U-TUBING RELATED TO PRIMARY CEMENTING

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ABSTRACT

For some time, the Petroleum Industry has recognized that fluids will experience "U-tubing" at some point during the placement in the wellbore. This "vacuum" effect has been especially noticeable during primary cementing operations, and it is largely attributed to the fact that the fluids used in cementing often are more dense than those originally in the wellbore. The phenomenon of the U-tube effect, although recognized, has never been fully understood. To better understand and predict this phenomenon, a mathematical algorithm has been developed to aid in analyzing fluid placement in the wellbore. It is based on a mass balance, an energy balance, a modified Bernoulli equation, and a full tracking routine to analyze fluid placement. Discussions encompassed in this paper will be to define the U-tube phenomenon, to evaluate its effects relating to cementing techniques, and to present an actual liner job in comparison to predictions made by this algorithm.

INTRODUCTION

As technology for the Petroleum Industry has progressed through the years, mathematical models or algorithms have been proposed to resolve and to predict the outcome of events from directional drilling to hydraulic fracturing and so forth. With all of these advancements in analysis and prognosis related to drilling and production operations, primary cementing has long been overlooked concerning dynamic analysis of fluid placement in the wellbore. Primary cementing operations play an important role in the producing life of a well. The objective of primary cementing is to obtain efficient zonal isolation and to protect the pipe. Without proficiency in cementing practices and techniques, this objective cannot be attained. One of the major factors contributing to this lack of placement analysis has been a deficiency in the knowledge of slurry movement through the wellbore. It has long been acknowledged that during most primary cementing operations, the well will U-tube or "go on a vacuum." The understanding of this phenomenon, and its effects, will aid in defining initial conditions, job design, implementation and evaluation for primary cementing.

BACKGROUND

Most all fluids pumped into the well for primary cement jobs have densities equal to or greater than the mud originally in the hole. This density differential aids mud removal to improve zone separation and pipe support. Because of these density differences, fluids will frequently experience U-tubing during the job. To assist in the understanding of this phenomenon, a manometer may be used to illustrate its effects in a static environment (Figure 1). The manometer in this case is open on both ends of the tube and, therefore, it is exposed to atmospheric pressure. Two fluids -- water and mercury -- are placed inside the tube. These have been chosen because they are immiscible. Due to the extreme density differential between these fluids, 1.0 vertical in. of mercury on one side of the "U" will support the hydrostatic pressure exerted by 13.6 vertical in. of water on the other side. This same simple effect may be related to the wellbore environment during slurry placement in a static condition. The process of cement placement, however, is not static. This elementary concept of U-tubing must be expanded to encompass the dynamics of fluid movement throughout the well. To accomplish this task, a mathematical algorithm has been developed to dynamically trace fluid movement through the wellbore. This model is predicated on a material and energy balance and Bernoulli's equation modified for friction pressure drop. In order to better perceive the concepts of U-tubing relating to primary cementing operations, attention must be focused on defining the dynamics of fluid movement and its effects.

DYNAMICS OF FLUID MOVEMENT

To characterize fluid movement in the wellbore, parameters such as fluid rheology, fluid density, hole variations, casing weight and sizes, displacement rates, and hole deviations need to be clearly defined. At times, it can be an overwhelming task to consider all variables in the engineering design of a job. Therefore, to simplify the characterization of U-tubing, the following assumptions will be made for a hypothetical well (Figure 2). In placing the cement on the backside, only three fluids will be pumped: a spacer slurry, a cement system and the displacement fluid which is the original mud. The casing is all the same size and weight, and the open hole varies in diameter. The pump rate will be held constant throughout the entire job and no plugs will be dropped. Also, assume

$$\rho_m < \rho_s < \rho_c.$$

In a static state before the operation commences and when no wellhead or backside pressure is applied, the summation of hydrostatic pressures from each partition both for the casing and annulus will be equal. These partitions will be based on variations in geometry, hole deviations, fluid densities and localized formation fracture gradients.

$$\sum_{i=1}^{m} (P_{ha} \cdot \cos A)_i - \sum_{j=1}^{n} (P_{hc} \cdot \cos B)_j = 0.0 \qquad (1)$$

When pumping begins with our spacer slurry, fluid dynamics must be incorporated into our characterization. Therefore, various fluid friction pressures must be accounted for due to fluid movement. In order to institute flow and to maintain it, wellhead pressure will be required.

$$P_{ba} + \sum_{i=1}^{m} (P_{ha} \cdot \cos A + P_{fa})_i - \sum_{j=1}^{n} (P_{hc} \cdot \cos B - P_{fa})_j - P_{wc} \qquad (2)$$

Assume $P_{ba} = 0.0$ psi.

As our spacer and/or cement slurries continue to be pumped downhole, due to their specific densities, the amount of wellhead pressure needed to maintain an equality for Equation 2 will steadily decrease. This process will persist until the wellhead pressure required is null. At this time, U-tubing in a dynamic state begins. The major effects of this phenomenon are illustrated in Figure 2a. Due to the growth of hydrostatic pressures inside of the casing, an imbalance exists at bottom conditions for each column. In order to maintain a conservation of energy, the fluids in the wellbore will pursue a rate to attain a balance or neutral point at the bottom. This acceleration in rate increases fluid friction pressures helping to maintain an equilibrium. As a consequence, the fluid level will fall away from the surface resulting in the creation of a void space below the wellhead. The fluids in the wellbore are free-falling, since under dynamic conditions, the fluids are not dependent on wellhead pressure for movement. With time, the fluid level continues to fall causing the void to extend into the casing. In this free-falling stage, the return rates will always be higher than our assumed constant pump rate. This stage will initially experience a gradual acceleration of fluid movement, but eventually as the job continues, a deceleration occurs because of the heavier fluids starting to round the shoe. When this occurs, our return rate will slowly converge back to the pump rate. Eventually, the effects of U-tubing cause the return rate and the pump rate to equalize again (Figure 2b). Then, the neutral point crosses over from the casing column tending to be heavier to the annular column. U-tubing is now reversed causing still deceleration of fluid movement, but also return rates that are less than our assumed pump rate. Once more, to maintain a continuity and energy balance, the fluids seek a rate to produce a bottom-hole equilibrium (Figure 2c). In doing so, the top of the fluid level inside the casing actuates toward the surface. This back-filling stage of U-tubing initially encounters deceleration of fluid movement, but dramatically accelerates toward the end of convergence of the fluid level and the wellhead. Many engineers refer to this point of convergence as "catching the fluid column." Throughout the rest of the job, in order to reach final placement, again, wellhead pressure will be in demand to lift the heavier fluids up the backside.

EFFECTS OF U-TUBING

The overall dynamics of fluid movement to maintain a mass and energy balance in the wellbore are summarized in Figure 3. The major effects of this phenomenon may be described using these graphs. If our hypothetical well was originally designed for plug flow displacement for the spacer and/or cement slurries, this flow regime is not preserved while the well is experiencing free-falling of fluids. This condition directly affects our ability to remove mud and to provide a good bond because the velocity profiles of our fluids are conducive for channelling and leaving pockets of mud behind the pipe. Conversely, if the original engineering displacement design was for a turbulent flow regime, the back-filling stage of U-tubing presents the same sort of problem. The fluids in the wellbore will again move toward a laminar flow regime. This presents itself at an extremely critical time because our cement systems are generally flowing past important zones of interest. Figure 3 also illustrates several other characteristics of this phenomenon. Fluid level inside the casing is always on the surface when in a lifting stage of the cement job, and because its on-surface wellhead pressure will be in demand to move the fluids up the backside. Once the well starts to experience U-tubing of fluids, the wellhead pressure theoretically will be zero, if the fluid friction pressure from the pump truck to the wellhead is ignored. Normally, this friction pressure will range from 50 to 150 psi, depending on the configuration of the treating iron on location. Also presented in Figure 3 is a graph showing the equivalent circulating density during the job. These values are a static equivalent for the dynamic bottom-hole pressures exerted during the displacement process.

Our discussion up to now has been limited to a constant pump rate. The effects of displacement rate variations, such as shutting down to drop the top plug or changing rates due to designed velocities of fluids rounding the shoe, should not be overlooked because they are common in any primary cement job. Therefore, Figure 4 is provided to help illustrate the first of these .two steps. Figure 4 shows the U-tube phenomenon as depicted in our above example with the addition of shutting down to drop the top plug after pumping all of the cement. Notice while the well is experiencing U-tubing and then a shutdown occurs, the fluids in the wellbore will continue to flow. This continuation of flow occurs because of fluid momentum and a lack of dependence on wellhead pressure. Based on fluids densities and friction pressures from one time step to another, the return rate will slow down gradually. In this example, the theoretical fluid level was in a back-filling state of U-tubing, but with the sudden drop in the pump rate, the fluid level starts free-falling. An iterative technique must be used to solve for this fluid movement in the wellbore and to determine the time period the return rate will come to rest. After pumping has resumed, the fluid level soon will start back-filling in the casing again. But because the amount of energy contained in the wellbore has dramatically shifted, the backside rate will be considerably slower than the pump rate. The fluids, again, must build up momentum.

Pump-rate variations without shutting down the pump will be our next concern relating to its effects of fluid movement in the wellbore (Figure 5). In this example, the pump rate was lowered while the well was free-falling. When this event occurs, the fluids will seek their own rate to uphold an equilibrium at the bottom-hole conditions. Fluid momentum, density of fluids and the amount of rate change play important roles in determining the return rate's reaction to this pump rate variation. The velocity of the fluid-level movement downward at this point progressively changes, reflecting the sudden rate variation and energy change in the wellbore. Another aspect of pump rate changes might be the increase of the pump rate while the well is free-falling as opposed to the decrease. This situation would be very similar to resuming the pump rate after shutting down the pumps in Figure 4. The pump rate would be increased but the return rate would not instantly reflect that change. This is due to fluid momentum buildup and maintenance of a bottom-hole equilibrium. As a result, the return rates would be initially lower than the pump rate, but would eventually catch up. During this time period, the velocity of the fluid level falling away from the wellhead would adjust accordingly.

A considerable amount of time could be spent on analyzing the effects of different parameters relating to the dynamic U-tube phenomenon, but the most important question is "How can this phenomenon be controlled, so that placement may be designed for optimum flow conditions"? In our investigation to resolve this question, the placement design must include considerations for density differentials between the fluids, pump rate and/or changes, backside pressure, rheology of the fluids, and wellbore geometry and deviations. Of all the parameters listed above, density differential and backside pressure have the greatest effects toward controlling U-tubing. The smaller the differential, the less the effect of U-tubing. This can be a paradox because studies may show better mud removal is attained when using larger fluid density differentials. Backside pressure also has its limitations. Most formations could not withstand the exertion of the back pressure needed to completely control this phenomenon. Pump rates and fluid viscosity can help to some extent, but to completely control U-tubing with just these two parameters is not effective. Therefore, to answer the question, optimization of all variable parameters is required.

ALGORITHM ILLUSTRATION

The algorithm that analyzes and predicts the fluid movement through the wellbore has been designated as the Slurry Placement Analysis simulator. This program is a useful tool in modeling and designing primary cement jobs. It allows for quick analysis of parametric effects on optimizing placement techniques. The following example of a surface pipe job has been provided for evaluation (refer to Figure 6). The well is slightly deviated with a measured depth of 6,000 ft. The hole size is 9-7/8 in. with 50% excess assumed and the casing is made up with only one weight of pipe. The casing outside diameter is 7-5/8 in. and the inside diameter is 6.765 in. The float collar is located at a measured depth of 5,920 ft. A formation at 2,842 ft has a fracture gradient of 0.644 psi/ft, and bottom-hole is 0.85 psi/ft. The job has been designed to pump 150 BBL of 10.5 lb/gal spacer followed by a 14.5 lb/gal cement system. The top of the cement column is to be lifted to 2,700 ft. When the spacer rounds the shoe, the pump rate will slow from 4 BPM to 2.5 BPM to bring the spacer up the back side in plug flow. After pumping, the cement is shut down to drop the top plug and displacement is resumed at 3.0 BPM. The rheology of the fluids has been either modeled Bingham Plastic or Power Law and is provided. In our example, the algorithm will print the well profile information every 10 BBL pumped or for every significant event in between. The following printout is also summarized in Figures 7 through 11.

CASE HISTORY

The Slurry Placement Analysis algorithm has been designed to be as realistic as possible. In doing so, it allows for multiple geometric variation both in the annulus and casing. It has the capabilities to track up to 14 different fluids through the wellbore. Also, it handles different rheological models, formation fracture gradients, hole deviations, etc. Actual field trials verify the accuracy of this model. Figure 12 shows the results of an actual cement job. The real-time data were monitored by using a computer-equipped van for data aquisition. This job was a liner at a depth of approximately 16,000 ft. In designing this job, a considerable effort was exerted to define all of the parameters of the well and to promote excellent mud removal. The figure illustrates the predictions of this algorithm vs the actual results. Overall, the model predicted the job effectively.

Slurry Placement Analysis

SET 1 FLUID DESCRIPTION

B I N G H A M   P L A S T I C   F L U I D

FL NO	DESCRIPTION	YIELD ft3/sk	SPECIFIC GRAVITY	PLASTIC VISCOSITY	YIELD POINT
1	MUD	0.000	1.14	9.97	0.12
2	SPACER	0.000	1.26	22.81	0.09989

P O W E R   L A W   F L U I D

FL NO	DESCRIPTION	YIELD ft3/sk	SPECIFIC GRAVITY	N-PRIME	K-PRIME
3	CEMENT	1.11	1.74	0.9596	0.003486

SET 3 JOB PERFORMANCE PROFILE

JOB TIME min	FL NO	VOLUME IN BATCH bbl	VOLUME IN TOTAL bbl	RATE IN bpm	FLUID LEVEL ft	VOLUME OUT bbl	RATE OUT bbl	ECD ppg	WHP psi	MUD REMOVAL TURB %	MUD REMOVAL PLUG %	CRITERIA FL NO	CRITERIA DEPTH ft
0.0	1	0.0	0	0.0	0	0	0.0	9.5	0	0.0	0.0	1	0

BACKSIDE CHOKE PRESSURE SET AT 0.0 PSI

DROP BOTTOM PLUG IF ANY

START SPACER (10.5 PPG)

2.5	2	10.0	10	4.0	0	10	4.0	9.8	119	0.0	100.0	1	0
5.0	2	20.0	20	4.0	0	20	4.0	9.8	107	0.0	100.0	1	0
7.5	2	30.0	30	4.0	0	30	4.0	9.8	96	0.0	100.0	1	0
10.0	2	40.0	40	4.0	0	40	4.0	9.8	84	0.0	100.0	1	0
12.5	2	50.0	50	4.0	0	50	4.0	9.8	72	0.0	100.0	1	0
15.0	2	60.0	60	4.0	0	60	4.0	9.8	60	0.0	100.0	1	0
17.5	2	70.0	70	4.0	0	70	4.0	9.8	48	0.0	100.0	1	0
20.0	2	80.0	80	4.0	0	80	4.0	9.8	37	0.0	100.0	1	0
22.5	2	90.0	90	4.0	0	90	4.0	9.8	25	0.0	100.0	1	0
25.0	2	100.0	100	4.0	0	100	4.0	9.8	14	0.0	100.0	1	0
27.5	2	110.0	110	4.0	0	110	4.0	9.8	2	0.0	100.0	1	0

FLUIDS NOW FREE-FALLING, U-TUBE EFFECT INCREASES

30.0	2	120.0	120	4.0	-15	121	4.3	9.8	-VAC-	0.0	100.0	1	0
32.5	2	130.0	130	4.0	-38	132	4.4	9.8	-VAC-	0.0	100.0	1	0
35.0	2	140.0	140	4.0	-61	143	4.4	9.8	-VAC-	0.0	100.0	1	0
37.5	2	150.0	150	4.0	-84	154	4.5	9.8	-VAC-	0.0	100.0	1	0

START CEMENT (14.5 PPG)

40.0	3	10.0	160	4.0	-199	169	6.0	9.8	-VAC-	0.0	100.0	1	0
42.5	3	20.0	170	4.0	-317	184	6.1	9.8	-VAC-	0.0	100.0	1	0
45.0	3	30.0	180	4.0	-436	199	6.1	9.8	-VAC-	0.0	100.0	1	0
47.5	3	40.0	190	4.0	-552	215	6.1	9.8	-VAC-	0.0	100.0	1	0
50.0	3	50.0	200	4.0	-668	230	6.1	9.8	-VAC-	0.0	100.0	1	0
52.5	3	60.0	210	4.0	-783	245	6.0	9.8	-VAC-	0.0	100.0	1	0
55.0	3	70.0	220	4.0	-899	260	5.9	9.8	-VAC-	0.0	100.0	1	0

SPACER AT SHOE, WITH 7.7 BBL IN ANNULUS

59.0	3	80.0	230	2.5	-998	274	3.8	9.8	-VAC-	0.0	100.0	2	5866
63.0	3	90.0	240	2.5	-1064	287	3.3	9.9	-VAC-	0.0	100.0	2	5640
67.0	3	100.0	250	2.5	-1126	300	3.2	9.9	-VAC-	0.0	100.0	2	5418
71.0	3	110.0	260	2.5	-1192	313	3.2	10.0	-VAC-	0.0	100.0	2	5192
75.0	3	120.0	270	2.5	-1253	326	3.2	10.0	-VAC-	0.0	100.0	2	4970
79.0	3	130.0	280	2.5	-1317	339	3.2	10.0	-VAC-	0.0	100.0	2	4746
83.0	3	140.0	290	2.5	-1384	351	3.2	10.1	-VAC-	0.0	100.0	2	4520
87.0	3	150.0	300	2.5	-1448	364	3.2	10.1	-VAC-	0.0	100.0	2	4294
91.0	3	160.0	310	2.5	-1511	377	3.2	10.1	-VAC-	0.0	100.0	2	4071
95.0	3	170.0	320	2.5	-1575	390	3.2	10.2	-VAC-	0.0	100.0	2	3847
99.0	3	180.0	330	2.5	-1637	403	3.2	10.2	-VAC-	0.0	100.0	2	3625
102.7	3	189.3	339	2.5	-1698	415	3.1	10.2	-VAC-	0.0	100.0	2	3415
104.2	3	3.6	343	2.5	-1701	418	2.6	10.3	-VAC-	0.0	100.0	2	3352

SHUT DOWN FOR 5.0 MIN

105.7	3	0.0	343	0.0	-1791	422	0.0	10.1	-VAC-	0.0	0.0	2	3282

RETURN RATE CAME TO REST AFTER 1.5 MIN, SHUTDOWN REMAINS

109.2	3	0.0	343	0.0	-1791	422	0.0	10.1	-VAC-	0.0	0.0	2	3282

LAUNCH PLUG AND BEGIN DISPLACEMENT

SHUTDOWN ENDED, PUMPING RESUMES

START MUD (9.5 PPG)

CEMENT AT SHOE, WITH 7.5 BBL IN ANNULUS

FLUIDS NOW BACK-FILLING, U-TUBE EFFECT DECREASES

112.5	1	10.0	353	3.0	-1605	424	0.5	10.3	-VAC-	0.0	100.0	3	5868
115.8	1	20.0	363	3.0	-1493	429	1.5	10.4	-VAC-	0.0	100.0	3	5781
119.2	1	30.0	373	3.0	-1382	434	1.5	10.5	-VAC-	0.0	100.0	3	5693
122.5	1	40.0	383	3.0	-1274	439	1.5	10.6	-VAC-	0.0	100.0	3	5601
125.8	1	50.0	393	3.0	-1167	445	1.6	10.6	-VAC-	0.0	100.0	3	5510
129.2	1	60.0	403	3.0	-1060	450	1.6	10.7	-VAC-	0.0	100.0	3	5419
132.5	1	70.0	413	3.0	-952	455	1.6	10.8	-VAC-	0.0	100.0	3	5328
135.8	1	80.0	423	3.0	-844	460	1.6	10.8	-VAC-	0.0	100.0	3	5236
139.2	1	90.0	433	3.0	-739	466	1.6	10.9	-VAC-	0.0	100.0	3	5143
142.5	1	100.0	443	3.0	-632	471	1.6	11.0	-VAC-	0.0	100.0	3	5052
145.8	1	110.0	453	3.0	-523	476	1.6	11.1	-VAC-	0.0	100.0	3	4963
149.2	1	120.0	463	3.0	-417	481	1.6	11.1	-VAC-	0.0	100.0	3	4870
152.5	1	130.0	473	3.0	-310	487	1.6	11.2	-VAC-	0.0	100.0	3	4779
155.8	1	140.0	483	3.0	-203	492	1.6	11.3	-VAC-	0.0	100.0	3	4687
159.2	1	150.0	493	3.0	-95	497	1.7	11.4	-VAC-	0.0	100.0	3	4595

FLUIDS CAUGHT, U-TUBE EFFECT SUBSIDES

162.5	1	160.0	503	3.0	0	503	3.0	11.5	18	0.0	0.0	3	4496
165.8	1	170.0	513	3.0	0	513	3.0	11.6	118	0.0	0.0	3	4320
169.2	1	180.0	523	3.0	0	523	3.0	11.7	217	0.0	0.0	3	4146
172.5	1	190.0	533	3.0	0	533	3.0	11.9	317	0.0	0.0	3	3971
175.8	1	200.0	543	3.0	0	543	3.0	12.0	417	0.0	0.0	3	3796
179.2	1	210.0	553	3.0	0	553	3.0	12.2	517	0.0	0.0	3	3622
182.5	1	220.0	563	3.0	0	563	3.0	12.3	616	0.0	0.0	3	3448
185.8	1	230.0	573	3.0	0	573	3.0	12.4	716	0.0	0.0	3	3273
189.2	1	240.0	583	3.0	0	583	3.0	12.6	815	0.0	0.0	3	3100
192.5	1	250.0	593	3.0	0	593	3.0	12.7	915	0.0	0.0	3	2925
195.8	1	260.0	603	3.0	0	603	3.0	12.9	1015	0.0	0.0	3	2752
196.9	1	263.2	606	3.0	0	606	3.0	12.9	1047	0.0	0.0	3	2693

PLUG BUMPS COLLAR AT DEPTH = 5920.0 FT PSI

MAXIMUM HYDRAULIC POWER REQUIREMENT = 77.0 HP

CONCLUSIONS

1. The understanding of fluid movement in the wellbore can be defined by using a tracking algorithm which incorporates a mass and energy balance and a modified Bernoulli equation to predict, optimize and design primary cementing operations.

2. U-tubing of fluids in the wellbore causes a variety of effects. The effects are either the free-falling of fluids in the casing or back-filling in the casing, when free-falling fluids in the wellbore experience rates greater than the pump rate. Whereas, back-filling occurs when the return rates are less than the pump rate.

3. Rate changes during the displacement of a primary cement job should be designed, and not haphazardly implemented.

4. The acceleration and deceleration of fluid movement, associated with this phenomenon, severely affect the flow regimes attempting to efficiently remove the mud, to provide for a good hydraulic bond.

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NOMENCLATURE

P_m = Density of the Mud, lb/gal

P_s = Density of the Spacer, lb/gal

P_c = Density of the Cement, lb/gal

P_{ha} = Hydrostatic Pressure of a Partition in the Annulus, psi

P_{hc} = Hydrostatic Pressure of a Partition in the Casing, psi

P_{fa} = Friction Pressure Loss of a Partition in the Annulus, psi

P_{fc} = Friction Pressure Loss of a Partition in the Casing, psi

P_{ba} = Backside Choke Pressure in the Annulus, psi

P_{wc} = Wellhead Pressure in the Casing, psi

A = Angle of Deviations from True Vertical in the Annulus, degrees

B = Angle of Deviations from True Vertical in the Casing, degrees

$\sum$ = Summation

m = Number of Partitions in Annulus

n = Number of Partitions in Casing

j = Counter for each Partition in the Annulus

i = Counter for each Partition in the Casing

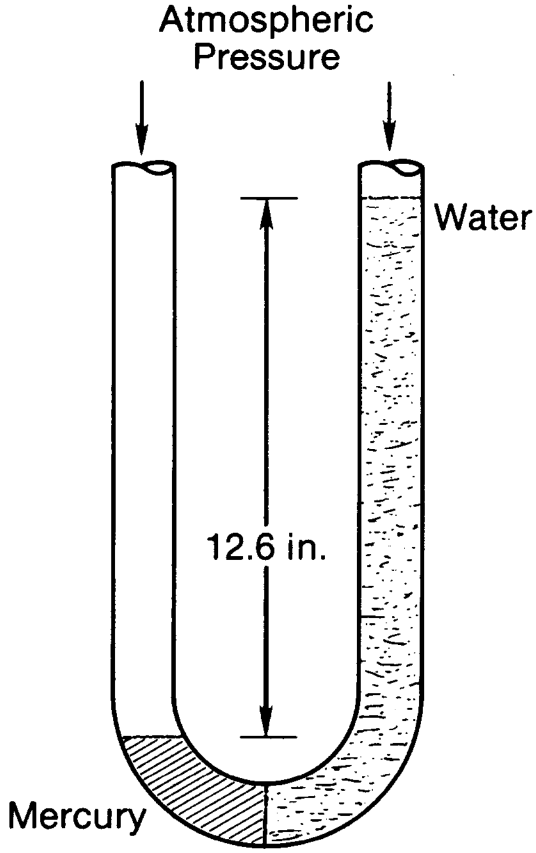


Figure 1 - U-tube manometer

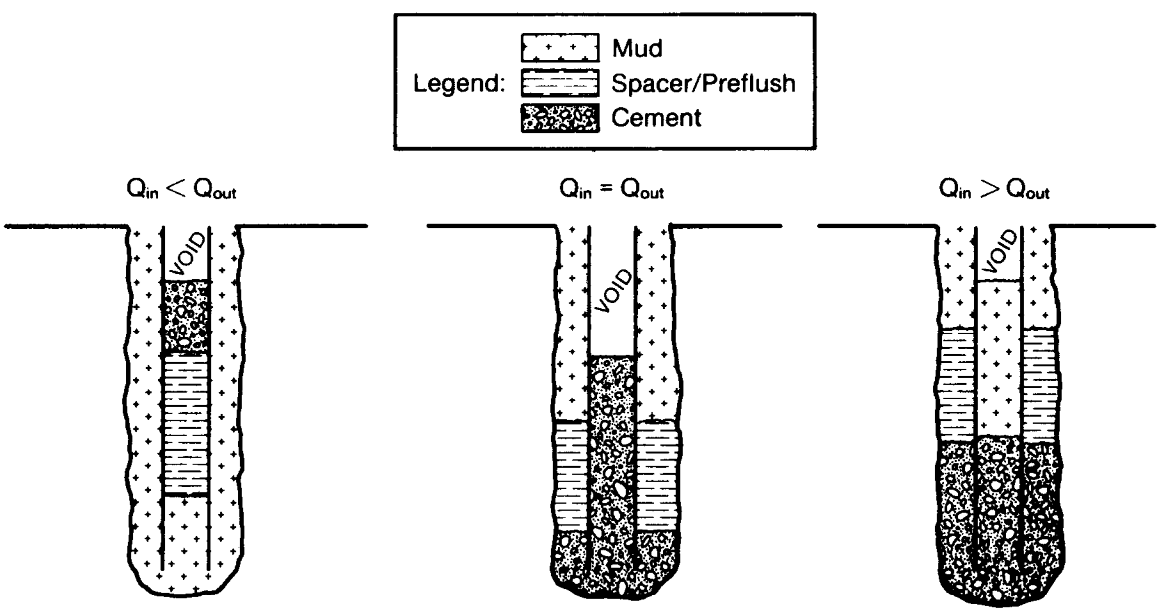


Figure 2a. Time = t_n Figure 2b. Time = $t_n + \Delta t_i$ ′ Figure 2c. Time = $t_n + \Delta t_i + \Delta t_j$

Figure 2 - Time step dynamics of U-tubing

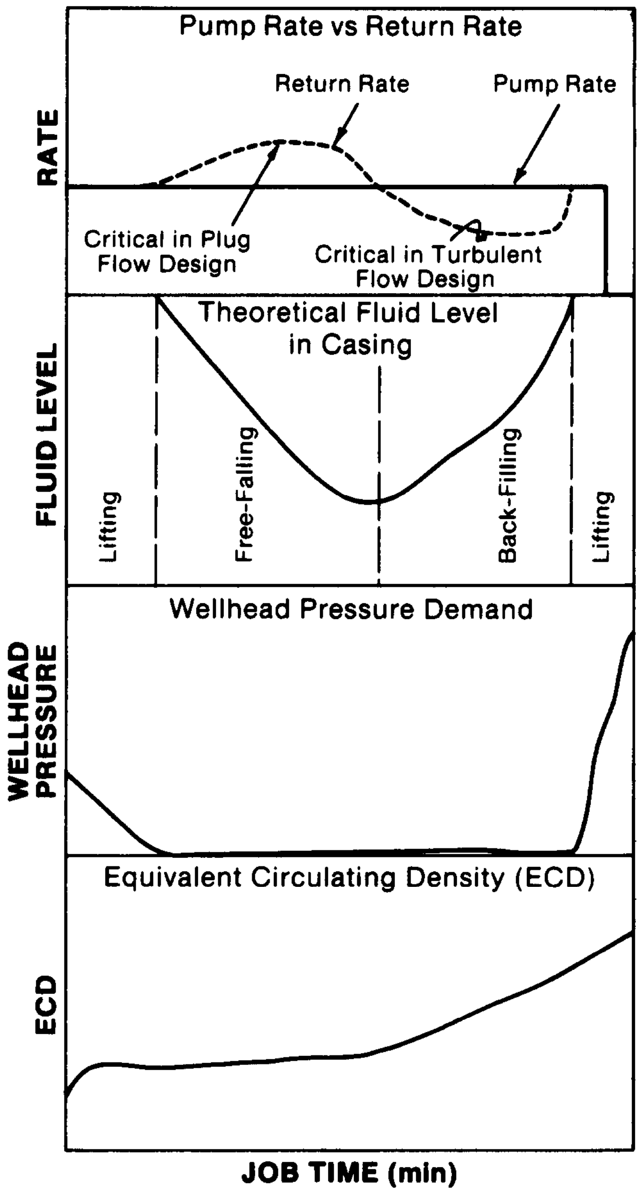


Figure 3 - Overall dynamics of fluid movement in the wellbore

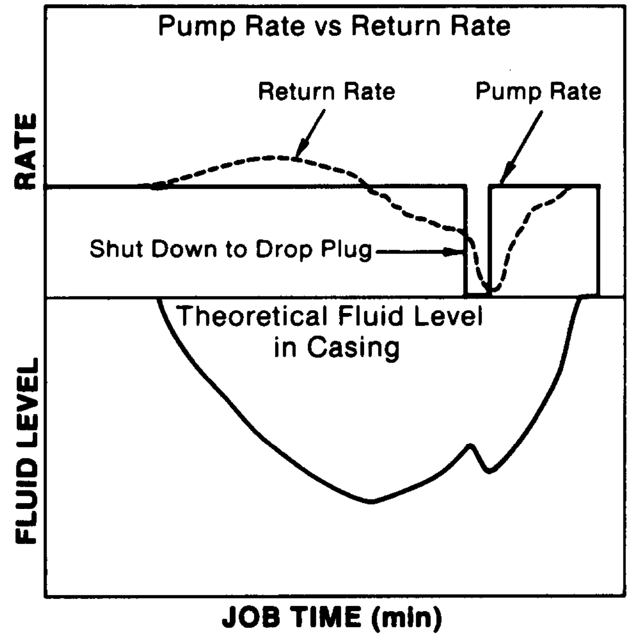


Figure 4 - U-tubing effects with pump rate shutdown

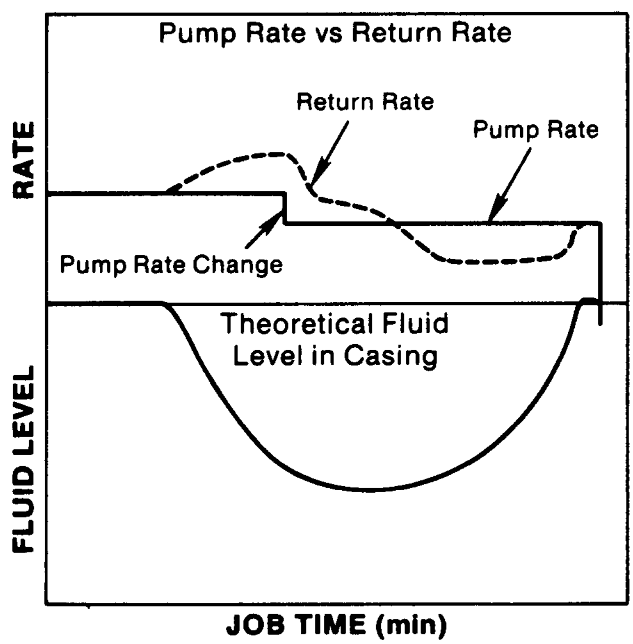


Figure 5 - Effect of rate change while fluids are free-falling

Pumping Schedule

1. Pump 150 BBL spacer @ 4 BPM
2. Begin pumping cement @ 4 BPM
3. When spacer rounds the shoe, slow rate to 2.5 BPM
4. When through pumping cement, shut down to drop top plug (5 min)
5. Displace at 3 BPM

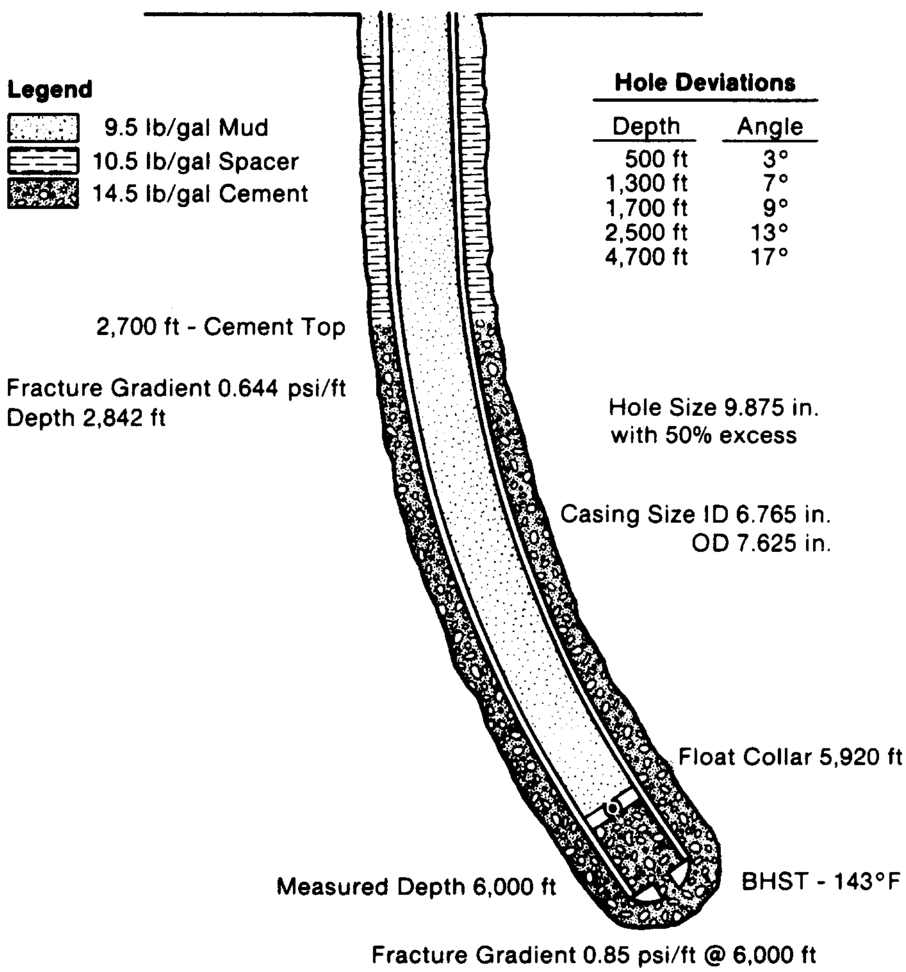


Figure 6 - Wellbore parameters with final placement

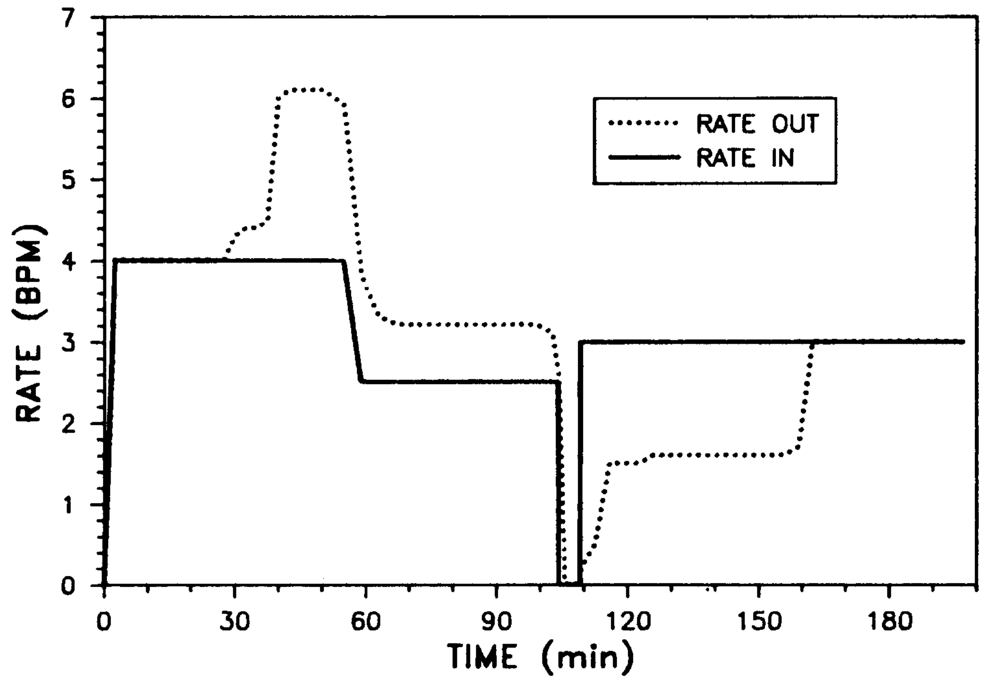


Figure 7 - Pump rate vs return rate

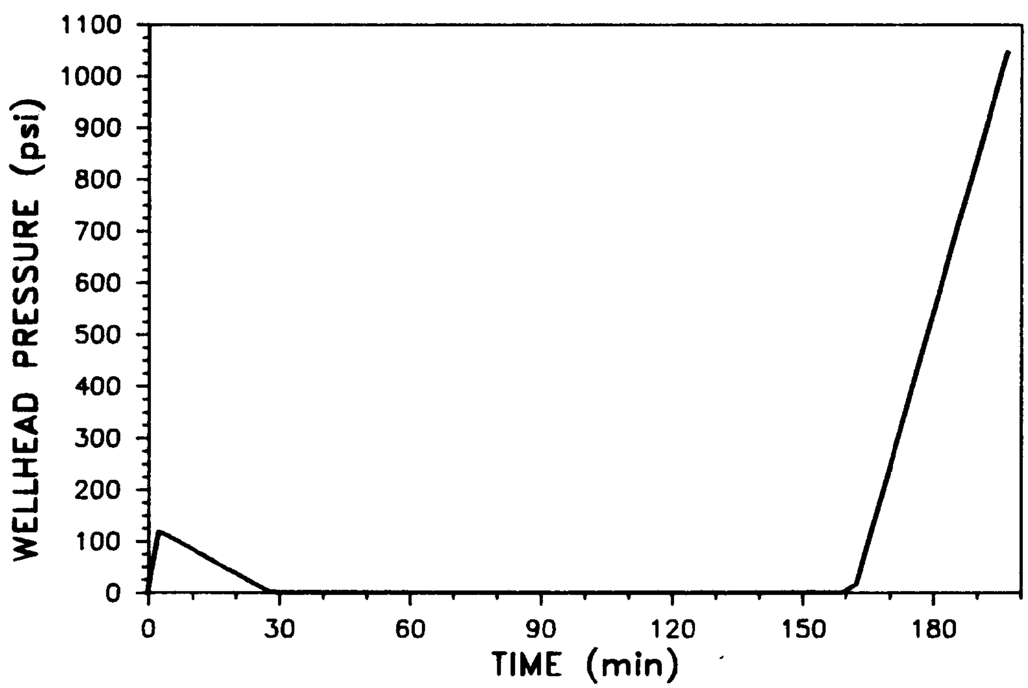


Figure 8 - Wellhead pressure demand

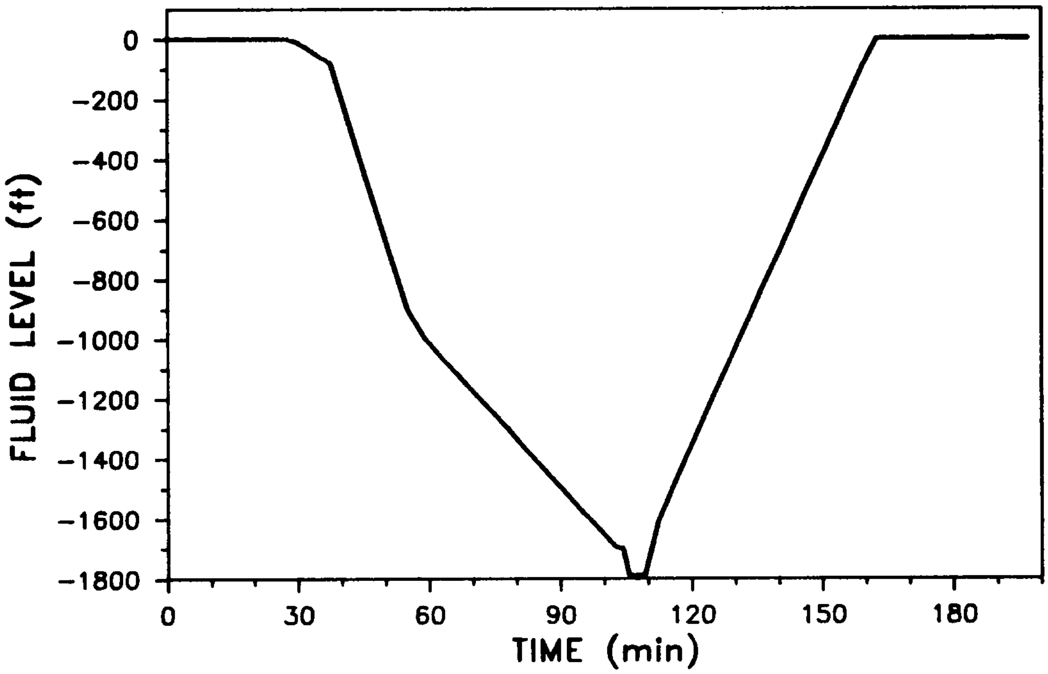


Figure 9 - Theoretical fluid level inside casing

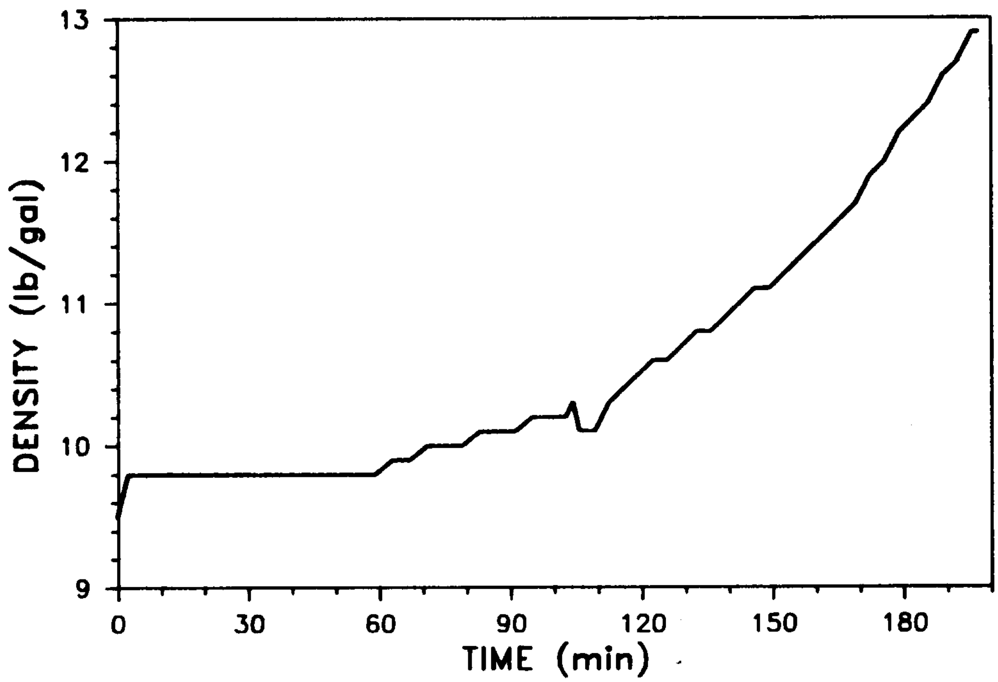


Figure 10 - Equivalent circulating density

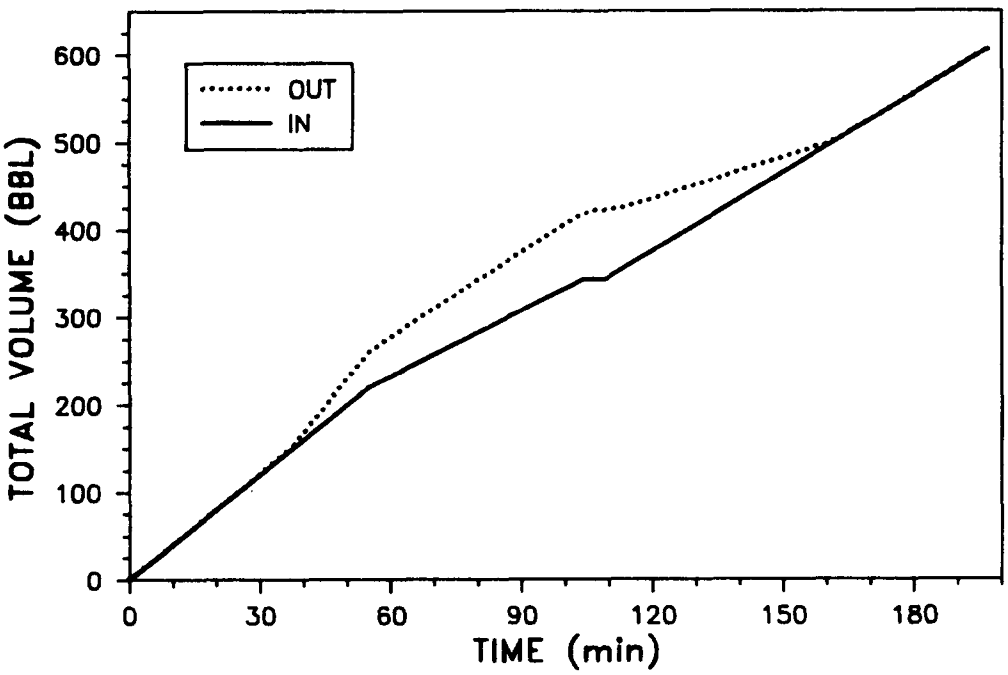
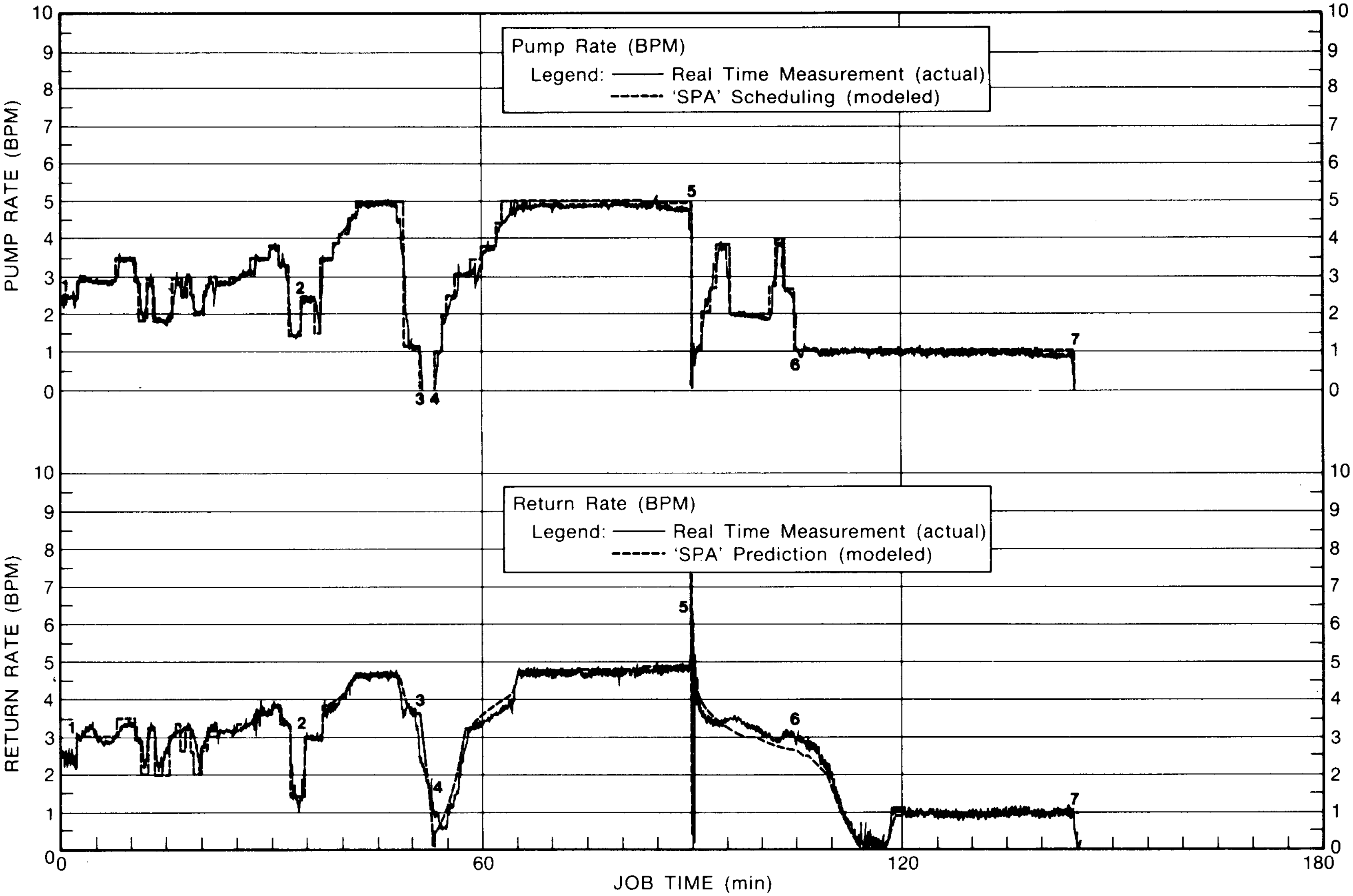


Figure 11 - Accumulative volume in and out of the well



1. Start pumping Spacer 3000.
2. Start pumping cement system.
3. Shut down to drop top plug.
4. Start pumping displacement fluid.
5. Shear wiper plug pins. Wellhead Pressure: Actual—1,800 psi; Modeled— 1,730 psi.
6. Cement rounds the shoe.
7. Plug bumps.

Figure 12 - Comparison of actual job vs SPA predictions