OIL FIELD APPLICATION OF LOW DENSITY FOAMED PORTLAND CEMENTS

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ABSTRACT

The routine use of minimum density cement slurries (4-11 lb/gal) in oil field applications has been limited in the past; primarily because no convenient, cost-effective process existed which could provide useful compressive strength development at low densities. The careful selection and use of surfactants and foam stabilizers in addition to the use of properly designed field equipment has enabled the mixing and placement of stable foam cement slurries with instantly variable, but controllable down-hole slurry densities from 3.5 - 14 lb/gal over a wide range of conditions. Typical physical properties such as compressive strength, porosity, and permeability for foam cements of various densities are presented. Foamed cement sluries have been successfully applied in the oil field on squeeze jobs, leaking LPG underground reservoirs, salt-zone wash-outs, as well as primary cementing jobs. Job histories covering 31 field jobs will be discussed.

INTRODUCTION

Cementing oil well casing has three basic objectives: to support the casing, prevent interzonal communication and protect the casing from corrosive fluids and gases. To accomplish these objectives the annulus behind casing must be filled with competent cement. There have always been areas where weak zones would support only a limited height of normal density (11-18 lb/gal) cement column without breaking down. In the past, multiple stage jobs were often attempted to obtain the needed annular fillup or the problem was simply neglected at the risk of later corrosion and interzonal communication.

Past attempts to formulate competent light weight cements with densities less than 11.0 lbs/gal with the traditional water extending additives have been unsuccessful. Since 1978 two new types of ultra-light weight cement slurries have been available as oil well services. Both incorporate a gas as the light weight additive. In one, gas has been encapsulated within hard, pressure-resistant hollow microspheres.[1,2] The use of microspheres can provide competent cement slurries with densities lower than that of water. The second concept is the subject of this paper - high pressure foam cement slurries. The application of pressurized gas to improve cement slurry displacement was first introduced as aerated mud or cement.[3,4] While this approach has been applied successfully it has never achieved wide acceptance. No attempts were made to stabilize the commingled gas and prevent coalescing and percolation of the gas through the cement column. If a pressurized gas were contained and dispersed uniformly throughout a cement slurry until the cement sets, then a true light weight foam cement would result. This concept is not new. Cellular foam concrete has long been available for surface applications,[5] and as early as 1975 Aldrich and Mitchell[6] proposed that foam cement be applied to oil field cementing. In 1981 Davies and Hartog[7] presented their experiences with foamed cement compared to the properties recorded in their extensive literature bibliography. They described the results of one trial oil field application of foamed cement. However, the conditions on this particular well were relatively undemanding.

The adoption of an efficient foam generator and liquified nitrogen trucks in conjunction with other standard oil field servicing equipment has been instrumental in making stable foam cement available to remedy a variety of oil field cementing problems, most of which were considered impossible situations prior to the availability of stable foam cement slurries.

LABORATORY DEVELOPMENT

Foam cement useful for field application requires that a stable foam be created wherein the entrained gas is trapped in discrete bubbles that are uniformly dispersed throughout the cement slurry. If the gas bubbles are not discrete and within a certain size range, then the foam can be unstable and the set cement will have high permeability and low compressive strength.[6,7] For these reasons, unstable foam cement is obviously not suitable for oil well cementing.

Selection of suitable foaming surfactants is critical in the preparation of stable foams. Table I illustrates how the chemical composition of the foaming surfactant can affect the volume of gas entrained and the physical nature and compressive strength of the set foam cement. Figure 1 shows the type of discrete cells required for good foam stability, high compressive strength, and low permeability.

Retained stability at high foam qualities is important for foam cements with densities less than 9 lb/gal. Small, fine foam bubbles are believed to promote stronger cement walls around the bubbles and provide a set cement of increased integrity.[8] For these reasons the alkylethoxylated sulfate with stabilizer was selected. In the laboratory stable foam cements are conveniently prepared with stirring devices that provide high shear rates. For routine testing, this atmospheric method of preparation is quick and convenient. For job simulation testing, foam cement slurries must be generated, transferred, tested, and cured under high pressures. Figure 2 presents a schematic of a stirring autoclave setup that has proven invaluable in accomplishing this task.

Except for thickening time tests, the majority of our laboratory testing has been conducted under atmospheric preparation conditions because of the convenience factor. Few major differences have been noted in physical results when atmospheric samples are compared to high pressure samples.

As with ordinary cement slurries, the water ratio of a foam cement slurry has a major effect on the strength of the set solid. This is illustrated by the results shown in Table II.

The chemical and physical properties of the cement can also have a major effect on strength development as is shown in Figure 3.

Permeability of set foam cement varies as a function of both entrained gas volume and curing temperature. Table III lists typical permeability data.

To those familiar with the lack of strength development of ordinary low density oil well cements (10 - 11.5 lb/gal) the ability of foam cement to achieve strengths in excess of 500 psi with air permeabilities less than 20 md at cool temperature conditions seems remarkable. Foam cement achieves higher strengths than water-extended cements primarily because of the very low density of gas versus that of water. As a result it takes fewer volumes of gas per volume of cement to achieve density reduction. The absence of these additional dilution volumes in foam cement results in much stronger, competent cement. These features are the primary reason foam cement offers an attractive cementious material for field applications

FIELD SCALE ADAPTATION

Although stable foam cement could be prepared in the laboratory early full scale model tests, conducted with a foam generator equipped with large bore jets, were not entirely successful. The foams generated in these tests were stable for only short periods of time. Modifications were clearly indicated.

Subsequent tests with modified foam generators eliminated the foam stability problems, and the process of foam cement was ready for field application. Current nitrogen servicing equipment is more than capable of providing sufficient quantities of gas at suitable rates for cementing purposes. Figure 4 illustrates the quantity of nitrogen per barrel of cement slurry which is required to prepare low density foam cements. Even for 8.5 lb/gal foam cement at 10,000 psi downhole pressure, only 3500 SCF/bbl is necessary. Existing trucks can deliver from 350 - 9000 SCFM. If more capacity or higher rates ever become necessary, additional nitrogen units can be brought to location.

On location the equipment and monitoring devices are connected as illustrated in Figure 5. In nearly all respects an ordinary cementing job with regular cementing equipment is set up. The foam generator is inserted in the cement slurry discharge line that is connected to the well head, and the nitrogen unit is connected to the foam generator. Cement slurry is mixed in a normal fashion and foam surfactants and stabilizers are injected into the slurry as it is picked up by the displacement pump truck. Coordination of the cement slurry pump rate, the surfactant injection rate, and the nitrogen delivery rate are the crucial parameters that must be planned and executed in order to properly deliver foam cement having the desired properties downhole. In foam cement applications instantaneous downhole density control is possible. This density flexibility allows a wide lattitude in designing the overall job before it is actually run in the field. Jobs can be planned with the option of changing the density as pressure and circulation events vary during the job.

DOWNHOLE PRESSURE - DENSITY BEHAVIOR OF FOAM CEMENT SLURRIES

Previous publications have suggested foam cement applications can be divided into two types: (A) constant gas rate and (B) constant slurry density.[9] These two designations represent the two extremes and are normally greatly modified to arrive at a practical job design.

A. CONSTANT GAS RATE FOAM CEMENT

Constant gas rate foam cement can be used to remedy pressure parting lost circulation problems, with certain limitations. Figure 6 shows the difficulties in attempting to use a constant gas rate foam cement and circulate foam cement back to the surface. This figure shows a foam cement with 30 standard volumes of nitrogen per unit volume of unfoamed slurry (SV/VUS) (168.3 SCF/bbl). With no back pressure on the annulus at the surface (0/0 lines) the pressure gradient (PG) is below the fluid entry gradient above 7000 ft. The cement placed above 2000 ft would not be dense enough to provide permeability low enough for casing protection. If the nitrogen content is reduced, the density at the shallow depths can be corrected but the maximum pressure gradient can easily be exceeded at the greater depths. The pressure gradient profile can be partly corrected by holding back pressure at the surface. The 500/0 lines in Figure 6 show the effect of holding 500 psi back pressure. However, application of this method runs the risk of break down into any weak, shallow formations unless an intermediate or deep surface casing has been set to about 1000 ft. A better approach to using a constant rate foam cement is to use a nonfoamed "cap" of either mud or regular light weight cement ahead of the foam cement. Figure 7 shows the results of using a 3000 ft cap of (a) 9.9 lb/gal mud and (b) a 12.9 lb/gal regular light weight cement. Even with the lighter 9.9 lb/gal mud cap, the foam slurry density is never less than 9.2 lb/gal, which will result in low permeability and sufficient compressive strength and the pressure gradient profile falls well within the maximum and minimum limits.

B. CONSTANT DENSITY FOAM CEMENT

Theoretically, constant density can be maintained throughout a foam cement column by continuously adjusting the gas ratio. In practice incremental adjustment are used but the increments are designed to cause only minor acceptable density variation throughout the column.

Figure 8 shows the results of changing the nitrogen ratio for every 1000 ft of slurry at the shallower depths and every 2000 ft at the greater depths. The initial ratio was 8.5 SV/VUS (4.77 SCF/bbl) for the slurry to be placed near the surface and this increased to 123 SV/VUS (690 SCF/bbl) for the slurry at 12,000 ft. The 8.5 SV/VUS requires only 191 SCF per minute nitrogen if the unfoamed slurry is pumped at 4 BPM. This rate is too low to accurately deliver with most of the nitrogen pumps now in use in oil well servicing. The properties of foam cement with only 8.5 SV/VUS in the top 500 ft (3-8 lb/gal) are marginal for competent cement. Unless an intermediate casing has previously been set and poor quality cement in the upper 500 to 1000 ft can be tolerated, placement of a non-foamed slurry cap is recommended followed by foam cement prepared by incrementally adjusting the nitrogen ratio.

Figure 9 shows the results of using only 200 ft of a neat Class C slurry cap or lead slurry. The minimum foam slurry density is 9.8 lbs/gal and the pressure gradient still does not exceed the breakdown pressure at 8000 ft.

Actual applications of foam cement have shown that a blending of fixed gas rate and constant foam slurry density procedures will provide the most practical method in field operations. The following suggestions are offered:

1. Use constant nitrogen ratios only for jobs where a non-foamed cap equal to 10 to 30% of the total depth can be used or where poor cement and low hydrostatic pressure can be tolerated in top 25% of the column.

2. Use incremental nitrogen ratio adjustment if a constant nitrogen ratio results in unacceptable strength or permeability in the upper part of the foam slurry in areas where some strength is needed.

3. Limit incremental adjustments to a maximum interval of 1000 ft for depths less than 6000 and 2000 ft for depths greater than 6000 ft.

FOAM SLURRY DESIGN PROCEDURE

The in-place hydrostatic pressures and the unfoamed slurry density on the surface are the major factors which determine the amount of nitrogen (or other gas) needed to achieve a desired in-place foam slurry density. Temperature has less influence but cannot be excluded. The hydrostatic pressure, estimated downhole temperature, and Z values are used with the general gas law equation to calculate gas density and volume of gas per unit volume of unfoamed slurry. The results are then used with the unfoamed slurry density to calculate the downhole slurry density. Expeditious solutions require a computer or at least a programmable calculator with a printer, because two or more of the variables are interdependent.

The data shown in Figures 6, 7, 8, and 9 were calculated using a programmable calculator to determine an approximate equation for the temperature and Z values based on hydrostatic pressure and temperatures typical for an oil well.

The general procedure for a foam slurry design is to:

1. Determine the maximum and minimum pressure gradients and plot as shown in Figures 6, 7, 8, and 9.

2. Select depth and density of cap fluid or unfoamed lead slurry based on general guide lines, well conditions and experience.

3. Calculate average foam slurry density needed for intervals as indicated by general guide lines.

4. Determine the nitrogen ratio, the foamed slurry density at the top and bottom of the interval, and the volume of unfoamed slurry in the interval.

If a constant nitrogen ratio is used over a very large interval, additional calculation programs should be run to check the pressure gradient at 500 ft increments across the entire foam cement interval.

POTENTIAL USES FOR FOAM CEMENT

A number of problems encountered in the oil field can potentially be remedied by the placement of a gas containing, ultra-low density fluid that will harden. Therefore, foam cement becomes a feasible option for:

Use 1. Placing extra-low density floating cement plugs on top of liquids contained in the entrance neck of underground storage caverns to be followed by placement of normal cement on the plug and eventually to cement a casing into the entrance shaft.

Use 2. Avoiding losses into zones that pressure part so a longer column of competent cement can be placed in one stage and help eliminate the problems and costs of multi-stage jobs that are necessary when using regular light weight slurries.

Use 3. Filling or sealing off cavernous or irregular megaDarcy lost circulation zones and allow the annulus above the zone to be cemented (present cementing procedures with regular light weight slurries place no cement above and rarely even place cement completely across a megaDarcy zone).

Use 4. Insulation of production pipe. Foam cement is an excellent insulator (K = 0.15 - 0.4) and provides insulation from cold water formations that cause paraffin deposits, for insulating steam injection pipe, or for protecting geothermal steam production pipe.

Use 5. Control of lost circulation in dry drilled (gas or air) or ordinary fluid drilled holes and to reestablish circulation so drilling can continue without the entry of unwanted fluid or gas into the wellbore.

Many of these applications have been attempted and most have been successful.

FIELD APPLICATIONS

Use 1: Although foam cement was available as an oil well service in 1978 to our knowledge it was in 1979 that it was first used. An underground LPG storage cavern leached from a salt zone was in communication with an old large-diameter 800' T.D. mine shaft that had been back-filled with rubble and abandoned. Injection wells had been placed into this shaft and numerous normal density cement squeeze jobs had been performed but all had been totally unsuccessful in relieving gas vapor pressure on the injection wells. Apparently these slurries channeled through the LPG-saturated matrix of the shaft all the way to the bottom. It was decided to apply foam cement at a density of 3.5 - 4.2 lb/gal in the belief that it would spread out on the top of any LPG zones and seal the matrix. After the first foam cement job, which provided about 8000 ft^3 of foam slurry, the vapor pressure was relieved by nearly 80% which indicated the rubble had been partially sealed. Communication between the injection wells had also been modified. After two subsequent jobs the remaining escaping gas was easily controlled and removed by surface compressor units (Table IV, #1, #2, #3).

Use 2: Primary field useage of foam cement to date has been in the multi-pay Spraberry Field of the Permian Basin of West Texas. Wells in this area are typically drilled with 8 - 10 lb/gal muds to a total depth of 6500' - 9500' with several lost circulation zones intermixed with corrosive water zones above the hydrocarbon bearing zones. Ideally maximum corrosion protection is accomplished when the casing-borehole annulus is filled from surface to total depth with competent cement.

Surface casing generally is set and cemented back to surface from 600 - 1000 ft T.D. with few problems. Some operators elect to run an intermediate string of casing but increased drilling times and high casing costs have made this unattractive. Also in certain areas, a severe lost circulation zone lies just above the pay intervals located at 6000 ft which is not covered by intermediate strings.

Commingled nitrogen followed by normal light density cements has allowed cement to be placed higher but not high enough to successfully tie back to the surface pipe or even cover all of the corrosive water intervals. Cement slurries containing large amounts of lost circulation materials have also been tried but they so greatly exceeded parting pressure that circulation was lost. Other operators have used strategically placed multiple stage cementers but this is usually not satisfactory due to the desire to avoid the expense of bringing a work-over rig to location to drill out the stage tools. Instead, the operators prefer to run casing down past the pay intervals with baffle rings in place in the casing string to separate the 3-4 zones of interest. These wells are then perforated, acidized, and fracture-treated through the casing with the benefit of wireline equipment.

An operator new to the Spraberry trend was concerned about casing failures and wanted to protect the casing from a T.D. of 6982' back to 2500'. This interval contained all the problem zones in that area. In normal density jobs cement had been brought back to only 3500' primarily due to losses into a severe lost circulation zone at 4200'.

The foam cement job performed was based on PV calculations and knowledge of the geographical area. The job design called for a 500' unfoamed cement cap from 2500' - 3000', foam cement from 3000' to 5000', and dense perforating cement from 5000' to a T.D. of 6982'. Cement volumes were calculated and normal excess cement volumes were included. The following field procedure was followed.

1. Pump 10 barrels mud flush.

2. Pump 5 barrels fresh water.

3. Mix 33 barrels Class "C" 50/50 pozzolan with 2% bentonite, 6 lb salt, 1/4 lb/sk cellophane flakes, and 0.5% friction reducer.

4. Mix 20 barrels Class "C" with 1/4 lb/sk cellophane flakes. Foam with 380 SCF/bbl nitrogen and foaming agent.

5. Mix 20 barrels cement mixture. Foam with 430 SCF/bbl nitrogen.

6. Mix 20 barrels cement mixture. Foam with 480 SCF/bbl nitrogen.

7. Mix 20 barrels cement mixture. Foam with 529 SCF/bbl nitrogen.

8. Mix 112 barrels cement mixture as #3 above.

9. Displace plug to shoe joint.

The specified nitrogen ratios resulted in a down hole slurry density of 9.5 lb/gal which was 0.3 lb/gal lower than the fluid used to drill the well. During the cement job, circulation remained excellent. Most of the mud was displaced from the annulus.

Results of the job were considered excellent with top of cement at 1500' with good apparent bonding. The higher-than-designed top of cement achieved was believed to be due to better-than-anticipated hole conditions through the foam protected interval. This operator has since completed three additional foam cement jobs in which the amount and density of the foam slurry was varied to suit individual well conditions (Table IV, #5, #7, #25, #30).

Uses 2,3: In the McElroy Field of West Texas, foam cement has been used to fill and seal off large caverns caused by leached out salt sections which also had megaDarcy lost circulation (see Table IV, #4, #8, #10, #14, #17). Foamed cement slurries and foamed fast-setting gypsum/portland cement slurries containing various solid lost circulation additives have been used to successfully place cement in these cavernous zones. These jobs were primarily conducted to repair damaged pipe or condition an old hole so that a new string of pipe could be run followed by placement of a solid sheath of foam cement around the new liner to provide protection.

Past efforts in this area included salt-saturated slurries, extremely fast setting slurries, thixotropic slurries and lost circulation plugs consisting of many different types of material. These methods were seldom successful due primarily to the excessive hydrostatic pressure exerted on the formation. Thus foam cement provided a useful solution, putting 8.5 - 9.0 lb/gal cement in place and staying under the zone parting pressure.

Use 4: Operators in one area of Wyoming have experienced excessive paraffin buildup in newly completed wells. Solvents, scrapers, and hot oil treatments provided only temporary relief. It was found that the cause of the problem was a very cold water-bearing formation between the oil zone and the surface which cooled the production fluids enough that paraffin was deposited.

It was suggested that the casing be insulated from the cool zone by placement of foam cement (Table IV, #20). The interval around 1800 ft was successfully covered using 9 lb/gal foam cement and the operator has had essentially no paraffin problems in this well.

EVALUATION OF RESULTS

Success of foam cement jobs can be measured in two ways: factors noticed during the job and post-job evaluations. During the job, such things as interrupted circulation, sudden or unexpected increases or decreases in surface pressure, and data about mixing and measuring procedures should be carefully recorded. Our experience indicates that certain guidelines should be followed in order to help assure the best possible results from a foam job. These basic items are important for a succesful foam cement job.

1. A means of mixing a unfoamed surface cement slurry at a specified air free density with a reasonable accuracy (e.g., $\pm$ 0.1 lbs/gal).

2. A means of measuring the unfoamed slurry pump rate and total volume with an accuracy of $\pm$ 5% or better.

3. A means of introducing foam stabilizing chemicals into the unfoamed slurry or nitrogen stream with an accuracy of $\pm$ 10%.

4. A means of measuring and controlling the gas injection rate based on mass or standard volume.

5. A means of injecting the gas into the unfoamed slurry stream with sufficient energy to obtain maximum stabilization.

6. An inline mixing device to add stability and uniformity to the foam slurry. (Previous papers[7] have inferred field mixing produced a more stable foam than in the laboratory, but in reality the shear energy use in a typical laboratory test is far greater than what the slurry received during their field mixing). Up to a point higher energy provides greater stability. Inappropriate field sampling methods can easily lead to false conclusions regarding the stability of field mixed foam cement.

Post treatment measurements using bond logs and temperature surveys have been used for evaluation of foam cement jobs.

Bond logs indicate the presence of foam cement primarily through attenuation of the amplitude curve and the micro-seismogram. The amplitude curve responds to the differing densities of both the conventional cements present and to the foam cements and is helpful in locating the interfaces of the two. To get the most information possible, it is recommended that the amplitude be set as high as possible providing a greater range and therefore better resolution on the curve which will better show the changes in density.

The micro-seismogram may not show good apparent bond through foam as with normal density slurries but arrival of formation signals along with each of free pipe signals indicate that bonding has occurred. Correlation of the micro-seismogram with gamma ray or density logs for verification of formation signals has been found to be a helpful tool in evaluating bond quality.

Temperature surveys run 8 - 24 hours after completion of the job have proven valuable in locating the top of the different intervals of cement. Cap and tail-in cements will show a temperature gradient greater than normal background while the foamed interval will be about the same as background profiles and has even shown a less than normal temperature gradient. Figure 10 shows a typical temperature survey that located the various cement interfaces in place behind the casing.

Evaluation of results should not be left to one graph, one chart, or one log but rather as much information as possible should be gathered and correlated.

SUMMARY AND CONCLUSIONS

Several important conclusions drawn from our experiences can be stated as follows:

1. Foam cement offers many attractive properties wherever there is a need for ultra-low density cements in the oil field. Among these properties are high strengths and reasonably low permeabilities.

2. Foam cement can be accurately prepared, placed, and cured both in the laboratory in the field.

3. Certain guidelines that must be followed to provide good results from foam cement jobs and these have been identified and are achievable.

4. Foam cement has proven to be very effective in remedying pressure parting lost circulation. However, one must recognize that large volumes of foam slurry can easily be lost into a fractured formation because most foam slurries have low API fluid loss values and a very low solid volume/ slurry volume ratios - the exact properties desired for an effective fracturing fluid. Therefore:

5. Successful lost circulation cntrol with foam cement depends mainly on its low density thixotropic properties. By contrast, light weight slurries that contain micro-spheres, gilsonite or walnut hulls owe much of their lost circulation control to their fracture plugging ability. For this reason, it is advantageous to incorporate solid lost circulation materials into foam cement slurries. Cellophane flakes have been routinely used.

6. In addition to overcoming the density limitations mandated by breakdown gradients, the successful foam cement job should always meet two general objectives:

   a. Provide sufficient hydrostatic pressure to prevent entry of fluids or gas into the annulus.

b. Provide good cement soundness and sufficently low permeability to prevent corrosive water and/or gas from penetrating the cement sheath and affecting the casing.

7. Foam cement promises to be one of the most versatile cementing services by virtue of its instantaneous density control which can be applied both to routine cementing problems and to the most impossible of jobs.

8. Foam cement jobs can be evaluated by the standard post-job procedures but special precautions should be exercised when running or interpreting cement bond logs. Temperature surveys have proven to be valuable evaluation tools.

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Table I

Effect of Foaming Surfactants on Foam Cement Properties

Surfactant	Surfactant Chemical Class	Comments about Foam Cement Visible Properties	Relative Maximum Foam Quality Achievable	24 hour, 100°F Compressive Strength (psi) of 8 lb/gal Foam Cement Cured at 100°F
alkylamidosulfo betaine	amphoteric	thin, large air cells	285	317
amidoalkyldimethyl betaine	amphoteric	thin, noticeable air cells	300	202
alpha-olefin sulfonate	anionic	very thick, not uniform	250	525*
alkylphenol polyglycolether sulfate	anionic	very thin, noticeable air cells	175	220**
alkylethoxylated sulfate	anionic	uniform texture	450	292
alkylethoxylated sulfate + stabilizer		smooth, fine uniform texturn	550	227

* because sufficient foam volume could not be achieved, this slurry actually had a density of 9.4 lb/gal

** because sufficient foam volume could not be achieved, this slurry actually had a density of 10.8 lb/gal

Table II

Compressive Strength of Foam Cement

Samples cured at atmospheric pressure.
All samples contained 1.5% surfactant
+ 0.75% stabilizer by volume of water.

		Samples Cured at 100°F							
Water Ratio		0.72		0.60		0.46		0.38	
Surface Density of Cement Slurry (lb/gal)		13.6[a]		14.5[b]		15.6[c]		16.4[d]	
		Compressive Strength (psi)							
		24 hr	72 hr	24 hr	72 hr	24 hr	72 hr	24 hr	72 hr
Density of Foam (lb/gal)	8	224	230	260	518	395	665	825	1070
	6	84	128	131	168	163	288	235	208
	4	43	57	38	82	18	56	20	60

[a] Lone Star H, w/c = 0.75 + 2% solids stabilizer + 2% $CaCl_2$

[b] Lone Star H, w/c = 0.60 + 3% $CaCl_2$

[c] Lone Star H, w/c = 0.46 + 3% $CaCl_2$

[d] Lone Star H, w/c = 0.38 + 3% $CaCl_2$

Table III

Permeability of Set Foam Cement K(air) millidarcy

Surface slurry = API Class H Cement + 2% $CaCl_2$; w/c = 0.38

	4	6	8	10	lb/gal foam cement density
65°F	129	28	1.3	1.5	
100°F	159	111	6.7	2.3	

Surface slurry = API Class C Cement + 2% $CaCl_2$; w/c = 0.56

	4	6	8	10	lb/gal foam cement density
65°F	---	15.2	1.32	1.12	
100°F	---	846*	0.42	0.11	

* sample most likely had a microcrack present

TABLE IV

SUMMARY OF FOAM CEMENT JOBS

	Date	Type of Job	Total Depth ft	Geographical Area	Field	Depth of Foam Cement ft	Quantity of Foam Cement sks	Quantity of Nitrogen SCF	Surface Density lb/gal	Foam Density lb/gal	Reasons For Running Foam	Past Types of Unsuccessful Jobs
1)	11/79	Propane Storage	600			125	1575	90,000	13.8	3.5-4.2	To seal off LPG storage cavern	Rapid Gelling Quick Setting Cements
2)	01/80	Propane Storage	600			125	2030	133,500	13.8	3.5-4.2	Same as #1	Same as #1
3)	02/80	Propane Storage	600			125	2020	107,250	13.8	3.5-4.8	Same as #1	Same as #1
4)	10/80	Squeeze	3200	Crane Co., Texas	McElroy	1600	500	113,000	14.2	6-8	Large cavern with very low Frac Gradient	Gypsum cement, sodium silicate, lost. circ. plugs
5)	11/80	4 1/2" Longstring	6982	Reagan Co., Texas	Spraberry	3000-5000	300	36,000	14.1	9.5	Low frac gradient, multiple stage tools not practical	N_2 aerated mud silicate extender cement
6)	01/81	5 1/2" Longstring	8600	Howard Co., Texas		2000-6000	750	80,000	14.1	8.5	Same as #5 above	Same as #5 above
7)	02/81	4 1/2" Longstring	6915	Reagan Co., Texas	Spraberry	3000-4500	200	30,000	14.1	9.3	Same as #5 above	Same as #5 above
8)	02/81	Squeeze	3200	Crane Co., Texas	McElroy	1540	400	100,000	14.2	8.0	Same as #4 above	Same as #4 above
9)	02/81	4 1/2" Longstring	9500	Martin Co., Texas		2000-5550	450	89,000	14.8	8.5	Same as #5 above	Same as #5 above
10)	02/81	5 1/2" Liner	2785	Crane Co., Texas	McElroy	Surface-1600	150	14,000	14.8	9.0	Large cavern, low Frac Gradient	Large volumes of lost circ. material
11)	02/81	5 1/2" Longstring	8600	Carter Co., Oklahoma		6200-8400	490	102,000	14.6	7.5-12	Severe lost circulation	cotton seed hulls cement plugs
12)	03/81	2 3/8" Liner	8770	Ector Co., Texas	Spraberry	4000-7000	650	100,000	14.8	8.5-90	Severe lost circulation parted pipe	
13)	03/81	5 1/2" Longstring	8450	Upton Co., Texas	Spraberry	2500-6000	450	60,000	14.1	9.0-8.5	Same as #5 above	Same as #5 above
14)	03/81	5 1/2" Liner	2778	Crane Co., Texas	McElroy	Surface-1600	125	11,000	14.8	8.5	Same as #10 above	Same as #10 above
15)	04/81	8 5/8" Intermediate	5212	Ector Co., Texas	Spraberry	Surface-4800	2250	212,000	14.8	9.0	Needed pipe protection low Fracture Gradient	

DATA (Cont'd)

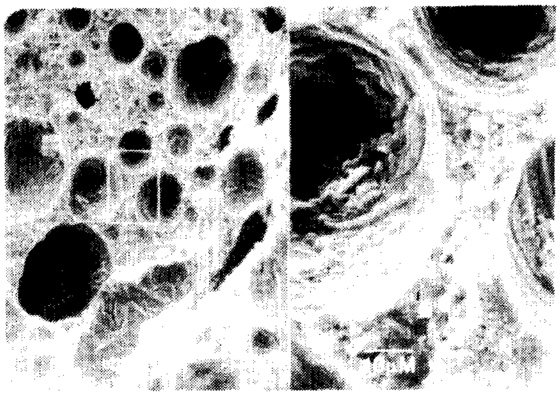
Table IV (Cont'd)

SUMMARY OF FOAM CEMENT JOBS

Date	Type of Job	Total Depth ft	Geographical Area	Field	Depth of Foam Cement ft	Quantity of Foam Cement sks	Quantity of Nitrogen SCF	Surface Density lb/gal	Foam Density lb/gal	Reasons For Running Foam	Past Types of Unsuccessful Jobs
16) 05/81	5 1/2" Prod. String	9520	Ector Co., Texas	Spraberry	500-7500	500	90,000	15.6	9.5	Desire to tie back into Intermediate strg.	
17) 05/81	5 1/2" Liner	2805	Crane Co., Texas	McElroy	Surface-1600	100	10,000	14.8	8.4	Same as #10 above	Same as #10 above
18) 05/81	4 1/2" Longstring	6400	Irian Co., Texas	Spraberry	Surface-3600	600	35,000	14.8	9.5	Circulate cement without Intermediate casing	
19) 06/81	4 1/2" Longstring	6400	Irian Co., Texas	Spraberry	Surface-3600	600	35,000	14.8	9.5	Same as #18 above	Same as #18 above
20) 07/81	5 1/2" Longstring	2300	Freemont Wyoming		1800	100	7,500	15.6	9.0	Insulate cold zone @ 1800' paraffin prob.	cont. use of solvents and scrapers
21) 06/81	7 5/8" Intermediate	9491	Crane Co., Texas	Devonian	6000-1000	750	80,000	14.1	10.2	Low Frac Gradient	Not attempted
22) 07/81	4 1/2" Longstring	6420	Irian Co., Texas	Spraberry	Surface-3200	600	35,000	14.8	9.5	Same as #18 above	Same as #18 above
23) 07/81	4 1/2" Longstring	8400	Upton Co., Texas	Spraberry	3750-5500	330	45,000	14.1	9.0	Low Frac Gradient	Silicate extended cement
24) 07/81	4 1/2" Longstring	6400	Irian Co., Texas	Spraberry	Surface-4000	600	35,000	14.8	9.1	Same as #18 above	Same as #18 above
25) 07/81	4 1/2" Longstring	7000	Reagan Co., Texas	Spraberry	4000-1500	360	43,000	14.1	9.0	Same as #5 above	Same as #5 above
26) 08/81	4 1/2" Longstring	8350	Upton Co., Texas	Spraberry	4000-2500	320	42,000	14.1	8.5	Same as #23 above	Same as #23 above
27) 09/81	5 1/2" Liner	10,500	Len Co., New Mex.		9000-4000	650	175,000	14.2	8.5	Tie back into intermediate low frac gradient	stage cementing
28) 10/81	4 1/2" Longstring	8700	Upton Co., Texas	Devonian	4000-7000	350	76,000	14.1	8.0	Low Frac Gradient	N_2 aerated mud
29) 10/81	4 1/2" Longstring	7150	Reagan Co., Texas	Spraberry	1000-5000	710	80,000	14.1	8.0	Same as #28 above	Same as #28 above
30) 11/81	4 1/2" Longstring	6850	Reagan Co., Texas	Spraberry	1500-4000	360	40,000	14.1	8.5	Same as #5 above	Same as #5 above
31) 11/81	5 1/2" Longstring	8350	Upton Co., Texas	Spraberry	2500-6000	570	80,000	14.1	9.0	Same as #28 above	Same as #28 above

FIGURE 1

Magnified View of Stable
10 lb/gal Foam Cement



200X 1000X

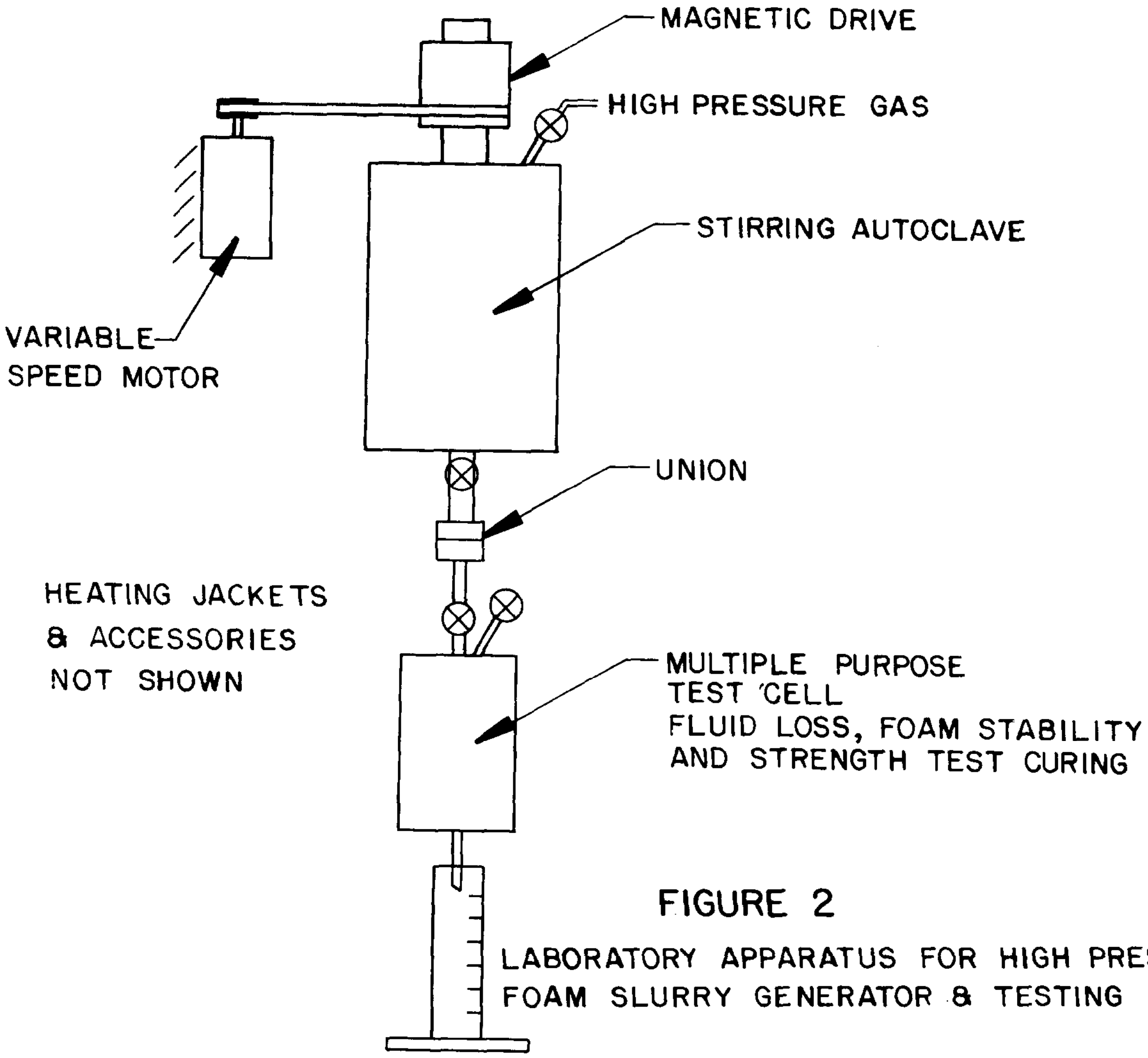


FIGURE 2

LABORATORY APPARATUS FOR HIGH PRESSURE FOAM SLURRY GENERATOR & TESTING

FIGURE 3
24 HR COMPRESSIVE STRENGTH DEVELOPMENT AT 100°F

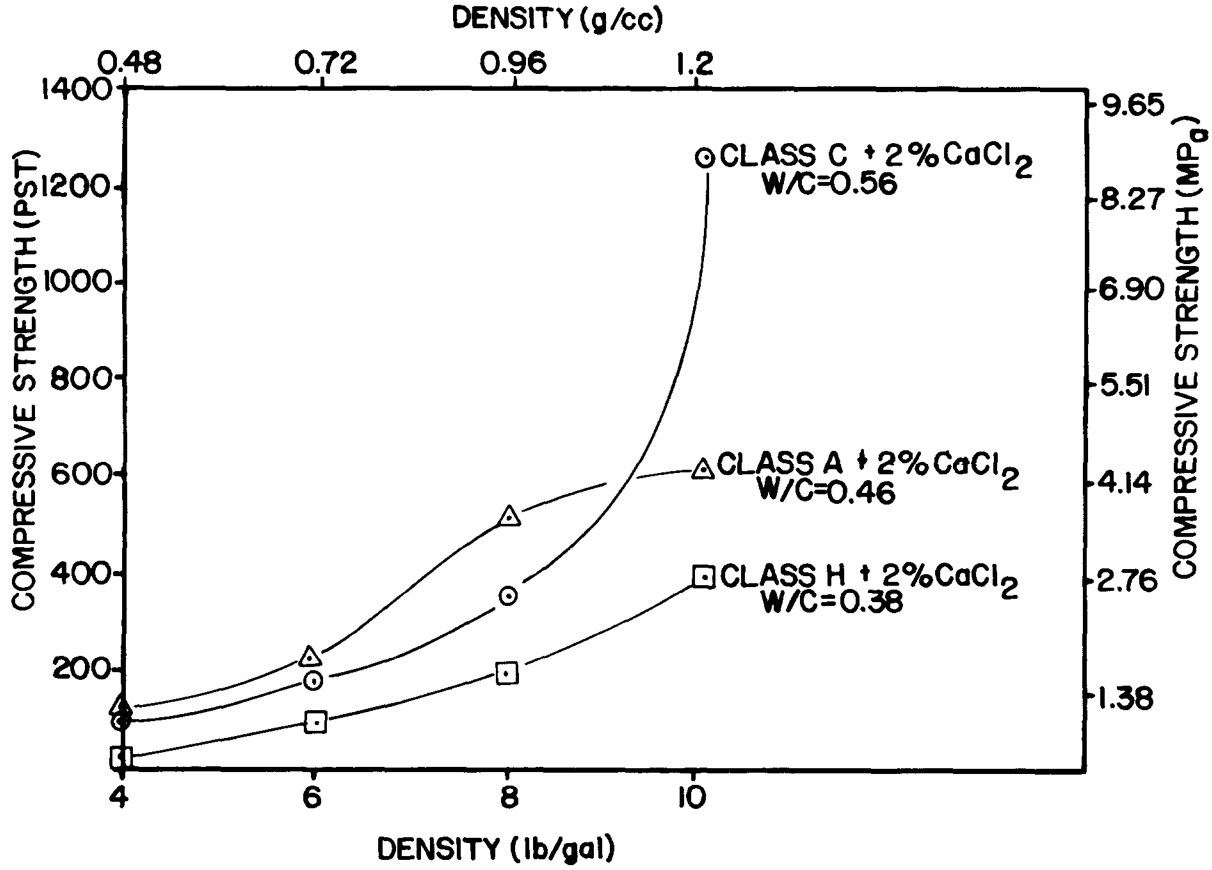
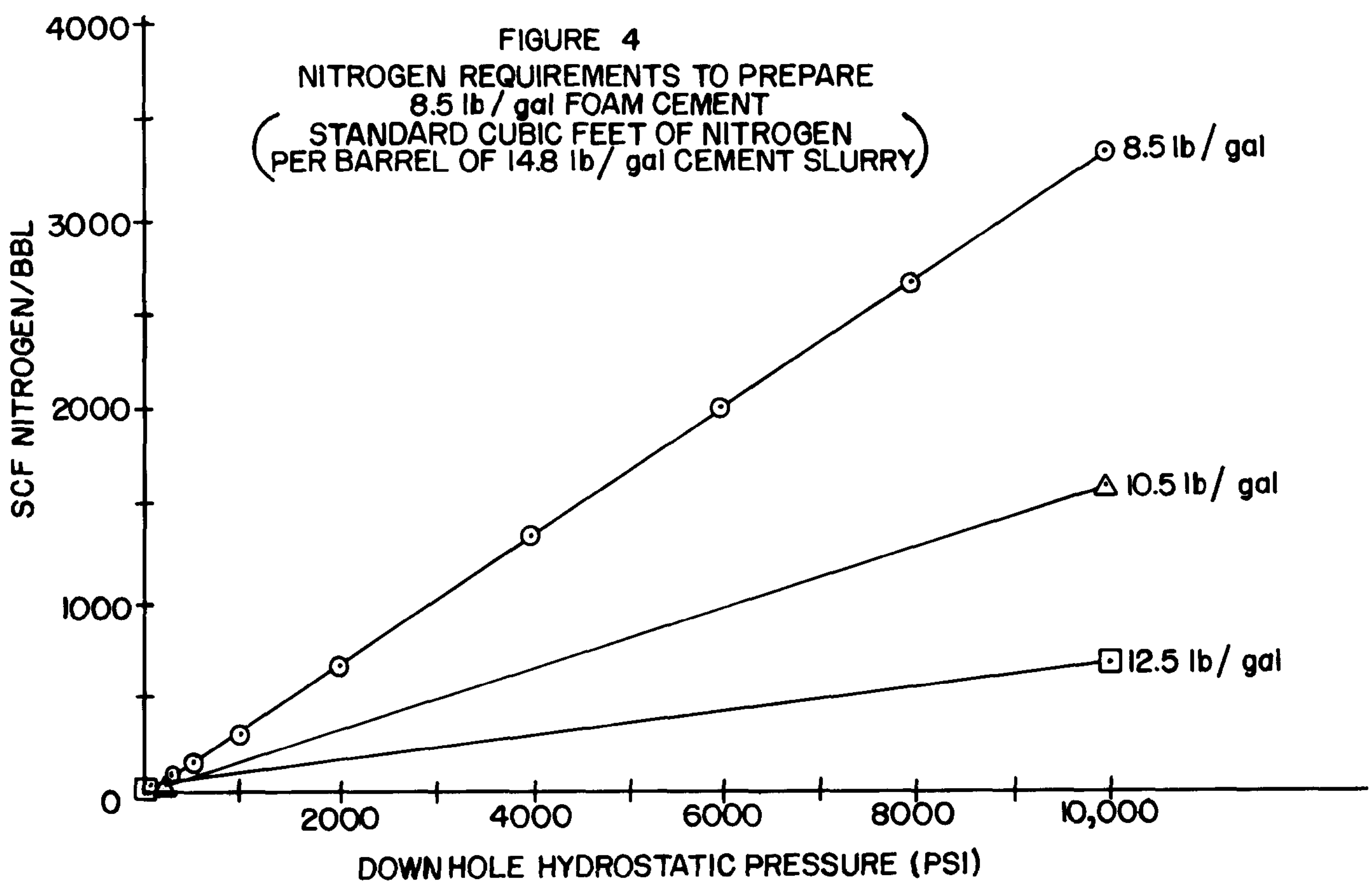


FIGURE 4
NITROGEN REQUIREMENTS TO PREPARE
8.5 lb / gal FOAM CEMENT
(STANDARD CUBIC FEET OF NITROGEN
PER BARREL OF 14.8 lb / gal CEMENT SLURRY)



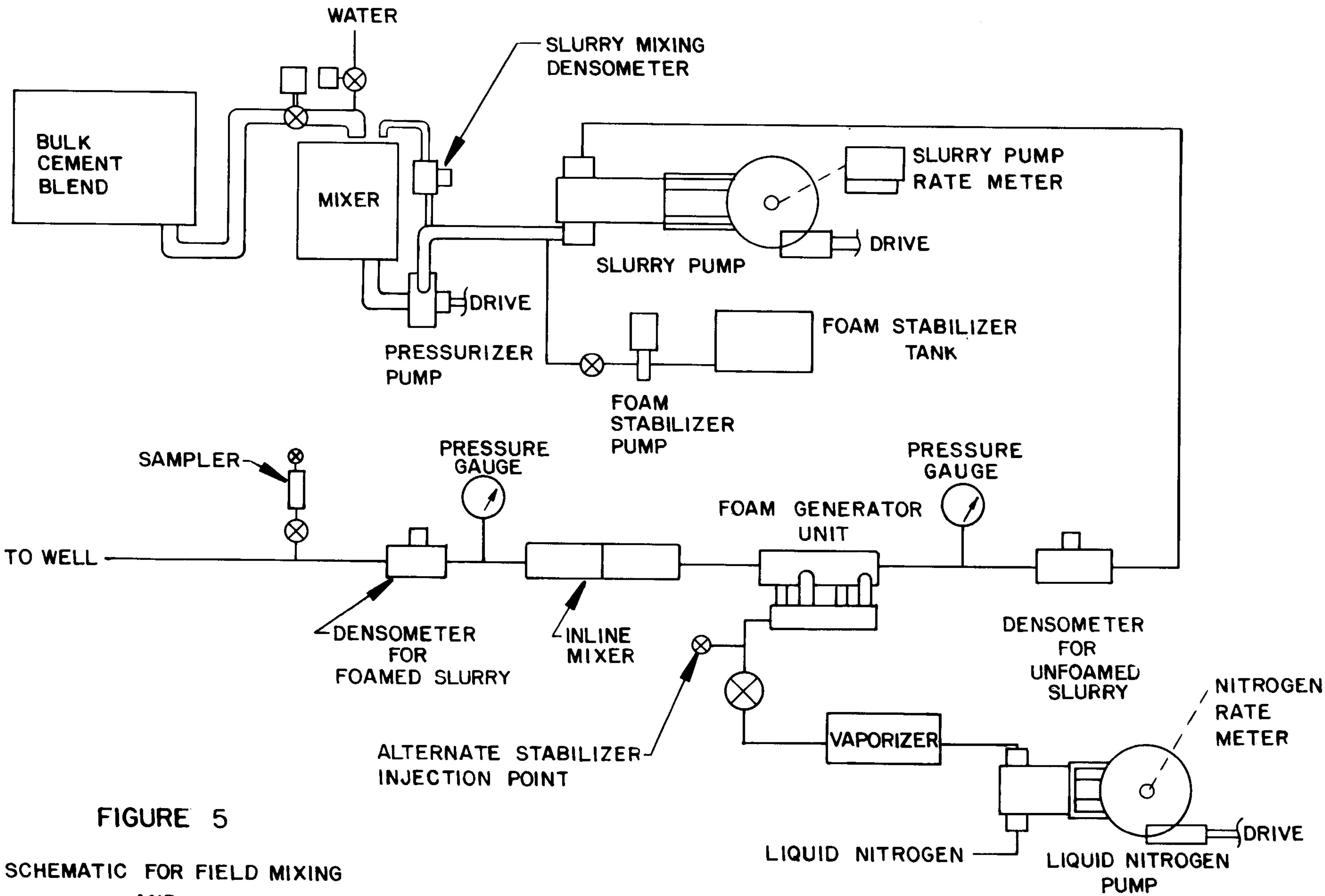


FIGURE 5

SCHEMATIC FOR FIELD MIXING
AND
MONITORING FOAM CEMENT

FIGURE 6

CONSTANT NITROGEN RATIO
SURFACE RATIO 30SV / VUS (168.0 SCF/Bbl US)
UNFOAMED SLURRY DENSITY 15.2 lbs/gal

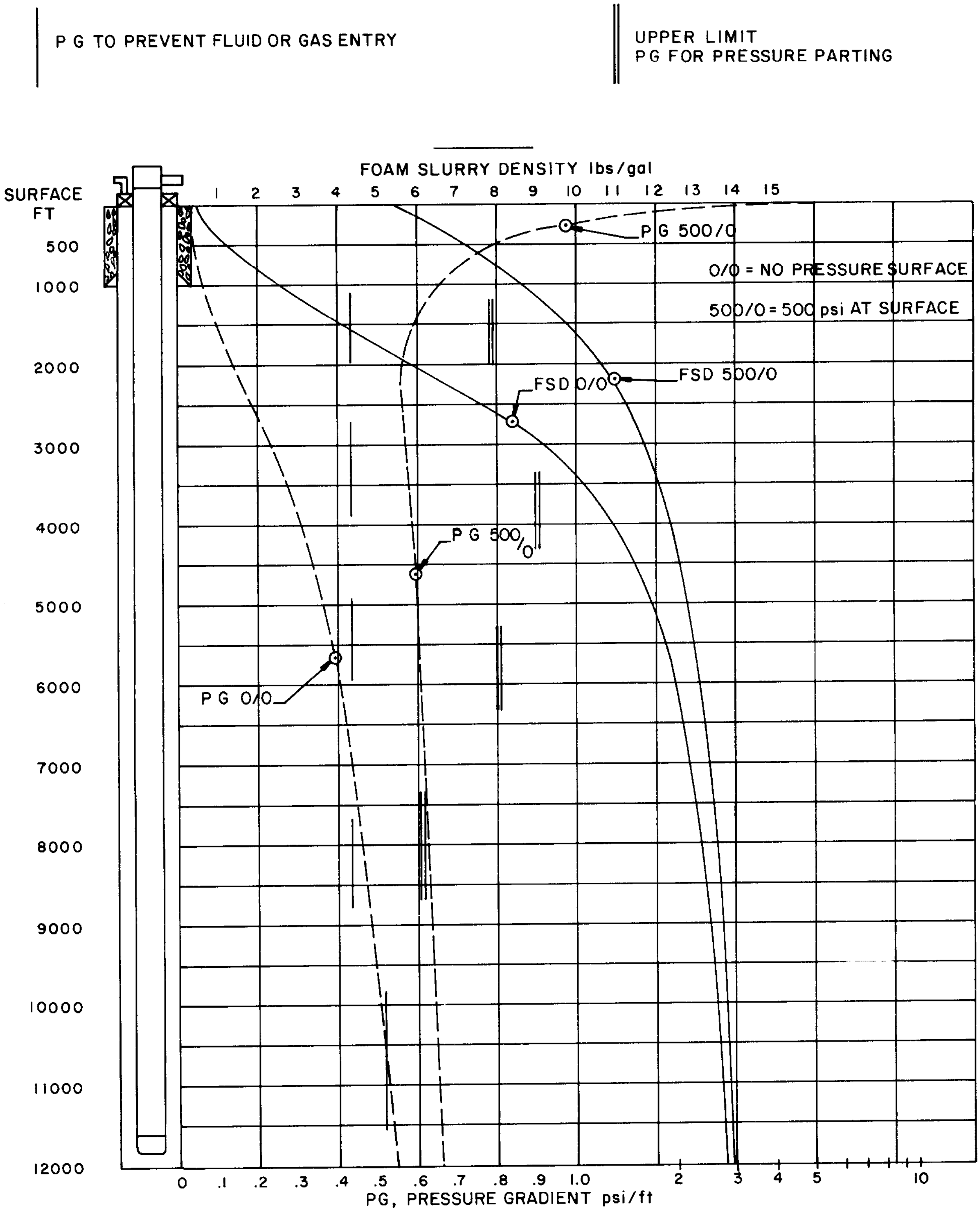


FIGURE 7

CONSTANT NITROGEN RATIO
WITH 3000ft OF MUD
30 SV/ VUS

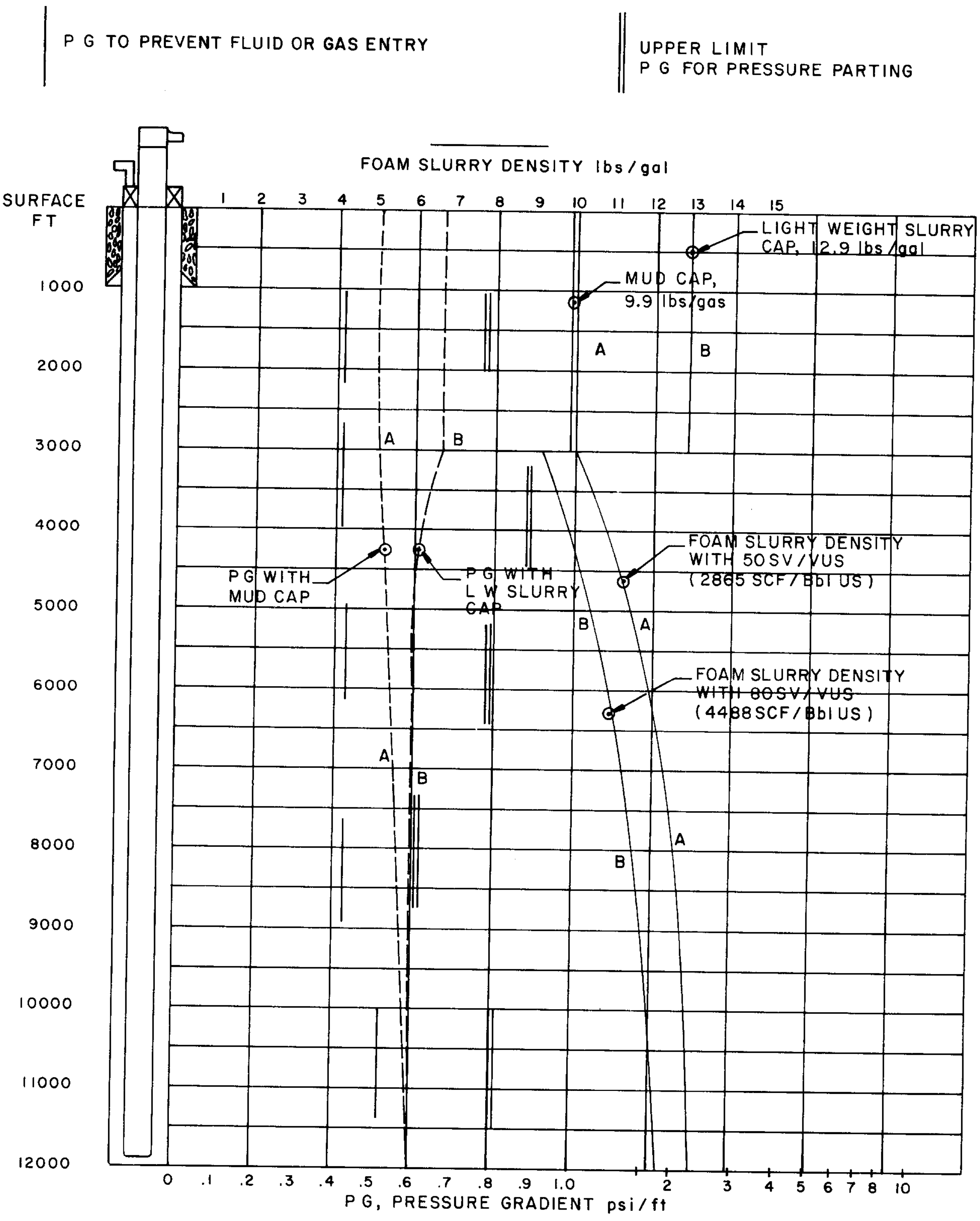


FIGURE 8

NITROGEN RATIO ADJUSTED
FOR AVERAGE FOAM SLURRY DENSITY AT 10.5 lbs/gal
WITH NO CAP FLUID OR PRESSURE ON ANNULUS

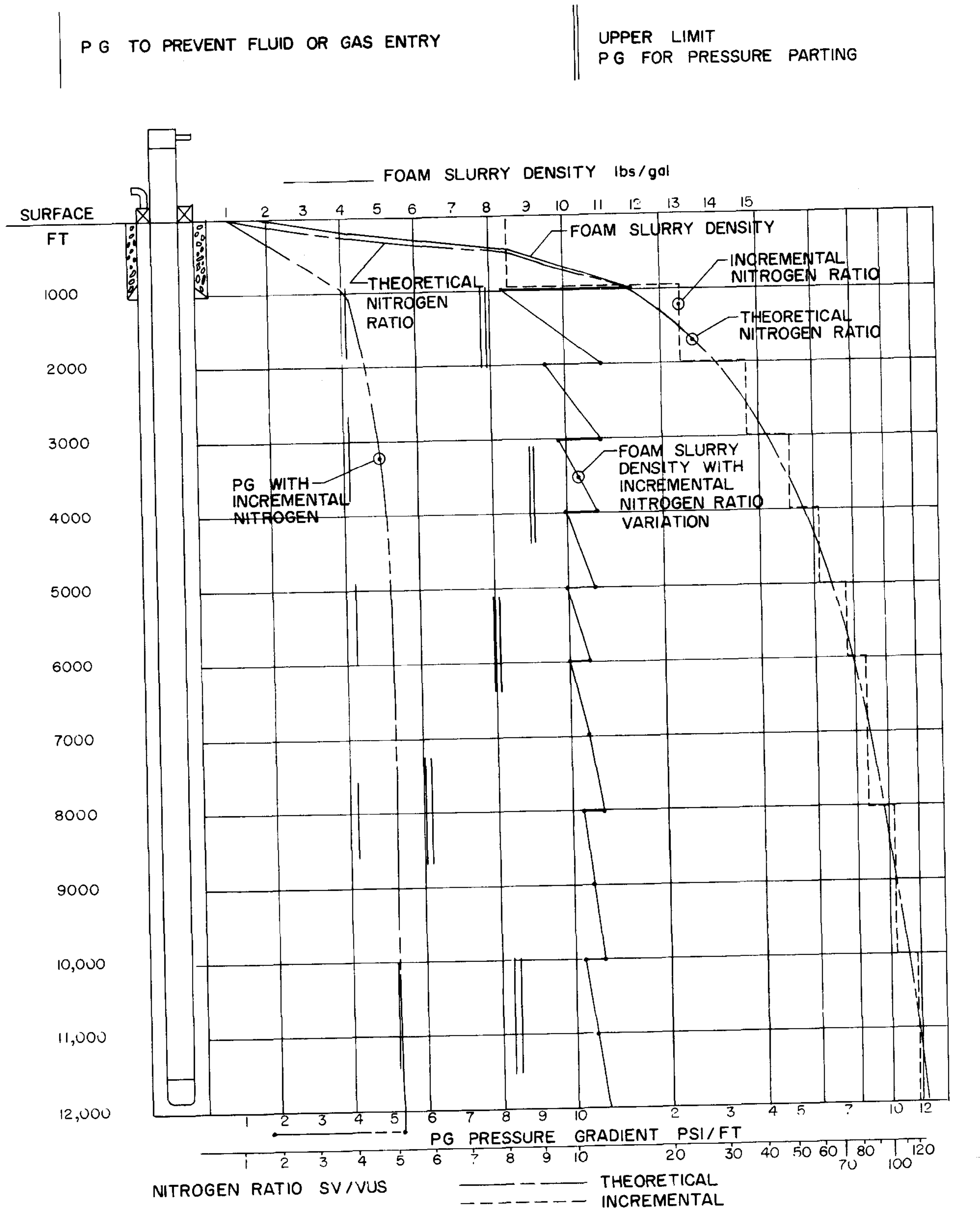
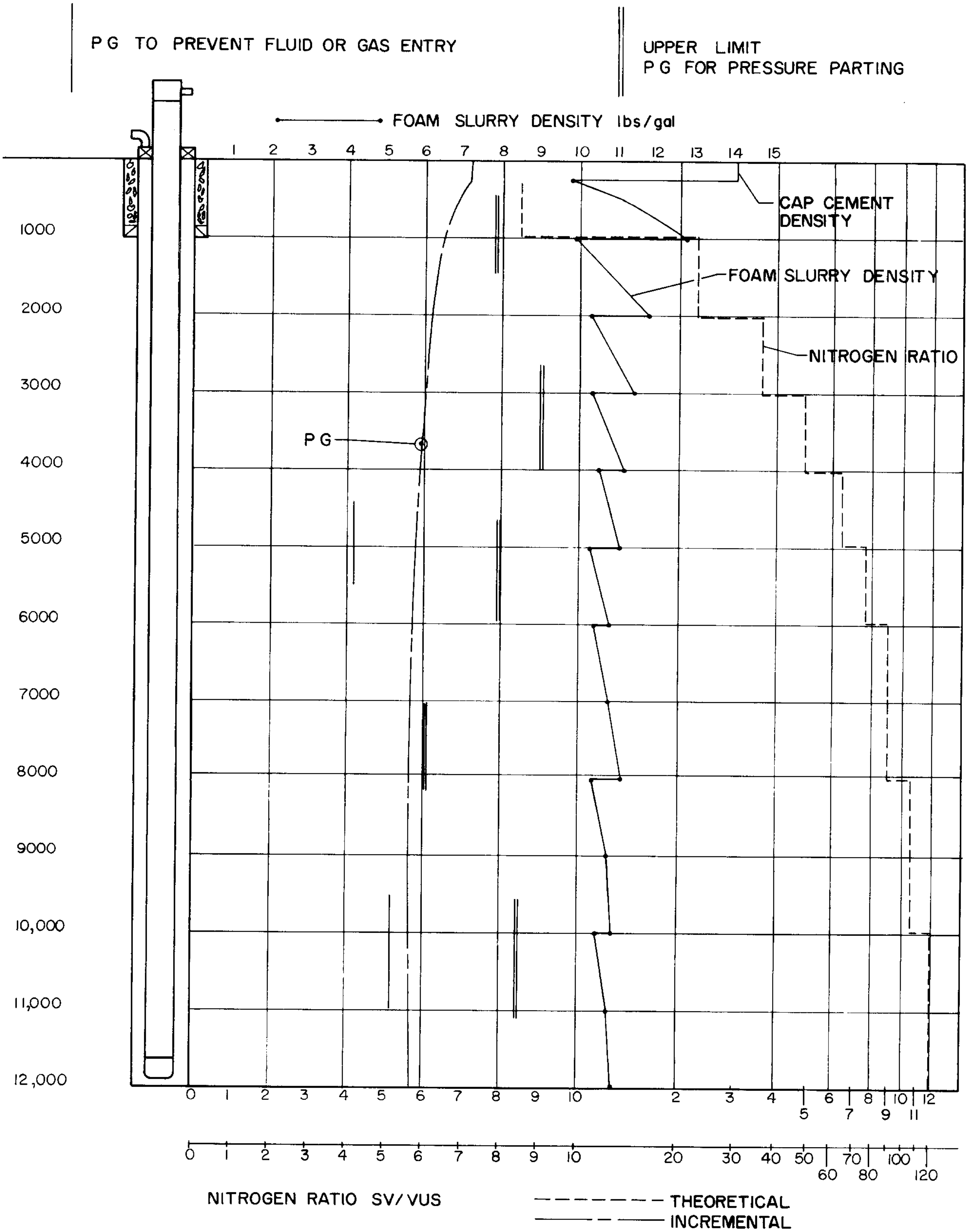
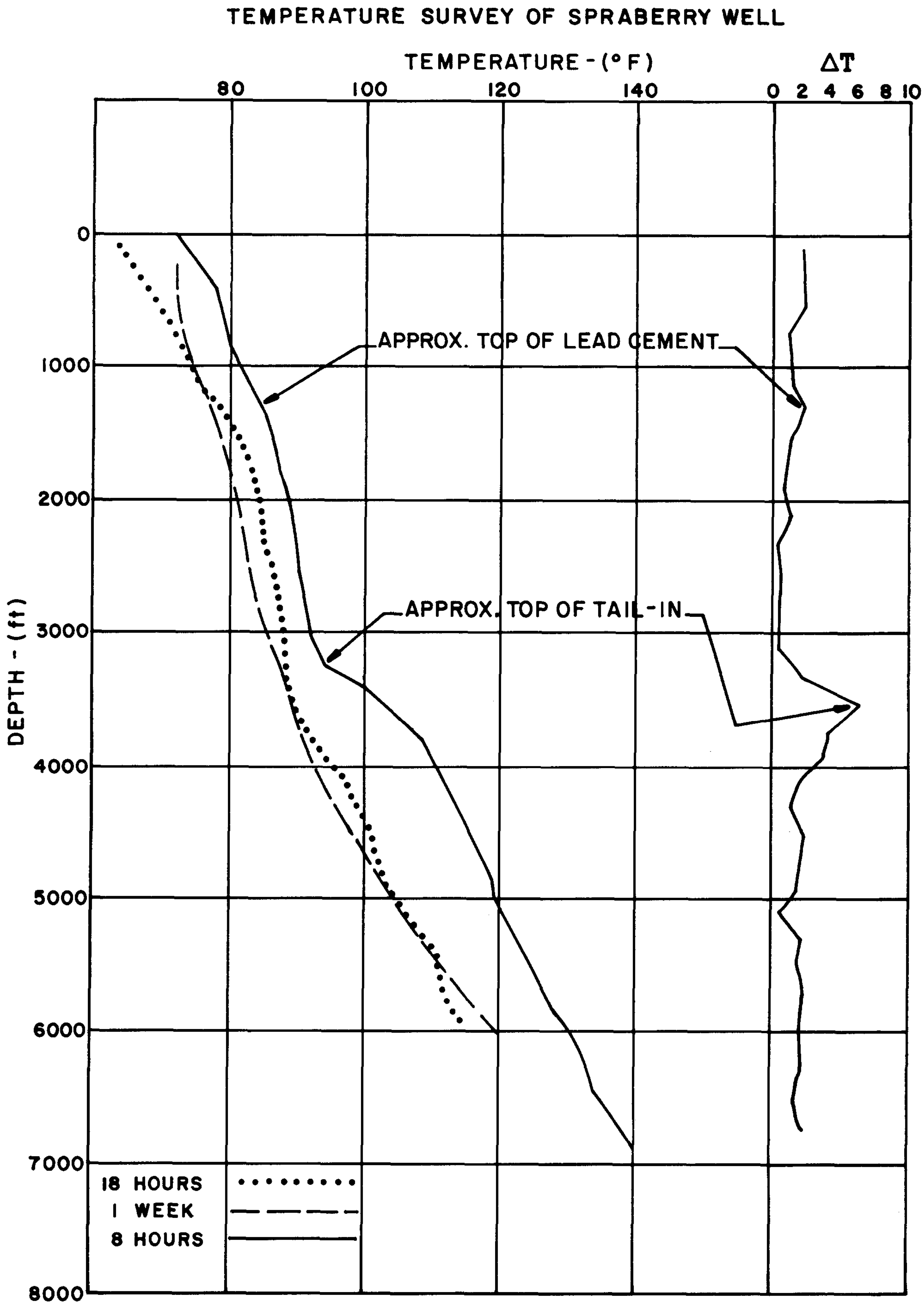


FIGURE 9

NITROGEN RATIO ADJUSTED
FOR AVERAGE FOAM SLURRY DENSITY (10.5 lbs/gal)
PLUS 200 ft. OF CEMENT CAP (14.1 lbs/gal)
UNFOAMED SLURRY DENSITY (15.2 lbs/gal)




TEMPERATURE SURVEY OF SPRABERRY WELL
TEMPERATURE - (° F)
ΔT
80
100
120
140
0 2 4 6 8 10
0
1000
2000
3000
4000
5000
6000
7000
8000
DEPTH - (ft)
APPROX. TOP OF LEAD CEMENT
APPROX. TOP OF TAIL-IN
18 HOURS
1 WEEK
8 HOURS