COMPUTER SIMULATION PROGRAM FOR CEMENT SQUEEZE APPLICATIONS

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ABSTRACT

Squeeze cementing for casing repair, zonal isolation, water shut-off, and various other remedial techniques has been used for several decades. However, these operations often are based on rules of thumb, repeat techniques, and operators' experience to achieve success. Technical improvements in slurry designs and additives have determined specific squeeze cementing behavior, but little emphasis has been placed on the actual downhole performance of the squeeze operation. The ability to estimate the performance of squeeze cementing has remained arbitrary and imprecise. A precise estimation of actual performance during the job would give the operator better control, increasing the possible success rate of the job.

Computerized simulations have been used successfully to design squeeze jobs and could be used to provide a better estimate of downhole performance. Subject paper describes such a simulator which uses fluid properties, well parameters, and well configurations in its determination of job surface pressure at progressive steps in the operation. Advance knowledge of surface pressure could allow operators to address the changes occurring downhole.

INTRODUCTION

Squeeze cement jobs are performed for a wide variety of reasons. Some are squeezing off perforations, repairing casing leaks, cementing liner tops, filling channels, effecting zonal isolation, performing water shutoff, and filling undesired void spaces. These actions are taken to achieve a hydraulic seal for protection and to fulfill well operation requirements. Recent developments in computer simulation for more precise operational control have given operators the ability to perform these jobs with valuable assistance in planning and executing the squeeze job by allowing critical design parameters to be determined before the job. Using the simulator to determine calculated surface pressures for a planned squeeze job at any point during the operation gives the operator a tool to compare actual versus predicted. This improvement in accuracy can eliminate many problems caused by the arbitrary means otherwise used to establish whether or not the particular job is achieving the desired results.

Certain aspects involved in squeezing cement into formations where low frac gradients, naturally occurring fractures, low pore pressure, high permeability, or vugular aspects can present placement problems. Foam cement has been used for the last 10 years to competently squeeze these types of formations. The computer simulator provides valuable assistance in planning and conducting these types of jobs since it determines the changes in density, viscosity, compressibility, expansion, and friction during a real-time dynamic operation. The capability to have a calculated foam cement density while compressing this slurry during real-time operations is a valuable operational tool.

Jobs where chemical treatments are injected into formations using placement techniques based on formation injection pressures below fracture gradients can be planned and executed using the computer simulator. Predicted surface pressures for real-time operation based on fracture initiation may be used to determine when to curtail the treatment. Many of these chemical treatments utilize cement tail-in for matrix strength and this can be included in the design along with various other stages of fluids to be simulated.

An analysis of the features of the squeeze simulator, including case histories, will illustrate its applications on various types of jobs.

Squeeze Job Simulator

Input data used to develop a squeeze job simulator include (1) the fluids to be pumped and their volumes, (2) rheological properties and pump rates for those fluids, (3) well geometries and deviation angle, (4) squeeze temperature, (5) lowest fracture gradient present, and (6) lowest fracture gradient zone depth. Data obtained from the simulator include the (1) volume of fluid pumped into the well at any given point in time during the job, (2) location of the leading edge of any selected fluid, (3) the equivalent circulating density or injection pressure of the selected fluid -- usually the cement slurry -- at any zone of interest, and (4) wellhead pressure throughout the job. Important features are (1) significant pumping "events" are highlighted to emphasize the time of their occurrence, (2) the pressure at the injection (squeeze) zone can be predicted for the duration of the job, and (3) the predicted surface pressure is calculated for the duration of the job.

An accurate estimate of when a squeeze pressure has been obtained can be determined by comparing the output pressure plot produced by the squeeze simulator to the actual surface pressure recorded during the squeeze job. Deviation of these two pressure values indicate that cement dehydration is occurring at any point in the duration of the job. The differential increase between these two pressure values may be used to establish the amount of squeeze pressure desired on the formation.

A critical factor in the utility of the squeeze job simulator has been its capability to analyze foam cement techniques. The nitrogen injection volume ratio required to obtain a specific foam cement density and the required base slurry volume to achieve a downhole foam volume can be calculated. The real-time analysis of a two-phase fluid with its density, hydrostatic loading, frictional pressure, compressibility, and expansion at dynamic and static conditions gives design parameters necessary to perform this type of job.

The output of the computer simulator model is presented in tabular form and as a graphical plot of the calculated surface injection pressure. The information is presented based on volume pumped for the job duration.

Table 1 is a condensed version of output data from the squeeze job simulator. An examination of this output reveals some of its more important features: (1) significant pumping "events" are highlighted to emphasize their occurrence, (2) pressure at the injection (squeeze) zone can be predicted for the duration of the job, and (3) predicted surface pressure is calculated for the duration of the job.

The squeeze job simulator can be used as a design tool to help eliminate the potential for fracture propagation from hydrostatic pressure of the cement column, which results in loss of surface pressure indication during the job. Alternate designs or techniques may be tried to reduce this potential by volume reductions, lowering the cement's density or, changing the method of cement placement. This evaluation is performed on a computer and not on the well planned to be squeezed, saving possible failures and the cost involved.

An accurate estimate of when a squeeze pressure has been obtained or when a maximum desired pressure is placed across the squeeze zone can be determined by comparing the pressure plot produced through computer simulation (Figure 1) to the actual surface pressure being observed during the job.

The tabular listing for the computer simulation also gives an incremental volume analysis to compare to during the job. When a desired increase in pressure is reached, the operator may choose to curtail the squeeze with the analysis of how much pressure is being applied to the zone being squeezed and in doing so, possibly eliminate fracturing into another zone. Many squeeze jobs are performed with only the initial injection pressure to establish a squeeze rate and the final pressure obtained either in a running technique or a hesitation method. Computer squeeze simulation is a technique for providing information to the operator about the entire process as it is happening and may be used to evaluate and test a job before actually performing it. The analysis may be set up to simulate a running or hesitation method since the volume - rate input is part of the design. The capability of simulation of complex jobs such as foam cement squeezing is used in their designs and planning.

Case Histories

The following case histories present examples of the application of the squeeze job simulator for squeeze jobs using chemical/cement injection, foam cement squeeze, and critical conventional cement squeeze application.

Case History 1

In this application, a polymer fluid was to be placed into a desired interval followed with a small particle size cement for matrix strength. The placement of the fluids was desired to divert the injection of carbon dioxide from this interval to eliminate injection breakthrough to adjacent producing wells. The interval was isolated at the wellbore and a desired maximum pressure was known if the treatment was to be done below fracture initiation.

A pre-job simulation was performed to obtain a calculated surface pressure listing and plot for the job. The operator was using the cement squeeze simulator to design the surface injection pressure based on the zone's fracture pressure. The technique was to inject fluid until the actual pressure at the surface began to exceed the calculated surface pressure for fracturing and stop injection. The actual wellhead pressure versus the calculated wellhead pressure predicted by the squeeze simulator is shown in Figure 1. The computer squeeze simulator tabular output is shown in Table 1.

The job listed (Table 1) was curtailed with 2 bbl of small particle cement remaining to be squeezed since its actual pressure had begun to exceed the design surface pressure. Excess slurry was reversed from the well, and following set times, the well was cleaned out and placed onto injection for evaluation.

Computer Simulation Design Parameters:

Tubular Data:	4-1/2 in., 10.5 lb/ft Casing (surface to 3,267 ft)
	3 in. Fiberglass Liner (3,267 to 4,157 ft) 2.5 in. ID
	2-3/8 in. tubing latched into liner hanger (surface to 3,267 ft)
Plug Back Depth:	3,845 ft with sand
Problem Perfs:	3,830 to 3,883 ft (CO_2 channeling)
Maximum BHTP:	3,615 psi.
Maximum Injection Rate:	1 bbl/min based on injection analysis.

Designed Job Procedure

1. Pump 16 bbl polymer at a maximum rate of 1 bbl/min at a maximum surface treating pressure calculated by the squeeze simulator based on the totalized volume of the job.

2. Mix and pump 4.7 bbl small particle cement at 1 bbl/min at a maximum surface treating pressure calculated by the squeeze simulator based on the totalized volume of the job.

3. Displace with fresh water at 1 bbl/min and slowing to 0.5 bbl/min if required at a maximum surface treating pressure calculated by the squeeze simulator based on the totalized volume of the job at the specified rates.

4. If the maximum pressure is reached any point of the treatment, discontinue injection and use calculated backpressure to circulate excess slurry out of the well (by coiled tubing) to the pit.

Injected Fluid Properties

Fluid	Density	n′	K′	Volume
Water in Tubulars	8.50	1.0000	0.0006	16.0
Polymer	8.80	1.0000	0.0008	16.0
Small Particle Cmt.	12.00	0.3500	0.1600	4.8
Water Displacement	8.34	1.0000	0.0006	15.5

Case History 2

In this application, foam cement squeeze jobs were performed on producing wells to temporarily plug the current production perforations so that the wells could be drilled to another deeper producing formation. The interval that was being produced had a low fracture gradient and low formation pore pressure. This interval would break down if the wells were loaded with conventional drilling fluid. To drill to the new depth, foam air drilling techniques were required in the past. The amount of produced gas from this interval was a hazard and time consuming during this type of drilling operation.

Foam cement squeeze jobs were designed to eliminate the need for this costly technology, and to prevent invasion of drilling fluids and fines into the older producing intervals. Following the squeeze jobs, the foam-squeezed perforations would be drilled out and the well deepened with conventional drilling fluids. Once the wells were deepened to the desired depth, liners were run and cemented.

Squeeze job computer simulator designs were performed to obtain the desired foam cement density (10.0 lb/gal) and to predict the wellhead pressures during the placement procedures. This density was desired to give enough compressive strength and minimal permeability for the foam cement so that it would hold up to the drilling mud's equivalent circulating density during the deepening operations and to control the influx of gas from the squeezed intervals.

The wells were successfully drilled to target depth without lost circulation problems and production liners were set.

Once the wells were completed and the new intervals stimulated, the formations containing foam cement squeezed perforations were reentered by perforating and acidizing. Resulting production data for the original zones showed decreased water:oil ratios without a decrease in oil production.

Figure 2 details actual surface pressure during a foam cement squeeze job versus the calculated wellhead pressure. The computer squeeze simulator tabular output is shown in Table 2.

Computer Simulation Design Parameters

Tubular Data:	5-1/2 in., 15.5 lb/ft casing (Surface to 5,890 ft)
	2-7/8 in. tubing with cement retainer (surface to 5,650 ft)
Production Perfs to Squeeze:	5,700 - 5,880 ft
Estimated BH Static Pressure:	2,500 psi
Estimated BH Fracture Pressure:	3,280 psi
Estimated BH Invasion Pressure:	2,650 psi
Planned Deepening Interval:	5,890 to 6,300 ft

Job Design Procedure

1. Pump 10 bbl fresh water at a rate of 2 bbl/min as a preflush loading the tubing.

2. Mix and pump 30 bbl Class "C" cement foamed with 500 scf/bbl nitrogen at a liquid rate of 1 to 2 bbl/min.

3. Mix and pump 5 bbl Class "C" cement as a tail-in slurry.

4. Displace with fresh water at 3 bbl/min and slowing to 2 bbl/min if the surface wellhead pressure begins to deviate from the squeeze simulator's calculated wellhead pressure based on the totalized volume of the job at the specified rates.

5. If the surface pressure increases to +/- 500 psi. above the calculated wellhead pressure, stop displacement. Reverse out any excess slurry through staked lines and a choke, to the pit.

Injected Fluid Properties

Fluid	Density	n'	K'	Volume
Water in Tubulars	8.90	1.0000	0.0006	38.2
Fresh Water Spacer	8.34	1.0000	0.0002	10.0
Foam Cement	14.80	0.3100	0.0900	30.0
Tail Cement	14.80	0.3100	0.0900	5.0
Water Displacement	8.34	1.0000	0.0002	32.0

The foam cement would have a zonal density of 10.7 lb/gal under dynamic conditions based on the fracture pressure of 3,280 psi. Following the placement, the foam cement is shown to have a zonal density of 9.5 lb/gal under the static formation pressure of 2,500 psi. The ability to analyze this variation in foam densities under these dynamic and static conditions allows the designer to plan a foam cement squeeze with final results calculated if a squeeze pressure buildup is not achieved and the foam cement expands under static conditions.

Case History 3

In this application, it was desired to squeeze off a thief zone on a producing well. Following acid stimulation and a follow-up survey, it was discovered that the stimulation had communicated down into a lower interval than desired. The survey also indicated that the bottomhole fracture pressure of the thief zone was 2,450 psi less than that of the desired interval. The top of the thief zone was 8 ft below the lowest perforation of the desired zone.

Utilizing the squeeze cement simulator, it was recommended to squeeze off the thief zone with an expanding cement slurry with less than 250 cc/30 minute fluid loss. The plan designed for was to use the fracture pressure of the desired pay interval as a base for injection. Using a cement retainer and spotting slurry to just above it, squeeze injection was to be performed until the actual surface pressure at any specific time of the job built up to match the calculated surface squeeze pressure. At this condition, the squeeze injection was to be stopped and excess slurry, if any, was to be reversed from the well.

After 24 hours, drill out the retainer and cement and reperforate the well. Break down the interval with an acid job after 48 hours, when the slurry should reach a compressive strength of +/- 2,800 psi @ 190 degrees F.

Figure 3 details actual surface pressure during this cement squeeze job versus the calculated wellhead pressure. The computer squeeze simulator tabular output is shown in Table 3.

Computer Simulation Design Parameters

Tubular Data:	5-1/2 in., 20 lb/ft casing (surface to PBTD w/ RBP @ 10,770 ft)'
	2-7/8 in tubing with cement retainer (surface to 10,650 ft)
Production Perfs to Squeeze:	10,682 to 10,732 ft
Thief Interval to Squeeze:	10,740 to 10,750 ft
Production Perfs below RBP:	10,798 to 10,858 ft
Estimated BH Static Pressure:	3,500 psi
Estimated BH Fracture Pressure:	8,000 psi @ 10,682 to 10,732 ft
Estimated BH Invasion Pressure:	5,600 psi @ 10,740 to 10,750 ft
BH Static Temperature:	190 Deg F

Job Design Procedure

1. Pump 62 bbl 2% potassium chloride water (tubing capacity) before setting tubing down into the cement retainer.

2. Following establishing injection rates at 1/2 and 1 bbl/min, pull out and above the retainer and load the hole with 2% potassium chloride water.

3. Mix and spot 21 bbl Class "H" cement containing expansive additive and fluid loss to within 15 bbl of the tool, insert into the tool and begin the squeeze job.

4. Compare surface injection pressure with the cement squeeze simulator's calculated surface pressure. If the actual pressure builds up to the simulator's calculated pressure, shut down injection. The injection may be repeated following a wait on time and once the pressures match, stop injection.

5. If the surface pressure builds up to the calculated wellhead pressure, discontinue the squeeze. The excess slurry, if any, should be reversed out of the well.

Injected Fluid Properties

Fluid	Density	n'	K'	Volume
2% Potassium Chloride	8.42	1.0000	0.0006	63.5
Fresh Water Spacer	8.34	1.0000	0.0002	10.0
Cement	15.60	0.9100	0.0025	21.0
Water Displacement	8.34	1.0000	0.0002	61.0

In Figure 3 the simulated pressure is that of the production zone. The recorded pressure is that of the thief zone. In this example we want our pressure to remain below the predicted curve. As long as the measure pressure remains below the prediction, from the zone, the cement should not be invading the production zone. At time 92 minutes the pressure reached 2300 psi and the remaining slurry was reversed out.

The placement of the squeeze cement is based on the logs run to determine infectivity using 2% KCL Water. Once cement slurry begins to enter and fill up void in this zone, it is reasonable to assume there will begin a bridging effect and slurry hydration. It is imperative not to fracture the desired interval during this process, causing invasion of cement slurry and possible damage to the formation.

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Table 1

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*****************************************************************
** DESCRIPTION 1: SMALL PARTICLE CEMENT SQUEEZE W/ POLYMER     **
** DESCRIPTION 2: CO2 INJECTION WELL PROFILE MODIFICATION      **
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-----VOLUME, RATE & ECD CALCULATIONS-----

TIME (MIN)	SURFACE FLUID IN	SURFACE FLUID OUT	UNFOAMED LIQUID VOLUME IN (BBLS)	RATE IN (BPM)	PRESSURE IN (PSI)	PRESSURE OUT (PSI)	EQUIVALENT CIRCULATING DENSITY TD (LB/GAL)	LEADING EDGE OF TRACER FLUID (FT)
0.0	1	1	0	1	2046	3615	18.2	0
1.0	2	1	1	1	2046	3620	18.2	0
2.0	2	1	2	1	2046	3626	18.2	0
5.0	2	1	5	1	2023	3621	18.2	0
11.0	2	1	11	1	2000	3632	18.3	0
16.0	2	1	16	1	1977	3630	18.2	0
************** Polymer IS ENTERING THE FORMATION **************								
17.0	3	2	17	1	1956	3615	18.2	259
20.8	3	2	20	1	1936	3615	18.2	1231
****************** DISPLACEMENT IS STARTING *******************								
24.8	4	2	25	1	1960	3615	18.2	2266
26.8	4	2	27	1	1960	3604	18.1	2783
29.8	4	2	30	1	1982	3615	18.2	3453
32.8	5	2	32	0.5	1908	3615	18.2	3782
************** Cement IS ENTERING THE FORMATION **************								
34.8	5	3	33	0.5	1908	3602	18.1	3830
36.8	5	3	34	0.5	1938	3615	18.2	3830
41.8	5	3	36	0.5	1973	3606	18.1	3830

IF THE WELL IS SHUT IN WITH 1973. PSI SQUEEZE PRESSURE THE EQUIVALENT GRADIENT ON THE INJECTION ZONE (3830. FT) WILL BE 8.4 LBS/GAL.

Table 2

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*****************************************************************
**   DESCRIPTION 1: FOAM CEMENT SQUEEZE FOR TEMPORARY PLUG     **
**   DESCRIPTION 2: DEEPENING PROGRAM FOR PRODUCERS            **
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-----VOLUME, RATE & ECD CALCULATIONS-----

TIME (MIN)	SURFACE FLUID IN	SURFACE FLUID OUT	UNFOAMED LIQUID VOLUME IN (BBLS)	RATE IN (BPM)	PRESSURE IN (PSI)	PRESSURE OUT (PSI)	EQUIVALENT CIRCULATING DENSITY TD (LB/GAL)	LEADING EDGE OF TRACER FLUID (FT)
0.0	1	1	0	2	773	3280	10.7	0
0.5	2	1	1	2	773	3276	10.7	0
1.0	2	1	2	2	773	3273	10.7	0
6.0	3	1	11	1	1277	3290	10.8	338
10.0	3	1	15	1	1179	3272	10.7	1670
10.5	4	1	16	2	1543	3271	10.7	1812
13.0	4	1	21	2	1449	3296	10.8	3248
15.5	4	1	26	2	1413	3291	10.8	4619
************ F W Spacer IS ENTERING THE FORMATION ************								
16.0	4	2	27	2	1404	3293	10.8	4890
19.0	4	2	33	2	1368	3287	10.8	5850
************ Foam Cement IS ENTERING THE FORMATION ***********								
19.5	4	3	34	2	1368	3291	10.8	5800
23.0	5	4	41	2	1180	3284	10.8	5800
24.0	5	4	43	2	1027	3294	10.8	5800
24.5	5	4	44	2	949	3292	10.8	5800
25.0	5	4	45	2	872	3289	10.8	5800
****************** DISPLACEMENT IS STARTING ****************								
25.3	6	4	46	3	990	3293	10.8	5800
28.7	6	4	56	3	854	3281	10.7	5800
34.5	7	4	73	2	635	3280	10.7	5800
35.5	7	4	75	2	718	3280	10.7	5800
36.0	7	4	76	2	760	3280	10.7	5800
36.5	7	4	77	2	802	3280	10.7	5800

IF THE WELL IS SHUT IN WITH 802. PSI SQUEEZE PRESSURE THE EQUIVALENT GRADIENT ON THE INJECTION ZONE (5800. FT) WILL BE 8.7 LBS/GAL.

Table 3

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**    DESCRIPTION 1: THEIF ZONE SQUEEZE                         **
**    DESCRIPTION 2: ANALYSIS WITH PROD ZONE BHTP AS BASE       **
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-----VOLUME, RATE & ECD CALCULATIONS-----

TIME (MIN)	UNFOAMED SURFACE FLUID IN	UNFOAMED SURFACE FLUID OUT	LIQUID VOLUME IN (BBLS)	LIQUID RATE IN (BPM)	EQUIVALENT PRESSURE IN (PSI)	EQUIVALENT PRESSURE OUT (PSI)	CIRCULATING DENSITY TD (LB/GAL)	LEADING EDGE OF TRACER FLUID (FT)
0.0	1	1	0	0.5	3355	8000	14.3	0
2.0	2	1	1	0.5	3355	7999	14.3	0
14.0	2	1	7	0.5	3355	7995	14.3	0
34.0	3	1	17	0.5	2922	8000	14.3	1209
52.0	3	1	26	0.5	2356	8000	14.3	2764
62.0	3	1	31	0.5	2041	8000	14.3	3628
***************** DISPLACEMENT IS STARTING ******************								
64.0	4	1	32	0.5	2041	7999	14.3	3801
124.0	4	1	62	0.5	2041	7977	14.3	8984
************ F W SPACER IS ENTERING THE FORMATION *************								
142.0	4	2	71	0.5	2041	7978	14.3	10539
********** 100 SKS. CEMENT IS ENTERING THE FORMATION **********								
148.0	4	3	74	0.5	2183	8000	14.3	10732
154.0	4	3	77	0.5	2374	8000	14.3	10732
160.0	4	3	80	0.5	2564	8000	14.3	10732
166.0	4	3	83	0.5	2755	8000	14.3	10732
172.0	4	3	86	0.5	2946	8000	14.3	10732
178.0	4	3	89	0.5	3137	8000	14.3	10732
184.0	4	3	92	0.5	3328	8000	14.3	10732

IF THE WELL IS SHUT IN WITH 3328. PSI SQUEEZE PRESSURE THE EQUIVALENT GRADIENT ON THE INJECTION ZONE (10732. FT) WILL BE 8.5 LBS/GAL.

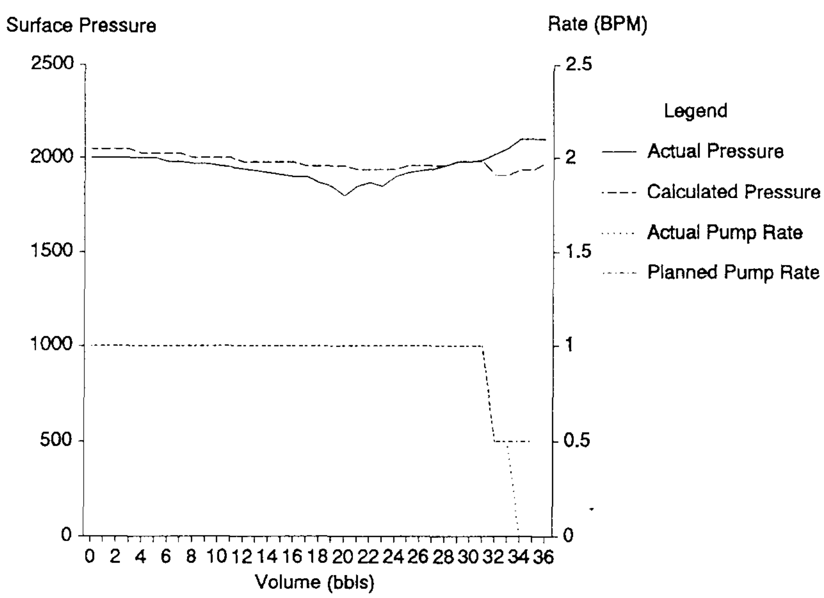

Figure 1 - Small particle cement squeeze following polymer injection

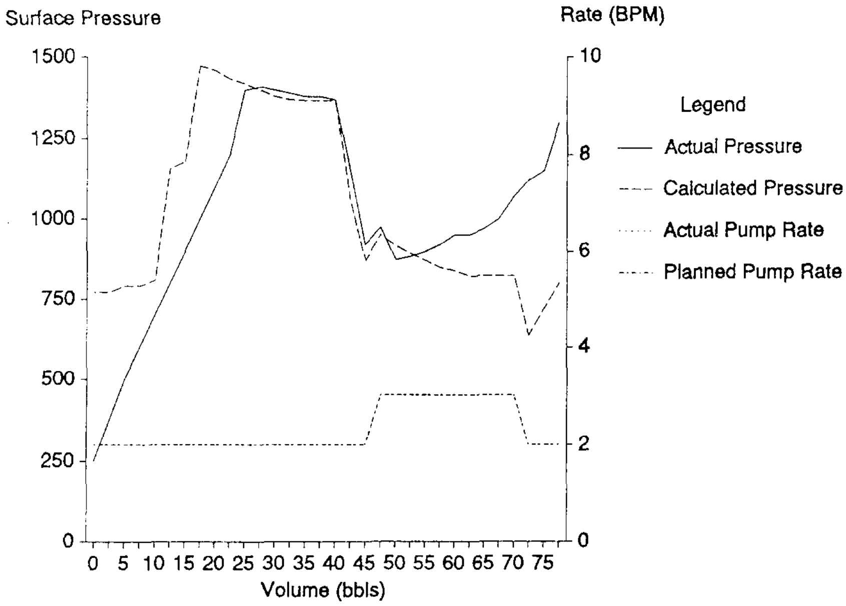

Figure 2 - Foam cement squeeze for temporary plugging

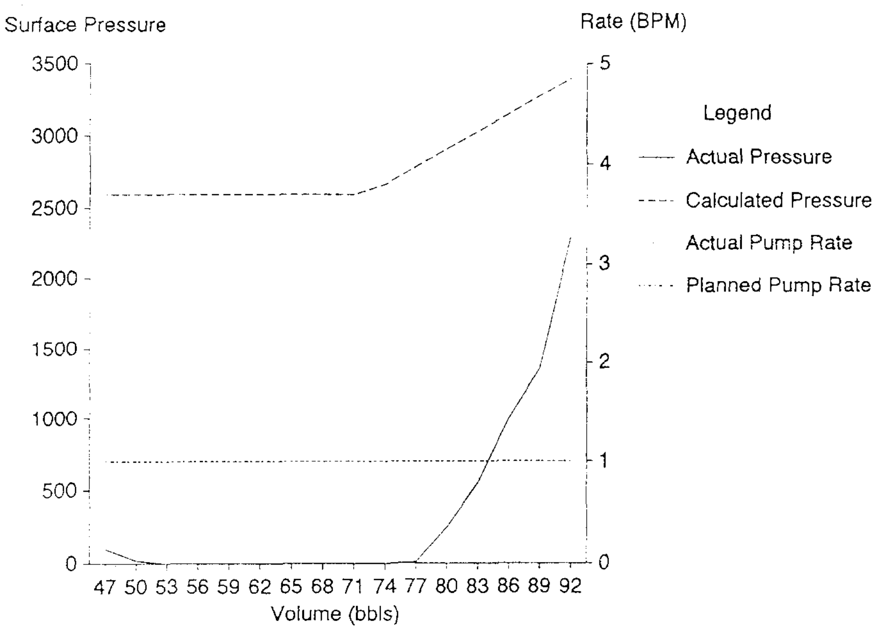

Figure 3 - Thief zone squeeze