Oilfield Data Services Inc.

Using the Wellbore as a d/p Meter to Calculate Gas Rate

Based on APPEA Journal Paper, 2015

Outline

- ODSI Real-time software features
- Gas Rate Calculation Theory and Process
  - Case Study 1
  - Case Study 2
  - Case Study 3
- Conclusions

ODSI Software Features

- Use DHPG and tree gauge to calculate the gas rate
- Calculate the pressure at any point in the wellbore using the calculated gas rate
- Rate validation if flow meter is present

ODSI Additional Features

- Automatic Pressure Transient Interpretation
  - Skin
  - Permeability
  - P*/Pres
  - Productivity (PI)
- Automated Static Material Balance (P/z)
- Automated Decline Analysis
  - Connected and Mobile Reservoir Volume Calculations

Gas Rate Calculation Process and Theory

Wellbore Fluid Flow Model Major Components:

- 1. PVT - Accurate prediction of properties of the wellbore fluid as a function of temperature and pressure
- 2. Wellbore Flow Path
- 3. Dynamic phase-thermal model
  - Calculation or prediction of the temperature at any point along the wellbore as a function of flow rate, time and fluid properties

Results of ODSI Flow Modeling

- Determination of the pressure drop in the wellbore, given a rate
- Determination of gas rate given a pressure drop
- Calculation of mid-completion (or "sweet spot" for horizontal wells) Bottomhole Pressure
  - Calculation to mid-completion BHP prevents the overestimation of skin and perm by accounting for head and friction below the pressure measurement

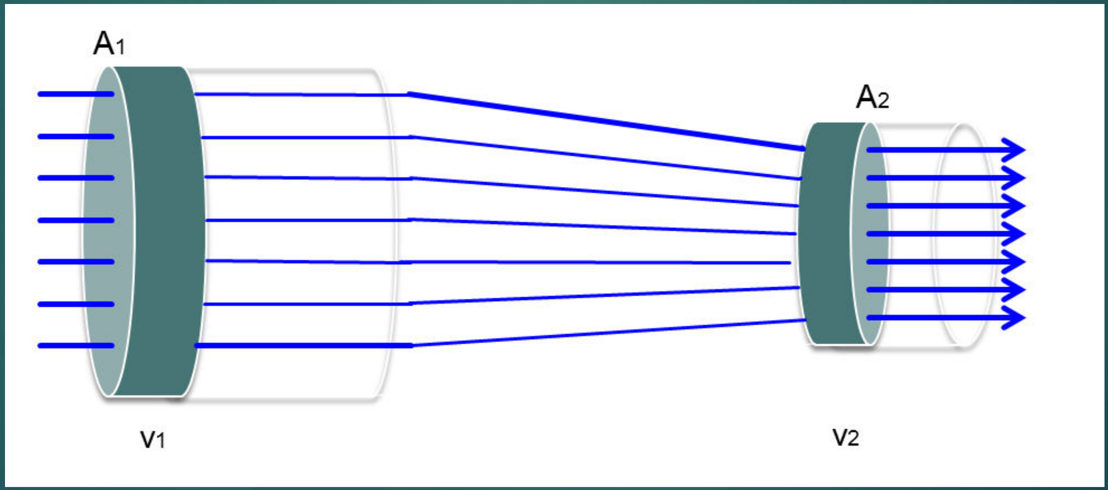
Wellbore Fluid Model Components

- Continuity equation
- Peng-Robinson – Peneloux Equation of State
- Mechanical Energy Balance
- Boundary Layer Disruption
- Modeling Heat Transfer through WB warming/cooling via conduction, convention & forced convection
- 3-Rate (or more) Test to tune thermals and friction

Continuity Equation

- Law of Conservation of Mass (0^{th} law of Thermodynamics)
  - Volume of fluid entering the pipe should be equal to the volume of fluid leaving the pipe
  - Assuming constant fluid composition and neglecting compressibility

$$\rho A_1 v_1 = \rho \, A_2 v_2$$



If continuity fails, the well is loading

Peng-Robinson-Peneloux Equation of State

- Defines relationship between the fluid's thermodynamic and physical properties
  - Thermodynamic properties: pressure, volume, temperature
  - Physical properties: density, viscosity, conductivity, heat capacity, fluid fractions, etc.

$$P = \frac{RT}{Vm - b} - \frac{a(T)}{Vm(Vm + b) + b(Vm - b)}$$

Mechanical Energy Balance

- 1st Law of Thermodynamics:
  - For slightly compressible fluids, including friction and losses at changes in the flow path,

$$\Delta\frac{1}{2}(v^2) + g\Delta h + \int_{p1}^{p2}\frac{dp}{\rho} + W_s + \sum_i\left(\frac{1}{2}v^2\frac{L}{R_h}f\right)_i + \sum_i\left(\frac{1}{2}v^2 e_v\right)_i = 0$$

- Where:
  - 1 – Kinetic Energy, 2 – DP due to gravity, 3 – pressure drop, 4- shaft work, 5– pressure loss due to friction and boundary layer disruption, 6 – potential energy changes due to pipe angle changes

Mechanical Energy Balance

- For predominantly gas-phase natural flow
  - neglecting insignificant terms, i.e. everything except for friction and head

$$\frac{dp}{\rho} = -\left(\frac{g sin\theta}{g_c} + \frac{2 f_f v^2}{g_c}\right) dL$$

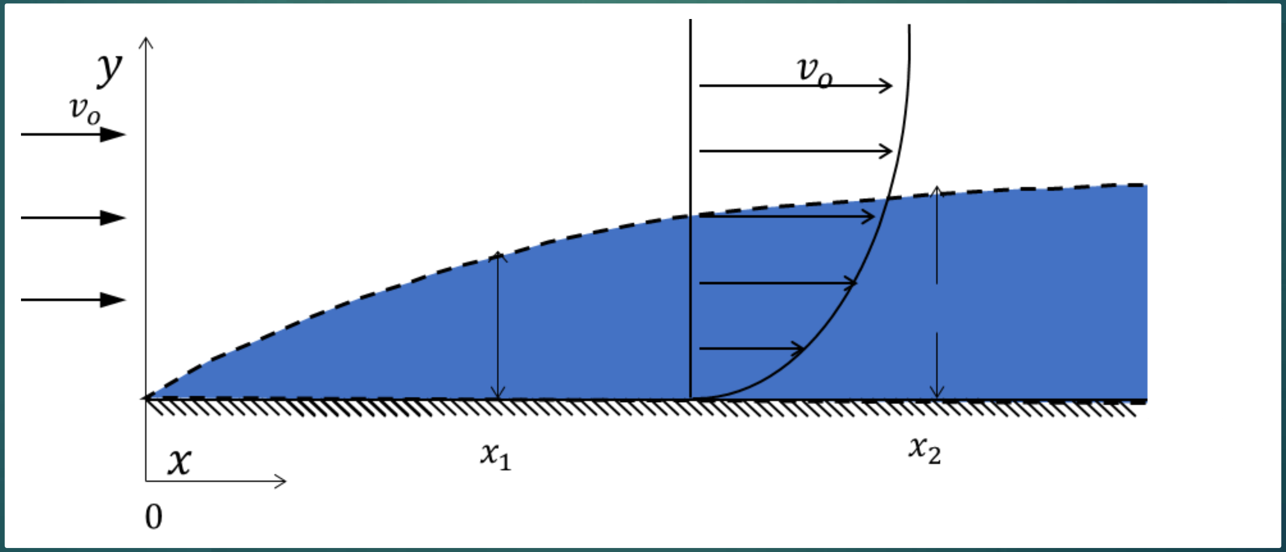
Mechanical Energy Balance

- Bernoulli equation for gas phase flow
- Neglect all pressure losses except friction and head loss
- After PTM and rate comparison re-arrange the MEB to solve for gas rate

$$\frac{ZRT}{MW_{gas}P}dP + \left\{\frac{g}{g_c}sin\theta + \frac{32f_f}{\pi^2 g_c D^5}\left[\frac{T}{P}\frac{P_{sc}}{T_{sc}}QZ\right]^2\right\}dL = 0$$

Boundary Layer Disruption

- Boundary Layer Disruption
  - Due to non-ideal connections (extra pipe dope extruding into the flow path)
  - Additional frictional losses



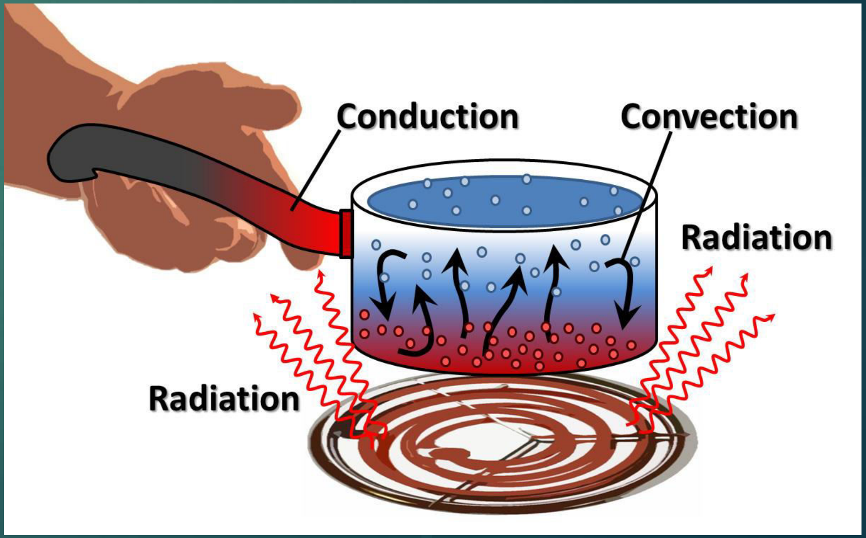
Friction and Boundary Layer Disruption

- Boundary Layer Disruption
  - At effective ID and pipe material changes
  - Mistakenly perceived as pipe friction losses

- Pressure drop calibration under constant fluid composition flowing conditions
  - Perform Multi-Rate Test
  - Effective friction factor can be back-calculated

Modeling the Heat Transfer

- WB Warming/Cooling via Conduction, Convection and Forced Convection
  - As warm fluid enters the WB from the reservoir and flows to the surface, heat is then transferred from fluid to WB, casing, cement and formation
- Heat Transfer Models
  - Conduction
  - Free/Natural Convection
  - Forced Convection
  - Radiation



Heat Transfer: Ambient Effects

- Ambient Effects have to be considered
  - Heat transfer from the surrounding environment

- All 4 heat transfer models can be modeled by conducting a **3-Rate Test**
  - Create a series of equations for individual mechanism/component
  - Generate overall heat transfer coefficient
  - Tune with real well temperature data to improve accuracy

Phase Thermal Model (PTM)

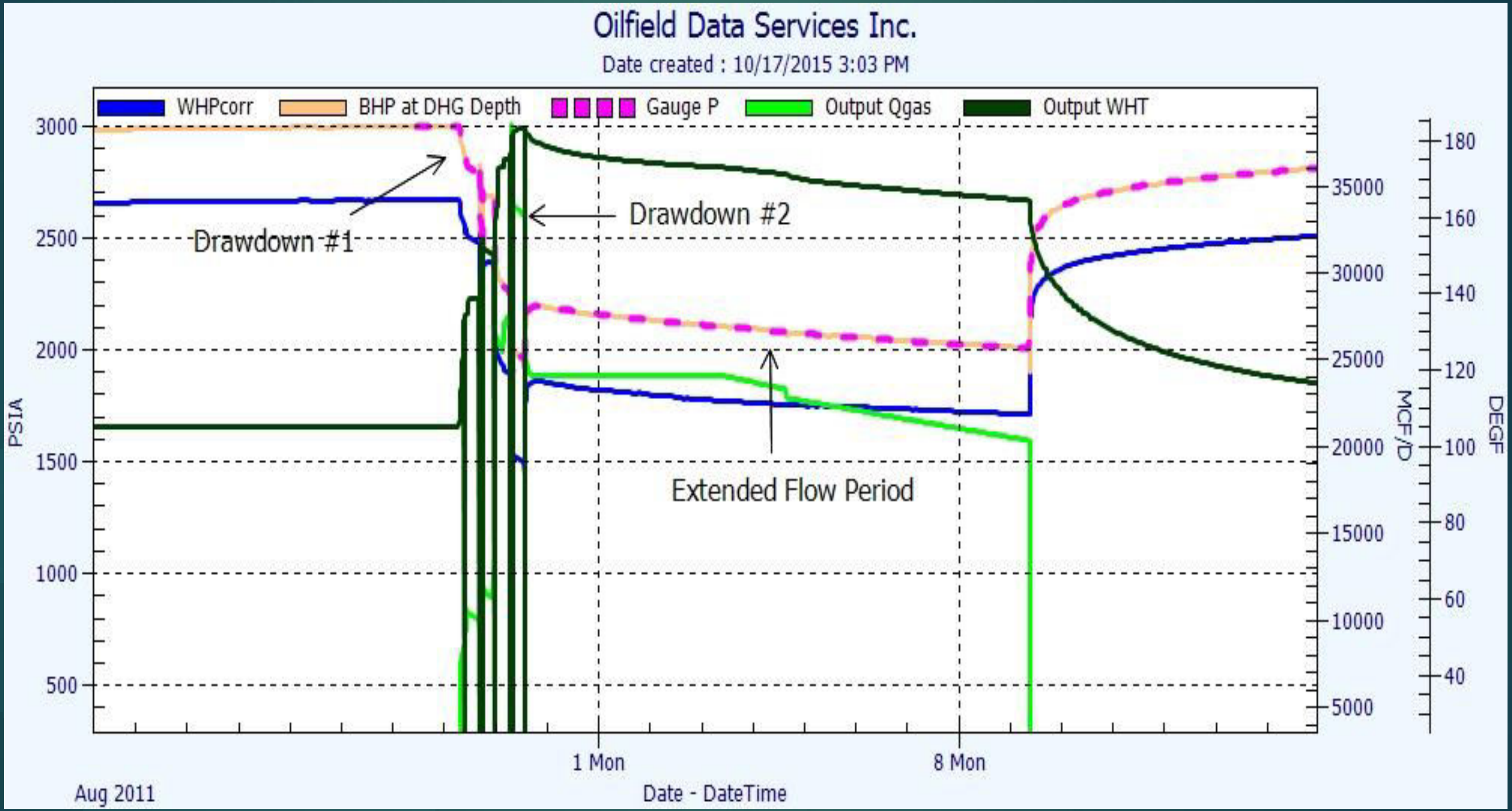
- Combination of EOS and Dynamic Heat Transfer
- Solution matrix for the various components of heat transfer
- Initial estimate for friction factor
- Thermal profile is generated as a function of rate and time
- When calculated DHG matches measured DHG temperatures the frictional component can be tuned to the measured rate

Tuning the Phase-Thermal Model Using a 3-Rate Test

3-Rate(or more Test)

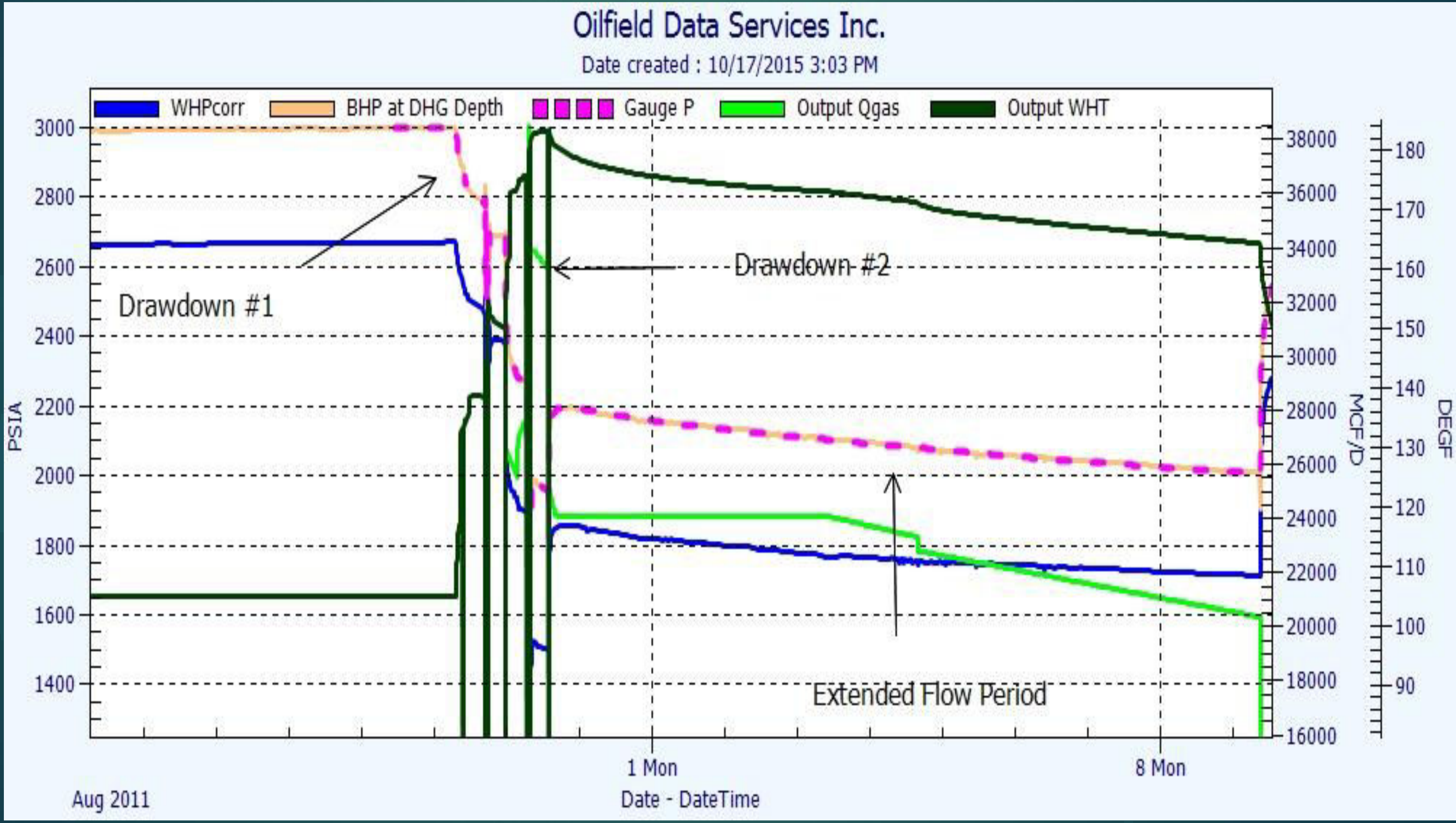
- Procedure:
  - Build EOS and tune the density and composition with a static pressure survey
  - Then flowing data can be simultaneously tuned for thermal profile and friction
  - Thermal profile can be generated as a function of rate and time and fluid properties

Thermal History Match: 3 – Rate Test



Fine tune the PTM to ensure that the converted downhole gauge pressures match the history of the data set

Thermal History Match: 3-Rate Test (Zoom 1)



Thermal History Match: 3-Rate Test (Zoom-2)

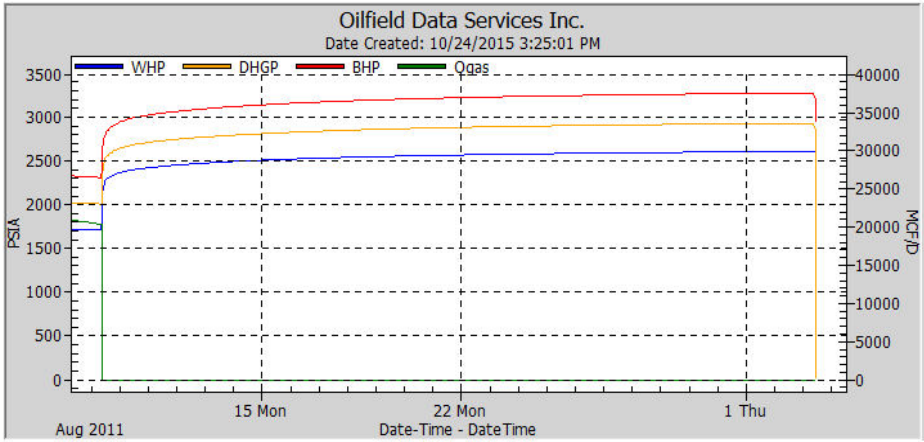
3-Rate Test Example

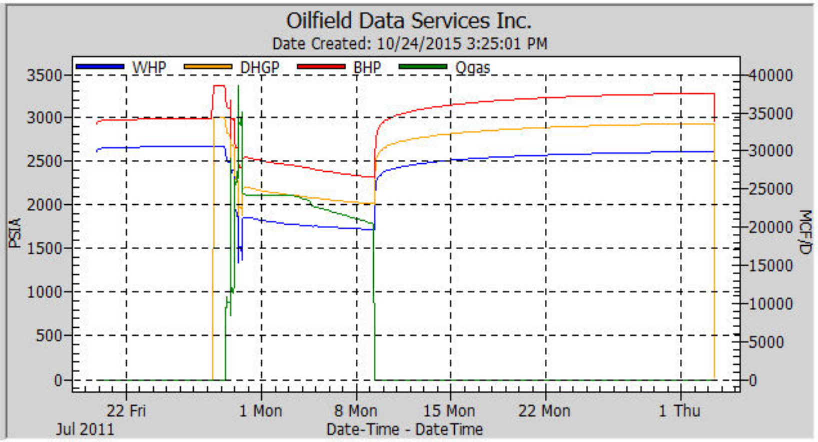
Additional Features:
Automated Well Test Analysis

Inputs | Summary | Outputs

Summary | PBU | DD | PTA/ Productivity | HC Volumes | P/z | Derivative | OilWaterRates | Analysis Events

	Start D/T ddMmmyyyy hh:mm:ss	End D/T ddMmmyyyy hh:mm:ss	Test Length Hours	Test Type	WHPi psia	WHPf psia	DHGPi psia	DHGPf psia	BHPi psia	BHPf psia	QGasi Mcf/D	QGas Mcf/D	Perm md	Skin	DPskin psi	PStar psia	PI Eff %	DPs/Q psi/MMcf	
1	19Jul2011 19:12:00	29Jul2011 06:59:13	227.79	PBU	NaN	2671	NaN	3001	NaN	3355	**NaN**	**NaN**	**NaN**	**NaN**	**NaN**	**3528**	**NaN**	**NaN**	ODSI
2	29Jul2011 23:14:13	30Jul2011 06:44:49	7.51	2-Rate	2386	1823	2683	2241	2982	2622	**11332**	**27215**	**2.2**	**-4.8**	**-1742**	**2603**	**4878**	**-45.18**	ODSI
3	09Aug2011 08:57:37	03Sep2011 10:56:44	601.99	PBU	1712	2610	2007	2614	2308	2927	**20351**	**20351**	**3.7**	**-2.5**	**-426**	**3349**	**204**	**-20.95**	ODSI





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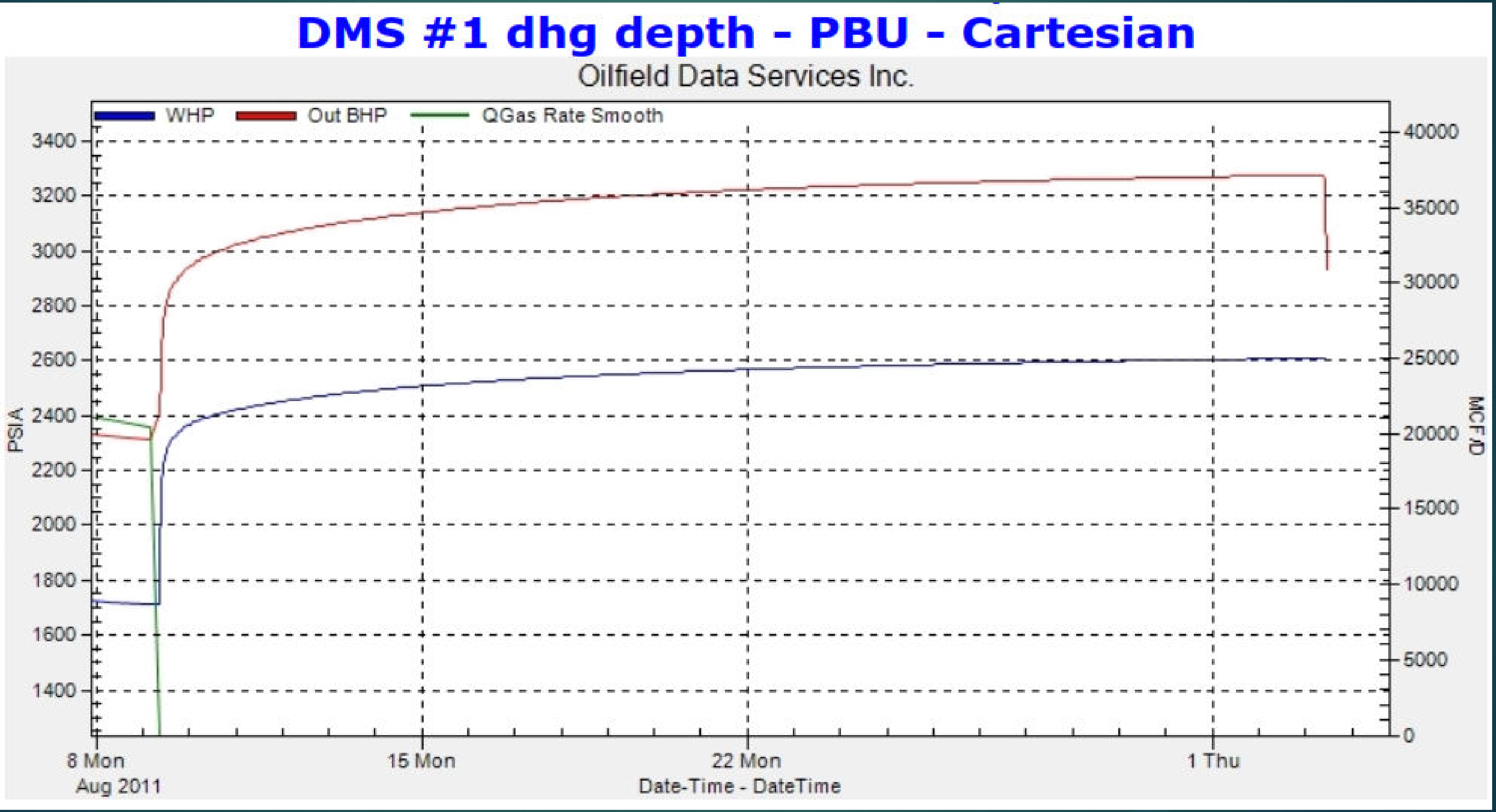
Ready

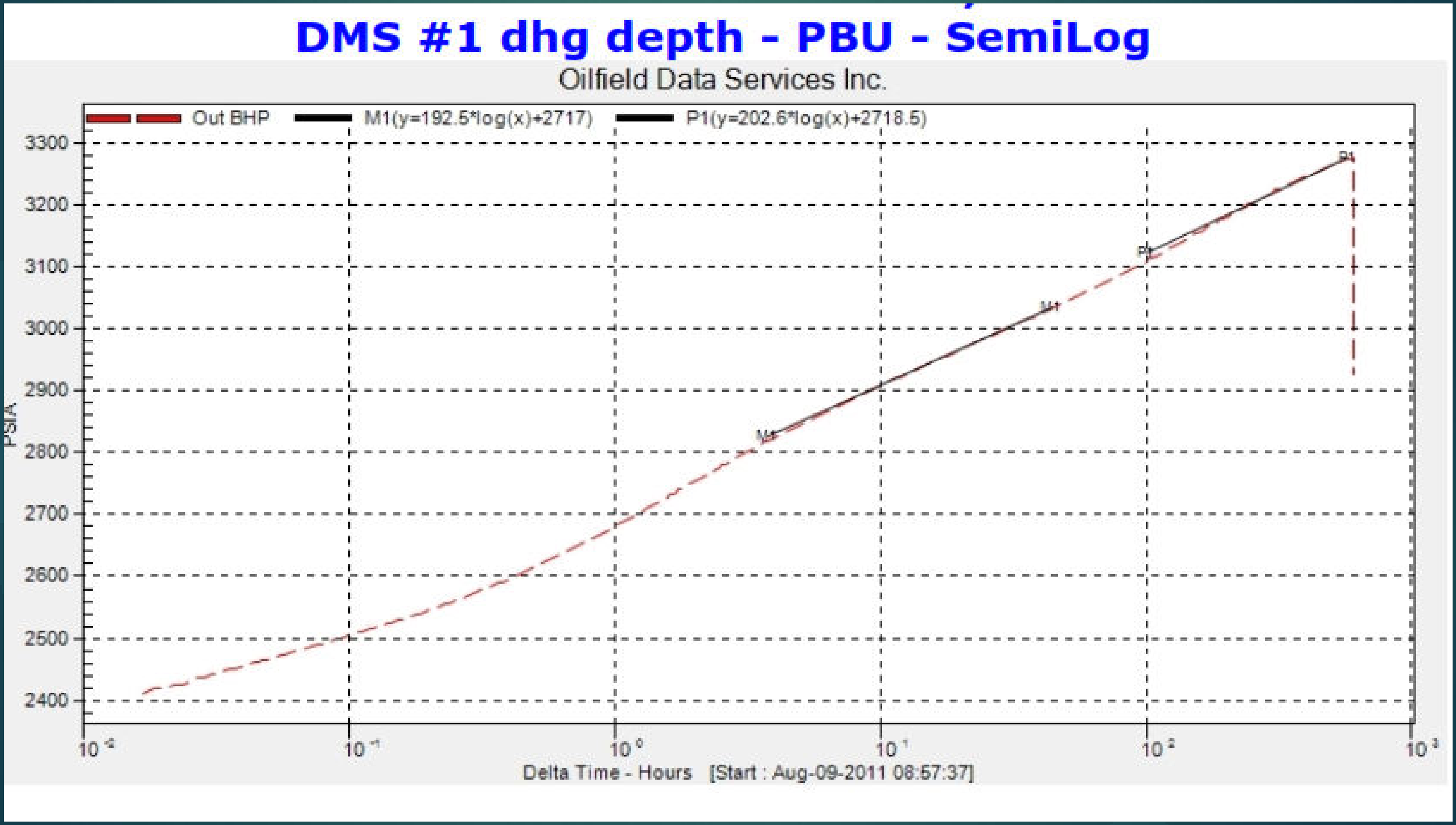
Automatic Well Test Analysis for skin, permeability, P*, PI etc.

3-Rate Test Example
Additional Features: Automatic Well Test Analysis Example

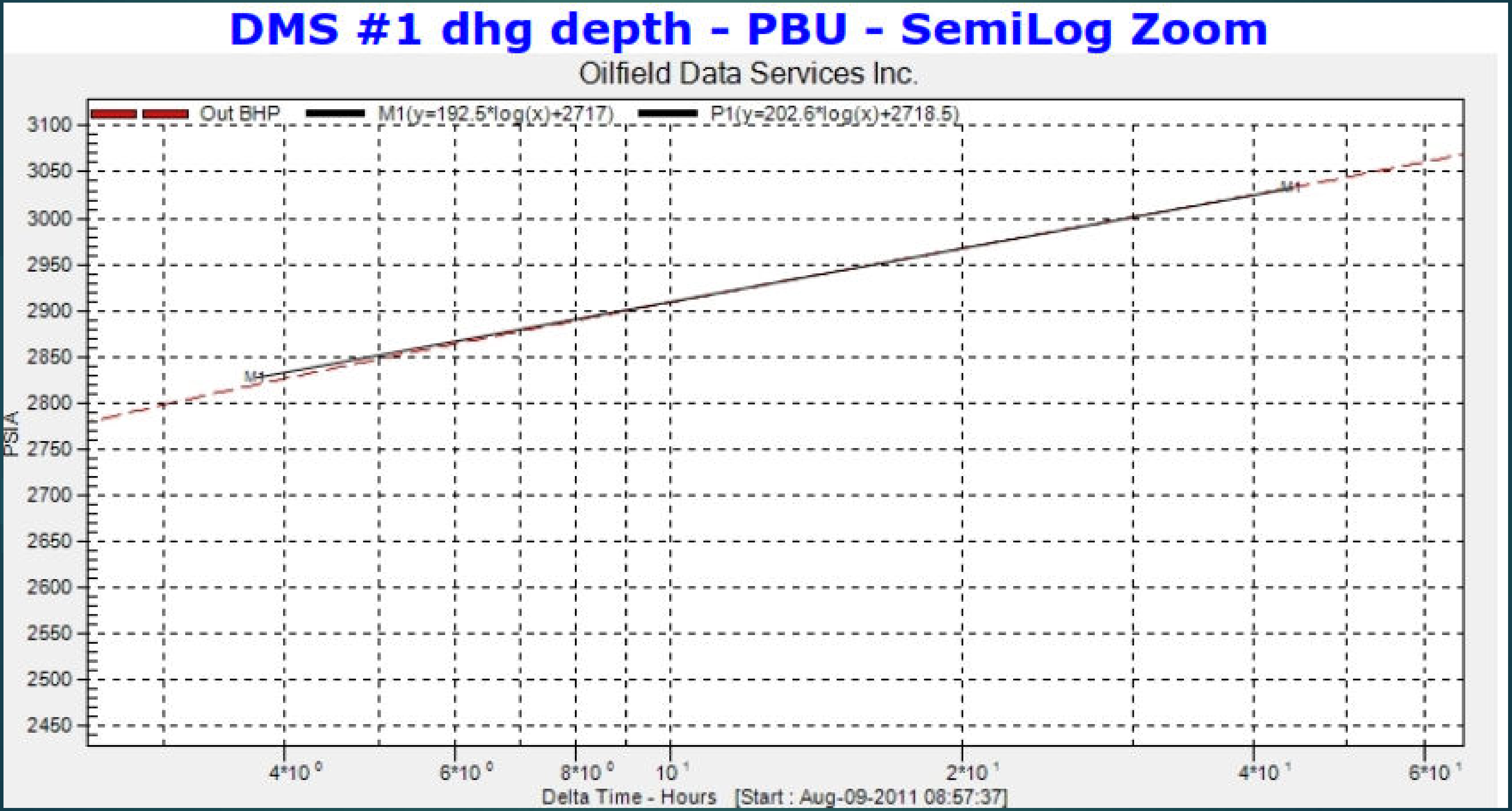


3 – Rate Test Example

Additional Features: Automatic Well Test Analysis Example



3 – Rate Test Example
Additional Features: Automatic Well Test Analysis Example



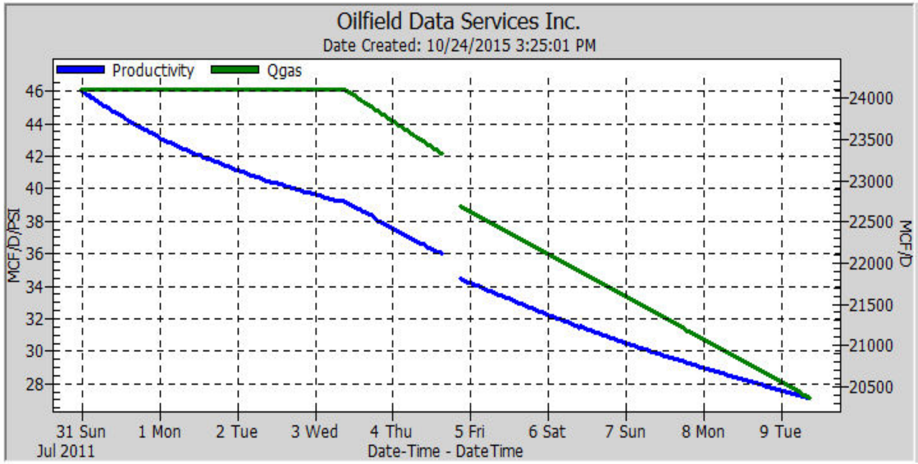
3 – Rate Test Example
Additional Features: Productivity

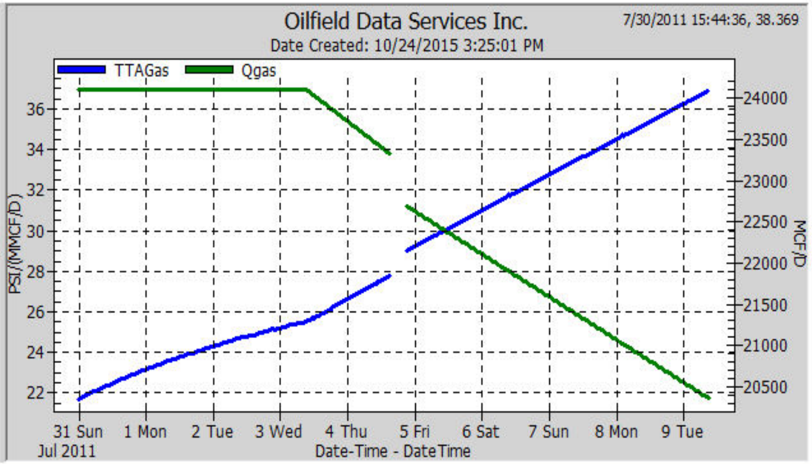
File | Memory | Analysis | Plot | View | Tools | Help

Inputs | Summary | Outputs

Summary | PBU | DD | PTA/ Productivity | HC Volumes | P/z | Derivative | OilWaterRates | Analysis Events

Initial Pres (PSIA)	0	
Last PBU DPskin/Q (PSI/(MMCF/D))	-20.95	09/03/2011 10:56:44
Last DD DPskin/Q (PSI/(MMCF/D))	-45.18	07/30/2011 06:44:49
Last P* (PSIA)	3349	09/03/2011 10:56:44
Last Productivity Q/DP (MCF/D/PSI)	27.7	08/09/2011 08:57:37
Last TTA (PSI/(MMCF/D))	36.05	08/09/2011 08:57:37





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Thermal History Match: 3-Rate Test Summary

- Perform a 3-Rate Test (or more)
  - Flow at different rates
  - Tube PTM to match DHGP conversion
  - < % 1 calculation error

- Additional software features:
  - Automated well test analysis for skin, permeability, PI, P* (PBU), Productivity Index etc.
  - Automated Static Material Balance (p/Z)
  - Automated Decline Analysis for hydraulically connected and mobile HC

Case Studies

Case Study 1

Case Study 1

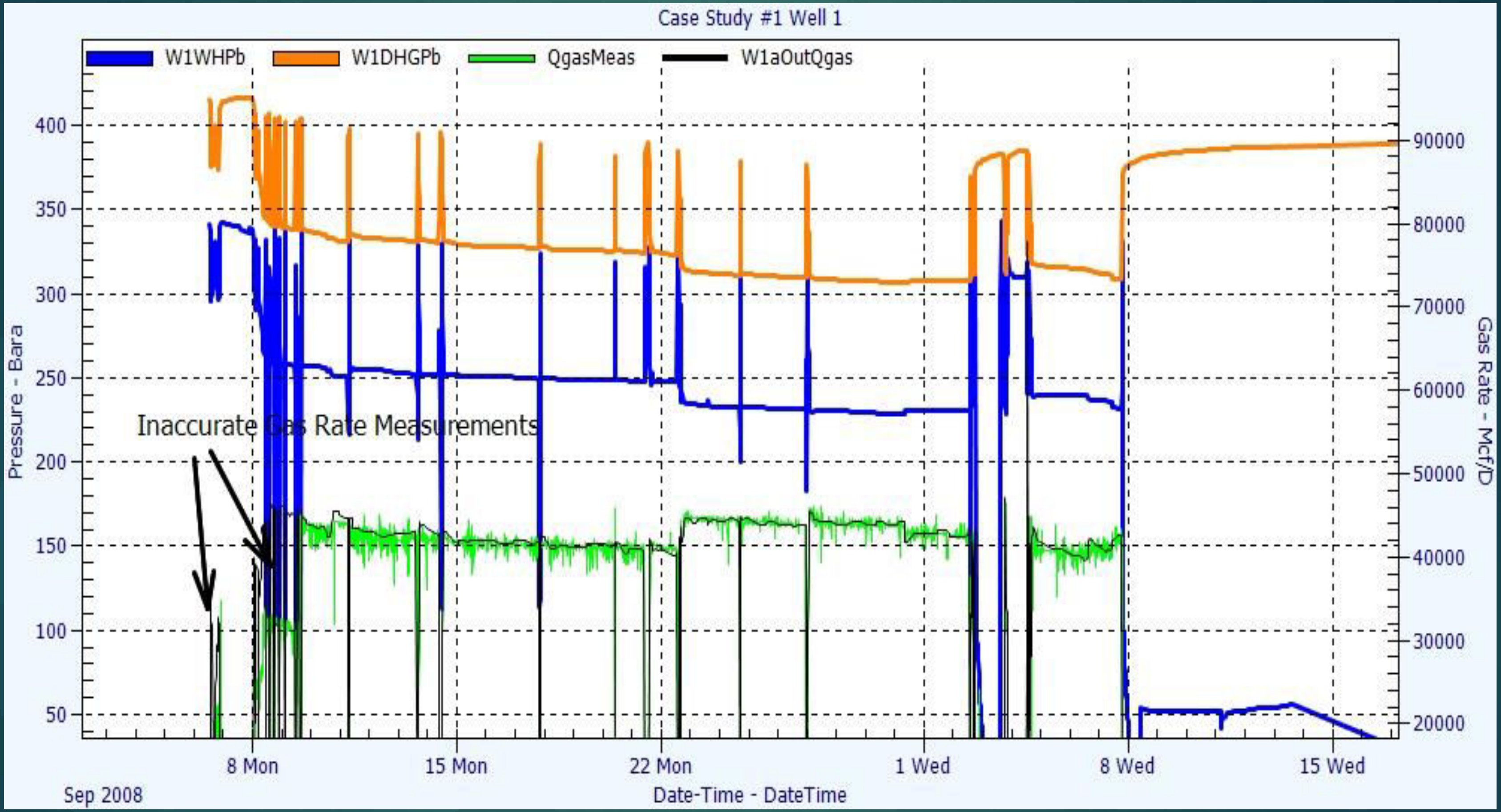
- North Sea
- Dry gas
- High resolution subsea tree and downhole gauges
- Multiple wells produce to central host facility
  - Total field rate is known; individual well rates are not known
  - Downhole gauge is significantly higher than the completion depth

Case Study 1

- Consider initial data (Well 1 is producing only)
  - Allowed direct comparison of platform measured gas rates vs d/p wellbore calculated gas rates
- Tune gas composition by using the pressure difference between downhole gauge and subsea tree gauge during shut-ins
- Tune friction using several stable flow rate points
- Generate PTM using the same data
- Calculate rates using the modified MEB

$$\frac{ZRT}{MW_{gas}P}dP + \left\{\frac{g}{g_c}Sin\theta + \frac{32f_f}{\pi^2 g_c D^5}\left[\frac{T}{P}\frac{P_{sc}}{T_{sc}}QZ\right]^2\right\}dL = 0$$

Case Study 1 Results
Measured vs. Calculated Gas rates



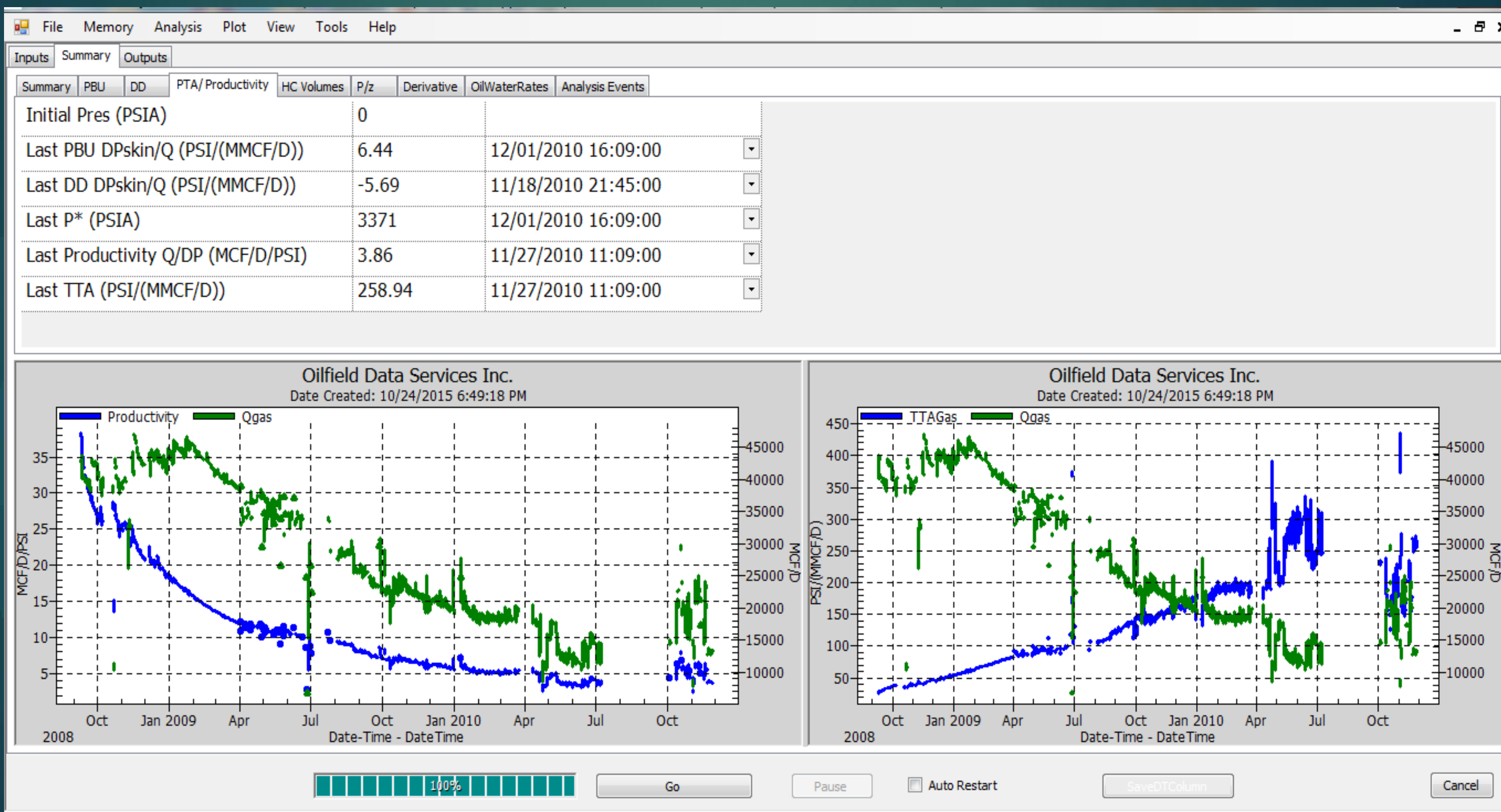
Note: Inaccurate rate measurement due to loss of communication with the meter and inappropriate calibration of the meter calculations

Case Study 1
Additional Features

- Automatic Well Test Analysis
  - The software recognizes new transients (DD/PBU/ Multi-Rate Tests) and analyzes them for skin, permeability, DP skin, Productivity Index etc.
- Automatic Static Material Balance (p/Z)
  - In-place HC Volume
- Automatic Decline Analysis
  - Hydraulically Connected and Mobile HC volumes

Case Study 1

Additional Features: Productivity and Inverse Productivity Plot



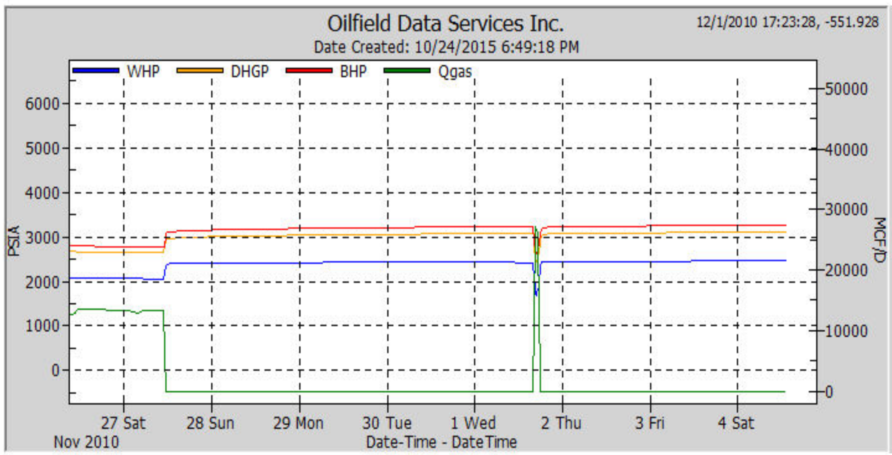
Case Study 1

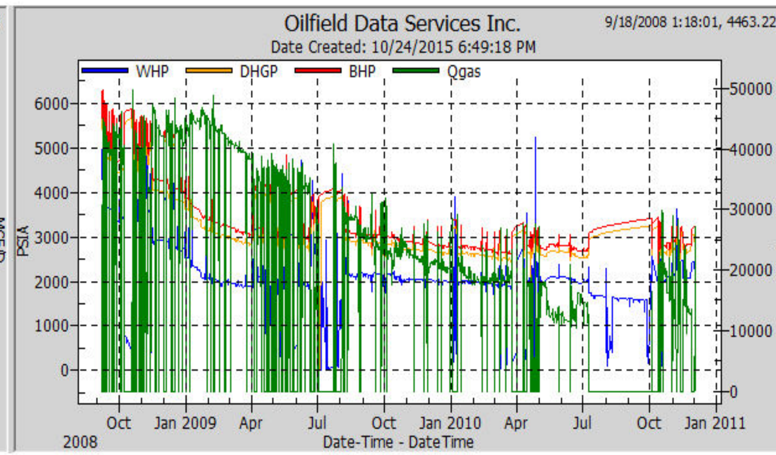
Additional Features: Automated Well Test Analysis

Inputs | Summary | Outputs

Summary | PBU | DD | PTA/ Productivity | HC Volumes | P/z | Derivative | OilWaterRates | Analysis Events

	Start D/T ddMmmyyyy hh:mm:ss	End D/T ddMmmyyyy hh:mm:ss	Test Length Hours	Test Type	WHPi psia	WHPf psia	DHGPi psia	DHGPf psia	BHPi psia	BHPf psia	QGasi Mcf/D	QGas Mcf/D	Perm md	Skin	DPskin psi	PStar psia	PI Eff %	DPs/Q psi/MMcf	
12	11Dec2008 05:39:00	13Dec2008 16:21:00	58.7	DD	4519	2758	5044	3844	5261	4088	**0**	**43599**	**13.2**	**7.5**	**575**	**3847**	**44**	**13.19**	K5
13	13Dec2008 17:45:00	16Dec2008 11:03:00	65.3	PBU	2740	4063	3844	5035	4089	5252	**43733**	**43733**	**9.8**	**4.5**	**442**	**5522**	**57**	**10.12**	K5
14	16Dec2008 11:03:00	21Dec2008 21:57:00	130.9	DD	3923	2729	5103	3820	5321	4062	**0**	**44468**	**12**	**6.5**	**551**	**3915**	**48**	**12.38**	K5
15	21Dec2008 21:57:00	22Dec2008 08:51:00	10.9	PBU	2729	4045	3820	4952	4062	5166	**43068**	**43068**	**9.8**	**4.3**	**413**	**5403**	**58**	**9.58**	K5
16	05Apr2009 07:15:00	08Apr2009 12:45:00	77.5	PBU	2167	2913	3026	3708	3220	3884	**33268**	**33268**	**9.9**	**3.9**	**303**	**4375**	**60**	**9.1**	K5
17	17Apr2009 10:33:00	21Apr2009 12:27:00	97.9	PBU	1940	2941	2850	3946	3053	4132	**36575**	**36575**	**10.4**	**4.8**	**401**	**4421**	**55**	**10.96**	K5





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Case 1:

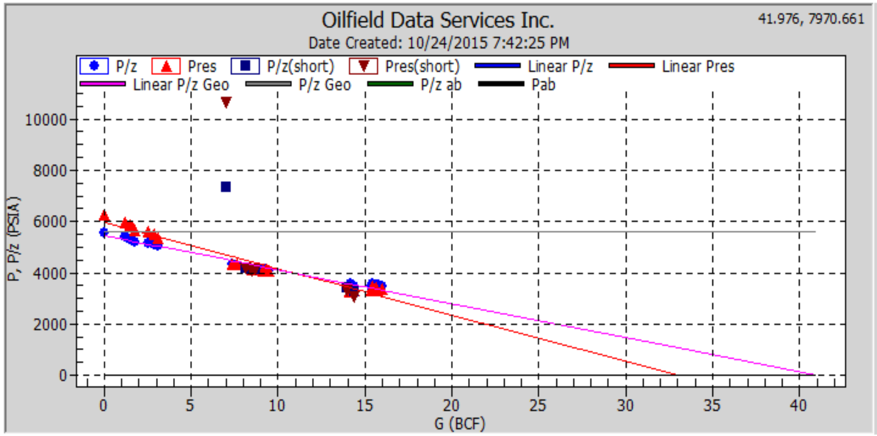
Additional Features: Static Material Balance (p/Z)

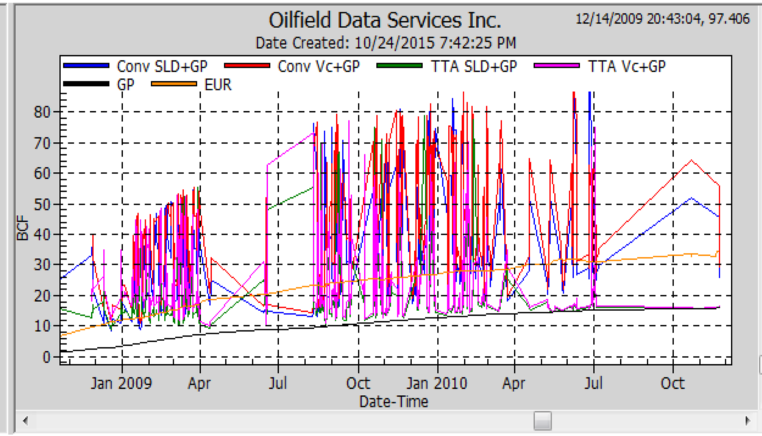
File Memory Analysis Plot View Tools Help

Inputs | Summary | Outputs

Summary | PBU | DD | PTA/Productivity | HC Volumes | P/z | Derivative | OilWaterRates | Analysis Events

Gas Produced	PBU Duration	Pres	z-Factor	P/z	GIP SLD @P=0	GIP SLD @P|ab=15	GIP P/z @P=0	GIP P/z @P/z|ab=15	GIP P/z geo @P=0	GIP P/z geo @P/z|ab=15	m Pres	m Pz	m Ge
BCF	HOURS	PSIA	dimless	PSIA	BCF	BCF	BCF	BCF	BCF	BCF	PSIA/BCF	PSIA/BCF	PS
0.000		6255	1.127	5548.9									
1.166	285	5962	1.107	5383.3	24.9	24.8			39.1	39.0	-251.4		-1
1.503	52	5857	1.101	5322.3	24.0	23.9			37.4	37.3	-261.2		-1
1.567	32	5810	1.097	5294.5	22.9	22.9			35.6	35.5	-273.2		-1
1.648	45	5828	1.099	5304.9	23.3	23.2			36.2	36.1	-268.8		-1





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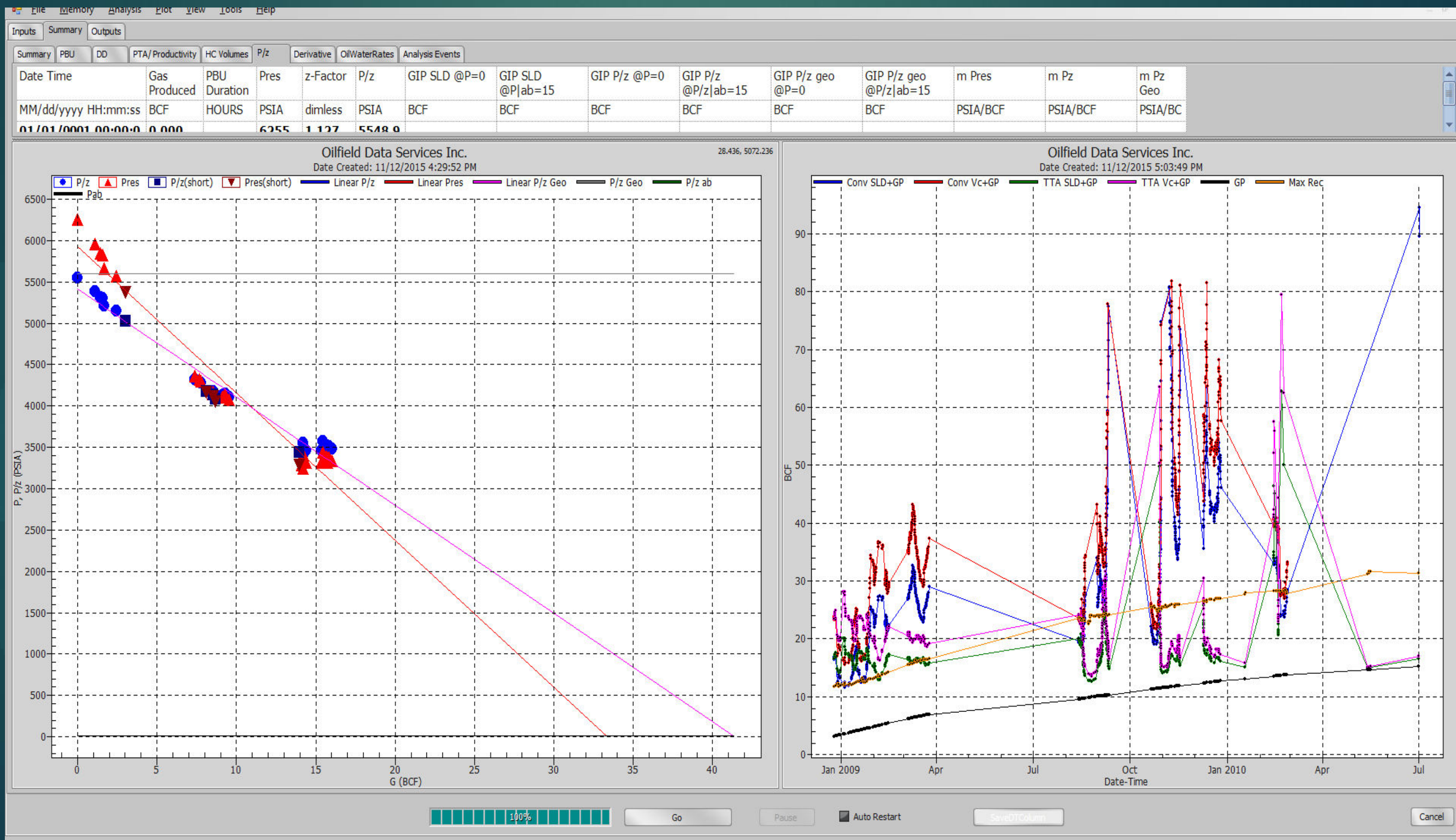
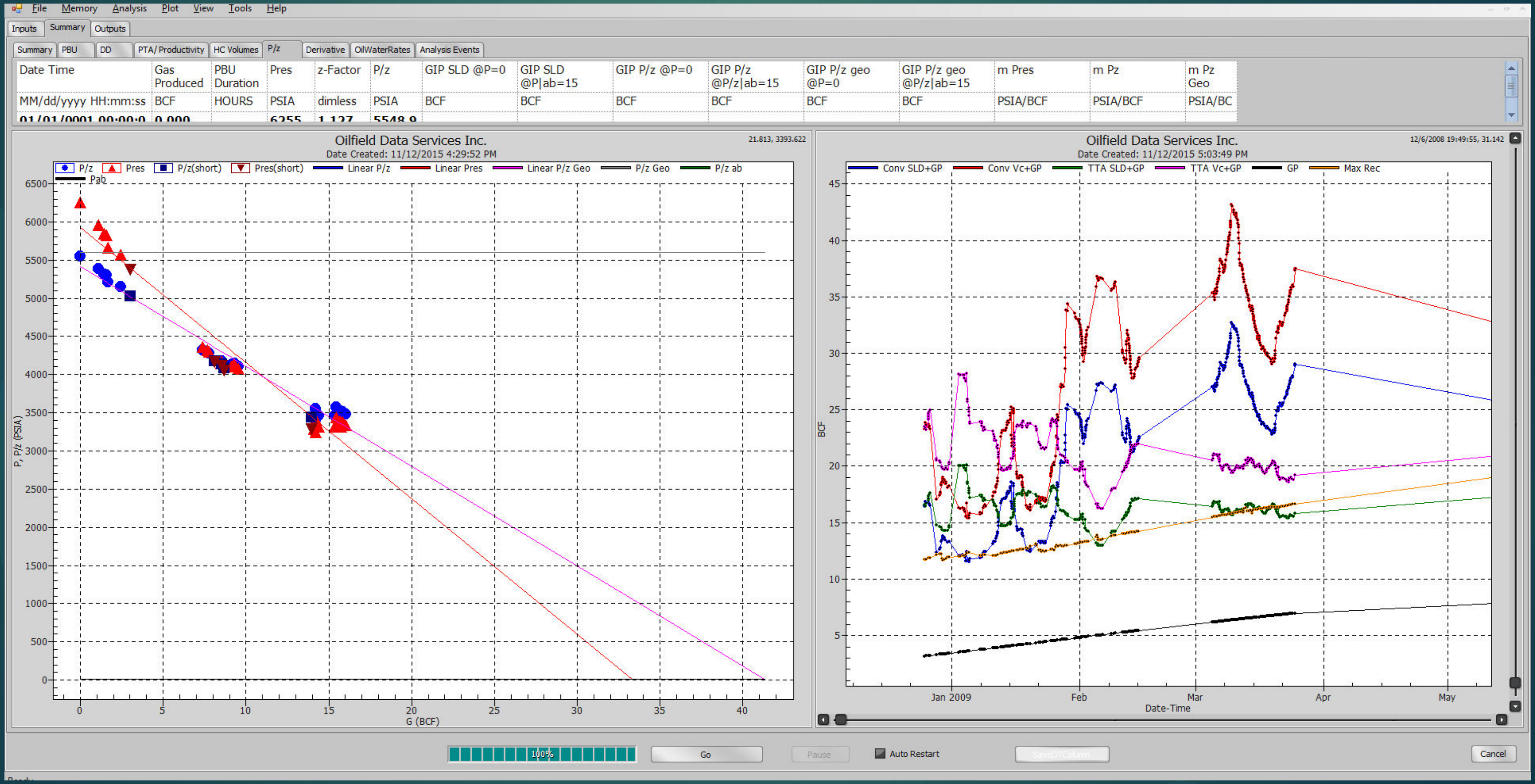
Case Study 1

Additional Features: HC Volume

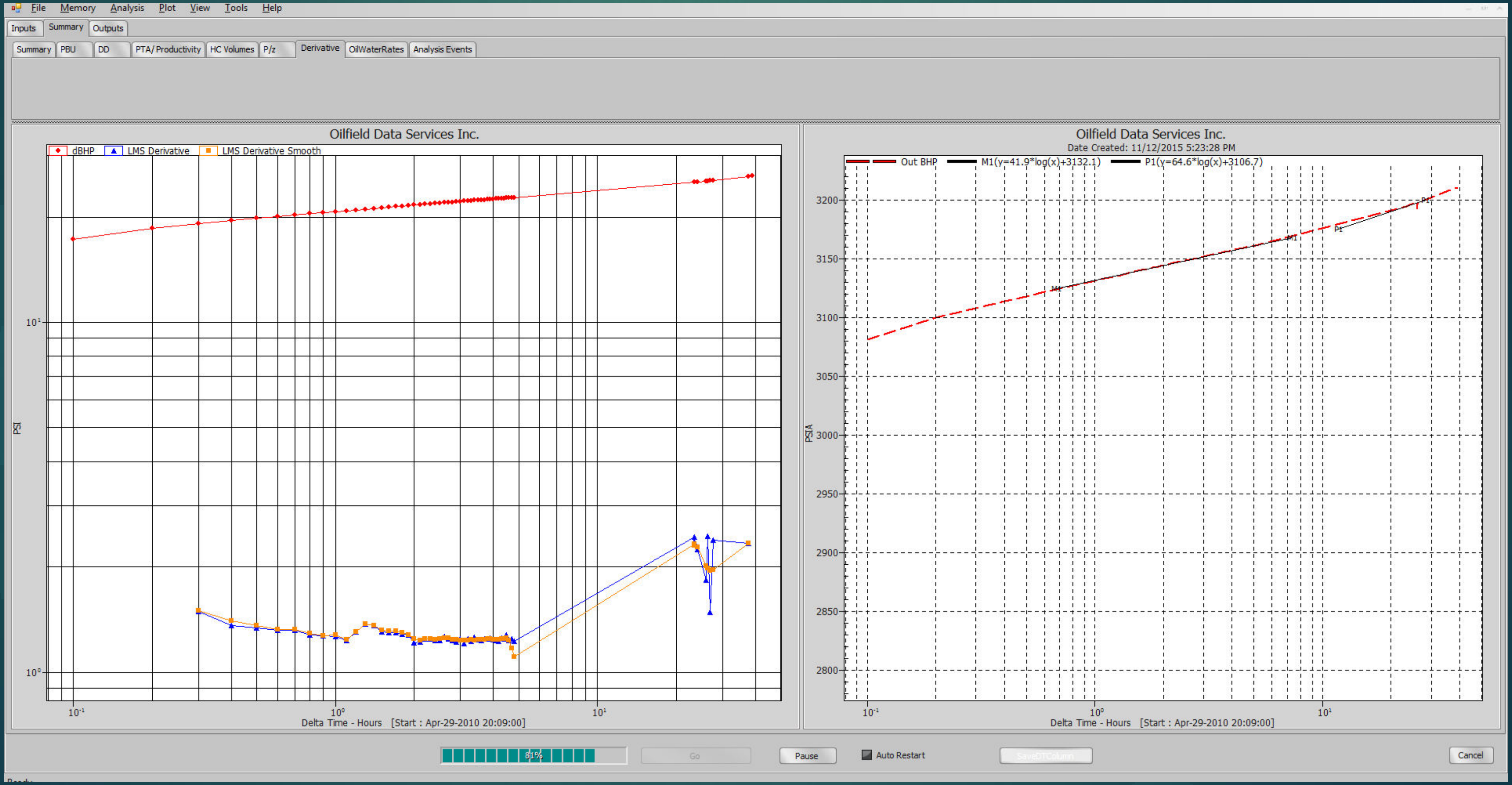


Case Study 1

Additional Features: HC Volume Before Water Mobilization



Case Study 1
Additional Features: Derivative Plot and Semi-log Plot for PTA



Case Study 2

Case Study 2

- North Sea subsea field
- Wet gas
- 2 wells are tied-back to the host facility
- Combined flow rates from both wells are measured at the host facility
- No subsea flowmeters

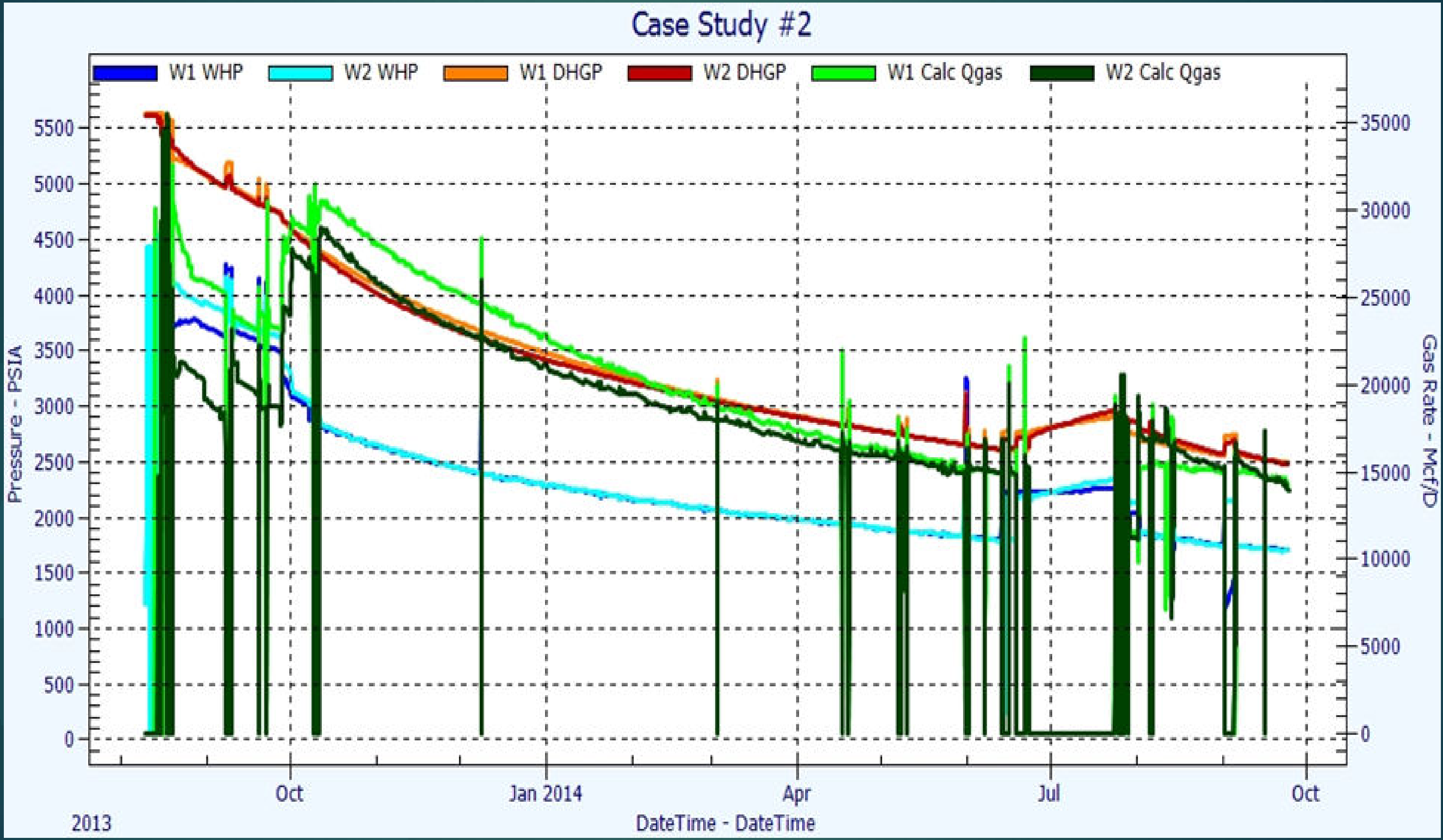
Case Study 2

- Initial density tuning was done using PBU following the flowback/initial completion test and compositional analysis
- Initial friction factor was acquired from DP WB during flow tests
- Further friction tuning was required due to the well clean-up
- Initial thermal model was generated

Case Study 2

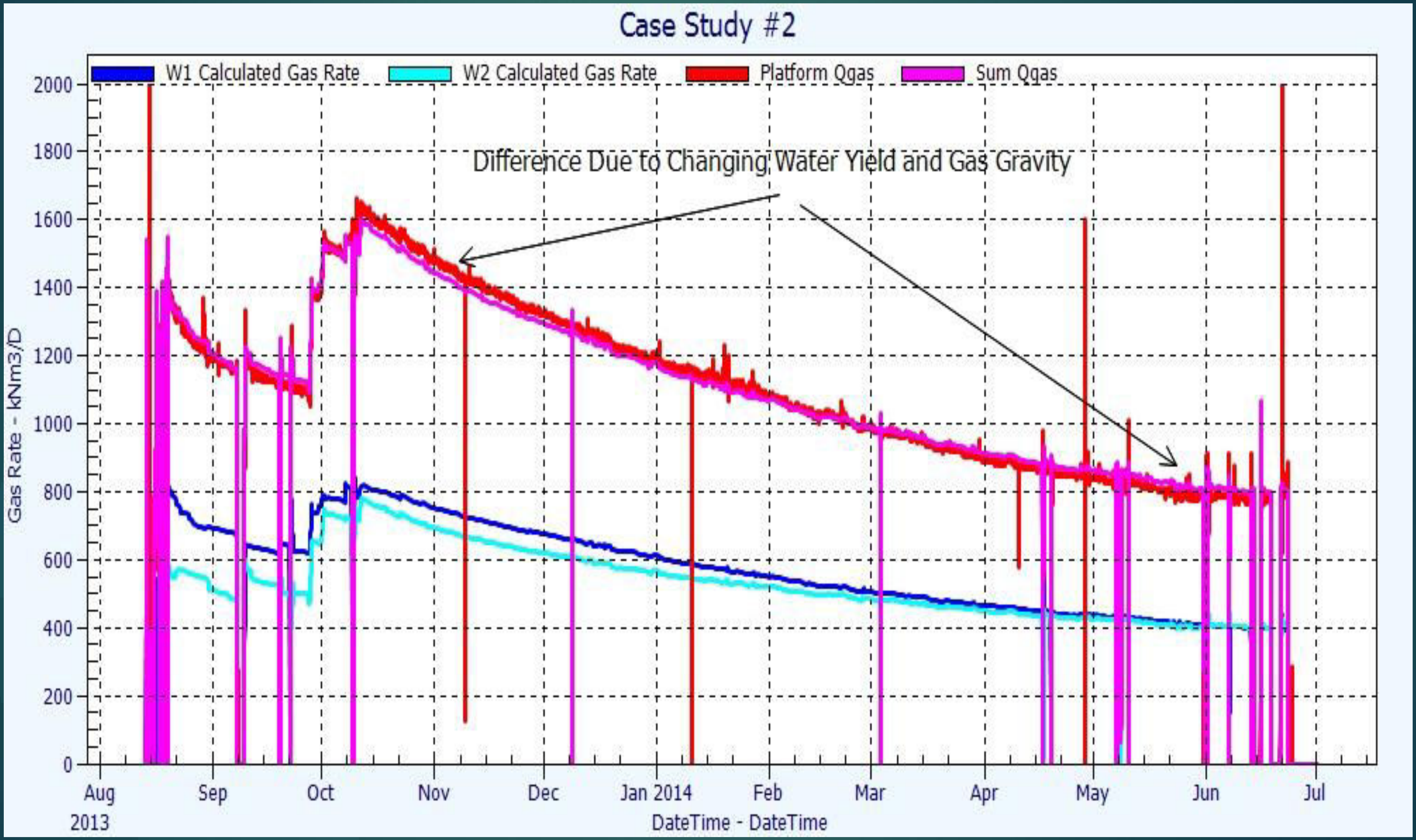
- Well 1 was brought on-line and flowed at several different rates. Then clean-up was confirmed and the well was shut-in
- Well 2 was then brought on-line, flowed at several rates, cleaned-up and shut-in
- When both well models were tuned, Well 1 and Well 2 were brought on-line together
- Sum of the calculated d/p rates from Well 1 and Well 2 matched host platform measured rates.

Case Study 2 Results



Wellhead and downhole pressures and individual calculated rates

Case Study 2 Results



Sum of calculated gas rates and platform rate comparison

Case Study 2 Results

- Individual tuning of the wells to live match measured platform rates
- When both wells were brought on-line together, sum of the calculated wellbore DP rates was compared to measured platform rate
  - < 1 % error
- Benefits of DP wellbore rate calculations
  - Assists in diagnosing errors in allocations
  - Detects onset water production
  - Detects change in gas composition during shut-ins
  - If flow meter fails, DP wellbore calculations can be used on its own to determine the rate
  - Does not require additional equipment installation
  - Low-cost investment

Case Study 2
Additional Software Features

- Automated Pressure Transient Test Analysis
  - The software recognizes new transients (DD/PBU/Multi-Rate tests) and analyzes them for skin, permeability, DP skin, Productivity Index etc.
- Automated Static Material Balance (p/Z)
  - In-place HC Volume
- Automated Decline Analysis
  - Hydraulically Connected and Mobile HC volumes

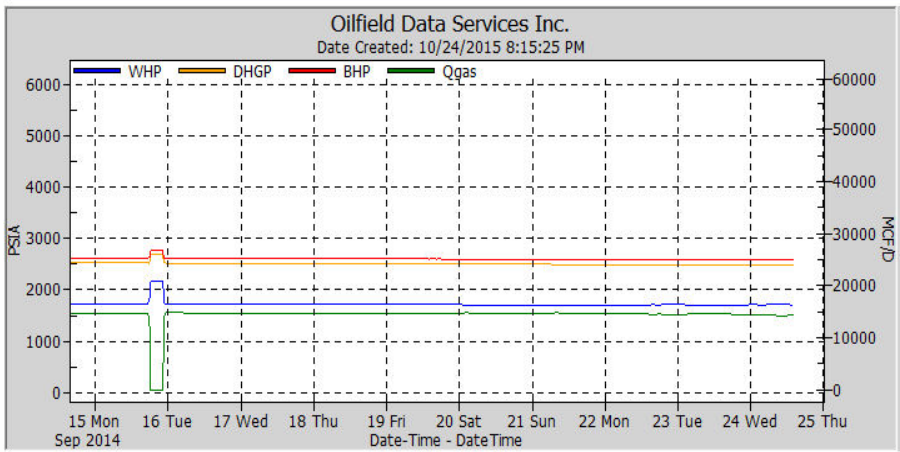
Case Study 2

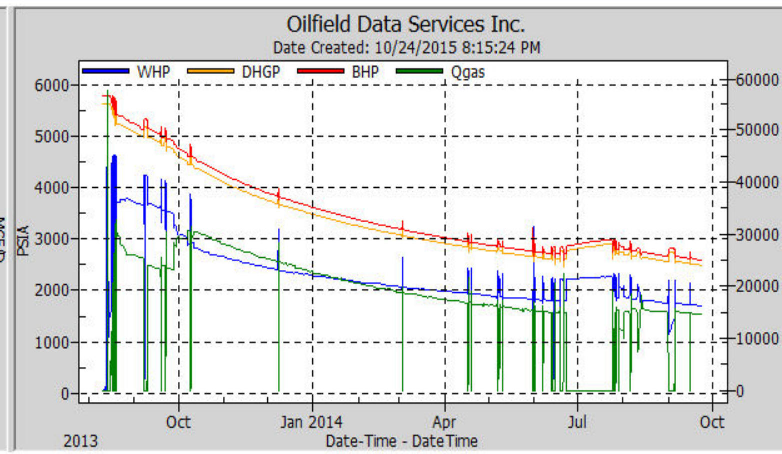
Additional features: Automated Well Test Analysis

Inputs | Summary | Outputs

Summary | PBU | DD | PTA/Productivity | HC Volumes | P/z | Derivative | OilWaterRates | Analysis Events

	Test Length Hours	Test Type	WHPi psia	WHPf psia	DHGPi psia	DHGPf psia	BHPi psia	BHPf psia	QGasi Mcf/D	QGas Mcf/D	Perm md	Skin	DPskin psi	PStar psia	PI Eff %	DPs/Q psi/MMcf	Report Link	Graph Link
14	13.37	DD	2243	1943	2765	2605	2851	2694	0	12437	5.8	-4	-372	2702	404	-29.9	K4Z1ODSIRTRep 2014Jun	K4Z1ODSIRTRep 2014Jun
15	46.37	PBU	1798	2157	2605	2738	2702	2824	14801	14801	44	3.7	53	2895	63	3.55	K4Z1ODSIRTRep 2014Jun	K4Z1ODSIRTRep 2014Jun
16	67.85	PBU	1797	2148	2605	2739	2703	2824	14880	14880	61.7	7.2	73	2894	48	4.9	K4Z1ODSIRTRep 2014Jun	K4Z1ODSIRTRep 2014Jun
17	17.34	DD	2229	1800	2783	2607	2870	2705	0	22667	11.7	-1.9	-166	2704	151	-7.3	K4Z1ODSIRTRep 2014Jun	K4Z1ODSIRTRep 2014Jun
18	746.91	PBU	1801	2221	2609	2860	2707	2950	14800	14800	64.6	8.4	82	2950	44	5.51	K4Z1ODSIRTRep 2014Jun	K4Z1ODSIRTRep 2014Jun
19	21.76	PBU	1860	2249	2699	2866	2801	2955	15277	15277	73.2	14.4	124	3008	32	8.13	K4Z1ODSIRTRep 2014Jul	K4Z1ODSIRTRep 2014Jul





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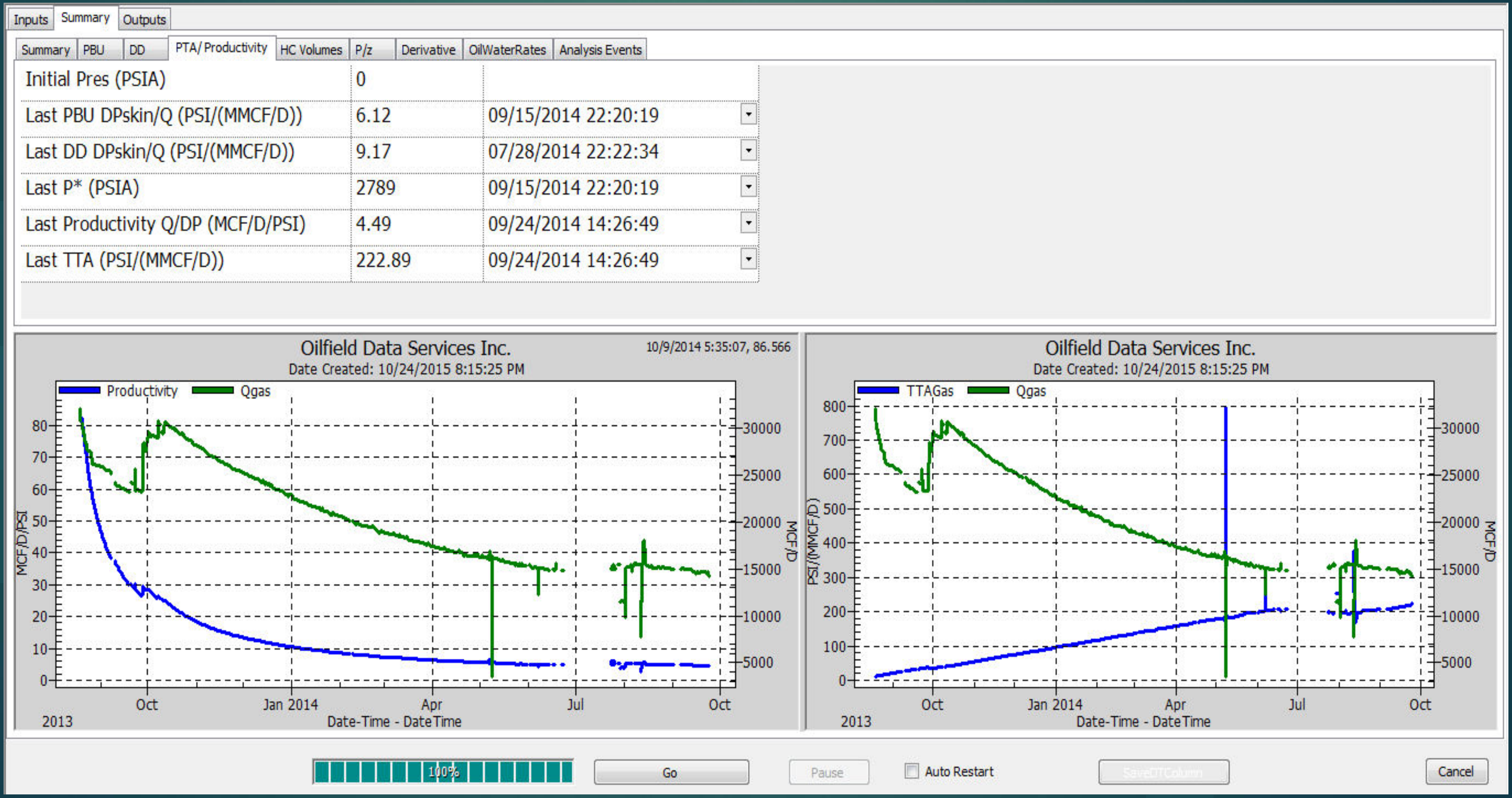
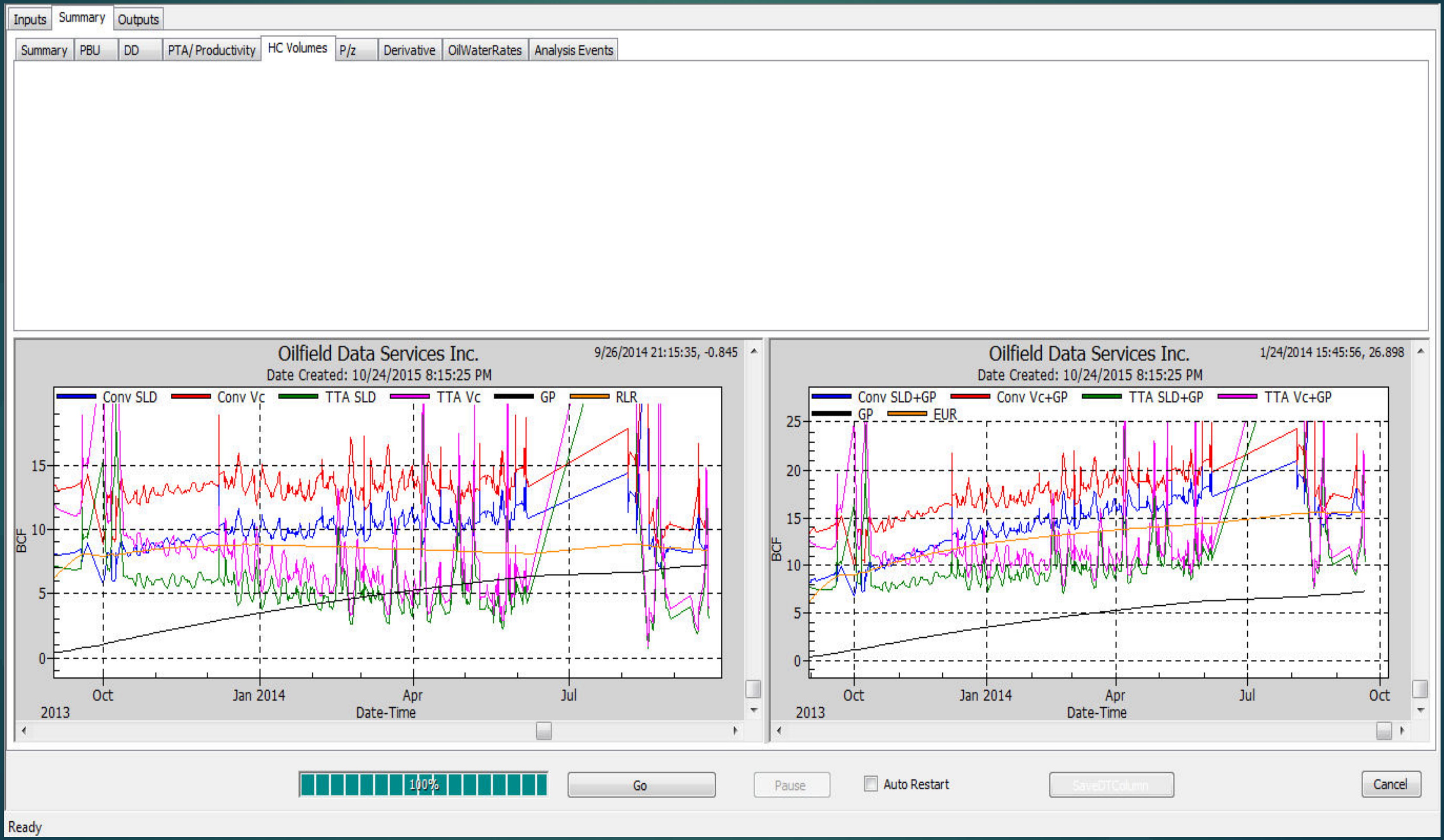
Case Study 2

Additional Features: Productivity and Inverse Productivity Plots



Case Study 2
Additional Features: HC Volume



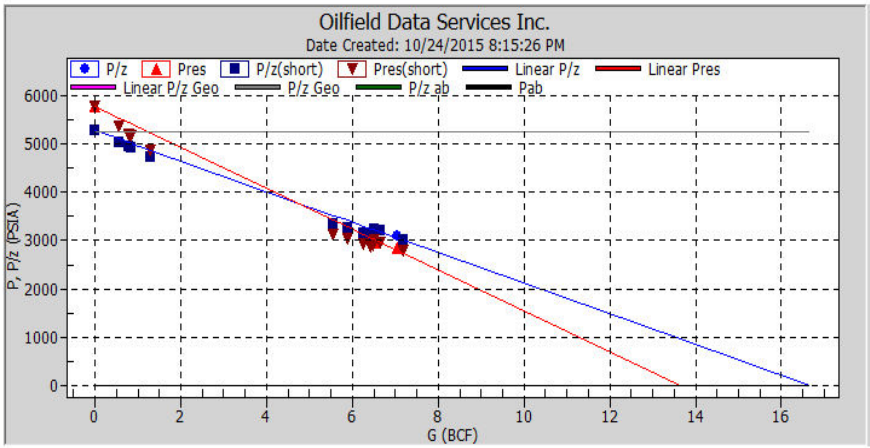
Case Study 2

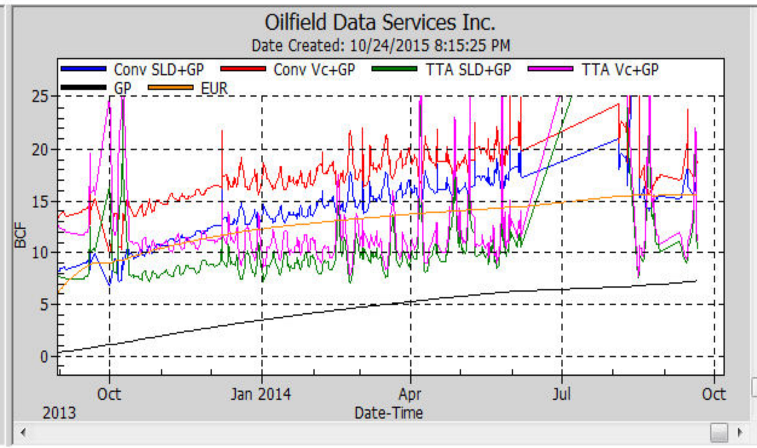
Additional Features: Static Material Balance (p/Z Plot)

Inputs | Summary | Outputs

Summary | PBU | DD | PTA/Productivity | HC Volumes | P/z | Derivative | OilWaterRates | Analysis Events

Date Time	Gas Produced	PBU Duration	Pres	z-Factor	P/z	GIP SLD @P=0	GIP SLD @P|ab=15	GIP P/z @P=0	GIP P/z @P/z|ab=15	GIP P/z geo @P=0	GIP P/z geo @P/z|ab=15	m Pres
MM/dd/yyyy HH:mm:ss	BCF	HOURS	PSIA	dimless	PSIA	BCF	BCF	BCF	BCF	BCF	BCF	PSIA/BCF
01/01/0001 00:00:0	**0.000**		**5775**	**1.093**	**5283.2**							
08/18/2013 00:10:52	0.009	2	5770	1.093	5280.32							
09/09/2013 15:20:52	0.561	45	5356	1.063	5038.06							
09/19/2013 13:28:22	0.787	4	5197	1.052	4940.04							
09/22/2013 11:33:22	0.849	8	5164	1.050	4919.31							

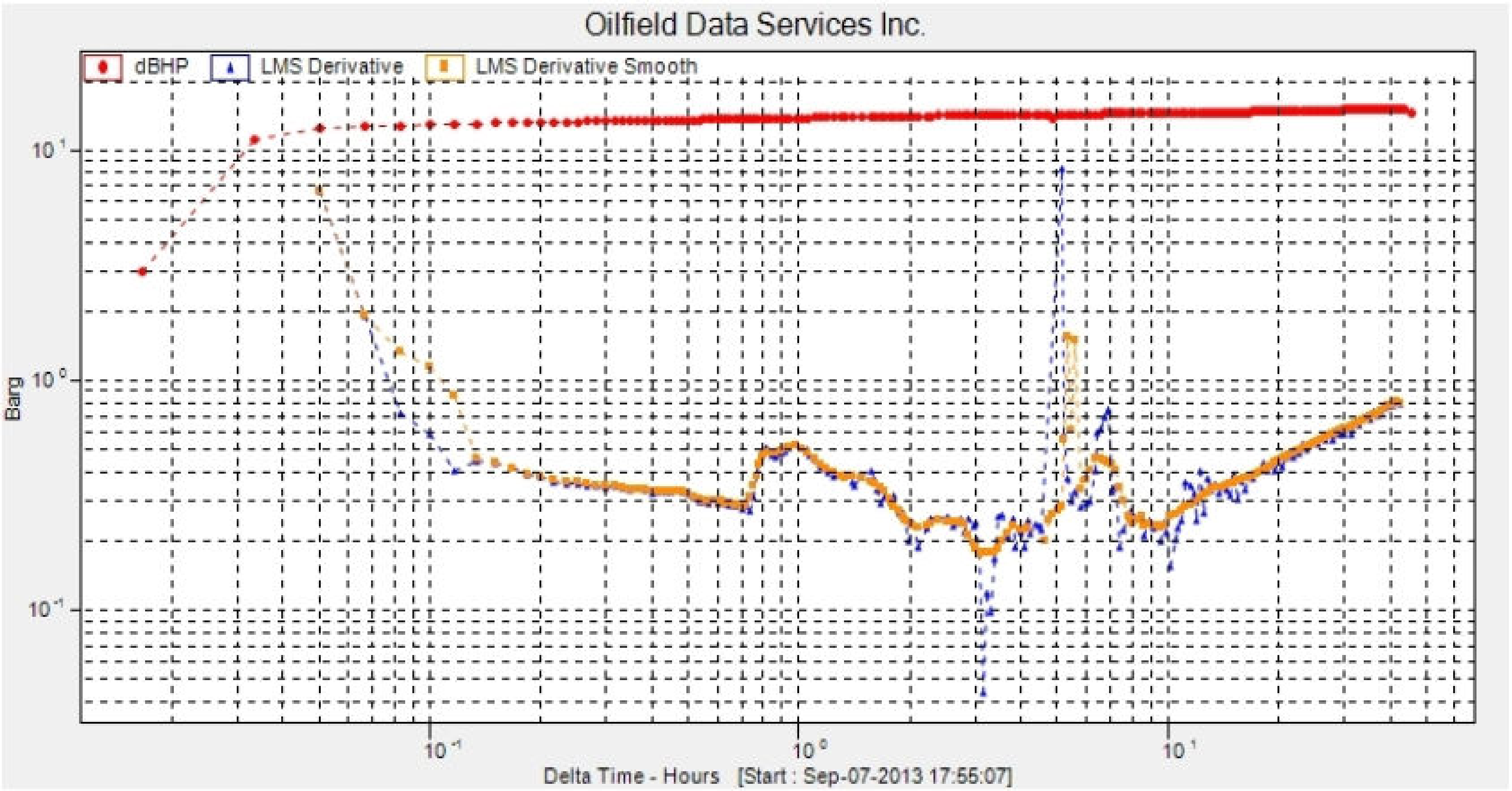




100%

Go | Pause | Auto Restart | SaveDTColumn | Cancel

Case Study 2
Additional Features: Derivative Plots



Case Study 3

Case Study 3

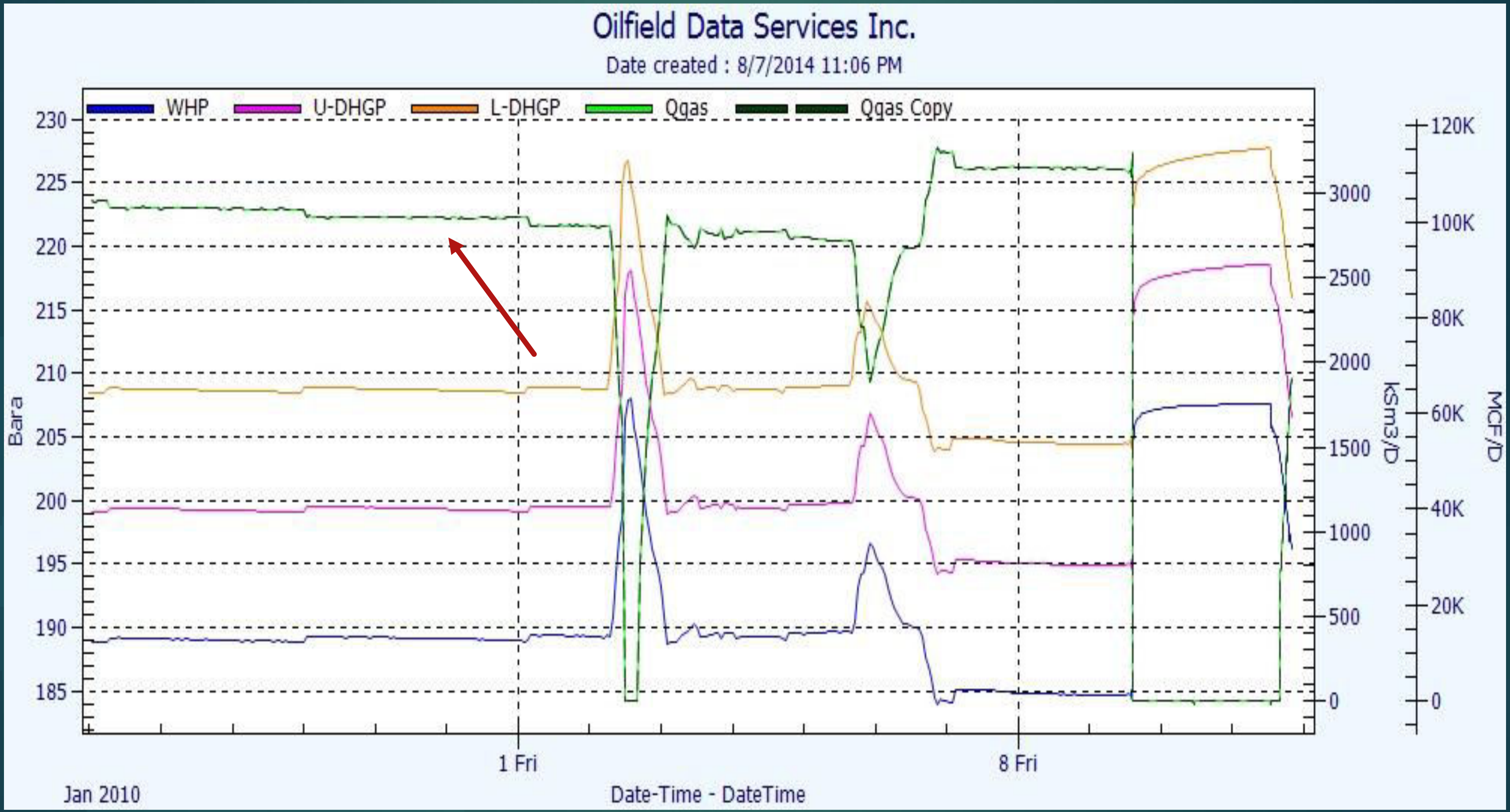
- North Sea
- Gas Condensate Well
- Well is equipped with multiple gauges
  - Tree gauge
  - Middle downhole gauge
  - Lower downhole gauge
- Objectives:
  - Validate rate
  - Validate middle and lower downhole gauge pressures
  - Perform well test analysis

Case Study 3

- Used shut-in data to calibrate PVT (gas gravity and condensate yield)
- Used tree data and middle DHG data to calibrate frictional pressure losses
- Used tree gauge and lower DHG data to confirm production rates
- Analyze well test using
  - WHP
  - Middle gauge pressure
  - Lower gauge pressure
  - Mid-completion BHP

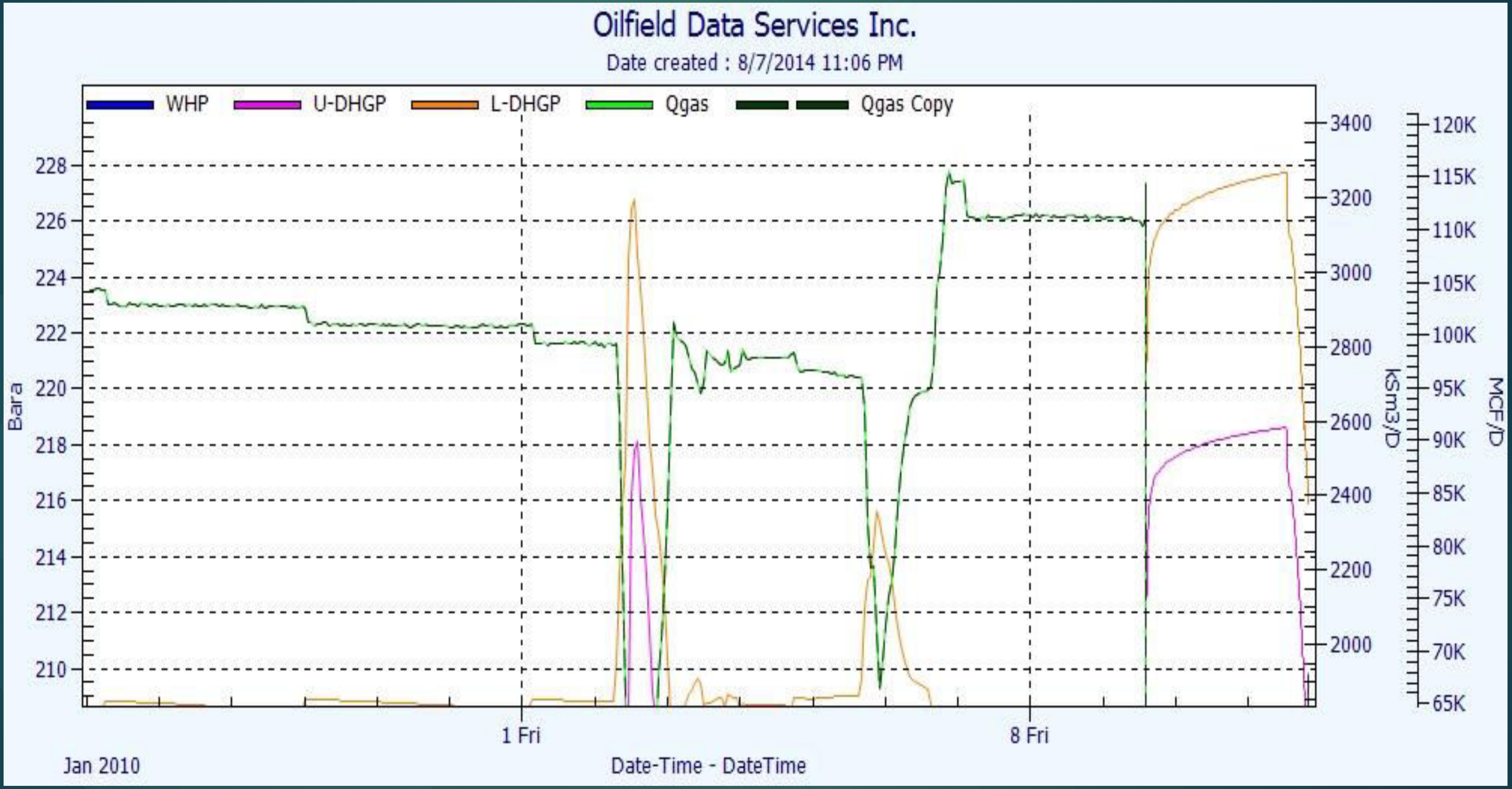
Rate Comparison

Case Study 3 Results



Measured Qgas vs. calculated Qgas (green and dark green respectively on the plot)

Case Study 3 Results
Rate Comparison Plot



< 1 % error in the Gas Rate Calculations (green – measured gas rate, dark green – calculated gas rate)

Case Study 3 Results

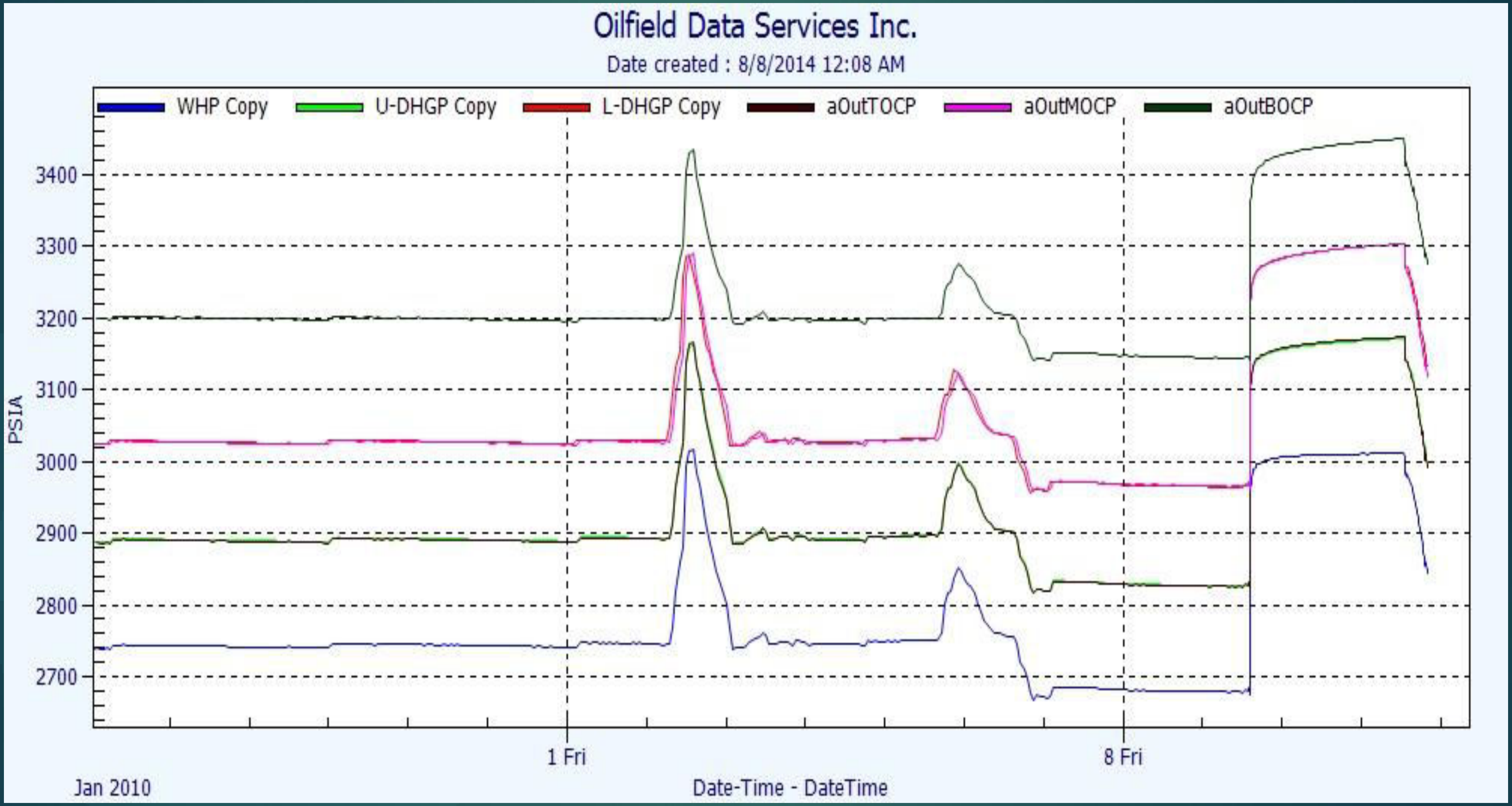
Rate Comparison Zoom Plot

< 1 % error in the Gas Rate Calculations (green – measured gas rate, dark green – calculated gas rate)

Case Study 3

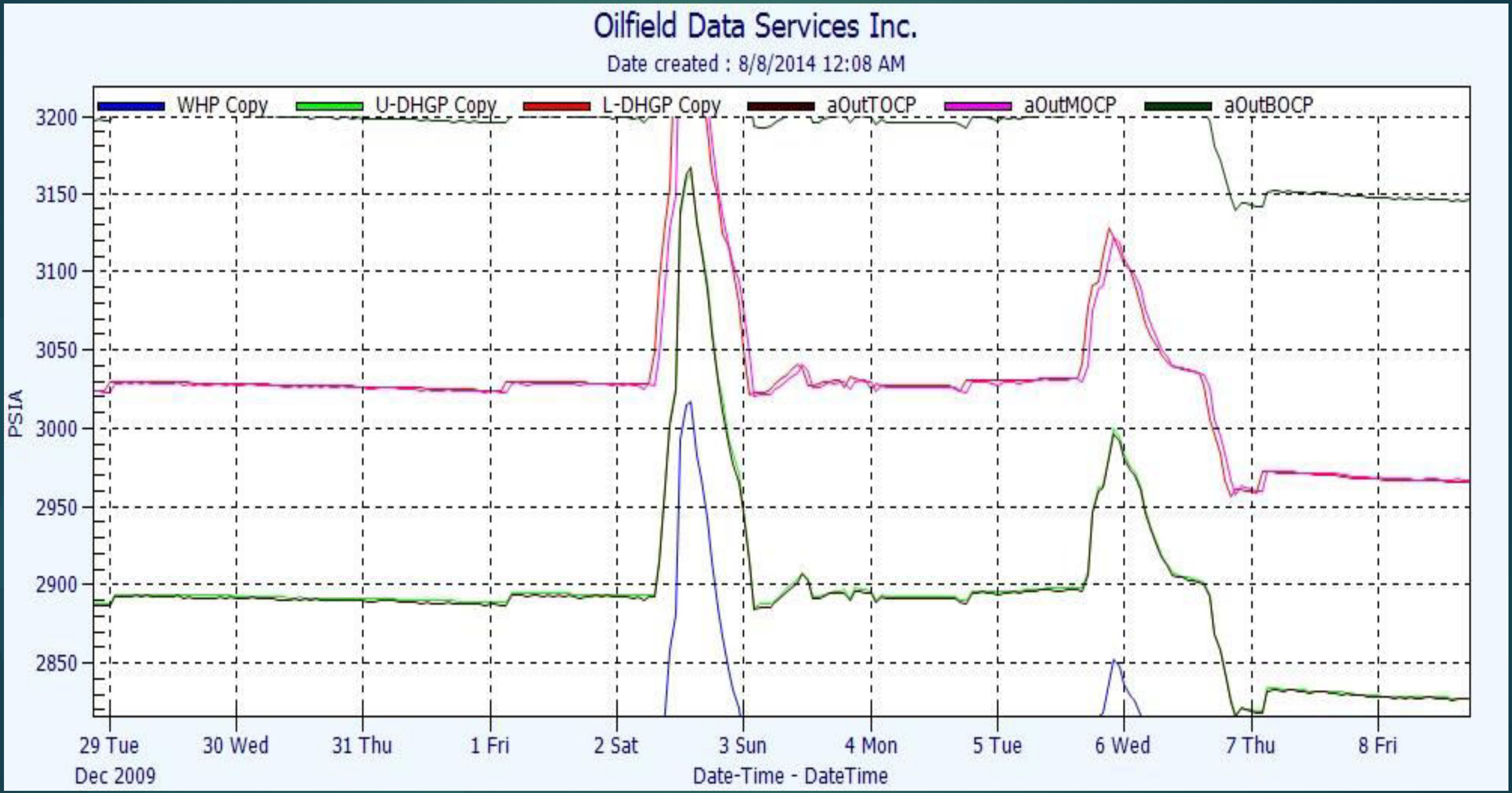
Pressure Comparison

Case Study 3
Pressure Comparison Results



Pressure can be calculated at any point in the wellbore (top of completion, mid-completion, bottom of completion depths)

Case Study 3
Pressure Comparison Results Zoom



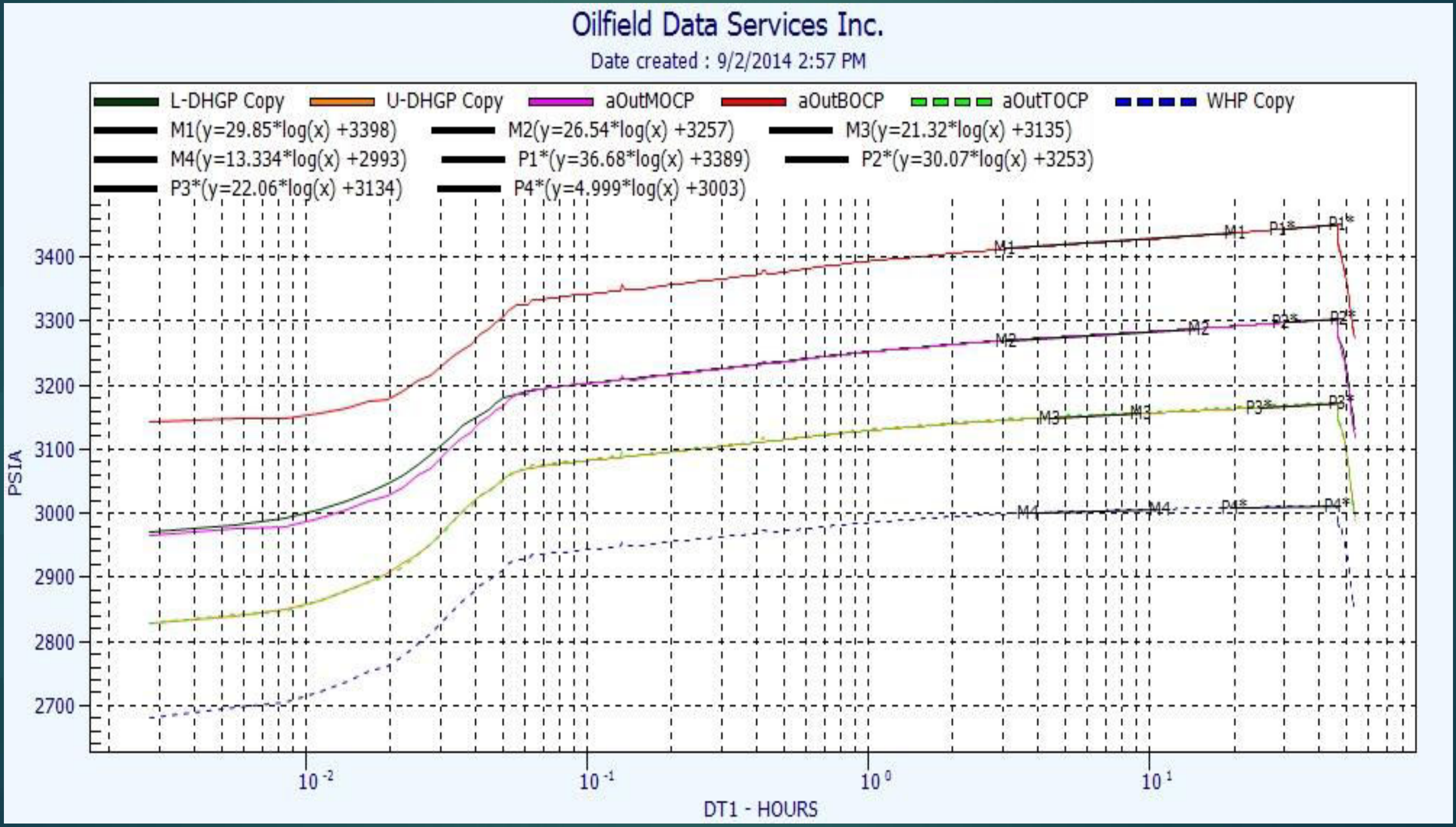
Accurate Pressure conversions (< 2 psi): top of completion, mid-completion, bottom of completion)

Case Study 3
Pressure Comparison Results Zoom Plot

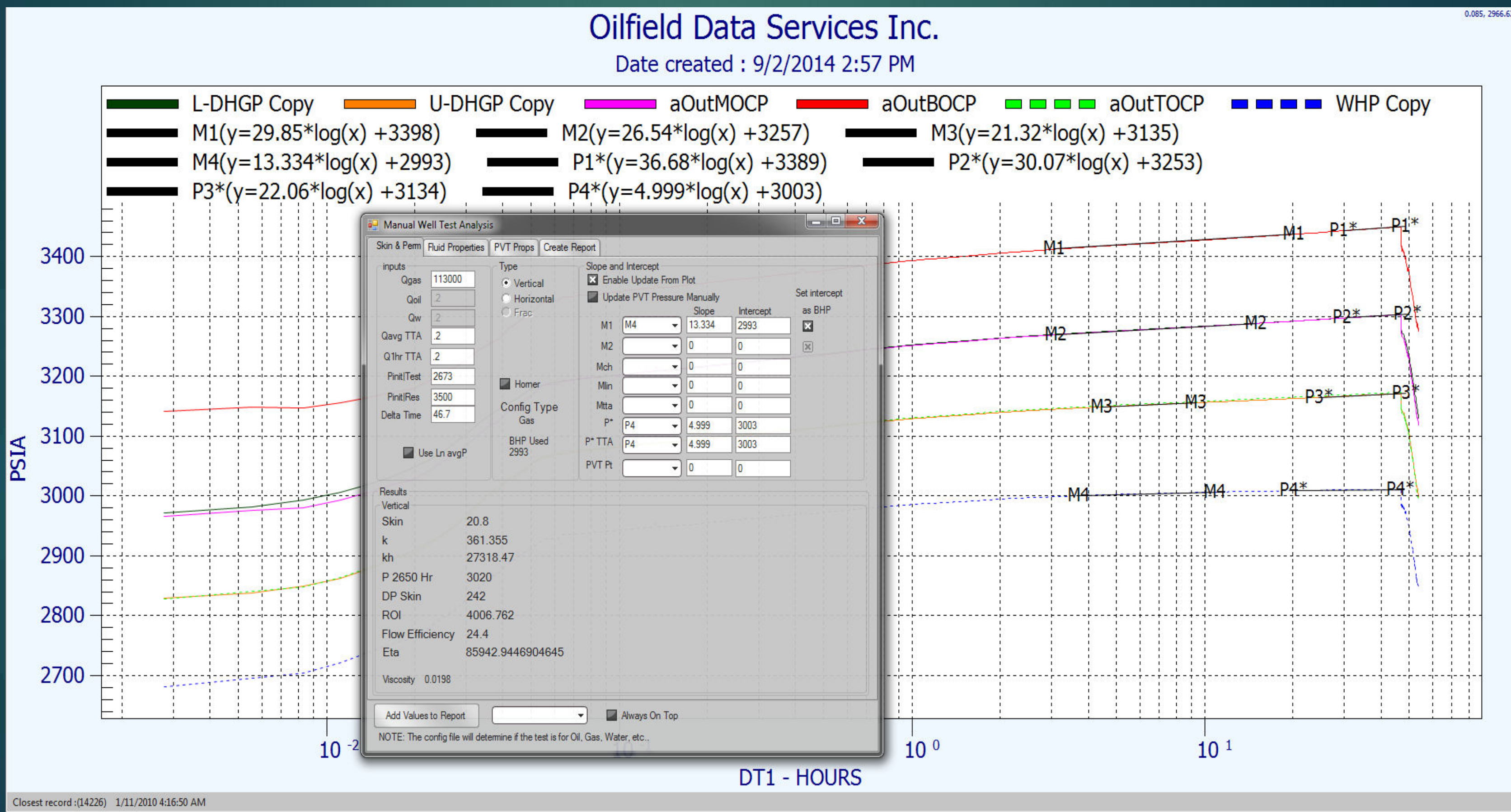
< 2 psi error for pressure conversion

Case Study 3
Well Test Analysis Results

Semi-log PBU Plot
All reference depths

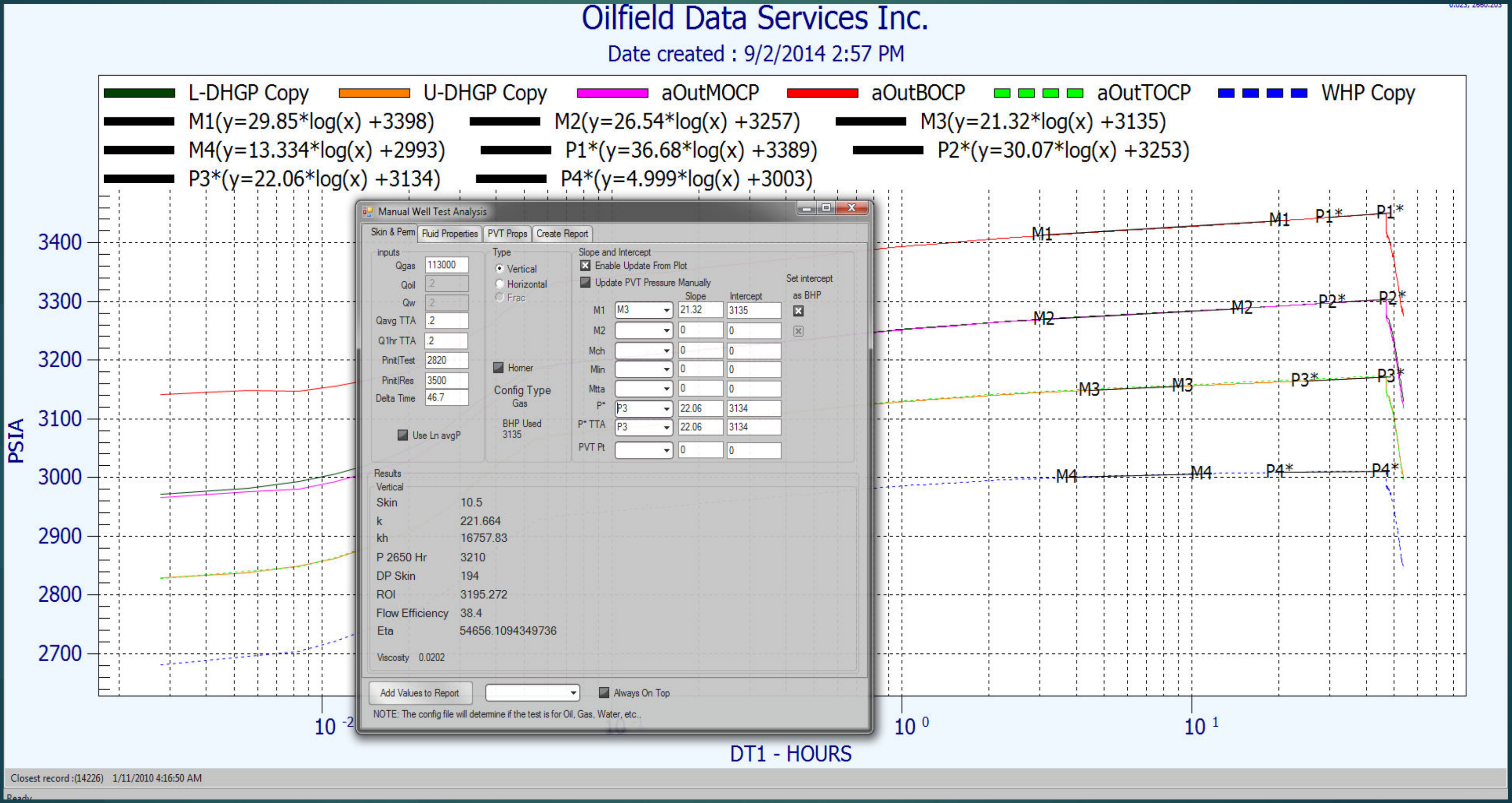


WHP/Tree Gauge
PBU Semi-log Analysis



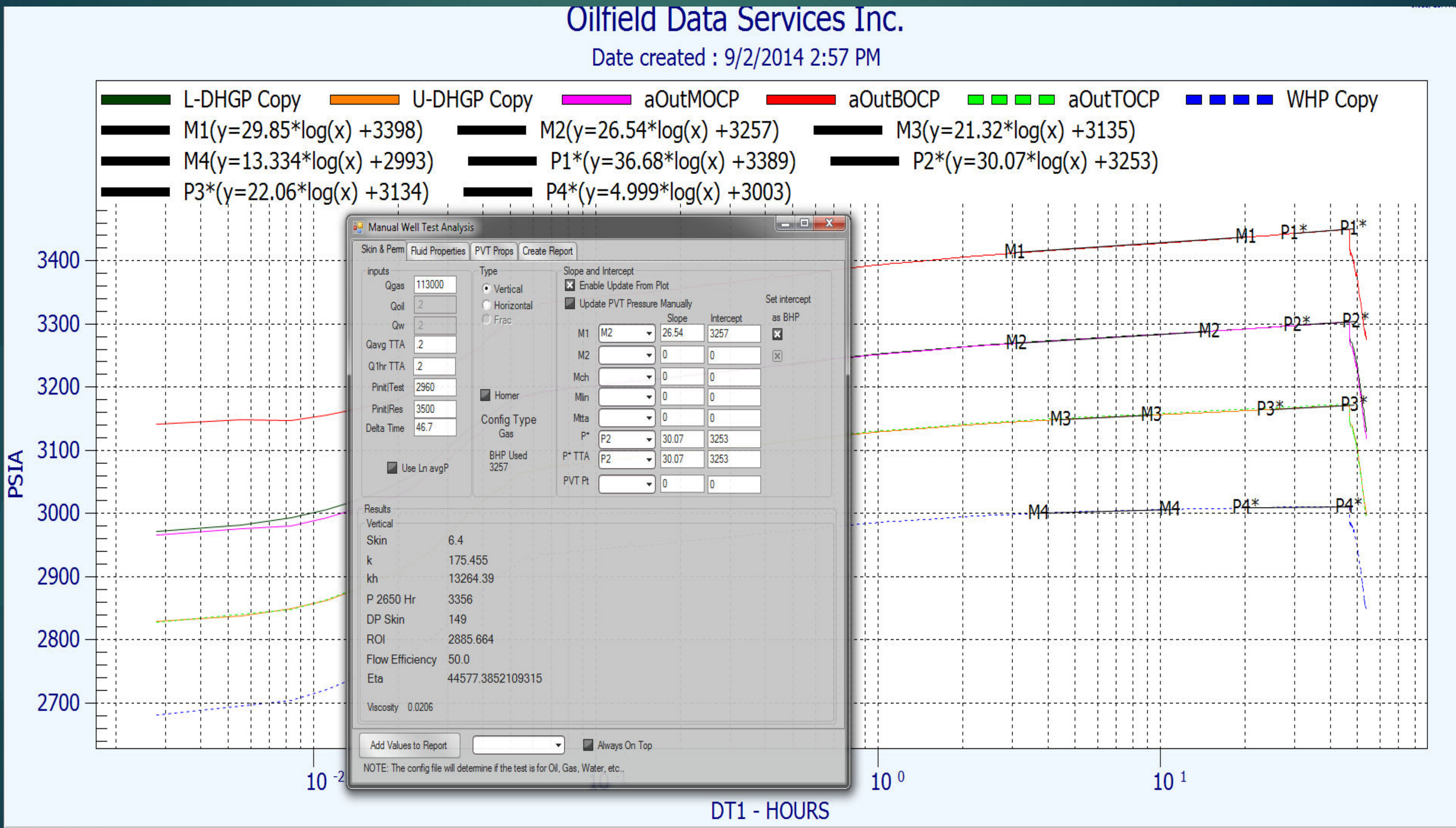
Skin = 20.8; permeability = 361 md

Upper DHG
Semi-log PBU Analysis



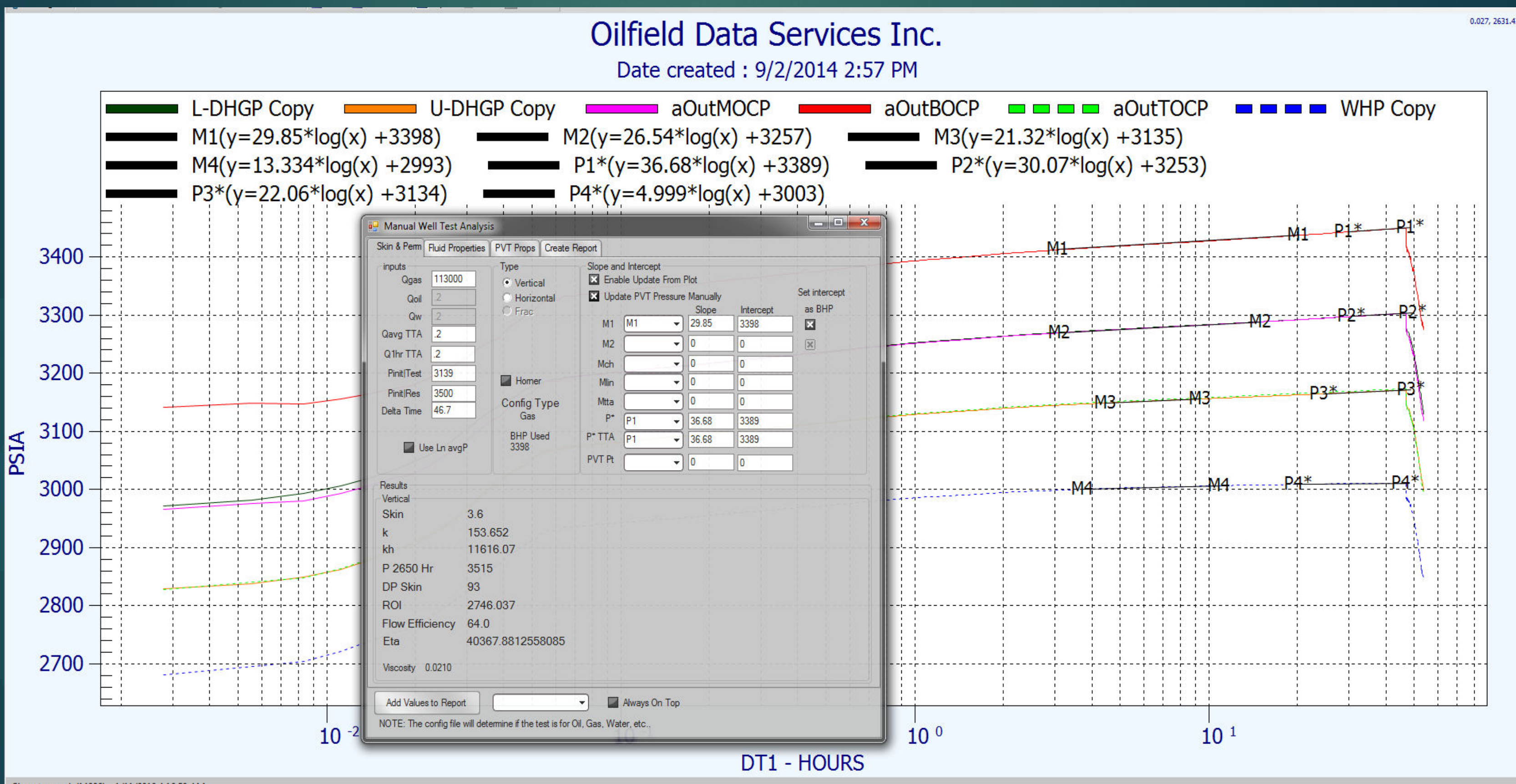
Skin = 10.5; permeability = 222 md

Lower DHG PBU semi-log Analysis



Skin = 6.4; permeability = 175 md

Mid-Completion Semi-log PBU Analysis



Skin = 3.6; permeability = 154 md

Semi-log PBU Analysis Summary

	Slope (psi/cycle)	Skin	DP Skin (psi)	DP Skin/Q (psi/MMCF/D)	Permeability-thickness (md-ft)	Perm (md)	ROI (ft)
WHP	13.33	20.8	242	2.14	27318	361	4007
U-DHGP	21.32	10.5	194	1.72	16758	222	3195
L-DHGP	26.54	6.4	149	1.32	13264	175	2886
BHP	29.85	3.6	93	0.82	11616	154	2746

It is important to calculate mid-completion BHP. Failure to do so leads to overestimating skin and permeability

Case Study 3 Results

- Using a direct solution to the Mechanical Energy Balance, PVT, Thermal and Frictional models, accurate pressure conversions can be performed at <u>any point in the wellbore</u>

Conclusions

- DP between gauges can be used to calculate gas rates. The procedure involves:
  - Bernoulli equation (Mechanical Energy Balance)
  - Parametric/Dynamic functions of heat transfer in/near well
  - Calibrated equation of state
  - Tuned frictional model

Conclusions

- Gas rate calculations using d/p wellbore
  - Accuracy of the technique Assists in diagnosing errors in allocations
  - If flow meter fails, the technique can be used on its own to determine the rate
  - Does not require additional equipment installation
  - Gas rate calculations can be done in real-time and on historic data
  - Low cost investment