FOAMED ACIDIZING AND SELECTIVE DIVERTING USING STABLE FOAM FOR IMPROVED ACID STIMULATION

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ABSTRACT

Foamed stimulation has been broadened to include the use of high- and low-quality (30% to 75% nitrogen) foams for acidizing soluble formations. To insure correct placement of foamed acidizing systems, foamed diverting techniques using high-quality (80% to 90% nitrogen) foamed water systems are currently being employed in several West Texas and Southeast New Mexico areas. Application of these techniques has been successful in both producing and injection wells. The mechanics of these systems will be discussed along with comparative results and current cost economics.

INTRODUCTION

The use of foam stimulation has been well documented in the literature in recent years. It has been used successfully with fracturing and proppant placement as well as with acidizing. Blauer, Mitchell, Kohlhaas, and others have described the mechanisms of foam rheology and efficiency within the realm of high-quality foams (those with high gas volume to total foam volume ratios).[1,2,3,4,5,6,7,8,9] Others have suggested foam properties in porous media [10,11,12,13,14] The ranges of the prescribed efficienceis for fracturing include those qualities between 0.5236 and 0.95 theoretically, and practically, those between 0.65 and 0.85. Low fluid loss with spurt losses approaching zero and C_l values of $1x10^{-4}$ are the known benefits with foamed fracturing systems. Actual field demonstrations and laboratory demonstration of this efficiency were the first steps in establishing a mechanism for the extended control of HCl acid reaction on soluble formations. Thus extended penetration of "live" HCl further away from the immediate wellbore became possible. Retardation of acids by a variety of means has been extensively investigated. Some of the systems mentioned for controlling acid reaction rate and ultimately acid penetration distance include emulsions of hydrocarbons and acid (both water and oil external types), chemically retarded systems utilizing oil-wetting surfactants and similar agents, gelled systems, high-strength HCl, and organic acid blends. [15,16,17,18,19] All of the above-mentioned systems for controlling acid reaction rate do so with the aid of a mechanism for fluid efficiency control and/or chemical methods involving higher efficiency with respect to rheology. Increasing the efficiency of acid via acid-fracturing techniques has shown that for more efficient fluids, stimulation is limited by acidized fracture conductivity—not acidized fracture length—and to improve acid fracturing treatments, acidized fracture conductivity must be improved. Novotny demonstrated that plain HCl treatments yield shorter but more conductive fractures and that low fluid-loss acid external emulsions generate long fractures with finite (lower) fracture conductivities. These long fractures are beneficial in wells with low closure stress or low permeability where acidized fracture length, not conductivity, limits stimulation.[15]

Nierode and Kruk determined that effective fluid-loss additives can significantly improve stimulation from an acid fracturing treatment but that most available particulate additives tested were ineffective at 200°F and none were effective if the filtration pressure exceeded 2,400 psi. They pointed out that viscous acids are retarded under acid fracturing conditions and can provide good fluid-loss control.[16] Emulsified acids, particularly a group of acid external emulsions, showed the best application for the acid fluid-loss control and retardation effect. Novotny went on to report that chemically retarded acids are not retarded under field conditions.[15] Liquid emulsion dispersion additives for fluid loss have been performing well in many low permeability situations.

Another type of emulsion system, foamed acid, not unlike the acid external emulsion system described by Nierode and Kruk as approximately 66-2/3% hydrocarbon and 33-1/3% acid, is a recognized candidate for efficient acid fracturing.[16]

If HCl acid is used in a stable foamed system as the external phase of what is actually an emulsion, or gas/liquid dispersion, in the 0.65 to 0.85 range which shows the most effective fracturing efficiency, then superior acidization length can be realized. This, in turn, can provide improved stimulation over any previously described system in wells with low closure stress or low permeability.

In addition, Holcomb has described the use of low percentage gas or low quality foamed HCl acid systems for providing more effective leak-off control and thereby greater penetration efficiency.[9] With low quality foamed acids in high solubility reservoirs the volume of acid is greater than the inert phase so that more acid conductivity can be gained. This lower quality range sacrifices some of the efficiency seen in higher quality foamed systems but still provides acid penetration distances greater than conventional retarded acid systems. In sandstone reservoirs where low concentration HCl or HF acid are used frequently for clean-up of formation

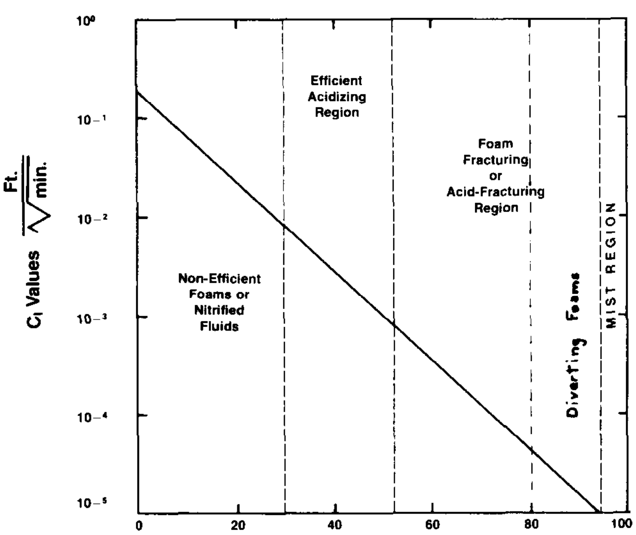

FIGURE 1—C_l VALUES VS GAS OR FOAM QUALITY

damage or as the base fluid for fracturing including proppant, the high-quality stable foams (0.52 to 0.80) are recommended.

The methods of selectively placing these foamed acids have varied and include an additional application of foam. High-quality stable foams with their highly efficient leak-off control (Figure No. 1) can and have been used to divert stages of foamed acid over large intervals of the formation to be treated. The mechanism for this involves building a resistance to penetration (with high-quality foamed water) in the zone which had been accepting low-quality foamed acid to breakdown and penetrating another portion of the interval which had not yet been acidized.

LOW-QUALITY FOAMS

It has been observed in the field that even those foam qualities deemed below the fracturing realm of 0.5236 described by previous authors possess merit with regard to efficiency and thus controlled reaction rate in soluble formations. These systems fall into a quality range in the gas/liquid dispersion category of 0.30 to 0.50; or more simply, 30% to 50% of the system is a gas with the remaining 70% to 50% being a predescribed strength of HCl or other acid. These low-percentage or low-quality systems, when used with the proper foaming agent, can provide efficiencies which rival gelled water, acid external hydrocarbon emulsions, chemically retarded acid, organic acids, or oil external emulsified acids.

SELECTION OF A FOAMING AGENT

Foaming-agent selection should follow these guidelines established by Blauer and Holcomb:[1]

1. Foaming agent must immediately produce a stable foam upon injection of gas.
2. Foaming agent must be chemically compatible with any type of liquid phase used for foam fracturing, such as fresh water, brine, and acid solutions.
3. Foaming agent must not have such stability that it will not readily break when pressure is released and bubbles expand.
4. Foaming agent must be compatible with the formation and not cause irreparable permeability damage.
5. Concentration of the foaming agent should be low to minimize problems of formation com-

patibility, mixing, and disposal of injected fluids.

6. Cost of foaming agent at the required concentration must be reasonable.

For foaming acids such as HCl at strength between 3% and 28%, the careful selection of the foaming agent and foaming agent concentration is required. Foaming agents from several groups have been tried, but those used most often are from a group including polyethylene glycol ethers of alkylated phenol, sodium dodecyl sulfate, and blends of these with a fluorinated alkyl quaternary ammonium iodide compound. The fluorinated compound increased foam stability and uniformity as well as acid and thermal stability. The blend of hydrocarbon and fluorochemical materials creates a synergism which improves the physical and chemical characteristics of foamed acid systems, particularly under pressure, temperature, and shear conditions. The mechanism for this improvement is the lowering of the contact angle or an improved wettability effect as well as the highly stable fluorochemical chain.[20]

Concentrations of foamers in acid foams between 0.5236 and 0.85 quality for fracturing and between 0.30 and 0.50 for matrix or natural fracture foam treatments are from 3 to 8 gal per 1,000 gal of acid. Usually more foamer is required in stronger acids, or a foamer with greater acid stability at higher acid concentrations.

Sufficient laboratory work has not been done to establish the proper quality range of foamed acids in the lower quality ranges (i.e., 0.30 to 0.50). It has been suggested, however, that 0.40 to 0.50 qualities be used in soluble formations with permeabilities in the range of 20 to 50 md and that 0.30 to 0.40 qualities be utilized in low permeability situations (i.e., 0.10 to 20.0 md).

HIGH-QUALITY DIVERTING FOAMS

Likewise the use of higher-quality stable foams (0.80 to 0.90) for diverting should be determined by gauging the permeability. High permeability (>25 md) should use 0.85 to 0.90 quality foams, and lower permeability (<25 md) should be a candidate for (0.80 to 0.85) quality foam as a diverter. Future experimental work should show the relative need of changing foam quality higher or lower to effect diverting. Also, it is not known at this time how large a volume of foam is required to divert a specific length of interval. However, radioactively tagged treatments have shown that 100 ft of openhole section can be treated adequately with 8,400 gal of 40 quality (Γ) foamed 15% HCl and divided into two stages of 4,200 gal each to cover the entire zone by using 3,000 gal of 80 quality foamed water between them.

LEAK-OFF EFFICIENCIES OF VARIOUS FOAM QUALITIES

Figure No. 1 shows the relative C_l values for foamed fluid systems using a 100 md core at 1,000 psi. The dimensions of the cylindrical core are 1 in. x

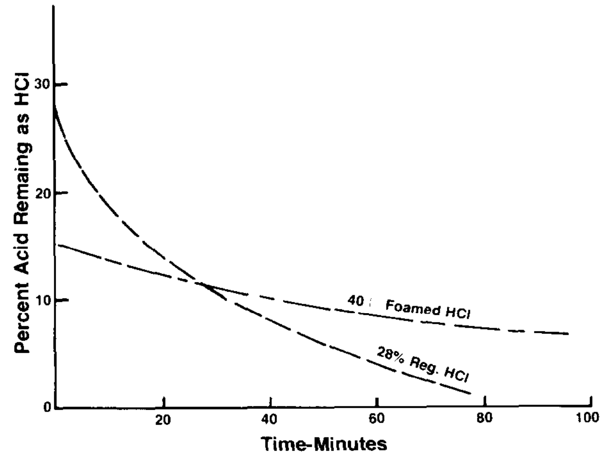

FIGURE 2—SPENDING TIME—LIMESTONE (30 md) @ 100°F

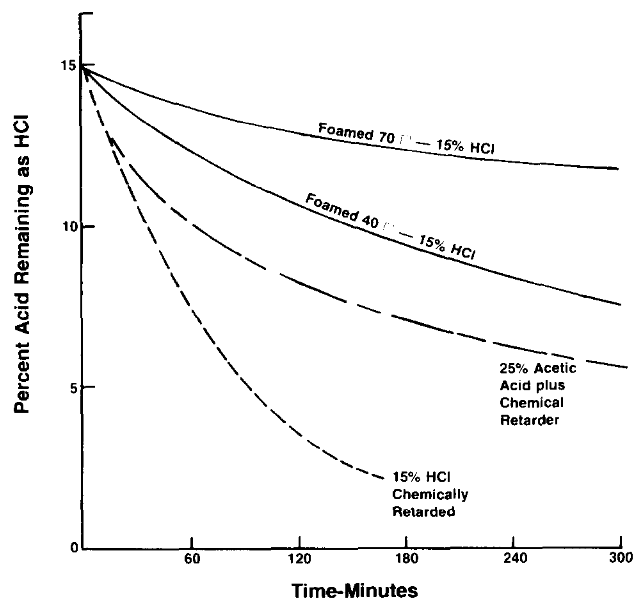

FIGURE 3—SPENDING TIMES ON LIMESTONE PACK AT 100°F—HIGH PERMEABILITY (150md)

1 in. The efficiency tests were run in both soluble (80% soluble 20 md Chester lime) and insoluble (Berea) cores to determine the effect of the acid on the fluid efficiencies. It was noted that there was little acidizing by the acid at fracturing qualities between 0.5236 and 0.90. Figures Nos. 2, 3, and 4 show the comparative spending times of various acid systems as compared to various quality foamed acid systems. Spending was determined using a 200-400 mesh limestone pack and flowing the various acidizing systems through it. The pack was 3.5 in. in diameter and 15 in. long. The flows were conducted at 1,000 psig with samples caught and titrated to obtain results of acid strength vs. time. Fluid volumes flowed were equivalent to the saturated pore volume of the pack plus 10% which was initially saturated with a 9 lb brine solution.

FOAM STRUCTURE

As Blauer and Holcomb described various foamed systems, foam was a homogeneous mixture of gas, aqueous solution, and surface-active agent. The gaseous phase exists as microscopic bubbles contained in the aqueous solution, and surface-active agent mixture. Foam quality is defined as the ratio of gas volume to total foam volume at a specified temperature and pressure:

$$F_{ftp} = V_g / V_f$$

where:

F_{ftp} = foam quality, dimensionless
V_g = volume of gas, cu ft
V_f = total foam volume, cu ft

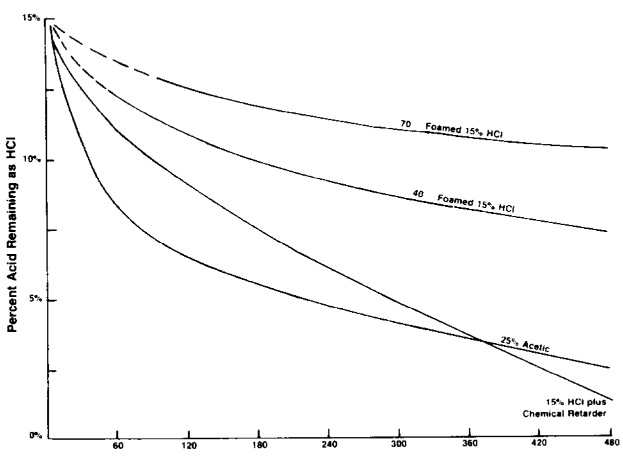

FIGURE 4—SPENDING TIME IN LOW PERMEABILITY FRACTURED LIMESTONE, WITH REGULAR ACIDS VS VARIOUS QUALITIES (Γ) FOAMED HCl

The bubble structure of foams having qualities between zero and 0.52 are uniformly dispersed spherical gas bubbles which contact one another in liquid media. Flow properties of foam with qualities below 0.52 are Newtonian. At 0.52 quality, the spherical bubbles are packed cubically and begin to interfere with each other during flow. Qualities between 0.52 and 0.74 show that static foam bubbles will form spheres packed rhombohedrally which deform to parallelopipeds during flow.[1,2] Flow characteristics of foams in this range are described by Blauer, Mitchell, and Kohlhaas.[3]

SUGGESTED REACTION SEQUENCE OF FOAMED HCl ACIDS

In the lower quality ranges (i.e., 0.30 to 0.50) foamed HCl acid reaction is effectively reduced by leak-off control via the mechanism of having less acid available to contact and penetrate per unit area of formation contacted. Experimental observation of foamed acid flow over soluble surfaces indicates that the sequence of maintaining the leak-off controlling configuration of the foam system takes precedence over the acid being liberated to react significantly with the reservoir rock.

Upon completion of pumping the low-quality foamed acid systems, and after shut-in, the gradual reaction of acid with the formation causes an increase in gas volume via temperature and pressure release. Subsequent expansion of the gaseous phase (nitrogen) as well as a subsequent production of CO_2 gas from the "gradual" acid reaction of the formation raises the quality of foam at the bubble-reservoir contact point to a level above the 96+ quality. Blauer indicates that foam reverts at this point to an inefficient mist, which leaks off and thereby starts the process over with the next available bubble layer. Meanwhile acid should react over a slower and controlled time period. (Figure Nos. 2, 3, 4). This reaction sequence is difficult to recreate experimentally because of the inability to differentiate between the blended CO_2 reaction product and expanded nitrogen. Also, the CO_2 should be maintained in liquid phase. However, the conditions present in the field and in laboratory situations indicate this is probably occurring and that subsequent major reaction of the acid on the formation for low-quality foamed acid systems begins as the foam breaks. This allows control while pumping through porous media and thereby allows maximum penetration into the formation by the acid system used.

TYPES OF FOAMED ACID SYSTEMS

Foamed acid can be generated using a variety of acid systems including chemically retarded acids for the additional benefits of greater conductivity out to several hundred feet away from the wellbore. Sufficient work has not been completed to show effective matrix penetration achieved by foamed acid systems, but it could be approximated using the combination of C_I efficiency data for the specific quality in question in combination with the reaction rates derived for the cases in Figure Nos. 2, 3, and 4.

As a helpful guideline in designing low-quality foams, Figure Nos. 5 and 6 are presented to indicate the hydrostatic pressures at various depths as well as friction properties of low-quality foams at various rates. Friction properties are derived from actual job data. Job design can be done using Blauer's or Holditch's equations.[4,6]

FOAMED DIVERTING SYSTEM DESIGN

Foamed diverting systems can be designed using Blauer's or Holditch's equations for deriving the pressures and gas volumes for using 0.80 to 0.90 quality foams at bottom-hole treating pressures.

FIELD RESULTS

It has been shown that low-quality foamed acid treatments have been quite successful in increasing oil production in several fields in the West Texas San Andres formation at an approximate 5,000 ft depth. The San Andres, in the region where these jobs were performed, is a relatively low to medium permeability limestone with moderate porosity. Many treatment techniques have been used in the area for stimulation including regular HCl acid jobs, acid jobs with various fluid loss and acid-diverting materials (i.e., 100-mesh sand, liquid emulsion additives, etc.), and nitrified acid treatments where the nitrogen and acid was not a system in a foamed state. The results shown are comparable or improved over conventional systems used in the past with regard to production increases. Many of these results were on wells which had been previously stimulated. Results comparing diverting foams (80 to 85 quality) used in conjunction with low-quality foamed acid treatments are presented in Table 1 and Table 2. Evaluation time has not been extensive with only a few tests extending 120 days, but trends look promising. To date approximately 25 jobs have employed the low-quality foams,

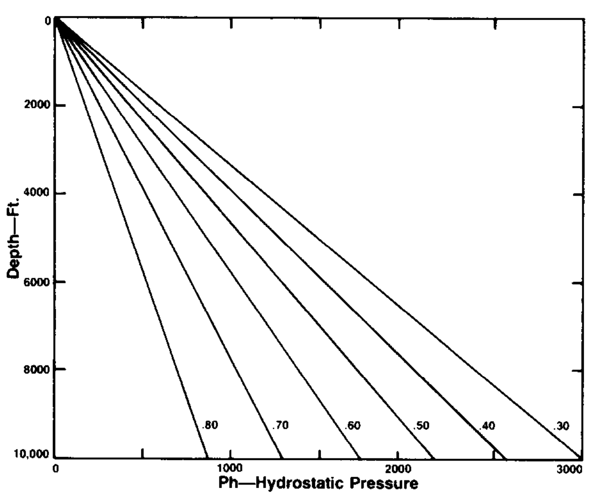

FIGURE 5—HYDROSTATIC PRESSURES OF VARIOUS QUALITY FOAMS

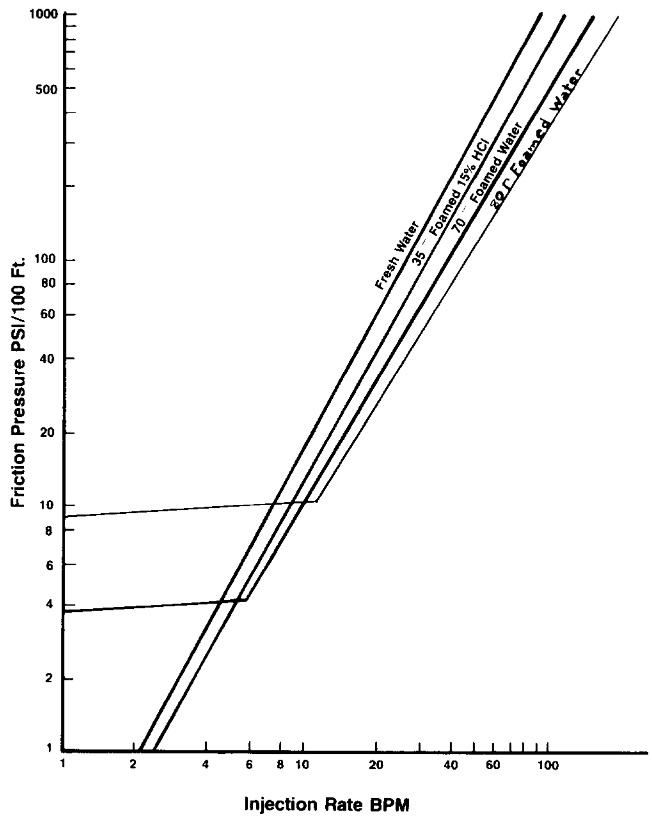

FIGURE 6—FRICTION PRESSURES OF VARIOUS QUALITY FOAMED SYSTEMS VS WATER USING 3-1/2-IN. TUBING

TABLE 1—FOAMED ACID CASE HISTORIES, SAN ANDRES FORMATION, HOCKLEY CO., TEXAS

Formation: San Andres @ 5000 ft
Treated Intervals: 150-200 ft O.H.
Foamed Acid Qualities: 0.33
Treatment Rate: 2-5 BPM

Producing Well No.	Treatment Volume gal	Pretreatment Production		Initial Results		30-Day Results		60-Day Results	
		BO	BW	BO	BW	BO	BW	BO	BW
1	6,000	103	654	92	656	106	632	131	752
2	6,000	124	348	189	410	189	474	161	607
3	8,000	124	496	135	660	151	707	153	748
4	8,000	128	400	308	444	312	644	310	555
5	8,000	44	134	52	172	56	217	59	190

Injection Well No.	Treatment Volume gal	Pretreatment Injection	Initial Results	30-Day Results	60-Day Results	90-Day Results
		BWPD	BWPD	BWPD	BWPD	BWPD
1	5,000	318	1,059	1,169	1,322	1,460
2	6,000	580	707	909	1,038	1,141
3	6,000	814	1,055	954	772	654
4	6,000	750	1,275	1,456	1,400	1,400
5	6,000	860	1,539	1,628	1,655	1,600

TABLE 2—TREATMENT HISTORIES FOR SAN ANDRES PRODUCING WELLS, HOCKLEY CO., TEXAS

5000 gal 40 Γ Foamed Acid with 80 Γ Foam Diverter Stages at 3,000 gal

PRODUCTION

Well No.	Before Treatment		Two Weeks		90 Days	
	BOPD	BWPD	BOPD	BWPD	BOPD	BWPD
A	75	110	102	164	50	175
B	88	64	112	103	85	85
C	118	68	107	106	130	90
D	100	70	146	194	137	112
E	23	10	35	42	45	10

usually in the range of 0.30 to 0.40. Seven jobs have been performed using the high-quality foams for diverting. Results on wells using the foamed diverting systems compare favorably with conventionally diverted treatments. Table 1 lists the well type, treatment volumes, and production changes for 10 (low-quality) jobs. Table 2 illustrates low-quality foamed acid plus foamed diverting technique results. Rates were in the 3.0 to 7.0 BPM range for most of these low-quality foam jobs, and pressures were maintained just below parting pressures because in this particular area there were significantly close water zones. In fact, some high water production increases were noted after several of the jobs. Both producing and injection wells were treated with good results on both, although there were fewer jobs involving injection wells. Again it is noted that comparison to other treatments has been favorable with regard to sucess, and application economics. Jobs using diverting foams appear to make less water and have held up longer. Future work will indicate this more extensively.

In addition to the control of the acid reactivity, the other benefits of foam systems noted by Blauer and others are also realized such as:[1,2,4,5]

1. Reduced likelihood of production blockage of formation pores by fluids, i.e., water, oil, or gas.
2. No need for special chemicals such as gels, emulsifiers (other than the foaming agent) and the like. These usually require breakers, time or other means to break before production can begin.
3. Reduced clean-up time required with the aid of the built-in compressed nitrogen, and less fluid to recover than in most conventional treatments.
4. Leak-off control as described earlier.
5. Some reduction in hydrostatic head of fluid existing in the wellbore, thus allowing more natural potential clean-up pressure from the formation for clean-out.
6. A reduction in total liquid base material and its associated storage and transportation costs. (Nitrogen equipment must be supplied in addition to conventional acidizing pumping equipment.)
7. Relatively simple job set-up. (Figure No. 7)

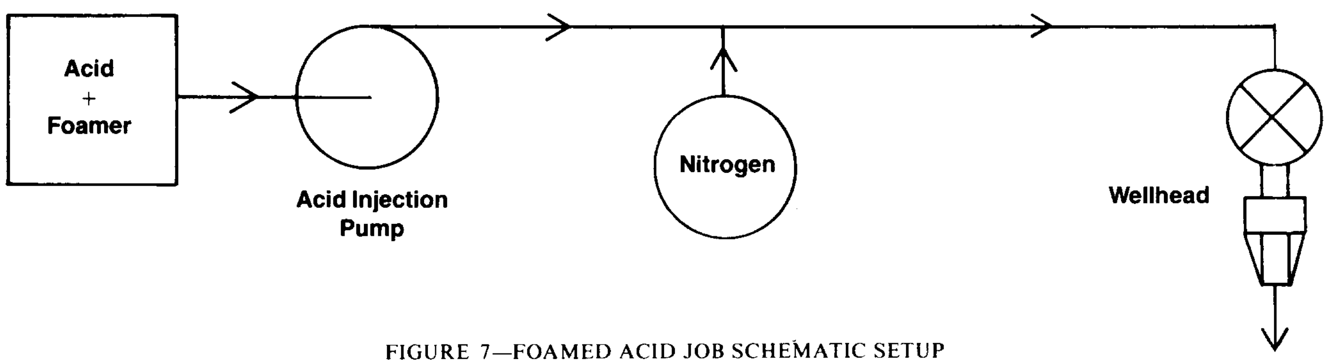

FIGURE 7—FOAMED ACID JOB SCHEMATIC SETUP

SUMMARY

1. Foamed acid in fracturing quality ranges (0.65 to 0.85) possesses those efficiency characteristics of foam fracturing fluids which allow acids to be injected great distances into the formation at fracturing rates and pressures. Although acid fractured length is greater, conductivity is limited.
2. Foamed acids in the less-than-fracturing quality ranges (0.30 to 0.50) still provide efficiency and subsequent acid reaction rate control for placing conventional acid strengths greater distances into the soluble formation either via matrix flow or into old fractures or naturally fractured reservoirs. Greater conductivity should be realized with the higher acid volumes.
3. High-quality foamed aqueous systems (.80 to 0.90) can be used effectively to divert low-quality foamed acid treatments for greater treatment selectivity without the concern for whether or not particulate matter diverters will be dissolved and/or recovered. The diverting appears to take place within the natural fracture system or matrix away from the wellbore. This makes conventional means of monitoring treatment specificity difficult.
4. Field results are promising with regard to the potential use of foamed acids for greater penetration and subsequently more effectively treated acid-soluble formations.
5. Properties of foamed acid systems, both fracturing and non-fracturing types, provide many of the same benefits produced by the foam fracturing systems. The lower-quality foams actually provide a more economical treatment in cases where higher hydrostatic pressures are needed to offset high fracture pressure and where depth and subsequent nitrogen or gas compression makes fracturing foam qualities less feasible.
6. Potentially damaging particulate-matter fluid-loss additives can be eliminated or reduced in acidizing treatments without sacrificing efficiency. Special liquid-emulsion additives can be used if needed.
7. With the properly designed foaming agent (a fluorochemical-hydrocarbon blend) high pressure and temperatures are no longer significant obstacles to efficient acidizing. This should allow deep, hot, soluble formations such as the Ellenberger of West Texas to be more effectively treated with acid.
8. With lower-quality foams the majority of the system is acid, not inert gas, soluble gas, or hydrocarbon as with other systems. This supplies the means for providing more effective conductivity over "just" additional acid-fracture penetration. Also the system is equally safe in oil or gas reservoirs. (Certain efficient oil external emulsion retarded acids contain small percentages of oil and should not be used in gas well stimulation in most cases.)
9. Low-quality foamed acids have worked in the San Andres formation of West Texas with equal or improved results compared to conventional treatments. This success has been noted in old producing wells as well as in injection wells.
10. Calculation of foamed acid treatment mechanics, job volumes, etc. can be derived from most of the references listed with foam-related work.
11. Job costs are comparable to conventional treatments which require the addition of fluid-loss materials or in-fracture diverting agents. Deeper wells may show slightly higher costs with foams due to the compressibility of the gaseous phase.
12. Foamed acids are gas/liquid emulsions or dispersions which provide efficiency factors comparable to other acid external emulsion systems. In the case of foamed acids in the lower qualities, more acid can be used in the same volumes comparable to acid external hydrocarbon emulsions.

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