FOAM-FRACTURING — APPLICATION AND HISTORY

R. E. BLAUER
Minerals Management, Inc.

D. L. HOLCOMB
Cardinal Chemical, Inc.

INTRODUCTION

Foam has been used successfully as a fracturing fluid as previously described by Blauer and Kohlhaas.[1] They presented analytical measurements of fluid-loss coefficients and sand settling rates. Other investigators[2–10] have discussed use of foam in other oilfield applications. Blauer, Mitchell and Kohlhaas[11] have reported rheological properties of foam.

The physical structure of aqueous foams used for fracturing is used to explain foam viscosity and sand-supporting properties. Figures are presented comparing fluid-loss coefficients, sand-settling ratios, and fracture areas for foam and other common fracturing fluids used in West Texas. Chemical compatibility of foaming surfactants with formation fluids and fracturing-fluid additives is discussed. Core flow data and case histories show foam can be used to stimulate formations in the West Texas area.

FOAM: DEFINITION AND STRUCTURE

Foam is a homogeneous mixture of a gas, an aqueous solution, and a 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:

$$\Gamma_{fTp} = \frac{V_g}{V_f} \qquad (1)$$

Spherical gas-bubbles in foams having qualities between zero and 0.52 are uniformly dispersed in the liquid and do not contact each other. 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. Between foam qualities of 0.52 and 0.74, static foam bubbles will form spheres packed rhombohedrally which deform to parallelepipeds during flow. Above 0.74 quality the static bubbles are no longer spheres and deform to parallelepipeds during flow, Fig. 1.

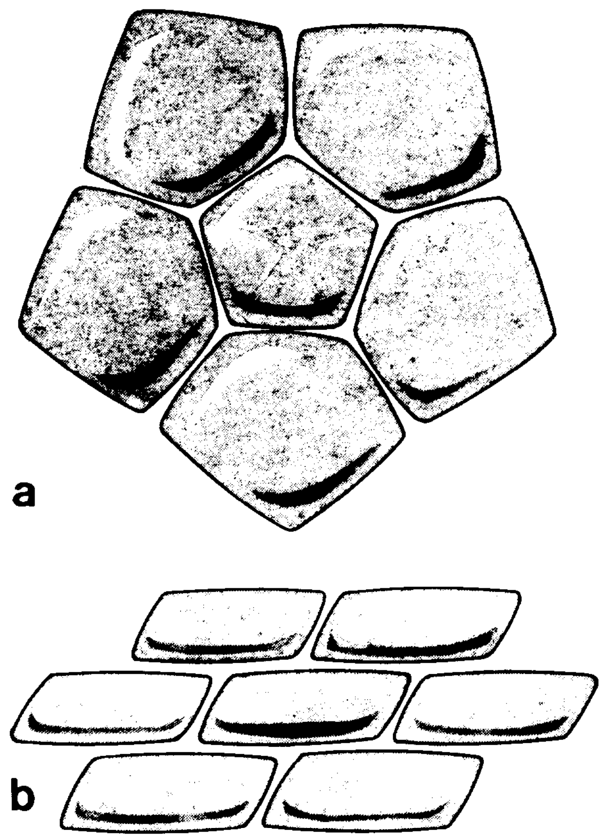

FIG. 1—PENTAGONAL DODECAHEDRONS AND PARALLELEPIPEDS OF STATIC AND FLOWING FOAM

The interference between the spherical bubbles of foams in the bubble interference region requires additional energy be applied to deform the bubbles to parallelepipeds before flow can be initiated. Mitchell[12] showed that values of Hatschek's viscosity for two-phase mixtures agree with laboratory measurements of foam viscosity in the bubble interference region.

$$\mu_f = \mu_b \, (1.0 + 4.5 \, f_{fTp}) \qquad (2)$$

Bubbles of foams with qualities greater than 0.74 deform from the static pentagonal dodecahedra to parallelepipeds during flow. Parallelepipeds are the only geometrical configurations which can flow in laminae. The apparent viscosity of the foam is caused by the shear of the fluid between the gas bubbles. Mitchell showed the viscosity of deformation region foams is:

$$\mu_f = \mu_b \, \frac{1}{1-(f_{fTp})^{1/3}} \qquad (3)$$

FOAM RHEOLOGY

In fully developed laminar flow, foam behaves approximately as a Bingham plastic fluid. Mitchell showed that the shear-stress to shear-rate relationship for foams with shear rates greater than 10,000 sec^{-1} is linear at any foam quality. The relationship for foam flowing with a shear rate below 20,000 sec^{-1} can be linearized by subtracting the apparent yield strength. The Bingham plastic foam shear-stress to shear-rate equation is:

$$(\tau - \tau_y) = \mu_p \, \phi \qquad (4)$$

Figure 2 shows Mitchell's Bingham plastic viscosity and Fig. 3 shows the yield strength of foam.

The effective viscosity of a Bingham plastic fluid is used in fluid flow equations for Newtonian fluids. Blauer, Mitchell, and Kohlhaas showed that use of the effective viscosity of foam permitted accurate prediction of pressure losses in pipes for all flow regimes. The effective viscosity of foam is:

$$\mu_e = \mu_p + 6.65 \, \frac{\tau_y d}{v_f} \qquad (5)$$

Figure 4 shows the effective viscosity of foam.

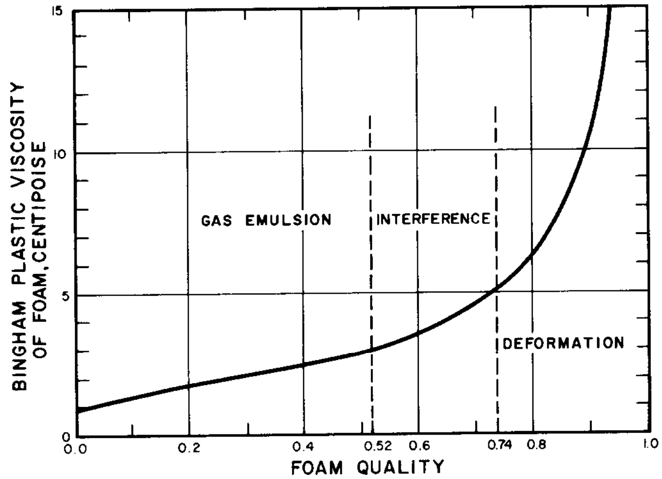

FIG. 2—BINGHAM PLASTIC VISCOSITY OF FOAM

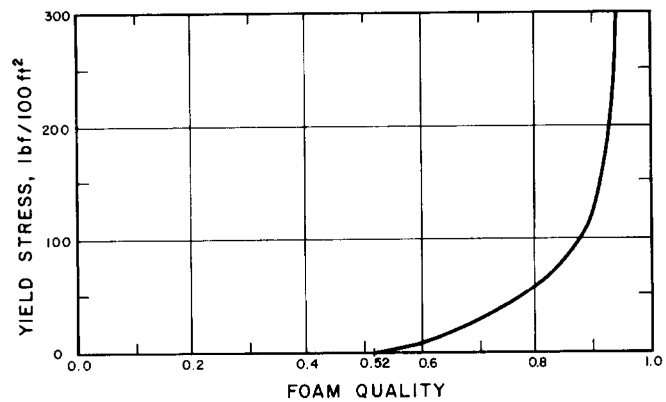

FIG. 3—YIELD STRESS OF FOAM

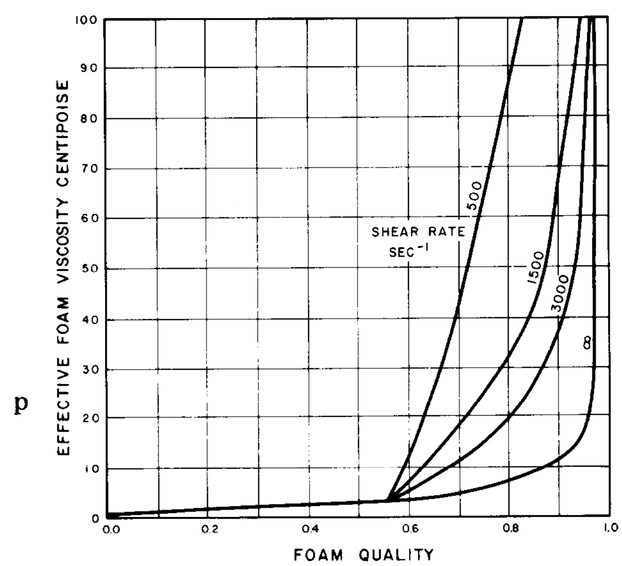

FIG. 4—EFFECTIVE VISCOSITY OF FOAM

Blauer and Kohlhaas measured foam fluid-loss characteristics and derived a value of the fluid-loss coefficient. Figure 5 is a comparison of fluid-loss coefficients for water, guar gum gel, crosslinked gel, and foam for formation conditions similar to the Canyon sandstone in West Texas. The low fluid-loss coefficient of the foam permits creation of large-area fractures with small volumes of foam injected into the fracture at low treating rates. Foam creates the largest area of the fluids examined at any volume of fracture fluid. Further, possible relative permeability damage caused by formation-fracture fluid interaction is minimized because actual liquid injected during a foam frac is between 10% and 40% of total foam volume.

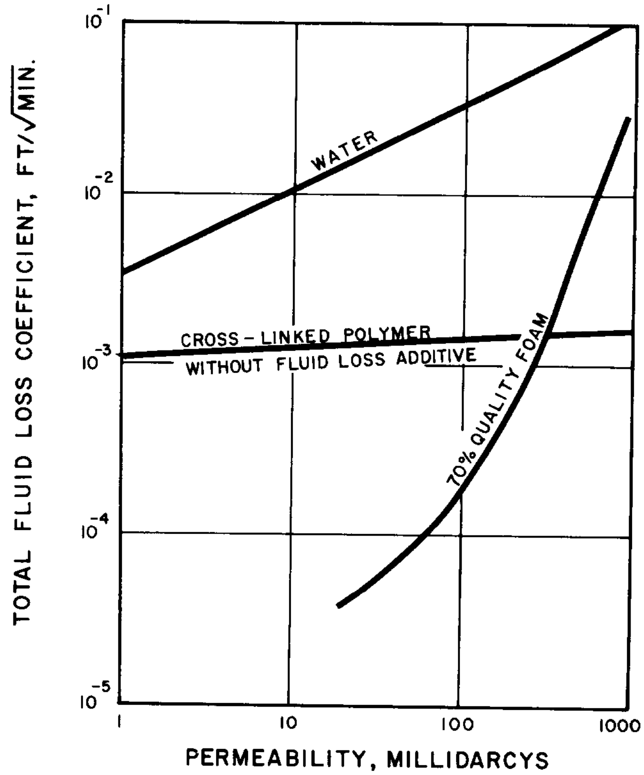

FIG. 5—TOTAL FLUID LOSS COEFFICIENT FOR FOAM, WATER, AND CROSS-LINKED POLYMER

Conventional fracturing fluids may be treated with fluid-loss additives which will reduce the fluid-loss coefficient to that of foam. However, Pye and Smith[13] have shown that these materials will cause reduction of fracture conductivity and loss of production efficiency through the fracture. Damage caused by wall-building or solid fluid-loss materials to the formation or the fracture is eliminated by foam.

SAND-SETTLING VELOCITY

Settling velocity of sand in foam is a function of viscosity, interfacial tension between the gas and liquid phase, particle size, bubble size and shear strength of the aqueous phase. Measured settling velocities in foams are much less than settling velocities in water, gelled water, or crosslinked gelled water, see Fig. 6.

Settling velocities of small-diameter proppants are much less than predicted by Stokes' Law because the particle is contained in the liquid pocket between adjacent bubbles and must deform the bubbles to fall. The energy to effect this deformation is very nearly equal to the potential energy of the particle. Thus, settling rate is near zero.

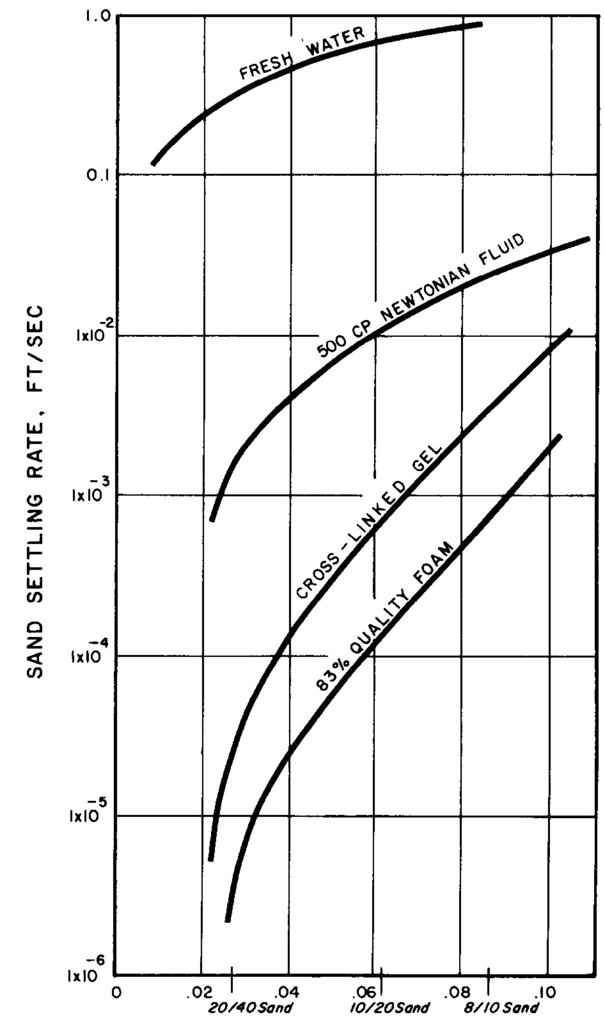

FIG. 6—SAND SETTLING VELOCITY OF SAND IN STATIC FOAM AND OTHER FLUIDS

FRACTURE AREA AND PRODUCTIVITY RATIOS

Figure 7 shows respective fracture area created by water, crosslinked gel, and foam in the Canyon sand of the Edwards Plateau region of Texas. Productivity increases are directly proportional to the created fracture area.

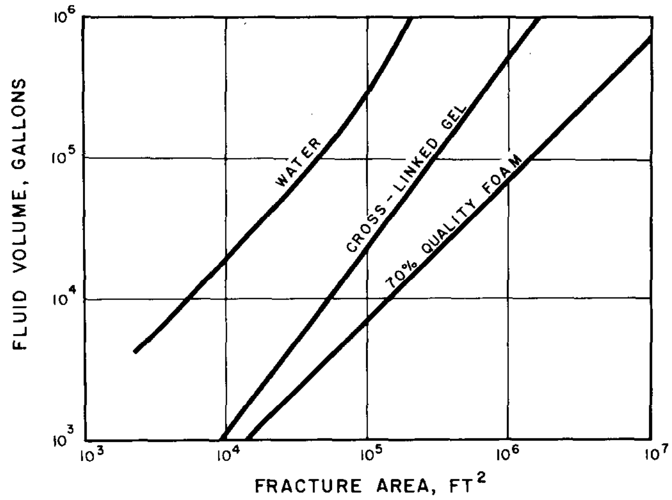

FIG. 7—FRACTURE AREA CREATED WITH VARIOUS FLUIDS

PRACTICAL APPLICATIONS AND CORE STUDIES

Current investigations are progressing towards developing foams and foaming agents which have stability under varied conditions. This work is continuing and will be presented in a later study. The foaming agent used in foam-fracturing must meet the following specifications:

1. The foaming agent must immediately produce a stable foam upon injection of gas.
2. The 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. The foaming agent must not have such stability that it will not readily break when pressure is released and the bubbles expand.
4. The foaming agent must be compatible with the formation and not cause irreparable permeability damage.
5. The concentration of the foaming agent should be low to minimize problems of formation incompatibility, mixing, and disposal of injected fluids.
6. Cost of foaming agent at required concentration must be reasonable.

Coreflow studies have been utilized to evaluate the interaction of various foaming agents and aqueous solution combinations. Cores selected have been from actual producing reservoirs. Evaluation of the results proves the importance of thorough testing of the foaming agent-fluid combination in an actual reservoir rock before use, particularly in tight reservoirs. This may not always be possible depending on the availability of core, although the substitution of similar core is better than none at all.

The commonly used foaming agent has been an alkyl-ether-sulfate type which is used at relatively low concentrations. Required concentration of this foaming agent is dependent upon aqueous-phase composition, and pH, treating pressure and temperature, shear rate, formation permeability, and foam quality.

Foam fracturing has proven most successful in stimulating low-to-medium permeability gas sandstones and shales. However, oil formations have been stimulated with foam when the foaming surfactant is compatible with the crude oil. Results of stimulation in the oil formations have been as promising as the history in gas formations.

An example of a typical foam frac in the Canyon sand is presented below. The well was acidized with 1500 gal. 15% HCl and produced 200 MCF/D absolute open-flow from perforations between 5150 ft and 5200 ft. The well was fraced with 29,000 gal. foam and 35,000 lb 20/40 sand at 14.7 BPM. Initial production test gave a potential of 4.5 MMSCF/D absolute open-flow. Conventional fracturing would have yielded a potential between 1.0 MMSCF/D and 1.5 MMSCF/D.

Table 1 presents additional case histories of several wells, with particular emphasis on the Canyon gas sands of the Edwards Plateau region of Texas. Low permeability, less than 1 md, is common. Additional problems of fines migration, clay swelling, siderite content, and low formation pressure complicate achieving a successful stimulation. Foam-fracturing has proven to be a highly successful fracturing technique in this formation. Production increases surpass most types of conventional treatments.

TABLE 1—CASE HISTORIES OF FOAM FRACS IN WEST TEXAS

TOTAL FOAM VOLUME	FORMATION	PRODUCTION BEFORE	PRODUCTION AFTER
37,000 gals.	Canyon	200 MCF	4.5 MMCF/D
26,000 gals.	Canyon	50 MCF	100 MCF/D
41,000 gals.	Canyon	0	200 MCF/D
30,500 gals.	Canyon	0	200 MCF/D
60,000 gals.	Canyon	TSTM	6.5 MMCF/D
29,900 gals.	Canyon	TSTM	2.15 MMCF/D
35,000 gals.	Canyon	dTSTM	3 MMCF/D
30,400 gals.	Canyon	200 MCF	No Test
34,300 gals.	Yates	TSTM	No Test
19,000 gals.	Canyon	40 MCF	200 MCF
34,000 gals.	Canyon	TSTM	No Test
27,000 gals.	Canyon	150 MCF	755 MCF/D
37,500 gals.	Douglas		2.2 MMCF/D + 24 BOPD
49,900 gals.	Douglas	250 MCF	8 MMCF/D
30,000 gals.	Escondita	TSTM	No Test

SUMMARY AND CONCLUSIONS

Foam may be utilized at qualities between 55% and 95% gas to provide an efficient fracturing system causing little formation damage, good proppant placement, and large fracture areas. External fluid-loss additives or gelling agents are not required to achieve fluid efficiencies and viscosities which surpass conventional systems. The Bingham plastic nature of foam provides enhanced apparent viscosity and fluid efficiency.

The low volume of liquid required for a foam-frac minimizes the amount of fracturing liquid exposed to the formation. However, it is still important to consider the chemical components of the liquid portion of the foam to insure compatibility. The high efficiency and effective viscosity of foam generates large fracture area and good proppant placement with low pumping rates.

Field results have confirmed the theoretical productivity increases from foam-fracturing. Formations in the West Texas area have responded better to foam than most conventional fracturing fluids.

LIST OF SYMBOLS

d = pipe ID
f_{fTp} = foam quality, dimensionless
v_f = foam velocity
V_g = volume of gas, ft^3
V_f = total foam volume, ft^3
μ_b = base liquid viscosity, cp
μ_e = effective foam viscosity
μ_f = foam viscosity, cp
μ_p = plastic viscosity, cp
τ = shear stress, lb$_f$/ft^2
τ_y = yield strength, lb$_f$/ft^2
ϕ = shear rate, sec^{-1}

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