Realtime Rate Allocation for Multilateral Wells Equipped with Downhole Valves and a PDHMS

BY

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Date

DEDICATION

To the Mother of My Children, the Wife, the Sister and the Friend

Acknowledgment

Most respectfully, I express my thanks to ALLAH for the endless help and support to complete the thesis. I would like then to express my appreciation and recognition to my family for their backing, encouragement and patience.

I would like to express my sincere thanks and appreciation to my advisor Dr. Mohammad Al-Marhoun. His mentorship and confidence in my abilities and talents have inspired me to strive for excellence.

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I would like finally to express my sincere appreciation to you, the reader of this report, for taking the time to read it. If it was not for you, this report would not have any value.

Saeed M. AlMubarak

Preface

The purpose of this report is to present within the available space, a methodology to allocate continuous production rates for individual-laterals that are equipped with downhole multi-position valves in multilateral wells equipped with a single permanent pressure and temperature gauge. The allocated data will be vital to determine the best downhole valve positions that facilitate meeting the production target of every single lateral by setting the downhole valves at their appropriate positions. These rate allocation data are very essential to optimize the production of the well to ensure proper withdrawals, better sweep efficiency and better reservoir(s) depletion estimation(s). In addition, it will provide means to perform better modeling, history matching and predictions.

The industry considers downhole valves and permanent downhole gauges two of the main enablers of real-time reservoir management (RTRM). The results of this study will serve as a step toward providing more efficient, accurate, and timely information — to the decision makers in a business environment to integrate the required information and control capabilities into their strategies.

For the sake of comprehension and to illustrate the importance of the efforts herein and put them in prospective, the study will present a quick practical overview of the current fundamental issues associated with RTRM.

Table of Contents

List of Figures

List of Tables

خلاصة الرسالة

اسم الطالب: سعيد محمد حسن آل مبارك

عنوان الدراسة: التقدير اللحظي للانتاج من الابار متعددة التفرعات والمزودة بصممات و جهاز قياس للضغط و الحرارة

التخصص: هندسة البترول

تاريخ الشهادة: يناير 2011 م

لقد سلمت صناعة البترول بدورتكنلوجيا الحقول الذكية الفاعل في الادارة اللحظية للمكامن. فقد دعم استخدام التكنولوجيا المناسبة صاحبوا القرار بادوات و معلومات للوصول الى قرارات سريعة ذات كفاءة و دقة. و هذا ما جعل لدخول هذه التكنولوجيا من الاثر الكبير في عالم التنقيب و الانتاج. ومن بين هذه التكنولوجيا، صمامات التحكم واجهزة الاستشعار الجوفية التي تستخدم للتحكم و مراقبة و رصد الانتاج من ابار متعددة الفروع.

هذه الدراسة تقدم منهجية معتمدة و موثقة على بيانات ميدانية من اجل تقديم تقدير لحظي للانتاج من الابار متعددة التفرعات والمزودة بصمامات متعددة الفتحات و جهاز قياس موحد للضغط و الحرارة. علما بان تفرعات هذه الابار قد تمتد الى طبقات او مكامن مختلفة.

درجة الماجستير في العلوم

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Thesis Abstract

Student Name: Saeed Mohammed Hassan Al Mubarak

Title of Study: Real-time Rate Allocation for Multilateral Wells Equipped with Downhole Valves and a PDHMS

Major Field: Petroleum Engineering

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The petroleum industry has recognized that intelligent field technologies have made it possible to manage hydrocarbon assets in real-time. Fit-for-purpose technologies provide more efficient, accurate, and timely information to the decision maker. The infusion of these intelligent field technologies into hydrocarbon upstream industries has significantly impacted the Exploration and Production business environment. Among these technologies are downhole valves and downhole sensors that have been utilized to control and monitor the production from multilaterals or multisegment wells.

The study shall provide a methodology that is based on field data to allocate continuous production rates for individual-laterals that are equipped with downhole multipositional valves in multilateral wells equipped with a single permanent pressure and temperature gauge. These multilateral wells may have branches that are extended to different layers or reservoirs.

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CHAPTER 1

INTRODUCTION

1.1 Background:

Several fields around the world have adopted drilling multilateral wells equipped with multiposition downhole valves and downhole permanent pressure and temperature gauges. The initial deployments of wells and completions were part of a proof of concept project to test and evaluate the impact of these technologies on reservoir, well performance and overall reservoir management strategies. The main objective to implement these advanced technologies was mainly to increase well productivity, optimize production rates from individual lateral, minimize water production and consequently improve the overall reservoir performance. Actual performance along with simulation assessment studies indicated that these wells outperform conventional wells, as far as well life span, productivity and water production management.

Several companies have assessed actual performance of multilateral wells and downhole multiposition valves from different vendors. During their assessment, they usually conduct very comprehensive testing programs that incorporated testing each lateral at different downhole valve settings. The main objective is to determine the best downhole positions that facilitate meeting the production target of every single lateral or segment of well by setting the downhole valves at

their appropriate positions and to give reasonable allocation of their production rates.

Results have highlighted several challenges with regards to well completions, downhole valve designs, testing procedures and optimization solutions to maximize the value of not only for future wells but also to optimize the existing completions. Based on field experience, several improvements have been already realized particularly in the completion and the downhole valves design. Other improvements are still deemed necessary to realize the maximum value of the investment on these wells. One of the challenges with these advanced completions is to estimate or back allocate the rates for individual laterals or segments that are controlled by downhole valves.

To optimize the performance of multilateral wells equipped with downhole valves and a single permanent gauge, it is very important to first understand the existing wells' performance at different well conditions; and then to establish a workflow that is tailored to meet the objective of the study, which is to facilitate continuous allocation of production rates for individual laterals. The study will be based on actual field data. The results of the study can be utilized as a component in a new automated workflow, which can be integrated within a real-time reservoir management environment, supporting systems to maximize the overall asset value throughout its various stages to meet companies' objectives.

1.2 Thesis Objectives

The study shall provide a methodology that is based on field data, to allocate continuous production rates for individual laterals that are equipped with downhole multiposition valves in multilateral wells, equipped with a single permanent pressure and temperature gauge. These multilateral wells may have branches that are extended to different layers or reservoirs.

The main objective is to determine the best downhole valve positions that facilitate meeting the production target of every single lateral, by setting the downhole valves at their appropriate positions and to give reasonable production rate allocations. This rate allocation data is essential to optimizing the production of the well to ensure proper withdrawals, better sweep efficiency and better reservoir(s) depletion estimation(s). In addition, it will provide the means to perform better modeling, history matching and predictions.

1.3 Approach

Models for actual multilateral wells equipped with downhole valves and a single PDHMS, the subject of the study, will be constructed using commercial well hydraulic modeling tool solutions capable of modeling inflow performance for production from complex wells with commingled production from multiple reservoirs or multiple segments. Field tests will be designed and conducted to get the required data for model matching and validation. Model results will be examined and reported against actual field data. Based on the results, an allocation factor will be recommended for total well and individual lateral production rates. These rates will be generated in real-time even when wells are not being tested.

CHAPTER 2

LITERATURE REVIEW

Multilateral wells equipped with downhole valves and permanent gauges — what is known as Intelligent Well technology — enables improved reservoir management, leading to increased reserve recovery through the control of the flow of fluids, from the reservoir into the wellbore isolated segments or laterals. Operators are embracing the ability not just to turn flow on or off, but to regulate the flow from individual zones, in the interests of better reservoir management.

Based on most literature reviews on the subject wells and upon analyzing the advantages and disadvantages of their completion scheme, it is clear that the potential benefits offset the potential costs associated. Moreover, field experiences on these wells have facilitated several improvements, including: the completion and downhole valves design, well architecture and downhole measurement instrumentation.

With regards to downhole rate measurements, the first downhole continuous flow measurement sensing technology for multilateral wells that was trial–tested, was incapable of providing reliable rate measurements across some positions of the downhole valves[1]. Further research is being done but has not been implemented in the field.

Other efforts were done to estimate lateral production in commingled production from multilateral wells. These wells were equipped with downhole valves and multiple downhole pressure sensors (across these

valves) using customized downhole valve choke performance models[2]. Several physics and correlation-based rate allocation efforts have been proposed. Among these is a method that is based on an optimization algorithm to minimize the difference between measured and predicted properties, which includes pressures, temperatures and rates, using both simulation and hydraulic well models[3]. Another method utilized fuzzy logic to calculate individual zone allocation factors, based on well log analysis and supported by bottom hole pressure data and fluid properties[4].

Further literature comprehensive review indicated that no efforts were made to calculate or back allocate individual lateral rates on a continuous basis, for multilateral wells equipped with multiple downhole valves; and a single gauge that is installed above the production packer. Although advertisements of several vendors' solutions insinuate the existence of more optimization and modeling capabilities of multilateral wells equipped with downhole valves, none of them indicated having the rate allocation functionality for the subject completion. Various efforts were made to back allocate rates from multilateral wells equipped with multiple downhole gauges across each of their downhole valves. They were done based on well and production system physical models [5, 6, 7, 8 &9].

This study will be the world's first effort to use actual well test data — to furnish workflow — to allocate individual lateral rates for multilateral wells, equipped with multiposition downhole valves, and a single permanent downhole measurement system (PDHMS).

CHAPTER 3

CURRENT STUDY DATA ACQUISITION

In this study, data from three different wells were used. These wells have different completion schemes namely, bi-lateral, tri-lateral and quad-lateral. Every well is equipped with at least one Permanent Downhole Measurement System (PDHMS) that measures pressure and temperature. Moreover, every lateral of these wells is equipped with downhole multiposition valve that can be operated from surface.

The data that was used in this study include:

1. Completion Details
2. Deviation Surveys
3. Surface Flow Rate Measurements
4. Surface Choke Size and Surface Pressures Readings
5. Downhole Valves Settings
6. PDHMS Pressure Reading
7. Fluid Properties

The available test data was utilized to validate the models after they were constructed using an analysis package(s) that uses nodal analysis techniques, to model reservoir inflow and well outflow performance. The analysis package is capable of modeling multilayer or multilaterals with each layer having its own fluid, completion and inflow model.

3.1 Data Description:

3.1.1. Completion Details

The data describes all components — from the bottom of the production tubing upwards — with reference to vertical and measured depth. These completions consist of downhole valves, various types of tubing configurations, PDHMSs and other components that are required for safety purposes. Figures: 3.1 to 3.3 illustrate the completions schematics for the three cases that are used in this study.

3.1.2 Deviation Surveys:

The data represents the position of a borehole or well path in three dimensional space (3D). The data includes drift, azimuth and inclination of a borehole with the vertical. These surveys are used to spatially locate the downhole path of a well or a lateral. Figures 3.4 to 3.6 show lateral locations in space.

3.1.3 Surface Flow Rate Measurements:

These measurements are taken utilizing multiphase flow metering systems that are either permanently or temporarily installed at a well site. They are referred to as Multiphase Flow Meters or MPFMs, which are designed to provide continuous measurement of the flow rates of oil, water and gas in the well stream, without the need for separation. These measurements can be transmitted remotely to engineers' desktops. These devices provide accurate data, as long as wells produce at the design rates and they would require frequent calibration. For the purpose

of this study, the subject wells had recently calibrated MPFMs and wells were operated within the design envelope. Tables 3.1 to 3.3 summarize the rate results from the tests on the three wells.

3.1.4 Surface Choke Sizes and Surface Pressure Readings

The subject wells of the study were equipped with chokes that can be adjusted remotely from the office. The system also includes two pressure gauges to measure upstream and downstream pressures that provide real-time pressure values, which are transmitted in real-time to the office Figure 3.7.

3.1.5 Downhole Valve Settings:

Downhole valves are designed to provide control of the withdrawal among multilateral or multisegment wells. This control is obtained by adjusting the valve positions in accordance with lateral or segment performance (i.e., productivity and pressure) and in accordance with the overall objective of the well. Different multiposition valve designs have been utilized in oil fields. A common type of these downhole valves is shown in Figure 3.8. They are all used to provide monitoring and control capabilities required to optimize the production of multilateral or multisegment wells.   The subject valves of this study provide ten positions and can be hydraulically controlled from the surface and remotely from the office. Knowing the positions of these valves is very vital for rate allocation for any corresponding segment or lateral. The settings of the valves examined during the well tests are indicated in Tables 3.1 to 3.3

3.1.6 PDHMS Pressure Readings

PDHMS are permanent downhole measurement systems that provide downhole pressure and temperature data in real-time basis. These data can be accessed at well location or can be transmitted to the office. In the subject wells of this study, these PDHMSs are installed above the production packer where they can only provide commingled pressure and temperature readings, influenced by the total production through the tubing. Special testing procedures have to be executed to evaluate pressure performance of individual laterals or segments. The PDHMS in the subject wells are Quartz that are very accurate and may not require any calibration. One of the commonly used PDHMS is shown in Figure 3.9. The PDHMS pressure readings for the wells are also shown in Tables 3.1 to 3.3. Please note that the productivity indices of all the laterals were calculated using the measured rates and pressures, as they are shown in the same tables 3.1 to 3.3.

3.1.7 Fluid Properties Data:

The subject wells of this study are located in different locations; however, their fluid properties are almost alike. Table 3.4 shows the range of these fluid properties. These properties are utilized when generating the models for the subject wells.

Table 3.1 Actual Rates, Valve Positions, Pressures and Calculated PI for the Bi-Lateral Well

Bi-Lateral Well Rate Test Data

Productivity Index for laterals (Brrls/psi/ft)

Lateral	PI
L-0	130
L-1	80

All Rate Tests Used in Modeling and Verification

Test #	L0 Valve Setting	L1 Valve Setting	Total Q (STB/d)	PDHMS Lower (psig)	PDHMS Upper (psig)	WHP (psig)
1	10	0	10800	1958	1887	240
2	0	10	10500	1955	1883	240
3	0	0	0	1696	1628	180
4	0	2	2500	1804	1737	190
5	0	4	3550	1814	1744	220
6	0	6	3700	2050	1983	370
7	0	10	2140	2088	2020	400
8	0	10	4080	2074	2006	385
9	0	10	6040	2051	1982	360
10	3	0	3700	1792	1725	210
11	5	0	4100	1970	1901	320
12	7	0	4300	2051	1982	380
13	10	0	2000	2077	2008	410
14	10	0	4000	2060	1991	390
15	10	0	6000	2026	1958	360
16	2	2	5200	1800	1731	210
17	6	6	11600	1984	1911	265
18	6	6	9500	1995	1932	285
19	10	6	11950	2005	1932	270
20	10	2	11200	1960	1890	255
21	10	4	12000	1973	1900	260
22	10	10	12500	2015	1941	270
23	10	10	11050	2025	1953	290
24	3	10	11600	1981	1909	260
25	5	10	11900	1997	1924	270
26	7	10	12400	2014	1940	270

Table 3.2 Actual Rates, Valve Positions, Pressures and Calculated PI for the Tri-Lateral Well

Tri-Lateral Well Rate Test Data

Productivity Index for laterals (Brrls/psi/ft)

Lateral	PI
L-0	100
L-1	110
L-2	100

All Rate Tests Used in Modeling and Verification

Test #	L0 Valve Setting	L1 Valve Setting	L2 Valve Setting	Total Q (STB/d)	PDHMS FBHP (psi)	WHP (psig)
1	3	0	0	7100	2069	289
2	5	0	0	8700	2220	345
3	0	3	0	8100	2057	336
4	0	5	0	9900	2206	397
5	0	0	3	8200	2160	336
6	0	0	5	9500	2287	382
7	0	3	5	10338	2283	400
8	0	3	10	15155	2293	400
9	0	5	10	12928	2378	450
10	3	5	10	11849	2375	450
11	3	0	5	12543	2230	380
12	3	0	10	8856	2453	500
13	5	0	10	4390	2550	550
14	5	3	10	17141	2303	400
15	5	3	0	11474	2205	360
16	10	3	0	12921	2244	380
17	10	5	0	12536	2329	420
18	5	5	5	11769	2381	450
19	10	10	10	13105	2395	460

Table 3.3 Actual Rates, Valve Positions, Pressures and Calculated PI for the Quad-Lateral Well

Quad-Lateral Well Rate Test Data

Productivity Index for laterals (Brrls/psi/ft)

Lateral	PI
L-0	4
L-1	20
L-2	11.5
L-3	14

All Rate Tests Used in Modeling and Verification

Test #	Setting (L0-L1-L2-L3)	L0 Valve Setting	L1 Valve Setting	L2 Valve Setting	L3 Valve Setting	Total Q (STB/d)	Oil Rate (STB/d)	Water Cut	GOR	PDHMS Upper FBHP (psi)	PDHMS Lower FBHP (psi)	WHP (psig)	Calcualted Average FBHP (psi)
1	10-10-10-10	10	10	10	10	9850	5950	40%	1357	3033	3096	800	3064
2	10-0-0-0	10	0	0	0	7813	2659	66%	1351	2474	2539	400	2507
3	10-0-0-0	10	0	0	0	5361	1560	71%	1576	2773	2835	860	2804
4	2-0-0-0	2	0	0	0	2848	913	68%	1522	2264	2326	400	2295
5	6-0-0-0	6	0	0	0	7350	3291	61%	742	2430	2494	400	2462
6	0-10-0-0	0	10	0	0	11420	10351	9%	402	2289	2349	400	2319
7	0-10-0-0	0	10	0	0	6800	6500	10%	372	2761	2818	800	2790
8	0-2-0-0	0	2	0	0	4452	2917	34%	626	1816	1868	380	1842
9	0-6-0-0	0	6	0	0	10099	8191	19%	478	2244	2304	400	2274
10	0-0-10-0	0	0	10	0	8721	3336	62%	721	2640	2707	400	2674
11	0-0-10-0	0	0	10	0	5436	1413	74%	1298	2851	2917	760	2884
12	0-0-2-0	0	0	2	0	2950	797	76%	1400	2575	2640	370	2608
13	0-0-6-0	0	0	6	0	6730	2323	65%	923	2672	2738	400	2705
14	0-0-0-10	0	0	0	10	11756	5858	50%	579	2708	2794	452	2751
15	0-0-0-10	0	0	0	10	6253	2495	60%	1087	2889	2952	750	2921
16	0-0-0-2	0	0	0	2	3230	1560	63%	612	2279	2340	380	2310
17	0-0-0-6	0	0	0	6	10850	3742	66%	744	2689	2756	400	2723
18	0-6-0-6	0	6	0	6	12422	7159	42%	645	2751	2819	450	2785
19	0-10-0-10	0	10	0	10	5791	2480	57%	833	1808	1860	750	1834
20	0-2-0-2	0	2	0	2	6255	3565	43%	402	2535	2595	450	3114
21	0-2-0-6	0	2	0	6	10350	5382	48%	700	2773	2833	450	3810
22	0-6-0-2	0	6	0	2	10820	7249	33%	375	2664	2724	400	5500
23	0-10-0-10	0	10	0	10	15600	9828	37%	720	2922	2982	400	5929
24	6-0-6-0	6	0	6	0	9800	4018	59%	633	2701	2761	450	3212
25	2-0-2-0	2	0	2	0	5940	1960	67%	1200	2471	2531	450	2279
26	2-0-6-0	2	0	6	0	8895	2920	68%	834	2628	2688	450	2968
27	6-0-2-0	6	0	2	0	8120	2842	65%	1200	2652	2712	400	2933
28	2-2-2-2	2	2	2	2	10050	5145	48%	593	2594	2654	350	3930
29	6-6-6-6	6	6	6	6	12300	6300	51%	1139	3139	3199	700	4583
30	2-6-2-6	2	6	2	6	10250	5228	49%	378	3115	3175	700	4488
31	6-2-6-2	6	2	6	2	8340	3670	56%	683	3100	3160	750	3569

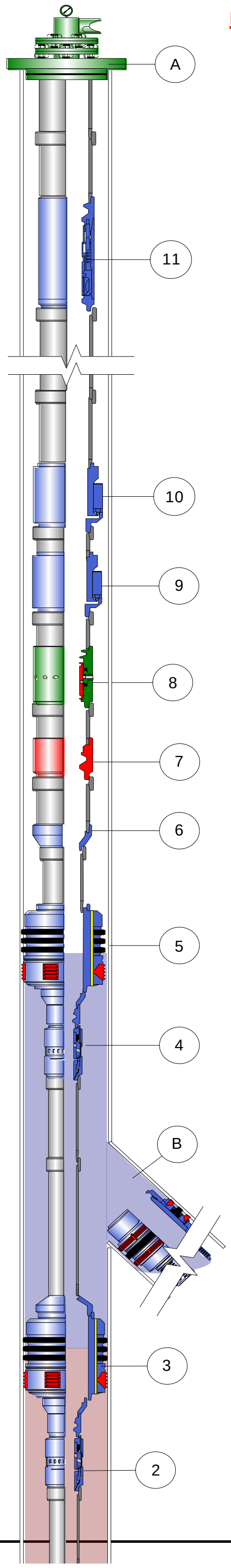
Table 3.4 Fluid Properties Tables

Fluid Compisition	Avgerage Composition Mol%
N_2	0.16
CO_2	3.8
H_2S	0.46
C_1	21.54
C_2	9.39
C_3	8.2
$i\text{-}C_4$	1.07
$n\text{-}C_4$	4.54
$i\text{-}C_5$	1.66
$n\text{-}C_5$	3.08
C_6	3.76
C_7^+	42.34

Properties	
API	30
MW	256
GOR (cfb)	450
BPP (psia)	1650
Temp. (^oF)	210
Density	0.886

Bi-Lateral Well Schematic and Improtant Components

(Dual Lateral Well with Dual Permanent Downhole Gauges for Temperature and Pressure)



Part	Description
A	4 1/2" Tubing Hanger w/ 4 x 3/8" NPT bypass
11	4-1/2 SCSSSV
10	4-1/2" upper Gauge Mandrel Dual
9	4-1/2" Lower Gauge Mandrel Single
8	4 1/2" 12.6# Durasleeve
7	4 1/2" x 3.81" X-Nipple
6	4-1/2", 12.6# X-over
5	9 5/8" x 3-1/2" 9.2# Packer#2
4	3-1/2" 9.2# Downhole Valve
B	Top (Lateral#1 Window)
3	9 5/8" x 3-1/2" 9.2# Packer#1
2	3-1/2" 9.2# Downhole Valve
1	Bull Plug
C	Lateral # 0 Screen Tie Back Packer depth

Figure 3.1 Completion Schematic of Bi-Lateral Well

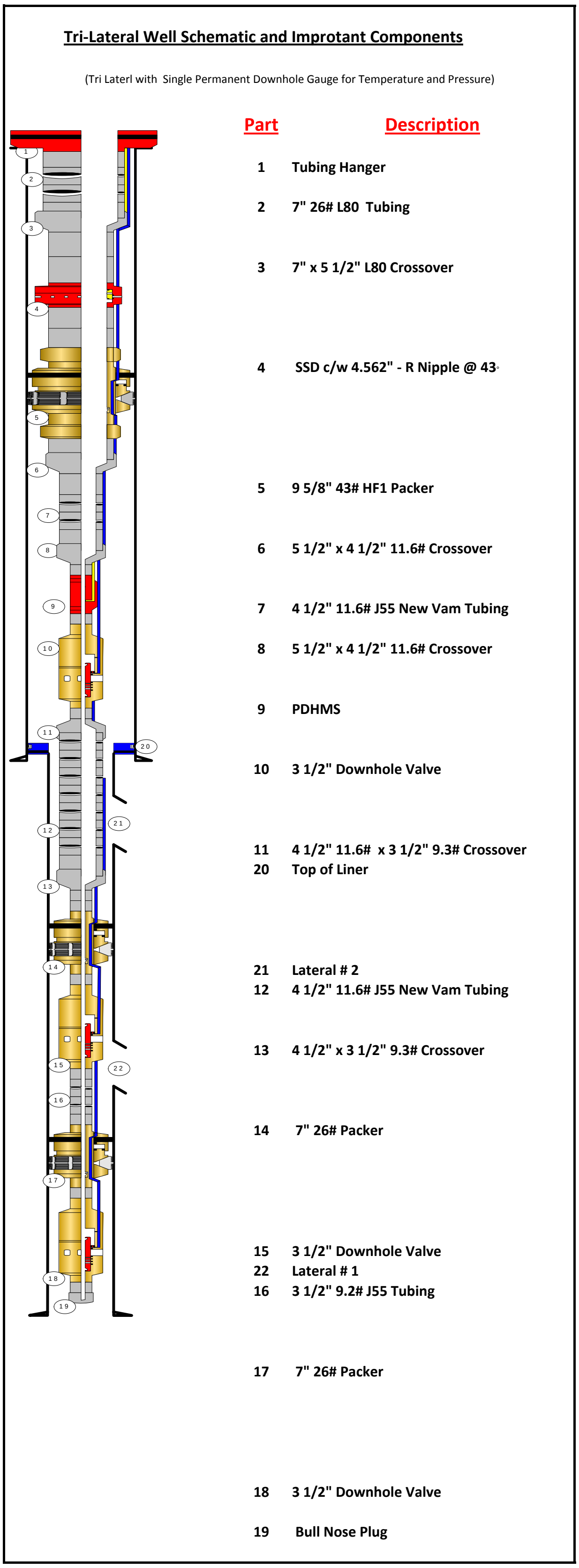
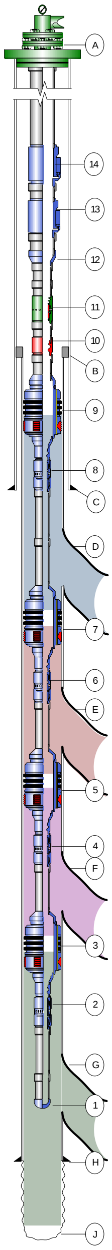


Figure 3.2 Completion Schematic of Tri-Lateral Well

Quad-Lateral Well Schematic and Improtant Components

(Tri Laterl with Single Permanent Downhole Gauge for Temperature and Pressure)



Part	Description
A	Tubing Hanger
14	PDHMS-1
13	PDHMS-2
12	X-over
11	3 1/2" XU Durasleeve
10	3-1/2" x 2.81" X-Nipple
B	7" Top of Liner
9	Packer
8	3-1/2" Downhole Valve
C	9 5/8" Shoe
D	L4 Lateral Window Top
7	Packer
6	3-1/2" Downhole Valve
E	L3 Lateral Window Top
5	Packer
4	3-1/2" Downhole Valve
F	L2 Lateral Window Top
3	Packer
2	3-1/2" Downhole Valve
G	L1 Lateral Window Top
1	3-1/2" Bull Plug
H	7" Liner Shoe
J	Motherbore TD

Figure 3.3 Completion Schematic of Quad-Lateral Well

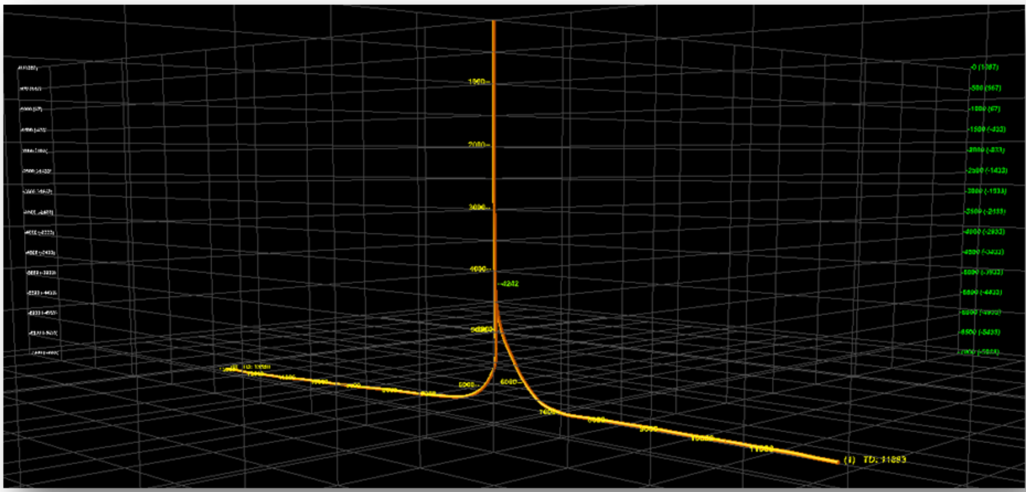


Figure 3.4 Actual 3D View of the Bi-Lateral Well

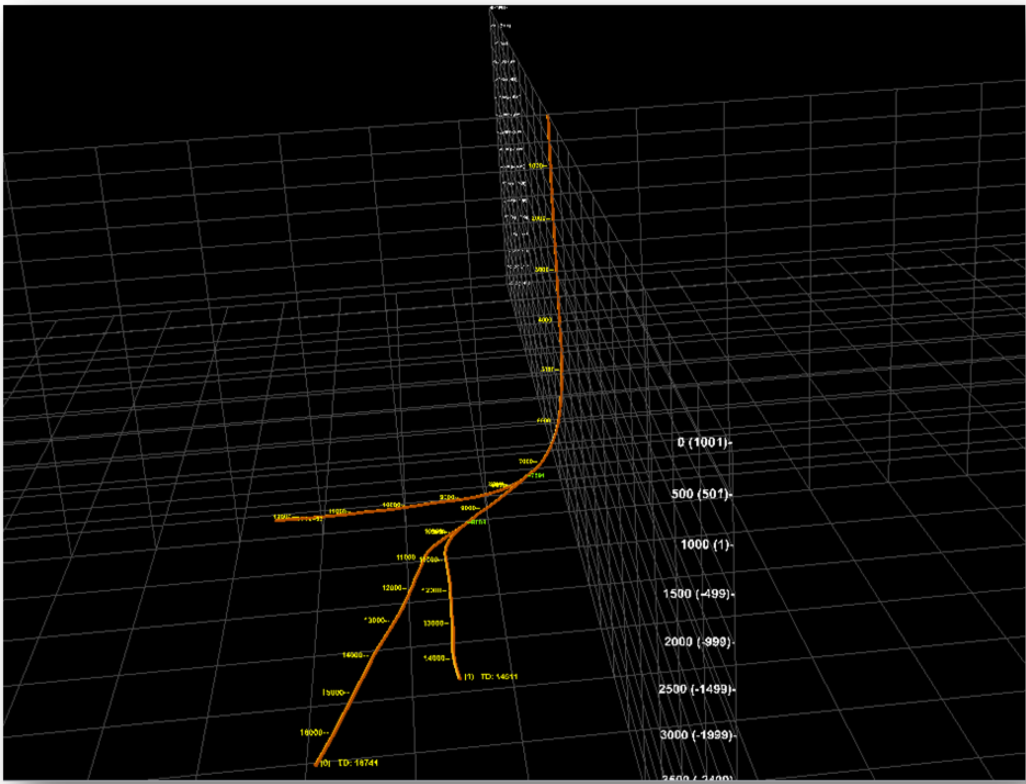


Figure 3.5 Actual 3D View of the Tri-Lateral Well

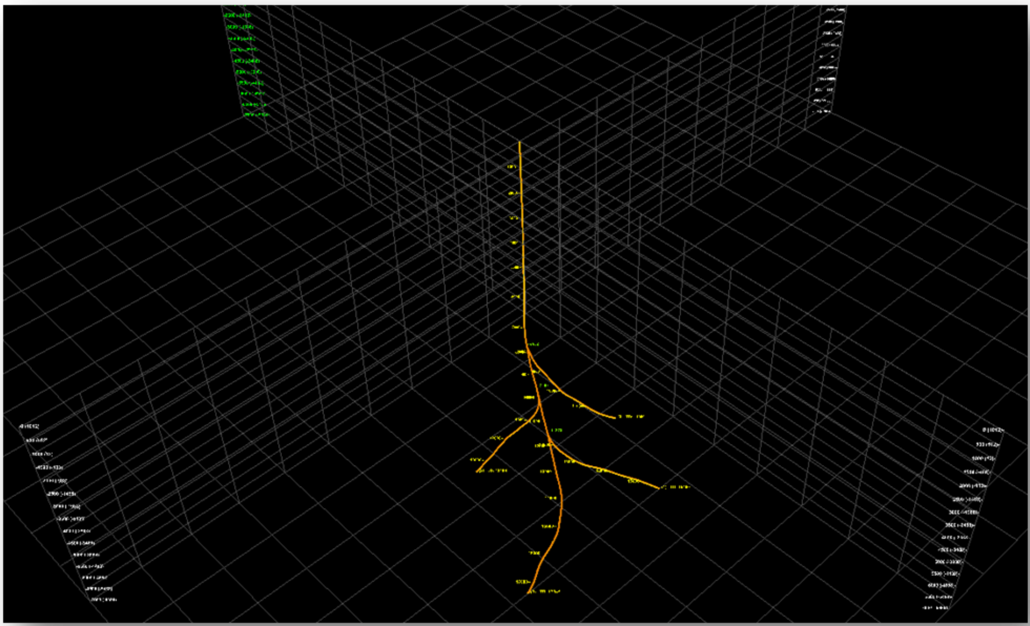


Figure 3.6 Actual 3D View of the Quad-Lateral Well

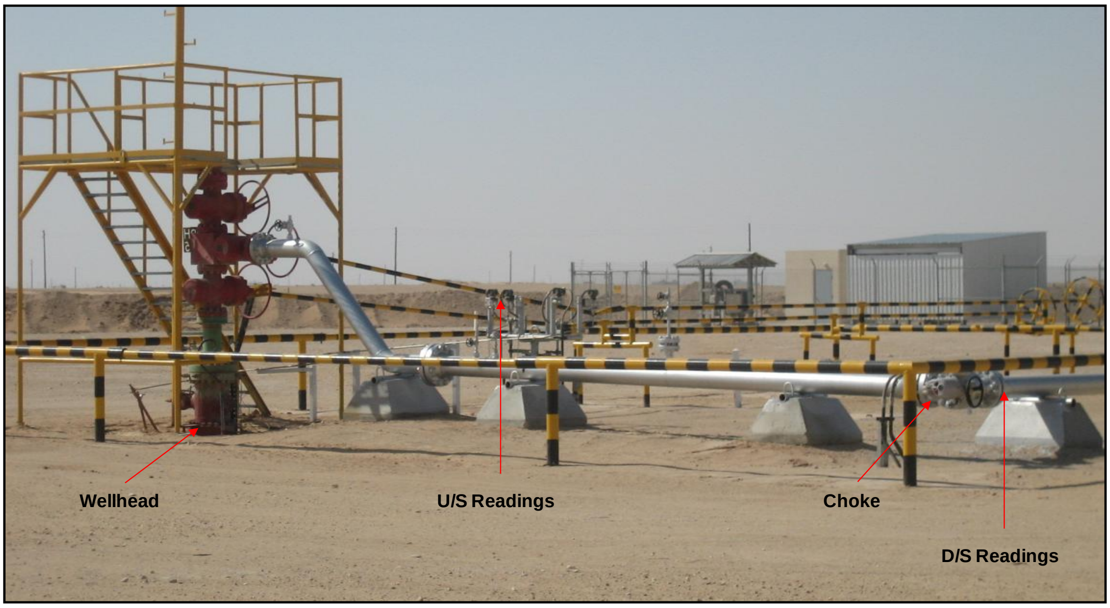


Figure 3.7 Actual Surface Oil Well Choke with Two Pressure Gauges (Downstream and Upstream)

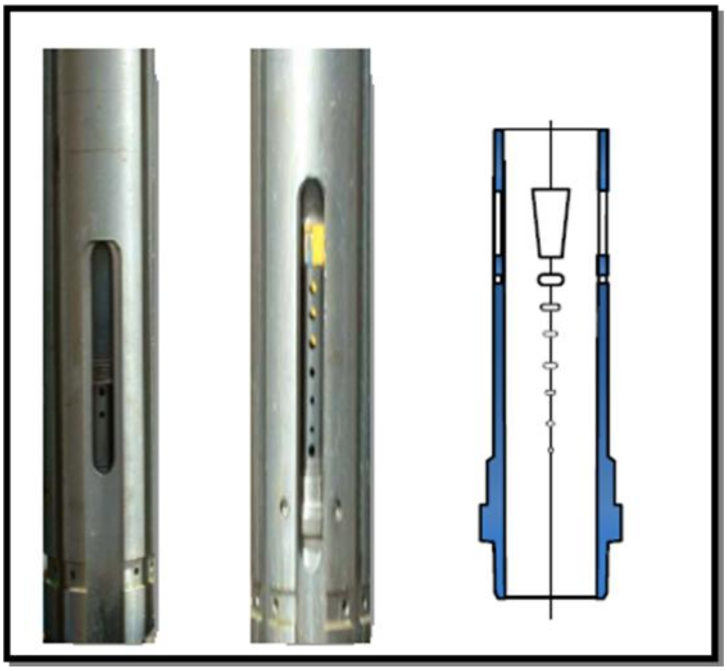


Figure 3.8 Schematic of Common Downhole Valve

Figure 3.9 Common Permanent Downhole Gauge

CHAPTER 4

Model Development

One of the most important aspects of field development and management is to be able to examine wells' productivity, analyze their behavior and optimize their performance. This chapter discusses the optimum testing procedures to acquire critical data necessary for constructing well analytical models. These models are ideal for well model calibration, productivity analysis, nodal analysis and optimum production performance.

Few well performance analysis packages are designed to construct models of multilateral wells equipped with downhole multiposition valves. These models provide users with the ability to address each aspect of well bore modeling (i.e., fluid properties and reservoir parameters), vertical lift performance (VLP) and inflow performance relationship (IPR).

An important step constitutes acquiring a matched model that can mimic well known performance. Hence, the constructed model can confidently be used to evaluate different scenarios and make predictions.

4.1 Testing Procedures

Designing the testing procedures for multilateral wells is a critical step to acquiring the necessary data to construct and validate well hydraulic models. The outcome of these tests has to provide enough data about reservoir pressure, lateral productivities and downhole valve performance. The following sections discuss these parameters in detail.

4.1.1 Reservoir Pressure

To obtain wells' bottom-hole pressure in the example reservoir, the wells are shut-in for at least 24 hours after a period of production. The pressure is measured or calculated at a point opposite to the producing formation. It may also be calculated in a static wellbore filled with a known fluid with the equation:

$$SBHP = \rho \; g \; h \qquad (4.1)$$

ρ: density Ib/ft^3.
g: gravity ft/sec^2 .
h: true vertical depth ft.

The same equation is used to correctly gauge pressure readings if the gauge is located downhole but not against the producing formation. The production strategy of the example wells calls for producing them above the reservoir pressure bubble point, which makes it reasonable and representative to use the above equation for reservoir pressure calculation while wells are shut in.

4.1.2 Productivities of Laterals

During the design stage of multilateral wells, several issues are considered to allow maximum productivity of every lateral and their commingled production. The downhole valves become essential when lateral production performances vary.

It is important to design production tests to define downhole valve capabilities and lateral productivities; hence defining their optimum choke positions at later stages of production.

The lateral productivities are obtained by testing individual laterals independently at the maximum choke settings — equivalent in flow area to the flow area of the tubing — used in the same completion. To define the productivity index of the laterals of a bi-lateral well, each lateral is tested at full open downhole choke while the other lateral is closed. The productivity index or PI is then calculated using the reservoir pressure (P_r), total rate (Q_t) and flowing bottom-hole pressure at the specific lateral (P_f). For a one phase oil well as it is the case in our examples, the relation is given by :

$$PI = Q_t/(P_r - P_f) \qquad (4.2)$$

In tables 3.1 to 3.3, the calculated productivity indices of all laterals are summarized. They were subsequently utilized in model construction and calibration.

4.1.3 Downhole Valves Performance

Downhole valve performance affects — to a large extent — the overall performance of a well, if it is producing from several laterals. Therefore the critical evaluation of downhole valves must be an integral part of the study to minimize uncertainties incorporated in well rate allocation. The element that is critical in realizing the potential benefits is identifying the proper discharge coefficient that can be used for subsequent calculation or model calibration. The following is a description of the methodology that was followed to assign a representative discharge coefficient (C_d) for the downhole valves examined in this study. These discharge coefficients would need to be re-estimated in the future, as these valves will be subjected to erosion or may develop leaks through the valve under a closed condition.

The trims of the downhole valves in the studied completions are not circular, thus a discharge coefficient will be associated with them. Vendors do not provide information about the discharge coefficients of their valves, and even if they do, it may not represent the actual value under reservoir conditions.

Data from six downhole valves measured at the third choke setting and at different discharge coefficient (C_d), were analyzed (C_d of 0.65, 0.7, 0.75 and 0.8). The analysis concluded that a C_d of 0.8 is the best value for these valves at the current conditions. Tables 4.1 and 4.2 and Figures 4.1 and 4.2 summarize the results of the analysis.

Table 4.1

Sensitivity Runs to Identify the Best C_d Values for Downhole Valves from Well-A

Cd	Lateral	Choke Position	FBHP (psi)	Actual Rate (STB/D)	Reservoir pressure	Model Rate (STB/D)	Difference	Average Difference for Cd
0.65	0	3	1951	7100	2872	6376	10.2	
0.65	1	3	2057	7300	2865	6472	11.3	
0.65	2	3	2051	7250	2574	5756	20.6	14.0
0.7	0	3	1951	7100	2872	6623	6.7	
0.7	1	3	2057	7300	2865	6750	7.5	
0.7	2	3	2051	7250	2574	6019	17.0	10.4
0.75	0	3	1951	7100	2872	6850	5.5	
0.75	1	3	2057	7300	2865	7018	1.2	
0.75	2	3	2051	7250	2574	6273	14.1	6.9
0.8	0	3	1951	7100	2872	7057	0.6	
0.8	1	3	2057	7300	2865	7269	0.4	
0.8	2	3	2051	7250	2574	6522	10.7	3.9

Table 4.2

Sensitivity Runs to Identify C_d Values for Downhole Valves from Well-B

Cd	Lateral	Choke Position	FBHP (psi)	Actual Rate (STB/D)	Reservoir pressure	Model Rate (STB/D)	Difference	Average Difference for Cd
0.65	0	3	1797	6600	2751	5494	16.8	
0.65	1	3	2040	8100	2744	6670	17.7	
0.65	2	3	2145	6800	2585	5679	16.5	17.0
0.7	0	3	1797	6600	2751	5663	14.2	
0.7	1	3	2040	8100	2744	6978	13.9	
0.7	2	3	2145	6800	2585	5936	12.7	13.6
0.75	0	3	1797	6600	2751	5816	11.9	
0.75	1	3	2040	8100	2744	7274	10.2	
0.75	2	3	2145	6800	2585	6184	9.1	10.4
0.8	0	3	1797	6600	2751	5994	9.2	
0.8	1	3	2040	8100	2744	7555	6.7	
0.8	2	3	2145	6800	2585	6422	5.6	7.2

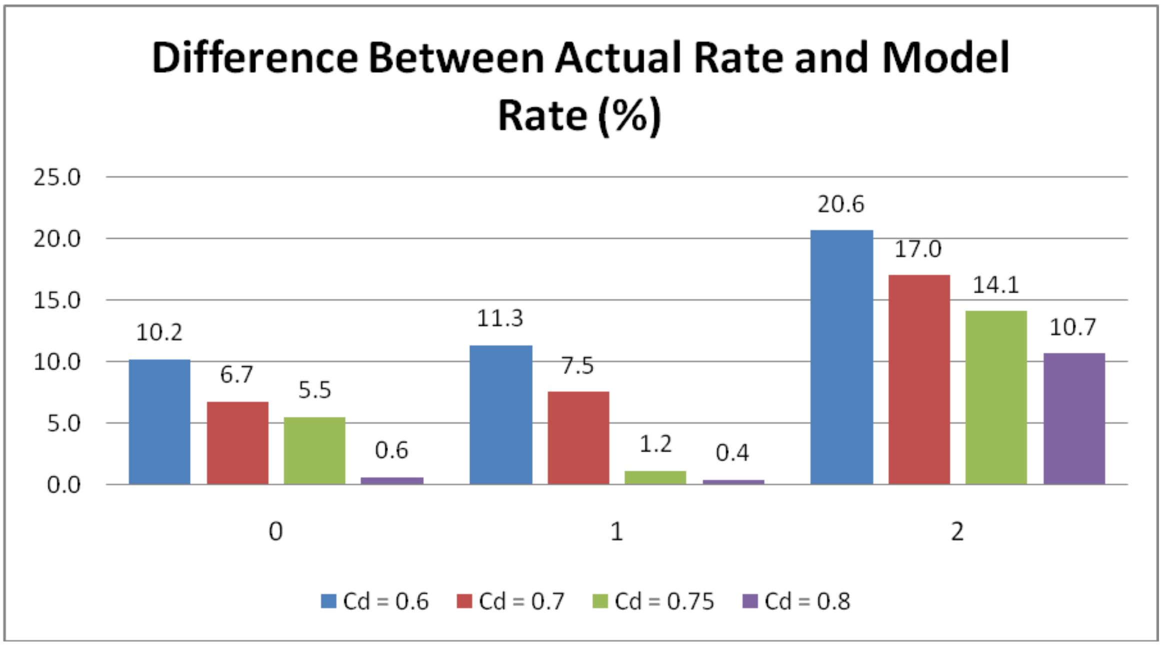


Figure 4.1

Calculated Difference Between Actual and Model Rates Using different C_d Values at Downhole Choke Setting 3 from Well - A

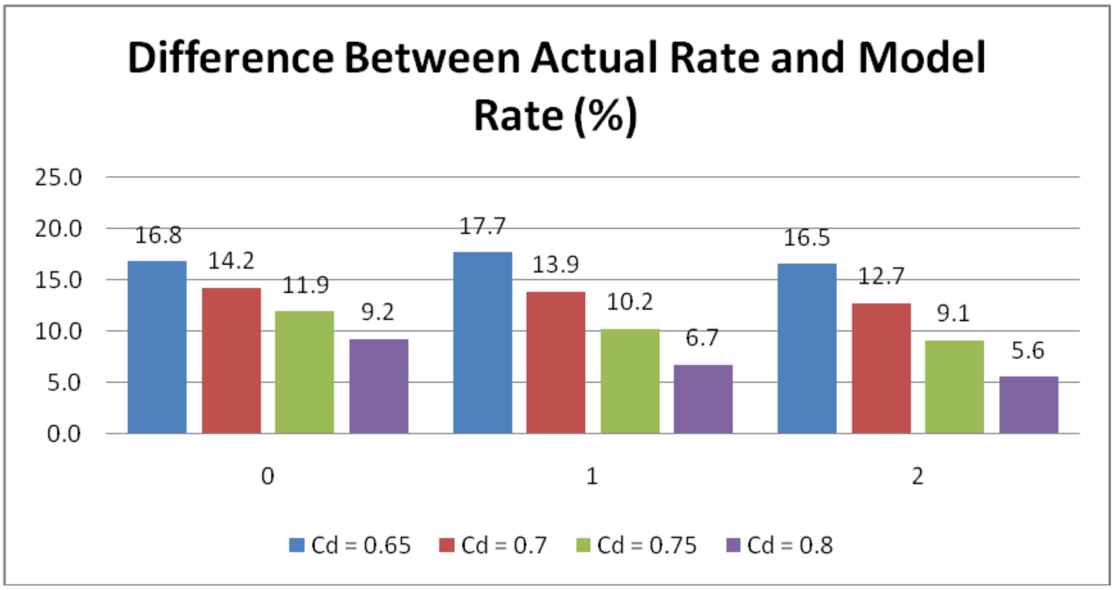


Figure 4.2

Calculated Difference Between Actual and Model Rates Using different C_d Values at Downhole Choke Setting 3 from Well - B

Figure 4.3 illustrated the estimated total rate across the different choke position of a 3-1/2" valve at various delta pressures. The equation to estimate the total rate is derived from Bernoulli's equation and considers incompressible fluid, steady-state flow, laminar flow in a horizontal pipe with negligible frictional losses.

$$Q = C\,A\,\sqrt{2\,(P_1 - P_2)/\rho} \qquad (4\text{-}3)$$

Q = volumetric flow rate (at any cross-section)

C = orifice flow coefficient, dimensionless

P_1 = fluid upstream pressure

P_2 = fluid downstream pressure

ρ = fluid density

Table 4.3 shows the positions and corresponding flow areas in square inches for one of the common downhole 3-1/2" valves used in the industry. Reader may notice that at the fully open position, the area is equivalent to the ID of tubing of the same size.

Table 4.3 Downhole Valve Positions with Corresponding Flow Area

Choke Position	Flow Area (in^2)	Equivalent Dia (in)	Equivalent Choke size (64th)
1	0	0	0
2	0.055	0.265	0.265
3	0.110	0.374	0.374
4	0.166	0.460	0.460
5	0.221	0.530	0.530
6	0.374	0.690	0.690
7	0.666	0.921	0.921
8	1.203	1.238	1.238
9	1.740	1.488	1.488
10	2.353	1.731	1.731
11	7.066	2.999	2.999

In the calculation, a discharge coefficient (C_d) of 0.8, a density of 0.33 and a leakage rate of 0.01 were considered in calculating the total rates illustrated in table 4.4 and Figure 4.3. These rates are estimation of rates across different settings of an individual valve. The estimation of rate — commingled from multiple valves opened at different choke positions and different delta pressures — is far more complex. The next section of this study discusses modeling multilateral wells equipped with multiple valves across different reservoir parameters.

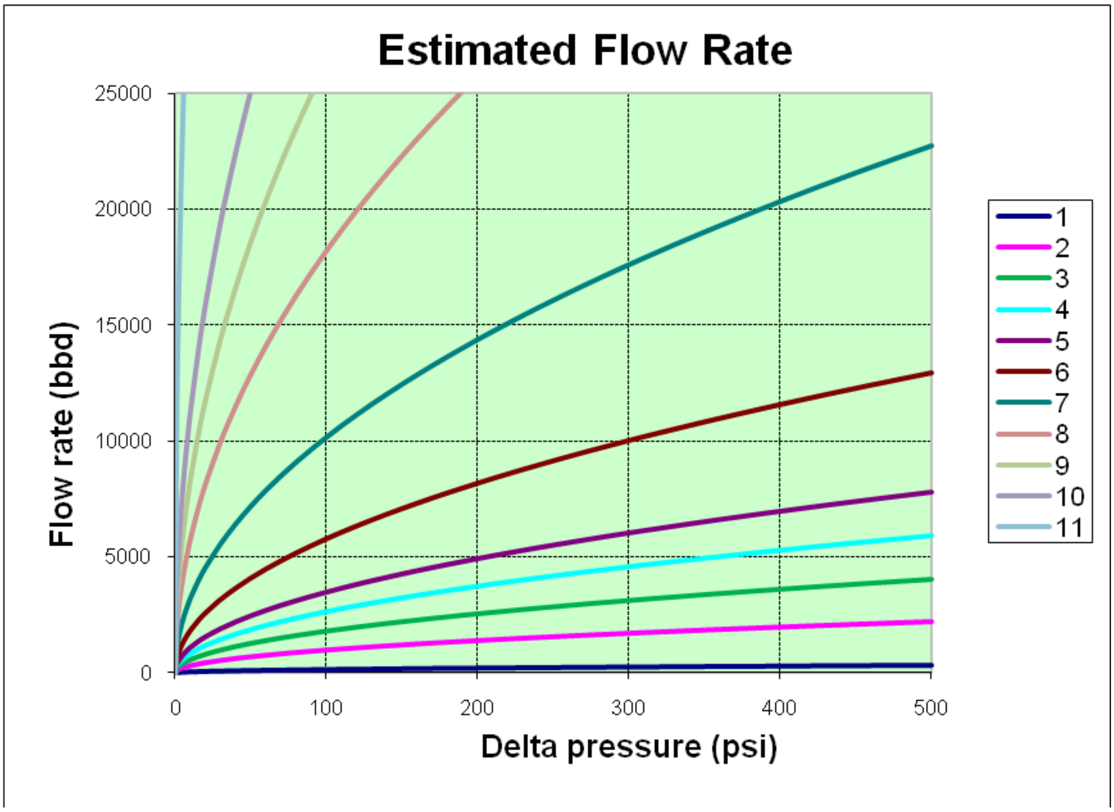


Figure 4.3

Estimated Total Rate across the Different Choke Position of a 3-1/2” Valve at Various Delta Pressures across the Valves

Table 4.4

Estimated Total Rate across the Different Choke Position of a 3-1/2” Valve at Various Delta Pressures across the Valves

Delta Pressure	Downhole Valve Positions										
	1	2	3	4	5	6	7	8	9	10	11
	Q (bbl)										
0	0	0	0	0	0	0	0	0	0	0	0
1	15	98	181	265	347	578	1017	1825	2632	3554	10644
2	21	138	255	374	491	817	1438	2580	3723	5027	15053
3	26	169	313	459	602	1000	1761	3160	4559	6157	18436
4	30	196	361	529	695	1155	2034	3649	5265	7109	21288
5	34	219	404	592	777	1292	2274	4080	5886	7948	23801
6	37	239	442	648	851	1415	2491	4469	6448	8707	26072
7	40	259	478	700	919	1528	2690	4828	6965	9404	28161
8	43	277	511	749	983	1634	2876	5161	7446	10054	30106
9	45	293	542	794	1042	1733	3051	5474	7897	10663	31932
10	48	309	571	837	1099	1827	3216	5770	8324	11240	33659
15	58	379	699	1025	1346	2237	3938	7067	10195	13766	41224
20	67	437	807	1184	1554	2583	4548	8160	11772	15896	47601
30	82	536	989	1450	1903	3164	5570	9994	14418	19469	58299
40	95	618	1142	1674	2198	3653	6431	11540	16649	22481	67318
50	106	691	1276	1872	2457	4084	7190	12902	18614	25134	75264
60	117	757	1398	2051	2692	4474	7877	14134	20390	27533	82447
70	126	818	1510	2215	2907	4833	8508	15266	22024	29739	89053
80	135	875	1615	2368	3108	5166	9095	16320	23545	31792	95202
90	143	928	1712	2512	3296	5480	9647	17310	24973	33721	100977
100	150	978	1805	2647	3475	5776	10169	18246	26324	35545	106439
110	158	1025	1893	2777	3644	6058	10665	19137	27609	37280	111634
120	165	1071	1977	2900	3806	6328	11139	19988	28836	38937	116598
130	172	1115	2058	3019	3962	6586	11594	20804	30014	40527	121359
140	178	1157	2136	3132	4111	6835	12032	21589	31147	42057	125940
150	184	1197	2211	3242	4256	7074	12454	22347	32240	43533	130361
160	190	1237	2283	3349	4395	7306	12862	23080	33297	44961	134636
170	196	1275	2354	3452	4531	7531	13258	23790	34322	46345	138780
180	202	1312	2422	3552	4662	7750	13643	24480	35317	47688	142803
190	207	1348	2488	3649	4790	7962	14016	25151	36285	48995	146716
200	213	1383	2553	3744	4914	8169	14381	25804	37228	50268	150528
210	218	1417	2616	3837	5035	8371	14736	26441	38147	51509	154245
220	223	1450	2677	3927	5154	8568	15082	27064	39045	52722	157875
230	228	1483	2738	4015	5270	8760	15421	27672	39922	53906	161423
240	233	1515	2796	4101	5383	8948	15753	28267	40781	55066	164895
250	238	1546	2854	4186	5494	9133	16078	28850	41622	56201	168295
260	243	1577	2911	4269	5603	9314	16396	29421	42446	57314	171628
270	247	1607	2966	4350	5710	9491	16709	29982	43255	58406	174897
280	252	1636	3020	4430	5814	9665	17015	30532	44048	59478	178107
290	256	1665	3074	4508	5917	9837	17316	31072	44828	60531	181259
300	261	1694	3126	4585	6018	10005	17612	31603	45594	61566	184358
310	265	1722	3178	4661	6118	10170	17904	32126	46348	62583	187405
320	269	1749	3229	4736	6216	10333	18190	32640	47090	63585	190404
330	273	1776	3279	4809	6312	10493	18472	33146	47820	64570	193356
340	277	1803	3328	4882	6407	10651	18750	33644	48539	65542	196264
350	281	1829	3377	4953	6501	10806	19024	34136	49248	66498	199129
360	285	1855	3425	5023	6593	10960	19294	34620	49946	67442	201954
370	289	1881	3472	5092	6684	11111	19560	35097	50635	68372	204740
380	293	1906	3519	5161	6774	11260	19822	35569	51315	69290	207488
390	297	1931	3565	5228	6862	11407	20081	36034	51986	70196	210200
400	301	1955	3610	5295	6950	11552	20337	36493	52648	71090	212878
410	305	1980	3655	5361	7036	11696	20590	36946	53302	71973	215523
420	308	2004	3699	5426	7121	11838	20839	37394	53948	72845	218135
430	312	2028	3743	5490	7205	11978	21086	37836	54587	73707	220717
440	316	2051	3786	5553	7289	12116	21330	38274	55218	74560	223269
450	319	2074	3829	5616	7371	12253	21571	38706	55842	75402	225791
460	323	2097	3871	5678	7453	12389	21809	39134	56459	76235	228286
470	326	2120	3913	5740	7533	12523	22045	39557	57069	77059	230754
480	330	2142	3955	5800	7613	12655	22278	39976	57673	77875	233196
490	333	2164	3996	5860	7692	12786	22509	40390	58271	78682	235613
500	336	2186	4036	5920	7770	12916	22738	40800	58862	79481	238005

4.2 Model Construction

In this part of the study, models of three multilateral wells were constructed using several software packages; based on applying nodal analysis techniques to model reservoir inflow and well outflow performance. These packages are used to construct well models (i.e., conventional vertical or multilateral wells) for completion evaluation or production assessment purposes. For multilateral well modeling, which can be considered as a composite system, every lateral can have its own specific parameters with regards to fluid properties, reservoir parameters or completion details.

The principle that forms the basis of nodal analysis considers that the reservoir inflow and wellbore outflow can be described independently as functions of flow rate. The single rate that balances the pressure losses in the inflow-outflow components to the pressure drop across the total system defines well flow. Starting from this basis, a logical approach can be developed and applied to automatically update the modeling software with the required parameters and to continuously monitor well performance.

Among the required information to model multilateral well are reservoir parameters and completion details. The completion details constitute of tubular parameters, gauges and valve sizes and locations, deviation surveys and completions specifics (i.e., sand screen, skin, perforations, etc.). Whereas reservoir parameters include, but are not limited to, reservoir pressure, IPR, PI, fluid data and depth.

What makes multilateral wells different from conventional vertical or single horizontal wells, is that every lateral can have properties that are different from the other laterals in the same well.

In all of the models, black oil fluid modeling is considered to be appropriate since all the wells are flowing above the bubble point pressure.

Figures 4.4 to 4.6 show a schematic of the models of the three wells as they appear in the modeling tool. All reservoir, well and completion data are incorporated during the construction stage of each of the models.

4.2.1 Models Assessment and Validation:

Once the models are constructed using the appropriate data, a process of validation is required to ensure that the models mimic actual well performance.

The process of validation consists of calculating inflow and outflow performance — under different scenarios and production conditions — and may include running sensitivity analysis.

The models were constructed and validated using several solutions. Models' results and actual field tests data are comparable with acceptable difference for all wells. The next chapters discuss the results and lessons learned in more details. A brief on potential improvement in the completion and workflow will be also covered.

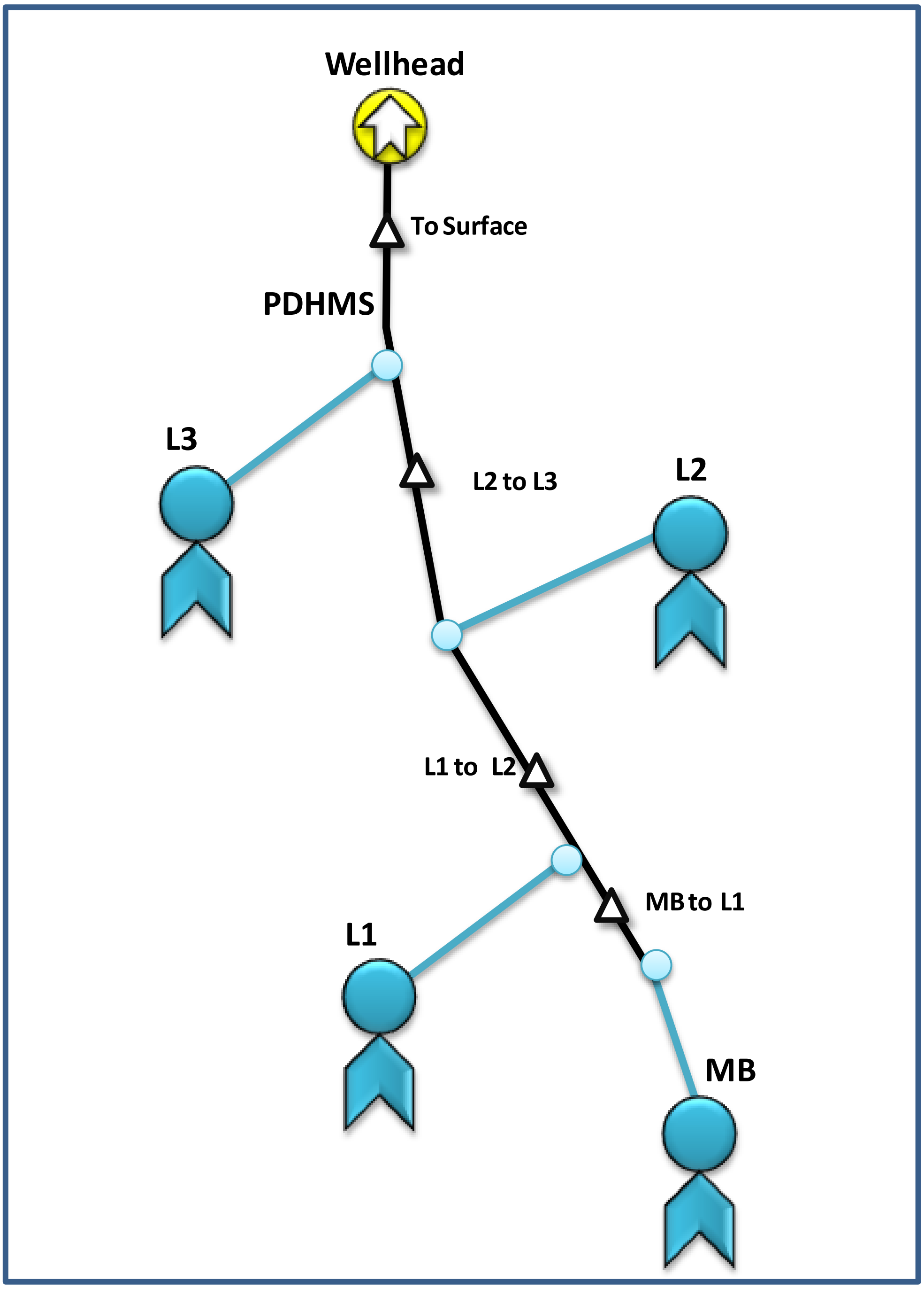


Figure 4.4

Schematic of the Quad-Laterals Well Model

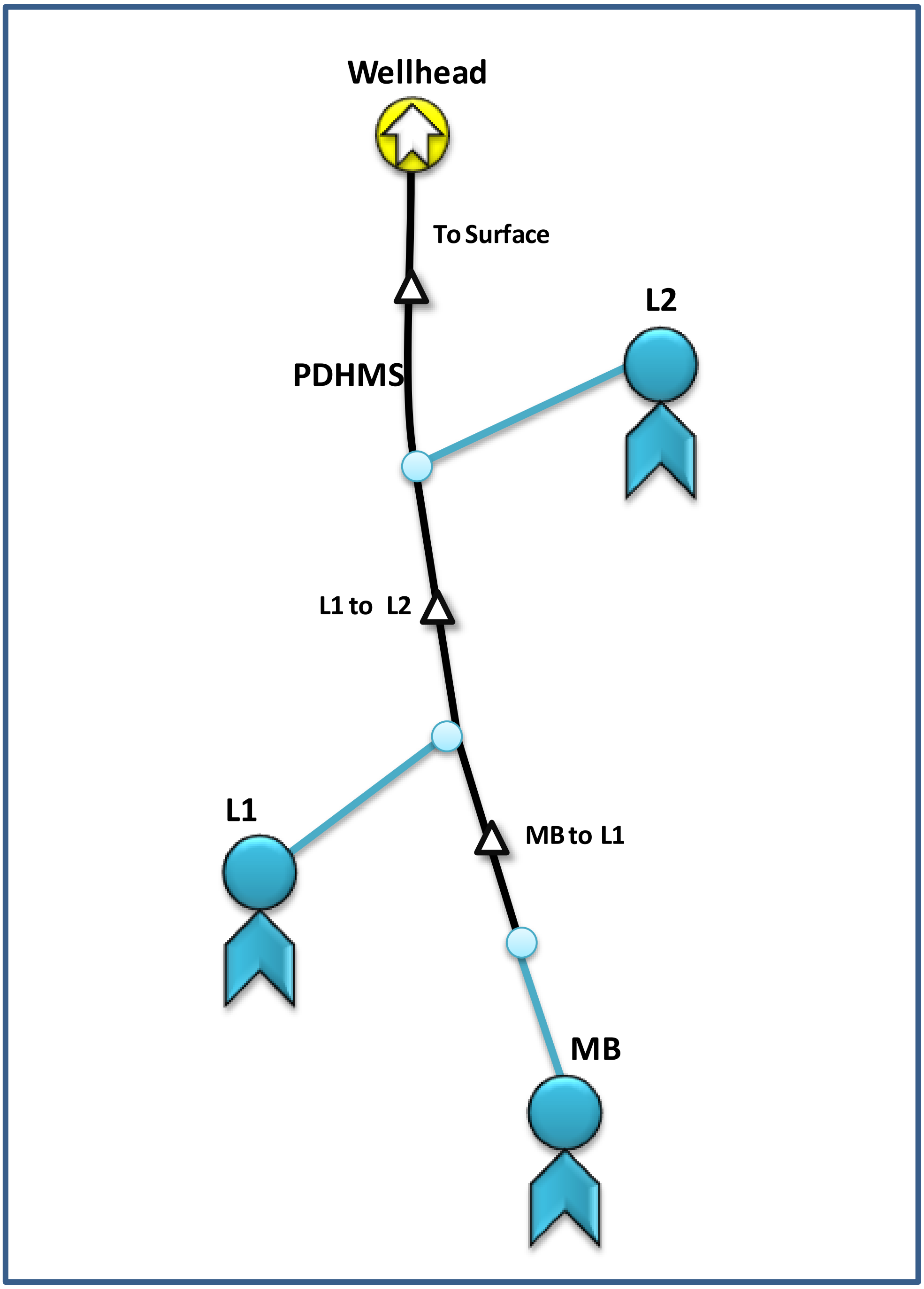


Figure 4.5

Schematic of the Tri-Laterals Well Model

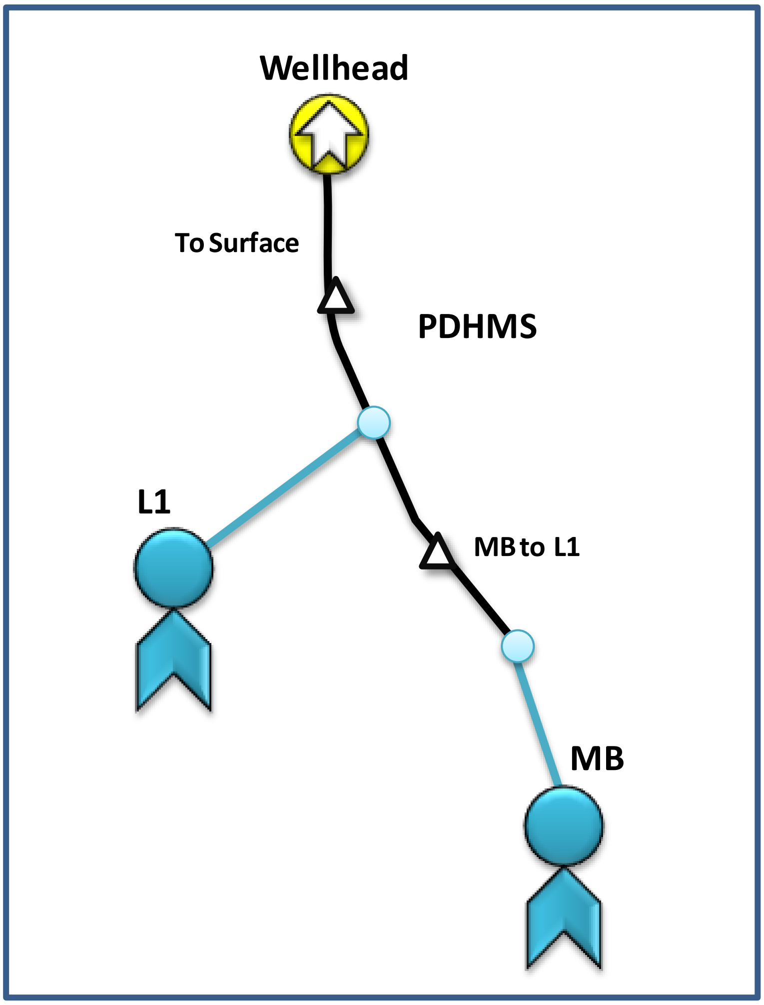


Figure 4.5

Schematic of the Bi-Laterals Well Model

CHAPTER 5

RESULTS & LESSONS LEARNED

This study examines unique completions of multilateral wells equipped with a single PDHMS above the production packer. These multilateral wells consist of at least two laterals that extend kilometers away from each other and can be subjected to various reservoir pressures and different reservoir properties. Since the actual production test data provide only total rate for every well, which is not sufficient for well and reservoir modeling purposes, proper testing procedures, and modeling efforts, were done to allocate rate per lateral for these wells. This effort can be considered as a first step in a workflow to automatically back allocate rates to individual laterals, with their valves set at various choke settings. The complete work flow is beyond the scope of this thesis and can be pursued in further studies.

For the purpose of the study, these multilateral wells were tested at various lateral choke settings to get the maximum data set to construct, validate and calibrate the models. These calibrated models were used to generate various scenarios, to identify an allocation factor that can be utilized, to allocate rate per lateral during commingled production. These steps can be part of an automated workflow that is tailored to provide real-time allocated rate measurements, for multilateral wells equipped with downhole multiposition valves.

At the beginning, a testing procedure was set to provide the required data for modeling. When the models were constructed and calibrated, several sensitivity runs using the calibrated model were run. These runs considered different downhole valve settings and the total commingled production rates of the well were recorded. The three wells then were scheduled for surface rate testing at the "sensitivity runs" settings (i.e., downhole valves positions) and surface rate tasting results were examined against model-estimated well commingled production rates.

Tables 5.1 to 5.9 show both the actual test rate measurements and the model calculated total and individual lateral rates for the three wells. The results are very comparable and very acceptable, considering all the uncertainties involved in actual rate measurements and in model estimation.

Results of the bi-lateral and tri-lateral wells that are producing dry oil indicated very acceptable variances in rates, which range from 4 to 15%. The results for the quad-lateral that is a wet producer indicated higher variances that reach 22% with regards to the total rate; however, the variance in oil rate does not exceed 12.1%. The results of the three wells are shown in Figures 5.1 to 5.36.

All the actual rate test data, along with model-estimated rates, were analyzed to determine an absolute allocation factor that can be used to estimate laterals' rates. Based on the results of the three wells, the absolute allocation rates factors are 8%, 4% and 9% for the bi-lateral, tri-lateral and quad-lateral respectively. These allocation factors beat that utilized in oil companies where most oil companies use allocation factors

of at least 10%, which accounts for the uncertainties in physical testing metering systems.

This study indicates the importance of designing testing programs to provide the necessary information to construct a reliable model. It also highlights the significance of the accuracy of test results on the well model results and their potential adverse impact on the whole work.

It is quite obvious that the completions of the studied wells are very advanced when compared to conventional completions with regards to downhole control and measurements; however, this advancement comes with its own unique complexity. The complexity is very pronounced in modeling and assessing of the performance. The advantages of these completions, when they are used as fit for purpose, have been demonstrated in various regions of the world. The study in hand is a forward leap that adds more value and understanding of the performance of multilateral wells, equipped with downhole valves and a single PDHMS.

There will be always room for improvement in studying and evaluating the performance of the existing wells. With variation in laterals' productivity and reservoir pressures, there will be no "One Size Fits All" for multilateral wells. It would be wise to custom design these completions to ensure that reservoir and well parameters are considered and to ensure that the defined objectives can be met. More improvement and better performance can be realized in future wells if modification in well completion is considered. Among these modifications can be installing downhole flow meters for every lateral, or installing multiple gauges that can provide pressure values upstream and downstream of

each valve. In theory, these recommendations are very reasonable; however, in practice, some can be impossible due to the unavailability of such technologies, or the unfeasibility of a desired completion design; or simply a financial limitation.

Table 5.1

Dual-Lateral Original Well Rate Test and Model Results Data

	Actual Rate Tests (Raw Data)								Model Results					
	Setting (L0-L1)	L0 Valve Setting	L1 Valve Setting	Total Q (STB/d)	PDHMS Lower (psig)	PDHMS Upper (psig)	WHP (psig)	Calculated Average Pressure	Model L-0 Q (STB/d)	Model L1 Q (STB/d)	Model Q (STB/d)	Model Gauge Pressure (psi)	Model WHP (psi)	Q % Difference
L1 Tests	0-2	0	2	2500	1804	1737	190	1771			2500	1631	175	0%
	0-4	0	4	3550	1814	1744	220	1779			3550	1815	270	0%
	0-6	0	6	3700	2050	1983	370	2017			3700	2001	380	0%
	0-10	0	10	2140	2088	2020	400	2054			2140	2039	415	0%
	0-10	0	10	6040	2051	1982	360	2017			6116	2004	360	1%
L0 Tests	3 - 0	3	0	3700	1792	1725	210	1759			3385	1703	210	-9%
	5 - 0	5	0	4100	1970	1901	320	1936			4324	1912	320	5%
	7 - 0	7	0	4300	2051	1982	380	2017			4786	2012	380	11%
	10 - 0	10	0	2000	2077	2008	410	2043			2000	2053	425	0%
	10 - 0	10	0	6000	2026	1958	360	1992			6037	2002	360	1%
Commingled Production	2- 2	2	2	5200	1800	1731	210	1766	2245	2200	4445	1718	210	-15%
	6 - 6	6	6	11600	1984	1911	265	1948	4985	4857	9842	1949	265	-15%
	10 - 6	10	6	11950	2005	1932	270	1969	6398	3852	10250	1972	270	-14%
	10 - 2	10	2	11200	1960	1890	255	1925	8750	1145	9895	1936	255	-12%
	10 - 4	10	4	12000	1973	1900	260	1937	8072	1994	10066	1947	260	-16%
	10 - 10	10	10	12500	2015	1941	270	1978	5374	5414	10788	1983	270	-14%
	3 - 10	3	10	11600	1981	1909	260	1945	1585	8774	10359	1957	260	-11%
	7 - 10	7	10	12400	2014	1940	270	1977	4719	5856	10575	1980	270	-15%

Table 5.2

Dual-Lateral Model Sensitivity Runs Results and Actual Test Data

Model Sensitivity Tests						Actual Rate Tests Results (Verification)							
Setting (L0-L1)	Model L-0 Q (STB/d)	Model L1 Q (STB/d)	Model Q (STB/d)	Model Gauge Pressure (psi)	Model WHP (psi)	L0 Valve Setting	L1 Valve Setting	Total Q (STB/d)	PDHMS Lower (psig)	PDHMS Upper (psig)	WHP (psig)	Calculatged Average Pressure	Q % Difference
0-10			4500	2020	385	0	10	4080	2074	2006	375	2040	10%
10 - 0			4223	2020	390	10	0	4000	2060	1991	400	2026	6%
6 - 6	4985	4857	9842	1949	265	6	6	11600	1984	1911	255	1948	-15%
6 - 6	4627	4477	9104	1962	285	6	6	9500	1995	1932	270	1964	-4%
10 - 10	5020	4844	9864	1990	290	10	10	11050	2025	1953	295	1989	-11%
5 - 10	2861	7390	10251	1970	270	5	10	11900	1997	1924	280	1961	-14%

Table 5.3

Dual-Lateral Actual and Model Results with Calculated Allocation Factor

Actual Rate Tests (Raw Data)								Model Results					Allocation Factor	
Setting (L0-L1)	L0 Valve Setting	L1 Valve Setting	Total Q (STB/d)	PDHMS Lower (psig)	PDHMS Upper (psig)	WHP (psig)	Calculated Average Pressure	Model L-0 Q (STB/d)	Model L1 Q (STB/d)	Model Q (STB/d)	Model Gauge Pressure (psi)	Model WHP (psi)	Q % Difference	Allocation Factor (Absolute Difference)
0-2	0	2	2500	1804	1737	190	1771			2500	1631	175	0%	
0-4	0	4	3550	1814	1744	220	1779			3550	1815	270	0%	
0-6	0	6	3700	2050	1983	370	2017			3700	2001	380	0%	
0-10	0	10	2140	2088	2020	400	2054			2140	2039	415	0%	
0-10	0	10	4080	2074	2006	375	2040			4500	2020	385	10%	
0-10	0	10	6040	2051	1982	360	2017			6116	2004	360	1%	
3 - 0	3	0	3700	1792	1725	210	1759			3385	1703	210	-9%	
5 - 0	5	0	4100	1970	1901	320	1936			4324	1912	320	5%	
7 - 0	7	0	4300	2051	1982	380	2017			4786	2012	380	11%	
10 - 0	10	0	4000	2060	1991	400	2026			4223	2020	390	6%	
10 - 0	10	0	2000	2077	2008	410	2043			2000	2053	425	0%	
10 - 0	10	0	6000	2026	1958	360	1992			6037	2002	360	1%	
2- 2	2	2	5200	1800	1731	210	1766	2245	2200	4445	1718	210	-15%	**8%**
6 - 6	6	6	11600	1984	1911	265	1948	4985	4857	9842	1949	265	-15%	
10 - 6	10	6	11950	2005	1932	270	1969	6398	3852	10250	1972	270	-14%	
6 - 6	6	6	11600	1984	1911	255	1948	4985	4857	9842	1949	265	-15%	
6 - 6	6	6	9500	1995	1932	270	1964	4627	4477	9104	1962	285	-4%	
10 - 10	10	10	11050	2025	1953	295	1989	5020	4844	9864	1990	290	-11%	
5 - 10	5	10	11900	1997	1924	280	1961	2861	7390	10251	1970	270	-14%	
10 - 2	10	2	11200	1960	1890	255	1925	8750	1145	9895	1936	255	-12%	
10 - 4	10	4	12000	1973	1900	260	1937	8072	1994	10066	1947	260	-16%	
10 - 10	10	10	12500	2015	1941	270	1978	5374	5414	10788	1983	270	-14%	
3 - 10	3	10	11600	1981	1909	260	1945	1585	8774	10359	1957	260	-11%	
7 - 10	7	10	12400	2014	1940	270	1977	4719	5856	10575	1980	270	-15%	

Table 5.4

Tri-Lateral Original Well Rate Test and Model Results Data

	Actual Rate Tests (Raw Data)							**Model Results**						
	Setting (L0-L1-L2)	L0 Valve Setting	L1 Valve Setting	L2 Valve Setting	Total Q (STB/d)	PDHMS (psig)	WHP (psig)	Model L-0 Q (STB/d)	Model L1 Q (STB/d)	Model L2 Q (STB/d)	Model Q (STB/d)	Model Gauge Pressure (psi)	Model WHP (psi)	Q % Differnce
L0 Tests	3-0-0	3	0	0	7100	2069	289	6961			6961	2069	289	-2%
	5-0-0	5	0	0	8700	2220	345	8761			8761	2220	345	1%
L1 Tests	0-3-0	0	3	0	8100	2057	336		8096		8096	2057	315	0%
	0-5-0	0	5	0	9900	2206	397		9640		9640	2206	348	-3%
L2 Tests	0-0-3	0	0	3	8200	2160	336			8433	8433	2160	336	3%
	0-0-5	0	0	5	9500	2287	382			9667	9667	2287	382	2%
Commingled Productio	0-3-10	0	3	10	15155	2293	400		2093	12673	14775	2293	400	-3%
	0-5-10	0	5	10	12928	2378	450		2322	9421	12368	2378	450	-4%
	3-0-5	3	0	5	12543	2230	380	3644		8147	11823	2230	380	-6%
	5-0-10	5	0	10	4390	2550	550	1749		2821	4570	2550	550	4%
	5-3-10	5	3	10	17141	2303	400	3632	2750	9507	15941	2303	400	-7%
	10-3-0	10	3	0	12921	2244	380	9649	3514		13161	2244	380	2%
	5-5-5	5	5	5	11769	2381	450	4089	2144	5318	12089	2381	450	3%

Table 5.5

Tri-Lateral Model Sensitivity Runs Results and Actual Test Data

Model Sensitivity Tests							**Actual Rate Tests Results (Verification)**						
Setting (L0-L1)	Model L-0 Q (STB/d)	Model L1 Q (STB/d)	Model L2 Q (STB/d)	Model Q (STB/d)	Model Gauge Pressure (psi)	Model WHP (psi)	L0 Valve Setting	L1 Valve Setting	L2 Valve Setting	Total Q (STB/d)	PDHMS (psig)	WHP (psig)	Q % Differnce
0-3-5		2182	8825	11028	2283	400	0	3	5	10338	2283	400	7%
3-5-10	2090	2494	7720	12349	2375	450	3	5	10	11849	2375	450	4%
3-0-10	1884		8256	8256	2453	500	3	0	10	8856	2453	500	-7%
5-3-0	8166	3947		12124	2205	360	5	3	0	11474	2205	360	6%
10-5-0	7493	4551		12096	2329	420	10	5	0	12536	2329	420	-4%
10-10-10	3293	1611	7539	12445	2395	460	10	10	10	13105	2395	460	-5%

Table 5.6

Tri-Lateral Actual and Model Results with Calculated Allocation Factor

Actual Rate Tests (Raw Data)							**Model Results**						**Allocation Factor**	
Setting (L0-L1)	L0 Valve Setting	L1 Valve Setting	L2 Valve Setting	Total Q (STB/d)	FBHP @ PDHMS (psig)	WHP (psig)	Model L-0 Q (STB/d)	Model L1 Q (STB/d)	Model L2 Q (STB/d)	Model Q (STB/d)	Model FBHP @ PDHMS (psi)	Model WHP (psi)	Q % Differnce	Allocation Factor (Absolute Differnce)
3-0-0	3	0	0	7100	2069	289	6961			6961	2069	289	-2%	
5-0-0	5	0	0	8700	2220	345	8761			8761	2220	345	1%	
0-3-0	0	3	0	8100	2057	336		8096		8096	2057	315	0%	
0-5-0	0	5	0	9900	2206	397		9640		9640	2206	348	-3%	
0-0-3	0	0	3	8200	2160	336			8433	8433	2160	336	3%	
0-0-5	0	0	5	9500	2287	382			9667	9667	2287	382	2%	
0-3-10	0	3	5	10338	2283	400		2182	8825	11028	2283	400	7%	
0-3-10	0	3	10	15155	2293	400		2093	12673	14775	2293	400	-3%	
0-5-10	0	5	10	12928	2378	450		2322	9421	12368	2378	450	-4%	
3-5-10	3	5	10	11849	2375	450	2090	2494	7720	12349	2375	450	4%	4%
3-0-5	3	0	5	12543	2230	380	3644		8147	11823	2230	380	-6%	
3-0-10	3	0	10	8856	2453	500	1884		8256	8256	2453	500	-7%	
5-0-10	5	0	10	4390	2550	550	1749		2821	4570	2550	550	4%	
5-3-10	5	3	10	17141	2303	400	3632	2750	9507	15941	2303	400	-7%	
5-3-0	5	3	0	11474	2205	360	8166	3947		12124	2205	360	6%	
10-3-0	10	3	0	12921	2244	380	9649	3514		13161	2244	380	2%	
10-5-0	10	5	0	12536	2329	420	7493	4551		12096	2329	420	-4%	
5-5-5	5	5	5	11769	2381	450	4089	2144	5318	12089	2381	450	3%	
10-10-10	10	10	10	13105	2395	460	3293	1611	7539	12445	2395	460	-5%	

Table 5.7

Quad-Lateral Original Well Rate Test and Model Results Data

	Actual Rate Tests (Raw Data)										Model Results										
	Setting (L0-L1-L2-L3)	L0 Valve Setting	L1 Valve Setting	L2 Valve Setting	L3 Valve Setting	Test Total Q (STB/d)	Test Oil Rate (STB/d)	Test Water Cut (%)	PDHMS (psig)	WHP (psig)	Model L-0 Q (STB/d)	Model L1 Q (STB/d)	Model L2 Q (STB/d)	Model L3 Q (STB/d)	Model Q (STB/d)	Model Oil Rate (STB/d)	Model Water Cut (%)	Model Gauge Pressure (psi)	Model WHP (psi)	Total Q % Differnce (%)	Oil Rate % Differnce
L0 Tests	10-0-0-0	10	0	0	0	7813	2659	66%	2507	400	7651				7651	2656	65%	2254	750	2%	0%
	2-0-0-0	2	0	0	0	2848	913	68%	2295	400	3321				3321	911	73%	1995	630	-17%	0%
	6-0-0-0	6	0	0	0	7350	3291	61%	2462	400	6351				6351	3249	49%	2489	565	14%	1%
L1 Tests	0-10-0-0	0	10	0	0	11420	10351	9%	2319	400		11407			11407	10278	10%	2619	172	0%	1%
	0-2-0-0	0	2	0	0	4452	2917	34%	1842	380		3813			3813	2938	23%	2224	125	14%	-1%
	0-6-0-0	0	6	0	0	10099	8191	19%	2274	400		10342			10342	8180	21%	2554	214	-2%	0%
L2 Tests	0-0-10-0	0	0	10	0	8721	3336	62%	2674	400			8588		8588	3314	61%	2634	471	2%	1%
	0-0-2-0	0	0	2	0	2950	797	76%	2608	370			3374		3374	809	76%	2190	919	-14%	-2%
	0-0-6-0	0	0	6	0	6730	2323	65%	2705	400			8305		8305	2356	72%	2506	574	-23%	-1%
L-3 Tests	0-0-0-10	0	0	0	10	11756	5858	50%	2751	452				9282	9282	5878	37%	2742	554	21%	0%
	0-0-0-2	0	0	0	2	3230	1560	63%	2310	380				2978	2978	1502	50%	2555	263	8%	4%
Commingled Production	0-6-0-6	0	6	0	6	12422	7159	42%	2785	450		7142		6388	13520	7081	48%	2899	584	-9%	1%
	0-10-0-10	0	10	0	10	5791	2480	57%	1834	750		5922		4304	6000	2490	58%	3123	460	-4%	0%
	0-2-0-2	0	2	0	2	6255	3565	43%	2565	450		3157		2944	6105	3663	40%	2565	450	2%	-3%
	0-2-0-6	0	2	0	6	10350	5382	48%	2803	450		2672		7150	9836	4820	51%	2803	450	5%	10%
	0-6-0-2	0	6	0	2	10820	7249	33%	2694	400		9322		2703	11712	8316	29%	2694	400	-8%	-15%
	6-0-6-0	6	0	6	0	9800	4018	59%	2731	450	4162		5902		10078	3694	63%	2731	450	-3%	8%
	2-0-2-0	2	0	2	0	5940	1960	67%	2501	450	2666		2898		5567	2060	63%	2501	450	6%	-5%
	2-0-6-0	2	0	6	0	8895	2920	68%	2658	450	2318		6804		9132	3288	64%	2658	450	-3%	-13%
	2-2-2-2	2	2	2	2	10050	5145	48%	2624	350	2334	2966	2605	2806	10675	5231	51%	2624	350	-6%	-2%
	6-6-6-6	6	6	6	6	12300	6300	51%	3169	700	1732	3890	2549	3056	11333	6006	47%	3169	700	8%	5%
	6-2-6-2	6	2	6	2	8340	3670	56%	3130	750	2266	1751	3178	1559	8705	4004	54%	3130	750	-4%	-9%
	10-10-10-10	10	10	10	10	9850	5950	40%	3064	800	1486	3869	2619	4131	10619	7560	38%	3139	800	-8%	-27%

Table 5.8

Quad-Lateral Model Sensitivity Runs Results and Actual Test Data

Model Sensitivity Tests										Actual Test Data								
Setting (L0-L1-L2-L3)	Model L-0 Q (STB/d)	Model L1 Q (STB/d)	Model L2 Q (STB/d)	Model L3 Q (STB/d)	Model Q (STB/d)	Model Oil Rate	Model Water Cut (%)	Model Reservoir FBHP (psi)	Model FWHP (psi)	Test Total Q (STB/d)	Oil Rate (STB/d)	Test Water Cut (%)	GOR	PDHMS Upper FBHP (psi)	PDHMS Lower FBHP (psi)	Test WHP (psig)	Total Q % Differnce (%)	Oil Rate % Differnce
10-0-0-0	6140				6140	1555	75%	2555	998	5361	1560	71%	1576	2773	2835	860	15%	-0.3%
0-0-10-0			5844		5844	1413	76%	2932	729	5436	1413	74%	1298	2851	2917	760	8%	0.0%
0-0-0-10				7564	7564	2501	67%	2853	964	6253	2495	60%	1087	2889	2952	750	21%	0.2%
0-0-0-6				8457	8457	3689	56%	2666	429	10850	3742	66%	744	2689	2756	400	-22%	-1.4%
0-10-0-10		8270		6598	14592	8901	39%	2952	400	15600	9828	37%	720	2922	2982	400	-6%	-9.4%
6-0-2-0	5670		2702		8385	3186	62%	2682	400	8120	2842	65%	1200	2652	2712	400	3%	12.1%
2-6-2-6	1092	4289	1393	3798	10608	5834	45%	3145	700	10250	5228	49%	378	3115	3175	700	3%	11.6%

Table 5.9

Quad-Lateral Actual and Model Results with Calculated Allocation Factor

Actual Rate Tests (Raw Data)										Model Results									Allocation Factor	
Setting (L0-L1-L2-L3)	L0 Valve Setting	L1 Valve Setting	L2 Valve Setting	L3 Valve Setting	Total Q (STB/d)	Oil Rate (STB/d)	Water Cut (%)	PDHMS (psig)	WHP (psig)	Model L-0 Q (STB/d)	Model L1 Q (STB/d)	Model L2 Q (STB/d)	Model L3 Q (STB/d)	Model Q (STB/d)	Model Oil Rate (STB/d)	Model Water Cut (%)	Model Gauge Pressure	Model WHP (psi)	Total Q % Differnce	Allocation Factor (Absolute Differnce)
10-0-0-0	10	0	0	0	7813	2659	66%	2507	400	7651				7651	2656	65%	2254	750	2%	9%
2-0-0-0	2	0	0	0	2848	913	68%	2295	400	3321				3321	911	73%	1995	630	-17%	
6-0-0-0	6	0	0	0	7350	3291	61%	2462	400	6351				6351	3249	49%	2489	565	14%	
0-10-0-0	0	10	0	0	11420	10351	9%	2319	400		11407			11407	10278	10%	2619	172	0%	
0-2-0-0	0	2	0	0	4452	2917	34%	1842	380		3813			3813	2938	23%	2224	125	14%	
0-6-0-0	0	6	0	0	10099	8191	19%	2274	400		10342			10342	8180	21%	2554	214	-2%	
0-0-10-0	0	0	10	0	8721	3336	62%	2674	400			8588		8588	3314	61%	2634	471	2%	
0-0-2-0	0	0	2	0	2950	797	76%	2608	370			3374		3374	809	76%	2190	919	-14%	
0-0-6-0	0	0	6	0	6730	2323	65%	2705	400			8305		8305	2356	72%	2506	574	-23%	
0-0-0-10	0	0	0	10	11756	5858	50%	2751	452				9282	9282	5878	37%	2742	554	21%	
0-0-0-2	0	0	0	2	3230	1560	63%	2310	380				2978	2978	1502	50%	2555	263	8%	
0-6-0-6	0	6	0	6	12422	7159	42%	2785	450		7142		6388	13520	7081	48%	2899	584	-9%	
0-10-0-10	0	10	0	10	5791	2480	57%	1834	750		5922		4304	6000	2490	58%	3123	460	-4%	
0-2-0-2	0	2	0	2	6255	3565	43%	3114	450		3157		2944	6105	3663	40%	2565	450	2%	
0-2-0-6	0	2	0	6	10350	5382	48%	3810	450		2672		7150	9836	4820	51%	2803	450	5%	
0-6-0-2	0	6	0	2	10820	7249	33%	5500	400		9322		2703	11712	8316	29%	2694	400	-8%	
6-0-6-0	6	0	6	0	9800	4018	59%	3212	450	4162		5902		10078	3694	63%	2731	450	-3%	
2-0-2-0	2	0	2	0	5940	1960	67%	2279	450	2666		2898		5567	2060	63%	2501	450	6%	
2-0-6-0	2	0	6	0	8895	2920	68%	2968	450	2318		6804		9132	3288	64%	2658	450	-3%	
2-2-2-2	2	2	2	2	10050	5145	48%	3930	350	2334	2966	2605	2806	10675	5231	51%	2624	350	-6%	
6-6-6-6	6	6	6	6	12300	6300	51%	4583	700	1732	3890	2549	3056	11333	6006	47%	3169	700	8%	
6-2-6-2	6	2	6	2	8340	3670	56%	3569	750	2266	1751	3178	1559	8705	4004	54%	3130	750	-4%	
10-10-10-10	10	10	10	10	9850	5950	40%	3064	800	1486	3869	2619	4131	10619	7560	38%	3139	800	-8%	
10-0-0-0	10	0	0	0	5361	1560	71%	2804	640	6140				6140	1555	75%	2555	998	-15%	
0-0-10-0	0	0	10	0	5436	1413	74%	2884	760			5844		5844	1413	76%	2932	729	-8%	
0-0-0-10	0	0	0	10	6253	2495	60%	2921	750				7564	7564	2501	67%	2853	964	-21%	
0-0-0-6	0	0	0	6	10850	3742	66%	2723	400				8457	8457	3689	56%	2666	429	22%	
0-10-0-10	0	10	0	10	15600	9828	37%	2952	400		8270		6598	14592	8901	39%	2952	400	6%	
6-0-2-0	6	0	2	0	8120	2842	65%	2682	400	5670		2702		8385	3186	62%	2682	400	-3%	
2-6-2-6	2	6	2	6	10250	5228	49%	3145	700	1092	4289	1393	3798	10608	5834	45%	3145	700	-3%	

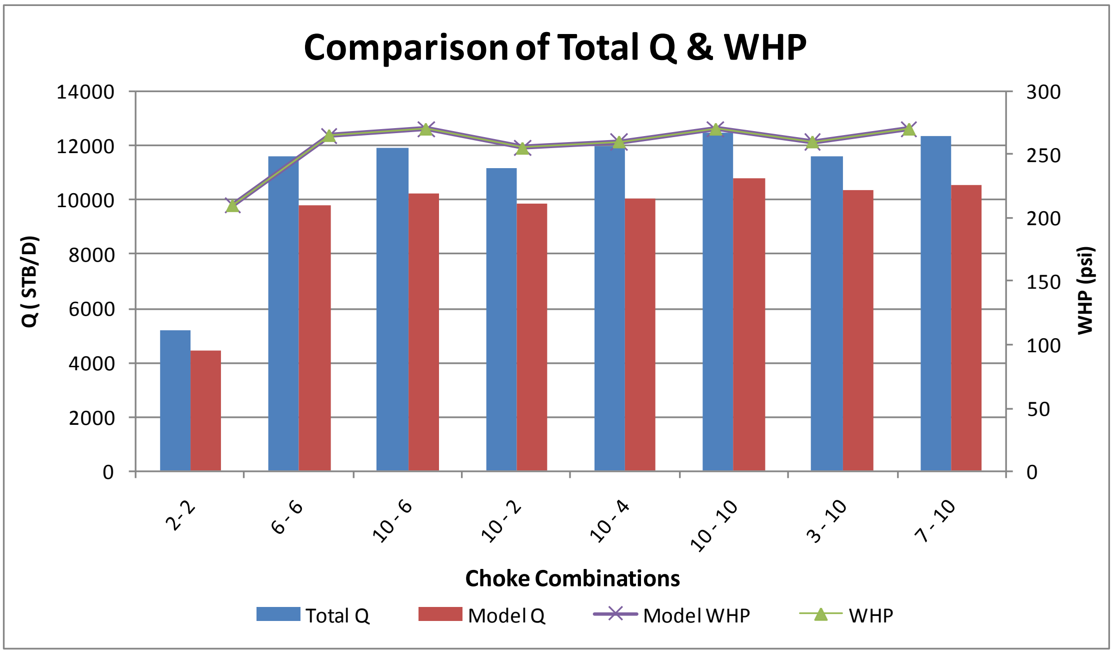


Figure 5.1

Dual-Lateral Original Well Rate Test and Model Results Data

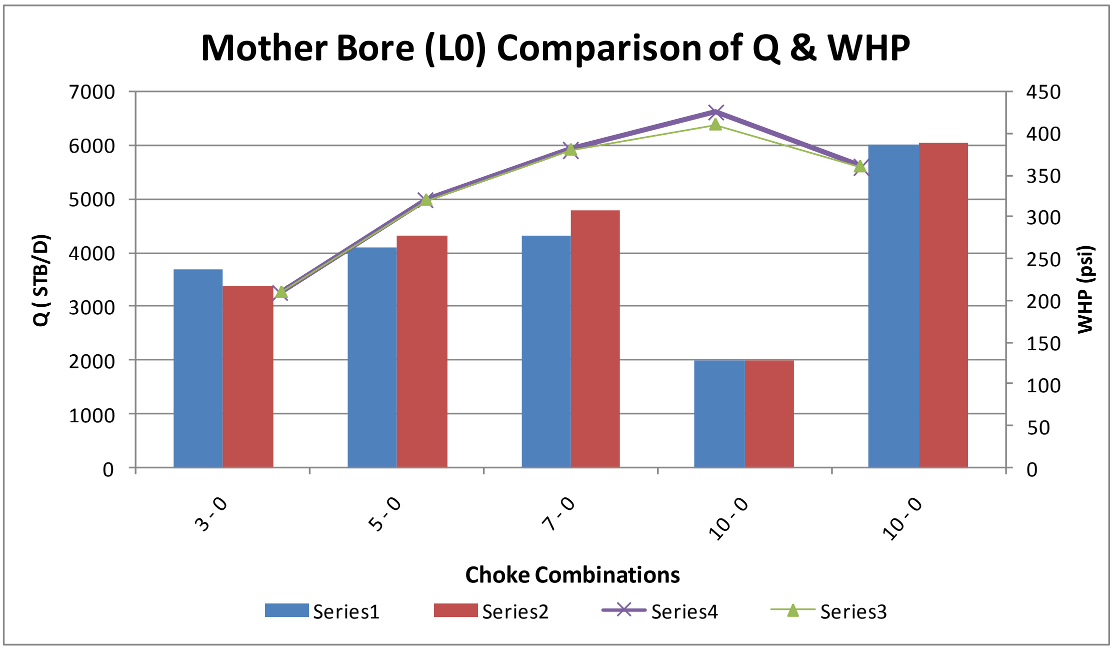


Figure 5.2

Dual-Lateral Original Well Rate Test and Model Results Data

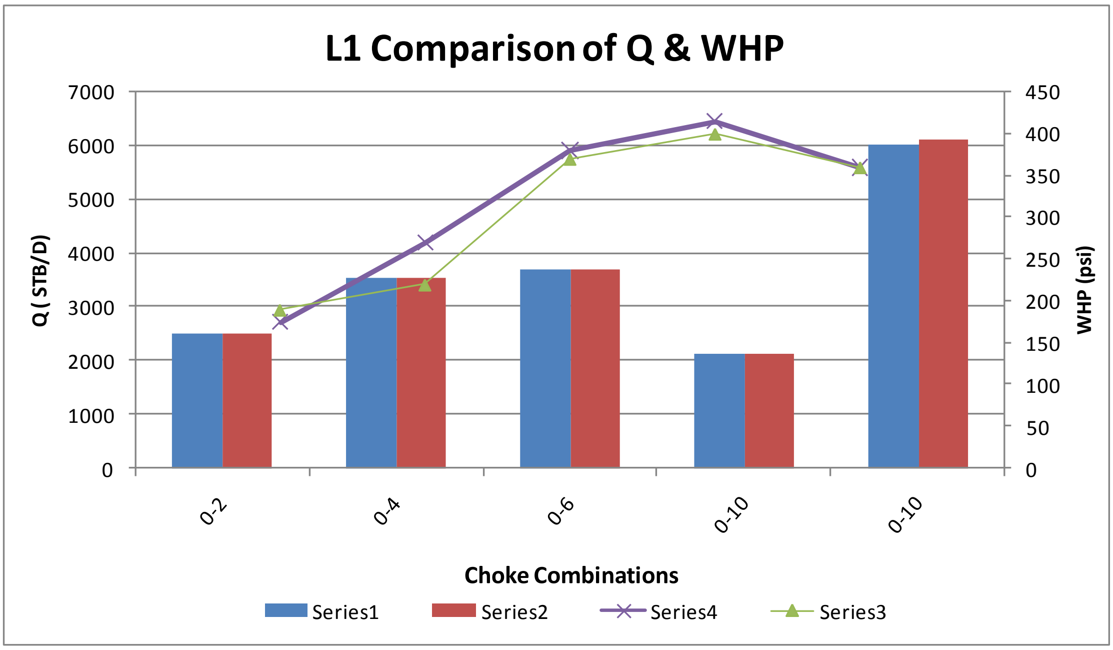


Figure 5.3

Dual-Lateral Original Well Rate Test and Model Results Data

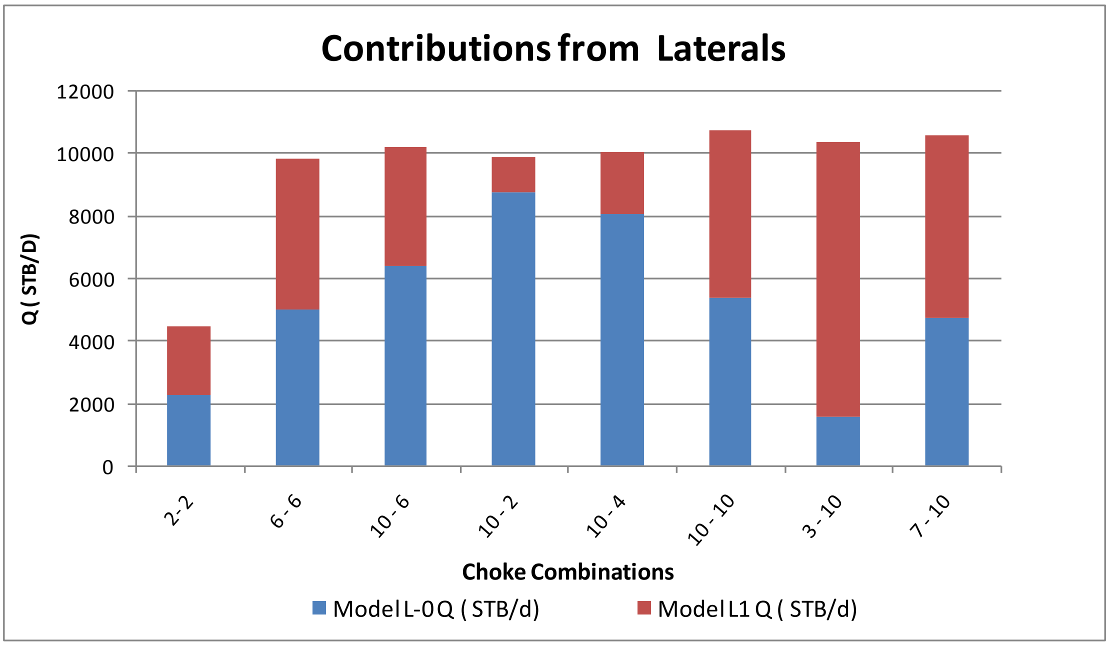


Figure 5.4

Dual-Lateral Original Well Rate Test and Model Results Data

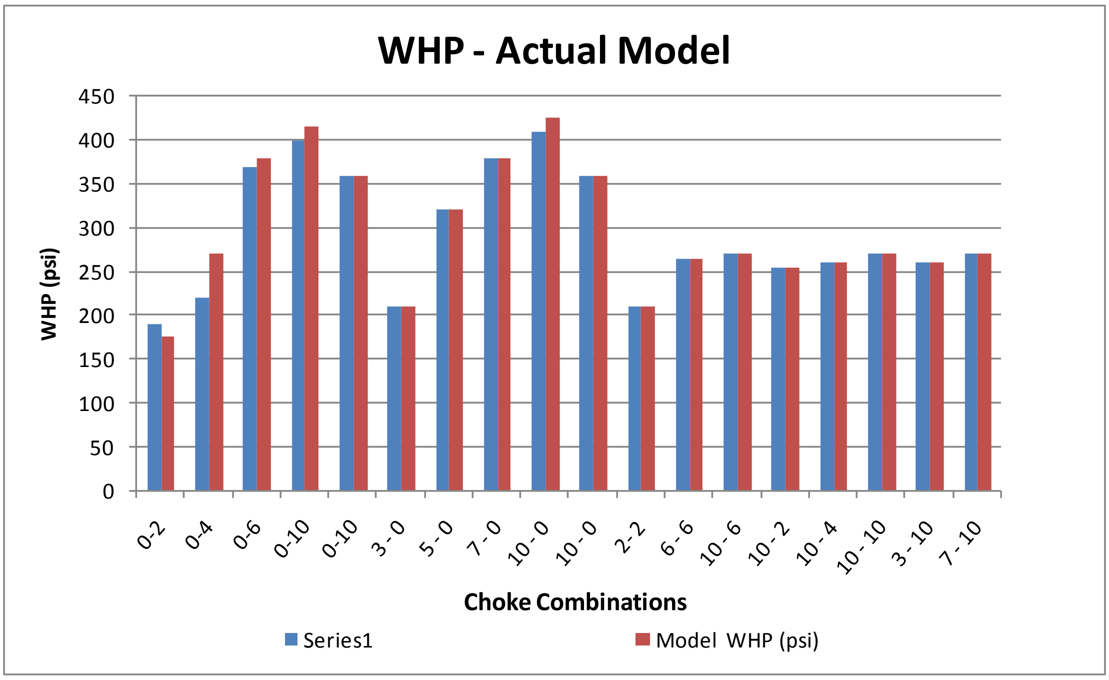


Figure 5.5

Dual-Lateral Original Well Rate Test and Model Results Data

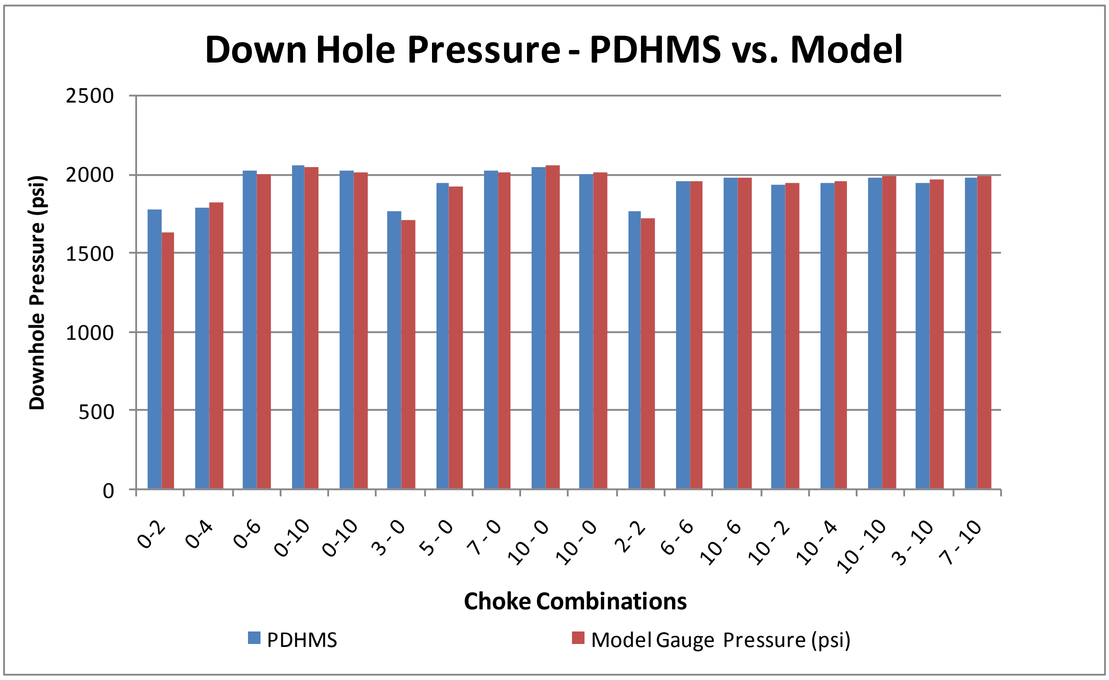


Figure 5.6

Dual-Lateral Original Well Rate Test and Model Results Data

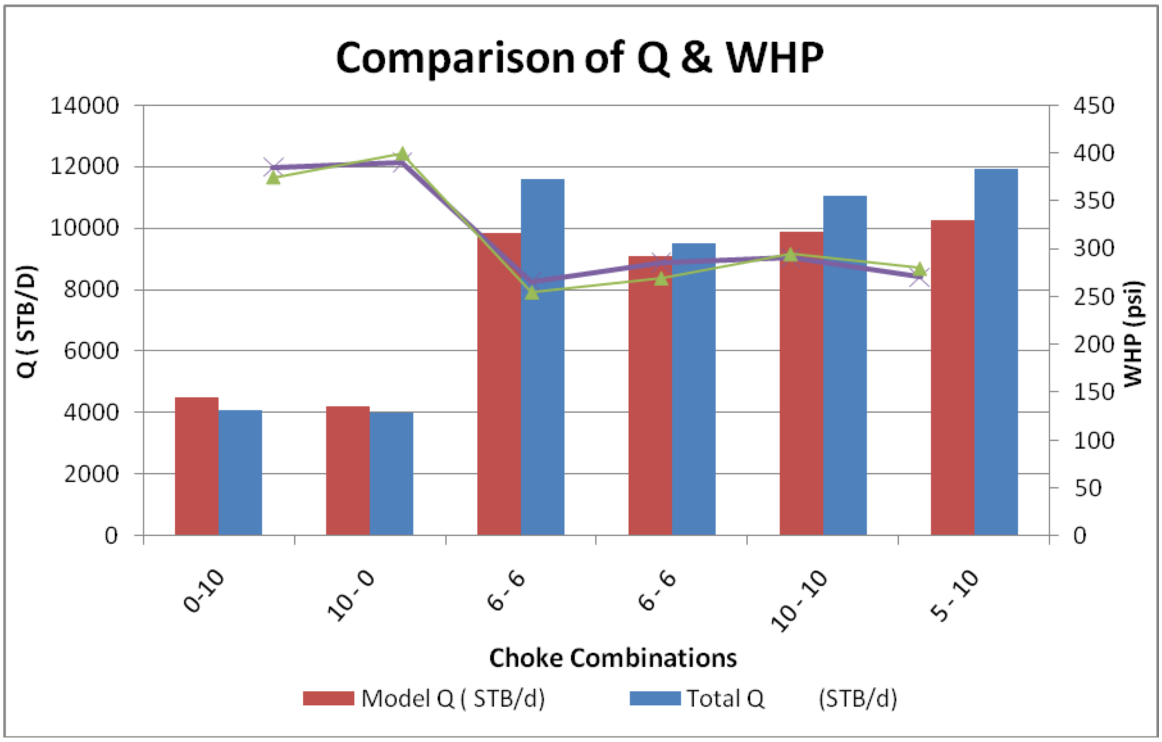


Figure 5.7

Dual-Lateral Model Sensitivity Runs Results and Actual Test Data

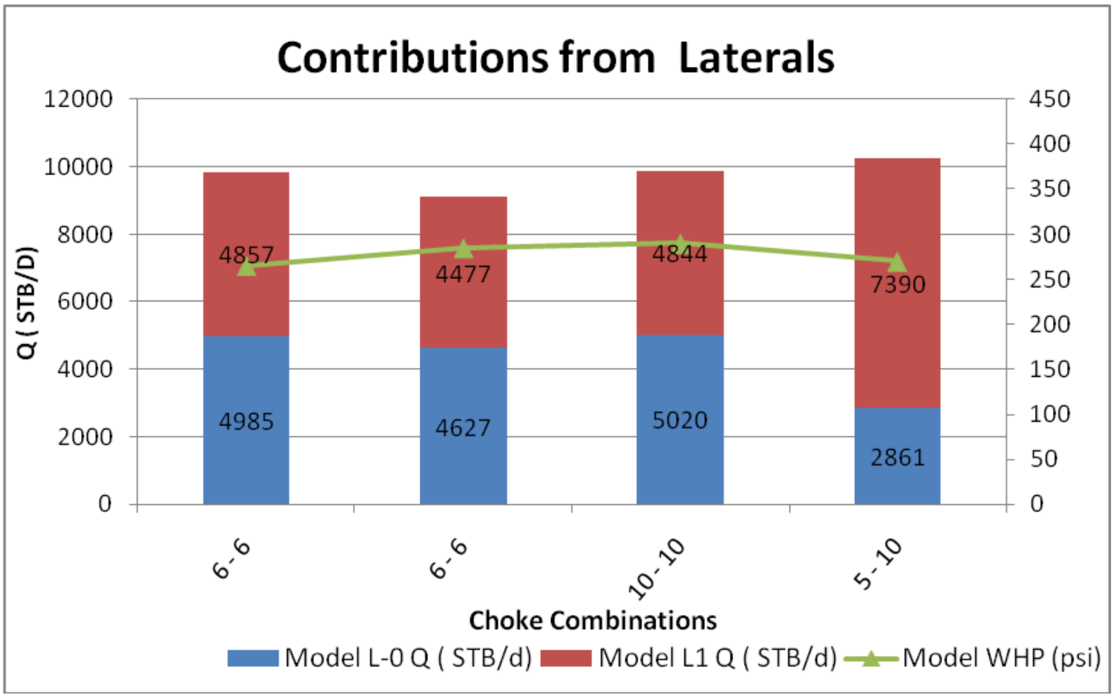


Figure 5.8

Dual-Lateral Model Sensitivity Runs Results and Actual Test Data

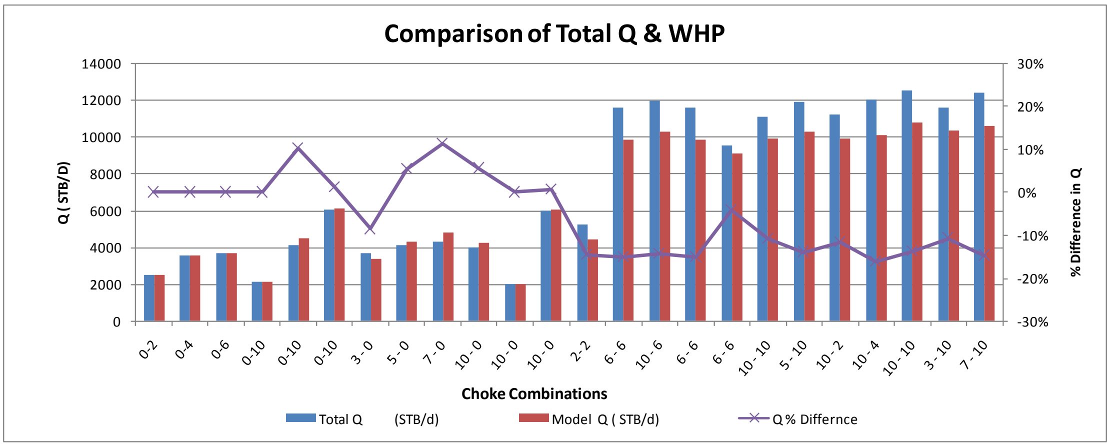


Figure 5.9

All Dual-Laterals Actual and Model Results

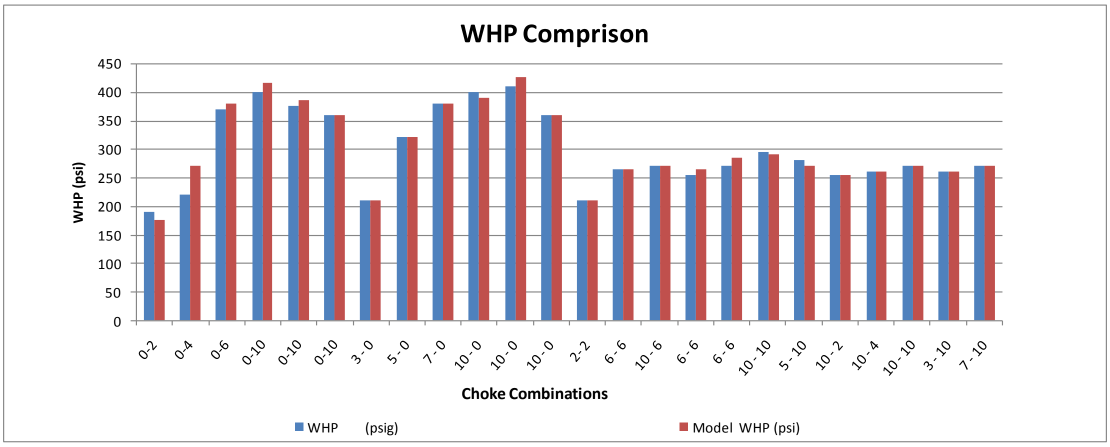


Figure 5.10

All Dual-Laterals Actual and Model Results

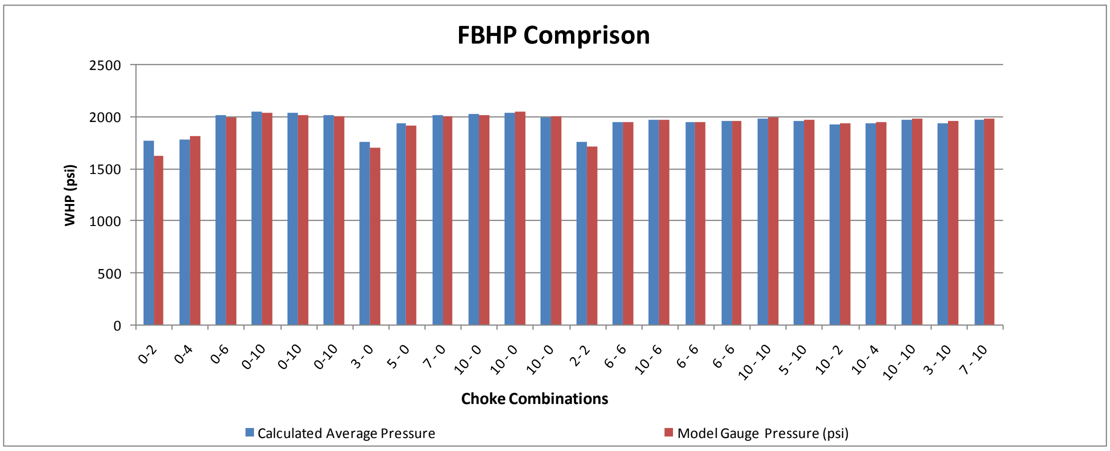


Figure 5.11

All Dual-Laterals Actual and Model Results

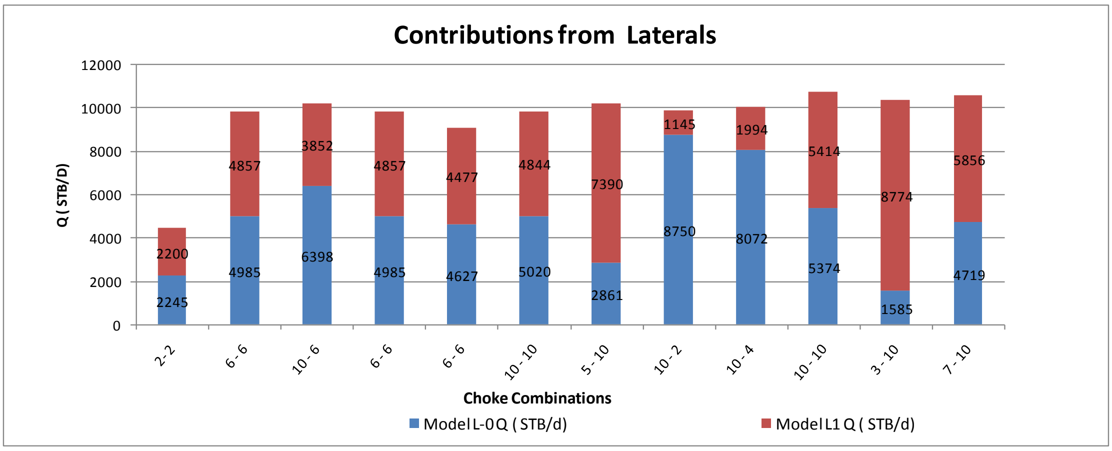


Figure 5.12

All Dual-Laterals Actual and Model Results

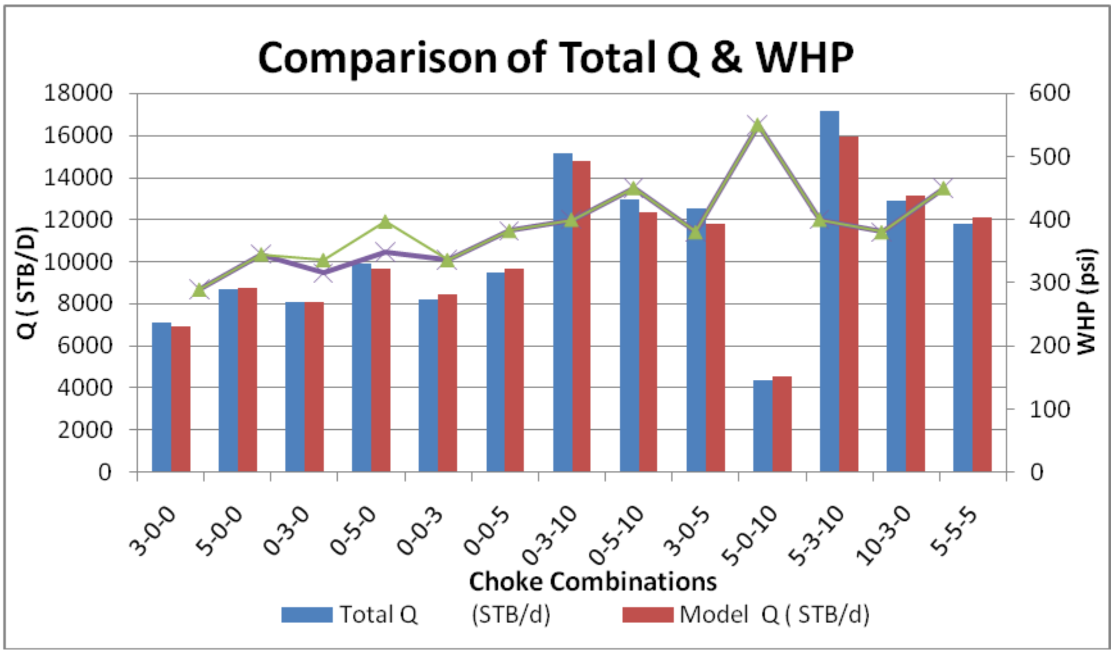


Figure 5.13

Tri-Lateral Well Original Rate Test and Model Results Data

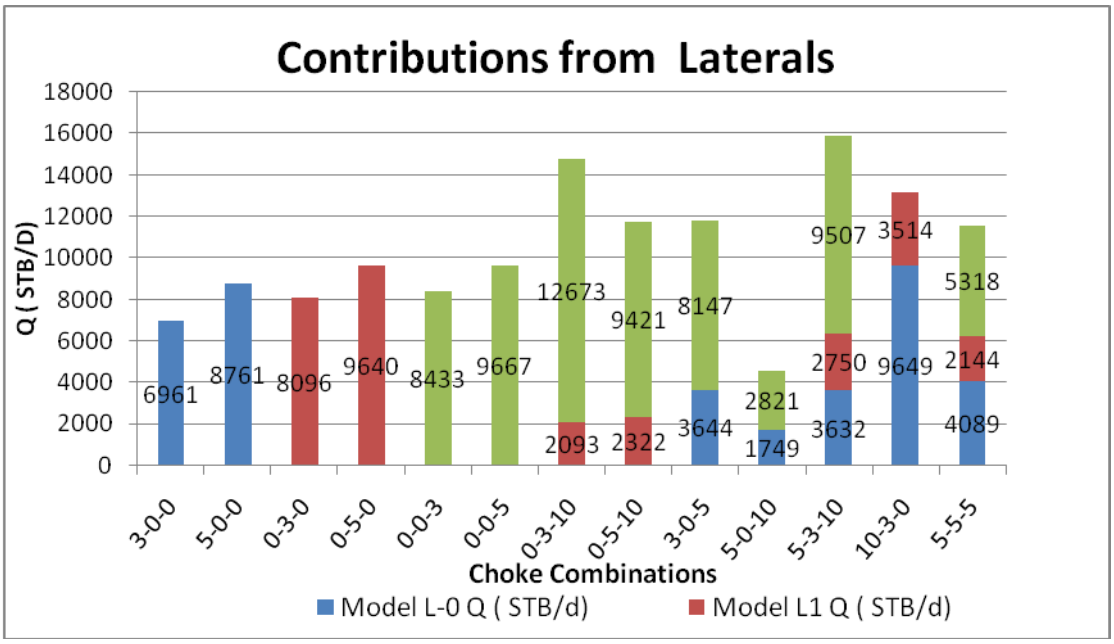


Figure 5.14

Tri-Lateral Well Original Rate Test and Model Results Data

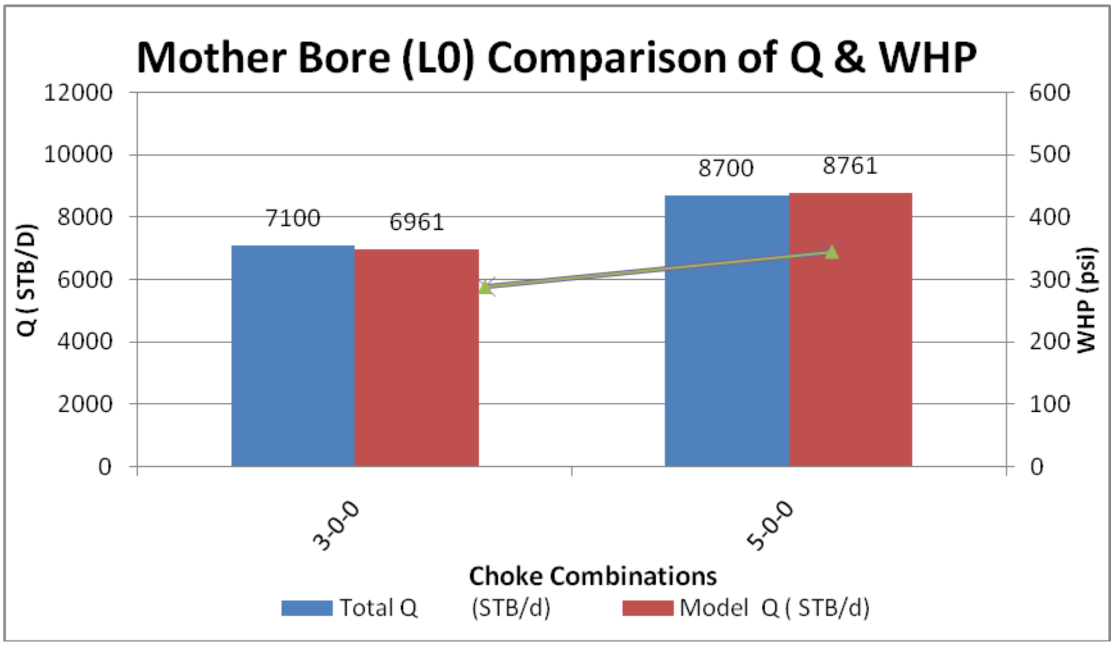


Figure 5.15

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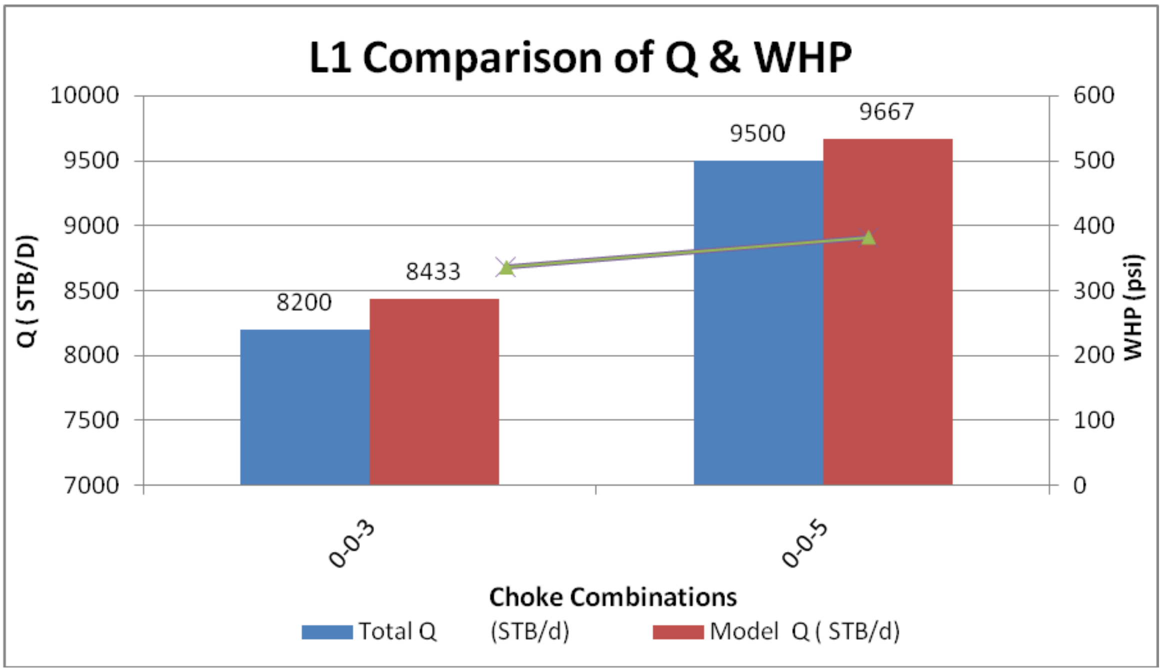


Figure 5.16

Tri-Lateral Well Original Rate Test and Model Results Data

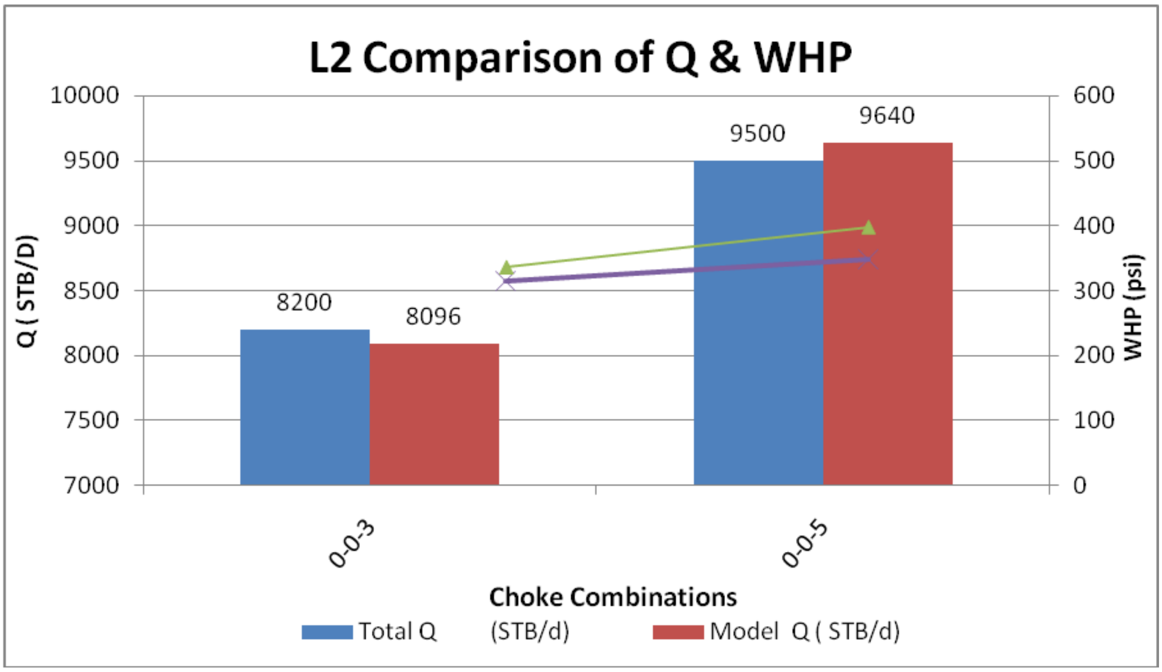


Figure 5.17

Tri-Lateral Well Original Rate Test and Model Results Data

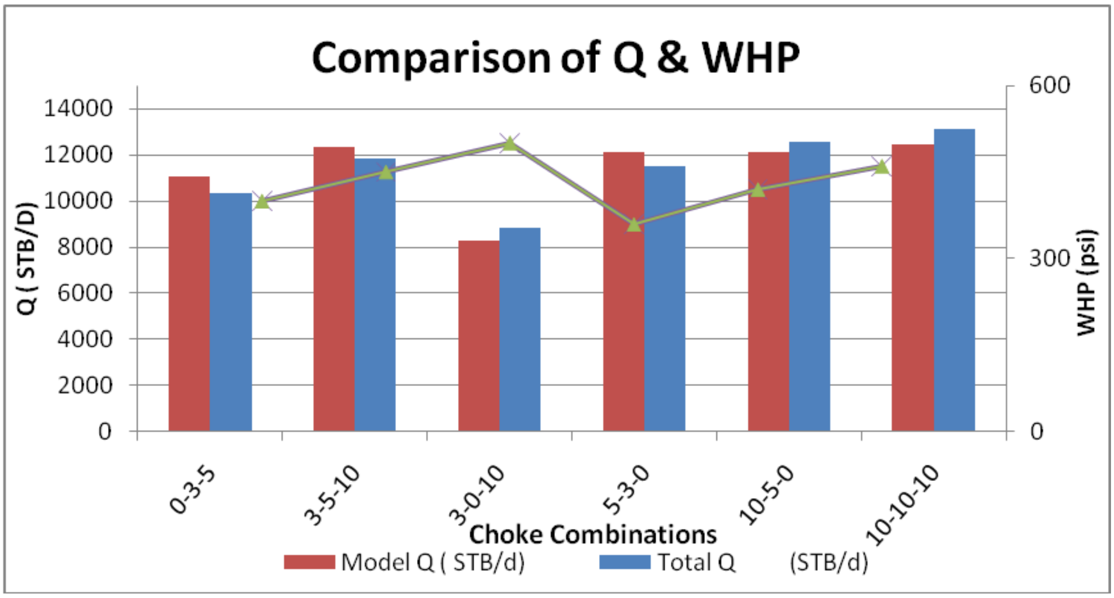


Figure 5.18

Tri-Lateral Model Sensitivity Runs Results and Actual Test Data

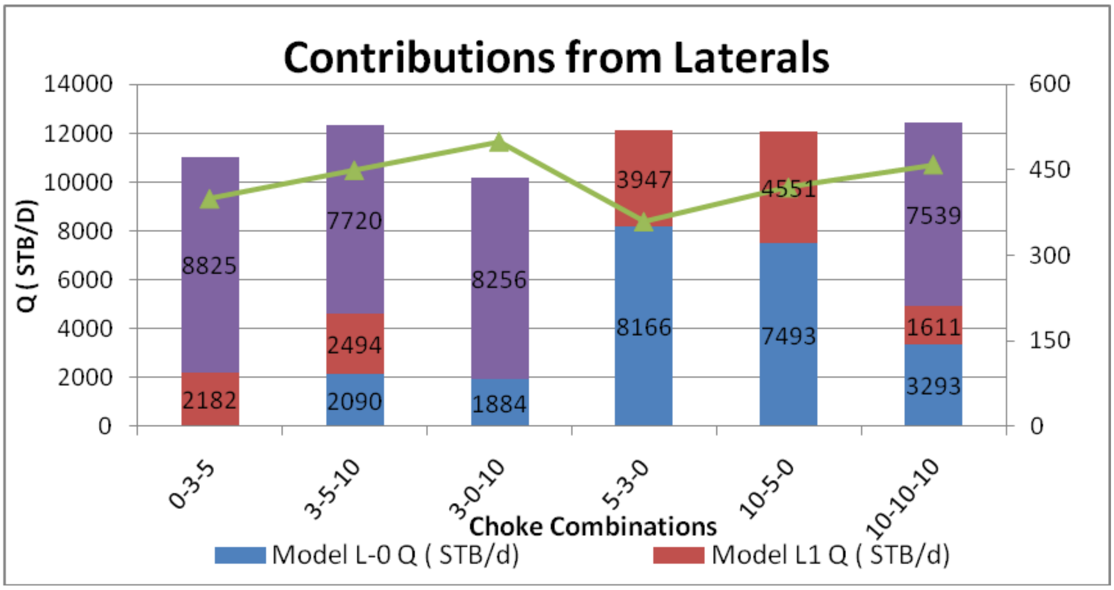


Figure 5.19

Tri-Lateral Model Sensitivity Runs Results and Actual Test Data

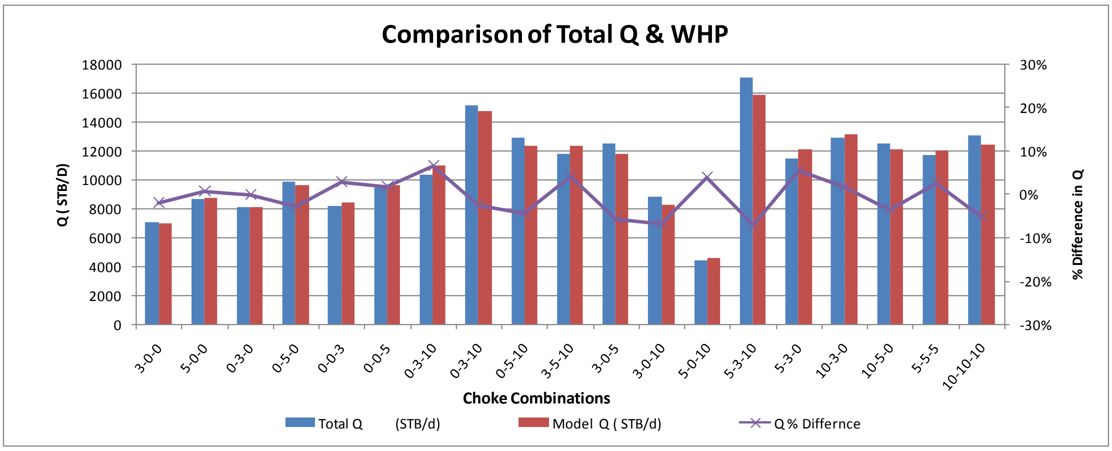


Figure 5.20

Tri-Lateral Well All Actual and Model Results

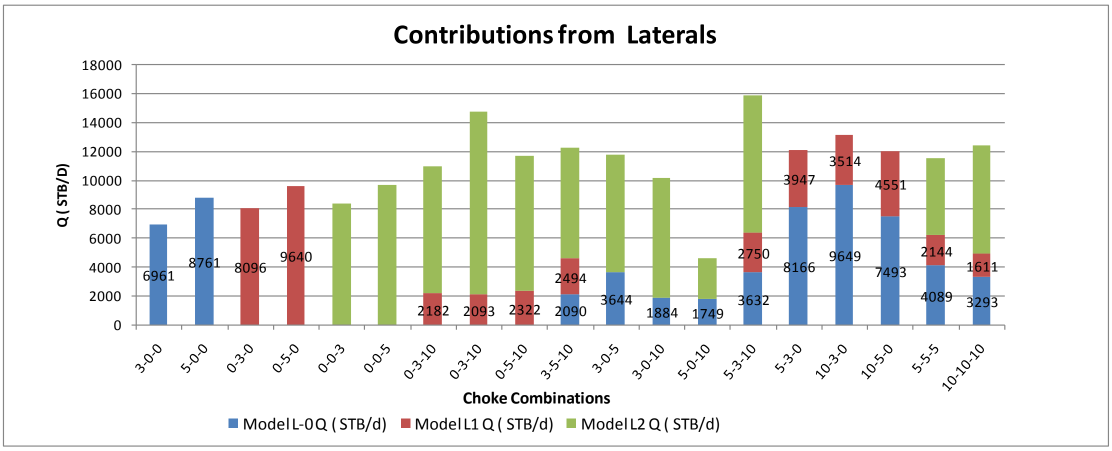


Figure 5.21

Tri-Lateral Well All Actual and Model Results

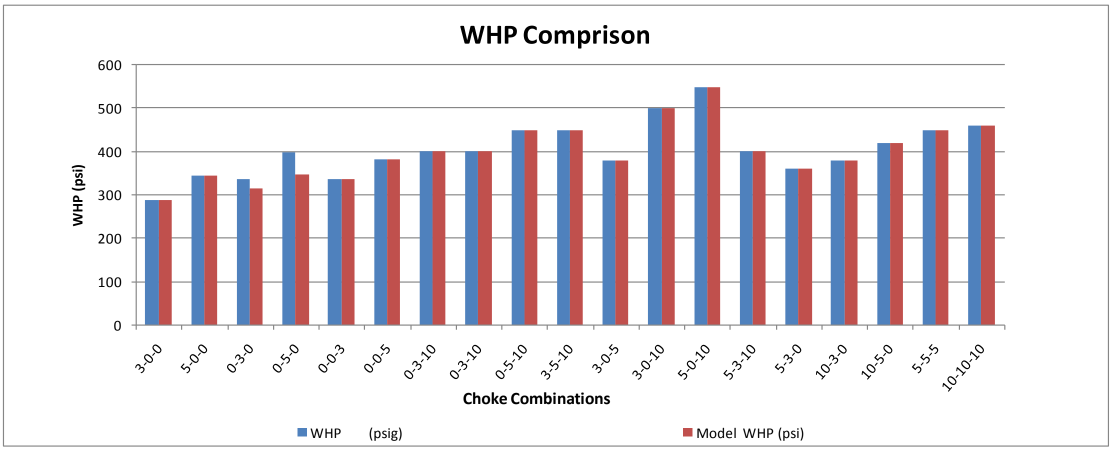


Figure 5.22

Tri-Lateral Well All Actual and Model Results

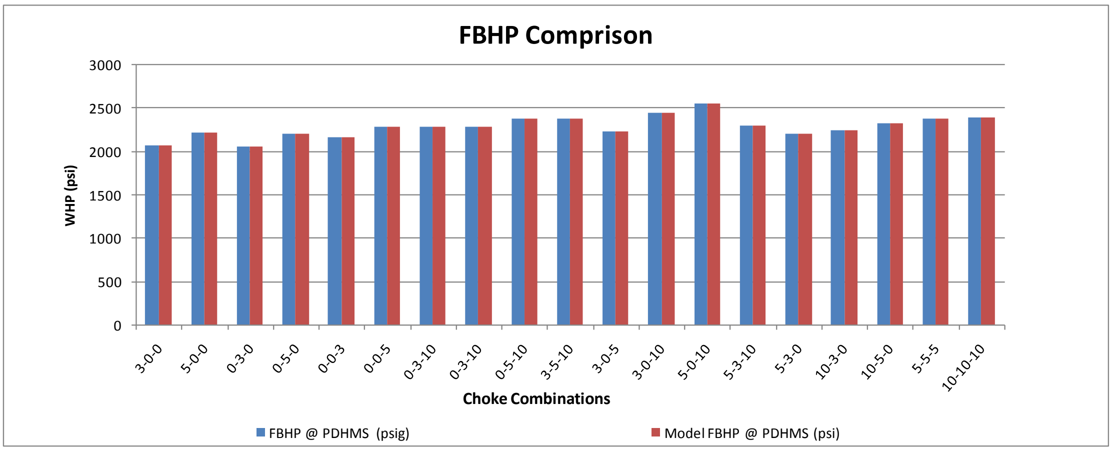


Figure 5.23

Tri-Lateral Well All Actual and Model Results

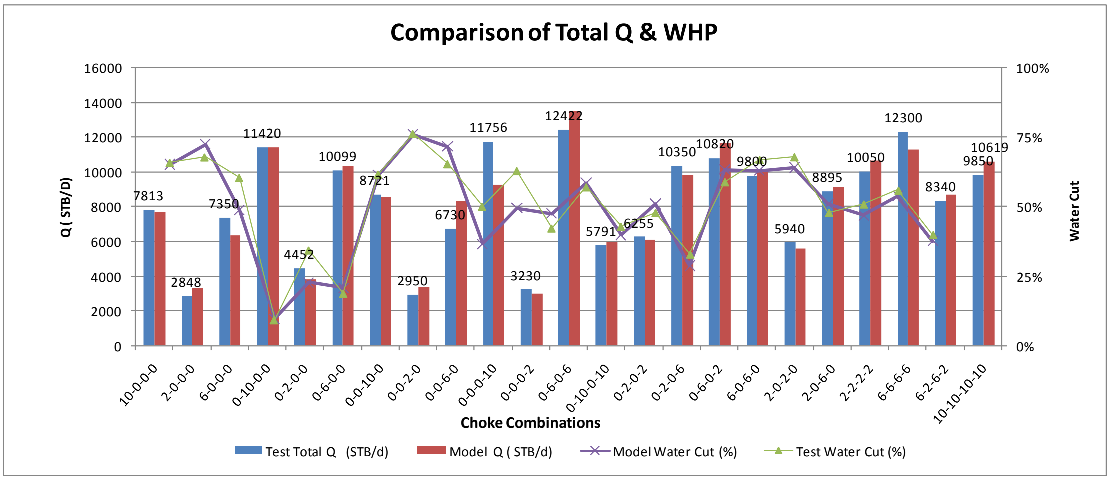


Figure 5.24

Quad-Lateral Well Original Rate Test and Model Results Data

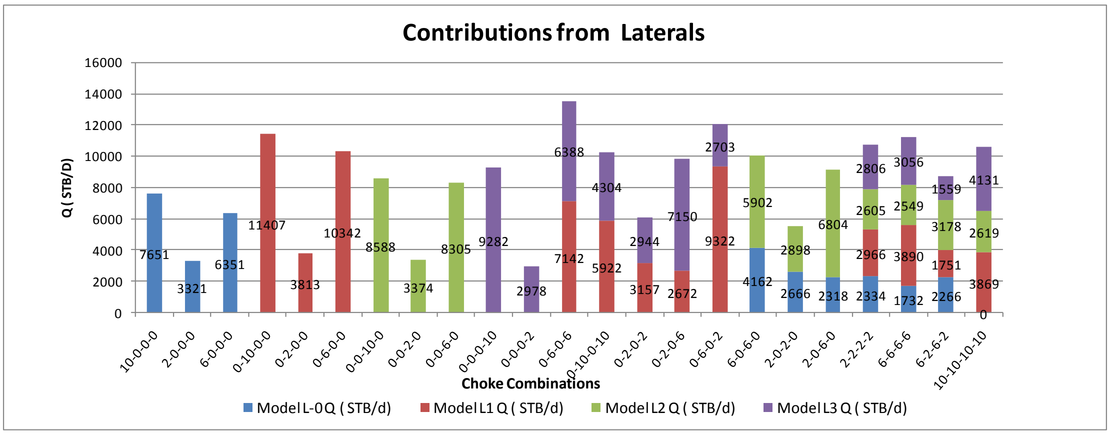


Figure 5.25

Quad-Lateral Well Original Rate Test and Model Results Data

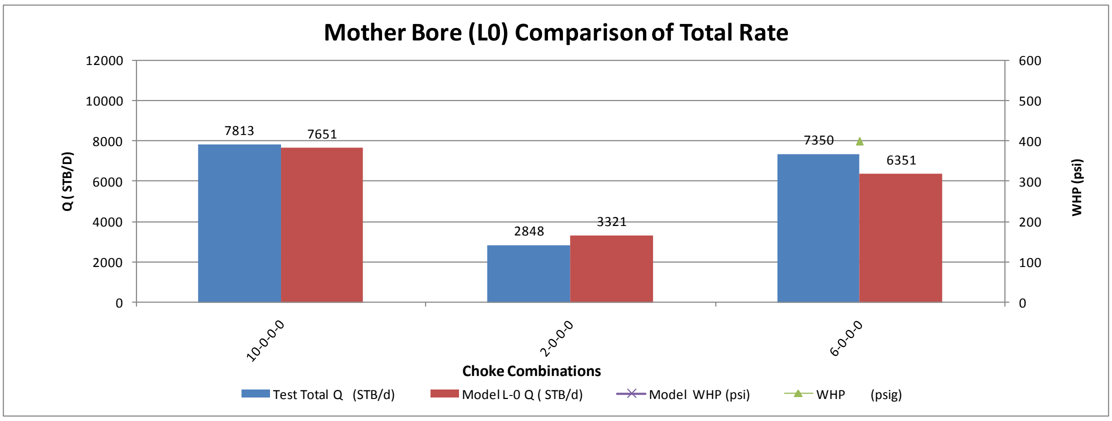


Figure 5.26

Quad-Lateral Well Original Rate Test and Model Results Data

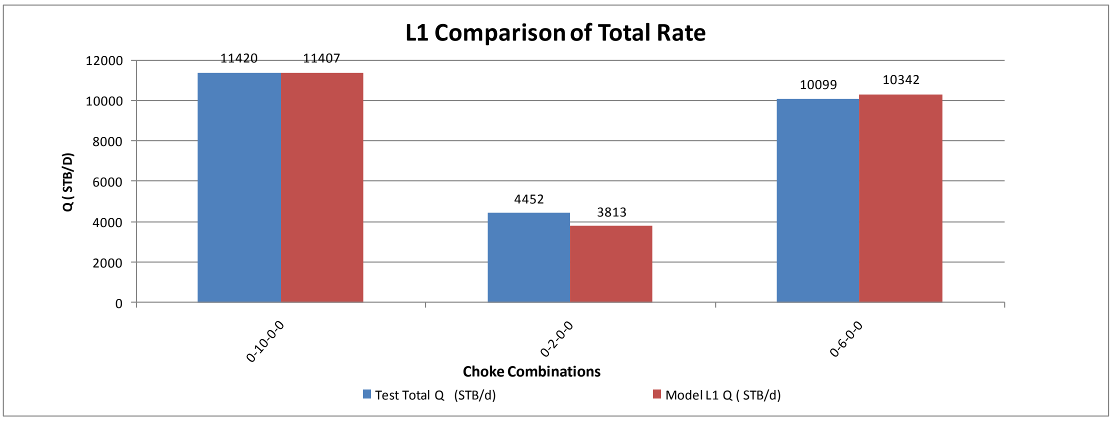
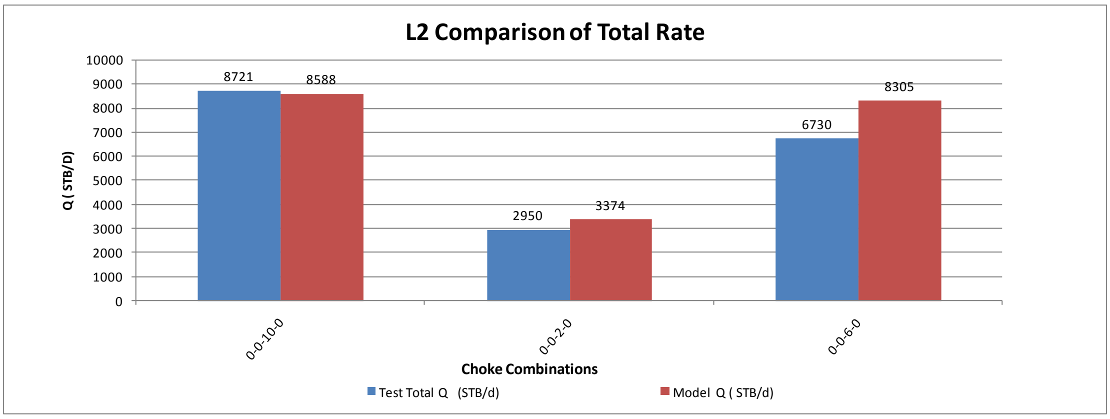


Figure 5.27

Quad-Lateral Well Original Rate Test and Model Results Data



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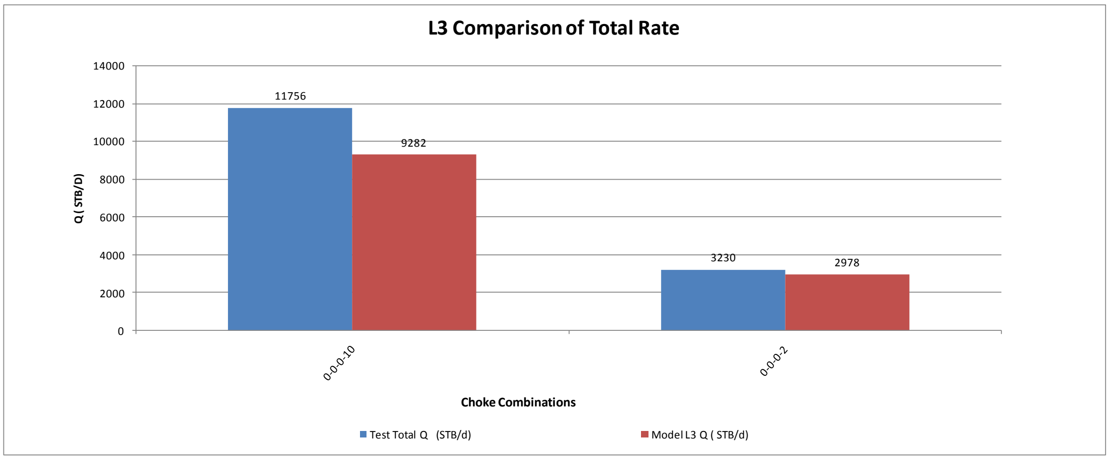

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Quad-Lateral Well Original Rate Test and Model Results Data

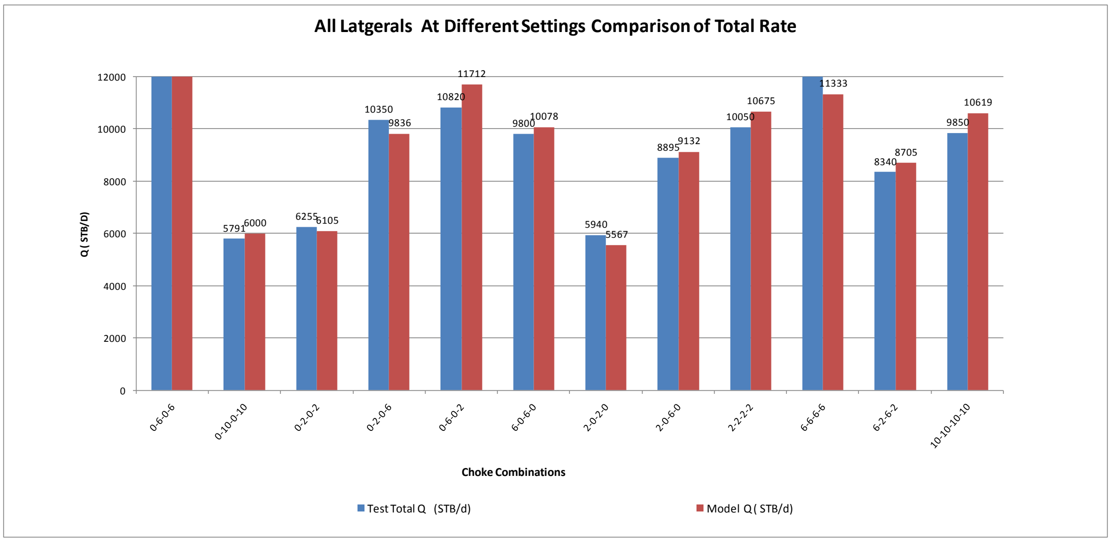

Figure 5.30

Quad-Lateral Well Original Rate Test and Model Results Data

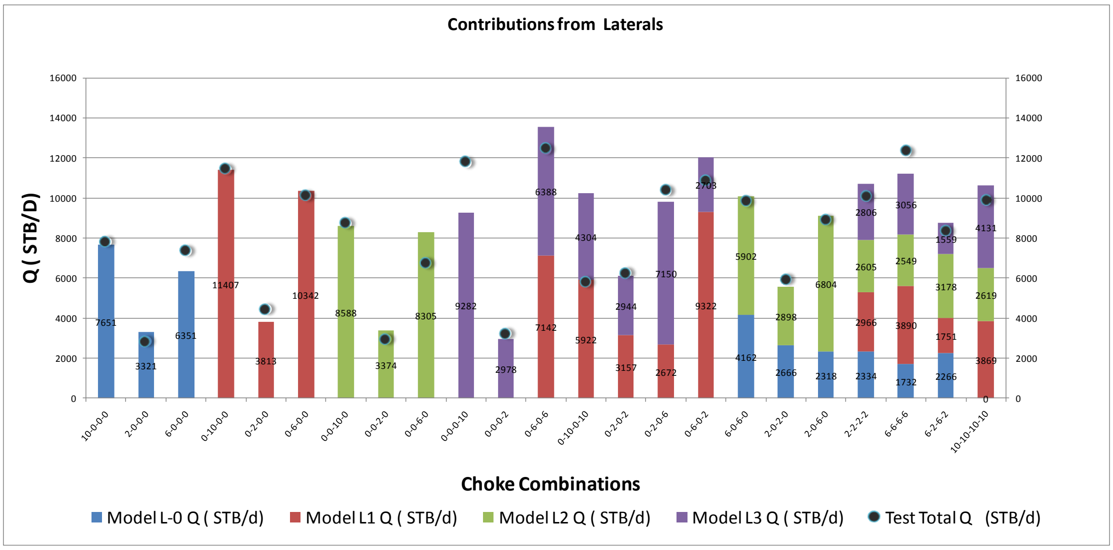

Figure 5.31

Quad-Lateral Well Original Rate Test and Model Results Data

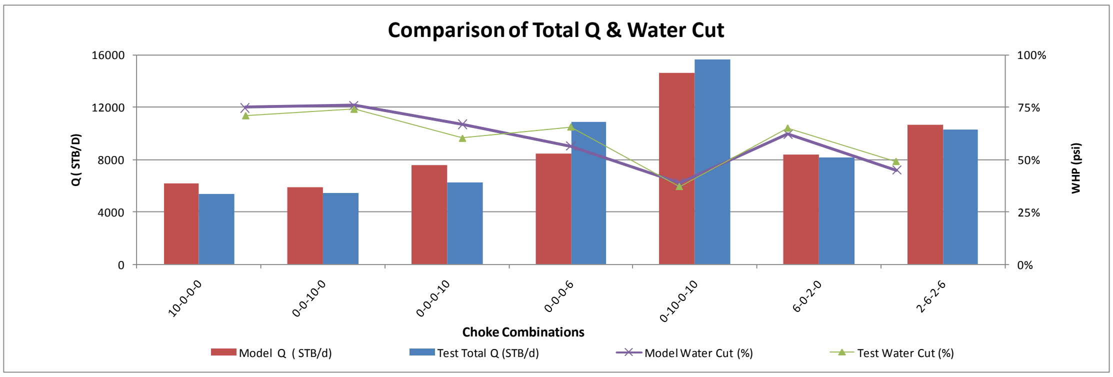

Figure 5.32

Quad-Lateral Model Sensitivity Runs Results and Actual Test Data

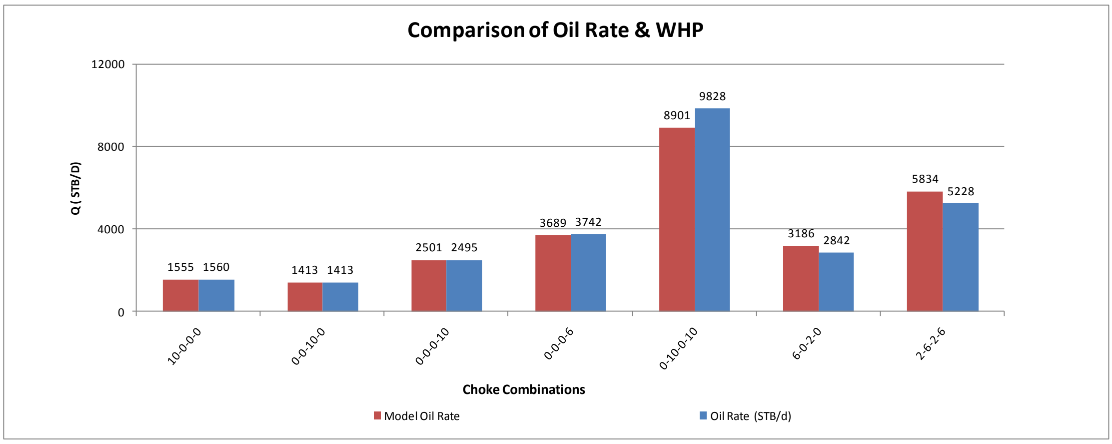

Figure 5.33

Quad-Lateral Model Sensitivity Runs Results and Actual Test Data

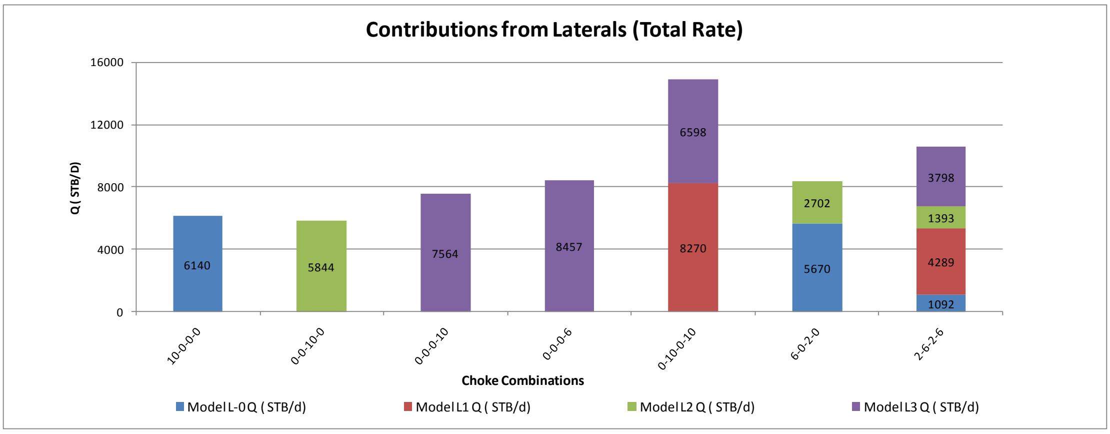

Figure 5.34

Quad-Lateral Model Sensitivity Runs Results and Actual Test Data

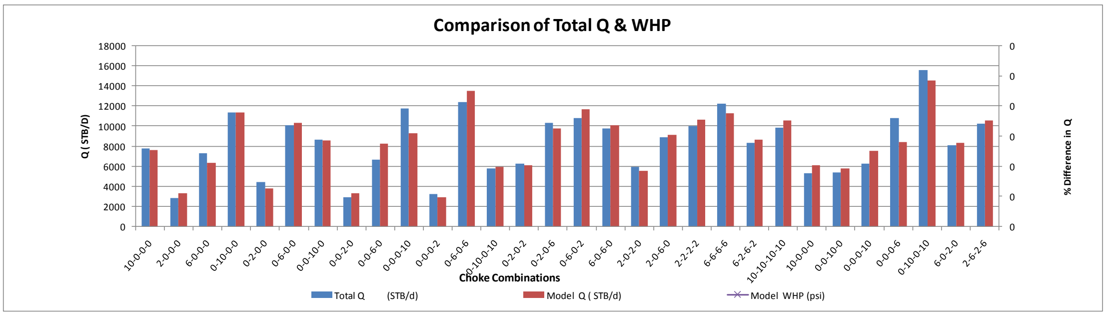

Figure 5.35

Quad-Lateral Well All Actual and Model Results

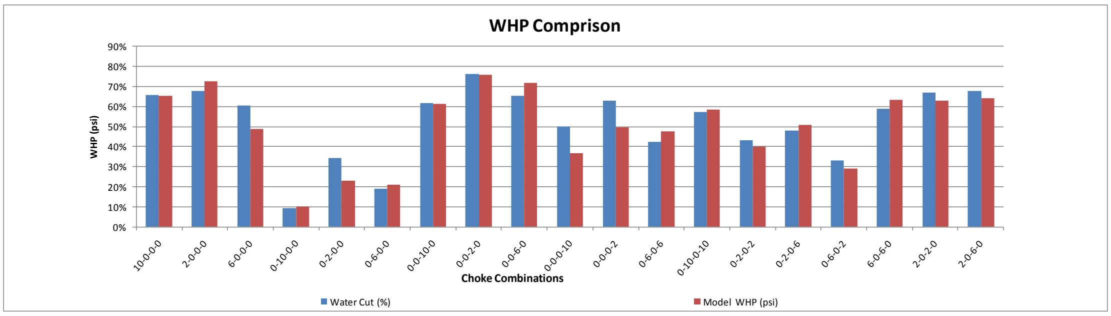

Figure 5.36

Quad-Lateral Well All Actual and Model Results

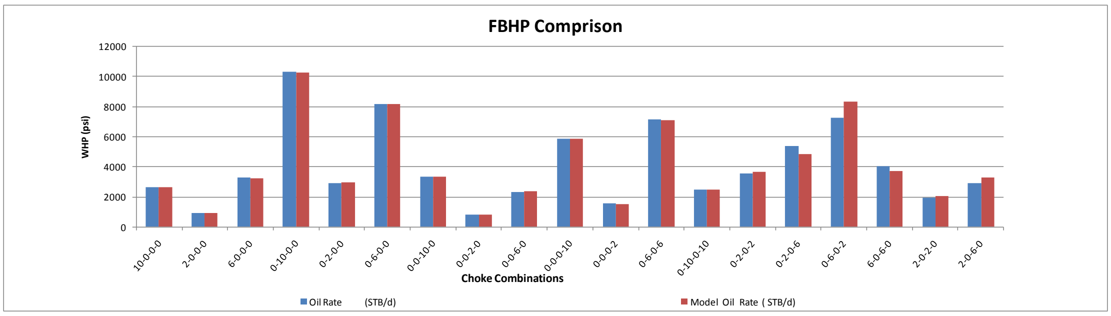

Figure 5.37

Quad-Lateral Well All Actual and Model Results

CHAPTER 6

SUMMARY AND CONCLUSIONS

1. Three models were constructed for three multilateral wells, bi-lateral, tri-lateral and quad-lateral wells. All wells were equipped by downhole valves and a single PDHMS, which was installed above the production packer.
2. Well models were matched and validated using actual test data.
3. Several sensitivity runs were run for all the valves using the validated models. The model rate data were then compared with subsequent actual test data.
4. All actual total rate tests data for the three wells were compared with total rate data produced using the models.
5. The model total rates of all the models were calculated by adding the contribution of their laterals. The contributions from each lateral were recorded for all wells' laterals.
6. Actual and model data were utilized to determine the allocation rates and were verified at a wide range of downhole valve positions and flow rates.
7. The identified allocation factors for the rates for the three wells were very acceptable.
8. The efforts spent in this study can fit as a component in a workflow or a system to ensure proper rate back allocation for a total field, hence provide better field understanding and monitoring capabilities.

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VITAE

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Experience:	Is a supervisor in the Reservoir Management Department in Saudi Aramco, and a specialist in real-time reservoir management (RTRM), intelligent fields, and advanced completions. He has been involved in the development, the design, and implementation of intelligent fields and various advanced well completion systems. He has more than 18 years of petroleum industry experience, and has written or co-written several technical internal and international publications. He led many technical discussions, and gave several presentations and keynote speeches in events around the world.

In 2009, he received the Middle East Regional Service Award for Management and Information. He has been lately nominated as a finalist in the 2009 World Oil award in the "Innovator Thinkers" category. He served as the 2009-2010 SPE Distinguished Lecturer in Realtime Reservoir Management. In 1992, Al-Mubarak received a B.S. degree in Chemical Engineering from King Fahd University of Petroleum and Minerals (KFUPM), Dhahran, Saudi Arabia. He lately has been granted a patent by the US patent office (US 20090071643A1) and recognized as an SPE Certified Petroleum Engineer.

In January 20, 2011, he was interviewed in a local TV station, Sabah Thaqafiyah. The interview was related to community workshops that he conducted about ambition, success and the power of integrating differences.