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STRESS ENGINEERING SERVICES INC.

HORIZON INCIDENT
FLOAT COLLAR STUDY – ANALYSIS

Report PN 1101198

Prepared for:

BP America Inc.
Houston, Texas

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EXECUTIVE SUMMARY

Background

Stress Engineering Services, Inc. (SES) was contracted by BP America Inc. (BP) to provide consulting support services to the BP incident investigation team relating to the float collar. SES reviewed the well MC252#1 drilling data (specifically the period between 04/19/2010 14:00:00 and 04/20/2010 01:00:00), performed analysis of the Weatherford 7" M45AP float collar (FC) and related equipment, and conducted various tests on specimens of the float collar. This document summarizes the analysis tasks including the drilling data interpretation. The test results are documented in a separate SES report [Ref. 1].

SES performed strength calculations for the float collar and reamer shoe based on proprietary data provided by Weatherford. These Weatherford data and calculations based on these Weatherford data cannot be included in this report to BP without the consent of Weatherford. This report presents a summary of the minimum calculated capacities.

Drilling Data Interpretation

Drilling data indicate that Well 252#1 experienced a blockage that prevented the float collar from converting during steady-state flow. The presence of a blockage is supported by the data from as early as the time when the diverter was closed using the Allamon ball, up to the last attempt to convert the float collar. While it is not known where the blockage was located, the data suggest that the blockage was located at or below the float collar. BP excluded the possibility of a blockage downstream from the reamer shoe (in the annulus) because the higher pressure would have fractured the formation.

The steady-state flow rate required to convert the float collar was provided by Weatherford and was confirmed by SES through physical testing as generally accurate for 14-ppg fluid. Based on a review of the data, the recorded flow-in rate was never high enough to have converted the float collar. However, it is possible that the float collar converted from increased transient flow during one of two flow surge events.

The drilling data recorded two flow surge events:

1. Flow Surge #1 after a 3121-psi pressure spike with 42 gpm flow-in and 486 gpm peak flow-out – last attempt to convert (04/19 16:17:35)
2. Flow Surge #2 after a 2900-psi pressure spike with 179 gpm flow-in and 295 gpm peak flow-out – attempt to burst bottom plug (04/20 00:25:00)

Drilling data measured during periods of uniform flow-in and flow-out after Flow Surge #1 indicate that the float collar had converted.

It is unknown why a pressure of 2900 psi was apparently required to burst open the bottom plug port. Based on the Weatherford data, the expected pressure to burst one of the bottom plug's two 2" ports is 900–1100 psi (primary burst tubes). Incidentally, the bottom plug has a (separate) secondary burst tube with a burst pressure of 2500–3000 psi, but this secondary tube is deactivated whenever the top plug is not attached. This high pressure (2900 psi preceding Flow Surge #2) might have been an indication of another blockage at or below the float collar.

Component Strength Analysis Results

The reamer shoe and float collar should have sufficient strength to sustain the measured loads during the period encompassing preparing to convert the float collar, circulating prior to cementing, and cementing (timeline between 04/19/2010 14:00:00 and 04/20/2010 01:00:00). The calculated conversion load (pressure) was lower than Weatherford's published data.

The sealability of the float collar and the flow characteristics before, during, and after conversion were investigated by physical testing.

Flow Surge Events – Flow Calculation Results

Since the actual flow rates through the float collar during these flow surge events are not known, SES conducted flow rate simulations based on the known field conditions in Well MC 252#1. These calculations were also used in the design of a test configuration that would supply an equivalent (or conservative) flow rate to simulate a flow surge to determine whether conversion could have occurred in the field during a flow surge. Two parallel analytical efforts were undertaken by SES to estimate the float collar flow surge: a Method of Characteristics (MOC) approach and a Time Domain (TD) method. Both methods were found to produce similar results for all simulations.

The simulation results showed that the decays of drill-pipe pressure for Flow Surge #1 and #2 are more closely aligned with calculated results for a converted float collar.

For Flow Surge #1 with an unconverted float collar, the two simulation methods predicted a similar peak flow rate (about 11 bpm). However, the flow rate decay for the test facility is more rapid than that predicted for Well 252#1, meaning that a test based on these simulated results will be conservative. The measured test data for a rehearsal test with a simulated auto-fill tube confirmed the predicted flow rates.

For both flow surge events, the flow calculations predicted a higher peak flow rate (about 30 bpm) if the float collar was assumed to have already converted prior to the surge. However, test configurations available during the program were not able to attain a peak flow rate of this magnitude due to flow frictional losses.

Test Results

Conversion tests of the float collar with steady-state flow rates confirmed that the Weatherford conversion equation is generally accurate for 14-ppg fluid.

Physical testing indicated that the float collar is expected to have converted during Flow Surge #1. The Flow Surge #1 test peak flow rate was equal to that predicted for the Well 252#2 float collar by flow calculations.

Tests that simulated a second flow surge after conversion did not cause damage to the converted float collar valve flappers. However, as stated, the test setup could not simulate the field conditions of Flow Surge #2 accurately enough to be conclusive. Flow frictional losses at the accumulator dip tube, burst disc (not opening fully), and the Chiksan connections contributed to reducing the achievable test peak flow rate from the calculated 30 bpm to about 13 bpm.

LIMITATIONS OF THIS REPORT

The scope of this report is limited to the matters expressly covered. This report is prepared for the sole benefit of BP. In preparing this report, Stress Engineering Services, Inc. (SES) has relied on information provided by BP America Inc. and Weatherford International Ltd. Stress Engineering Services, Inc. (SES) has made no independent investigation as to the accuracy or completeness of such information and has assumed that such information was accurate and complete. Further, Stress Engineering Services, Inc. (SES) is not able to direct or control the operation or maintenance of the Client's equipment or processes.

All recommendations, findings and conclusions stated in this report are based upon facts and circumstances, as they existed at the time that this report was prepared. A change in any fact or circumstance upon which this report is based may adversely affect the recommendations, findings, and conclusions expressed in this report.

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1. INTRODUCTION

Stress Engineering Services, Inc. (SES) was contracted by BP America Inc. (BP) to provide consulting support services to the BP incident investigation team relating to the float collar. SES reviewed the well MC252#1 drilling data, performed analysis of the Weatherford 7" M45AP float collar (FC) and related equipment, and performed tests on identical model float collars. This document summarizes results for the analysis tasks including the drilling data interpretation. Test results are provided in a separate SES report [Ref. 1].

BP provided drilling data to SES in electronic format along with various documents describing the construction steps for well MC252#1. SES focused on the timeline involved in preparing to convert the float collar, circulating prior to cementing, and cementing. This encompasses the period between 04/19/2010 14:00:00 and 04/20/2010 01:00:00. The drill-pipe data were provided in 5-sec intervals (possibly time-averaged), while the cement data were provided at 1-sec intervals. SES reviewed the field data to identify points of interest that may help in understanding the status of the well (blockage, etc.) and help determine the state of the float collar (converted or not, structural integrity, etc.). Data interpretation also provided a means to identify areas where additional analysis and physical testing might be needed.

BP also provided documents from Weatherford on the float collar equipment, the dual wiper plug cementing system (DWP-NR System), and various other drawings.

SES performed strength calculations on the float collar based on proprietary data provided to SES by Weatherford. The Weatherford data and calculations based on the Weatherford data cannot be included in this report to BP without the consent of Weatherford. This report provides only a summary of the minimum calculated capacities.

Flow calculations were performed to investigate the float collar flow rate during two identified flow surge events. Two independent analytical methods were pursued to predict the field float collar flow rates and to help design a test setup that would conservatively test whether the float collar was expected to have converted during these events. These methods are described in Sections 6 and 7.

Sealability of the float collar and the flow characteristics before, during, and after conversion were investigated by physical testing.

Documents and data received by SES are described in Section 2. Results of interpretation of the drilling data are provided in Section 3. Results of the strength evaluation of the float collar and reamer shoe are provided in Section 4. Section 5 provides a summary of field data and conditions used to develop the flow simulations. Flow simulation results using Method 1 are described in Section 6, and those using Method 2 in Section 7. A general comparison of results from the analyses and tests is provided in Section 8.

2. DOCUMENTS AND DATA

SES received various documents and data from BP and Weatherford.

BP provided drilling data and documents describing the well configuration, as well as Weatherford documents on the float collar equipment, the dual wiper plug cementing system (DWP-NR System), and various other drawings. Documents provided by BP are listed in Appendix A.

Weatherford provided "confidential and proprietary" drawings and material specifications through their law firm, Jones & Walker. These documents display a unique "WFT…" identifier on each of the pages. The Weatherford-provided documents are listed in Appendix B with their reference identifier.

2.1 CONFIDENTIALITY AND PROTECTION OF PROPRIETARY DATA

BP provided SES with confidential flow data and details on the well configuration and sequence of events leading up to the incident. BP also provided SES with selected documents provided to BP by Weatherford.

Weatherford provided to SES "confidential and proprietary" drawings and material specifications through their law firm. Weatherford provided three packages through Jones & Walker (June 30, July 15, and August 2). Weatherford provided most of the data needed to perform hand calculations and/or analysis. The only exception was the auto-fill tube, for which Weatherford did not provide yield or tensile data, or details of the auto-fill tube composite construction. Therefore, FEA with material anisotropy and non-linearities could not be performed. Weatherford provided only enough constitutive model data to enable performing an elastic isotropic analysis. Mechanical testing was used as an alternative approach to assess the auto-fill tube.

Calculations performed by SES are based on confidential and proprietary data provided by BP and Weatherford. Weatherford was not shown BP data, analyses, or documents, or SES documents derived from such data. As part of this report, BP is provided with a summary of results without disclosing Weatherford confidential and proprietary data.

SES is able to reference specific items noted in the Weatherford drawings provided by BP since BP already has access to these documents. The same is not true for drawings and data that were unique to the documents provided to SES by Weatherford through their lawyer.

The Weatherford data and calculations using the Weatherford data cannot be provided to BP without the consent of Weatherford.

2.2 DRILLING DATA DOCUMENTS

BP provided drilling data to SES in electronic format file (Cement Job Data.xls). The file contained data worksheets on "Older HAL Realtime," "HAL Realtime," "Cement Unit," and "Pits." The HAL realtime worksheet provided drill pipe data from 04/19/2010 13:00:00 to 04/20/2010 06:59:55 in 5-sec intervals. It is unclear if the drill pipe data were recorded in 5-sec intervals or whether a 5-sec moving average was calculated and recorded. The "cement unit" worksheet included data from 04/19/2010 15:00:00 to 04/20/2010 07:00:00 in 1-sec intervals. The worksheet "Pits" was recorded at the same period and rate as the cement data. The drill-pipe data labeled "Older HAL Realtime" included data from running the production casing, and provided data from 04/18/2010 00:00:00 to 04/19/2010 16:00:00 in 5-sec intervals.

BP also provided the following BP documents:

1. Timeline Animation for 5-25-10 Presentation.ppt – PowerPoint presentation illustrating a timeline of the events between 04/09/2010 and 4/20/2010 21:14.
2. Plugs and FC.pps – PowerPoint animation depicting the sequence of events from after running and landing the casing until completing the cement job and releasing the running tool.
3. Macondo_MC 252_1 _Schematic_Rev15 2_04222010_withBOP.xls – Well schematic.

BP also provided the following Weatherford documents:

1. M45AP 7 H513 32 ppf 6 drift.pdf; Drawing D000401284 – Assembly drawing of 7" M45AP float collar, mid bore, 5–7 bpm (500–700 psi).
2. Mid-bore Auto Fill Float Collar.pdf; File M47A-TU – Brochure of mid-flow auto-fill tube float collar model M47A0. BP stated that the model used in the well was M45AP, which includes the ball and a ball cage.
3. DWP ELAS-TU-006 N-R Rev B 3-31-2010.pdf; File ELAS-TU-006 – Brochure of dual wiper plug cementing systems (DWR-NR System).

2.3 REAMER SHOE DATA

The 7" CSG × 8¼" reamer shoe is located at the bottom of the production casing at about 18,304 ft MD, which is 190 ft below the float collar. Between the float collar and reamer shoe, there are a number of Q125 casing joints threaded with 7" 32 ppf TenarisHydril Wedge thread connectors. The reamer shoe body, threaded to the lowest casing joint and supporting the reamer shoe nose, is constructed of P110 material (WFT000480-486).

2.3.1 Reamer Shoe Drawings and Data Provided by BP

BP provided SES with Weatherford drawings for the guide shoe and reamer shoe. BP stated that the reamer shoe was used in this well, while the guide shoe was not. BP provided file WFT000480(L0093330).pdf containing Weatherford documents WFT000480-486 of the reamer shoe. Drawing 01211284 (WFT000481) shows the reamer shoe assembly containing three components: body, nose, and baffle plate. Document WFT000480 states that the reamer shoe nose has three 40-mm diameter circulation ports. The reamer shoe is threaded to the reamer shoe body.

2.3.2 Reamer Shoe Drawings and Data Provided by Weatherford

Weatherford provided three packages with "confidential and proprietary" drawings and material specifications through their law firm, Jones & Walker (June 30, July 15, and August 2). Weatherford provided data necessary for performing hand calculations and/or analysis.

2.4 FLOAT COLLAR DATA

The 7" M45AP float collar is located at about 18,114 ft MD, which is 190 ft above the bottom of the casing string and/or reamer shoe. The float collar joint containing the float collar components is 2½ ft long. The float collar is connected to the casing joints above and the reamer joints below with 7" 32 ppf TenarisHydril Wedge thread connectors constructed of HCQ125 material. The 7" casing joints above and below the float collar are constructed of HCQ125 material.

2.4.1 Float Collar Drawings and Data Provided by BP

BP provided SES with various Weatherford drawings for the float collar. BP provided file "WFT000526(L0093335).pdf" containing Weatherford documents WFT000526-528 for the float collar. Drawing D000401284 (WFT000528) shows the float-collar assembly containing several components:

- Float Collar Shell (7" 32 ppf, Hydril 513, 7.055" OD, 6.151" ID, 30" long)
- Wiperlok System Plate
- Wiperlok System Extension
- Ball Retainer Assembly
- 2" Diameter Weighted Ball
- 6.070" OD Upper Seat Valve with Flapper Plate Assembly
- Autofill Tube 5–8 bpm Assembly
- 6.070" OD Lower Seat Valve with Flapper Plate Assembly
- Cement

Document WFT000528 states that the float collar auto-fill tube has two 37/64" diameter side ports. This version of the float collar ships with a 2" ball that is held in the float collar by a ball cage at the top and a tube ballseat (1.93" ID opening) at the bottom of the 2.19" ID auto-fill tube.

Document WFT000527 states that the flapper valves are made of aluminum, there are four brass shear screws securing the auto-fill tube, the body (shell) is made of HCQ125, and that the body burst pressure and collapse pressure ratings are 14,160 psi and 11,710 psi, respectively.

2.4.2 Float Collar Drawings and Data Provided by Weatherford

Weatherford provided "confidential and proprietary" drawings and material specifications to SES through their law firm, Jones & Walker, in three separate packages (June 30, July 15, and August 2). Weatherford provided most of the data needed to perform hand calculations and/or analysis. The only exception was the auto-fill tube, for which Weatherford did not provide yield or tensile data, or details of the auto-fill tube composite construction. Therefore, FEA with material anisotropy and non-linearities could not be performed. Weatherford provided only enough constitutive model data to enable performing an elastic isotropic analysis.

2.4.3 Float Collar Conversion

One of the most important points of interest of the investigation is whether the float collar flow rate was sufficient to convert the float collar. Conversion of a float collar refers to the separation of the auto-fill tube from the float collar bore, which allows the two float collar flapper valves to close. Conversion requires sufficient pressure differential across the float collar auto-fill tube to shear four screws at the top of the auto-fill tube, which allows the tube to clear the valves. The pressure differential is supplied by orifice flow through two 37/64" side auto-fill ports, with the axial through-flow blocked by a 2" ball restrained at the bottom 1.93" ID opening (tube ballseat) of the auto-fill tube.

Based on Weatherford labeling on the 7" M45AP float collar drawing D000401284, conversion should occur at a flow rate of 5–7 bpm, which should generate a pressure differential of 500–700 psi. Based on Weatherford conversion data in document M47A-TU (brochure of Mid-flow auto-fill tube float collar model M47A0), the conversion equation for an auto-fill tube with two 37/64" ports is as follows:

$$Q = \sqrt{\frac{P}{1.259\rho}}$$

where Q = flow rate in bpm

P = conversion pressure in psi

ρ = fluid density in ppg

Therefore, conversion for 14-ppg fluid should occur between 5.33 bpm (for 500 psi) and 6.30 bpm (for 700 psi). The Weatherford document also shows that the pressure drop through a converted M45AP float collar with a flow of 5 bpm is expected to be less than 10 psi.

The conversion flow rate and associated pressure drops were confirmed as generally accurate for 14-ppg fluid by steady-state flow rate testing. Details are provided in the SES test report.

3. DRILLING DATA INTERPRETATION

BP provided drilling data to SES in electronic format, as well as documents describing the construction steps for well MC252#1. SES focused on the timeline involved in preparing to convert the float collar, circulating prior to cementing, and cementing. This corresponds to the period between 04/19/2010 14:00:00 and 04/20/2010 01:00:00. SES reviewed the data to identify points of interest that may help the team to understand the status of the well (blockage, etc.) and help determine the state of the float collar (converted or not, structural integrity, etc.). Data interpretation had potential to highlight areas where additional analysis and physical testing were needed.

The points of interest were separated into two categories: (1) specific noteworthy events and (2) general noteworthy events. Specific events are tied to a discrete period of time, while the general events are based on general observations for the overall data set.

3.1 SPECIFIC NOTEWORTHY EVENTS

The drilling data were plotted against time (Figure 3.1 through Figure 3.13) and against cumulative flow-in (Figure 3.14 through Figure 3.17). Figure 3.1 shows the drilling data during running of the 7" × 9⅞" production casing string. Figure 3.2 shows an overall view of the time period including closing of the diverter with the Allamon ball, attempts to convert the float collar, circulating prior to cementing, and cementing up to the apparent bumping of the top plug at the float collar location. Figure 3.3 shows a more detailed view of the events prior to cementing.

3.1.1 Production Casing String – 10-kip Load at 18,218 ft (Casing Running)

The 7" × 9⅞" production casing string was run between 04/18/2010 00:00:00 and 04/19/2010 14:00:00. BP noted that the only time the casing "took weight" was toward the end of the casing run at 18,218 ft when the casing string was under a load of about 10 kip. The casing run data are plotted in Figure 3.1.

The 10-kip load represents a possible reamer shoe load. This compressive load was considered in the strength checks for the reamer shoe components.

The source of the blockage that was observed during the attempts to convert the float collar is unknown. It is unknown whether this event could have contributed to the blockage by plugging the three reamer shoe holes.

3.1.2 Residual Drill-Pipe Pressure while Closing and Testing Allamon Diverter

After the production casing was run, the casing and drill-pipe bore was to be isolated from the riser annulus by closing the Allamon diverter. This involved dropping a 1.625" diameter ball and sliding the diverter gate from the open to the closed position, and then testing the diverter with the diverter test device. This sequence occurred between 04/19/2010 14:08:00 and 14:18:00 (Figure 3.4).

The data indicate residual drill-pipe (DP) pressure after the two pressure spikes corresponding to the Allamon ball clearing the diverter gate and then the diverter test device. The first and second residual pressures were ~500 psi and ~980 psi, respectively. This 500-psi residual pressure is the first indication of blockage in the system.

During the time between the two pressure plateaus, 1.1 bbl of mud was added to the system. The pressure build-up in the system corresponds to a compressibility of (980–500)/1.1 or about 436 psi/bbl. (This issue is discussed further in the next section.)

During this time, the top and bottom plug are supported below the diverter, and they are in the path of the Allamon ball. The minimum internal diameter of the plugs is 1.78", which is larger than the Allamon ball diameter (1.625"). While the clearance is small, it should not cause a blockage.

The Allamon ball is expected to find its way to the top of the float collar ball cage. The Allamon ball, when resting at the top of the float collar, is expected to reduce the effective flow area at that location. Selected physical tests including the Allamon ball would include the effect of the

Allamon ball on the flow and pressure drop across the float collar. Tests of the float collar marked as SN-04 reported in the SES test report [Ref. 1] included the Allamon ball at the top of the float collar.

3.1.3 Compressibility Change after Testing Allamon Diverter

Between the time the diverter was first closed and the time it was tested, the system exhibited a different compressibility as compared to subsequent events with presumed blockage. Specifically, during the first drill-pipe pressure increase (2330 psi, see Figure 3.4), with the ball against the closed diverter gate, the compressibility was ~2735 psi/bbl. During the second drill pipe pressure increase (2681 psi), with the ball against the diverter test device, the compressibility was ~2202 psi/bbl.

However, as mentioned in the previous section, the compressibility with no blockage at the diverter is significantly lower (~436 psi/bbl). Furthermore, there are several other instances of apparent blockage with consistent compressibility values of near 360 psi/bbl. This level of compressibility occurred during each of the nine attempts to convert (see Figure 3.2 through Figure 3.7) and was similar to that observed when the bottom plug (~345 psi/bbl) and the top plug (~356 psi/bbl) were believed to have bumped at the top of the float collar (see Figure 3.11). Based on the available data, a compressibility of 436 psi/bbl is not significantly different from ~360 psi/bbl.

The significant difference in compressibility between blockage at the diverter (Allamon ball at diverter) and blockage at the top of the float collar (top or bottom plug at top of float collar) suggests that a compressibility of about 360 psi/bbl may indicate blockage at or below the float collar. Comparison of the compressibility values between (1) when the Allamon ball cleared the diverter and the test device, (2) at each of the attempts to convert the float collar, and (3) the presumed blockage at the top of the float collar, suggests that the blockage during those events was at or below the float collar. However, there is not enough detail in the available drilling data to distinguish between blockages at the float collar or the reamer shoe.

BP stated that the blockage could not have occurred downstream from the reamer shoe because the higher pressure would have fractured the formation. Therefore, attention was focused on presumed blockages in the bore of the production casing or tubing.

3.1.4 Initial Flow-in Rate Insufficient to Convert Float Collar

As stated in Section 2, Weatherford's published data for float collar conversion flow rates indicate a minimum flow rate of 5.3 bpm for 14-ppg fluid. The initial (flow-in) flow rate during the first attempt to convert was 43 gal/min (~1 bpm), which is significantly lower than the conversion flow rate. In fact, the flow-in data indicate that the flow-in rate never exceeded the minimum conversion flow rate during the period of time under consideration (04/19/2010 14:00:00 and 04/20/2010 01:00:00).

The flow-out data indicate that the flow-out rate was, for a short time, higher than the conversion flow rate. The flow-out comprises flow returns, bypass flow, decompression of fluid, or flow from the formation. There is no absolute confirmation where the flow-out originated. There is also a delay between flow-in and flow-out recorded data. It is not clear whether this delay is real, or if this is an artifact of how and from where the data were gathered and recorded.

Increased drill-pipe pressure is not sufficient in itself (in most cases) to convert the float collar. What is needed to convert the float collar is sufficient differential pressure across the auto-fill tube. This is accomplished by increasing the flow rate through the unconverted float collar. The float collar will not convert from increased drill-pipe pressure if there is:

- *Blockage at the reamer shoe.* In this case, pressure above and below the auto-fill tube are similar, thus, no conversion.
- *Blockage above the float collar.* In this case, pressure end load is supported by the float collar components, thus, no conversion.

One scenario in which drill-pipe pressure would cause conversion is a blockage at the two 37/64" ports of the auto-fill tube. For this case, a drill-pipe pressure of 500–700 psi is expected to cause conversion.

In summary, flow rate though the float collar is almost always required to create the differential pressure that results in conversion. The Weatherford equation (Section 2.4.3) defining the steady-state flow rate required to convert the float collar was confirmed by physical testing as generally accurate for 14-ppg fluid.

3.1.5 Flow Surge #1 after 3121-psi Pressure Spike – Last Attempt to Convert Float Collar

As stated in Section 3.1.4, the flow-in rate never exceeded the conversion rate. However, during the ninth attempt to convert the float collar (04/19/2010 16:17:00 to 16:17:20, see Figure 3.7 and Figure 3.8), a (flow-out) flow surge occurred. During this conversion attempt, the flow-in rate was maintained at 43 gpm. The drill-pipe pressure reached 3121 psi, at which point the pressure decreased rapidly to about 135 psi. Flow-out increased rapidly to approximately 486 gpm and then decreased to about 2 times the flow-in rate 60 seconds after the surge peak rate. This is a short-duration event that was recorded at 5-sec intervals (or time-averaged). Consequently, it is possible that a significantly higher flow-out peak rate occurred but was not captured in the recorded data. The mud weight below and above the float collar was 14 ppg.

The expected conversion flow rate is 5.3 bpm (223 gpm) based on 500-psi conversion pressure and 14-ppg mud.

As described in Section 3.1.3, the compressibility data for this pressure spike (~360 psi/bbl) suggest that the apparent blockage was approximately at or below the float collar. If the blockage were located at the top of the float collar or at the reamer shoe, then conversion would depend on the subsequent flow surge, since pressure alone would not have caused the conversion. If the blockage were at the auto-fill tube, then conversion would have occurred at a pressure differential of 500–700 psi, even without flow.

The float collar flow rate during this event is not known. Calculations were performed for the well field conditions to determine the float collar flow rate. The same calculations were performed to help design a test setup to match or define a conservative flow rate to verify if conversion could have occurred.

3.1.6 Flow Surge #2 after 2900-psi Pressure Spike – Attempt to Burst Bottom Plug

Toward the end of the cementing operation, the bottom plug burst tube was presumed to have burst (04/20/2010 00:23:00 to 00:28:00, see Figure 3.11 and Figure 3.12), resulting in a (flow-out) flow surge. During the cementing operation, the flow-in rate was maintained at ~180 gpm. The drill-pipe and cement pressure reached a peak value of ~2900 psi, at which point the pressure decreased rapidly to about 500 psi. Flow-out increased rapidly to approximately 295 gpm and then decreased to near the flow-in rate 48 seconds after the surge peak rate. This is a short-duration event recorded at an interval of 5 sec (or time-averaged). It is therefore possible that a significantly higher flow-out peak rate occurred and was not captured. The cement data were recorded at 1-sec intervals, but did not include flow-in or flow-out rates.

The fluid weight below the float collar was 14 ppg and immediately above the float collar was 16.7 ppg. Above the 8 bbl of heavy cement (16.7 ppg) and up to the top plug, there were about 60 bbl of lighter nitrified cement (14.5 ppg). Above the top plug, there was 14-ppg mud. Therefore, during this surge event, the fluid flowing through the float collar was 16.7-ppg cement.

With the blockage (bottom plug) located at the top of the float collar, possible conversion (if it had not already occurred) may depend on the subsequent flow surge, since pressure alone would not have caused conversion. The (Weatherford) expected conversion flow rate is 4.9 bpm (205 gpm) based on 500-psi conversion pressure and 16.7-ppg mud. This set of parameters was not verified by physical testing, but the equation (Section 2.4.3) was confirmed by physical testing as generally accurate for 14-ppg fluid. It is expected to be fairly accurate for 16.7-ppg fluid.

It is not known why a pressure of 2900 psi was apparently required to burst open the bottom plug port. Based on Weatherford's data, the expected pressure to burst one of the bottom plug's two 2" ports is 900–1100 psi (primary burst tubes). Incidentally, the bottom plug has a (separate) secondary burst tube pressure of 2500–3000 psi, but this secondary tube is deactivated whenever the top plug is not attached.

As described in Section 3.1.3, the compressibility data for this pressure spike (~345 psi/bbl) helped define the possible location of the apparent blockage for other apparent blockage events, such as the attempts to convert the float collar and the bottom plug bumping.

A scenario where there is a separate blockage at or below the float collar just prior to bottom plug bumping at the top of the float collar (similar to the blockage during conversion attempts) might explain the higher 2900-psi pressure spike. However, BP stated that, based on their volume-displacement calculations, the bottom plug bumped at the appropriate time.

The float collar flow rate during this event is unknown. Calculations were performed for the (Well 252#1) field conditions to estimate the float collar flow rate (Sections 6 and 7). Calculations to help design a test setup for Flow Surge #2 were not performed, but the setup was not expected to be significantly different from the setup for Flow Surge #1.

3.1.7 Flow-in Almost Equal to Flow-out During Circulation

After the conversion attempts and before the cementing operation, mud was circulated through the system. During this time period (04/19/2010 16:21:00 to 19:30:00, see Figure 3.9), there were three periods of almost constant and equal flow-in and flow-out:

1. 17:00:00 – flow-in, flow-out, and DP pressure are about 180 gpm, 150 gpm, and 350 psi
2. 17:24:00 – flow-in, flow-out, and DP pressure are about 180 gpm, 145 gpm, and 390 psi
3. 19:05:00 – flow-in, flow-out, and DP pressure are about 180 gpm, 145 gpm, and 335 psi

The consistency of pressure/flow data during these three separate circulation events may be used to investigate whether the float equipment had been converted.

The average measured drill-pipe pressure drop was 360 psi and corresponded to an average flow-in rate of 175 gpm. Based on Weatherford's data, the pressure drop through an unconverted float collar is 325 psi (for 175 gpm). However, the BP-estimated system pressure losses are about 300 psi, which includes about 60-psi pressure drop through the surface piping. Therefore, assuming that the Weatherford float collar conversion data are correct, the measured system pressure losses (while flowing with 175 gpm) are too low, which suggests that the float collar had converted.

Based on the Weatherford data, the pressure drop through a converted float collar is less than 10 psi for this flow rate, which was confirmed as generally accurate by physical testing.

3.1.8 Flow-in Almost Equal to Flow-out during Cementing

A similar sequence of events—flow-in similar to flow-out—occurred during cementing operations before and after the bottom plug bumped at the top of the float collar and after the plug burst tube ruptured. During this time period (04/19/2010 23:00:00 to 04/20/2010 00:30:00, see Figure 3.11), there were three periods of almost constant and equal flow-in and flow-out:

1. 04/19 23:15:00 – flow-in and DP pressure are about 180 gpm and 520 psi (prior to bump)
2. 04/20 00:20:00 – flow-in and DP pressure are about 180 gpm and 280 psi (prior to bump)
3. 04/20 00:27:00 – flow-in and DP pressure are about 180 gpm and 300 psi (after burst)

After the bottom plug was presumed to have burst, drill-pipe pressure increased gradually from 300 psi to 430 psi.

Compared to the circulating events (described earlier), for this case there was less consistency in the pressure/flow data, making it more difficult to use these data to investigate whether the float equipment had converted. The inconsistencies in the data may be due to the mixed content (14 ppg, 14.5 ppg, 16.7 ppg) and the presence and movement of plugs and plug darts in the production casing.

3.1.9 Reduced Compressibility at End of Pressure Spikes

Toward the end of the cementing operation, the top plug is believed to have bumped at the top of the bottom plug while the bottom plug was at the top of the float collar (04/20/2010 00:35:00 to 00:38:00, see Figure 3.11). Data for this time period are shown in Figure 3.17 with cumulative (flow-in) flow rate (as opposed to time). The system compressibility (slope of the flow-in line in Figure 3.17) appears to be reduced and level off toward the end of the pressurization despite continued flow-in (at a reduced rate). It appears that the pressure stops increasing (or increases at a very low rate) when the flow-in begins to decrease.

This scenario—drill-pipe pressure leveling off at the end of flow-in—had occurred during other periods of time, including at the end of each attempt to convert the float collar. During the last attempt to convert, there were two times that the pressure was increased prior to the flow surge (see Figure 3.16). Figure 3.14 shows the first attempt to convert the float collar, Figure 3.15 the second attempt, and Figure 3.16 the last attempt. A similar figure can be produced for each attempt. Each of these figures shows the same behavior during the top plug bumping. The compressibility appears to soften and then level off toward the end of the pressurization despite continued flow-in (at a reduced rate).

3.2 GENERAL NOTEWORTHY EVENTS

In addition to the specific noteworthy events described in the previous section, there are various general events noted by SES.

Flow-in Generally Higher than Flow-out during Cementing

Flow-in was generally higher than flow-out; this was especially true during cementing operations (Figure 3.11).

Flow-in Rate is Always Lower than Expected Rate for Float Collar Conversion

The flow-in data indicate that the flow-in rate never exceeded the calculated conversion flow rate during the time period under consideration (04/19/2010 14:00:00 and 04/20/2010 01:00:00).

Flow-in Not Always Followed by Flow-out

Flow-in was not always followed by flow-out. This occurred several times, both prior to the apparent float collar conversion and after the apparent conversion (see Figure 3.5 through Figure 3.7). The flow-out can comprise flow returns, bypass flow, decompression of fluid, or flow from the formation. There is no absolute confirmation regarding the source(s) of the flow-out. There is also a delay between flow-in and flow-out recorded data. It is not clear whether this delay is real, or if this is an artifact of how and from where the data were gathered and recorded.

3.3 CONCLUSIONS REGARDING DRILLING DATA

Review of the drilling data and other documents provided by BP yielded several points of interest. These are described in the paragraphs below.

The presence of a blockage is supported by the data from as early as when the diverter was closed using the Allamon ball, until the last attempt to convert the float collar. It is not known where the blockage was located. The data suggest that the blockage was located at or below the float collar. BP excluded the possibility of a blockage downstream from the reamer shoe (in the annulus), because the higher pressure would have fractured the formation.

The flow rate required to convert the float collar was provided by Weatherford and was confirmed by physical testing. Since the Weatherford data were shown to be generally accurate, then circulation event data (Section 3.1.7) indicate that conversion had occurred. Even though the recorded flow-in was never high enough to have converted the float collar, the float collar could have converted from increased flow during one of the two flow surge events. These flow surge events are characterized by rapid decompression of the fluid resulting from the clearance of a blockage in the flow path.

The drilling data contain two notable flow surge events:

1. Flow Surge #1 after a 3121-psi pressure spike (last attempt to convert)
2. Flow Surge #2 after a 2900-psi pressure spike (attempt to burst bottom plug)

The flow rate through the float collar during these events is unknown. Flow calculations were performed for the (Well 252#1) field conditions to determine the float collar flow rate. The same calculations were performed to help design a test setup to match or define a conservative flow rate to verify if conversion could have occurred. The flow calculations are presented in Sections 6 and 7.

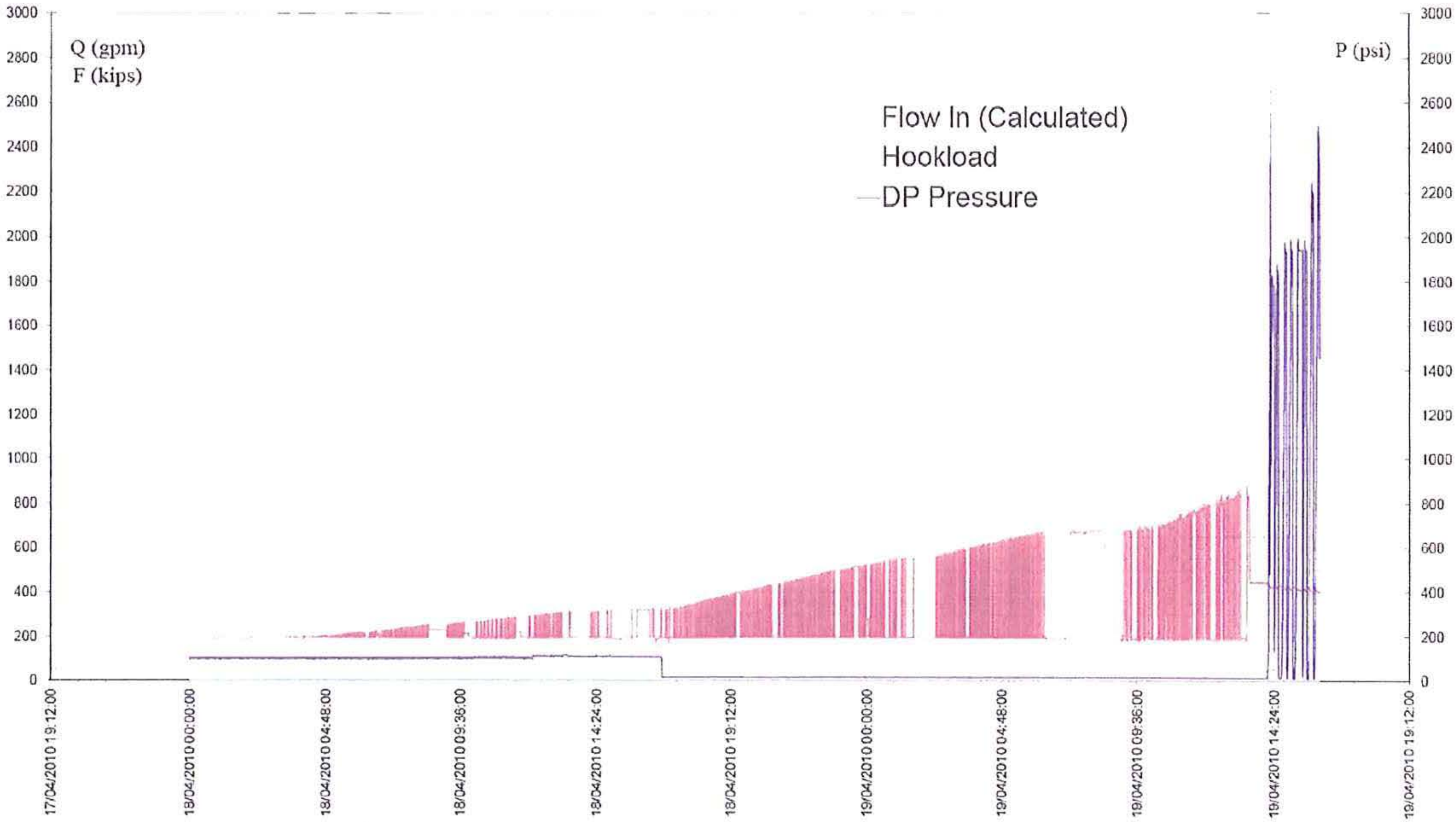


Figure 3.1: Running Casing (Well MC252#1)

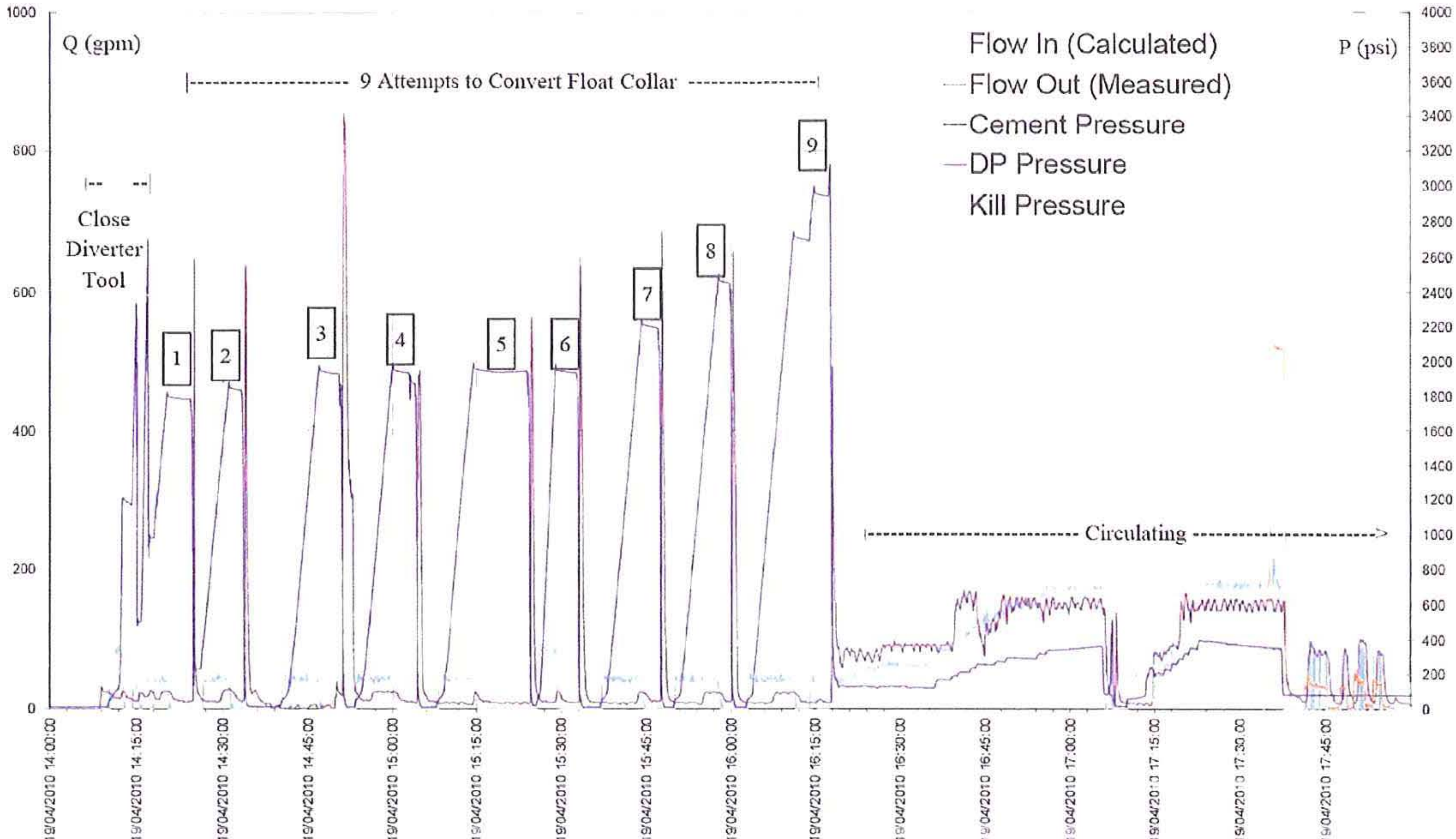
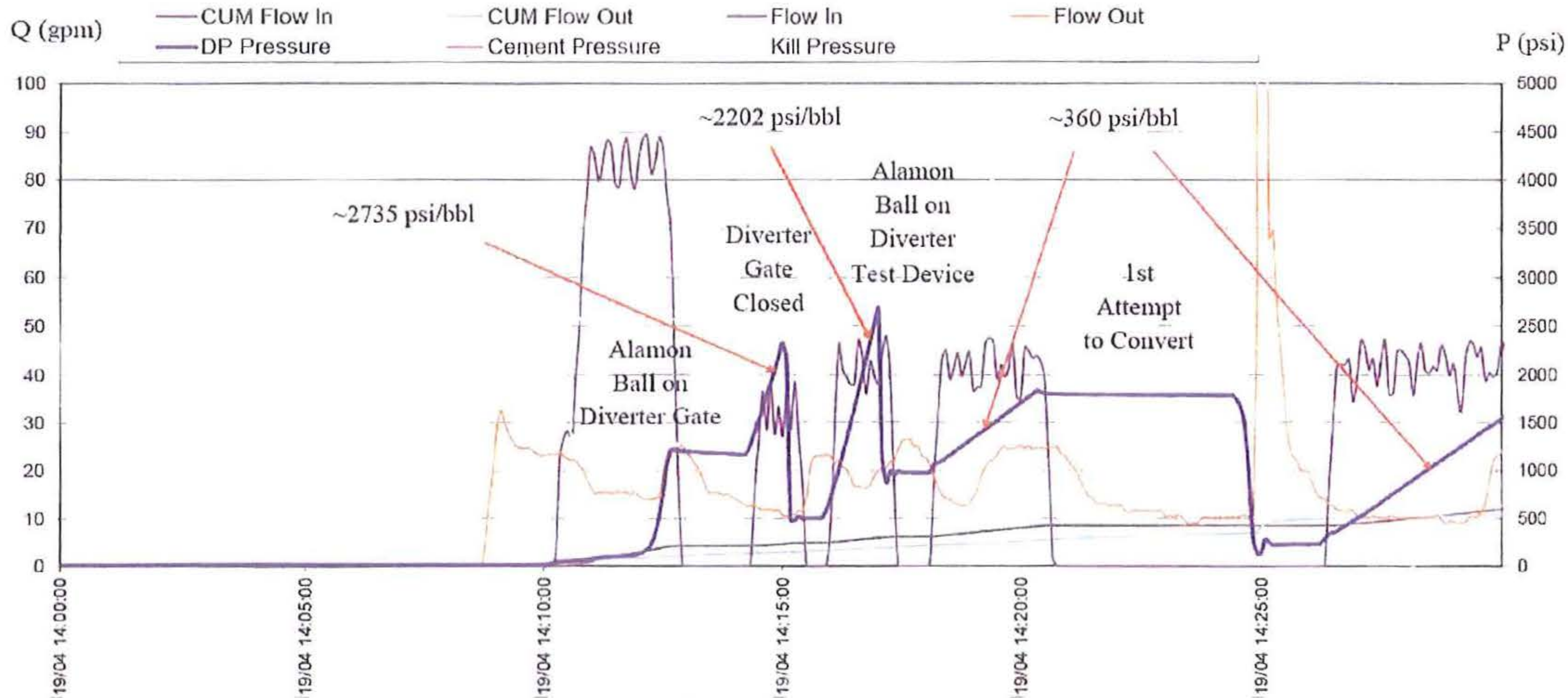


Figure 3.3: Pumping prior to Cementing (Well MC252#1)



After Allamon ball cleared diverter gate and diverter test device, DP pressure does not reduce to zero. Minimum plug ID = 1.78"; Allamon ball OD = 1.625"; Allamon ball is small enough to clear plugs.

Figure 3.4: Closing and Pressuring Diverter (Well MC252#1)

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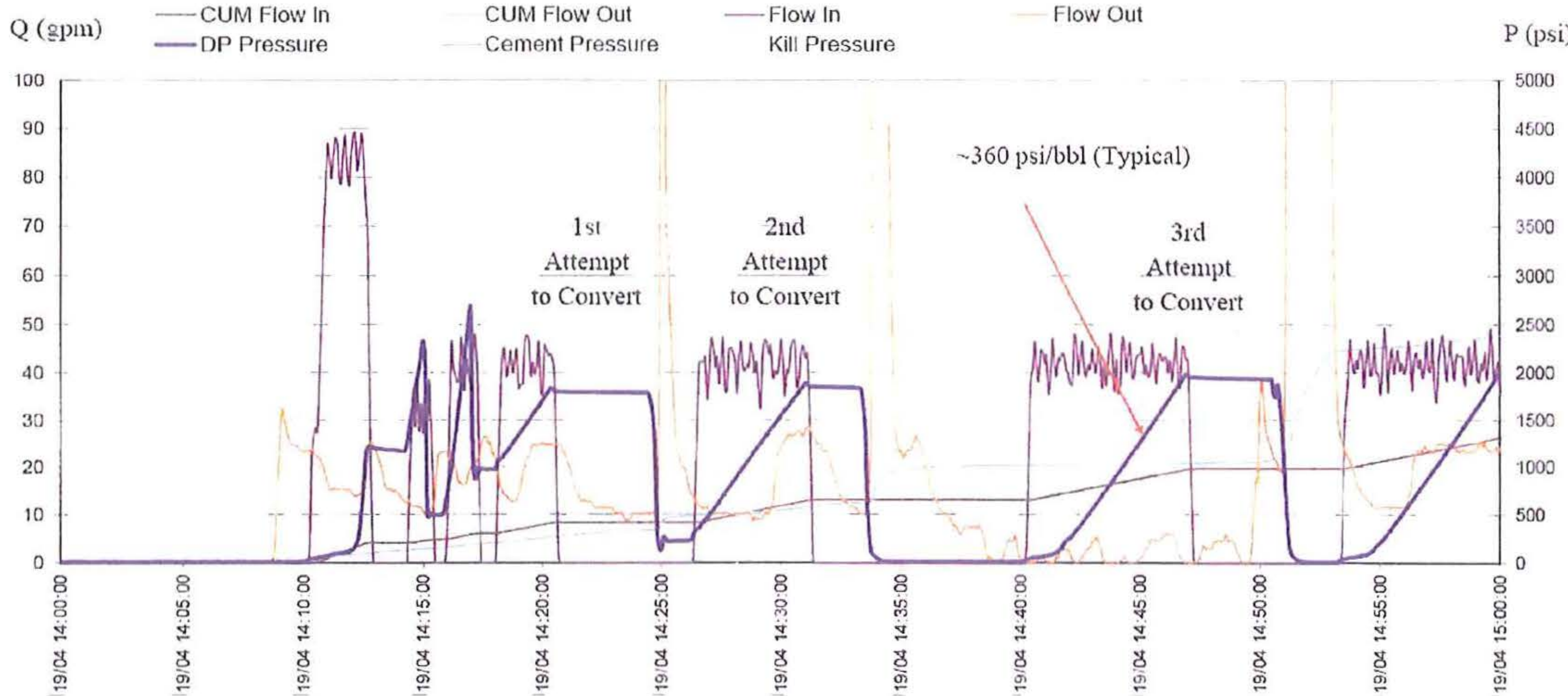
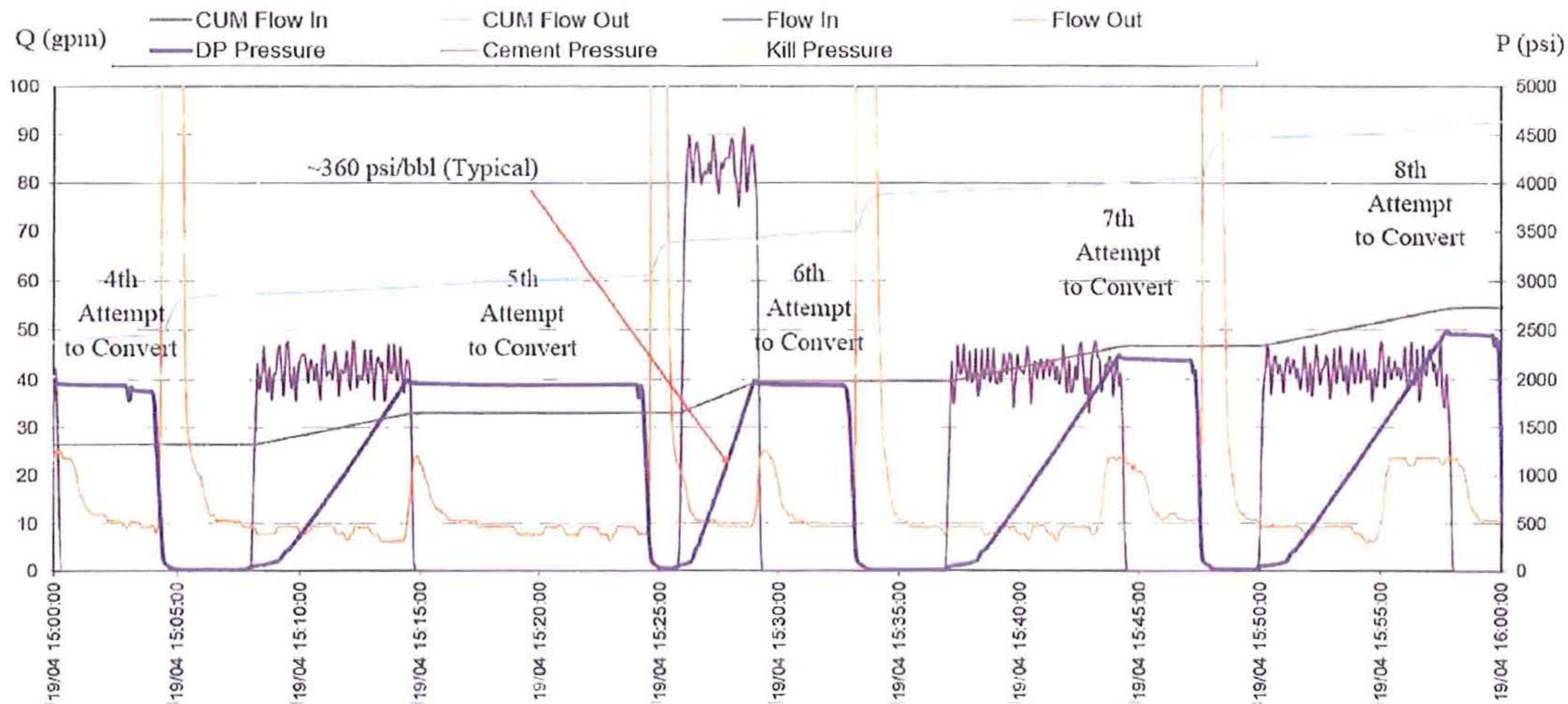


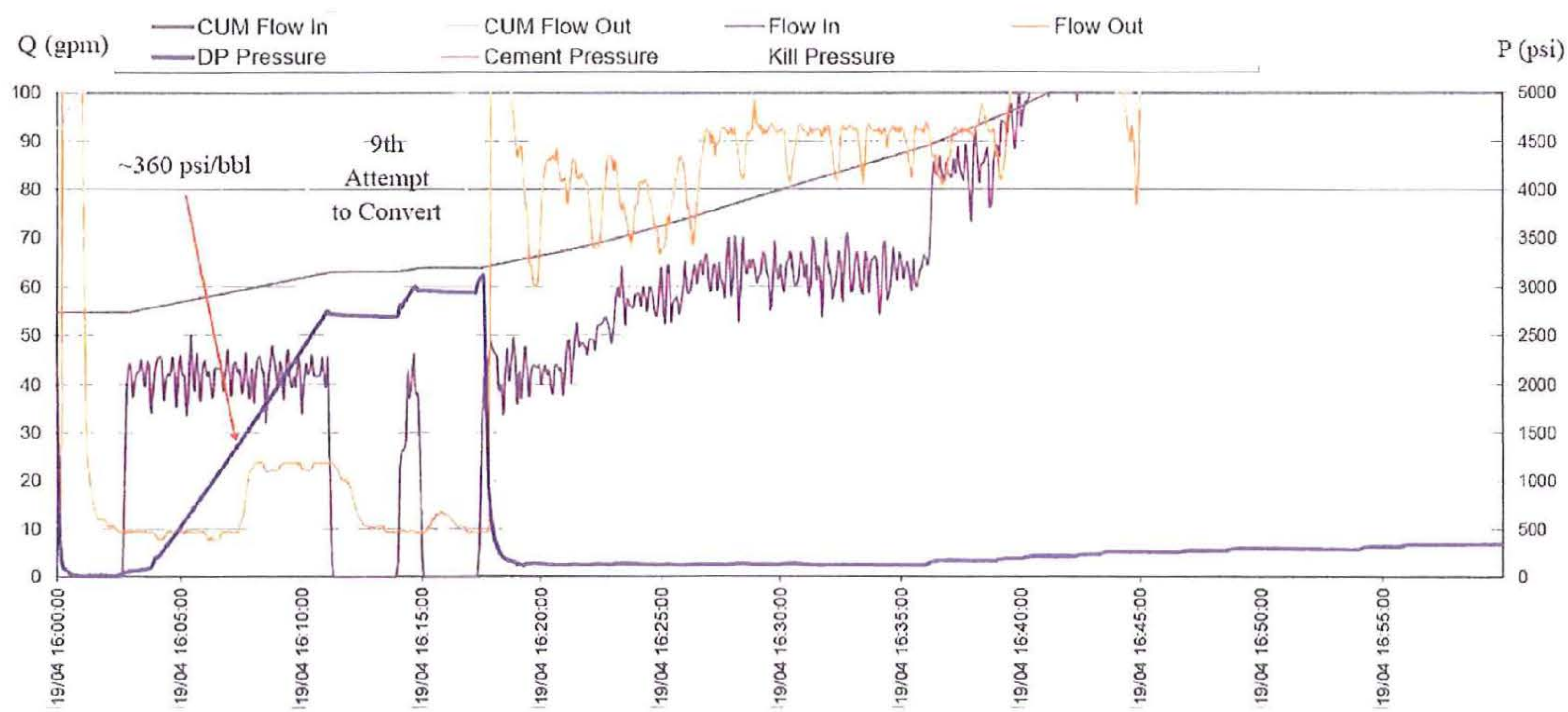
Expected conversion pressure (pressure differential across float collar based on flow) = 500–700 psi.

Figure 3.5: Attempts #1–#3 to Convert Float Collar (Well MC252#1)



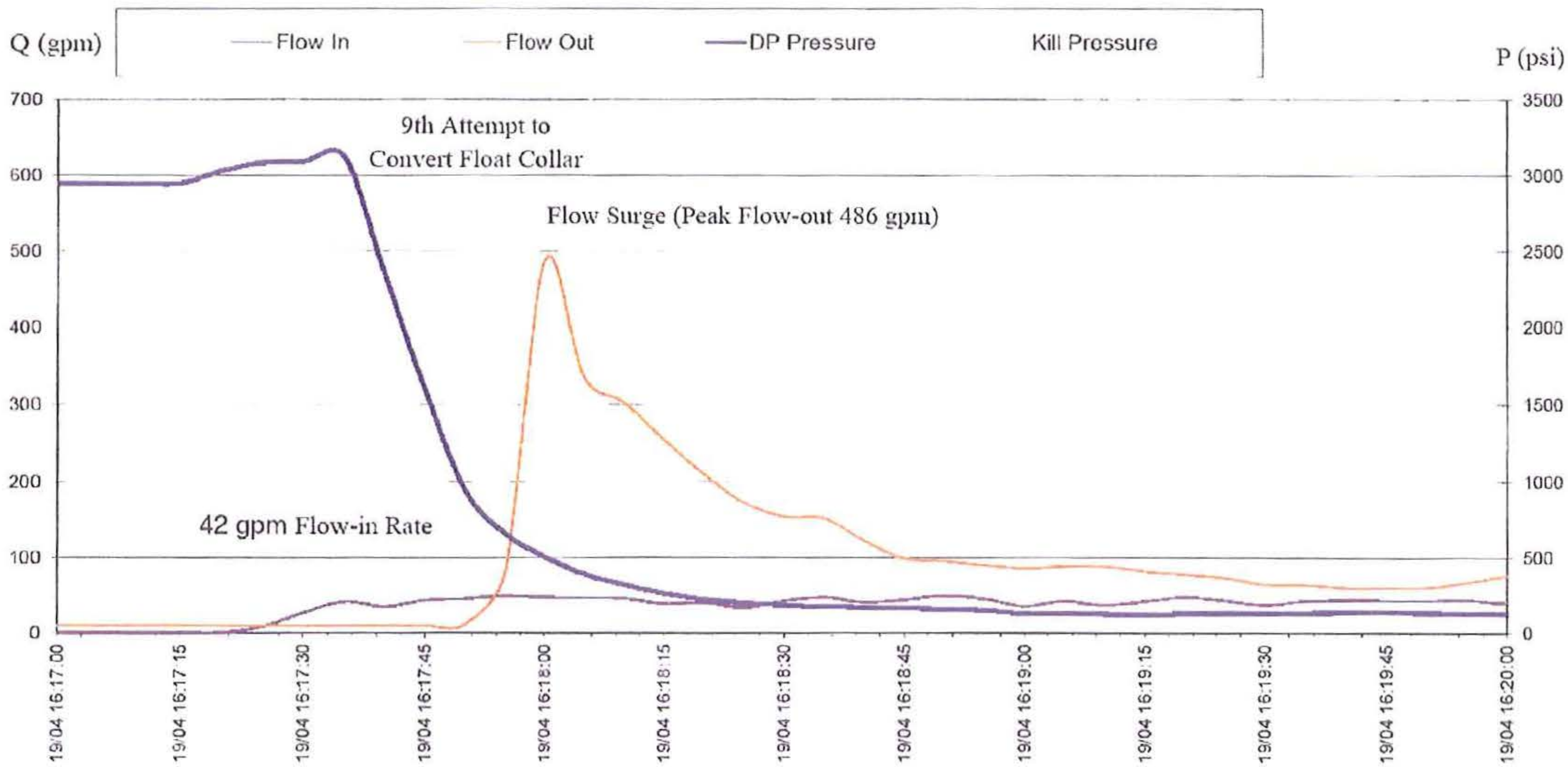
Expected conversion pressure (pressure differential across float collar based on flow) = 500–700 psi.

Figure 3.6: Attempts #4–#8 to Convert Float Collar (Well MC252#1)



Expected conversion pressure (pressure differential across float collar based on flow) = 500–700 psi.

Figure 3.7: Attempt #9 to Convert Float Collar (Well MC252#1)



Expected conversion pressure (pressure differential across float collar based on flow) = 500–700 psi.

Figure 3.8: Flow Surge #1 – Attempt #9 to Convert Float Collar (Well MC252#1)

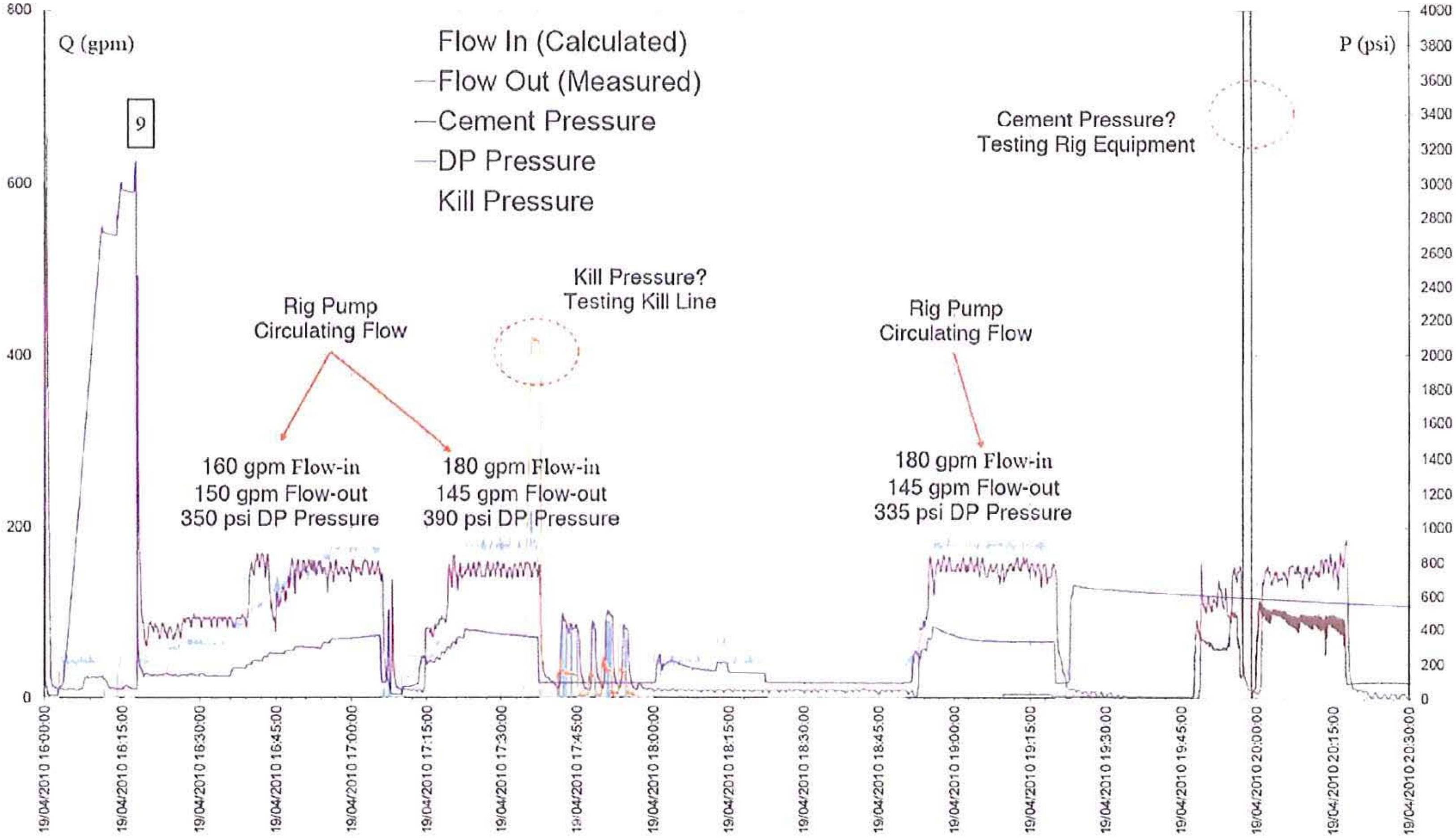


Figure 3.9: Circulating Flow – Periods with Equal Flow-in and Flow-out (Well MC252#1)

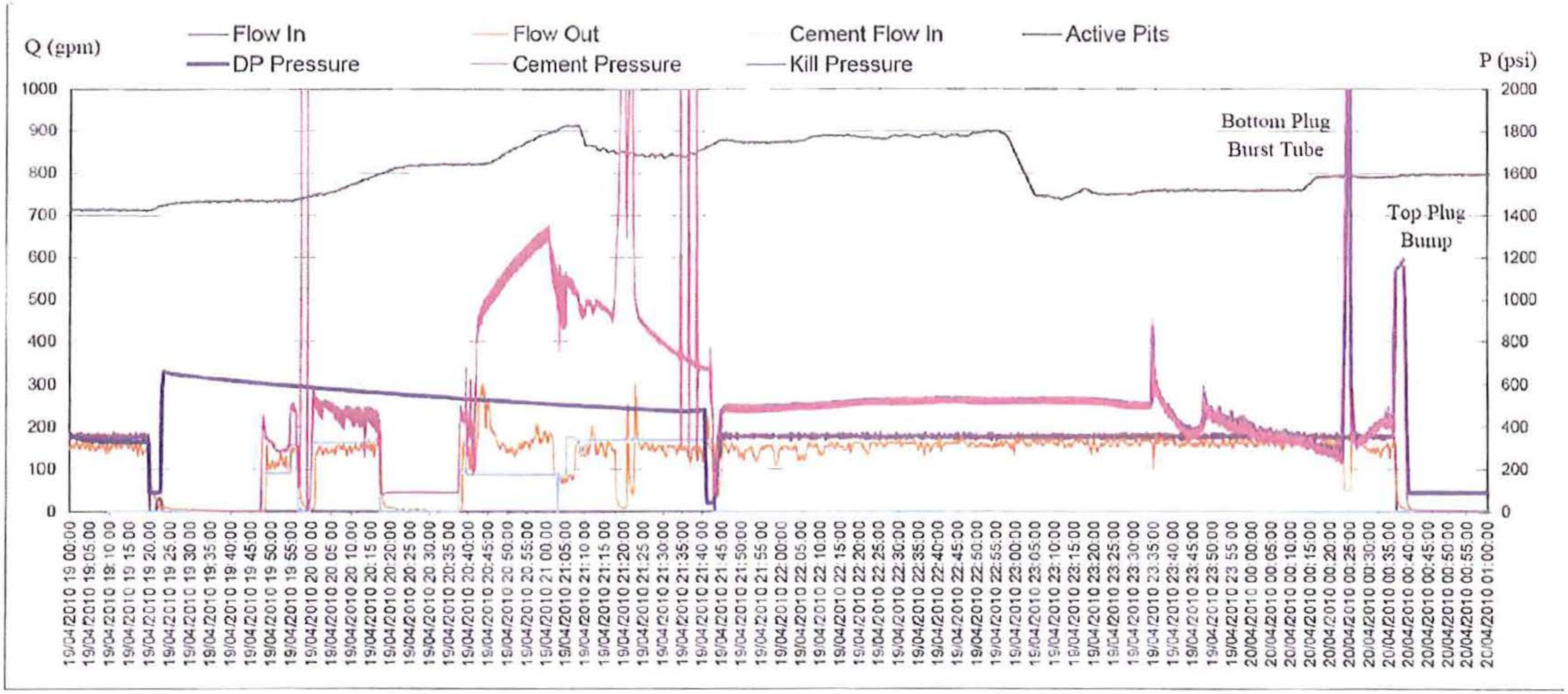


Figure 3.10: Cementing – Releasing and Bumping Plugs, Cementing (Well MC252#1)

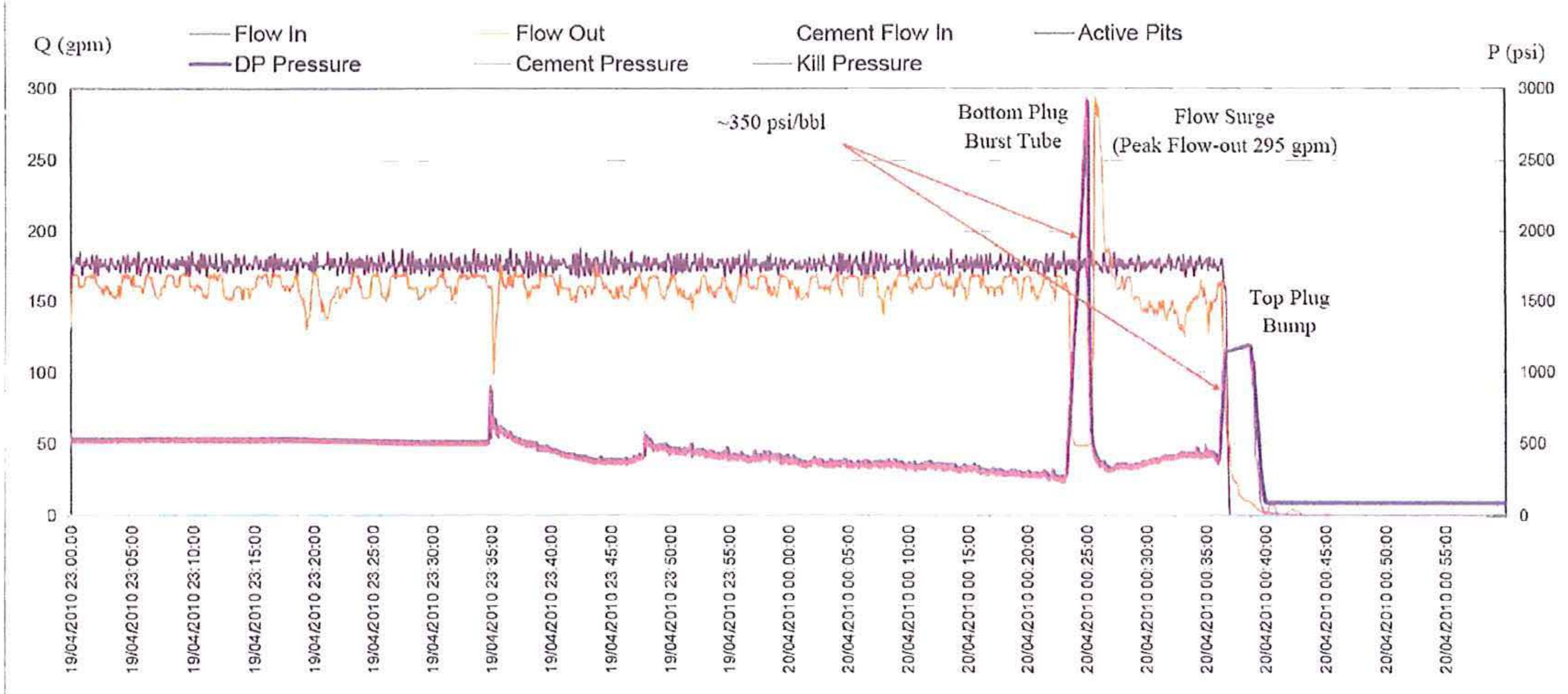
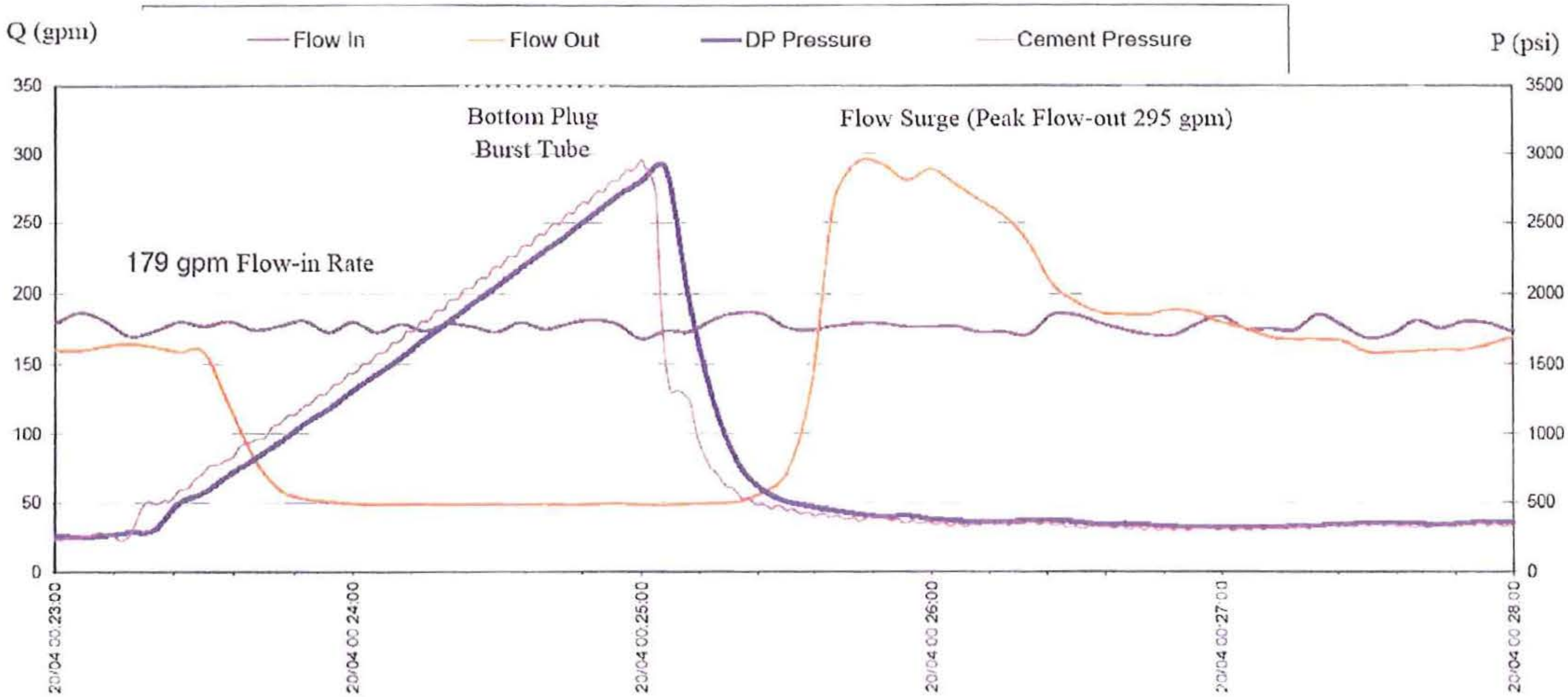


Figure 3.11: Cementing – Bumping Plugs (Well MC252#1)



Bottom plug expected (primary burst tube) burst pressure = 900–1100 psi.
Bottom plug expected (secondary burst tube) burst pressure = 2500–3000 psi (only when top plug is engaged with bottom plug).

Figure 3.12: Flow Surge #2 – Bursting of Bottom Plug Primary Burst Tube (Well MC252#1)

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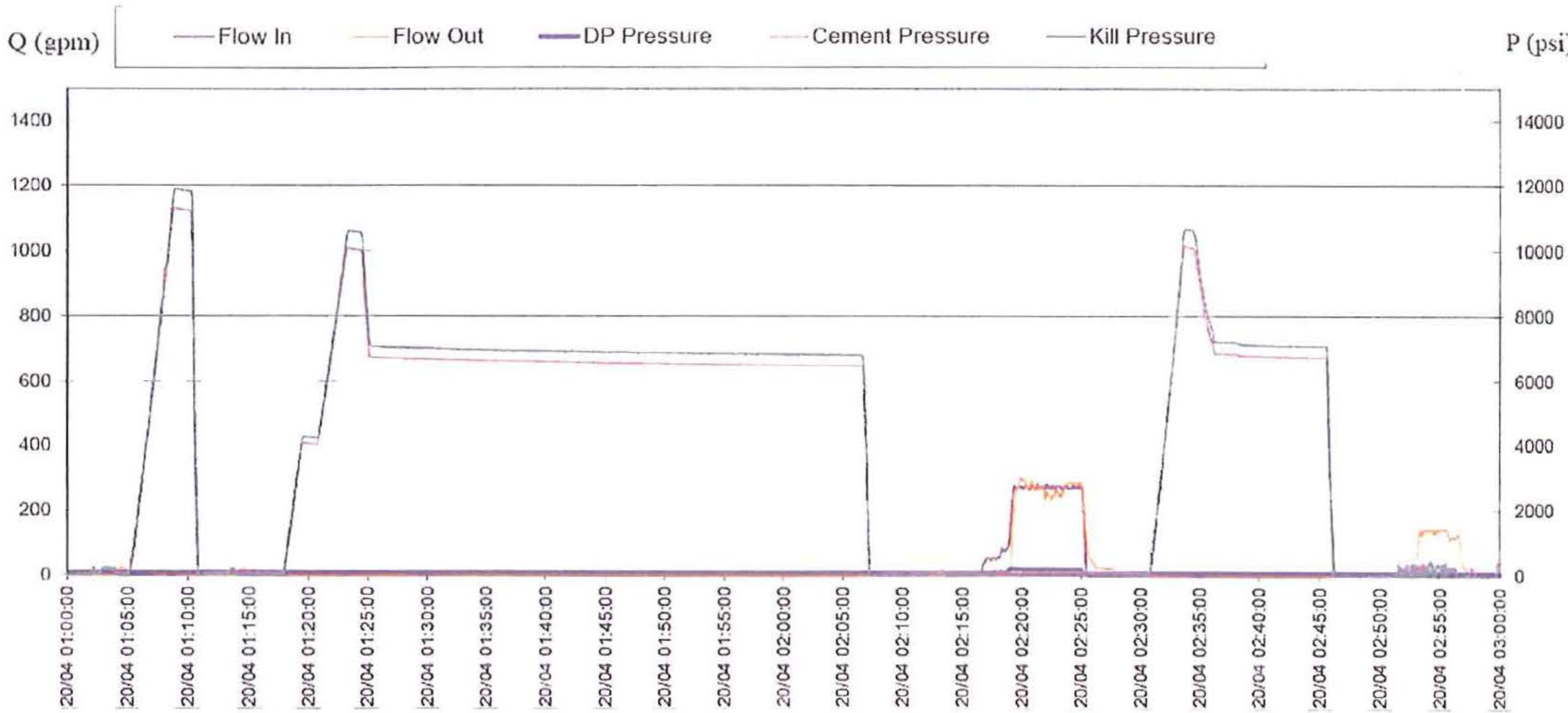

Release running tool, set seal assembly at 5059 ft to seal 9⅞" annulus, test pressure seal assembly.

Figure 3.13: Pressure Test of Seals (Well MC252#1)

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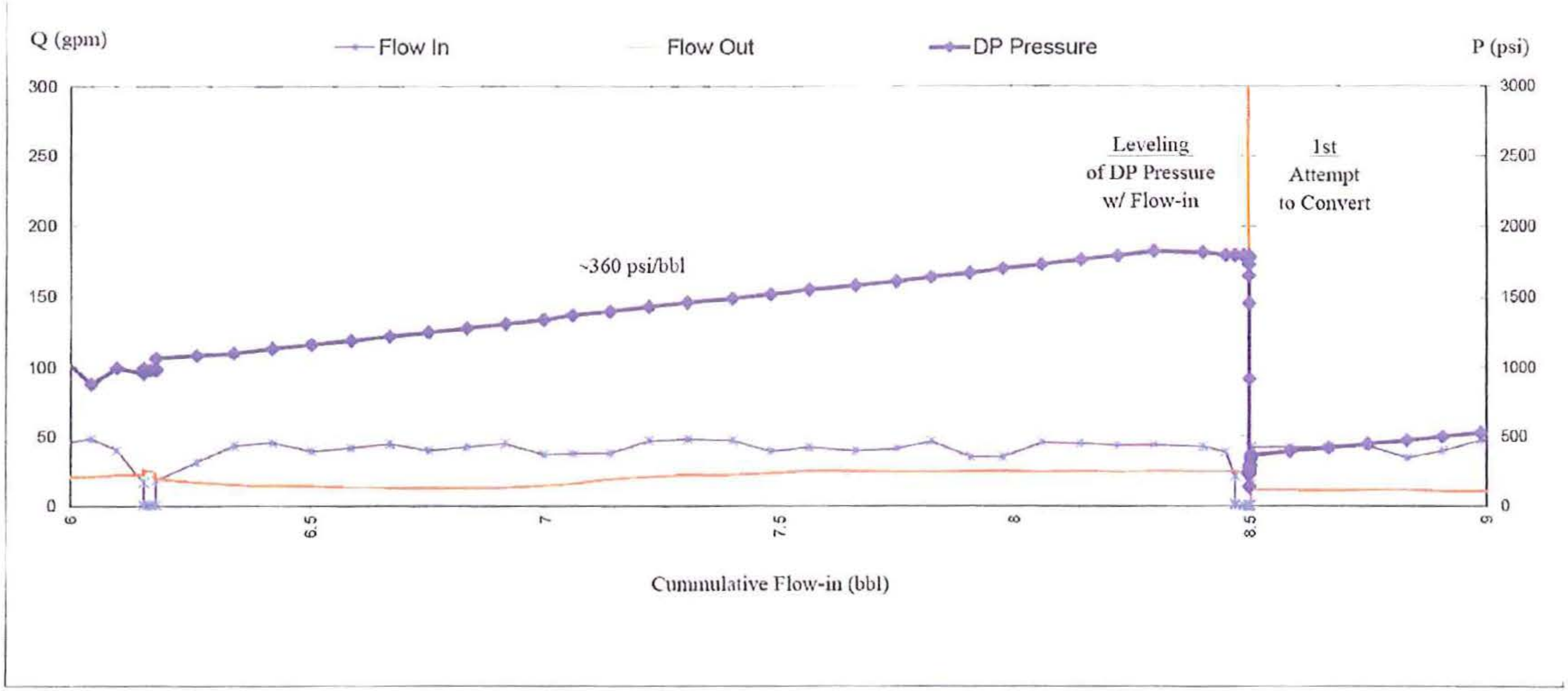

Figure 3.14: Leveling of DP Pressure while Flowing in – First Attempt to Convert (Well MC252#1)

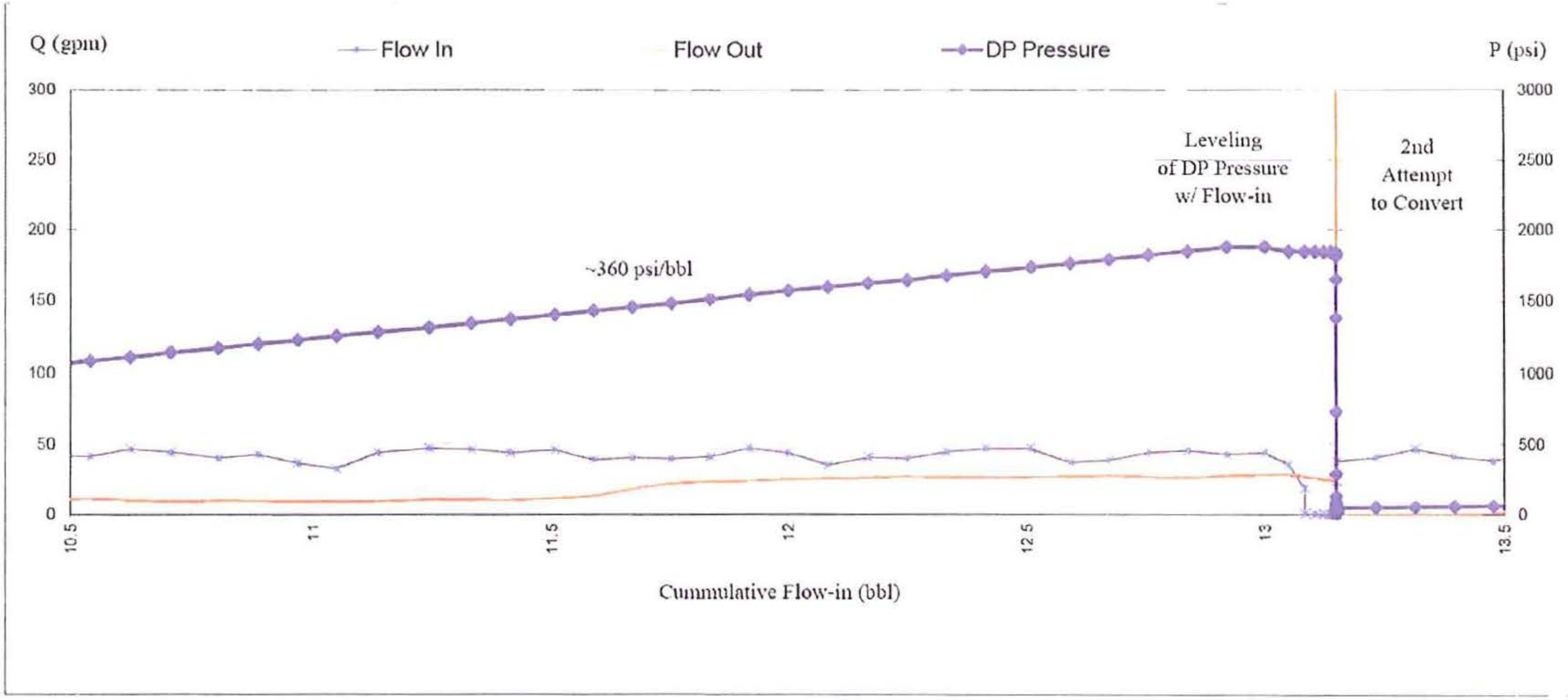

Figure 3.15: Leveling of DP Pressure while Flowing in – Second Attempt to Convert (Well MC252#1)

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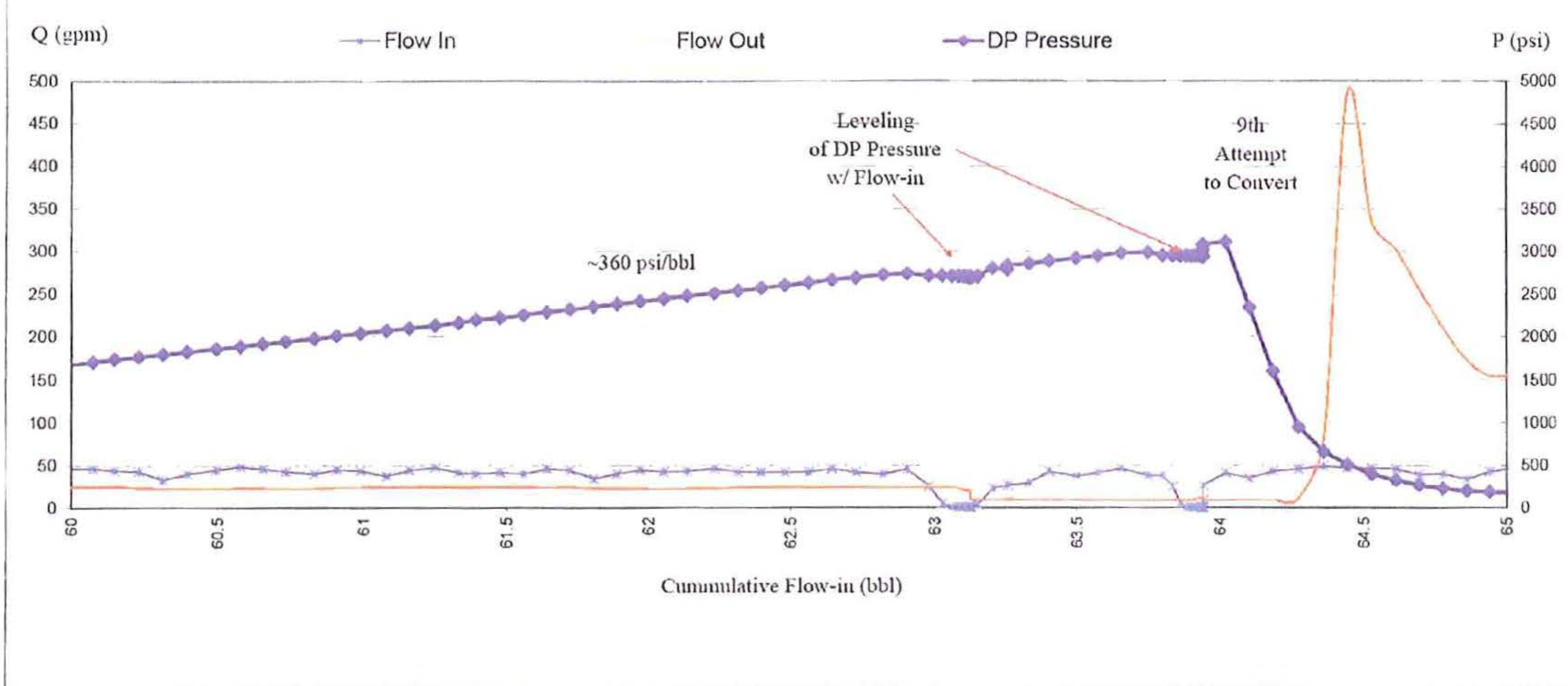

Figure 3.16: Leveling of DP Pressure while Flowing in – Ninth Attempt to Convert (Well MC252#1)

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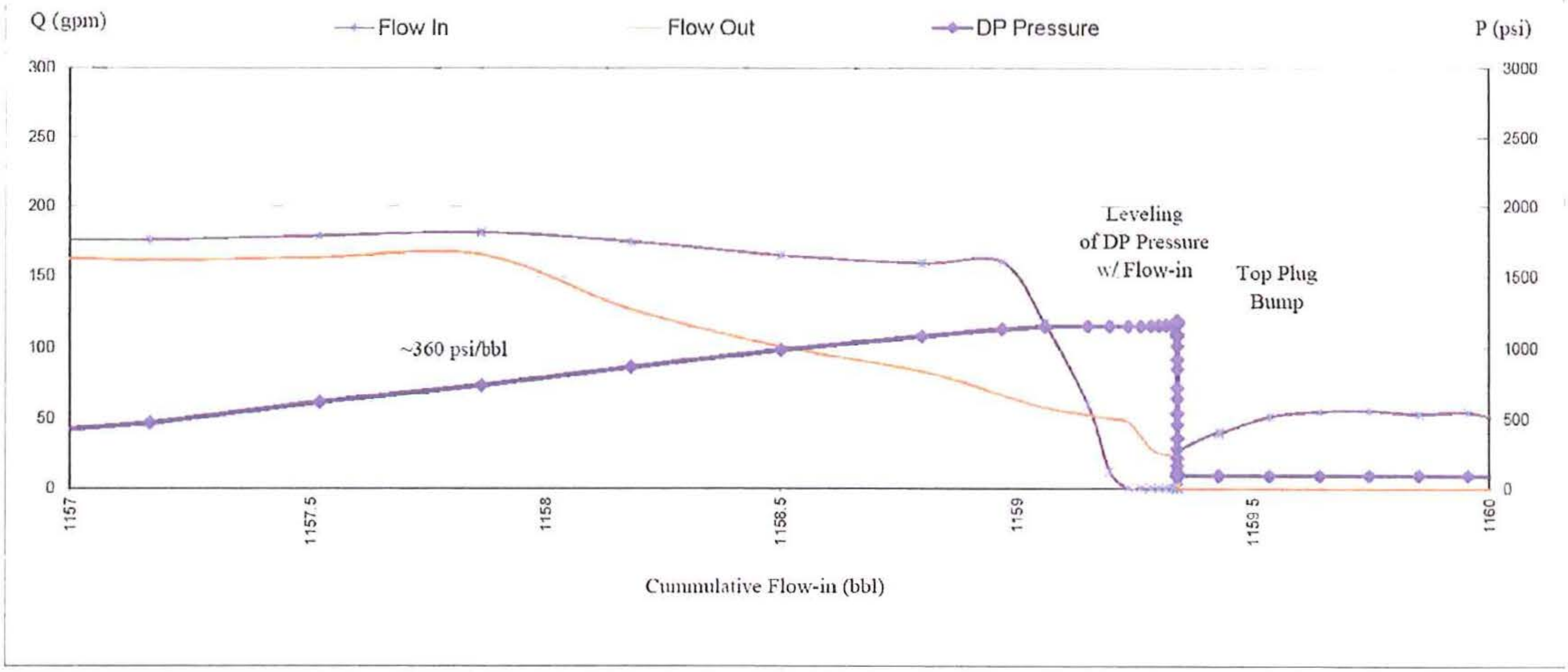

Figure 3.17: Leveling of DP Pressure while Flowing in – Bumping Top Plug (Well MC252#1)

4. COMPONENT STRENGTH ANALYSIS

The component strength evaluation completed by SES was limited to the Weatherford 7" M45AP float collar and 7" CSG × 8¼" reamer shoe and their components. The float collar is located at about 18,114 ft MD and is threaded between the 7" casing joints and reamer shoe joints. The reamer shoe is located at the bottom of the production casing at about 18,304 ft MD, which is 190 ft below the float collar.

SES performed strength calculations for the float collar and reamer shoe based on proprietary data provided by Weatherford. These Weatherford data and calculations based on these Weatherford data cannot be included in this report to BP without the consent of Weatherford. Correspondingly, Appendix C (which would otherwise present these calculations) is intentionally left blank. A summary of the minimum calculated capacities is provided in this section.

SES did not perform detailed finite element analysis (FEA) for any component. The approach was to recommend FEA if the hand-calculated strength values were low or if SES was not able to estimate the strength. Based on the hand calculations, the only candidate for FEA was the auto-fill tube. However, Weatherford did not provide to SES yield or tensile data, or details of the auto-fill tube composite construction. Therefore, FEA with material anisotropy and non-linearities could not be performed by SES. Weatherford provided only enough constitutive model data to enable completing elastic isotropic analysis. Consequently, mechanical testing was used as an alternative approach to assess the auto-fill tube.

4.1 REAMER SHOE HAND-CALCULATION RESULTS

The 7" CSG × 8¼" reamer shoe calculated minimum capacities are:

- Pressure minimum capacity = 8,192 psi
- Axial load capacity = 242.7 kip

The value for pressure capacity is based on the assumption that the three circulation ports are closed and that the calculated pressure is a differential pressure. The 10-kip compressive load described in Section 3.1.1 is well within the reamer shoe load capacity. The calculated capacities are sufficiently higher than the loads under consideration and, therefore, a detailed finite-element analysis was not required.

4.2 FLOAT COLLAR HAND-CALCULATION RESULTS

The 7" M45AP float collar components can be exposed to a range of loads depending on various downhole scenarios. Blockage at the top of the float collar (such as resulting from the plugs, etc.) exposes the float collar to a pressure end load based on the full float collar bore. This load would be transmitted through the various internal components until the entire load is transferred to the float collar body (shell wall, Weatherford Drawing D000401284). Pressure differential generated by flow through the 37/64" side ports or blockage of these ports, places a load on the auto-fill tube. This load passes through the four shear screws into the float collar body. Failure (shearing) of the shear screws allows the tube to clear the flapper valves. After conversion, any back-pressure would load the lowest valve, which transfers the load to the float collar body.

The calculated minimum load capacities for the float collar auto-fill tube are listed in Table 4.1.

Table 4.1: Calculated Capacities for Auto-Fill Tube

	Tube Pressure Differential	Equivalent Load
Based on min material strength	392 psi	1941 lb
Based on max material strength	460 psi	2276 lb

Several failure modes were considered for the auto-fill tube. The controlling failure mode was failure of the four shear screws at the top of the auto-fill tube. The calculation does not include failure modes related to the auto-fill tube itself (e.g., ball passing through ball seat prior to failure at the top of the tube, burst of tube, etc.) since Weatherford did not provide sufficient data to SES (see Section 2). Physical testing will be relied on to check the tube failure modes.

The calculated minimum capacities for float collar bore pressure differential are:

- Bore pressure differential = 12,175 psi
- Equivalent axial load = 361.8 kip

These calculations are based on the assumption that the cement does not transfer any portion of the load to the float collar body, but rather the applied load passes through to the valve body and into the float collar body. Therefore, this calculated rating is the same for bore pressure from above or below the float collar. (Note that "cement" in this paragraph refers to the pre-installed cement in the float collar and not the cement that is part of the Well 252#1 cementing operation.)

With the exception of the auto-fill tube failure modes (not addressed by analysis), the calculated capacities are sufficiently higher than the loads under consideration. Consequently, a detailed finite element analysis is not required for the float collar.

4.3 MISCELLANEOUS CHECKS

The top and bottom cement plugs are supported below the diverter and are in the path of the Allamon ball. The minimum internal diameter of the plugs is 1.78", which is larger than the Allamon ball outside diameter of 1.625". Although the clearance is small, the ball should not cause a blockage.

The Allamon ball is expected to eventually land on top of the float collar ball cage. The opening at the top of the 7" M45AP float collar is smaller than the Allamon ball. Selected physical tests including the Allamon ball would include the effect of the Allamon ball on the flow and pressure drop across the float collar. Flow tests with float collar marked as SN-04 reported in the SES test report included the Allamon ball at the top of the float collar.

The 7" × 9⅞" production casing string contains a crossover at 11,153 ft MD, which includes a 10° interior diameter transition taper. Based on the Weatherford cement plug brochure, this taper angle is acceptable for safe passage of Weatherford cement plugs.

Sealability of the float collar and flow characteristics before, during, and after conversion were investigated by physical testing.

4.4 CONCLUSIONS FOR COMPONENT STRENGTH

The reamer shoe and float collar should have sufficient strength to sustain the measured loads during the period involved in preparing to convert the float collar, circulating prior to cementing, and cementing (timeline between 04/19/2010 14:00:00 and 04/20/2010 01:00:00). The calculated conversion load (pressure) was lower than Weatherford's published data.

5. WELL CONFIGURATION AND DATA FOR FLOW SIMULATIONS AND TEST DESIGN

Flow rates were calculated for the field conditions of Well 252#1 to estimate the float collar flow rate during the two identified flow surge events (see Section 5.2). Similar calculations were performed to help design a test setup to match the estimated float collar surge flow rate or define a conservative surge flow rate to use in blockage flow surge tests. The well configuration, well data, and the designed test configurations are summarized in this section. The flow calculations are provided in Sections 6 and 7.

The physical tests performed by SES are summarized in a separate report [Ref. 1].

5.1 GEOMETRY

The configuration of Well 252#1 during cementing operations is described below. Also provided are test configurations for various blockage flow surge tests performed by SES.

5.1.1 Well Configuration

The well schematic for Well 252#1 is provided in BP document, "Macondo_MC 252_1 _Schematic_Rev15 2_04222010_withBOP.xls; Well schematic." Data from this document were used to generate the well schematic and data shown in Table A-2.1 and Figure A-2.1. The table provides geometric data for the tubing, casing, and annulus that were used to construct the flow rate calculation models.

Dimensions of the float collar and reamer shoe and their components were provided in Weatherford drawings. Dimensions of the float collar auto-fill tube holes and the reamer shoe holes are provided with the schematic in Figure A-2.1.

No details were provided to SES on the surface piping connecting the top of the riser to the location where the drill-pipe pressure and flow-in rate were measured, or on the piping between the riser and the location where flow-out was measured. These components were not included.

5.1.2 Test Configurations

Physical tests performed by SES are summarized in a separate report [Ref. 1]. Several test configurations were designed and employed; drawings of the test configurations are provided in Appendix D. Drawing numbers from Appendix D are used here to identify each configuration. Below are described test configurations for which data were measured for comparison to flow calculation results:

1. Float Collar SN-03 – Conversion Test
   a. Conversion test, steady-state flow rate – Float Collar #3 (Drawing KY1751225-01-05)
2. Rehearsal – Blockage Flow Surge Rehearsal Test
   a. Conversion test, steady-state flow rate – Simulated float collar auto-fill tube (Drawing KY1751225-01-05)
   b. Conversion test, surge flow rate, Flow Surge #1, downstream blockage – Simulated float collar auto-fill tube (Drawing KY1751225-01-06)
3. Float Collar SN-05 – Blockage Flow Surge Test
   a. Conversion test, surge flow rate, Flow Surge #1, downstream blockage – Float Collar #5 (Drawing KY1751225-01-06)
   b. Second flow surge on converted collar, downstream blockage – Float Collar #5 (Drawing KY1751225-01-07)
4. Float Collar SN-04 – Blockage Flow Surge Test
   a. Conversion test, surge flow rate, Flow Surge #1, downstream blockage – Float Collar #4 (Drawing KY1751225-01-08)
   b. Second flow surge on converted collar, upstream blockage – Float Collar #4 (Drawing KY1751225-01-09)

The required flow rate for the steady-state flow rate conversion tests (SN-03 and Rehearsal) was obtained using the mud pumps. Accumulators were not required. For the Rehearsal test, the constant flow rate was increased to a higher flow rate (as compared to SN-03) since conversion was not physically possible for the simulated auto-fill tube. A choke was added downstream from the float collar to choke the flow and increase system pressure. Higher system pressure was believed to mitigate possible cavitation at the auto-fill tube ports.

Achieving the necessary surge flow rates estimated for Flow Surge #1 and Flow Surge #2 required adding accumulators to the test setup. The blockage flow surge tests for float collars SN-04 and SN-05 (and the Rehearsal flow surge conversion test) employed two accumulators—a 262-gal accumulator upstream and a 385-gal accumulator downstream.

5.2 FLOW SURGE EVENTS

According to data provided by Weatherford, with the drilling mud density used, the float collar is designed to convert at a differential pressure of 500 to 700 psi, which would occur with a flow rate of 5 to 7 bpm through the side ports in the float collar. Field data provided by BP show that BP encountered difficulties establishing sufficient flow through the float collar to cause conversion. Each time BP attempted to increase the pump rate in the well, the pressure increased without an increase in flow rate (flow-in or flow-out), suggesting a blockage somewhere in the well flow path.

A review of the drilling data by SES revealed two significant flow surge events (see also Sections 3.1.5 and 3.1.6):

1. Flow Surge #1 follows a 3121-psi pressure spike, corresponding to the ninth attempt to convert the float collar.
2. Flow Surge #2 follows a 2900-psi pressure spike, corresponding to the rupture of the burst tube on the bottom plug during the cementing procedure.

While the pump rate, drill-pipe pressure, and surface discharge flow rate were measured during these events, the flow rate local to the float collar during these events is unknown. Flow rate calculations based on the field conditions can be used to estimate the float collar flow rate. Results of these calculations can then guide experiments to determine if the flow surges caused conversion of the float collar.

Flow Surge #1 occurred during the ninth attempt to convert the float collar. The maximum recorded drill-pipe pressure prior to the surge was 3121 psi. The pump was supplying 1 bpm of 14-ppg mud to the string during the conversion attempt. The flow surge appears to be the result of a blockage clearing from the flow path. While it is not known exactly where the blockage was located, it is reasonable to assume that it was located in the vicinity of the float collar or reamer ports (nozzles). Consequently, for the flow models, the blockage for Flow Surge #1 was considered to be at the reamer ports.

Flow Surge #2 occurred during the cementing procedure, possibly after the bottom plug landed on the float collar. The bottom plug burst tube appears to have ruptured at a drill-pipe pressure of about 2900 psi, rather than the 900 psi specified. The sudden rupture of the burst plug could have converted a previously unconverted float collar, or could have generated a flow surge that could have affected the functionality of the float collar if Flow Surge #1 had already converted the float collar.

5.3 CONTENT, FLOW, AND PRESSURE DATA

The content, flow, and pressure data for Well 252#1 during cementing operations are described in Section 3. Flow and pressure were recorded only at the surface. Flow rates, pressures, and pressure changes at the float collar are not known.

For the physical tests by SES, pressure was measured with pressure transducers upstream and downstream from the float collar, and the flow rate was measured with a flow meter.

5.3.1 Well Data

Section 3 describes that the recorded flow-in rate was never sufficiently high (as compared to Weatherford's data) to have converted the float collar. The flow calculations in Sections 6 and 7 are based on the assumption that the pressure drop through the float collar auto-fill tube was defined by the Weatherford equation listed in Section 2.4.3. Steady-state flow rate tests by SES confirmed that the Weatherford equation was generally accurate for 14-ppg fluid.

If conversion did not occur during a steady-state flow condition, then two flow surge events could have caused conversion of the float collar.

During Flow Surge #1 (see Section 3.1.5), the tubing, casing, and annulus were assumed to be filled with 14-ppg hydrocarbon-based mud. The mud properties and rheology data were provided by BP and are included in Appendix A-3. The field-reported properties for 14-ppg mud data for 19 April 2010 are PV = 28 cP and YP = 14 lb/100 ft^2 at 150°F. For Flow Surge #1, the flow-in rate was 43 gpm, surge pressure was 3121 psi, and surge flow-out rate was 486 gpm.

During Flow Surge #2 (see Section 3.1.6), the tubing, casing, and annulus were assumed to be filled with 14-ppg mud except for ~60 bbl of cement located between the bottom and top cement plugs. During this event, the bottom plug was believed to be resting on top of the float collar. Immediately above the bottom plug, 8 bbl of 16.7-ppg heavy cement was present, followed by lighter 14.5-ppg nitrified cement. Properties of the heavy cement were provided by BP (see Appendix A-3): PV = 62 cP and YP = 1 lb/100 ft^2 at 135°F (the bottom circulating temperature). For Flow Surge #2, the flow-in rate was 180 gpm and surge pressure was 2900 psi, while the surge flow-out rate was 295 gpm.

Pressure losses in the surface piping system that connected the top of the riser to the flow-in and flow-out components were not provided to SES.

It is important to note that an 18,114 ft, 14-ppg mud column will generate a hydrostatic pressure of 13,170 psi. This is the approximate hydrostatic pressure expected during the conversion and flow surge events.

5.3.2 Test Data

The rated pressure of the SES test setup was 5000 psi; therefore, the initial system pressure could not approach levels that were expected downhole. The system pressure of the physical test was ~1000 psi or less, significantly less than the estimated float collar field hydrostatic pressure. For the steady-state flow rate conversion tests, the test system pressure was about 1000 psi and was achieved using a choke downstream from the float collar. For the surge flow rate tests, the system pressure was 500 psi and was generated by pre-charging the accumulators. The specific choice of a 500-psi pre-charge pressure was intended to obtain a desired flow rate decay (discussed further in Sections 6 and 7).

For the purposes of analysis calculations and physical testing, the mud was assumed to be water-based rather than hydrocarbon-based fluid. The tests were performed with water-based mud with rheology properties that matched the well data listed in the previous section.

Conversion tests with steady-state flow rates were performed with 14-ppg mud. The flow rate was held constant for a period of time and then increased incrementally until conversion. These tests were performed to confirm whether the Weatherford equation relating flow rate to conversion pressure and fluid density (see Section 2.4.3) is accurate.

Blockage flow surge tests were only performed with 14-ppg mud corresponding to Flow Surge #1. Blockage flow tests with 16.7-ppg mud corresponding to Flow Surge #2 were not performed because the float collar converted during the simulated Flow Surge #1 (which chronologically preceded Flow Surge #2).

A second flow surge test was performed with the float collar already converted to investigate whether the valve flappers might be damaged by Flow Surge #2. Rather than setting up the second flow surge test with mud equivalent to 16.7-ppg cement, the test was performed with readily available 14-ppg mud. The peak flow rate with 16.7-ppg mud was not expected to be significantly higher than with 14-ppg mud. The second surge tests on a converted float collar were performed first with a downstream blockage (SN-05) and then with a (more likely) upstream blockage (SN-04).

The flow-in rate during the flow surge tests was maintained at 42 gpm. The flow-in rate corresponding to Flow Surge #2 (180 gpm) was never used since Flow Surge #2 was not tested.

5.4 CONVERSION DATA

Details of the float collar auto-fill tube geometry and Weatherford conversion equation are provided in Section 2.4. The flow calculations described in Sections 6 and 7 are based on the assumption that the pressure drop through an unconverted float collar is defined by the

Weatherford float collar conversion equation. The pressure drop through a converted float collar is assumed to be significantly lower.

Steady-state flow rate conversion test data confirmed that the Weatherford float collar conversion equation is generally accurate for 14-ppg fluid.

6. SIMULATION OF FLOW SURGE EVENTS USING METHOD OF CHARACTERISTICS (MOC)

6.1 APPROACH TO FLOW SIMULATIONS

The Weatherford float collar is converted by creating a differential force across the auto-fill tube. This differential pressure is generated by circulating above a critical flow rate (with the critical flow rate a function of mud weight). Field data show that the pump rate, during the period under consideration, never exceeded the critical flow rate required to convert the float collar. Two flow surge events were identified, however, that could have resulted in locally high velocities and created sufficiently high differential pressures across the float collar to cause conversion.

To investigate whether these flow surges would have been expected to cause conversion of the float collar, SES performed a series of flow calculations and simulations of the float collar flow rate during this interval. SES constructed computer models to simulate behavior of the fluid in the wellbore and annulus to help correlate theoretical expectations to the existing surface pressure and flow data.

Two SES analysts pursued flow simulation and modeling using two independent methods. It was anticipated that the results from the two analyses could be used to cross-check one another.

The first flow prediction method (described in this section) is referred to as the "Method of Characteristics" (MOC). Results from a second independent simulation method, referred to as the "Time-Domain" (TD) approach, are presented in Section 7.

The first objective of the flow calculations was to estimate the flow rate through the float collar during the two flow surge events (see Section 5.2). The analysis was performed assuming that the float collar *did not* convert, as well as that the float collar *did* convert. The resulting flow parameters could then be compared with data acquired from Well 252#1. The second objective of the flow simulations was to model various test configurations, so that a test facility could be developed in which the test flow parameters were representative (or conservative) of the flow rates during the field flow surge events.

6.2 INITIAL CALCULATIONS USING MODIFIED QUASI-STEADY METHOD

Prior to applying the method of characteristics (see Section 6.3), SES first used a relatively simple analytical method to characterize the flow surges and to determine if they provided a potential for conversion of the float collar. This first analysis approach can be considered as a "modified quasi-steady" method. Typically, the quasi-steady flow approach to modeling transient flow is characterized by the absence of inertial and elastic effects on the flow behavior, and by the mass flow rate being constant along a flow path at any time. In this study, the quasi-steady approach was modified by including the effects of fluid compressibility and pipe elasticity on the mass flow rate, which allows mass to accumulate in sections of piping.

This quasi-steady approach is based on conservation of mass in the piping. The total length of piping is divided into segments, and each segment is assumed to be at a uniform pressure. At the boundaries of each segment, it must be possible to define the mass flow through the boundary in terms of the pressure difference between the segments. This requires that the boundaries be located at flow restrictions, such as nozzles, orifices, and significant diameter changes. Mass accumulation in a pipe segment is accompanied by a change in the segment pressure. An algebraic relation between the mass in each segment and the corresponding pressure accounts for the compressibility of the drilling mud and elastic deformation of the piping.

A primary assumption in this approach is that, at any given time, pressure is uniform throughout each segment. This approximation is generally well-suited to short pipes and slow events (with short and slow being relative to the speed of sound in the fluid). Also, the frictional losses through a segment become greater for longer segments and higher flow rates. While this assumption is likely reasonable for segments on the order of the length of the float collar (and possibly for the roughly 190 ft segment between the float collar and reamer shoe), it is not reasonable for the total length of tubing, casing, liner, etc. between the surface and float collar. Therefore, while this method may be useful for providing estimates of flow rates and pressures in the vicinity of the float collar, it cannot provide data to compare to properties measured at the surface, i.e., the pump pressure and flow-out rate. However, the simplicity of this approach makes it useful as an initial screening tool to investigate the potential for surge flow to convert the float collar.

It is also assumed in this method that the standard quasi-steady orifice flow and frictional-loss equations are applicable. Effects of unsteady flow on pressure losses through an orifice and on frictional losses in a segment of pipe are not well understood; no attempt was made to account for such effects. In addition, the pressure term used in the calculations is the difference between the time-varying pressure and hydrostatic pressure. The density increase due to hydrostatic pressure was also neglected. This leads to a small error in fluid density, and a corresponding small error in calculated pressure losses and flow rates. A Newtonian friction model was applied to the annular section of the well, and friction was neglected in the segment of the piping between the float collar and reamer shoe and in the upstream segment.

Data from Well 252#1 show that, during attempts to convert the float collar, drill-pipe pressure increased at a rate of approximately 360 psi/bbl of mud pumped (see Section 3.1.3). This compression factor was used in the initial modeling approach to provide a relationship between pressure and mass in the segment of piping upstream of the float collar. A correlation provided by Weatherford was used to determine mass flow rate through the unconverted float collar as a function of pressure drop and fluid density (see Section 2.4.3). Weatherford documentation also provided a graph of the flow rate through a converted float collar as a function of pressure. A curve fit of the graph was used in the calculations. The reamer shoe nozzles were modeled as an orifice equivalent to three 40-mm diameter holes, and a discharge coefficient of 0.7 was estimated.

6.2.1 Flow Surge #1

Flow from the pump was set to 1 bpm throughout the simulation of Flow Surge #1. The flow surge through the float collar began when the pressure reached 3121 psi and an assumed blockage at the reamer shoe cleared. Figure 6.1 shows the calculated flow rate through an unconverted float collar during Flow Surge #1. Also shown are calculated pressures upstream and downstream of the float collar. Note that the pressure shown does not include hydrostatic pressure. Pressure downstream of the float collar is seen to drop rapidly, leading to a peak surge flow rate through the float collar of approximately 12.5 bpm. The flow rate then drops nearly linearly until it reaches a steady-state flow rate of 1 bpm (the pumping rate). This linear decrease in flow rate has been shown to be characteristic of a linear spring accumulator, and the compressibility of the fluid and elasticity of the pipe walls act as a linear spring.

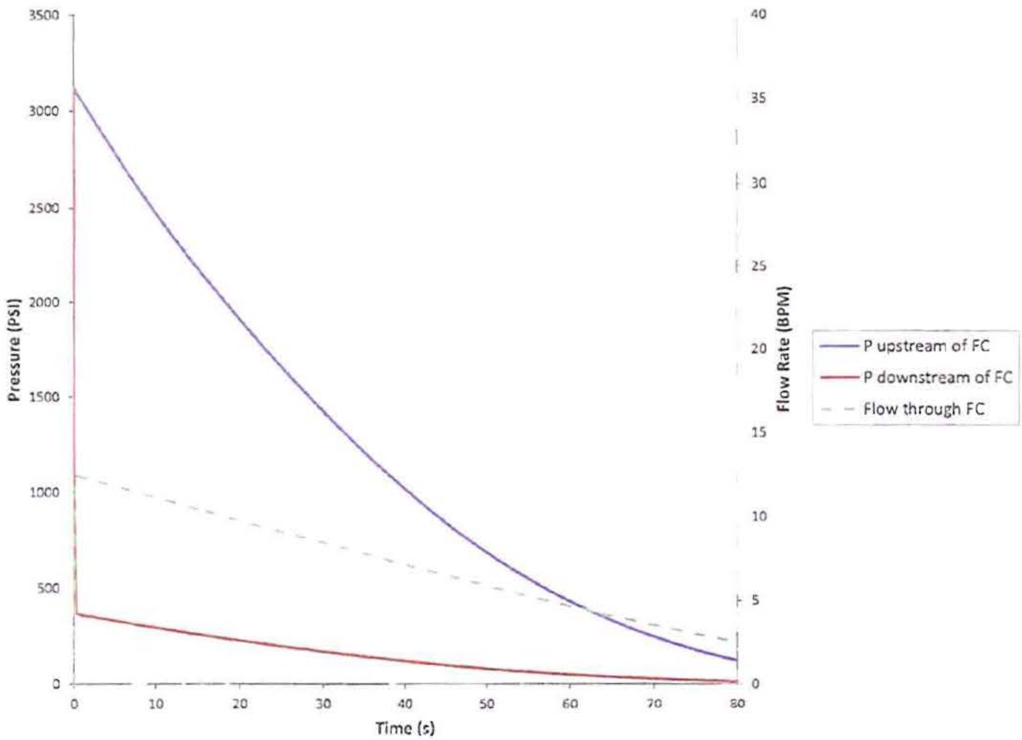

Figure 6.1: Pressures Upstream and Downstream and Flow Rate through Unconverted Float Collar for Flow Surge #1 Calculated via Modified Quasi-Steady Approach

The calculated flow rate through a converted float collar during a simulation of Flow Surge #1 is shown in Figure 6.2. Calculated pressures upstream and downstream of the float collar are also shown. When the float collar is modeled as converted, pressure downstream of the float collar does not drop rapidly. In this case, the model shows that the majority of the pressure loss in the piping occurs at the reamer shoe nozzles. The peak surge flow rate through the float collar is predicted to be much higher—approximately 39 bpm. Both the flow rate and pressure decrease much more rapidly if conversion is assumed to have occurred. Because losses in the rest of the system are not sufficiently detailed in this model and their importance relative to the float collar losses is much greater after conversion occurs, the accuracy of the predicted decay rate is lower than the unconverted simulation. However, the predicted initial flow rate through the float collar is expected to provide a good estimate of the actual peak flow rate, and the results clearly indicate that the surge will decay much faster if the float collar converts.

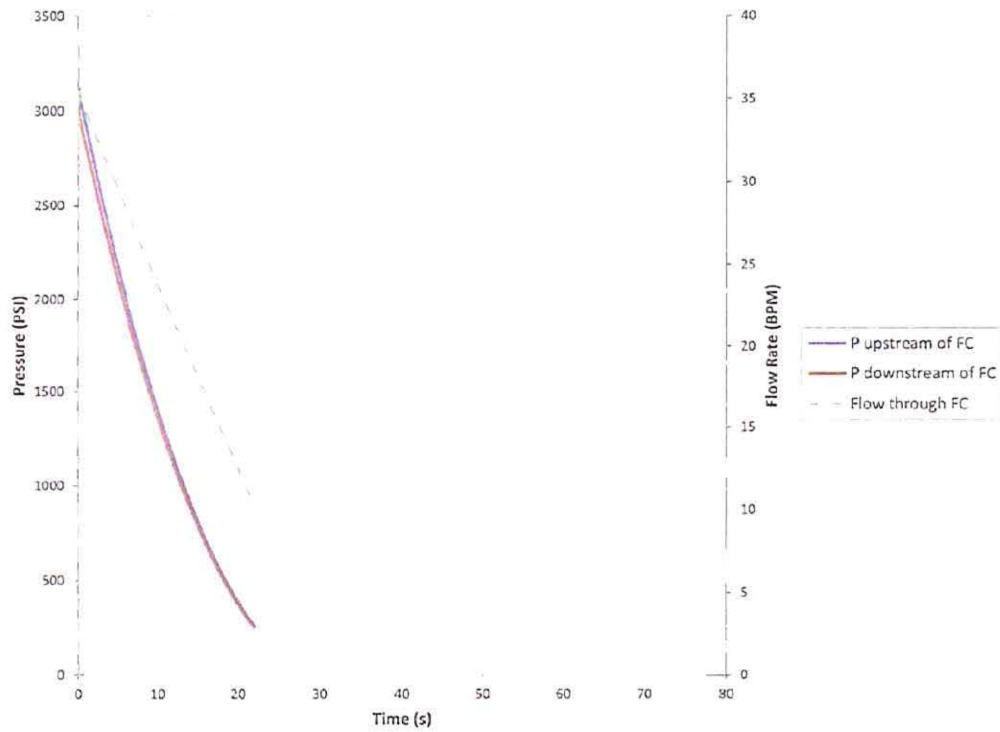

Figure 6.2: Pressures Upstream and Downstream and Flow Rate through Converted Float Collar for Flow Surge #1 Calculated via Modified Quasi-Steady Approach

6.2.2 Flow Surge #2

Flow Surge #2 occurs when the burst tube in the bottom plug ruptures during the cementing operation. The data show that this event required a pressure of approximately 2900 psi (see Section 3.1.6). In this case, the blockage (due to the bottom plug) was located just above the float collar. Also, the material upstream of the bottom plug, and therefore the material flowing through the float collar during the surge, was modeled as 16.7-ppg cement, while the remainder of the fluid in the piping was modeled as 14-ppg drilling fluid. The pumping rate was set to 4 bpm throughout the simulation. Figure 6.3 shows the calculated flow rate through an unconverted float collar, as well as the calculated pressures upstream and downstream of the pipe in the flow behavior. If inertial effects as well as the elastic effects of the fluid and pipe are significant and must be considered to obtain an accurate characterization of the transient, an approach that can account for hydraulic shock ("water hammer") must be employed. Analysis of hydraulic shocks requires the application of Newton's second law and the Euler equation.

In terms of velocity, head, and the Darcy-Weisbach friction, the Euler equation can be written as

$$\frac{1}{g}\frac{\partial V}{\partial t}+\frac{\partial}{\partial s}\left(H+\frac{V^2}{2g}\right)+\frac{f}{D}\frac{V|V|}{2g}=0$$

where V = velocity of the fluid

H = piezometric head

f = coefficient of friction

g = gravity constant

D = pipe diameter

Larock et al. [Ref. 2] show that conservation of mass leads to a second independent equation for H and V:

$$a^2\frac{\partial V}{\partial t}+g\frac{\partial H}{\partial t}+\frac{g}{2}\frac{\partial H^2}{\partial s}=0$$

where a = wave propagation speed in the pipe

For pipes, the wave propagation speed is given by

$$a^2=\frac{k/\rho}{1+\frac{kD}{Ee}C_1}$$

where k = bulk modulus of the fluid

ρ = fluid density

E = modulus of elasticity of the pipe

e = wall thickness of the pipe

C_1 is a constant based on ν (Poisson's ratio), defined as follows [Ref. 3]:

$C_1=\frac{5}{4}-\upsilon$ for a pipe free to expand axially

$C_1 = 1 - \upsilon^2$ for a pipe restrained from axial movement

$C_1 = 1 - \frac{\upsilon}{2}$ for a pipe with distributed expansion joints

A number of numerical techniques can be used to approximate the solution of the Euler and conservation of mass equations shown above. The **method of characteristics (MOC)** is most popular for hydraulic shock calculations, and is considered to have the desirable attributes of accuracy, simplicity, and numerical efficiency. Of 11 commercial water-hammer software packages reviewed by Ghidaoui et al. [Ref. 4], eight are based on the MOC. However, SES found that no commercially available package provided the necessary combination of boundary conditions and elements required for this analysis along with the ability to use non-Newtonian friction models. Consequently, in-house software was modified and used for this MOC analysis.

The non-linear terms in the Euler and conservation of mass equations can be shown to be negligible for low Mach number flows. Since even during surge events, flow velocities are expected to be small compared to the wave propagation speeds, these terms are neglected in this analysis. Linearizing the equations reduces the need for interpolation when using a fixed-grid MOC approach. The fixed-grid MOC requires that a common time step be used for the numerical solution in all pipe segments of the model. However, pipes in the actual system have different lengths and wave speeds (due to the varying pipe sizes and wall thicknesses), making it impossible to satisfy the Courant condition exactly. This discretization problem can be addressed by interpolation techniques and/or by artificially adjusting the wave speed or segment lengths. Interpolation and failure to exactly satisfy the Courant condition cause artificial smoothing of wave fronts. To avoid interpolation entirely in this analysis, pipe lengths were adjusted slightly based on the number of elements used in the calculation, to provide an integral number of elements in each pipe segment modeled and to ensure that the Courant condition was exactly satisfied. While it is more typical to vary the wave propagation speed in each segment rather than the length, the end result is essentially the same. The fundamental element size was based on the shortest segment in the model (a 174-ft annular section between the production casing and unlined 8.5" hole), and enough elements were used to ensure that the maximum error in the length of any segment was not more than 3 ft in the well simulations.

6.3.1 Boundary and Initial Conditions

The upstream flow boundary is considered to be the pump. The drilling fluid is supplied by a positive displacement pump, so the flow rate is considered to be set by the pumping rate (and the pressure is variable). Variations in flow rate due to the operation of pump valves were not modeled. Details of the piping between the pump and drill pipe were unknown and not modeled. During Flow Surge #1, the pump flow rate was modeled as a constant flow at 1 bpm. The same flow rate was used to model surge tests in the test facility.

For Flow Surge #2, the pump flow rate was modeled as 4 bpm throughout the simulation. A simplified model was assumed of the fluid present in the well prior to the rupture of the bottom plug and Flow Surge #2. A section of piping upstream of the float collar was modeled as full of 16.7-ppg cement, and the remainder of the well piping and annular sections were assumed to be filled with 14-ppg mud. The effects of the nitrified cement and top plug were not considered.

The downstream boundary was modeled as a release from an open end of the riser to a reservoir at atmospheric pressure. Details of the actual discharge path on the rig are not known.

The calculations were initiated with no flow throughout the piping and the pump starting flow into the inlet. A blockage was modeled in the piping (at the reamer shoe for Flow Surge #1 and at the bottom plug for Flow Surge #2), and pressure was permitted to build up between the pump and blockage, while downstream of the blockage was held at hydrostatic pressure. When pressure reached the peak pressure measured during the surge event being modeled, the blockage was removed.

6.3.2 Interior Junctions

Interior piping junctions occur at restrictions in the flow or where the piping size changes. In the model, an interior junction occurs between each pipe segment. Each pipe segment is subdivided into a number of elements, which do not have a discrete pressure drop between them. The pressure losses across interior junctions are modeled using resistance coefficients. Forward and reverse flow resistance coefficients are defined for each junction, since the pressure loss at a junction can vary with flow direction. Due to a lack of adequate transient models, it was assumed that the steady-flow equations adequately describe pressure losses through orifices and area changes.

Calculation of the resistance coefficients for the float collar in both the unconverted and converted states required determining the flow coefficients of the float collar. Data from Weatherford documentation was used to determine the flow coefficients for the float collar in an unconverted and converted state based on the orifice flow equation:

$$Q = C_f A_o \sqrt{\frac{2\Delta p}{\rho}}$$

where Q = volumetric flow rate

C_f = flow coefficient,

A_o = area of the orifice

Δp = pressure drop across the orifice

ρ = density of fluid flowing through the orifice

The corresponding discharge coefficients for the unconverted and converted float collar were determined to be 0.65 and 0.92, respectively. The equation was experimentally validated for flow through an unconverted float collar by using the measured pressure difference across the float collar to predict the flow rate. Figure 6.4 shows the measured pressure difference across an unconverted float collar, measured flow rate, and flow rate calculated using the orifice equation. Other than the high-frequency component that is filtered out by the flow meter, the measured and calculated flow rates match very well.

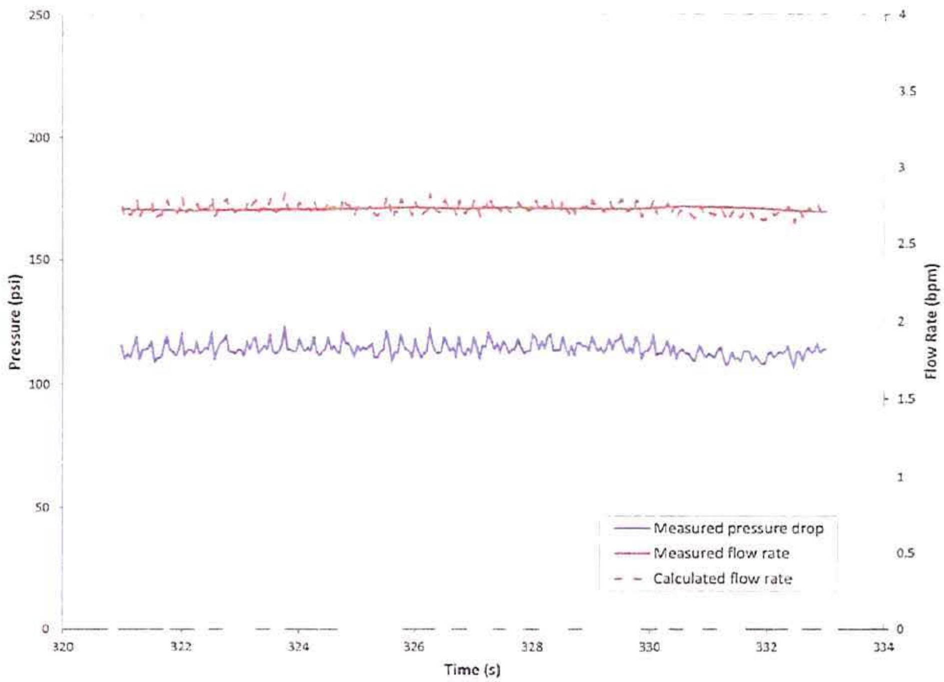

Figure 6.4: Experimental Validation of Equation Relating Pressure Drop across an Unconverted Float Collar to Flow Rate

The two other flow restrictions modeled were at the reamer show and at the Allamon diverter. The reamer shoe nozzles were modeled as an orifice equivalent to three 40-mm diameter holes, and a discharge coefficient of 0.7 was estimated. The Allamon diverter seats were modeled as a single orifice of 1.625" diameter, and a relatively low discharge coefficient of 0.6 was assumed to account for the two seats.

The resistance values for the flow restrictions are determined from

$$k = \frac{1}{C_f^2 \beta^4}$$

$$\beta^2 = \frac{A_p}{A_o}$$

where k = flow resistance

A_p = cross sectional area of the pipe

At interior junctions where the pipe diameter changes, the flow undergoes either an expansion or a contraction, depending on the direction of the flow. Flow resistance values for flow expansions and contractions are computed using the methods described in Crane Technical Paper 410 [Ref. 5].

6.3.3 Friction Models

The MOC routine was originally developed using a Darcy-Weisbach friction model, and then extended to include both Bingham and Power Law friction models to account for the effects of non-Newtonian rheological properties of the drilling fluid. Frictional loss in each element was calculated based on the average of the velocity values at each end of the element, and the calculations were solved iteratively to avoid lagging the friction calculations a time-step.

For Newtonian flows, friction coefficients were determined using the Colebrook equation for Reynolds numbers greater than 3200 and the Darcy equation for fully laminar flows with Reynolds numbers less than 2100. For the critical region ($2100 < Re < 3200$), a friction factor was determined by linearly interpolating between the upper laminar value and the lower turbulent value.

Rheology models for friction were also implemented. Bingham Plastic and Power Law friction models outlined by Albright [Ref. 6] were used. The Bingham Plastic model requires values for the yield point and plastic viscosity of the fluid. Reported values for the drilling fluid for 19 April 2010 were PV = 28 cP, and YP = 14 lb/100 ft^2 at 150°F. The Power Law model requires a flow index exponent, n, and a consistency factor, K. These can be calculated from the viscometer readings of PV and YP using equations in API RP-13D [Ref. 7]. The calculated values used in the MOC calculations for Power Law friction were $n = 0.737$ and $K = 0.425$ lb s^n/100 ft^2.

6.3.4 Compressibility

Pressure data from Well 252#1 show that, during the conversion attempts, well pressure built up at a rate of approximately 360 psi/bbl of mud pumped into the well (see Section 3.1.3). Since the bulk modulus of the drilling fluid was not known, its value was adjusted in the model until the compressibility in the simulation approximately matched that observed in the well. A bulk modulus value of 3.6×10^5 psi was determined to provide a good comparison. Figure 6.5 shows the calculated pressure rise with 1 bpm flow into the blocked pipe and a line representing 360 psi/bbl for comparison.

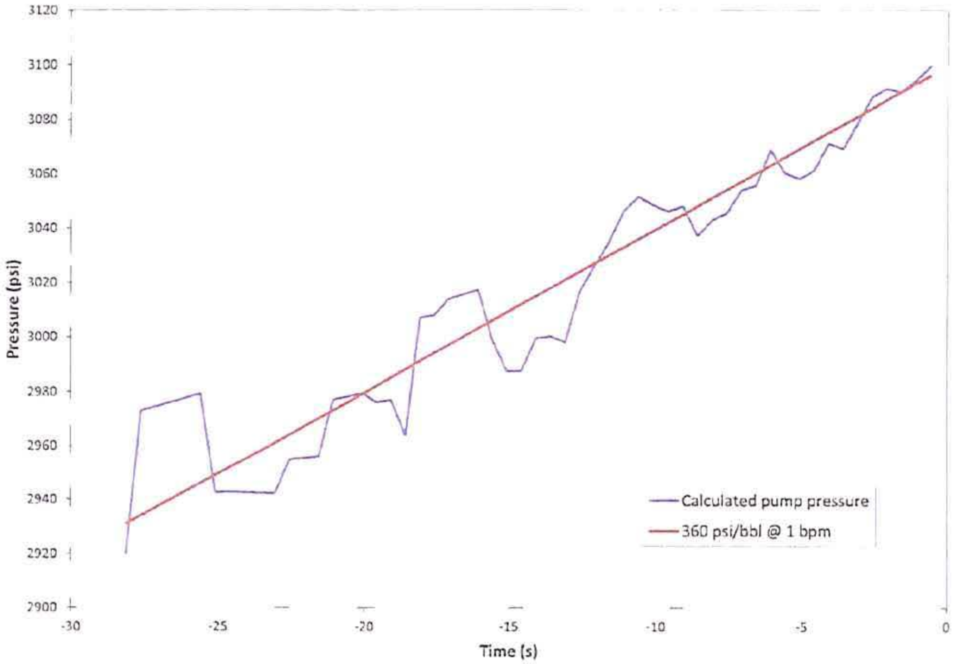

Figure 6.5: Calculated Pressure Increase Due to 1 bpm flow into Blocked Pipe and Increase for Compressibility of 360 psi/bbl

6.4 RESULTS FOR METHOD OF CHARACTERISTICS SIMULATION

6.4.1 Simulation of Flow Surge #1

MOC calculations were used to estimate the flow rate through the float collar during Flow Surge #1. Several friction models were available in the program (as described above), and the flow surge was modeled using each method. The calculated pump pressure at the upstream inlet for each of the friction models is shown in Figure 6.6, along with drill pipe pressure (analogous to pump pressure) measured during Flow Surge #1, assuming that the float collar did not convert. As illustrated, the surge decays over time and the pump pressure decreases to a level required to maintain steady-state recirculation. As expected, the Newtonian friction model under-predicts the steady-state circulation pressure because it does not account for the behavior of the drilling fluid at low flow rates. The Bingham model over-predicts the steady-state frictional losses. The Power Law model slightly under-predicts the circulating pressure, but provides the closest values.

Based on this comparison with the circulating pressure predictions, the Power Law model was chosen as the best model for this analysis, and the results below are calculated using the Power Law friction model.

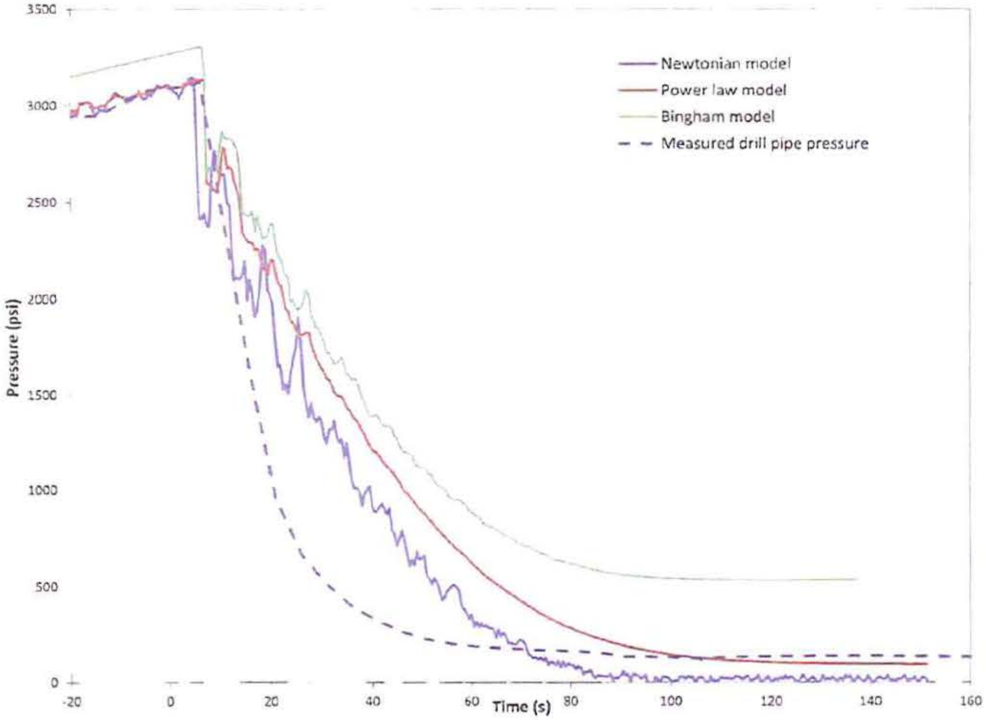

Figure 6.6: Comparison of Measured Drill Pipe Pressure during Flow Surge #1 and Pump Pressures Calculated with MOC for an Unconverted Float Collar and Three Friction Models

A simulation was then run to investigate the expected flow and pressure distribution that would occur if the float collar did not convert during Flow Surge #1. Figure 6.7 shows the calculated pressure (minus the hydrostatic pressure) at the pump during Flow Surge #1, along with the calculated pressures at the upstream and downstream sides of the float collar. Time zero represents the moment that the blockage cleared. The results show that, because of the high flow resistance at the unconverted float collar, pressure in the shoe track (downstream of the float collar) drops rapidly after the blockage clears, while pressure upstream of the float collar remains at near the pump pressure. The pressure decay is shown to occur over a period of about 100 seconds if the float collar does not convert.

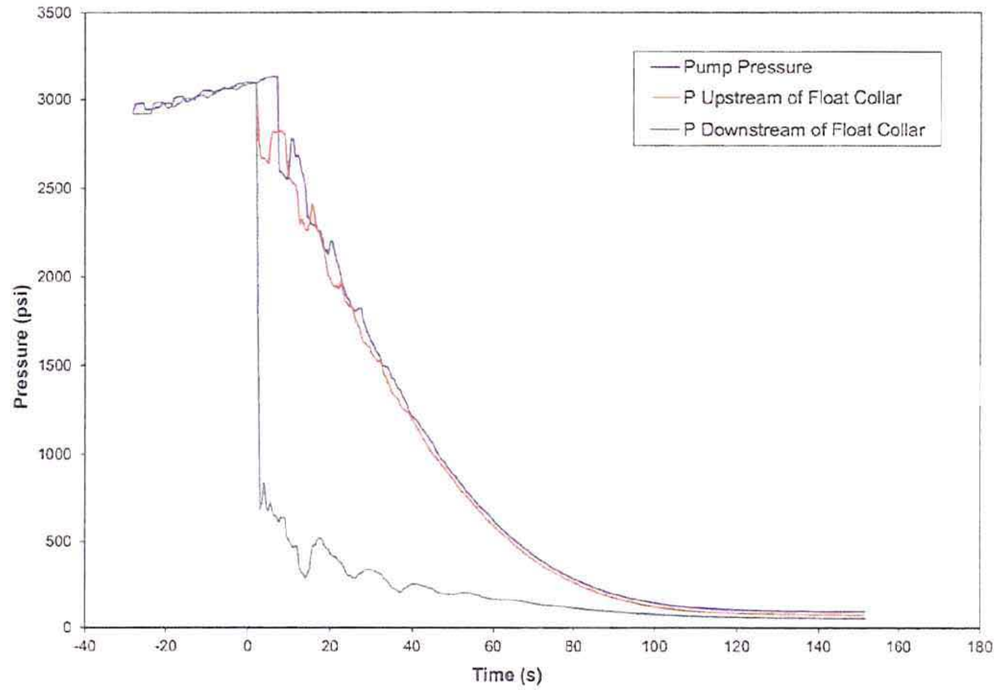

Figure 6.7: Calculated Pressure Values at Pump and at Upstream and Downstream Ends of Float Collar during Flow Surge #1 for Unconverted Float Collar

Figure 6.8 shows the calculated flow rates at the float collar, reamer shoe, and rig deck outlet for the same simulation (float collar does not convert). The figure shows that, following a brief spike in the flow rate at the reamer shoe, the float collar and reamer shoe flow rates are nearly identical during the surge. The maximum surge flow through the unconverted float collar is calculated as about 11.2 bpm (470 gpm) for this simulation. The flow rate then decays roughly linearly over time, which is in agreement with predictions of the initial calculations (see Section 6.2). The well outflow value is shown to spike to about 40 bpm and oscillate up and down during the surge due to pressure reflections from the outlet. This behavior was not observed in the well data. The discrepancy may be due to inaccuracies in the modeling of the outflow boundary condition, since the piping configuration on the rig was not known. Also, the field data collection method is not known, and any averaging or filtering has not been accounted for in the simulation. The HAL realtime worksheet provided drill-pipe data in 5-sec intervals. It is unclear whether the drill pipe data were recorded in 5-sec intervals or whether a 5-sec moving average was calculated and recorded. Data recorded in 5-sec intervals may have missed the peak flow rate, and averaging would smooth the peak out of the data. It is also possible that fluid losses to the formation occurred during the pressure surge event, and these potential losses have not been simulated here.

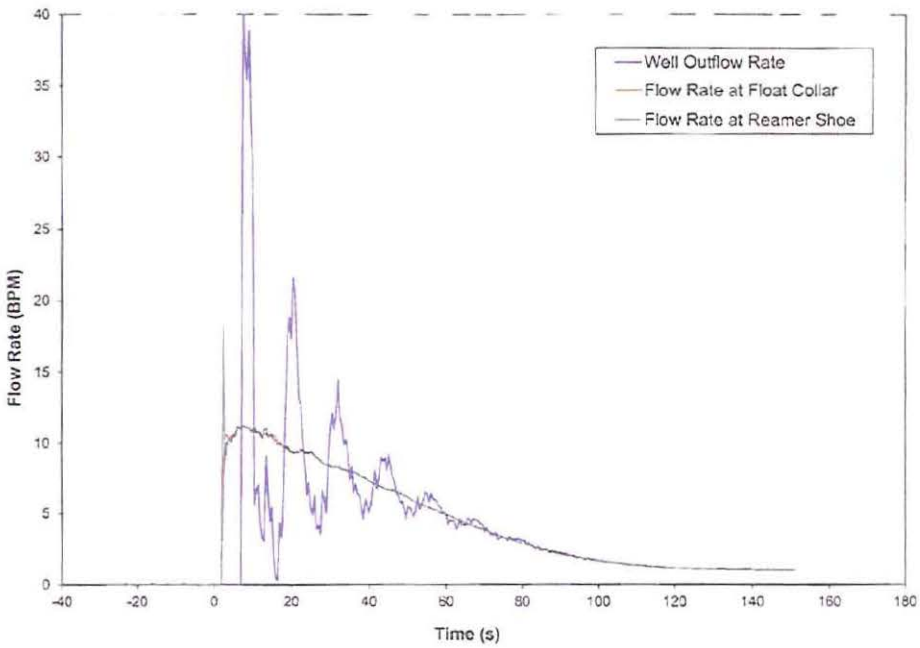

Figure 6.8: Calculated Flow Rates at Float Collar, Reamer Shoe, and Rig Deck Outlet during Flow Surge #1 for Unconverted Float Collar

An MOC simulation of Flow Surge #1 was then run for a case in which the float collar converts at the beginning of the surge event. Figure 6.9 shows the calculated pressure at the pump during Flow Surge #1, along with calculated pressures at the upstream and downstream sides of the float collar. In this case, results show that the pressure in the shoe track does not diverge significantly from the pressure upstream of the float collar, indicating that a converted collar is not a significant pressure loss in the circulation loop. For a converted float collar, the pressure decays over a period of about 40 seconds, significantly more rapidly than for an unconverted float collar.

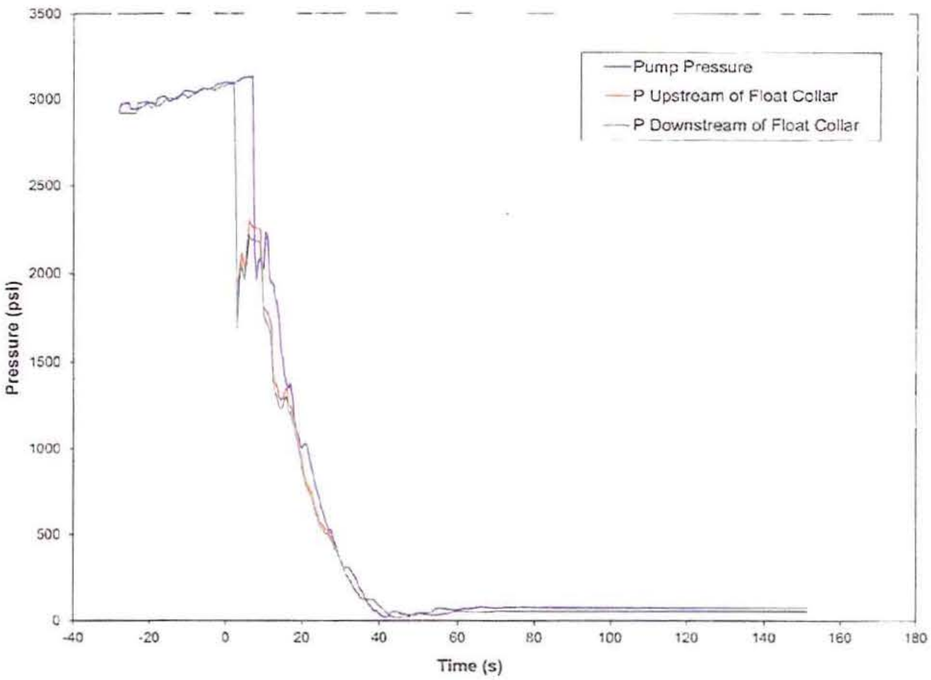

Figure 6.9: Calculated Pressures at Pump and at Upstream and Downstream Ends of Float Collar during Flow Surge #1 for Converted Float Collar

Figure 6.10 shows calculated flow rates at the float collar, reamer shoe, and rig deck outlet for this simulation. As for the previous case, the float collar and reamer shoe flow rates are nearly identical during the surge. The maximum calculated surge flow through the converted float collar spikes briefly to over 30 bpm (1260 gpm). The well outflow value peaks at over 40 bpm and again is observed to oscillate during the surge event.

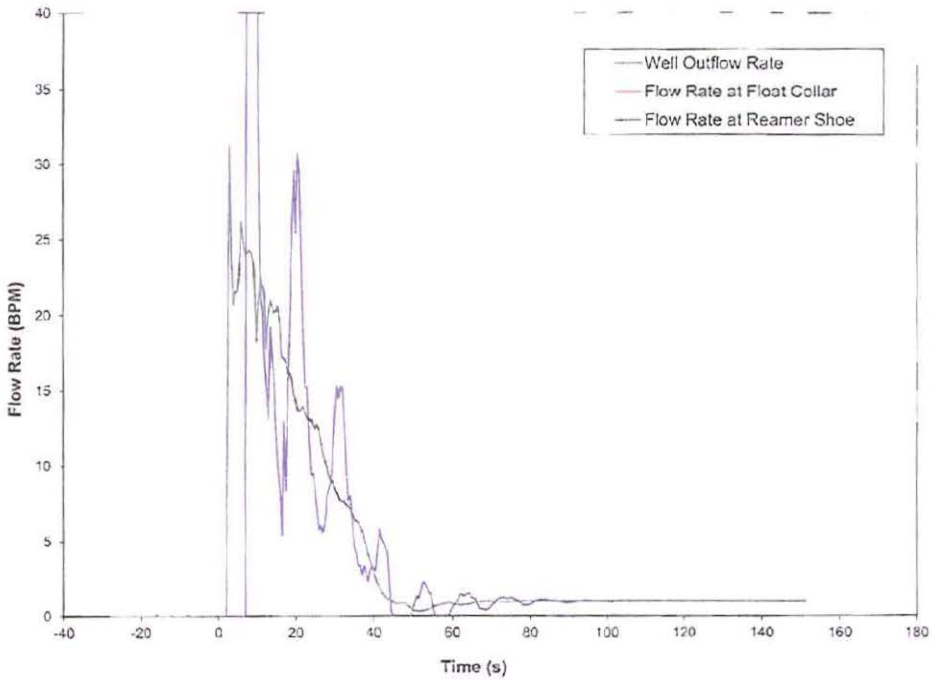

Figure 6.10: Calculated Flow Rates at Float Collar, Reamer Shoe, and Rig Deck Outlet during Flow Surge #1 for Converted Float Collar

A comparison is shown in Figure 6.11 between measured Well 252#1 pressure and calculated pressures for a converted and an unconverted float collar during Flow Surge #1. The decay rate of the field pump pressure matches more closely the simulation of a converted float collar than it does an unconverted float collar. Note that, for both the converted and unconverted simulations, the calculations show a rapid drop in pressure followed by a brief increase in pressure. This brief increase ("bump") in pressure results from physical phenomena in the modeled well. The smoothness of the curve for the measured drilling data during Flow Surge #1 suggests that it was averaged or filtered in some way (details of the data processing were not provided to SES). As can be seen in Figure 3.12, the measured drill-pipe pressure during Flow Surge #2 is also smooth, while the cement pressure curve shows a pressure "bump" during the surge.

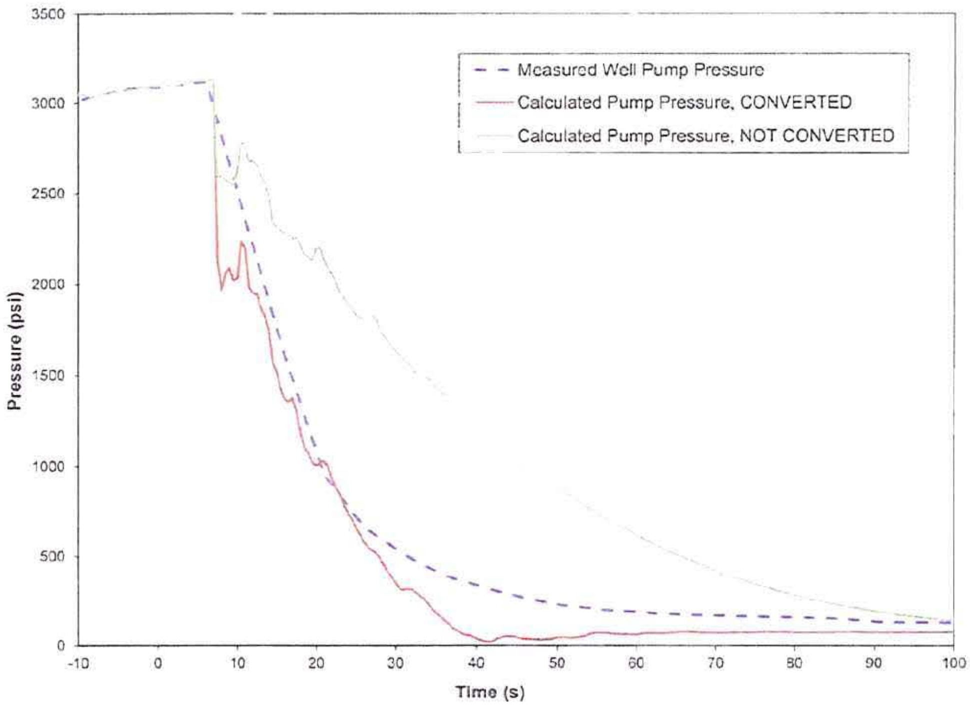

Figure 6.11: Comparison of Pump Data during Flow Surge #1 to Calculations with Unconverted and Converted Float Collar

6.4.2 Simulation of Flow Surge #2

The MOC model was also used to simulate Flow Surge #2. In this event, flow was blocked at the bottom plug when it bumped the top of the float collar. The surge occurred when the pressure was increased to rupture the burst tube in the bottom plug. During the surge, 16.7-ppg cement was assumed to flow through the bottom plug and float collar.

A simulation was run to estimate flows and pressures that would occur if the float collar did not convert during Flow Surge #1 and remained unconverted through Flow Surge #2. Figure 6.12 shows the calculated pressure at the pump during Flow Surge #2 if the float collar is not converted, along with the calculated pressures at the upstream and downstream sides of the float collar. Time zero corresponds to the bottom plug rupturing. As in the simulation of Flow Surge #1, the high flow resistance of the unconverted float collar results in a large difference in the pressures upstream and downstream of the float collar. In this case, however, the pressure downstream of the float collar begins at zero because the blockage is located at the inlet of the float collar. Pressure upstream of the float collar remains near the pump pressure. The pressure decay is slower than for Flow Surge #1 with an unconverted float collar due to the higher viscosity and density of the cement in Flow Surge #2.

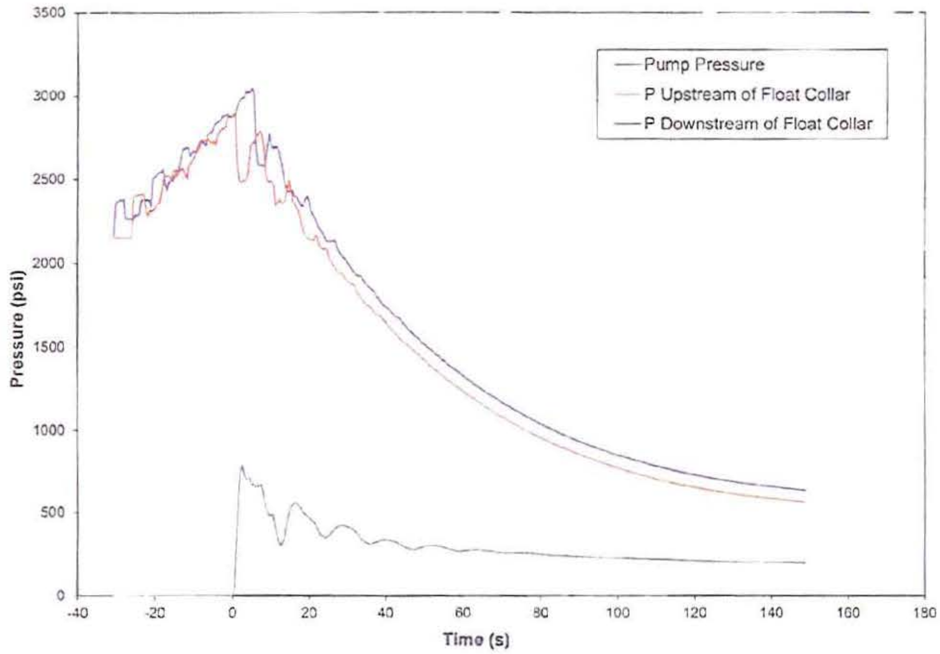

Figure 6.12: Calculated Pressures at Pump and at Upstream and Downstream Ends of Float Collar during Flow Surge #2 for Unconverted Float Collar

Calculated flow rates at the float collar, reamer shoe, and rig deck outlet for the same simulation (i.e., float collar does not convert) are shown in Figure 6.13. As was observed in the Flow Surge #1 simulations, the float collar and reamer shoe flow rates are nearly identical during the surge. The peak flow through the unconverted float collar is calculated as about 10 bpm (420 gpm) for this case.

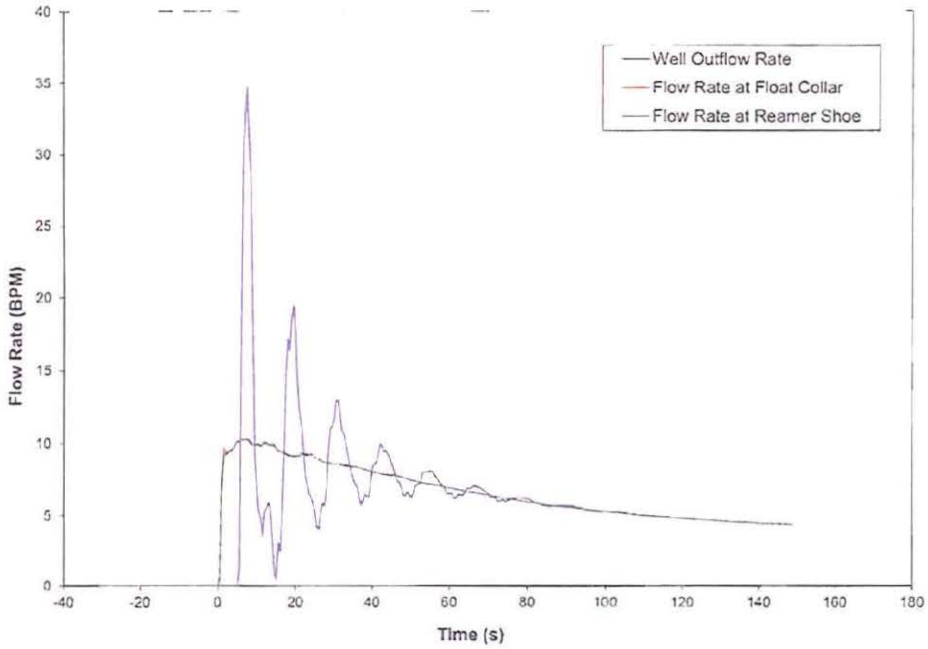

Figure 6.13: Calculated Flow Rates at Float Collar, Reamer Shoe, and Rig Deck Outlet during Flow Surge #2 for Unconverted Float Collar

Flow Surge #2 was also simulated for the case when the float collar is presumed to have converted during Flow Surge #1. Figure 6.14 shows the calculated pressure at the pump during Flow Surge #2, along with calculated pressures at the upstream and downstream sides of the float collar. Following the rupture of the bottom plug, pressure in the shoe track rapidly rises to nearly the pressure upstream of the float collar, and remains similar through the remainder of the surge. As observed for Flow Surge #1, the pressure decays significantly more rapidly for this case than for an unconverted float collar.

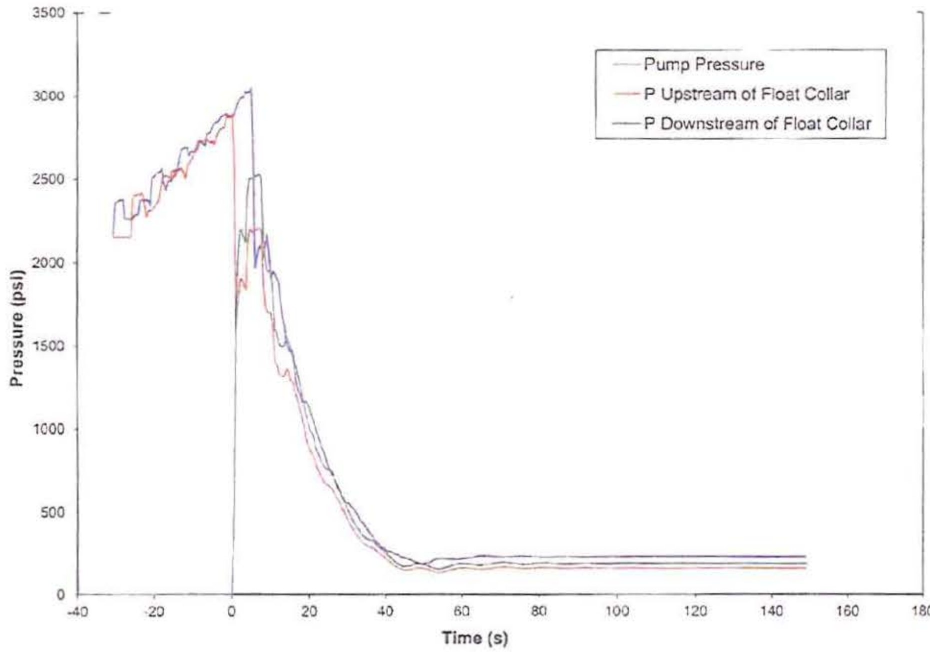

Figure 6.14: Calculated Pressures at Pump and at Upstream and Downstream Ends of Float Collar during Flow Surge #2 for Converted Float Collar

Figure 6.15 shows calculated flow rates at the float collar, reamer shoe, and rig deck outlet for this simulation (float collar is already converted). As in the previous cases, the float collar and reamer shoe flow rates are nearly identical during the surge. The peak calculated flow through the converted float collar spikes briefly to about 30 bpm (1260 gpm).

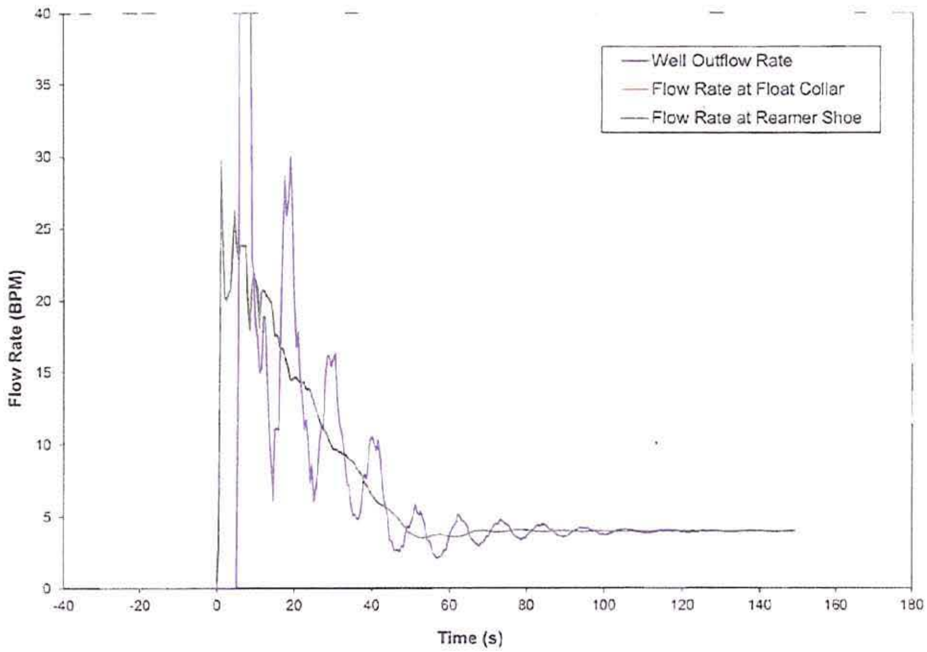

Figure 6.15: Calculated Flow Rates at Float Collar, Reamer Shoe, and Rig Deck Outlet during Flow Surge #2 for Converted Float Collar

6.4.3 Modeling of Test Configuration

The second objective of the flow modeling calculations was to model various test configurations so that a test setup could be developed in which the test flow rate was representative of the flow rate during the actual flow surge events. The basic design of the test facilities is described in Section 5.1.2 and in the SES test report [Ref. 1]. Schematics of various test configurations are also presented in Appendix D.

The test setup used a rupture disk to simulate the sudden clearing of a flow blockage in the well and the initiation of a flow surge event. Initial calculations showed that, due to the small size of the test facility compared to the length of the well piping, a means of accumulating energy would be necessary or any flow surges would occur over a very short period of time. Simulations were performed to predict the pressures and surge flow rates in the test facility configured with an accumulator both upstream and downstream of the float collar. Figure 6.16 shows a comparison of the calculated results for the well during Flow Surge #1 and for the test facility for the case when the float collar does not convert. Results show that the calculated peak surge flow rate in the test facility is about the same as that calculated for the well. The surge flow decays much more rapidly in the test facility than in the well model, dropping to the pump flow rate in near 40 seconds. The predicted pressure drop across the float collar follows a similar trend, since the flow rate and pressure drop are directly related. This simulation indicates that the test facility should provide a surge flow rate similar to what may have been experienced by the float collar in the well, but that the overall surge volume in the test facility will be conservative compared to the actual event.

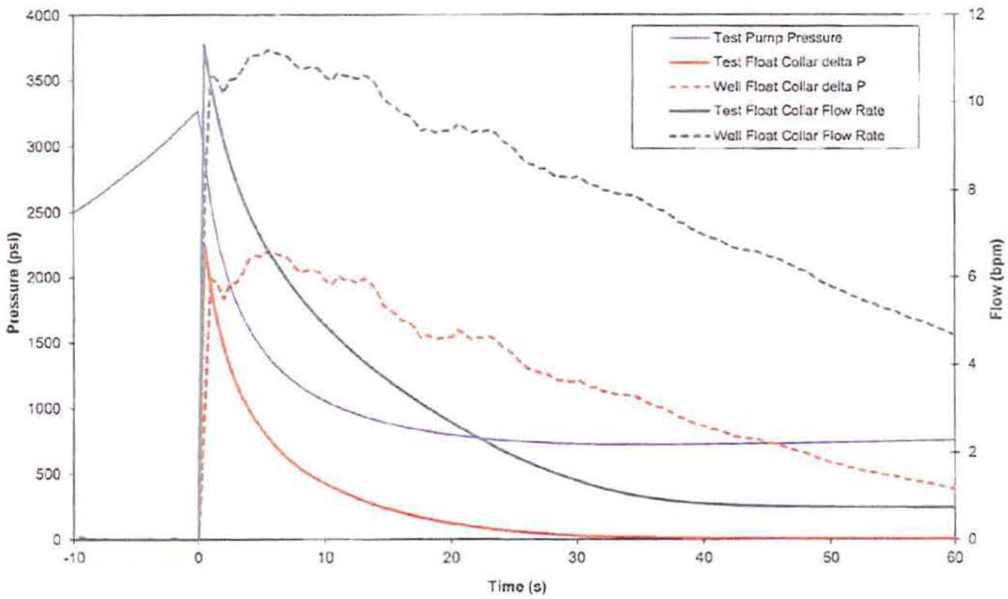

Figure 6.16: Comparison of Calculated Flow Results for Flow Surge #1 and for Test Facility with Unconverted Float Collar

The simulations were repeated to investigate the flow surge in the test facility if the float collar converts immediately after the flow surge begins. Figure 6.17 shows a comparison of the calculated results for the well during Flow Surge #1 and the test facility when the float collar is converted. The calculated peak surge flow rate in the test facility was lower than that calculated for the well. The surge flow decays much faster than for the unconverted case, dropping to the pump flow rate in about 20 seconds. Because the pressure drop across a converted float collar is not significantly greater than other loss terms in the flow loop, modeling the rest of the flow loop becomes more important in obtaining an accurate prediction of the surge decay. As for the unconverted case, these results show that the test facility should provide a peak surge flow rate similar to that experienced by the float collar in the well, but that the overall surge volume will be conservative compared to the actual event.

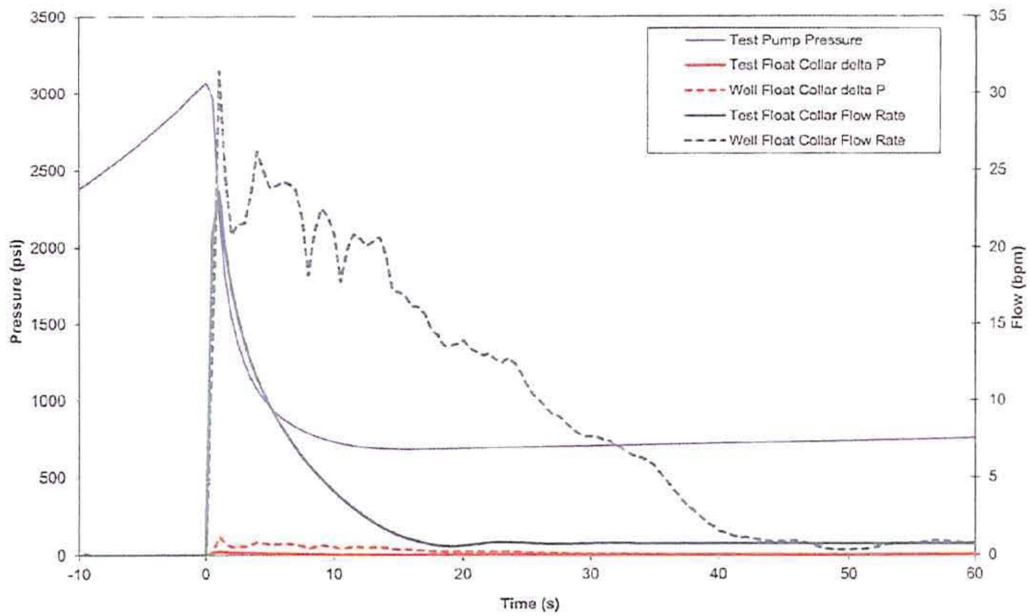

Figure 6.17: Comparison of Calculated Flow Results for Flow Surge #1 and for Test Facility with Converted Float Collar

SES has a long history of creating custom time-domain models such as used here to simulate complex dynamic systems. Specifically, SES has modeled the transient dynamics of disconnecting deepwater drilling risers, predicted performance of downhole motors, simulated pressure variation in the output of triplex mud pumps, modeled mud pulser performance, and simulated the performance of hand-held pumps and other systems. Further, this technique is used by commercial simulation software packages such as Matlab Simulink®.

Because the behavior of the pressure vs. flow during the attempts to convert the float collar was atypical, there remained a question as to whether the float collar had converted. A goal of the time-domain model was to simulate this event and provide theoretical evidence regarding whether the float collar converted due to the transient flow surge created when the blockage cleared.

The drilling mud is a non-Newtonian fluid, and a flow-loss rheology algorithm must be assumed for the simulation. The two common algorithms used to describe flow-loss behavior in non-Newtonian fluids are the Bingham Plastic and Power-Law formulations. An early finding of this flow study was that the Bingham Plastic fluid algorithm predicted excessive flow-loss pressures compared to the flow and pressure recorded on the rig. The Power-Law flow loss equations were found to yield results much closer to measured data.

7.3 RESULTS FOR TIME-DOMAIN SIMULATION

7.3.1 Simulation of Flow Surge #1

For simulation of Flow Surge #1, SES used the drilling data that showed that the pumps had been started and stopped several times during the "conversion attempt 9" immediately preceding the surge event (see Figure 3.6 and Figure 3.7). The pump flow rate and time data were used as a "forcing function" in the model. A blockage was assumed to be present at the bottom of the reamer shoe; the flow rate was set to zero at that point. Once the modeled surface pressure reached 3121 psi (the maximum pressure recorded during Flow Surge #1), this zero flow condition was removed from the model. In this way, the surge event was simulated to produce a "depressurization" curve that could be compared to the actual field data recorded.

The depressurization curve was produced using two different operational conditions: with and without conversion of the float collar. To simulate conversion, the mass and forces on the float collar were modeled, and the acceleration, velocity, and position of the float collar fluid were computed if the differential pressure on the float collar exceeded 600 psi (the median of the specified 500–700 psi conversion pressure). A nominal frictional drag load was placed on the float collar and the conversion time was predicted. If the differential pressure exceeded 600 psi, the float collar was assumed to have converted, and the flow resistance added by the float collar was removed.

When Flow Surge #1 was modeled assuming no conversion, the auto-fill tube was not allowed to move and the flow resistance provided by the float collar remained in the model throughout the simulation time. A very important tell-tale of conversion is that, if the float collar converts, the pressure in the casing will decrease rapidly after the "blockage" is cleared (i.e., the restrictive auto-fill tube is removed from the flow path). On the other hand, if the float collar remains unconverted, well pressure will decrease more gradually. Actual de-pressurization curves are available from drilling data for comparison with simulated results.

Results of the simulation of Flow Surge #1 yielded several notable observations. First, the simulated surface pressure best agreed with actual rig data (including the ~360 psi/bbl measured compressibility with blockage) when the bulk modulus of the well fluid was set to 305,000 psi. (Bulk modulus is a property of fluids that reflects their volumetric "stiffness," and is expressed as the pressure increase that results when the fluid is compressed.) This particular value is slightly below the theoretical bulk modulus of water. It is known that the observed bulk modulus in the field will be slightly less than the theoretical values due to the elasticity of the well casing. The actual bulk modulus of the well fluid is not known since this parameter is not commonly reported. However, the modeled bulk modulus was almost exactly what would be expected for water in a wellbore. This agreement adds credibility to the model results. With this value for bulk modulus, the pressure traces generated by the simulation agreed almost perfectly with the recorded data.

A second observation from the simulation results is that the assumed location of the blockage must have been correct, that is, near the bottom of the well. The pressurization rate of a well subjected to net in-flow is dictated by the fluid bulk modulus and the total volume being subjected to pressure. The blockage location defines the well volume. Since there was good agreement between the model and measured pressure data, the location of the blockage must have been correctly positioned near the bottom of the well.

A third observation was that, if the float collar was allowed to convert during Flow Surge #1, it did so. In other words, the flow surge that occurred following release of the blockage was sufficient to convert the float collar. The simulation indicated that the time it would have taken for the float collar to fully convert was on the order of 0.02 seconds. The simulated pressure decay also agreed closely with actual surface pressure data (Figure 7.1).

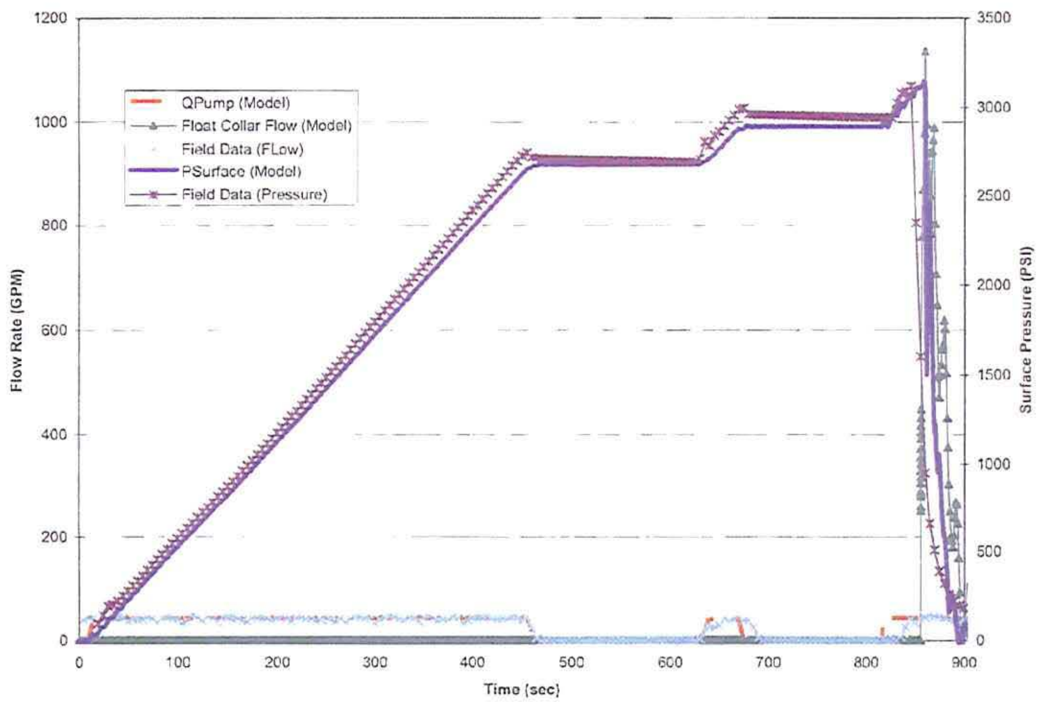

Figure 7.1: Simulated and Actual Pressure Decay for Flow Surge #1 (float collar converted)

If the float collar was not allowed to convert during Flow Surge #1, the simulated pressure decayed much more slowly than the drilling data (Figure 7.2). Therefore, the simulation results indicate that the actual float collar must have converted during Flow Surge #1.

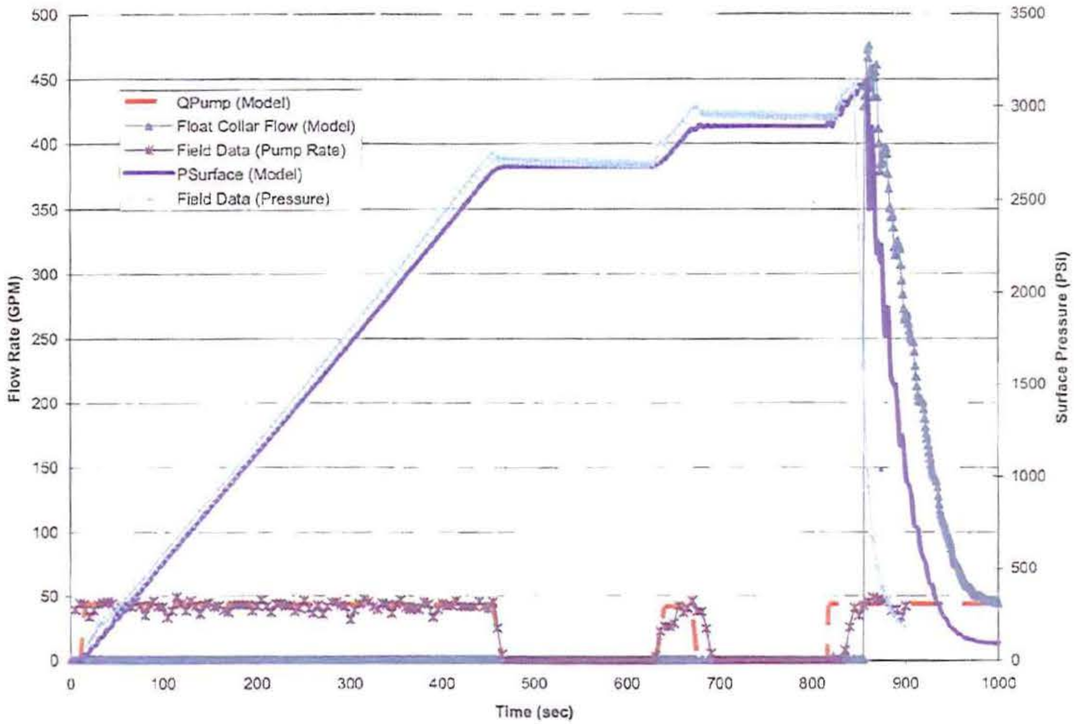

Figure 7.2: Simulated and Actual Pressure Decay for Flow Surge #1 (float collar not converted)

7.3.2 Simulation of Flow Surge #2

Flow Surge #2 resulted from the attempt to "bump the plug." To simulate this event, the model used for Flow Surge #1 was modified slightly to increase the fluid density to account for cement above the float collar. The simulated blockage point was moved to directly above the float collar. This model of Flow Surge #2 was developed to further confirm whether the float collar had previously converted. Therefore, cases were run with the float collar already converted at the start of the event, as well as cases where the auto-fill tube was still in place.

Simulated results for Flow Surge #2 with a previously converted float collar showed pressure decay rates similar to the field data (Figure 7.3), whereas the case with an unconverted float collar yielded significantly slower pressure decay rates (Figure 7.4). These findings are further theoretical evidence that the float collar converted during Flow Surge #1.

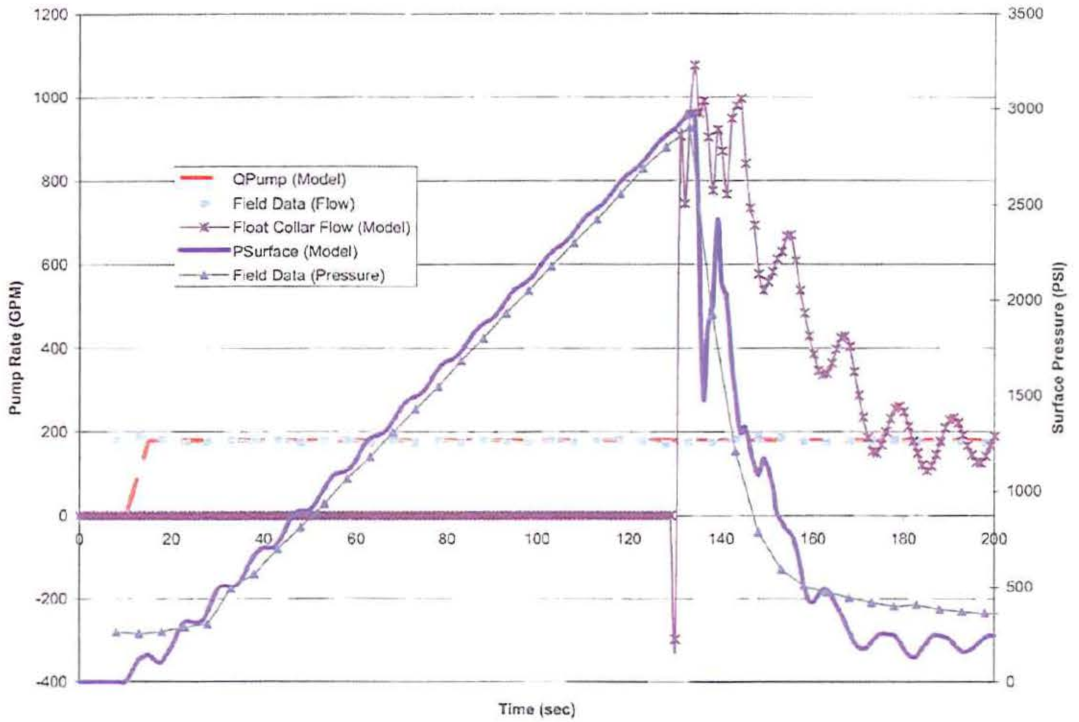

Figure 7.3: Simulated and Actual Pressure Decay for Flow Surge #2 (float collar converted)

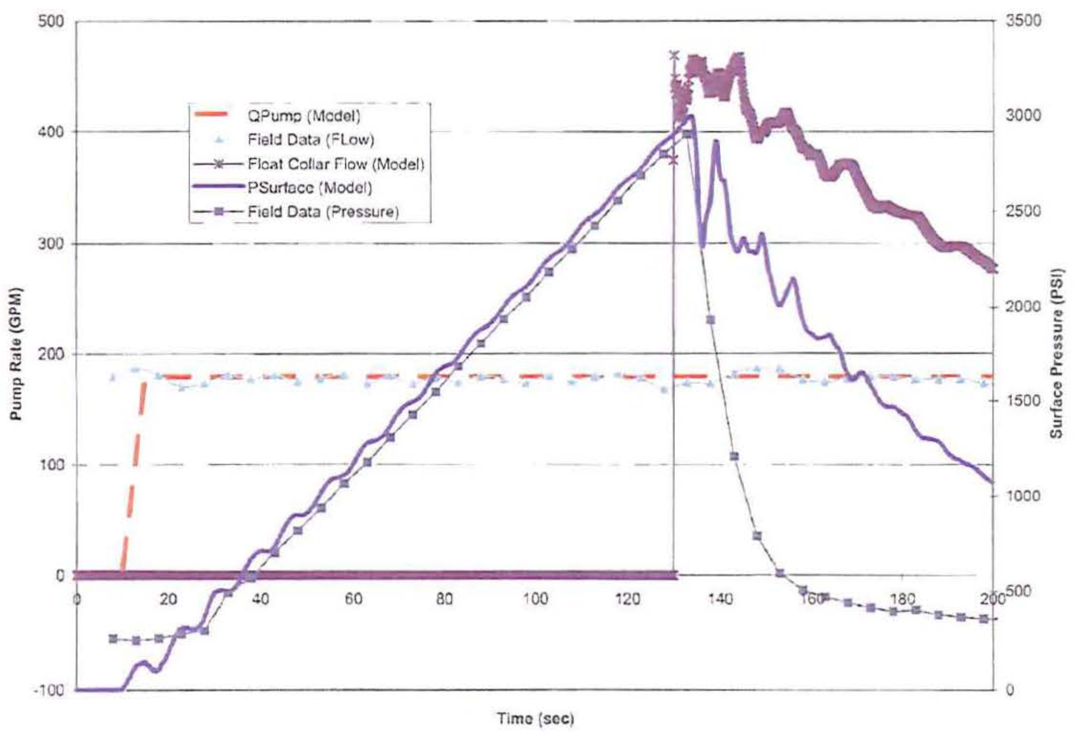

Figure 7.4: Simulated and Actual Pressure Decay for Flow Surge #2 (float collar not converted)

7.3.3 Modeling of Test Configuration

SES performed flow testing to document the performance of the float collar using both steady-state flow and transient flow. Steady-state testing was designed to measure conversion conditions for comparison with performance data published by Weatherford. A pump truck was used to gradually increase flow rate through specimen float collars while observing the flow rate that converted the float collar and measuring the differential pressure across the float collar at the time of conversion.

Transient flow testing to represent the flow surge events was more complicated because the fluid volumes and pressures in the actual well could not be duplicated with any practical available equipment due to the large volume of the well fluid. Fortunately, the time frame of interest was limited to the short period required to convert the float collar, so the entire well volume does not impact the float collar immediately following the clearing of blockage. Two pressure vessels (accumulators) were pre-charged with gas pressure and used to provide a source and sink for pressurized fluid to simulate the transient events. To simulate a well blockage clearing at approximately 3000 psi, a burst disk device was installed downstream of the float collar in the test setup.

A version of the time-domain model was created that simulated the test setup to help predict test facility performance and to observe if the test facility could create conditions that mimicked the actual well for the short amount of time involved in the conversion. This approach was believed to be conservative in that the actual well had orders of magnitude more energy to produce sustained flow during conversion. The model predicted that the test setup would be sufficient to create conditions that would cause conversion.

The predicted float collar peak flow rate for an unconverted float collar is 11.2 bpm (470 gpm) and for a converted float collar is 30.9 bpm (1300 gpm).

8. SUMMARY AND COMPARISON OF DRILLING DATA, FLOW SIMULATIONS, AND TEST DATA

The float collar study conducted by SES included several related tasks as follows:

- Review of the Well 252#1 drilling data recorded during cementing operations
- Identification of specific points of interest during operations
- Evaluation of the float collar and reamer shoe structural strength
- Flow calculations to estimate the flow rates and pressure drops associated with conversion of the float collar
- Various physical tests on the float collar in a test facility

This section provides comparisons of the various aspects of the study.

8.1 STRUCTURAL STRENGTH OF COMPONENTS

The calculated minimum strength of the float collar and reamer shoe should have sufficient capacity to sustain anticipated loads during cementing operations (see Section 4).

8.2 COMPARISON OF FLOW SIMULATION METHODS 1 AND 2

Results of the two flow simulation methods (Method 1 – Method of Characteristics (Section 6) and Method 2 – Time-Domain Modeling (Section 7)) were similar. This was true for simulating both the field conditions of float collar conversion and the physical tests.

Data describing the flow rates and pressure drops at the float collar are not available for Well 252#1. Recorded surface data, such as flow-in and flow-out rates and drill-pipe pressure, were used as input or output variables to help estimate the float collar data. Therefore, for the field conditions, the float collar data from the two simulation methods can only be compared to each other, while, for the test conditions, results from the two methods are compared to each other and to the measured test data.

Simulated flow rates and pressure drops for Flow Surge #1 were similar for the two methods, both for converted and unconverted float collar conditions. Both methods guided the design of the Flow Surge #1 test setup, which generated a predicted peak flow rate of about 11 bpm and a flow decay that was faster (more conservative) than the calculated field flow rate decay. Table 8.1 compares the two methods assuming the float collar remains unconverted. The table shows the agreement between the two simulation methods for the predicted Well 252#1 flow rate and pressure differential across the float collar. Table 8.1 also shows that, for the selected test setup, the two methods predict a similar peak flow rate and then a flow rate decay that is faster than the predicted Well 252#1 decay, again meaning that the test will be conservative with respect to the estimated flow rates. The measured test data for the rehearsal test with simulated auto-fill tube confirmed the predicted flow rates.

As was true for Flow Surge #1, the simulated flow rates and pressure drops for Flow Surge #2 were similar for the two flow simulation methods. Both methods estimated that the peak flow rate through the (converted) float collar for Flow Surge #2 was near 30 bpm based on field data. However, achieving this peak flow rate would have required further reductions in piping length, which was not practical with current laboratory testing. Instead, a second flow surge event was tested with a lower peak flow rate of about 13 bpm (extrapolated; maximum recorded flow rate was 10.8 bpm). Table 8.2 provides a comparison of results for the converted float collar. The table shows that a higher test peak flow rate is needed to match the predicted Well 252#1 peak flow rate for an already-converted float collar.

Table 8.1: Comparison of Test Data and Analysis Results (Unconverted Float Collar)

Flow Blockage Test through Simulated Float Collar – Flow Surge #1 14 ppg mud; 1 bpm pump rate; 2780 psi burst disk; 500 psi initial back-pressure Upstream accumulator with 262 gal; downstream accumulator with 385 gal						
Elapsed Time[1] (sec)	Test Data		Test Simulation Analysis Results (Power Law)			
	Rehearsal Test with Simulated Auto-Fill Tube		Method #1 – Method of Characteristics		Method #2 – Time Domain	
	Flow Rate (bpm)	Δ Pressure (psi)	Flow Rate (bpm)	Δ Pressure (psi)	Flow Rate (bpm)	Δ Pressure (psi)
0	9.5[2]/8.0[3]	2000	11.5	2340	11.2	2200
6	7.3	540	7.9	1100	7.5	1000
12	5.3	290	6	635	5.7	580

Estimated Float Collar Flow Rate and Δ Pressure – Flow Surge #1 Surge #1 Field Conditions – 14 ppg mud, 1 bpm pump rate, 2900 psi drill-pipe pressure						
Elapsed Time[1] (sec)	Field Conditions Data		Test Simulation Analysis Results (Power Law)			
			Method #1 – Method of Characteristics		Method #2 – Time Domain	
	Flow Rate (bpm)	Δ Pressure (psi)	Flow Rate (bpm)	Δ Pressure (psi)	Flow Rate (bpm)	Δ Pressure (psi)
0	*Unknown*	*Unknown*	10.6	1990	12.0	2500
6	*Unknown*	*Unknown*	11.2	2190	11.4	2300
12	*Unknown*	*Unknown*	10.6	1980	10.7	2000

Notes: [1] Elapsed time since conversion of float collar.
[2] Extrapolated from test results.
[3] Maximum recorded flow rate.

Table 8.2: Comparison of Test Data and Analysis Results (Converted Float Collar)

Flow Blockage Test through Simulated Float Collar – Flow Surge #1
14 ppg mud; 1 bpm pump rate; 2780 psi burst disk; 500 psi initial back-pressure
Upstream accumulator with 262 gal; downstream accumulator with 385 gal

Elapsed Time[1] (sec)	Test Data		Test Simulation Analysis Results (Power Law)			
	Second Flow Surge Thru Converted Float Collar[2]		Method #1 – Method of Characteristics		Method #2 – Time Domain	
	Flow Rate (bpm)	Δ Pressure (psi)	Flow Rate (bpm)	Δ Pressure (psi)	Flow Rate (bpm)	Δ Pressure (psi)
0	13.0[3]/10.8[4]	1536	36.9	133	30.9	600
6	8.8	18	13	17	12.2	2.6
12	5.0	2.3	4.5	2	5.2	0.3

Estimated Float Collar Flow Rate and Δ Pressure – Flow Surge #1
Surge #1 Field Conditions – 14 ppg mud, 1 bpm pump rate, 2900 psi drill-pipe pressure

Elapsed Time[1] (sec)	Field Conditions Data		Test Simulation Analysis Results (Power Law)			
			Method #1 – Method of Characteristics		Method #2 – Time Domain	
	Flow Rate (bpm)	Δ Pressure (psi)	Flow Rate (bpm)	Δ Pressure (psi)	Flow Rate (bpm)	Δ Pressure (psi)
0	*Unknown*	*Unknown*	31.5	120	26.6	20
6	*Unknown*	*Unknown*	24.3	72	20.4	7.6
12	*Unknown*	*Unknown*	20.6	52	16.9	8.3

Notes: [1] Elapsed time since peak of flow surge through float collar.
[2] Results from tests of float collar SN-04.
[3] Extrapolated from test results.
[4] Maximum recorded flow rate.

8.3 COMPARISON OF STEADY-STATE FLOW RATE CONVERSION TEST AND WEATHERFORD CONVERSION EQUATION

The validity of Weatherford's float collar conversion equation was important to confirm because it relates flow rate and fluid density to pressure drop through the float collar. The steady-state flow rate conversion tests conducted by SES confirmed that the Weatherford conversion equation is generally accurate for 14-ppg fluid, and that the pressure drop after conversion is very small. Using the Weatherford conversion equation for the flow calculations in simulation methods 1 and 2 along with interpretation of the drilling data was shown to be a valid approach.

8.4 FLOW SURGE #1 CONVERSION COMPARISONS

Both flow simulation methods guided the design of the test setup for Flow Surge #1. The analytical methods were used to estimate the float collar flow rate and pressure drop for Flow Surge #1, and then to estimate the float collar flow rate for various test configurations. The Flow Surge #1 test setup was designed to generate the predicted peak flow rate (11 bpm) and a flow rate decay that was faster than the calculated field condition flow rate decay.

Physical testing with short-duration flow of 14-ppg mud at a peak flow rate of 11 bpm (simulating Flow Surge #1) was consistently shown to convert the float collar.

Physical testing of Flow Surge #2 to convert the float collar was not performed since testing with Flow Surge #1 consistently converted the float collar.

8.5 INDICATIONS OF FLOAT COLLAR CONVERSION

Based on the general validation of the Weatherford conversion equation for 14-ppg fluid by testing (Section 8.3) and the possible conversion during Flow Surge #1 (Section 8.4), the observed field flow data described in Section 3.1.7 support the assertion that the float collar had converted. During the described field events of constant flow-in and flow-out, the average system pressure drop was about 360 psi. The pressure drop for the unconverted float collar is about 325 psi (for 175 gpm), and the Well 252#1 system had a built-in pressure loss (according to BP) of about 300 psi; therefore, the data suggest that the measured pressure drop during this interval indicates that the float collar had converted.

The flow simulation data show significant differences between data for unconverted and converted float collars. This difference could be used as an indicator of the state of the float collar. For example, Figure 7.1 and Figure 7.2 (for Flow Surge #1) show that Well 252#1 data are in better agreement if the float collar has converted. Figure 7.3 and Figure 7.4 (for Flow Surge #2) show a very similar difference. Therefore, a comparison of Well 252#1 data and simulation data indicates that conversion had occurred during Flow Surge #1.

8.6 SECOND FLOW SURGE WITH CONVERTED FLOAT COLLAR

If the float collar converted prior to Flow Surge #2, then the question was raised as to whether a second flow surge might possibly damage the valve flappers. The second flow surge was an approximation of Flow Surge #2. The test simulation of the second flow surge used a lighter fluid, the blockage was at least 5 ft away (see discussion below), and the blockage was considered both above and below the float collar. The inertia of the flapper and the stiffness of the flapper spring would tend to maintain the valve closed, resisting the load from peak flow surge. This would, in turn, load the pin holding the flapper in place. Failure of the flapper pin would render the valve ineffective.

The test of a second flow surge with a converted float collar used the same test setup as Flow Surge #1. Rather than setting up the second flow surge test with mud of equivalent rheology to 16.7-ppg cement (corresponding to Flow Surge #2), this test was performed with 14-ppg mud. Both flow simulation methods estimated that the float collar peak flow rate was about 30 bpm for the field conditions with a second flow surge and a converted float collar. However, the second flow surge was tested with an (extrapolated) peak flow rate of about 13 bpm. The lower peak flow rate, compared to the estimated 30 bpm, is believed to have been caused by frictional losses in the piping, accumulator dip tube, burst disc (not opening fully), and the Chiksan connections. Reducing the losses from all these factors was not practical with current laboratory testing. Piping length was reduced slightly between tests of float collars SN-05 and SN-04; however, this modification did not change the (measured) peak flow rate. In addition to the reduced peak flow rate, the other difference for the second flow surge test with respect to Well 252#1 field conditions was that the blockage in the physical test was placed about 5 ft from the float collar and not at the top of the float collar, as was indicated by the field data.

The second flow surge physical test did not damage the float collar, based on visual inspection.

Physical testing of a second flow surge after conversion did not cause damage to the converted float collar valve flappers. However, the test did not, and could not, simulate the field conditions accurately enough to be conclusive. Flow losses at the accumulator dip tube, burst disc (not opening fully), and the Chiksan connections contributed to reducing the test peak flow surge from about 30 bpm to about 13 bpm.

9. REFERENCES

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5. "Flow of Fluids Through Valves, Fittings, and Pipe," Technical Paper 410-M (Metric Ed.), Crane Co., 1982.

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7. API RP-13D, "Rheology and Hydraulics of Oil-Well Fluids," 6th Ed., 2010.

APPENDIX A

DATA PROVIDED BY BP

APPENDIX A-1

BP DOCUMENT REFERENCES

Table A-1.1: Data Provided by BP for Well MC252#1

Issuer	Filename	Content	Component	Reference #	Revision	Sheets
BP						
	Cement Job Data.xls	Drilling Data	Well MC252#1 Data	N/A	N/A	N/A
	Timeline Animation for 5-25-10 Presentation.ppt	Timeline	Well MC252#1 Data	N/A	5/25/2010	25
	Plugs and FC.pps	Animation	Cementing Operation	N/A	N/A	N/A
	Macondo_MC 251_1_Schematic_Rev15 2_04222010_withBOP.xls	Schematic	MC252#1 Well Schematic (As Drilled)	N/A	15	N/A
K&B Machine						
	1816_001.pdf	Drawing	Crossover, 9-7/8" 62.80# TSH 523 Box x 7' 32.0# TSH 513 Pin LG	KB-TOX-0978-0014	B	1
Weatherford						
	M45AP 7 H513 32ppf 6 drift.pdf	Drawing	M45AP float collar Assembly, Mid Bore, 5-7 bpm (500-700 psi)	D000401284	A	1
	Mid-bore Auto Fill Float Collar.pdf	Brochure	Mid-Flow Auto-Fill Tube Float Collar Model M47A0	M47A-TU	9/19/2003	9
	DWP ELAS-TU-006 N-R Rev B 3-31-2010.pdf	Brochure	Dual Wiper Plug Cementing Systems (DWR-NR System)	ELAS-TU-006	B	10
	WFT000432 (L0093328).pdf	Document	Monthly Rental Report	WFT000432-436	N/A	5
	WFT000437 (L0093329).pdf	Sale Order	Guide Shoe, Float Collar, Centralizer Sub	WFT000437-479	N/A	43
	WFT000480 (L0093330).pdf	Data/Drawings	7" CSG x 8-1/4" OD Reamer Shoe w/Baffle	WFT000480-486	A.4	7
	WFT000487 (L0093331).pdf	Data/Drawings	Plug Set, SSR 7" x 9-5/8" DWP HP N-R	WFT000487-496	C.1	10
	WFT000497 (L0093332).pdf	Test Data	Plug Test Report	WFT000497-519	N/A	23
	WFT000520 (L0093333).pdf	Data/Drawings	Centralizer Subs, ROT 7" 541R HCQ125 Hydril 513 32ppf 10.75" OD	WFT000520-522	A.3	3
	WFT000523 (L0093334).pdf	Data/Drawings	7" Guide Shoe M22W Conc. Cmpst. HCQ125 Hydril 513 32 ppf	WFT000523-525	A.2	3
	WFT000526 (L0093335).pdf	Data/Drawings	Float Collar, 7" M45AP HCQ125 NR Hydril 513 32 ppf	WFT000526-528	A.2	3

APPENDIX A-2

WELL DATA FOR WELL MC252#1

Table A-2.1: Well MC252#1 Well Data

Based on data provided by BP

ANNULUS DATA

Start Depth ft	End Depth ft	Liner ID in	Casing OD in	Annulus Area in^2	Hydraulic Diam. in	Section Length ft
0	5067	19.5	6 5/8	264.18	12 7/8	5067
5067	11153	14.85	9 7/8	96.61	5	6086
11153	12488	12.375	9 7/8	43.69	2 1/2	1335
12488	12803	12.375	7	81.79	5 3/8	315
12803	14759	10.711	7	51.62	3 5/7	1956
14759	17168	8.625	7	19.94	1 5/8	2409
17168	18130	9.875	7	38.10	2 7/8	962
18130	18304	8.5	7	18.26	1 1/2	174
18304	18360	8.5			8 1/2	56

TUBING DATA

Start Depth ft	End Depth ft	Casing OD in	Weight ppf	ID in		Section Length ft
0	880	6.625	48	5.345		880
880	5109	6.625	46	5.375		4229

PRODUCTION CASING DATA

Start Depth ft	End Depth ft	Casing OD in	Weight ppf	ID in		
5067	12488	9.875	62.8	8.625		7421
12488	18111	7	32	6.094		5623
18111	18114	7	32	6.094		3
18114	18304	7	32	6.094		190

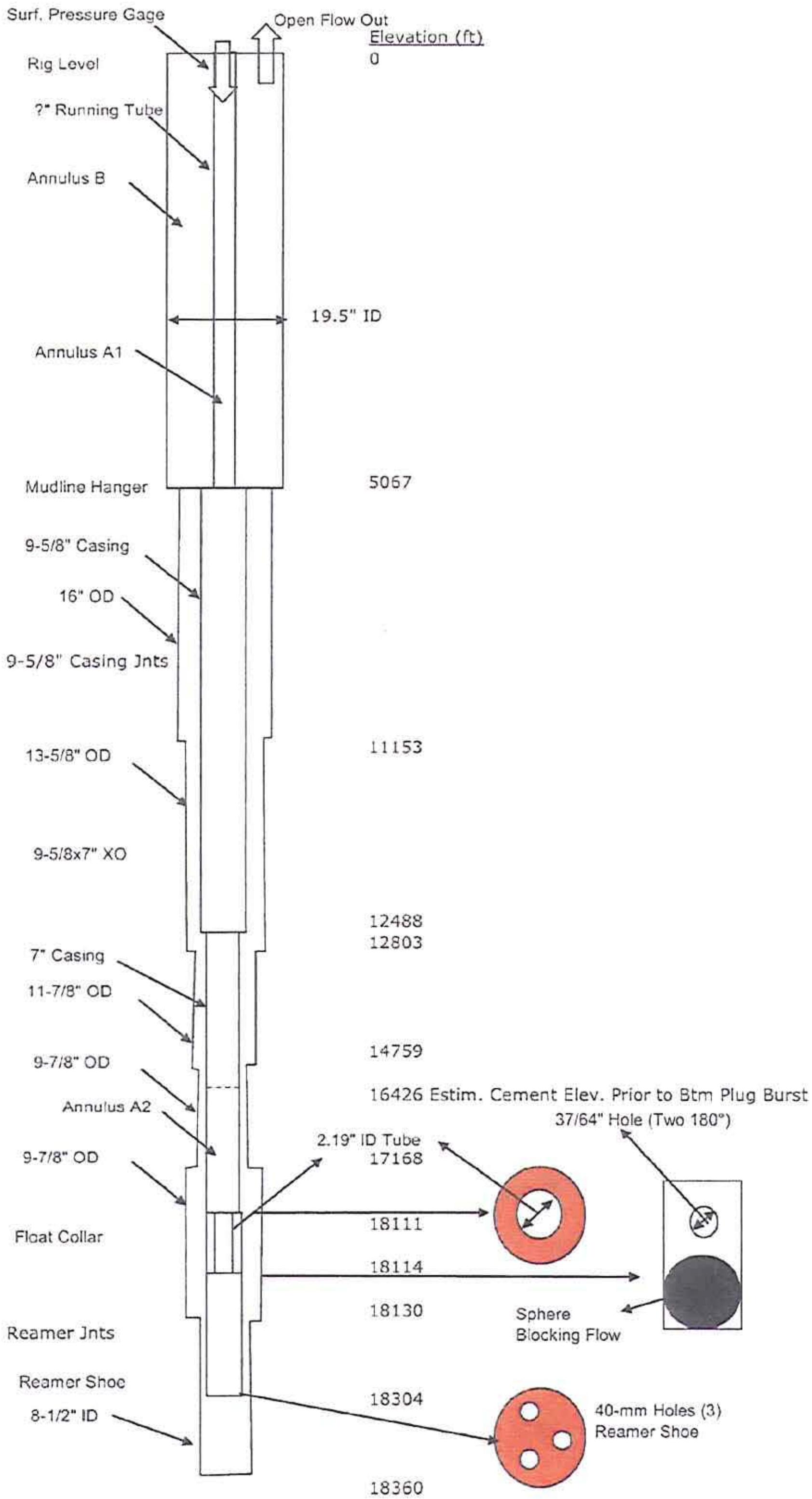

Figure A-2.1: Well MC252#1 Well Schematic

APPENDIX A-3

FLUID DATA FOR WELL MC252#1

Andreas Katsounas Friday, October 29, 2010 1:23 PM

Subject: RE: Float Collar Testing Sequence
Date: Friday, July 9, 2010 4:47 PM
From: Winters, Warren J <Warren.Winters@bp.com>
To: Jim Kronjaeger Jim.Kronjaeger@stress.com
Cc: Ken Young Ken.Young@stress.com, Andreas Katsounas Andreas.Katsounas@stress.com, Tommy Power Tommy.Power@stress.com, Renter, Stephen Stephen.Renter@bp.com

Jim,

1. Although hydrocarbon based mud was used in the Macondo well, we recommend water based fluid for the flow loop testing. We will judge from water based test results whether supplemental testing with hydrocarbon based mud is advisable.

2 The 14.0 ppg mud properties in the Macondo well were

Mud Weight	lb/gal	14.0@80
Funnel Viscosity	s/qt	94
Rheology Temp	°F	150
R600/R300		71/43
R200/R100		32/20
R6/R3		10/9
PV	cP	28
YP	lb/100ft²	15
10s/10m/30m Gel	lb/100ft²	14/23/29
API Fluid Loss	cc/30min	--
HTHP Fluid Loss	cc/30min	2.4@250
Cake APT/HT	1/32"	--/1
Unc Ret Solids	%Vol	27
Correct Solids	%Vol	26.15
Synthetic	%Vol	52.5
Uncorr Water	%Vol	20.5
Synthetic/Water Ratio		72/28
Alkal Mud (Psm)		0.9
Cl- Whole Mud	mg/L	27000
Salt	%Wt	17.09
Lime	lb/bbl	1.17
Emul Stability		248

It is probably most important that the water based mud for flow loop testing closely matches the density value, and approximately matches PV.

The 16.7 ppg mud is a substitute for 16.7 ppg cement slurry. The cement slurry properties were

Mud Balance Density

Density (ppg)

16.7

Test temp (°F)	600	300	200	100	60	30	20	10	6	3
80	160	84	56	28	26	8	6	4	2	2

An empirical correlation of the multi-speed viscometer data indicated PV = 80, YP = 4.

As for sand content of the 14.0 ppg fluid, let's stick to the API RP 10F sand content guideline of 2-4 vol% as this will be used in an API RP 10F-style durability test
As for sand content of the 16.7 ppg fluid, let's accept what it becomes once the 14.0 ppg fluid is weighted-up to 16.7 ppg

Warren J. Winters
Senior Drilling Engineer
EPT Drilling & Completions
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voice (281) 366-3897
mobile (281) 865-6788
facs (281) 366-5025

BP Corporation
501 Westlake Park Blvd, Houston, TX 77079-2696
MC 13 106B
P.O. Box 3092, Houston, TX 77253-3092

Andreas Katsounas **Friday, October 29, 2010 2:21 PM**

Subject: RE: Yield Point
Date: Monday, August 23, 2010 3:47 PM
From: Winters, Warren J <Warren.Winters@bp.com>
To: Andreas Katsounas Andreas.Katsounas@stress.com, Renter, Stephen Stephen.Renter@bp.com
Cc: Ken Young Ken.Young@stress.com, Larry Matta Larry.Matta@stress.com, Jack Miller Jack.Miller@stress.com

In Steve's note (time-stamped Wed 8/18/2010 9:05 AM) he stated "The closest data point we have is a YP of 12 at 150deg F".
That was in reference to the mud properties report of 17 Apr 2010 (PV 30 YP 12 @ 150F). The reported properties on 18 Apr 2010 were PV 29 YP 13 and on 19 Apr 2010 were PV 28 YP 14, all at 150F.

The cement yield point was very low (PV 62 YP 1 @ 135F). 135F was the estimated bottom-hole circulating temperature.

We are confident of the 135F temperature estimate. It has been independently modeled several times.

Warren J. Winters
Senior Drilling Engineer
EPT Drilling & Completions

mail winterwj@bp.com <mailto:winterwj@bp.com>
desk (281) 366-3897
mobile (281) 865-6788
facs (281) 366-5025

APPENDIX B
DATA PROVIDED BY WEATHERFORD

APPENDIX B-1

WEATHERFORD DOCUMENT REFERENCES

Table B-1.1: Data Provided by Weatherford

Documents Provided by Weatherford's Law Firm of Jones & Walker

Issuer	Filename	Content	Component	Reference #	Revision	Sheets
Weatherford						
	Package #1 - Dated June 30, 2010	Data/Drawings	Reamer Shoe and Float Collar	WFT000480-486	N/A	N/A
			Reamer Shoe and Float Collar	WFT002021-2028	N/A	N/A
			Reamer Shoe and Float Collar	WFT003076-3175	N/A	N/A
	Package #2 - Dated July 15, 2010	Data	Float Collar	WFT003180-3192	N/A	N/A
	Package #3 - Dated August 2, 2010	Data	Float Collar and Plugs	WFT003193-3195	N/A	N/A

APPENDIX C

COMPONENT STRENGTH ANALYSIS RESULTS

(Content Not Included –

Confidential Data per Section 2.1)

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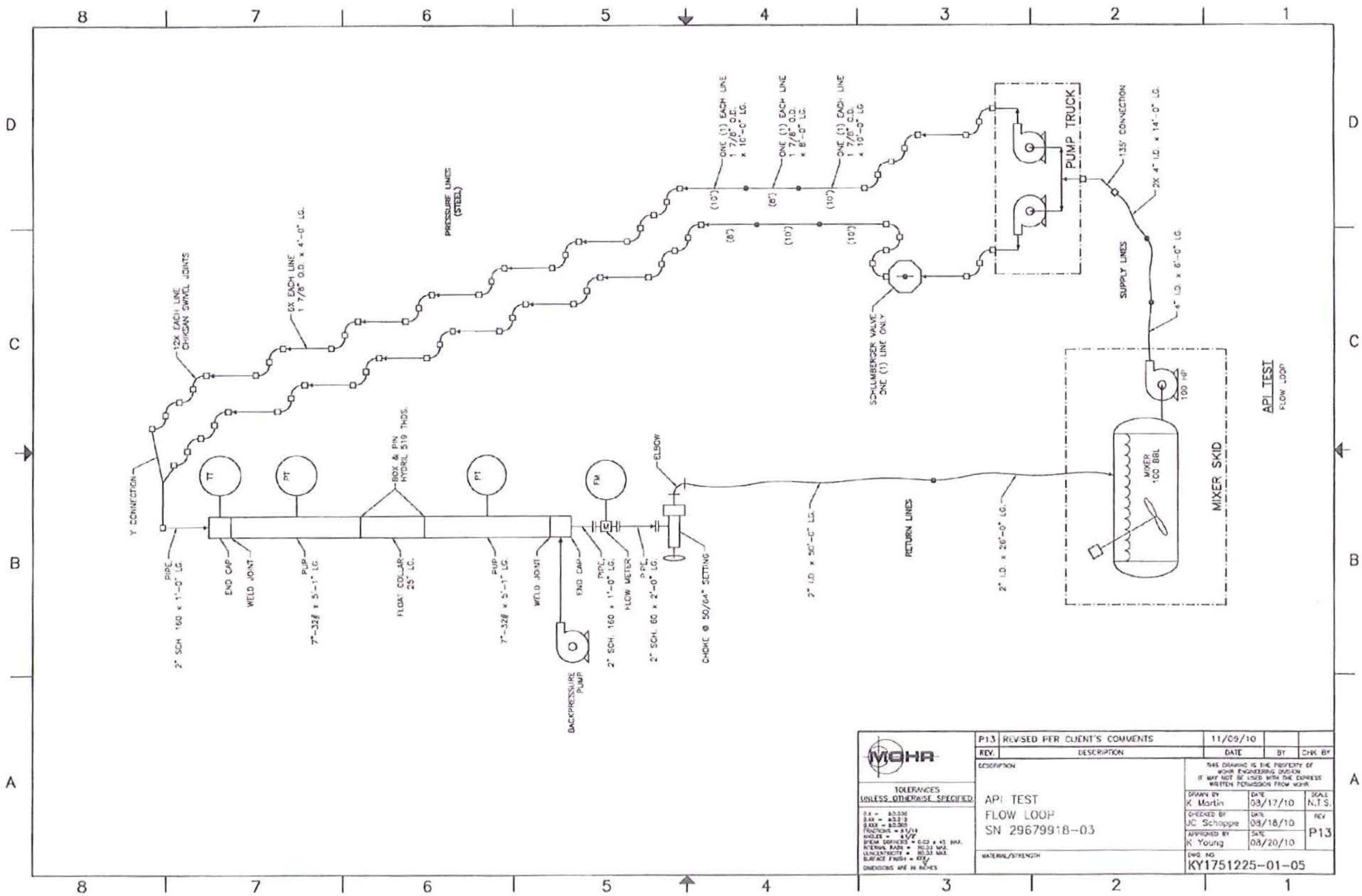
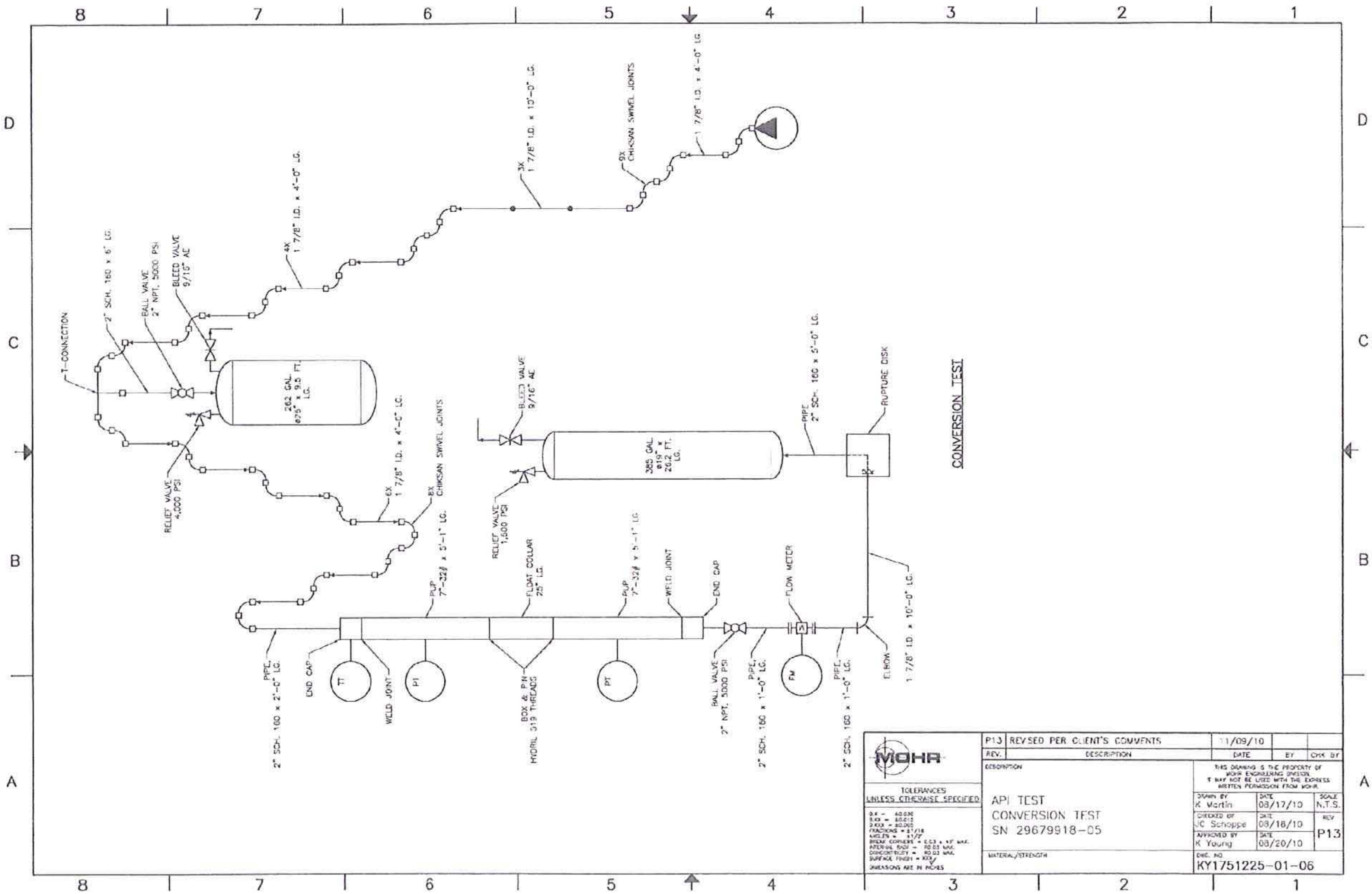
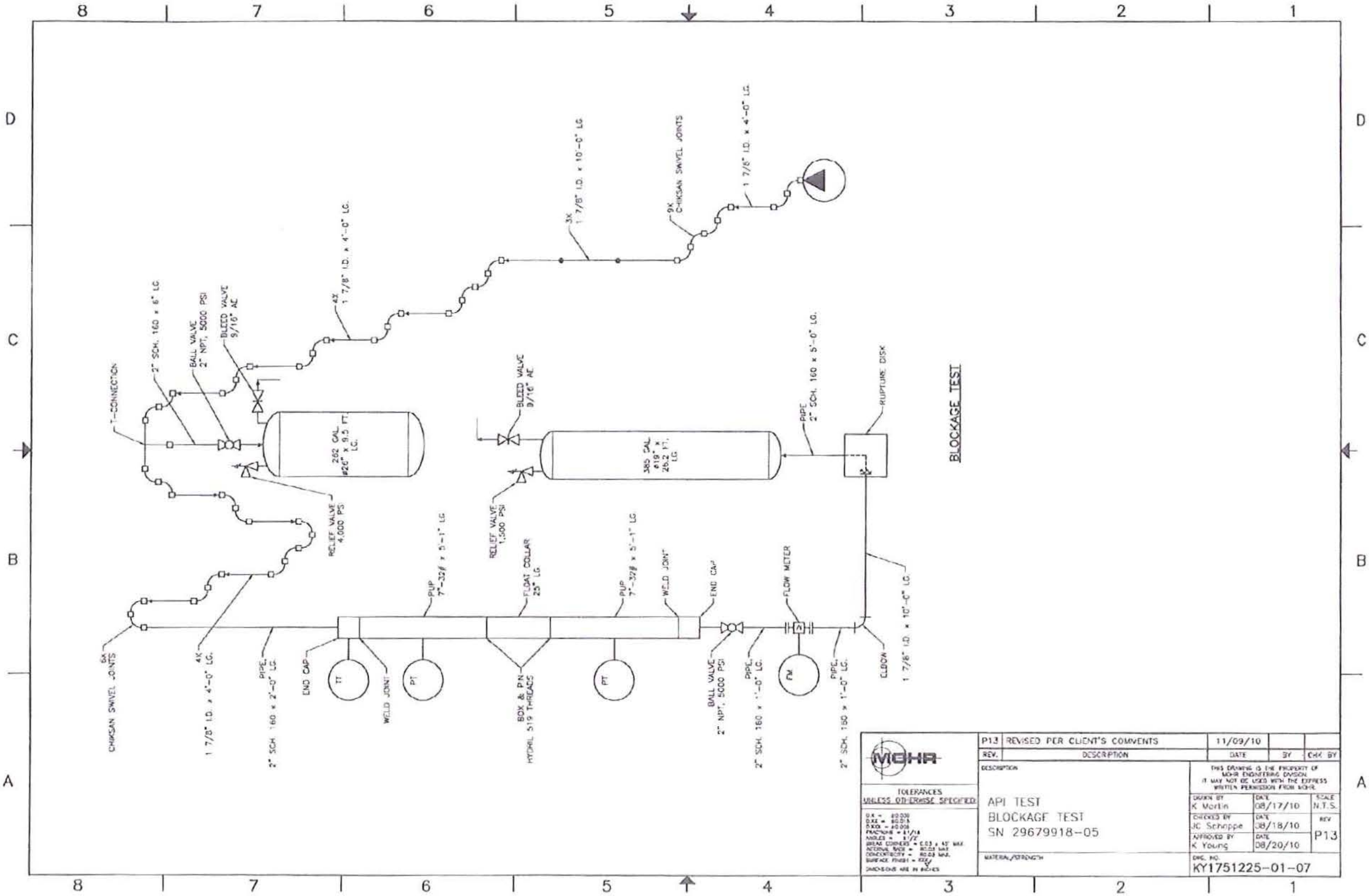
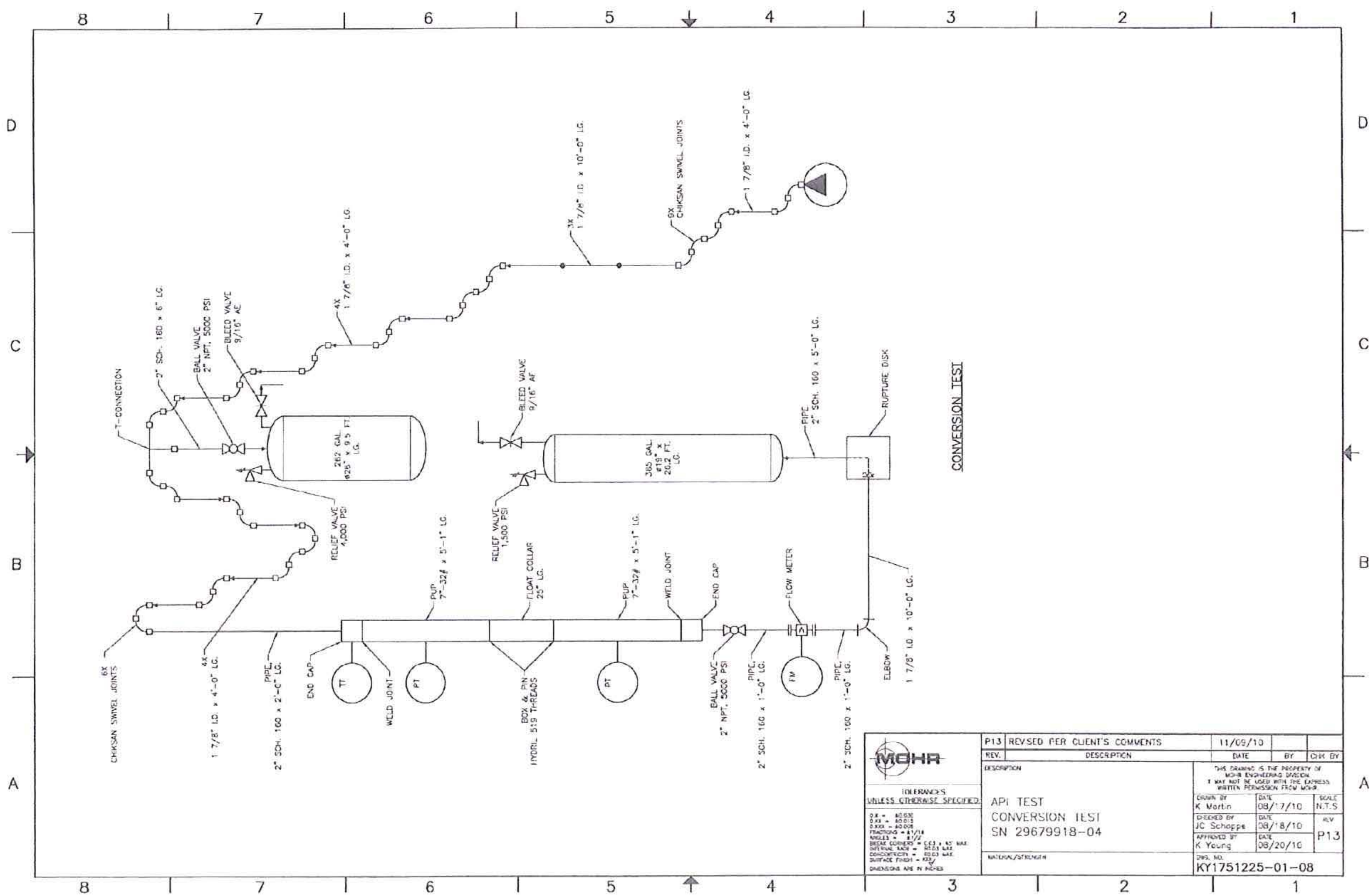
APPENDIX D
SCHEMATICS OF TEST CONFIGURATIONS
FOR PHYSICAL TESTING

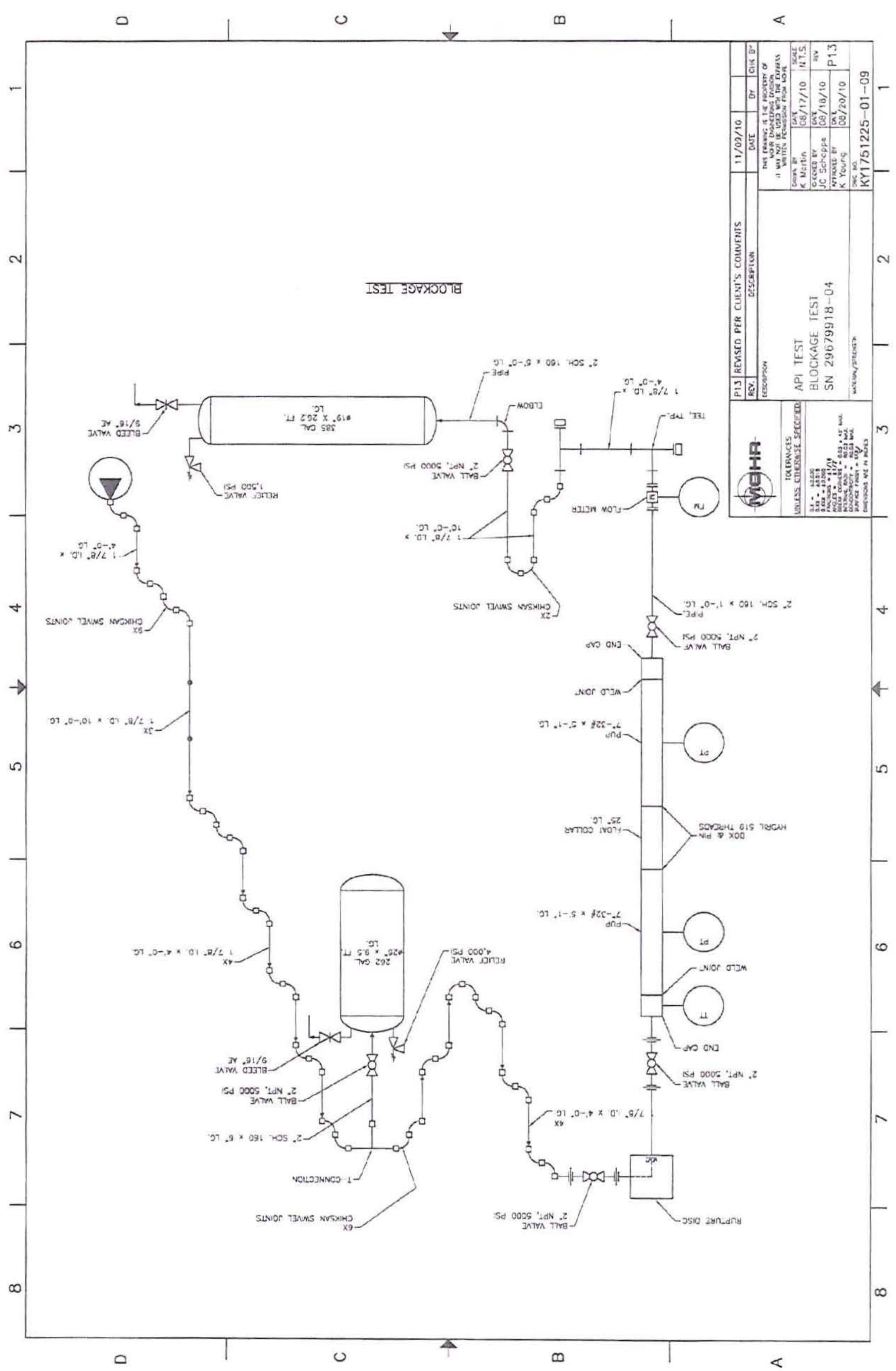

API TEST
FLOW LOOP
MIXER SKID
MIXER
100 BBL
100 HP
4" I.D. x 6'-0" LG.
2X 4" I.D. x 14'-0" LG.
135° CONNECTION
SUPPLY LINES
PUMP TRUCK
ONE (1) EACH LINE 1 7/8" O.D. x 10'-0" LG.
ONE (1) EACH LINE 1 7/8" O.D. x 8'-0" LG.
ONE (1) EACH LINE 1 7/8" O.D. x 10'-0" LG.
(10') (8') (10')
SCHLUMBERGER VALVE ONE (1) LINE ONLY
PRESSURE LINES (STEEL)
6X EACH LINE 1 7/8" O.D. x 4'-0" LG.
12X EACH LINE CHIKSAN SWIVEL JOINTS
Y CONNECTION
2" SCH 160 x 1'-0" LG. PIPE
END CAP
WELD JOINT
TT
PT
7"-32# x 5'-1" LG. PUP
FLOAT COLLAR 25" LG.
BOX & PIN HYDRIL 519 THDS.
BACKPRESSURE PUMP
FM
2" SCH. 160 x 1'-0" LG. PIPE
FLOW METER
2" SCH. 60 x 2'-0" LG. PIPE
CHOKE @ 50/64" SETTING
ELBOW
2" I.D. x 50'-0" LG.
RETURN LINES
2" I.D. x 26'-0" LG.
MOHR
TOLERANCES UNLESS OTHERWISE SPECIFIED
P13 REVISED PER CLIENT'S COMMENTS 11/09/10
REV. DESCRIPTION DATE BY CHK BY
DESCRIPTION
API TEST
FLOW LOOP
SN 29679918-03
MATERIAL/STRENGTH
THIS DRAWING IS THE PROPERTY OF MOHR ENGINEERING DIVISION IT MAY NOT BE USED WITH THE EXPRESS WRITTEN PERMISSION FROM MOHR
DRAWN BY K Martin DATE 08/17/10
CHECKED BY JC Schoppe DATE 08/18/10
APPROVED BY K Young DATE 08/20/10
SCALE N.T.S.
REV P13
DWG NO. KY1751225-01-05



WFT-MDL-00003726


BLOCKAGE TEST
CHIKSAN SWIVEL JOINTS
6X
9X
1 7/8" I.D. x 4'-0" LG.
4X
3X
1 7/8" I.D. x 10'-0" LG.
2" SCH. 160 x 2'-0" LG.
PIPE
END CAP
TT
WELD JOINT
PT
PUP
7"-32# x 5'-1" LG
BOX & PIN
HYDRIL 519 THREADS
FLOAT COLLAR
25" LG
BALL VALVE
2" NPT, 5000 PSI
2" SCH. 160 x 1'-0" LG.
FLOW METER
FM
ELBOW
1 7/8" I.D. x 10'-0" LG.
RUPTURE DISK
2" SCH. 160 x 5'-0" LG.
385 GAL
⌀19" x
26.2 FT.
LG.
BLEED VALVE
9/16" AE
RELIEF VALVE
1,500 PSI
262 GAL
⌀26" x 9.5 FT.
LG.
RELIEF VALVE
4,000 PS
T-CONNECTION
2" SCH. 160 x 6" LG
MOHR
TOLERANCES
UNLESS OTHERWISE SPECIFIED
P13 REVISED PER CLIENT'S COMMENTS 11/09/10
REV. DESCRIPTION DATE BY CHK BY
DESCRIPTION
API TEST
BLOCKAGE TEST
SN 29679918-05
MATERIAL/STRENGTH
THIS DRAWING IS THE PROPERTY OF MOHR ENGINEERING DIVISION. IT MAY NOT BE USED WITH THE EXPRESS WRITTEN PERMISSION FROM MOHR.
DRAWN BY K Martin DATE 08/17/10 SCALE N.T.S.
CHECKED BY JC Schnippe DATE 08/18/10 REV
APPROVED BY K Young DATE 08/20/10 P13
DWG. NO. KY1751225-01-07


CONVERSION TEST
RUPTURE DISK
1 7/8" I.D. x 10'-0" LG.
ELBOW
PIPE, 2" SCH. 160 x 1'-0" LG.
PIPE 2" SCH. 160 x 5'-0" LG.
FLOW METER
FM
BALL VALVE 2" NPT, 5000 PSI
END CAP
WELD JOINT
365 GAL. ø19" x 26.2 FT. LG.
PUP 7"-32# x 5'-1" LG.
PT
FLOAT COLLAR 25" LG.
BOX & PIN HYDRIL 519 THREADS
BLEED VALVE 9/16" AE
RELIEF VALVE 1,500 PSI
TT
END CAP
262 GAL. ø26" x 9.5 FT. LG.
RELIEF VALVE 4,000 PSI
PIPE, 2" SCH. 160 x 2'-0" LG.
4X 1 7/8" I.D. x 4'-0" LG.
BALL VALVE 2" NPT, 5000 PSI
2" SCH. 160 x 6" LG.
T-CONNECTION
6X CHIKSAN SWIVEL JOINTS
3X 1 7/8" I.D. x 10'-0" LG.
1 7/8" I.D. x 4'-0" LG.
MOHR
TOLERANCES UNLESS OTHERWISE SPECIFIED
P13 REVSED PER CLIENT'S COMMENTS 11/09/10
REV. DESCRIPTION DATE BY CHK BY
API TEST
CONVERSION TEST
SN 29679918-04
THIS DRAWING IS THE PROPERTY OF MOHR ENGINEERING DIVISION. IT MAY NOT BE USED WITH THE EXPRESS WRITTEN PERMISSION FROM MOHR.
DRAWN BY K Martin DATE 08/17/10 SCALE N.T.S
CHECKED BY JC Schoppe DATE 08/18/10 REV P13
APPROVED BY K Young DATE 08/20/10
DWG. NO. KY1751225-01-08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ø19" X 26.2 FT. LG.
262 GAL.
ø26" X 9.5 FT. LG.
BLEED VALVE 9/16" AE
RELIEF VALVE 1,500 PSI
RELIEF VALVE 4,000 PSI
BALL VALVE 2" NPT, 5000 PSI
2" SCH. 160 X 6'-0" LG. PIPE
ELBOW
1 7/8" I.D. X 4'-0" LG.
TEE, TYP.
FLOW METER
1 7/8" I.D. X 10'-0" LG.
2X CHIKSAN SWIVEL JOINTS
6X CHIKSAN SWIVEL JOINTS
3X 1 7/8" I.D. X 10'-0" LG.
4X 1 7/8" I.D. X 4'-0" LG.
2" SCH. 160 X 1'-0" LG. PIPE
END CAP
WELD JOINT
PUP 7"-32# X 5'-1" LG.
FLOAT COLLAR 25" LG.
HYDRIL 519 THREADS BOX & PIN
2" SCH. 160 X 6" LG.
T-CONNECTION
RUPTURE DISC
P13 REVISED PER CLIENT'S COMMENTS 11/09/10
REV. DESCRIPTION DATE BY CHK BY
API TEST
BLOCKAGE TEST
SN 29679918-04
DRAWN BY K. Martin DATE 08/17/10
CHECKED BY JC Schoppa DATE 08/18/10
APPROVED BY K. Young DATE 08/20/10
SCALE N.T.S.
REV P13
DWG. NO. KY1751225-01-09