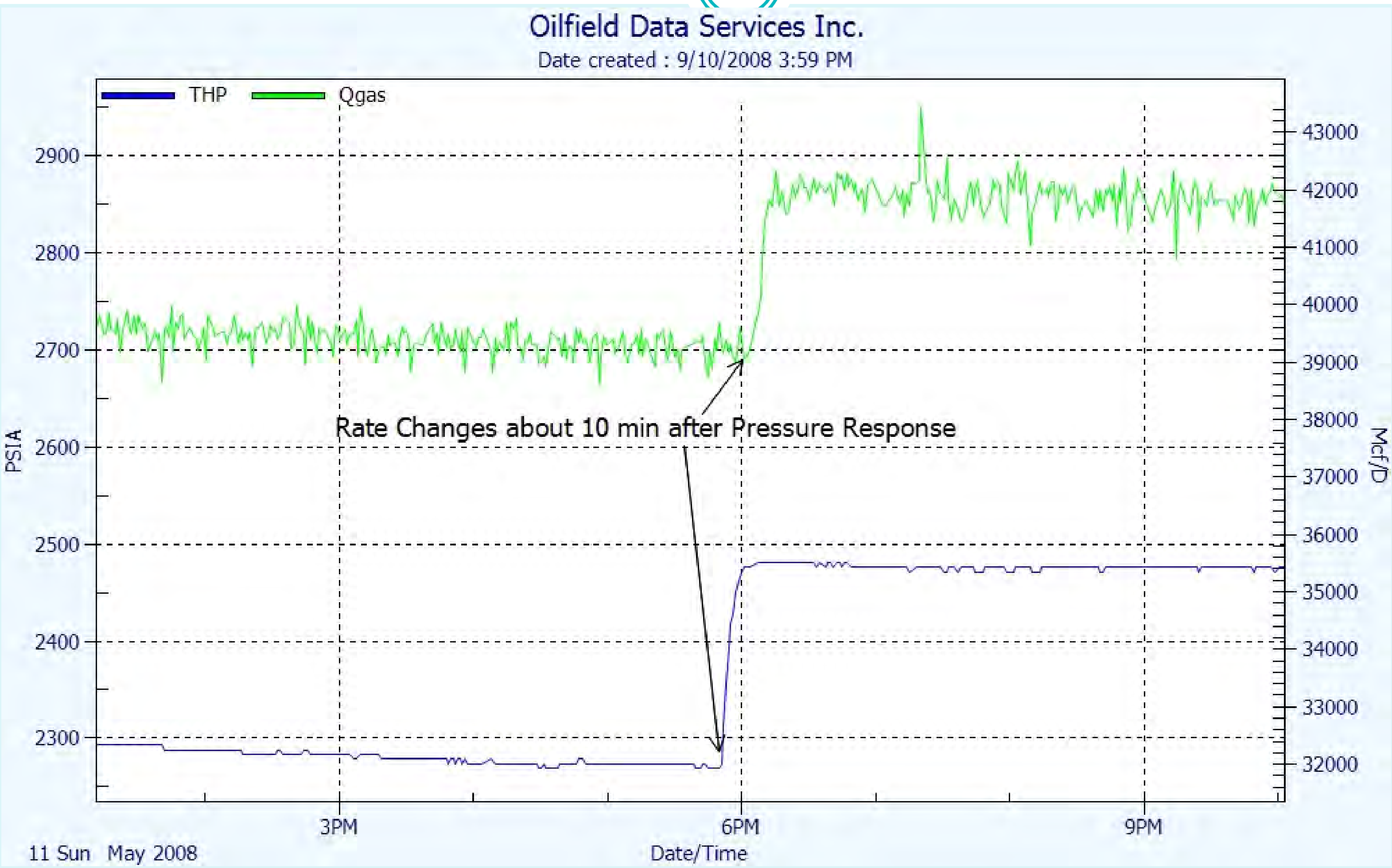
# Important Relationships For Multi-Phase Wells

- Well Bore
  - PVT Relationships
    - Density
    - Viscosity & Internal Energy
    - Effective Friction Contribution
    - Phase Interaction (Phase to Phase & Phase to Pipe BL)
- Rock & Fluid Interactions
  - Formation Compressibility and Elasticity (System Comp)
  - Capillary Forces & Capillary Memory
  - Threshold Pressure (Capillary Entry Pressure)
  - Relative Permeability
  - Inertial Forces

# Other Complications

- Residence Time
- Joule-Thompson Cooling/Heating
- Partial Penetration/Perforation
- Pay Loss/Growth away from Completion
- Coupled Effects
  - Rate Surge/Decay
  - Rate-Thermal
  - Phase Blocking (Water Block, Condy Block)
  - Rate-Thermal-Phase Effects

# Residence Time

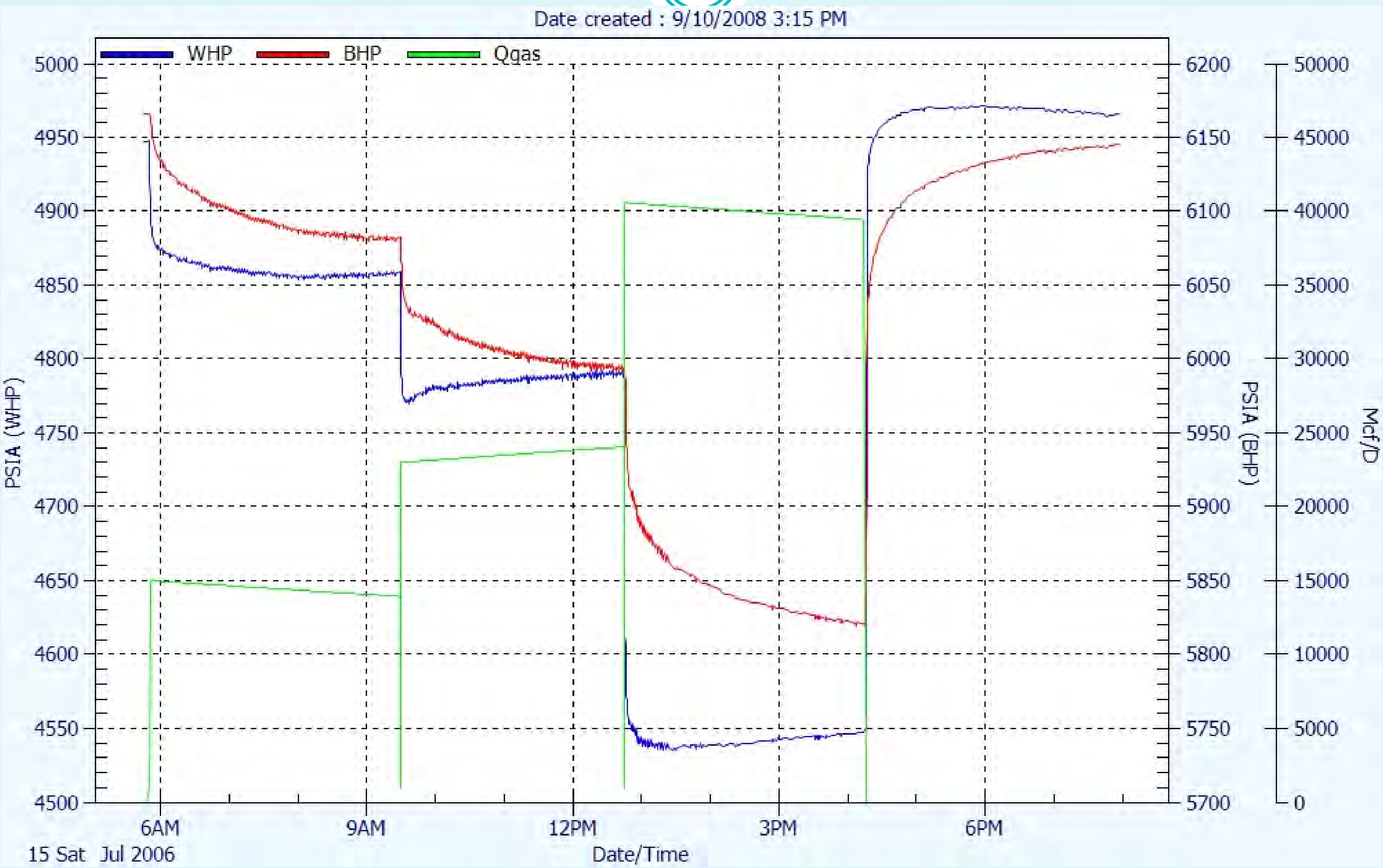


# Rate Surges-Decays

# Coupled Rate-Thermal Problem

- DHG responds "normally"
- WHP gauge responds differently
- WHP increases as DHGP decreases during flow
- Wellbore starts off "cool" & with higher inflow potential (flush production)
- Wellbore heats up, density decreases (head decreases)…mass flow rate decreases…which affects the heat loading…which affects the density…
  - And so on…and so on…
  - Continues until the well reaches thermal equilibrium

# Rate Surge #2



Date created : 9/10/2008 3:15 PM
WHP
BHP
Qgas
PSIA (WHP)
PSIA (BHP)
Mcf/D
5000
4950
4900
4850
4800
4750
4700
4650
4600
4550
4500
6200
6150
6100
6050
6000
5950
5900
5850
5800
5750
5700
50000
45000
40000
35000
30000
25000
20000
15000
10000
5000
0
6AM
9AM
12PM
3PM
6PM
15 Sat Jul 2006
Date/Time

# Analysis/Evaluation Tools

**WHAT THEY ARE AND WHAT THEY TELL YOU**

# Analysis Types and Their Objectives

- PTA (Pressure Transient Analysis)
  - Skin, Perm, Deliverability, Communication, Productivity, Reservoir Boundaries, Reserves
- RTA (Rate Transient Analysis)
  - Same as PTA, but with less reliability on boundaries
- Pres/z Plots (gas) & DPres Plots (oil)
  - Oil and/or Gas in Place
- Decline Analysis: Flowing BHP vs Time
  - Apparent Reserves – Running MBAL
- Inverse Productivity Analysis (DP/DQ vs Time)
  - Apparent Reserves – Running EBAL

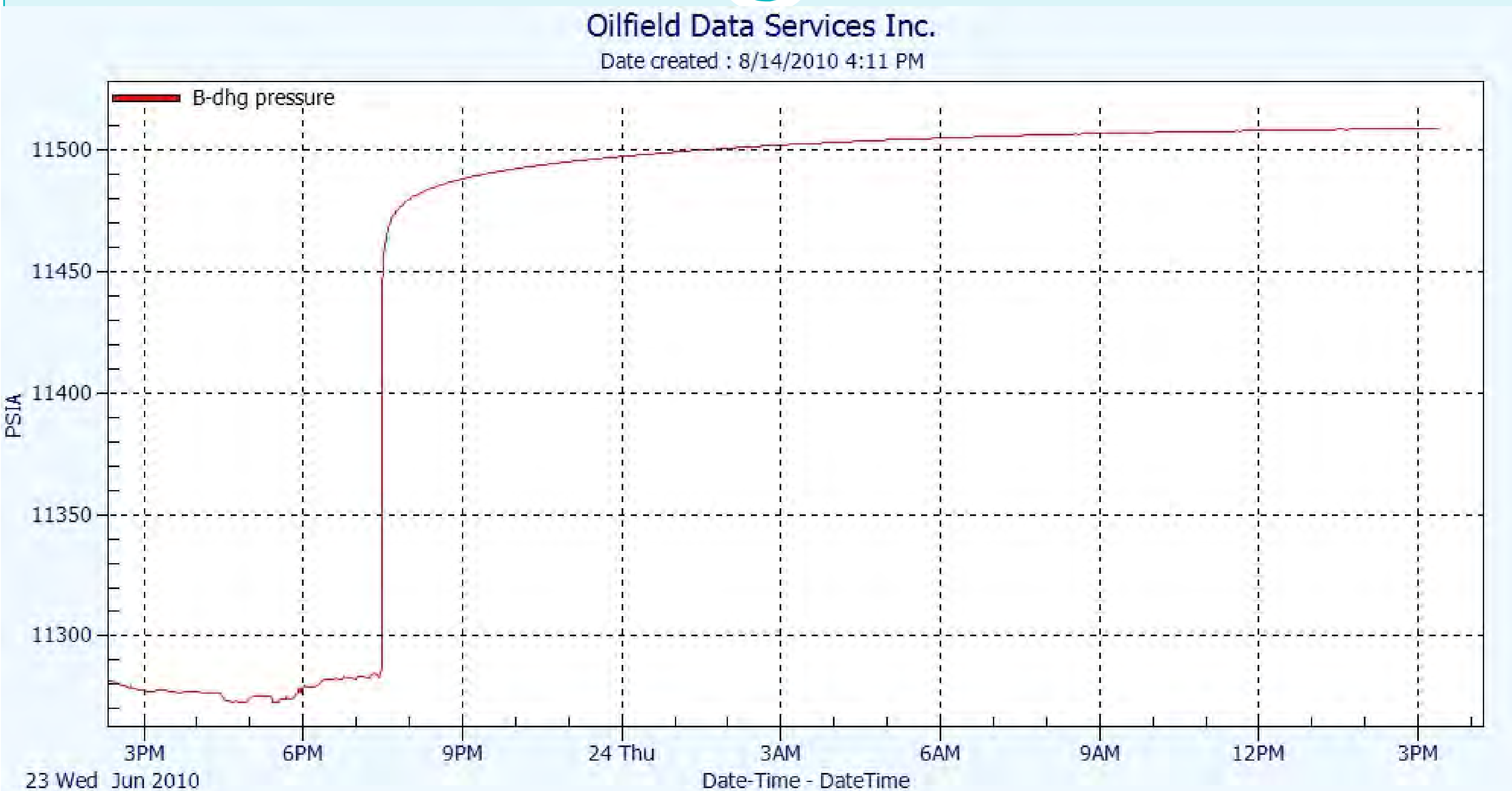
# Analysis/Evaluation Tools: PTA

- Build-up: After flowing the well for a while, shut it in and observe the pressure response
- Drawdown: After shutting in the well for a while, flow it on a constant choke and observe the pressure and rate response
- 2-rate: Change the rate enough to create a new transient; observe P & Q
- Multi-rate: Change the rates and compare DP vs Q
- Communication: Shut-in a well and see if a neighboring well causes the Pressure to drop

# Analysis Type Examples

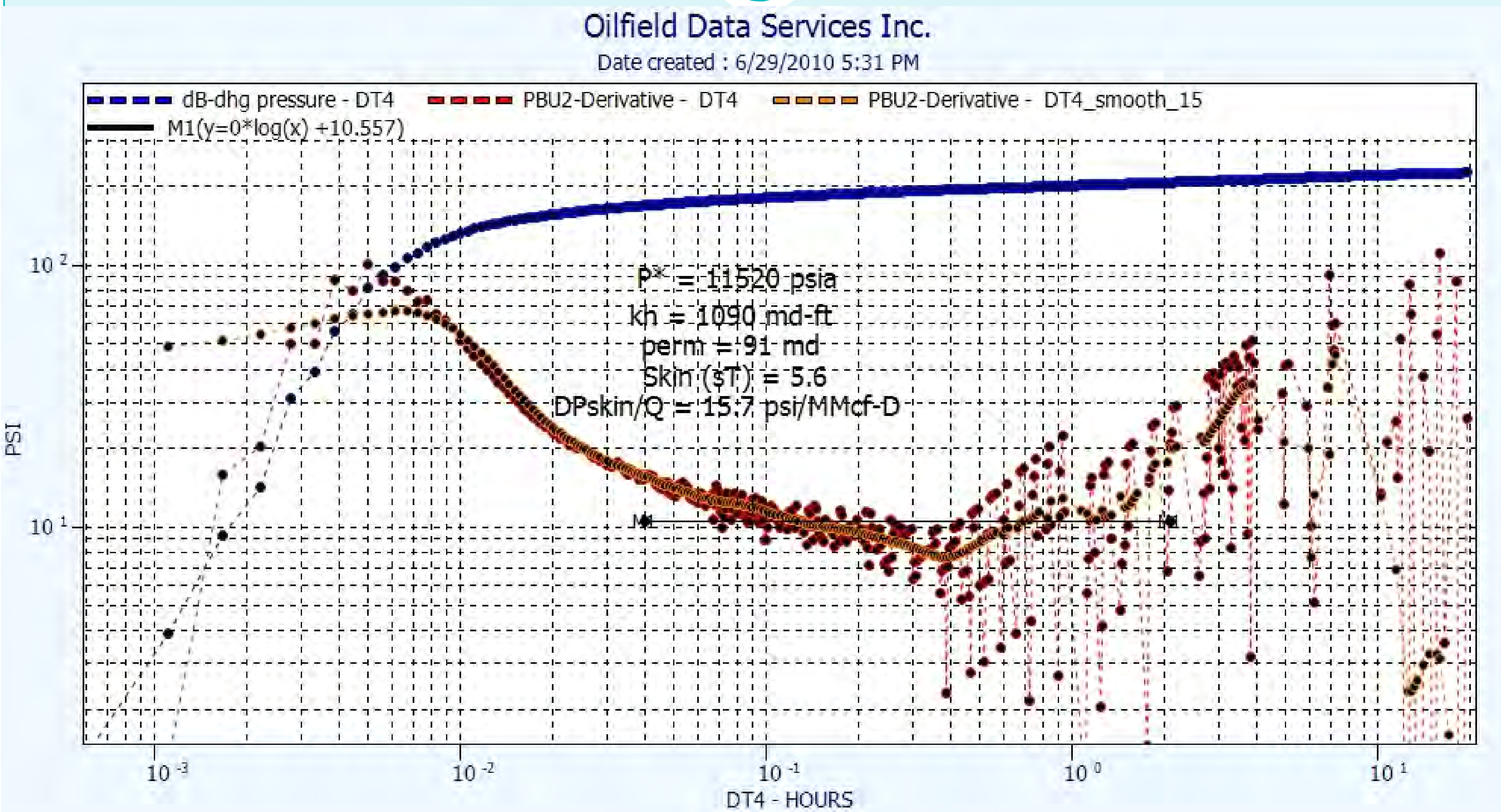
- Build-up PTA Derivative
- Drawdown PTA Semilog
- RTA
- P/z
- Decline Analysis (Running MBAL)
- IPA (Running EBAL)

# Build-up PTA

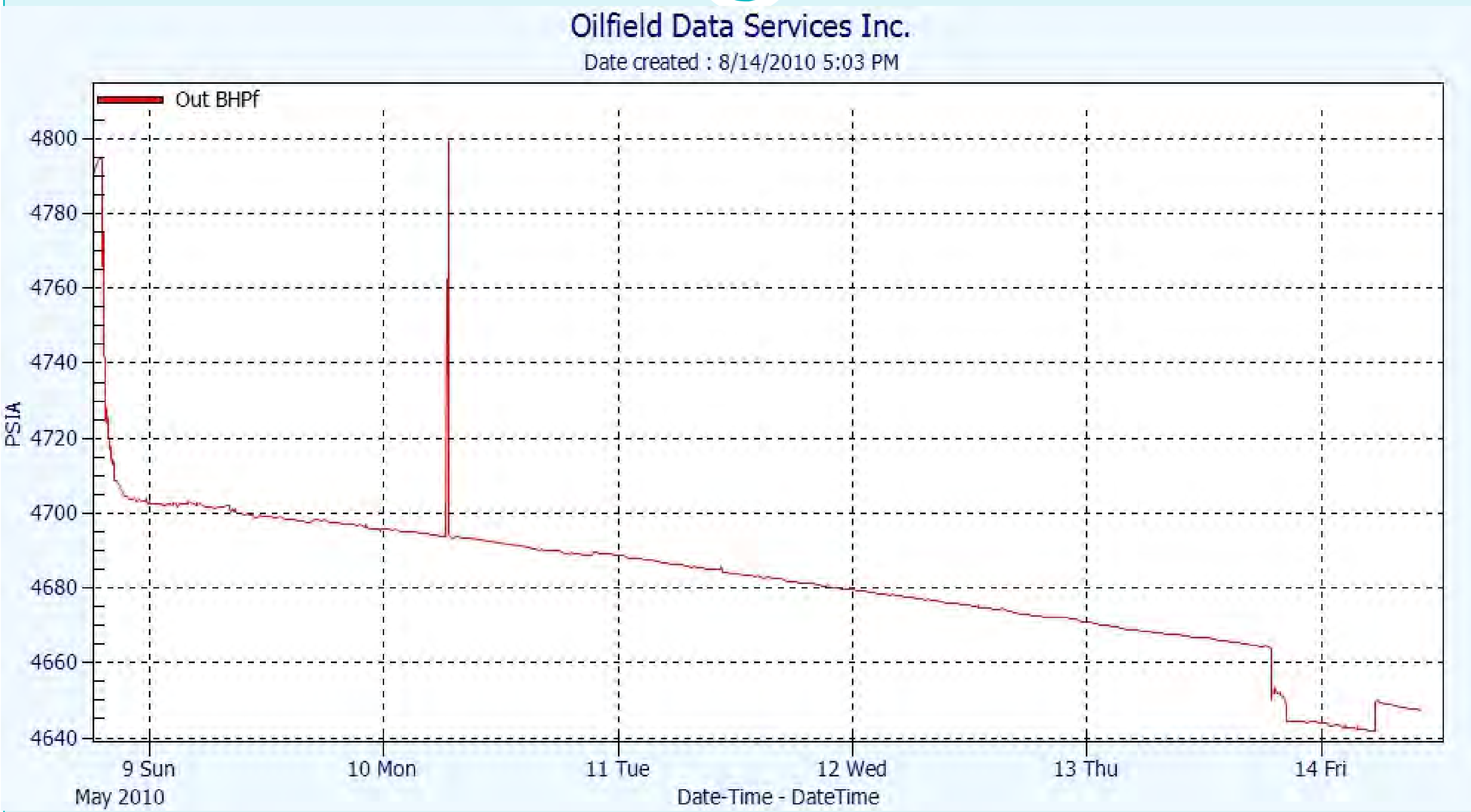


Oilfield Data Services Inc.
Date created : 8/14/2010 4:11 PM
B-dhg pressure
PSIA
11500
11450
11400
11350
11300
3PM
6PM
9PM
24 Thu
3AM
6AM
9AM
12PM
3PM
23 Wed Jun 2010
Date-Time - DateTime

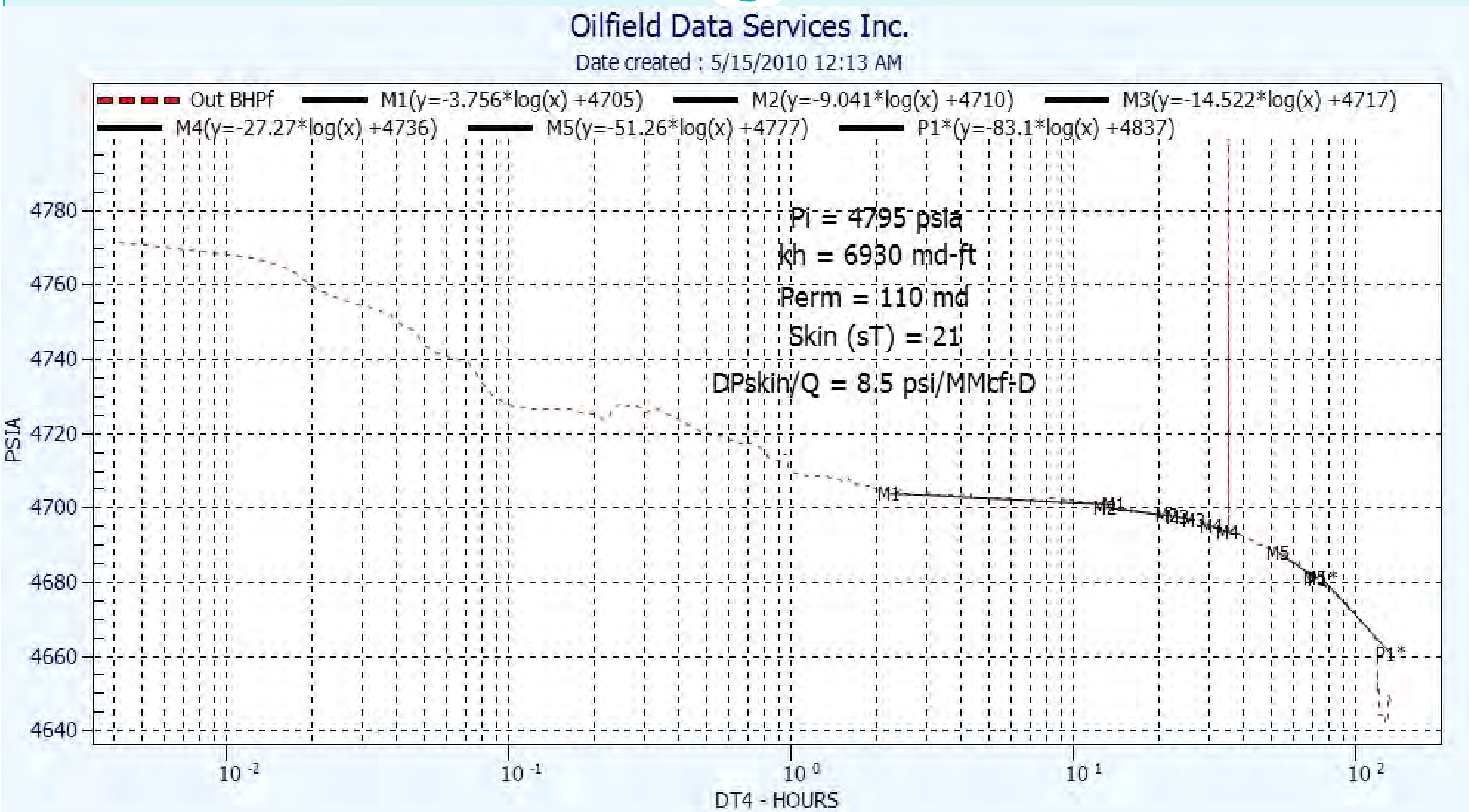
# Build-up Derivative Analysis



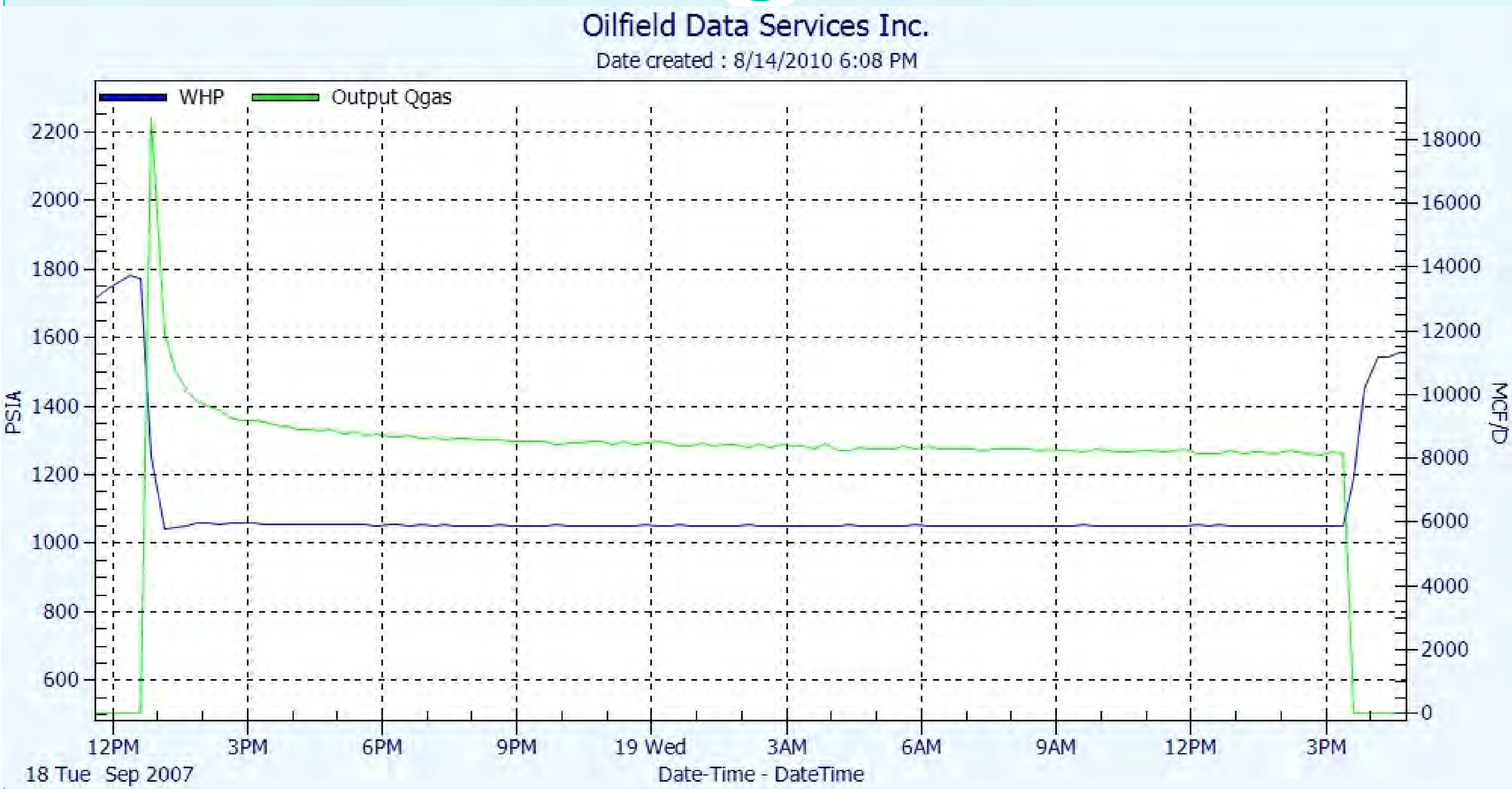
# Drawdown - PTA



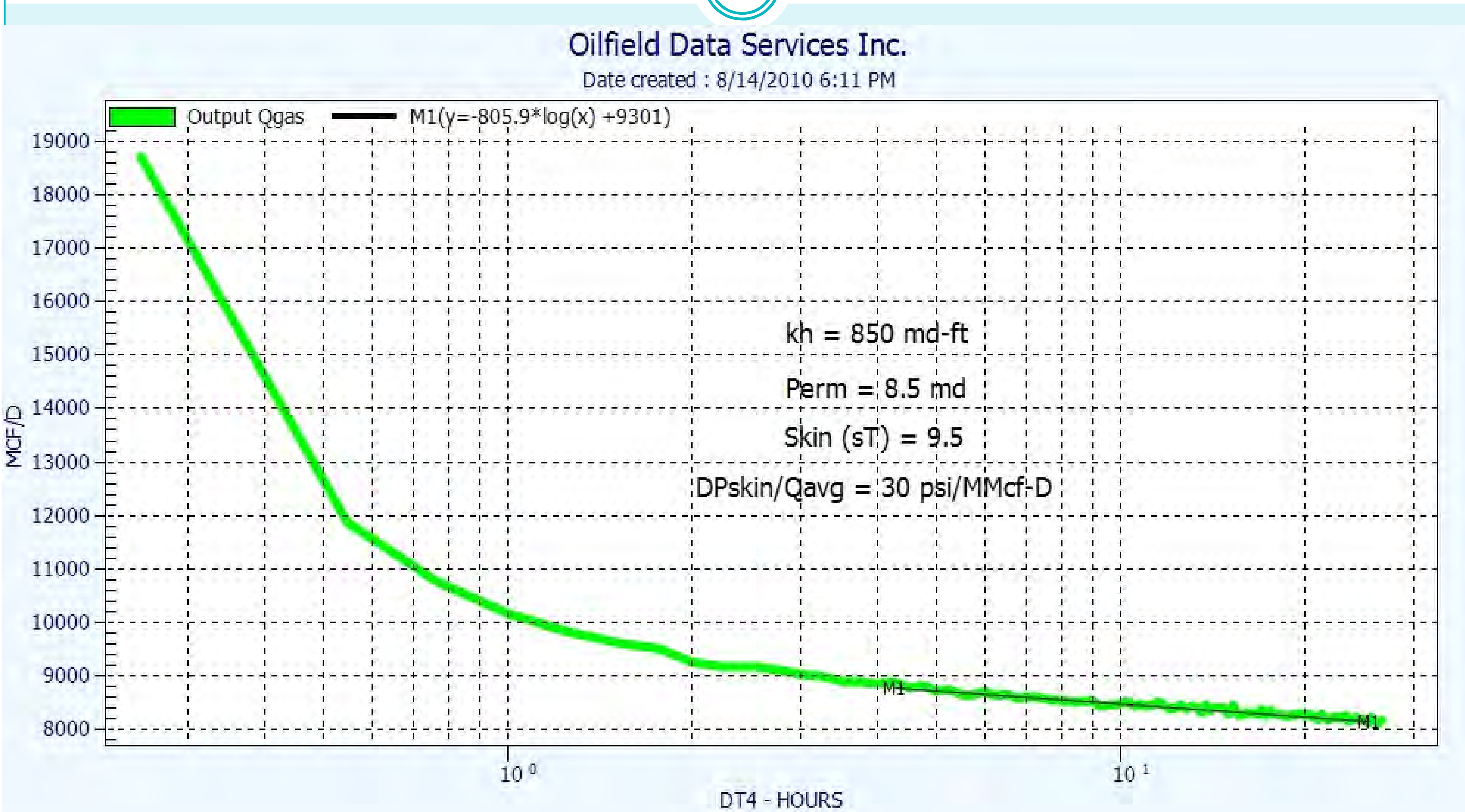
# Drawdown PTA - Semilog Analysis



# RTA Example - Cartesian



# RTA – Semi-log Analysis



# P/z Example

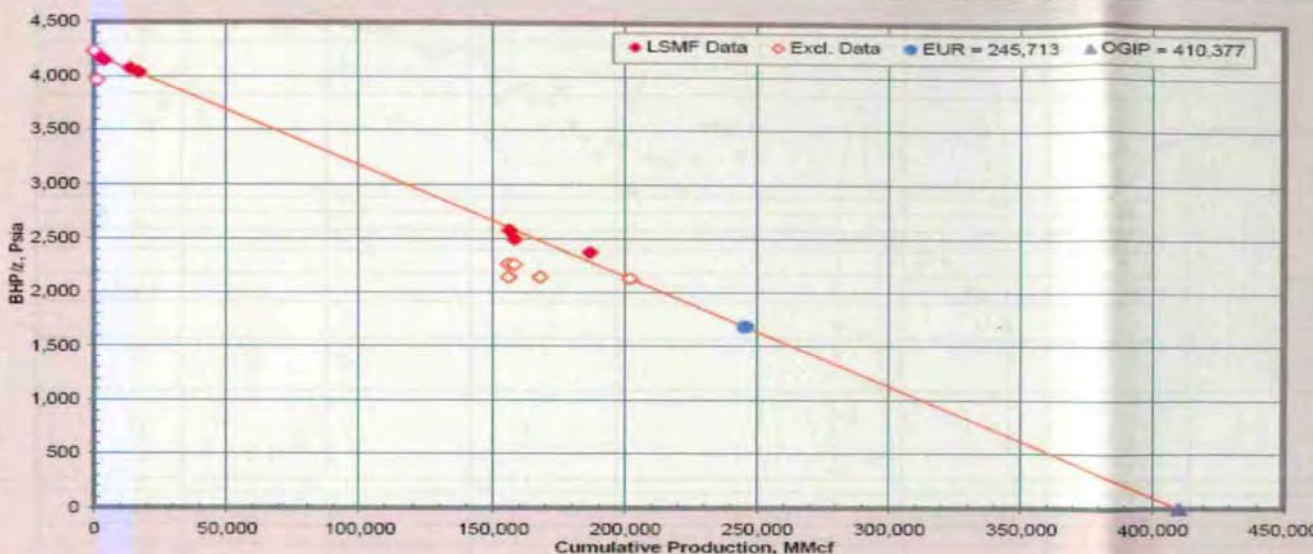
(Protected)

* Wichert-Aziz correction for contaminants, if any

| | |
|---|---|
| WELLHEAD TEMP, °F: | 80.0 |
| BOTTOMHOLE TEMP, °F: | 148.0 |
| WET GAS GRAVITY: | 0.58 |
| TVD, FEET: | 7,000 |
| COND. CORR? (Y/N): | n |
| Corrected* Tc, °R: | 352.30 |
| Corrected* Pc, Psia: | 673.09 |

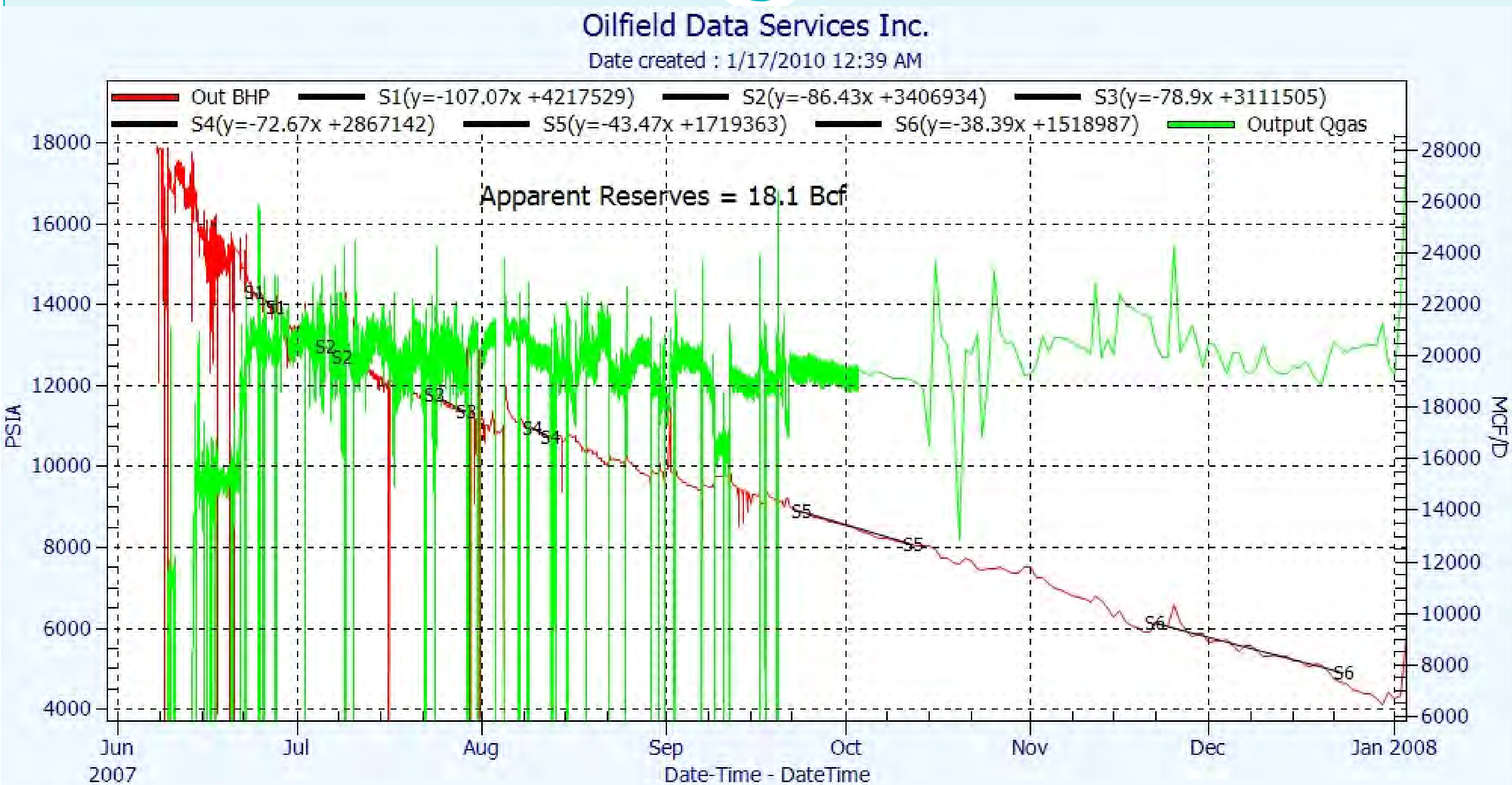
| SOUR GAS | MOLE % |
|---|---|
| $N_2$ | 0.00 |
| $CO_2$ | 0.00 |
| $H_2S$ | 0.00 |

| Least Squares Mean Fit Results | |
|---|---|
| Y-Intercept, BHP/z | 4,200 |
| *OGIP, MMCF* | 410,377 |
| | |
| *EUR, MMCF* | 245,713 |
| Recovery Factor | 0.5988 |
| BHP/z @ Abandonment | 1,685 |

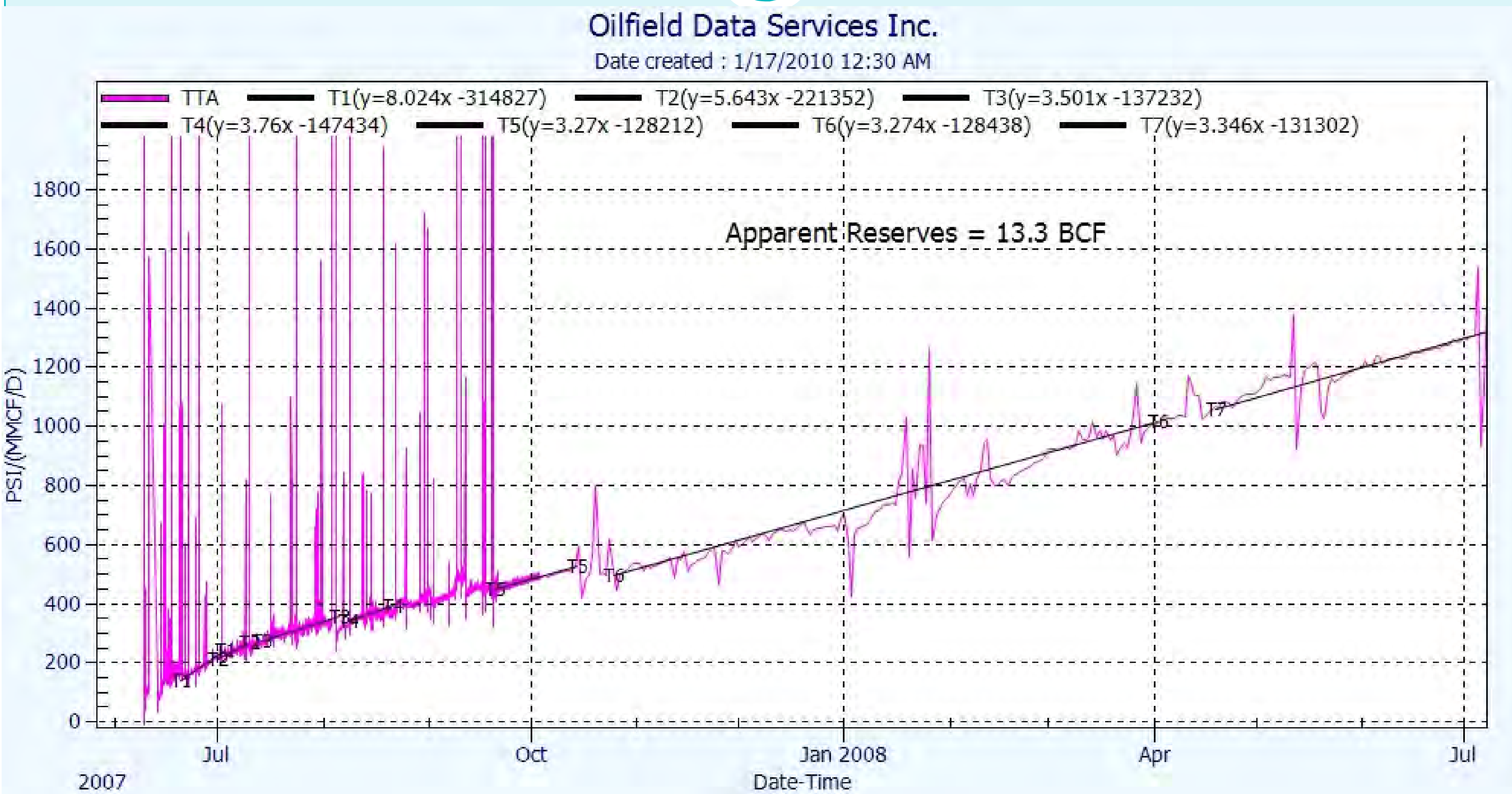



| POINT NUMBER (Automatic) | DATE (Optional) | SITP, Psia | BHP, Psia | Z | BHP/Z, Psia | CUM PROD, MMcf | LSMF Include? (Y/N) |
|---|---|---|---|---|---|---|---|
| 1 | 11/1/1976 | | 3590 | 0.9054 | 3,965 | 1173.4709 | n |
| 2 | 12/1/1976 | | 3843 | 0.9185 | 4,184 | 2042.88545 | Y |
| 3 | 2/1/1977 | | 3801 | 0.9162 | 4,149 | 3958.01439 | Y |
| 4 | 8/1/1977 | | 3713 | 0.9116 | 4,073 | 13682.8566 | Y |
| 5 | 10/1/1977 | | 3670 | 0.9094 | 4,036 | 16983.9284 | Y |
| 6 | 5/25/1988 | 1640 | 1981 | 0.8751 | 2,264 | 156214.923 | n |
| 7 | 5/27/1988 | 1600 | 1881 | 0.8772 | 2,144 | 156224.793 | n |
| 8 | 7/20/1988 | 1825 | 2245 | 0.8721 | 2,574 | 156596.908 | Y |
| 9 | 6/7/1989 | 1700 | 1979 | 0.8751 | 2,261 | 158568.731 | n |
| 10 | 6/12/1989 | 1100 | 2175 | 0.8725 | 2,493 | 158602.323 | Y |
| 11 | 6/17/1993 | 1878 | 1880 | 0.8772 | 2,143 | 168145.103 | n |

# Decline Evaluation



# IPA Example

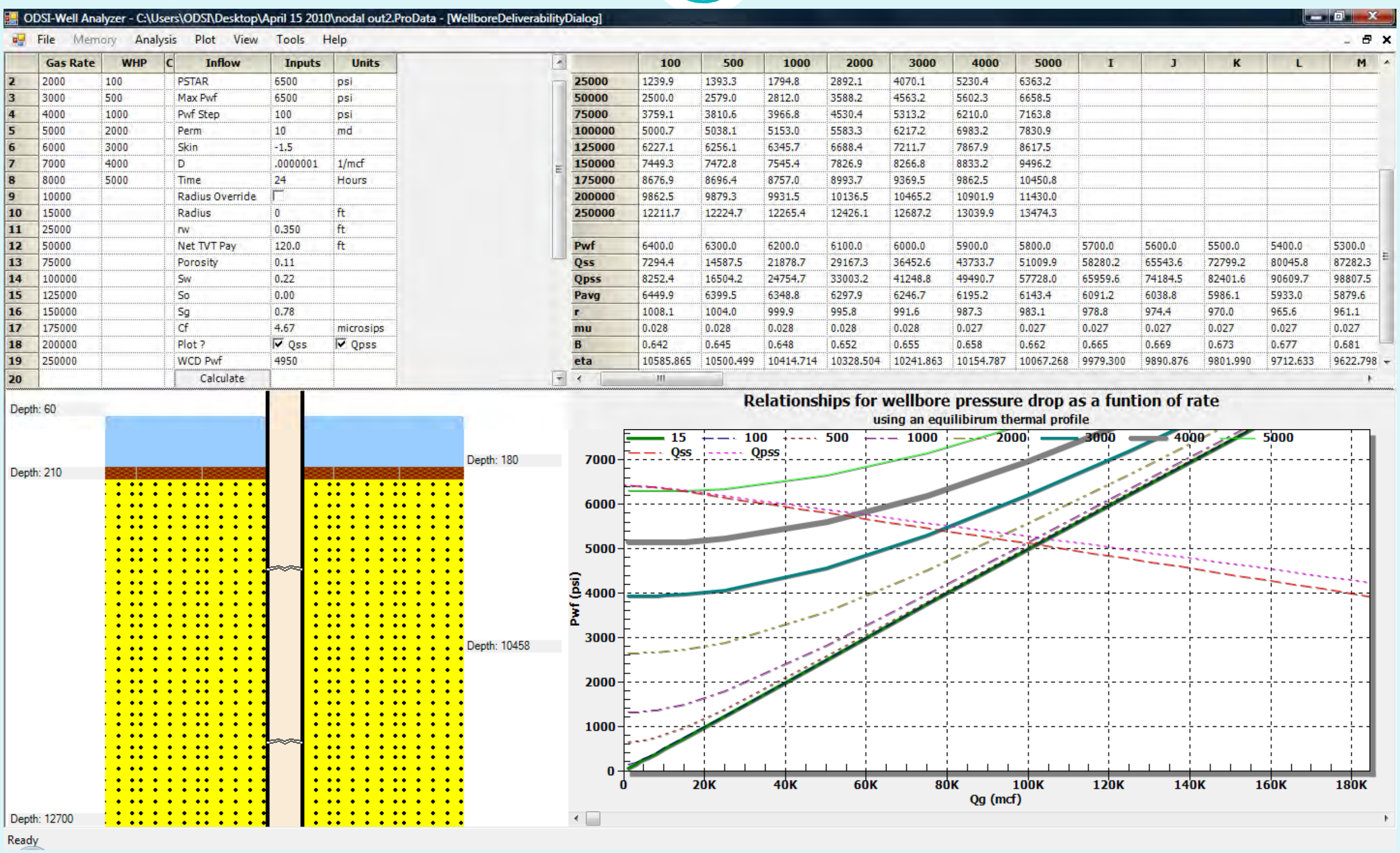


Oilfield Data Services Inc.
Date created : 1/17/2010 12:30 AM
TTA
T1(y=8.024x -314827)
T2(y=5.643x -221352)
T3(y=3.501x -137232)
T4(y=3.76x -147434)
T5(y=3.27x -128212)
T6(y=3.274x -128438)
T7(y=3.346x -131302)
Apparent Reserves = 13.3 BCF
PSI/(MMCF/D)
0
200
400
600
800
1000
1200
1400
1600
1800
Jul
Oct
Jan 2008
Apr
Jul
2007
Date-Time

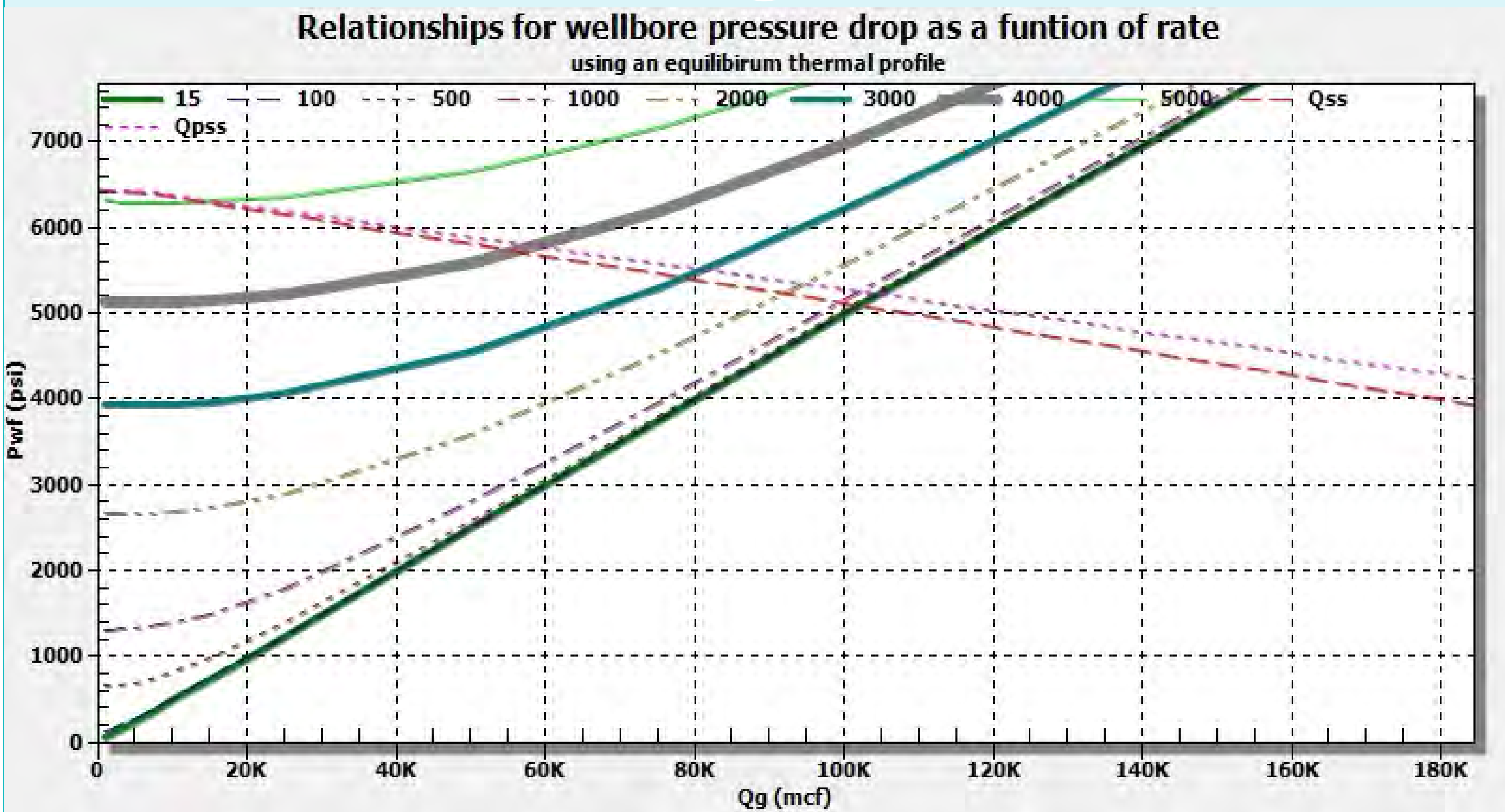
# Nodal Analysis

- Compares Reservoir Inflow (IPC) with Wellbore Performance (VLP)
  - Allows Prediction of DP to achieve a Rate (vice versa)
  - Allows Prediction of Liquid Loading Scenarios
  - Allows Optimization of Tubular Design
- Problems with Nodal
  - Infinite # of combos of skin & perm calculate the same rate (Can’t use nodal to determine skin or perm)
  - User has to pick the right inflow model and right VLP correlation
  - Doesn’t handle transient situations well – may match your well today, but not next month

# Nodal – IPC + VLP



# Nodal VLP-IPC Plot

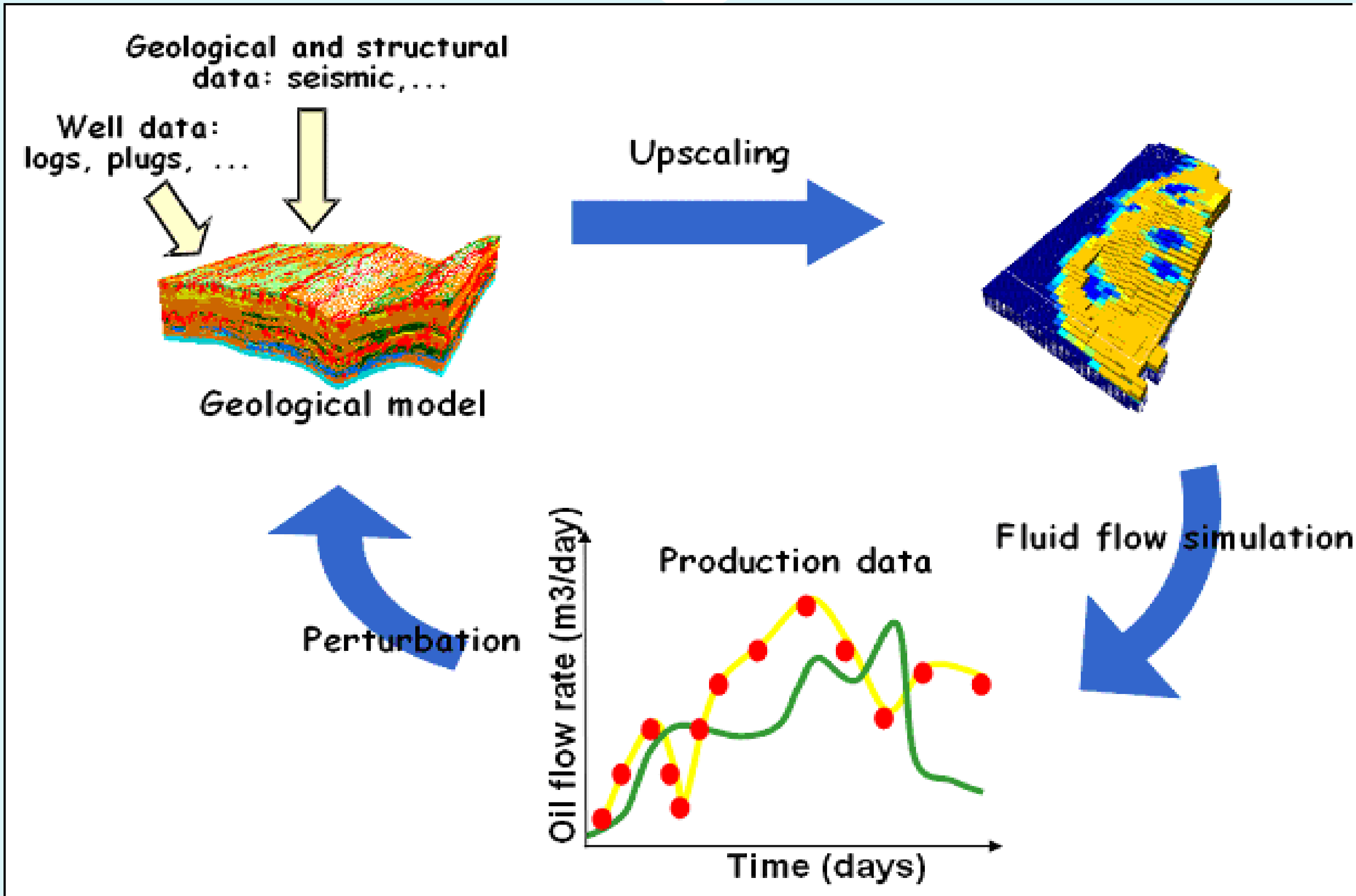


# Reservoir Simulation

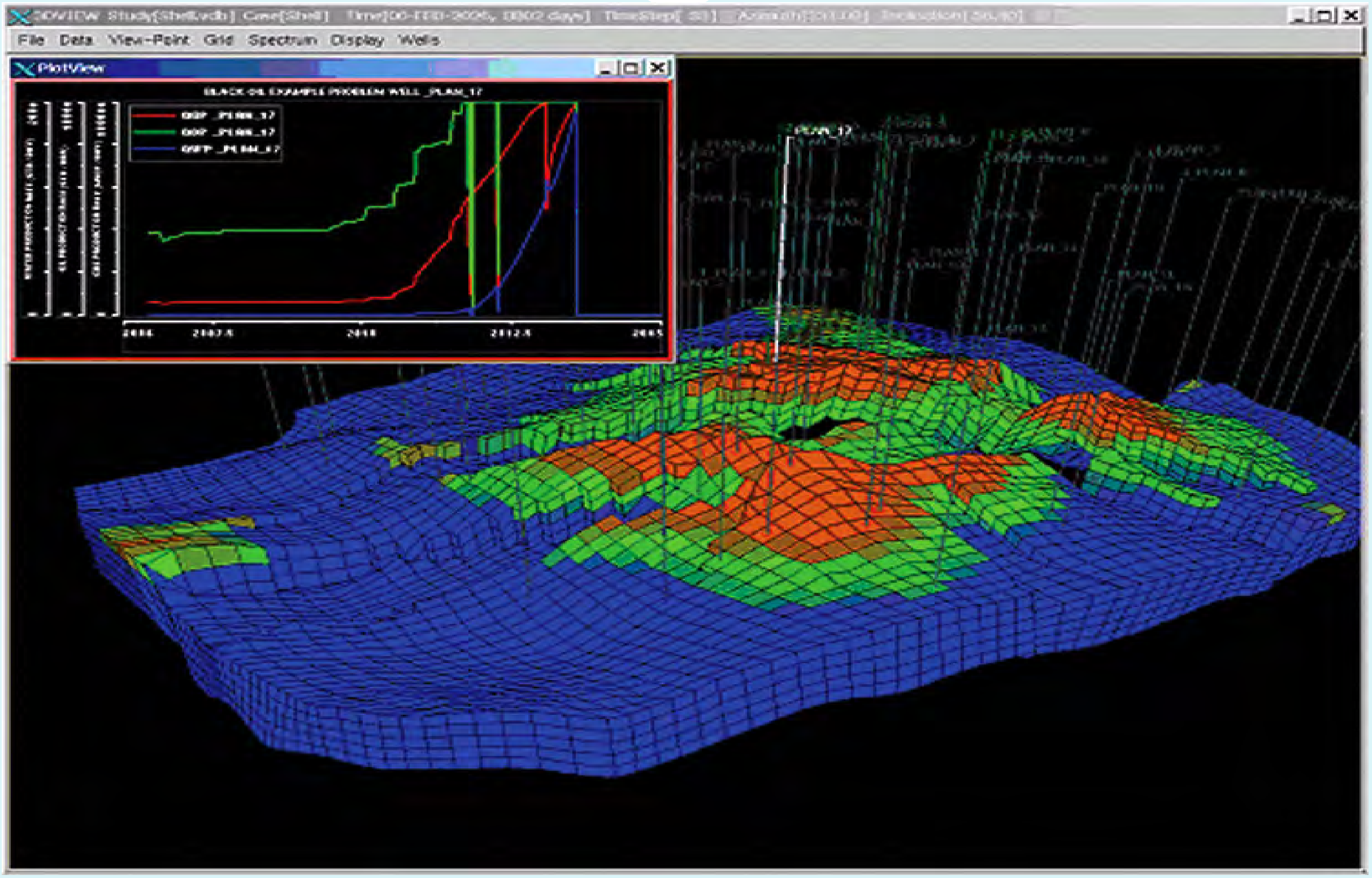
- Tracks behavior (esp Pressure and Saturation) in the reservoir
- Incorporates Multiple Wells/Multiple Zones
- Matches History and Attempts to Predict Future Performance
- Coupled with a Wellbore Simulator, can do amazing things

- Drawback: It takes a while to run…but they're getting faster

# Simulation Gist…



# Simulation: Well Grid



# Components of a Real-Time Well Evaluation Package

TAKE ALL THE BITS AND BOLT THEM TOGETHER

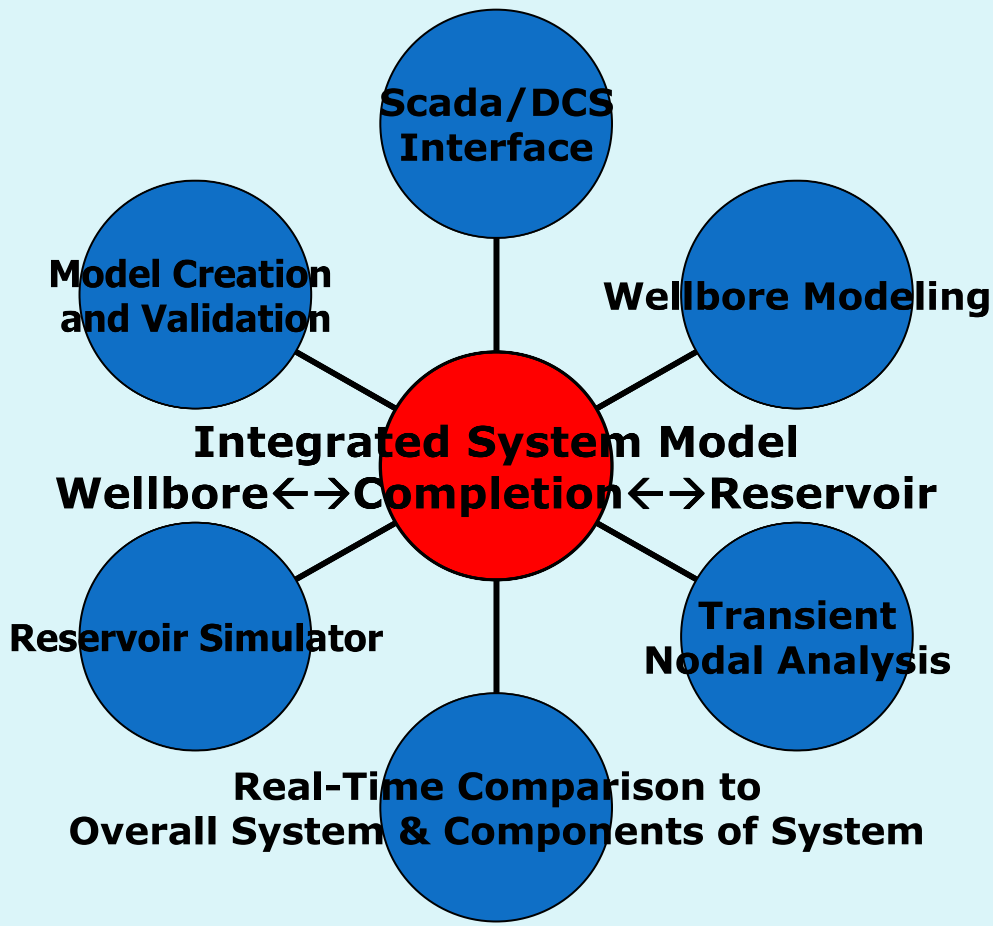
# What Do We Already Have? (Batch Process)

- Hopefully…adequate data frequency and quality
- “Snapshot” VLP
- “Snapshot” Inflow
- Reservoir Simulator
- Wellbore Model
- Geologic/Geo-Physical Model
- Enough Well History?

# What Do We Need to Make it Real-Time?

- Link to RT Data (w/Validation of Data)
- Closed-Loop Wellbore Solution (w/Thermal Modeling)
- Closed-Loop Completion Solution - Can incorporate w/Reservoir Model
- Closed-Loop Reservoir Model
- Transient Recognition
- Regime Recognition
- Prediction vs. Actual Comparison
- Engineering by Difference (Did anything Change?)

# The Bits…


Scada/DCS
Interface
Model Creation
and Validation
Wellbore Modeling
Integrated System Model
Wellbore←→Completion←→Reservoir
Reservoir Simulator
Transient
Nodal Analysis
Real-Time Comparison to
Overall System & Components of System

# Closed-Loop WB Components

- Wellbore Thermal Modeling (Warming/Cooling)
- Liquid Drop Out (Build-ups)
- Liquid Surge (Start-up)
- Phase Behaviour EOS Calcs
  - Use SRK or PR w/Peneloux
- Rate Modeling
  - Residence Time
  - Rate Surging & Decay
- Coupled Effects (Rate-Thermal-Phase)

# Developing Thermal/PVT Models

- Run Static Temp/Pressure Survey
- Run Flowing Temp/Pressure Survey
  - Multiple Rates
- Develop Heat Transfer Model – Account for:
  - Heat Capacity of Fluids/Tubulars/Annuli/Sinks
  - Heat X-fer via Conduction
  - Heat X-fer via Convection
  - Heat X-fer via Forced Convection
- Can Tune PVT using same data…just get a good sample first

# Continuity Equation

$$\frac{\partial \rho}{\partial t} = -(\nabla \bullet \rho v)$$

- Rate of Change in Density Caused by Changes in Mass Flux

# Differential Form of Bernoulli Eqn Compressible Conditions

$$\Delta \tfrac{1}{2}(v)^2 + g\Delta h + \int_{p1}^{p2} dp/\rho + Ws +$$

$$\sum_i \left(\tfrac{1}{2} v^2 \tfrac{L}{R_h} f\right)_i + \sum_i \left(\tfrac{1}{2} v^2 e_v\right)_i = 0$$

# Mechanical Energy Balance (Bernoulli Equation)

- For Single-Phase Gas Flow in Pipes, the MEB reduces to:

$$dp/\rho = -(g \sin \theta / g_c + 2 f_f u^2 / g_c D)\, dL$$

- Basis for CS, Gray & A-C

# Bernoulli for Single Phase Oil Incompressible Conditions

$$\frac{dp}{d\rho}+\frac{vdv}{g_c}+\frac{g}{g_c}dz+\frac{2f_f v^2 dL}{g_c D}+dW_s=0$$

- Basis for Hagedorn-Brown & Beggs/Brill

# Bernoulli Solution Process

Build Parametric Models

↓

Assume Continuity

↓

Solve Bernoulli (MEB)

↓

Check Continuity

Note: If Continuity Doesn't Hold, the Well is Loading–up (which is important to know)

# Using a Direct Bernoulli Solution for WB

- Works for Oil, Gas or Water (Continuity)
- Gas
  - Have DP, solve for rate
  - Have Rate, solve for DP
- Oil
  - Have Rate, solve for Water cut
  - Have DP, solve for Water cut
- Much Easier to Apply Parametric Models:
  - Thermal Transients
  - Rate Transients
  - Phase Transients
  - Combined Rate, Phase & Thermal Transients

# Completion Modeling

- Reconcile Well Geometry (frac, horizontal, etc.) with base inflow
  - Build Dual Perm Model
  - Build "skin" model (easiest way if it works)
- Reconcile Completion/Reservoir Interaction
  - Partial Perforation/Penetration
  - Pay Loss/Growth
  - Near Well Stresses – Elasto-Plastic Rock
- True "Afterflow" vs. Terminal Velocity Flow

# Closed-Loop Reservoir Solution

- Dr. Fred…Wavex Theory
- Focus on fact that it’s the same sol’n as conventional in radial flow and in PSS flow, but has a banded regime solution during post-boundary transient flow

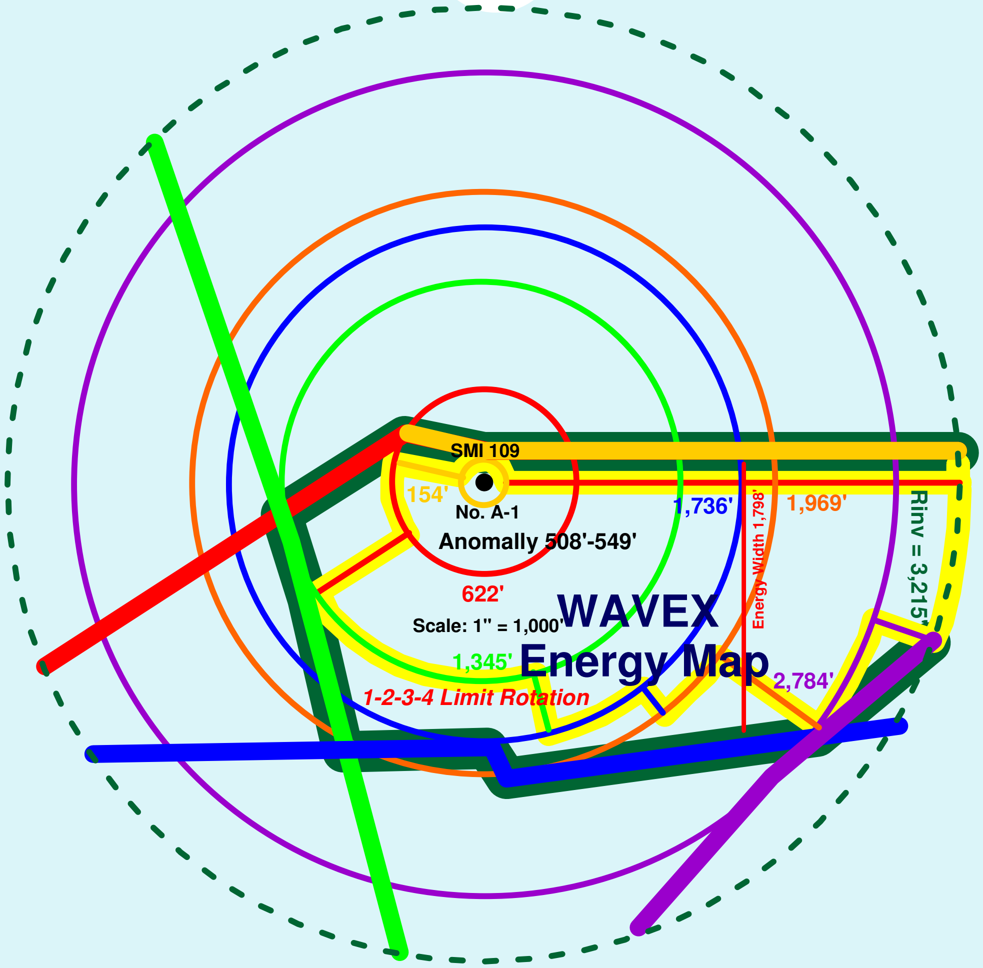
# Boundary Contact Types

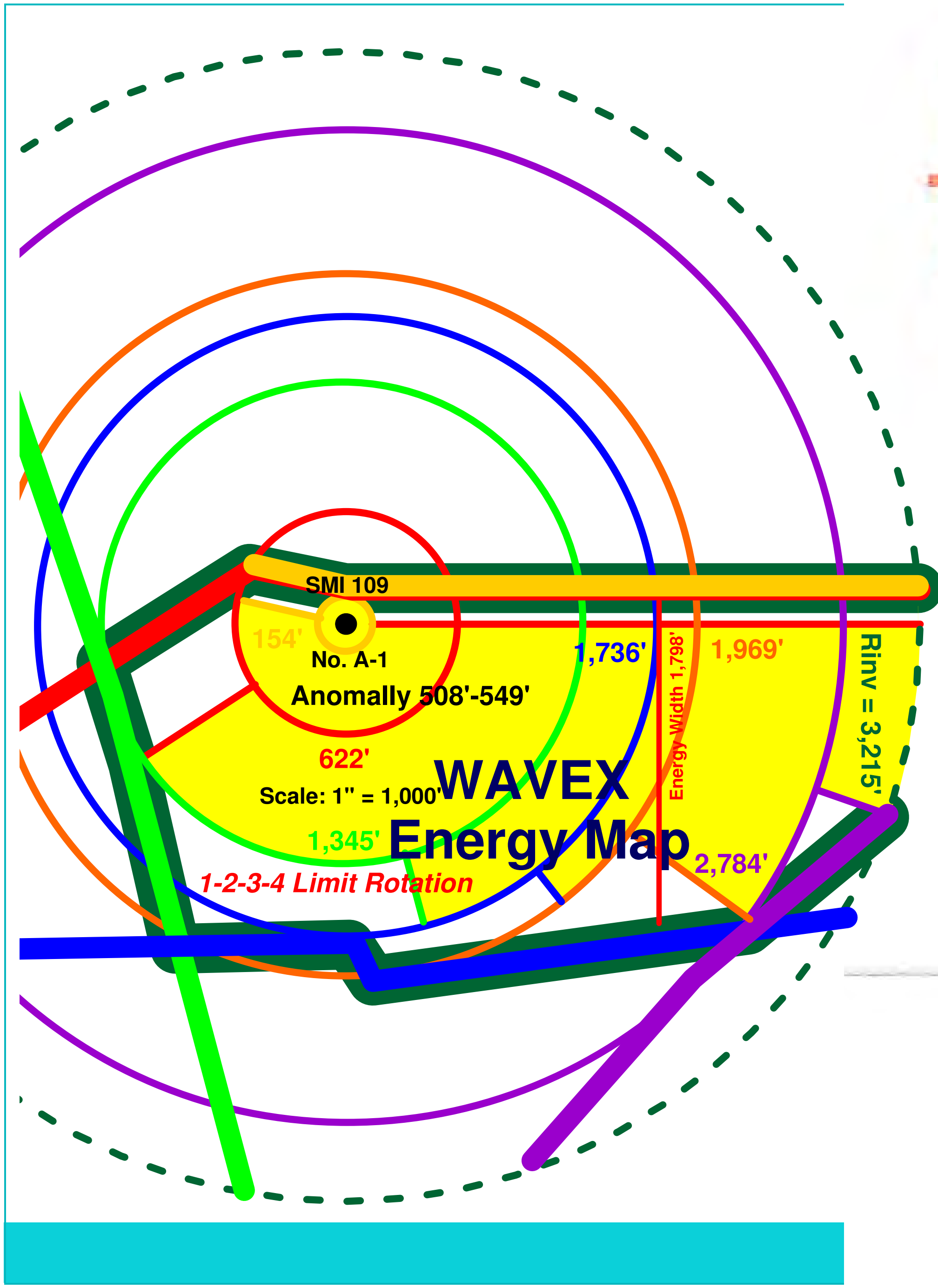
- Dr. Fred talks about boundary contact types, especially gas-water contacts and fizzy oil-water contacts

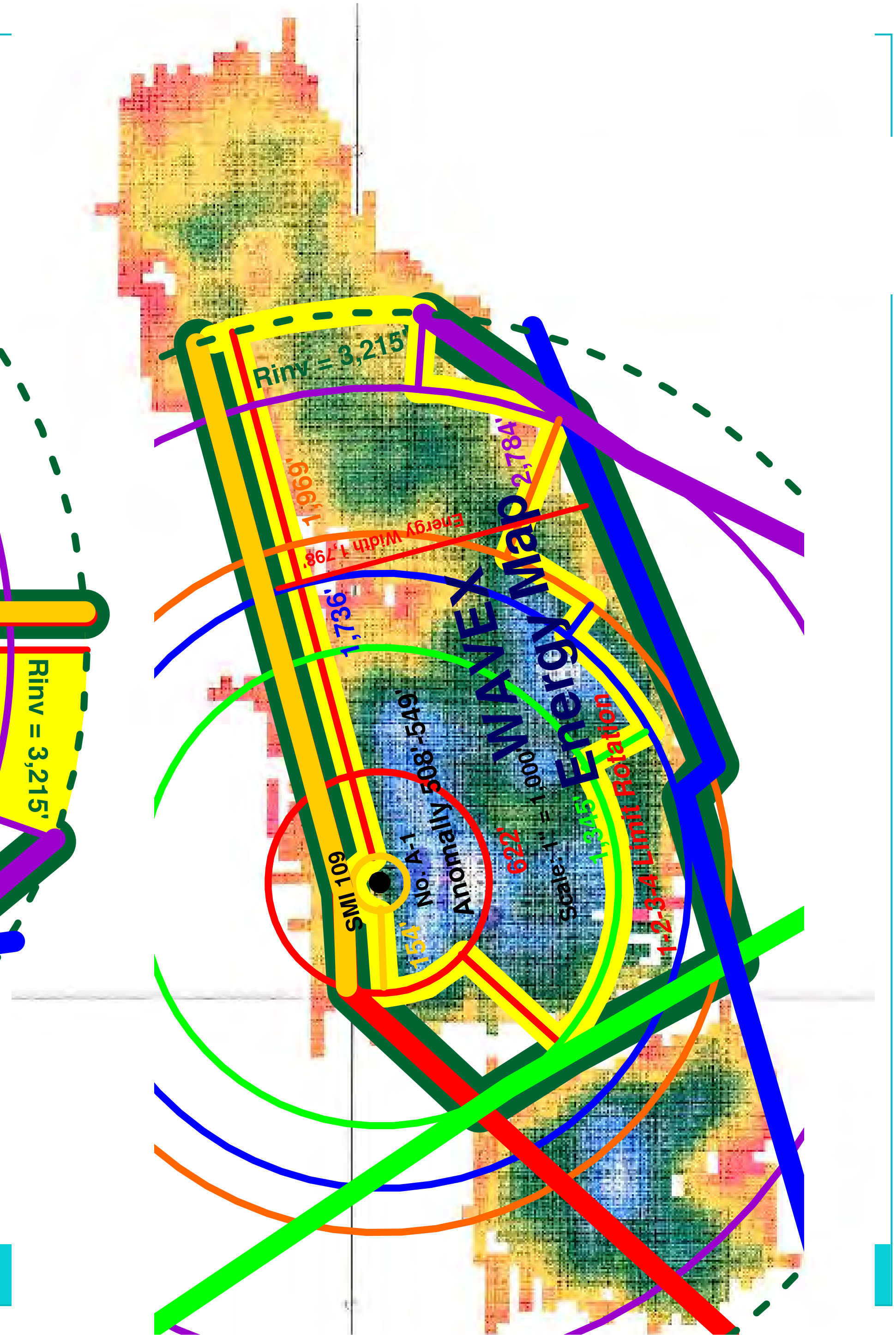
# Results of the WaveX Method…

- A Closed Solution
- Running Volumetrics – don’t have to reach PSS to get a volume
- More Accurate Permeability-Thickness
- More Accurate Distances to Limits
- Differentiate between Faults, Strat-outs & Gas-Liquid Contacts
- Relative Position of Limits to Each Other
- A Map You can show the G&G guys without getting laughed out of the room

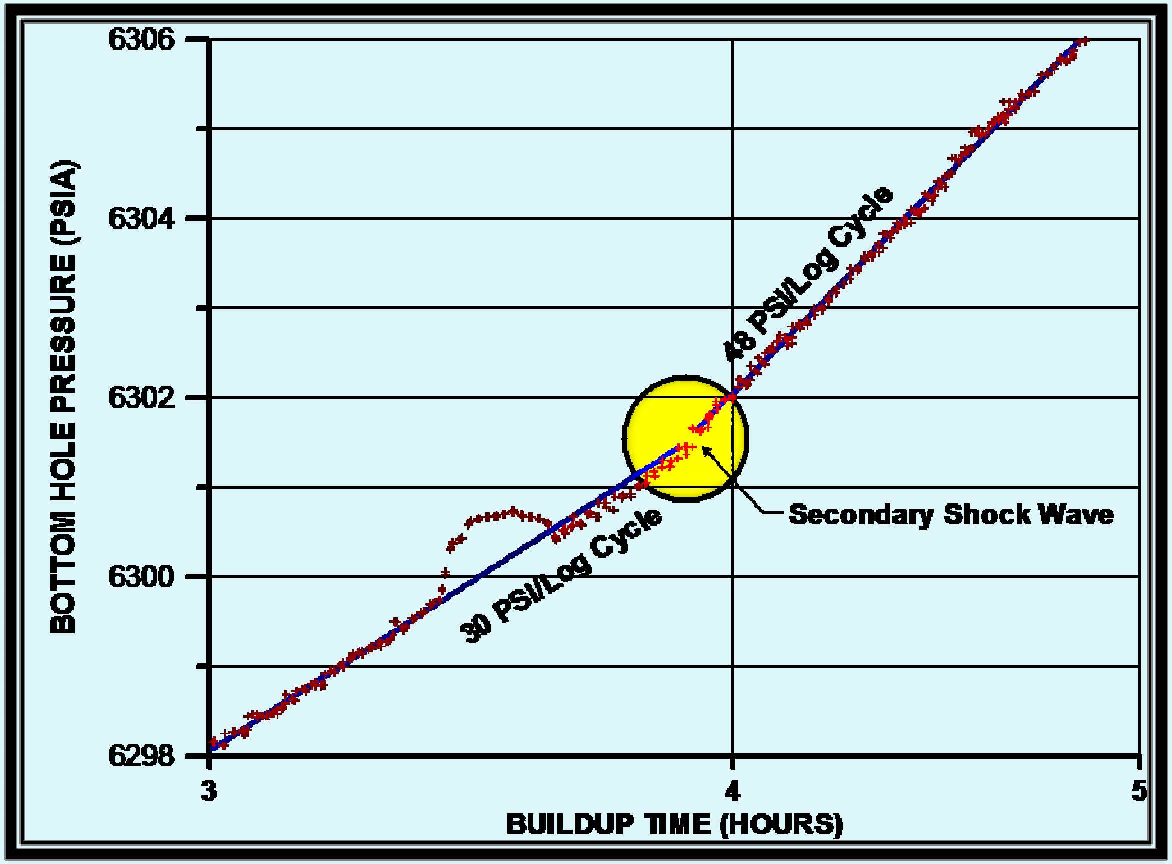
# Closed Solution – Volumetrics & Geometry




SMI 109
154'
No. A-1
Anomally 508'-549'
1,736'
Energy Width 1,798'
1,969'
Rinv = 3,215'
622'
Scale: 1" = 1,000'
WAVEX
Energy Map
1,345'
2,784'
1-2-3-4 Limit Rotation



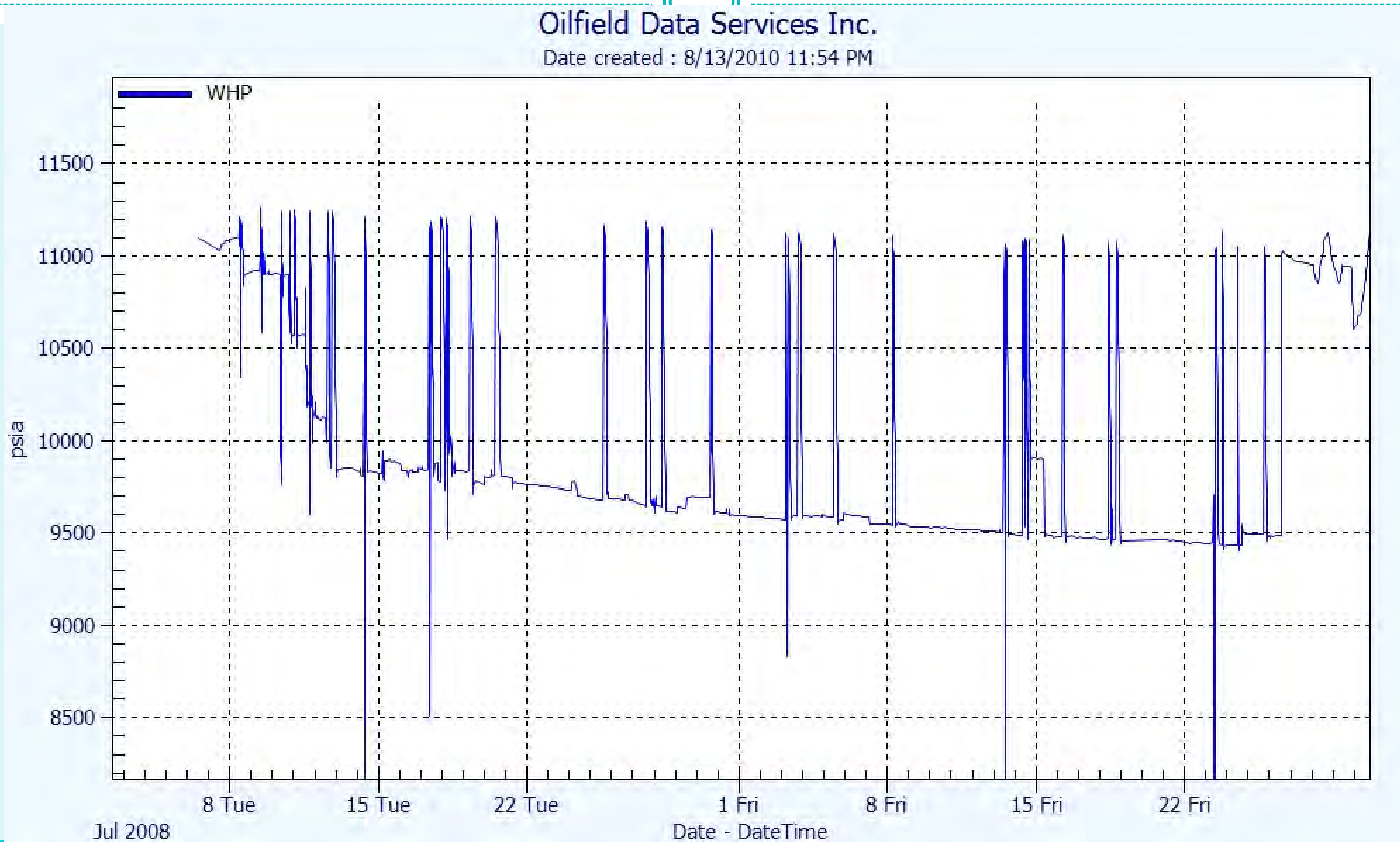
# Boundary Contact Typing: $H2O$ Contact



# Transient and Regime Recognition

- Locate New Transients
  - Rate goes to zero, Rate stops being zero
  - Rate changes enough to start new transient
  - Pressure Methods
    - Wavelets
    - De-convolution Variance
    - DP Logic
- Banded Response Recognition
  - Transient vs. Steady-State
  - Boundary Recognition
  - Transition Recognition

# Transient Recognition



ERROR: stackunderflow
OFFENDING COMMAND: ~

STACK: