A NOVEL APPROACH TO ACID FRACTURING TREATMENT DESIGN

Stephen A. Baumgartner and Larry J. Harrington
The Western Company of North America

ABSTRACT

The productivity of oil and gas wells can be improved through the use of efficiently designed acid fracturing treatments. The approach to acid fracturing treatment design presented in this paper enables a comparison of the production increases for various types of acid systems. In this study, four hydrochloric acid systems (plain, foamed, gelled and crosslinked) were used to design acid fracturing treatments. An acid fracturing stimulation design comparison for three reservoirs is presented.

INTRODUCTION

The reaction of acid with carbonate rock occurs at a rapid rate and the acid is spent quickly. The rapid spending of acid limits the penetration of live acid into the formation. In order to increase penetration of live acid into the formation, many techniques and systems have been developed to retard the spending rate of acid.

In this study, three systems: foamed acid, gelled acid and crosslinked acid are compared to plain hydrochloric acid. The four acid systems without pad or pre-pad stages are incorporated into acid fracturing treatment designs. Three different reservoirs with bottomhole temperatures of 120, 150 and 225°F are analyzed. The reservoirs produce oil and have a range of permeability from 1 to 20 md.

ACID FRACTURING DESIGN

Fracture Geometry

The first step is to determine the fracture geometry created by the acid system. A computer program may be used to calculate the fluid loss coefficient of the acid system at reservoir conditions. The fluid loss coefficient must be corrected for the effect of net/gross fracture height. A computer program can then calculate the width and penetration created by the acid system at reservoir conditions. Initially, select values for n' and K' for each acid system at reservoir temperature. A predicted temperature profile of the fluid in the fracture should be performed in order to fine tune the design fluid temperature for the fluid loss coefficient, n' and K' values. Multiple runs of these programs may be required to determine the design fluid temperature.

Acid Geometry

A computer program to predict acid concentration of the acid system in the fracture and the amount of acid soluble rock removed should be run. The acid reaction rate coefficient should be selected according to the type of acid and design fluid temperature predicted in the created fracture geometry. The rock dissolving power of a foamed acid treatment must be reduced by the amount of gas added to the system. In order to evaluate an equivalent amount of acid, a larger volume of foamed acid based on foam quality must be used.

An acid concentration versus penetration graph for the acid systems analyzed should be constructed. A graphical presentation of different types of acid systems as well as different gellant loadings can be used to help choose the most effective system. An acid concentration of three percent is the lowest acid concentration considered to be effective in the fracture.

Etched Fracture Width and Conductivity

In order to determine an etched fracture conductivity, a rock removal profile for the acid system is required. First, select the total rock removed for each increment of fracture length. Next, determine the density of the rock being removed by the acid from core analysis, literature or experience. The average etched fracture width in each increment can then be determined from the following equation:

$$W = \frac{RR}{(D)(L)(H)} \tag{1}$$

Where:

- W = average etched fracture width, ft
- RR = total rock removed, lb
- D = density of rock removed, lb/ft^3
- L = fracture length increment, ft
- H = net etched fracture height, ft

An average etched fracture conductivity in each increment can be determined from the following equation:[2]

$$K_{ef}W_{ef} = 4.533 \times 10^6(W^3) \tag{2}$$

Where:

- $K_{ef}W_{ef}$ = average etched fracture conductivity, D-ft
- W = average etched fracture width, ft

An average etched fracture conductivity versus penetration graph for the acid systems analyzed can then be constructed. A graphical presentation of different types of acid systems as well as different gellant loadings can be used to help choose the most effective system.

Optimum Etched Fracture Conductivity

A graph of estimated production increase after fracturing for vertical fractures, Figure 1, as found in Hydraulic Fracturing by Howard and Fast can be used to determine an optimum etched fracture conductivity. The production increase is a function of fracture penetration and of the permeability contrast. The permeability contrast is dependent on fracture conductivity, formation permeability and well spacing.

$$PC = \frac{K_{ef}\,W_{ef}}{K_e}\sqrt{\frac{40}{WS}} \tag{3}$$

Where:

- PC = permeability contrast
- $K_{ef}W_{ef}$ = average etched fracture conductivity, D-ft
- K_e = effective horizontal permeability, md
- WS = well spacing, acres

In order to find the optimum etched fracture conductivity, first rearrange equation (3) to solve for average etched fracture conductivity:

$$K_{ef}W_{ef} = \frac{PC\ K_e}{\sqrt{\frac{40}{WS}}} \qquad (4)$$

K_e (formation permeability) and WS (well spacing) are properties of the well to be analyzed. In order to find the optimum PC (permeability contrast), determine at what point the production increase curves become horizontal over the range of penetrations obtained from the acid systems being examined. A horizontal production increase curve indicates that increasing the etched fracture conductivity will result in a small incremental increase in the expected production increase. At the point where the curves level off, drop vertically to the permeability contrast axis and choose the corresponding value of PC. Now plug this value of PC, and the known values K_e and WS into equation (4) and solve for $K_{ef}W_{ef}$. This value is the optimum etched fracture conductivity for these corresponding reservoir conditions.

Draw the optimum etched fracture conductivity line on the average etched fracture conductivity graph. A comparison of acid systems and/or gellant loadings can be performed to see which one is closest to the optimum etched fracture conductivity line. An acid system that is much higher than the line is producing more etched fracture conductivity than is necessary. Conversely, an acid system that is lower than the line is producing insufficient etched fracture conductivity to efficiently drain the reservoir. The most effective treatment will be the one with the longest penetration that maintains an etched fracture conductivity greater than the optimum etched fracture conductivity.

ACID FRACTURING DESIGN STUDY

Reservoir A

The acid fracturing treatment design technique was used on a typical well in Reservoir A. The reservoir properties and treatment parameters may be found in Table I. The treatment fluid parameters for Reservoir A may be found in Table II. A total of four fluids, plain acid, foamed acid (70 quality, nitrogen), gelled acid (90 lb gellant/1000 gallons acid) and crosslinked acid (40 lb gellant/1000 gallons acid) were evaluated in this study. The design programs were run with the properties of each fluid. Figure 2 is a graph of acid concentration versus penetration for the four fluids. Figure 3 is a graph of average etched fracture conductivity versus penetration for the four fluids.

An optimum etched fracture conductivity was then determined. A permeability contrast of 10 was selected as the point where the production increase curves flatten out (minimal production increase for etched fracture conductivity increase) in the range of acid penetrations (15 to 65 percent). Solving equation (4):

$$K_{ef}W_{ef} = \frac{10(1)}{\sqrt{\frac{40}{40}}} = 10 \text{ D-ft}$$

An optimum etched fracture conductivity of 10 D-ft was then drawn on Figure 3.

In this study, the regular acid only penetrated 100 feet into the formation with acid at a concentration of greater than three percent. A productivity index of 3.0 was predicted from the etched fracture conductivity data. The foamed acid penetrated 450 feet. A total volume of 50,000 gallons was analyzed (15,000 gallons acid + 35,000 gallons nitrogen). A productivity index of 6.2 is predicted. The gelled acid and crosslinked acid penetrated 340 and 275 feet into the formation, respectively. A productivity index of 8.4 and 7.6 were predicted for the gelled acid and crosslinked acid. The foamed acid conductivity began to fail below the 10 D-ft optimum at about 150 feet of penetration. The gelled acid fell below the optimum line at 250 feet of penetration. In this analysis both the gelled acid and crosslinked acid are above or near the optimum conductivity line. This reservoir has a permeability of 1 md and needs a long, conductive fracture to obtain high productivity indexes. The gelled acid has lower viscosity than the crosslinked acid and in this case penetrates further, thus giving a higher predicted productivity increase.

Reservoir B

The acid fracturing treatment design technique was used on a typical well in Reservoir B. The reservoir properties and treatment parameters may be found in Table I. The treatment fluid parameters for Reservoir B may be found in Table III. A total of four fluids, regular acid, foamed acid (70 quality, nitrogen), gelled acid (112 lb gellant/1000 gallons acid) and crosslinked acid (50 lb gellant/1000 gallons acid) were evaluated. The design programs were run and analyzed. Figure 4 is a graph of acid concentration versus penetration for the four fluids. Figure 5 is a graph of the average etched fracture conductivity versus penetration for the four fluids.

An optimum etched fracture conductivity was then determined. A permeability contrast of 4 was selected as the point where the production increase curves flatten out over the range of acid penetrations (5 to 40 percent). Solution of equation (4) gives an optimum etched fracture conductivity of 160 D-ft.

In this study, the gelled acid and crosslinked acid penetrated 570 and 555 feet, respectively. Because of the low etched fracture conductivity, both acid systems predict a productivity index of 2.2. The foamed acid with a penetration of 200 feet had a predicted productivity index of 2.8. The regular acid penetrated 65 feet and had a predicted productivity index of 2.0. In this study, all the acid systems did not provide enough conductivity which resulted in the low predicted productivity indexes. This reservoir has a permeability of 20 md and needs a highly conductive etched fracture to achieve higher productivity indexes. An improved design for this reservoir should include a viscous (crosslinked) pad to create a wide fracture before introduction of acid.

Reservoir C

The acid fracturing treatment design technique was used on a typical well in Reservoir C. The reservoir properties and treatment parameters may be found in Table I. The treatment fluid parameters for Reservoir C may be found in Table IV. A total of four fluids, regular acid, foamed acid (70 quality, nitrogen), gelled acid (135 lb/gellant/1000 gallons acid) and crosslinked acid (50/lb gellant/1000 gallons acid) were evaluated. The design programs were run and analyzed. Figure 6 is a graph of acid concentration versus penetration for the four fluids. Figure 7 is a graph of the average etched fracture conductivity versus penetration for the four fluids.

An optimum etched fracture conductivity was determined. A permeability contrast of 10 was selected as the point where the production increase curves flatten out over the range of acid penetration (5 to 60 percent). Solution of equation (4) gives an optimum etched fracture conductivity of 10 D-ft.

In this study, the regular and foamed acid penetrated only 25 and 35 feet, respectively. The high reservoir temperature has reduced fluid viscosity and leak-off control for these two system resulting in short penetrations. The short penetrations predict a productivity index of 2.2 for each system. The gelled acid and crosslinked acid penetrate 325 and 415 feet, respectively. The higher reservoir temperature has reduced the fluid loss properties of the gelled acid more than the crosslinked acid. The difference in viscosity of the two fluids is also smaller than in the other two analyses. As a result, the crosslinked acid penetrated farther. However, since both systems are below the optimum etched fracture conductivity, the difference in the predicted productivity index is small. The gelled acid has a productivity index of 5.0 versus a productivity index of 5.2 for the crosslinked acid. An improved design would include a viscous (gelled) pad to cool the formation and to help control the fluid loss of the acid fluid systems.

CONCLUSIONS

In general, an acid fracturing design technique has been developed to aid in selection of an acid system for a particular reservoir. This technique also helps determine the etched fracture conductivity and penetration required to efficiently improve productivity.

The acid fracturing design technique consists of the following steps:

1. Determination of fracture geometry.
2. Determination of an acid geometry.
3. Prediction of an etched fracture width and conductivity.
4. Determination of an optimum etched fracture conductivity.
5. Review and analyze.

ACKNOWLEDGEMENT

The authors thank the management of The Western Company of North America for permission to publish this paper. Special thanks are expressed to Donna McKee for typing the manuscript and preparing the graphs.

SELECTED REFERENCES

1. Williams, B. B., Gidley, J. L. and Schechter, R. S.: Acidizing Fundamentals, SPE Monograph Series, Millet the Printer, Inc., Dallas, TX, 1979.

2. Amyx, J. W., Bass, D. M., Jr. and Whitig, R. L.: Petroleum Reservoir Engineering, McGraw-Hill Book Company, New York, 1960.

3. Baumgartner, S. A. and Harrington, L. J.: "Acid Fracturing Treatment Design", Completion Engineering Newsletter, The Western Company of North America, Fort Worth, TX (1985).

4. Howard, G. C. and Fast, C. R.: Hydraulic Fracturing, SPE Monograph Series, Millet the Printer, Inc., Dallas, TX, 1970.

Table 1 (I)
Reservoir Properties

	Reservoir A	Reservoir B	Reservoir C
Spacing, acres	40	160	40
Depth, feet	7400	8500	11,500
Solubility in Acid, percent by weight	[illegible]	85	90
Permeability to Reservoir Fluid, md	1	20	2
Porosity, percent	12	10	12
Reservoir Fluid	oil	oil	oil
Reservoir Fluid Viscosity, cp	[illegible]	.5	2
Reservoir Pressure, psi	1500	2000	5500
Bottomhole Static Temperature, F	[illegible]	150	225
Bottomhole Fracture Pressure, psi	4100	5300	8200
Reservoir Fluid Compressibility, psi^{-1}	.0005	.0001	.0005
Youngs Modulus	3E6	4E6	1E7
Zone Height, net/gross, feet	30/150	30/75	50/100

Table 2 (II)
Treatment and Fluid Parameters
Reservoir A

	Regular	Foam (70Q)	Gelled Acid	Crosslinked Acid
Volume, gallon	15,000	50,000	15,000	15,000
Pump Rate, bbl/min	20	20	20	20
HCl Concentration, percent	15	15	15	15
Gellant Loading, lb/1000 gal	none	none	90	40
Cc, $ft/min^{\frac{1}{2}}$	.00130	.00017	.00028	.00020
Viscosity, cp (170 sec^{-1})	1	46	60	138
n'	1.0	.33	.53	.57
K', lbf $sec^{n'}/ft^2$	2.1×10^{-5}	.030	.014	.034
Average Etched Fracture Width, in. 10 Percent Penetration	.779	.209	.198	.234
Average Etched Fracture Width, in. 50 Percent Penetration	.218	.103	.171	.210
Average Etched Fracture Width, in. 90 Percent Penetration	.042	.047	.148	.198
Productivity Index, J/J_o	3.0	6.2	8.4	7.6

Table 3 (III)
Treatment and Fluid Parameters
Reservoir B

	Regular	Foam (70Q)	Gelled Acid	Crosslinked Acid
Volume, gallon	21,000	70,000	21,000	21,000
Pump Rate, bbl/min	16	16	16	16
HCl Concentration, percent	15	15	15	15
Gellant Loading, lb/1000 gal	none	none	112	50
Cc, $ft/min^{\frac{1}{2}}$	.00784	.00245	.00102	.00063
Viscosity, cp (170 sec^{-1})	1	48	83	195
n'	1.0	.36	.48	.43
K', lbf $sec^{n'}/ft^2$	2.1×10^{-5}	.027	.025	.076
Average Etched Fracture Width, in. 10 Percent Penetration	2.141	.795	.213	.196
Average Etched Fracture Width, in. 50 Percent Penetration	.826	.428	.151	.156
Average Etched Fracture Width, in. 90 Percent Penetration	.038	.166	.096	.121
Productivity Index, J/J_o	2.2	2.8	2.2	2.2

Table 4 (IV)
Treatment and Fluid Parameters
Reservoir C

	Regular	Foam (70Q)	Gelled Acid	Crosslinked Acid
Volume, gallon	15,000	50,000	15,000	15,000
Pump Rate, bbl/min	12	12	12	12
HCl Concentration, percent	15	15	15	15
Gellant Loading, lb/1000 gal	none	none	135	50
Cc, $ft/min^{\frac{1}{2}}$	.00527	.00063	.00132	.00073
Viscosity, cp (170 sec^{-1})	1	46	85	116
n'	1.0	.39	.47	.53
K', lbf $sec^{n'}/ft^2$	2.1×10^{-5}	.022	.027	.027
Average Etched Fracture Width, in. 10 Percent Penetration	2.320	1.826	.221	.161
Average Etched Fracture Width, in. 50 Percent Penetration	.957	.654	.115	.090
Average Etched Fracture Width, in. 90 Percent Penetration	.030	.178	.040	.039
Productivity Index, J/J_o	2.2	2.2	5.0	5.2

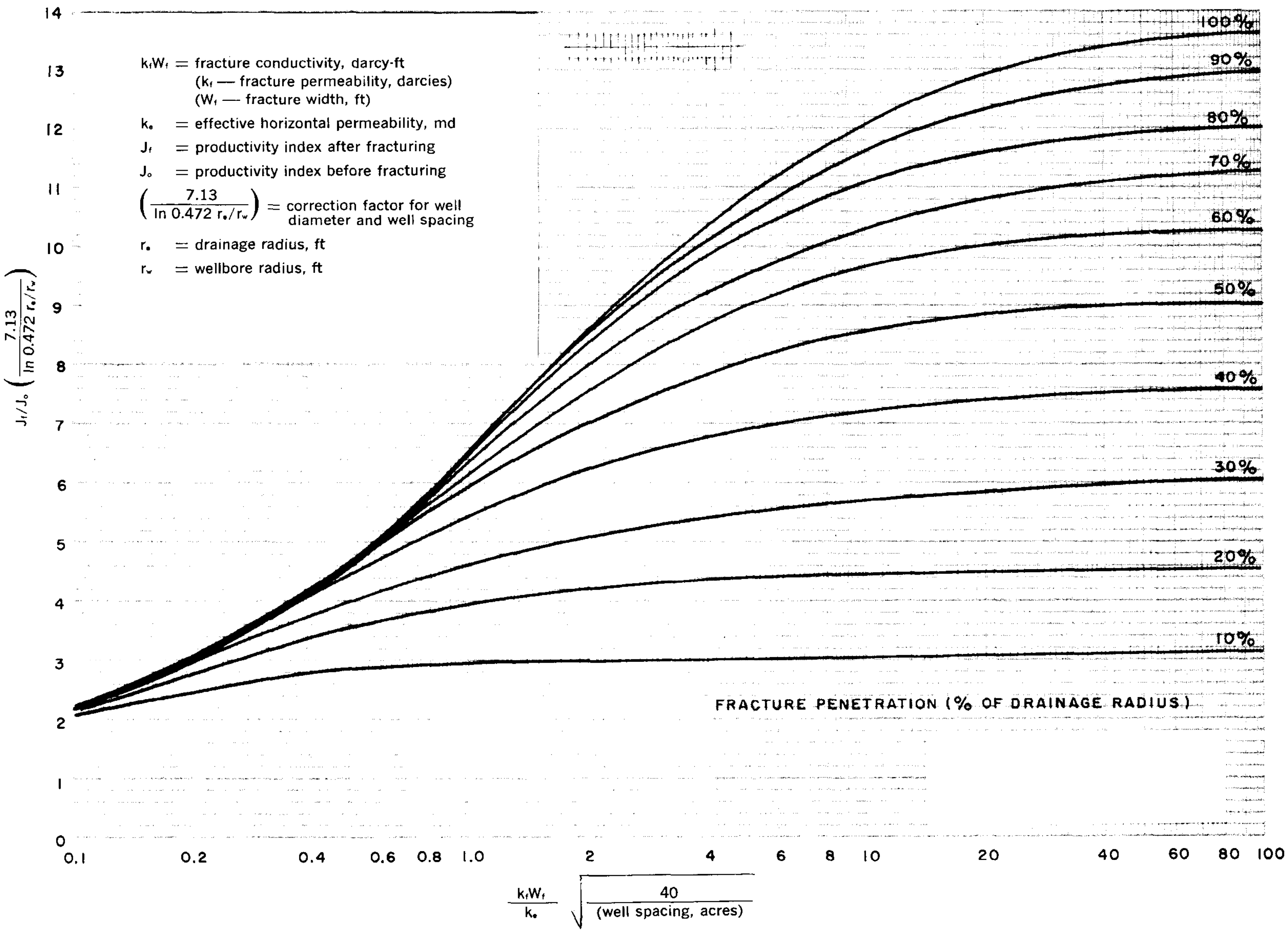

Figure 1—Estimated production increase after fracturing (vertical fractures)

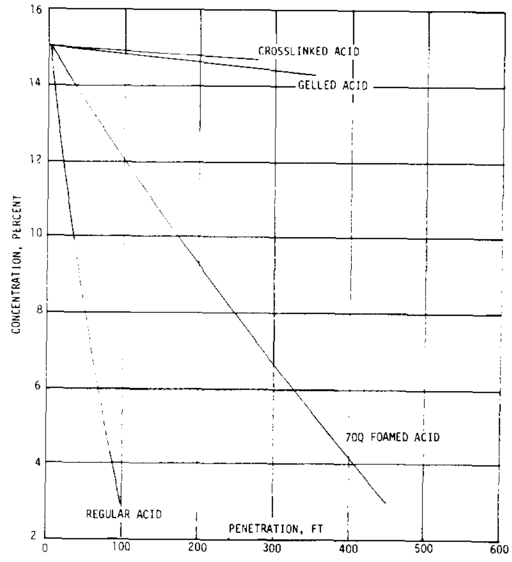

Figure 2—Acid concentration versus penetration—Reservoir A

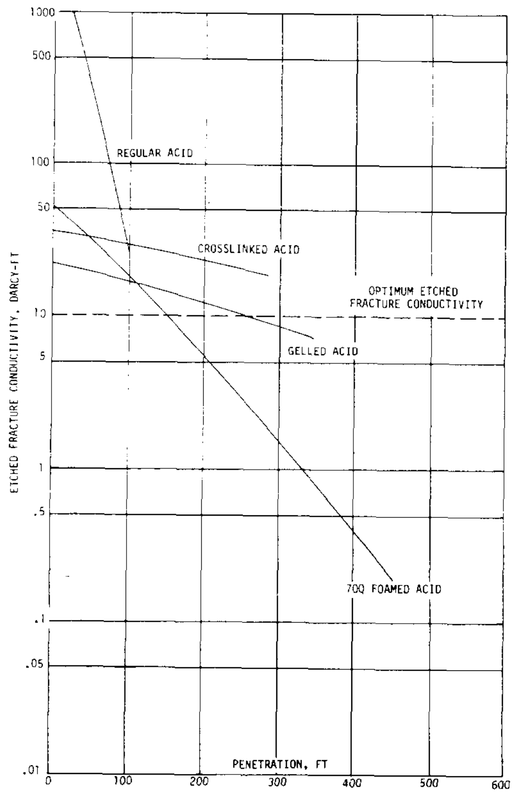

Figure 3—Average etched fracture conductivity versus penetration—Reservoir A

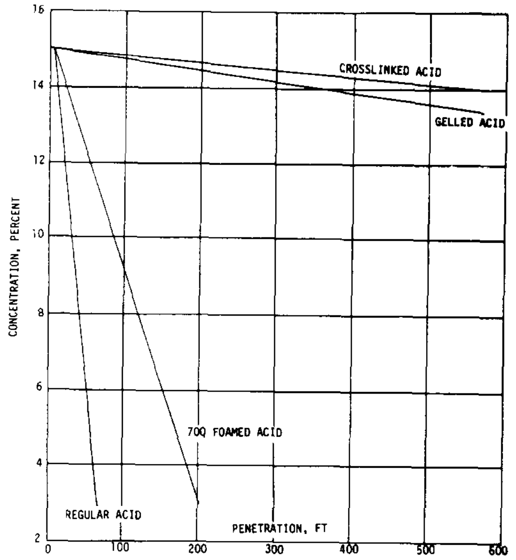

Figure 4—Acid concentration versus penetration—Reservoir B

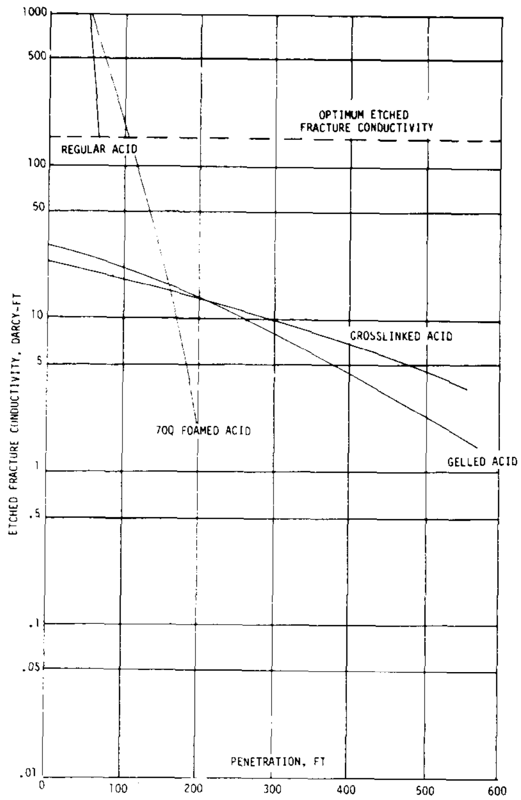

Figure 5—Average etched fracture conductivity versus penetration—Reservoir B

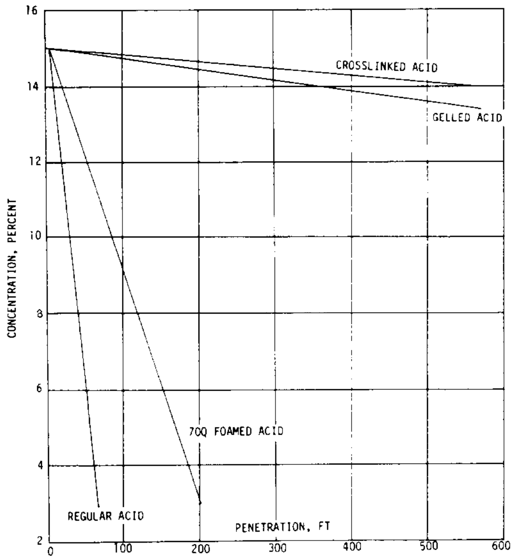

Figure 6—Acid concentration versus penetration—Reservoir C

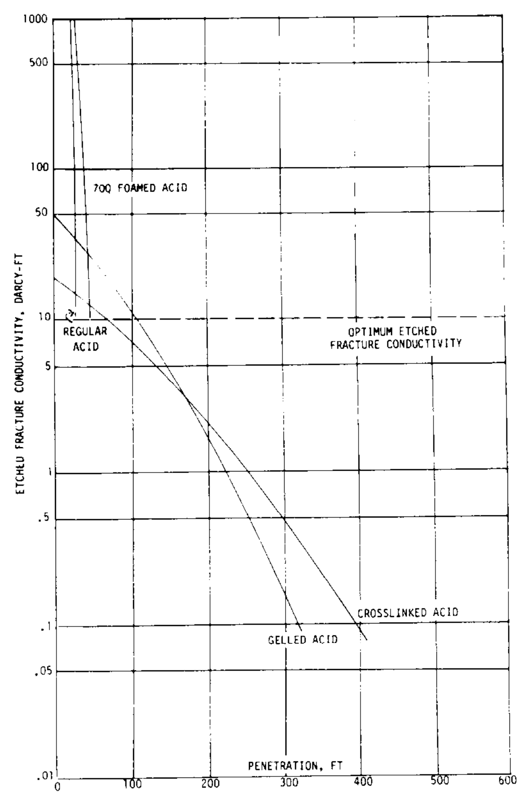

Figure 7—Average etched fracture conductivity versus penetration—Reservoir C