# FOAMED ACID, AN EFFECTIVE STIMULATION FLUID

William G. F. Ford, Ph.D.
Halliburton Services

## ABSTRACT

Dynamic laboratory testing of foamed acid on limestone cores has established the effectiveness of foamed acid as a stimulation fluid. The effects of foam quality, foam stability, and chemical compatibility on fluid loss and fracture flow capacity were investigated. Recommendations are presented for deriving maximum benefits from a foamed acid treatment. Field results are presented that show the effectiveness of foamed acid in the stimulation of both oil and gas wells.

## INTRODUCTION

The use of foam in fracturing treatments has gained widespread acceptance in the past few years. The low liquid content, good fluid loss control, and quick cleanup are just a few reasons why foams are being used.[1-4] The fluid loss properties of foam as a fracturing fluid and the flow of foam through porous media have been investigated by several authors.[4-18] The use of foamed acid in fracture acidizing has been reported to give the same benefits as foam in hydraulic fracturing treatments.[19-23] This is the first work where fluid loss of foamed acid has been directly measured and the effect of foamed acid on fracture conductivity has been studied. This paper presents laboratory data describing the effects of foam quality, foam stability, chemical compatibility, formation permeability, and pressure differential on fluid loss and fracture flow capacity with foamed acid on limestone.

## APPARATUS AND TEST PROCEDURE

### Fluid Loss Tests

The system used to study foamed acid fluid loss is illustrated in Fig. 1. The liquid and gas portions of the foam were maintained constant by separate control mechanisms. A 1500 ml volume Ampcoloy floating piston cell was used to hold the acid solution and the driving fluid for this cell was supplied by a positive displacement Jaeco pump. Flow rates were mechanically set on the pump and tested to be 20 ml/min at 1500 psi. The flow rate of nitrogen at 1500 psi was measured with an integral orifice meter equipped with a digital readout supplied by Fisher Porter with a No. 2 orifice. The meter was calibrated for various nitrogen flow rates at 1500 psi through

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the use of a GCA/Precision Scientific wet test meter. The pressure of the system and nitrogen flow rates were adjusted manually by the use of a backpressure regulator for coarse settings and a needle valve for fine settings. Once pressure and flow rate were stabilized at the start of the test, very little adjustment was needed to maintain the proper pressure and flow rate.

The foam generator consists of a 180 ml volume Ampcoloy cell and impeller driven at a speed of 2200 RPM's. This type of foam generator was chosen over the wire screen in a pipe type due to the reactive nature of the test solution. With time, the acid would tend to react with and erode away the screen, thus limiting the chances of reproducing a foam with the same texture (bubble size) and consistency from test to test.

Foamed acid was generated and allowed to pass through two visual flow cells and out to the waste trap through a high pressure, backpressure regulator. The visual flow cells were used to check the condition of the foamed acid before the fluid loss test begins with uniform small bubbles and no gas pockets conditional to a stable foam. Once this condition was reached, a portion of the foamed acid was allowed to flow into the fluid loss cell while continuing to flow foamed acid through the system to the waste trap. The fluid loss cell was a standard Hassler Sleeve apparatus used in dynamic fluid loss tests with an associated heating jacket for testing at elevated temperatures. Discharge from the fluid loss cell was through another visual flow cell that contained a 10 ml graduated cylinder to measure any liquid leakoff through the core. Any leakoff of nitrogen through the core went through a high pressure, backpressure regulator and into a wet test meter. This high pressure, backpressure regulator was used to maintain the desired pressure differential across the core.

All fluid loss tests were conducted with an upstream pressure of 1500 psi. Bedford Indiana limestone cores (six inches long and 1.75 inches in diameter) were placed in the Hassler Sleeve and heated to 110°F. The system pressure was raised to 1500 psi and a permeability of the core to nitrogen was measured at 110°F. Once a stable acid foam was generated, it was allowed to flow across the inlet face of the core. The Hassler Sleeve was mounted horizontally so that flow was from the bottom side to the top of the inlet core face. This was done to insure that uniform quality and texture foam was always in contact with the core. Gas loss and liquid loss was then recorded as a function of time.

## Fracture Flow Capacity Tests

The system used to study foamed acid fracture flow capacity was a modification of the system used to study foamed acid fluid loss. The fluid loss cell, the visual flow cell containing the 10 ml graduated cylinder, the backpressure regulator, and the wet test meter were replaced with a fracture flow capacity cell. The fracture flow capacity apparatus consisted of a Ampcoloy cell which uses two three inch diameter Bedford Indiana limestone cores. These cores were mounted in the cell with a fracture width between them of 0.05 inches. The test solution was then allowed to enter the cell through a hole in the center of the lower core and flow radially across the faces of these cores for a specified period of time. An overburden or closure pressure was then hydraulically applied to the cores to simulate the closing of a fracture after a stimulation treatment. The amount of rock crushed and removed was then measured. Kerosene was then used to displace test solution and was also flowed radially across the faces of the cores to measure a fracture flow capacity. The closure pressure was then released and the cores equally spaced 0.05 inches apart. This procedure was repeated three more times for each test solution to determine fracture flow capacity versus etching time. An upstream pressure of 1500 psi was used in the fracture flow capacity tests and cores were heated to 110°F.

## RESULTS

### Fluid Loss Tests

Table 1 shows the effect of foam quality and two different foaming agents on fluid loss control. Conventional 15% HCl channeled through a six inch core in less than one minute and exhibits little or no fluid loss control. Fig. 2 shows the face of this core and several large wormholes indicating where acid breakthrough occurred. Fig. 3 shows the face of the core across which the 90 quality foamed acid, 15% HCl + 1% Foamer A, was flowed for 36 minutes. There was no fluid loss for 36 minutes and the large number of small holes on the face of the core indicates 90 quality foamed acid gave good fluid loss control. These same results were noted for 80 quality foamed acid. When the quality of this foamed acid was lowered from 80 to 70, breakthrough occurred after 18 minutes. At breakthrough foam came through the core rather than separate gas and liquid phases. The bubble size in this foam was much larger than when the foam was initially generated. The 60 quality foamed acid broke through the core in 7 minutes. These tests were repeated substituting 1% Foamer B for 1% Foamer A and results indicated no acid or foam fluid loss occurred for 36 minutes when any of these four quality foamed acids were tested. However, nitrogen loss did occur when the 70 and 60 quality foamed acids were tested. These results show the effect of chemical compatibility in a foamed acid system. Foamer A made a stable foamed acid with 15% HCl but when this foamed acid came in contact with a large amount of spent acid, such as when a 70 or 60 quality foamed acid was run, the foam apparently collapsed and subsequently broke through the core. Foamer B appeared to be more compatible with spent acid than Foamer A so no foam breakthrough occurred. It is important that all chemicals used in a foamed acid system be checked for compatibility in spent acid as well as in the live acid.

The effects of foam quality and acid concentration on foamed acid fluid loss are shown in Table 2. No acid fluid loss occurred for any of the four qualities of foamed 15% HCl. Nitrogen loss did occur with the 70 and 60 quality foamed 15% HCl. This same trend was shown when acid concentrations were increased from 15 to 28 percent HCl.

Effect of acid type, formation permeability, and pressure differential are illustrated in Table 3. The two types of acid studied, 28% HCl and a mixture of mineral and organic acid, foamed equally well and gave virtually the same fluid loss control. When foam breakthrough occurred, bubble size of the foams were about equal to the bubble size just after generation. Upon examination of the 80 quality foamed 28% HCl system, it was noticed that the 0.15 md permeability core maintained fluid loss control for 25 minutes before foamed acid breakthrough. The more permeable 0.41 and 0.53 md cores experienced foamed acid breakthrough in two minutes. An increase in differential pressure from 100 psi to 500 psi changed the fluid loss control of the foamed acid considerably. Comparison of the foamed 28% HCl results from Table 2 with the results given in Table 3 clearly illustrates the difference.

A similar trend was noted for conventional acids containing solid fluid loss material as shown in Table 4. With increasing pressure differential, it is more difficult to maintain fluid loss control. One way to help minimize the effects of the increased pressure differential is to stabilize the foamed acid. This can be accomplished by increasing the viscosity of the acid before it is foamed. Table 5 denotes the large increase in fluid loss control derived from this procedure. The 90 and 80 quality foamed acids show only nitrogen fluid loss but no acid fluid loss for 36 minutes where previously they broke through the core in 2 to 3 minutes. The 70 and 60 quality foamed acids maintain fluid loss control for 10 to 11 minutes. Increasing the acid viscosity to help stabilize a foamed acid and improve fluid loss control without the use of wall building additives is keeping with the idea of a true foamed acid. Extremely large pressure differentials and large formation permeabilities may, however, necessitate the need for the addition of conventional fluid loss additives to be incorporated into the foamed acid system. Fluid loss in high permeability formations can be reduced by using a pad fluid ahead of the foamed acid.[23]

## Fracture Flow Capacity Tests

These data have shown that foamed acid can give good fluid loss control. However a successful fracture acidizing treatment does not depend only on good fluid loss control. Adequate fracture flow capacity must be established by the acid system used. The quantity of rock removed and the pattern in which it is removed from the fracture faces are important. Fracture flow capacity is dependent upon the nature of the rock and the volume, type and concentration of acid used. In order to eliminate some of the variables, Bedford Indiana limestone was selected as a homogeneous rock and was tested with one concentration of acid (28% HCl). Table 6 shows the results of equal velocities of treating solution as well as equal amounts of acid. Tests No. 1 and 3 were both conducted at a total flow rate of 200 ml/min. The foamed acid in Test No. 3 was only one-tenth the amount of 28% HCl as compared to the conventional acid in Test No. 1 and created more fracture flow capacity. Comparison of Tests No. 2 and 3 which used equal amounts of 28% HCl indicated the foamed acid created more fracture flow capacity. Also, the foamed acid system removed more core than either of the two conventional acid systems tested. It was noted in Test No.3 that some fracture flow capacity was lost between the first and second time intervals. This effect, called overetching, is quite common in homogeneous cores where rock is often removed evenly.

The effect of foamed acid quality on fracture flow capacity is shown in Table 7. Excellent fracture flow capacities were obtained when any of the four qualities of foamed acid were used. A large amount of core was also removed in each of the four cases. The 70 and 60 quality foamed acids did not obtain the maximum fracture flow capacity that the 90 and 80 quality foamed acids obtained. The effect of overetching was also more pronounced in the 70 and 60 quality foamed acids.

Foam stability effects acid etched fracture flow capacity the same as it effects fluid loss control. The acid viscosity was increased and 70 and 60 quality foamed acids generated and Table 8 compares these results. The 70 and 60 quality foamed acids achieved maximum fracture flow capacity and no sign of overetching was detected. A smaller amount of rock was removed from the core faces but the pattern of removal was more effective.

Tables 9 and 10 show the results of acid etched fracture flow capacity studies with conventional and foamed 28% HCl. The tests were similar to those reported in Table 6 with the exception of a different foaming agent and just one heterogeneous core being used. However, the same conclusions were drawn. The foamed acid achieved better fracture flow capacity when compared to conventional acid at equal velocities of treating solution as well as equal amounts of acid.

## FIELD RESULTS

Foamed acid has been used to stimulate wells in the United States and Canada.

### Case History #1

Eight oil wells were drilled in the Petit limestone formation in Arkansas at depths of 4200 to 4750 feet with an average porosity of 15% and permeability of 10 md. Initial production averaged 30 BOPD, however thirty days after completion the production had declined to 10-15 BOPD. Four wells were given a conventional fracture acidizing treatment with a 10,000 gallon mixture of mineral and organic acid. These wells were slow to clean up and required a swabbing unit to recover most of the treating fluids. Initial production after these treatments ranged from 37-80 BOPD. Four weeks later, production had declined to the original 10-15 BOPD level. The other four wells were stimulated with a 60-65 quality foamed acid which utilized a 4,000-6,000 gallon mixture of mineral and organic acids. The total volume of foamed acid was approximately 12,000 to 20,000 gallons. These wells exhibited rapid cleanup and were put on production overnight. It was noticed during flowback that a large quantity of fines were being returned after the foamed acid treatments. Initial production after treatment ranged from 42 to 72 BOPD. Six months later these four wells were still producing 30-50 BOPD.

### Case History #2

A new gas well was completed at a depth of 6884 ft in the Chester limestone formation in Harper County, Oklahoma. An initial acid cleanup using 2000 gallons of 15% HCl tested 740 MCF/D at 250 psi on a 16/64 choke. The formation was highly naturally fractured so a 10,000 gallon gelled water pad was pumped ahead of the foamed acid. A 30,000 gallon 75 quality foamed acid treatment consisting of a mixture of mineral and organic acid was performed. Production after treatment was 1.18 MMCF/D at 500 psi on a 20/64 choke. One week later, the well was producing 1.027 MMCF/D at 850 psi on a 14/64 choke.

## Case History #3

Two gas wells were completed in the Marble Falls limestone in North Central Texas. Experience indicated the formation was highly naturally fractured and acid solubility was 50 to 60 percent. Fluid recovery using conventional fracturing fluids, even with $N_2$ and $CO_2$, had been 60 percent or less. The first well was treated with a 75 quality foam which utilized 10,000 gallons of 20% HCl containing 1 lb/gal Oklahoma #1 sand. Initial production had been a slight gas show, however, production after treatment was 400 MCF/D with no water. The second well was treated with a 75 quality foam using a 5,000 gallon mixture of mineral and organic acid containing 1 lb/gal Oklahoma #1 sand. Initial production had also been a slight gas show with production after treatment of 200 MCF/D with no water. Most of the treatment fluid was recovered on both of these wells.

## Case History #4

An oil well was completed to a depth of 3660 ft in the Salem limestone formation in Clay County, Illinois. An initial acid cleanup of 15% HCl was used and the well was put on pump. Most wells completed in the Salem limestone produce about 30 BOPD after completion but production drops off very rapidly. This same trend occurs after a conventional fracture acidizing. After most treatments, a swabbing unit is required to recover the load fluid before the well is put on pump. Production before treatment was 10 BOPD and 24 BWPD. A treatment consisting of 3,200 gallons of 80 quality foamed 28% HCl was used to stimulate this well. Production following treatment was 135 BOPD and 145 BWPD with most of the treating fluid recovered.

## Case History #5

A gas well in Canada had been abandoned since 1960. In January, 1979, the hole was re-entered and production casing set. A treatment consisting of 20,000 gallons of 80 quality foamed 28% HCl was used to stimulate this well. Production after the treatment was 3 MMCF/D.

## CONCLUSIONS

1. Fluid loss control can be obtained in low permeability reservoirs using a foamed acid without conventional fluid loss additives.

2. Excellent fracture flow capacity can be obtained using foamed acid.

3. Chemical compatibility of foaming agents with spent acid as well as other chemicals in the system plays an important role in foam stability.

4. Increasing the viscosity of the acid to be foamed will help increase the foam stability.

5. An acid viscosifier should be employed when foam qualities below 75% are used.

6. Both oil and gas wells have responded successfully to foamed acid stimulation treatments.

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REFERENCES

1. Blauer, R. E., and Kohlhaas, C. A.: "Formation Fracturing With Foam", SPE Paper 5003, presented 49th Annual Fall Meeting, 1974.

2. Abbott, William A., and Vaughn, Herachel F.: "Foam Frac Completions for Tight Gas Formations", Petroleum Engineer, April, 1976.

3. Blauer, R. E., and Holcomb, D. L.: "Foam Fracturing Shows Success in Gas, Oil Formations", Oil and Gas Jour. (Aug. 4, 1975) 73, 57-60.

4. Bullen, R. S., and Bratrud, T. F.: "Fracturing With Foam", The Journal of Canadian Petroleum Technology, (April-June, 1976), 27-32.

5. King, George E.: "Factors Affecting Dynamic Fluid Leakoff With Foam Fracturing Fluids", SPE Paper 6817, presented 52nd Annual Fall Meeting, 1977.

6. Holm, L. W.: "The Mechanism of Gas and Liquid Flow Through Porous Media in the Presence of Foam", SPE Paper 1848, presented 42nd Annual Fall Meeting, 1967.

7. Bernard, George G., Holm, L. W., and Jacob, W. L.: "Effect of Foam on Trapped Gas Saturation and On Permeability of Porous Media to Water", SPE Paper 1204, Presented Fall Meeting, 1965.

8. Bernard, George G., and Holm, L. W.: "Effect of Foam on Permeability of Porous Media to Gas", Soc. Pet. Eng. J. (Sept. 1964) 267-274; Trans., AIME, Vol. 231.

9. Marsden, S. S., and Khan, S. A.: "The Flow of Foam Through Short Porous Media and Apparent Viscosity Measurements", Soc. Pet. Eng. J. (March 1966) 17-25; Trans., AIME, Vol. 237.

10. Raza, S. H., and Marsden, S. S.: "The Streaming Potential and the Rheology of Foam", Soc. Pet. Eng. J. (Dec., 1967) 359-368, Trans., AIME, Vol. 240.

11. Albrecht, Robert A., and Marsden, Sullivan S.: "Foams as Blocking Agents in Porous Media", Soc. Pet. Eng. J., 10, 51-55 (1970).

12. Kanda, M., and Schechter, R. S.: "On the Mechanism of Foam Formation in Porous Media", SPE Paper 6200, presented 51st Annual Fall Technical Conference, 1976.

13. Minssieux, L.: "Oil Displacement by Foams in Relation to Their Physical Properties in Porous Media", Soc. Pet. Eng. J., 46, 100-108 (1974).

14. Bernard, George G., and Holm, L. W.: "Model Study of Foam as a Sealant for Leaks in Gas Storage Reservoirs", Soc. Pet. Eng. J., 42, 9-16 (1970).

15. David, Amiel, and Marsden, Sullivan S.: "The Rheology of Foam", SPE Paper 2544, presented 44th Annual Fall Meeting, 1969.

16. Aizad, Tanweer, and Okandan, Ender: "Flow Equation for Foam Flowing Through Porous Media and Its Application as a Secondary Recovery Fluid", SPE Paper 6599, presented International Symposium on Oilfield and Geothermal Chemistry, June 27-28, 1977.

17. Fried, A. N.: "The Foam Drive Process for Increasing the Recovery of Oil", U.S.B.M. Report of Investigation No. 5866 (1961).

18. Blauer, R. E., Mitchell, B. J., and Kohlhaas, C. A.: "Determination of Laminar, Turbulent, and Transitional Foam Flow Losses in Pipes", SPE Paper 4885, presented 44th Annual California Regional Meeting, April 4-5, 1974.

19. Holcomb, D. L.: "Foamed Acid as a Means For Providing Extended Retardation", SPE Paper 6376, presented at the Permian Basin Oil and Gas Recovery Conference, March 10-11, 1977.

20. Wilson, Stephen C.: "Foamed Acid Stimulation of the San Andres: An Area Study", Petroleum Engineer International, May 1978.

21. Holcomb, David L., and Wilson, Stephen C.: "Foamed Acidizing and Selective Diverting Using Stable Foam For Improved Acid Stimulation" Southwest Petroleum Short Course, Proceedings of the 25th Annual Meeting, Texas Tech University, Lubbock, Texas, April, 1978.

22. Petryk, R. P., and Goruk, Bernie W.: "Fracture Acidizing With Foamed Acid: Success in the Crossfield D-1 Carbonate," Paper No. 79-30-37, presented at 30th Ann. Tech. Mtg. of Pet. Soc. of CIM, Banff, Alberta, May 8-11, 1979.

23. Scherubel, Gary A., and Crowe, Curtis W.: Foamed Acid, A New Concept in Fracture Acidizing", SPE Paper 7568, presented 53rd Annual Fall Meeting, 1978.



TABLE 1—EFFECT OF FOAM QUALITY AND FOAMING AGENTS UPON FLUID LOSS OF FOAMED ACID P = 100 psi

| Foam Quality | Rock Permeability to $N_2$ At 110°F (md) | Breakthrough Time (Minutes) |
|---|---|---|
| Test Solution: 15% HCl | | |
| 0 | 0.85 | <1 |
| Test Solution: 15% HCl + 1% Foamer A | | |
| 90 | 0.83 | >36 |
| 80 | 0.72 | >36 |
| 70 | 0.84 | 18 |
| 60 | 0.66 | 7 |

| Foam Quality | Rock Permeability to $N_2$ at 110°F (md) | 36 Minute $N_2$ Fluid Loss (l) | 36 Minute Acid Fluid Loss (ml) |
|---|---|---|---|
| Test Solution: 15% HCl + 1% Foamer B | | | |
| 90 | 1.21 | 0 | 0 |
| 90 | 0.26 | 0 | 0 |
| 80 | 0.63 | 0 | 0 |
| 80 | 0.61 | 0 | 0 |
| 70 | 0.88 | 0.07 | 0 |
| 70 | 1.14 | 0.69 | 0 |
| 60 | 0.69 | 0.22 | 0 |
| 60 | 1.83 | 0.46 | 0 |

TABLE 2—EFFECT OF FOAM QUALITY AND ACID CONCENTRATION UPON FLUID LOSS OF FOAMED ACID P = 100 psi

| Foam Quality | Rock Permeability to $N_2$ at 110°F (md) | 36 Minute $N_2$ Fluid Loss (l) | 36 Minute Acid Fluid Loss (ml) |
|---|---|---|---|
| Test Solution: 15% HCl + 1% Foamer B | | | |
| 90 | 1.21 | 0 | 0 |
| 90 | 0.26 | 0 | 0 |
| 80 | 0.63 | 0 | 0 |
| 80 | 0.61 | 0 | 0 |
| 70 | 0.88 | 0.07 | 0 |
| 70 | 1.14 | 0.69 | 0 |
| 60 | 0.69 | 0.22 | 0 |
| 60 | 1.83 | 0.46 | 0 |
| Test Solution: 20% HCl + 1% Foamer B | | | |
| 90 | 0.65 | 0 | 0 |
| 90 | 0.28 | 0 | 0 |
| 80 | 0.24 | 0 | 0 |
| 80 | 0.53 | 0 | 0 |
| 70 | 0.53 | 0.148 | 0 |
| 70 | 0.53 | 0.28 | 0 |
| 60 | 0.50 | 0.065 | 0 |
| 60 | 0.48 | 0 | 0 |
| Test Solution: 28% HCl + 1% Foamer B | | | |
| 90 | 0.48 | 0 | 0 |
| 90 | 0.41 | 0 | 0 |
| 80 | 0.55 | 0 | 0 |
| 80 | 0.69 | 0 | 0 |
| 70 | 0.47 | 0.06 | 0 |
| 70 | 0.70 | 0.25 | 0 |
| 60 | 0.71 | 0.20 | 0 |
| 60 | 0.78 | 0.97 | 0 |

TABLE 3—EFFECT OF ACID TYPE UPON FLUID LOSS OF FOAMED ACID P = 500 psi

| Foam Quality | Rock Permeability to $N_2$ At 110°F (md) | Breakthrough Time (Minutes) |
|---|---|---|
| Test Solution: 28% HCl + 1% Foamer B | | |
| 90 | 0.43 | 3 |
| 90 | 0.39 | 3 |
| 80 | 0.53 | 2 |
| 80 | 0.15 | 25 |
| 80 | 0.41 | 2 |
| Test Solution: HCl-HAC + 1% Foamer B | | |
| 90 | 0.41 | 4 |
| 90 | 0.37 | 4 |
| 80 | 0.32 | 3 |
| 80 | 0.31 | 2 |

FIGURE 4—EFFECT OF SOLID FLUID LOSS ADDITIVES UPON FLUID LOSS OF CONVENTIONAL ACID, P = 500 psi

| Rock Permeability* (md) | Breakthrough Time (Minutes) |
|---|---|
| Test Solution: 15% HCl + 0.1% Surfactant + 100 lbs Fluid Loss Material/1000 gal | |
| 3.2 | 3 |
| Test Solution: 15% HCl + 0.1% Surfactant + 150 lbs Fluid Loss Material/1000 gal | |
| 2.5 | 3 |
| 3.2 | 12 |
| 3.3 | 6 |
| Test Solution: 15% HCl + 0.1% Surfactant + 200 lbs Fluid Loss Material/1000 gal | |
| 3.7 | 24 |
| Test Solution: 15% HCl | |
| 3.7 | 1 |
| 1.3 | 1 |
| 6.6 | 0.5 |

*-Permeability to standard brine. Initial flow through the core was measured with standard brine. Flow was then measured with kerosene and finally fluid loss measurement was made with 15% HCl containing additives at 200°F.

| Rock Permeability* (md) | Breakthrough Time (Minutes) |
|---|---|
| Test Solution: 15% HCl | |
| 1.9 | 3.2 |
| Test Solution: 15% HCl + 150 lbs Fluid Loss Material/1000 gal | |
| 2.0 | 4.8 |
| Test Solution: 15% HCl + 1% Foamer C (80 Quality Foam) | |
| 2.0 | 25 |

*-Permeability to standard brine. Initial flow through the core was measured with standard brine then fluid loss measurement was made with 15% HCl containing additives at 200°F.

TABLE 5—EFFECT OF FOAM QUALITY AND FOAM STABILITY ON FLUID LOSS OF FOAMED ACID P = 500 psi

| Foam Quality | Rock Permeability to $N_2$ At 110°F (md) | Breakthrough Time (Minutes) |
|---|---|---|
| Test Solution: 28% HCl + 1% Foamer B | | |
| 90 | 0.43 | 3 |
| 90 | 0.39 | 3 |
| 80 | 0.53 | 2 |
| 80 | 0.15 | 25 |
| 80 | 0.41 | 2 |

| Foam Quality | Rock Permeability to $N_2$ at 110°F (md) | 36 Minute $N_2$ Fluid Loss (l) | 36 Minute Acid Fluid Loss (ml) |
|---|---|---|---|
| Test Solution: 28% HCl + 1% Foamer B + 4% Foam Stabilizer | | | |
| 90 | 0.48 | 13.55 | 0 |
| 90 | 0.30 | 3.235 | 0 |
| 80 | 0.41 | 7.72 | 0 |
| 80 | 0.37 | 4.84 | 0 |

| Foam Quality | Rock Permeability to $N_2$ At 110°F (md) | Breakthrough Time (Minutes) |
|---|---|---|
| Test Solution: 28% HCl + 1% Foamer B + 4% Foam Stabilizer | | |
| 70 | 0.44 | 10 |
| 70 | 0.38 | 10 |
| 60 | 0.35 | 11 |
| 60 | 0.37 | 10 |

TABLE 6—ACID ETCHED FRACTURE FLOW CAPACITY WITH CONVENTIONAL AND FORAMED 28% HC1

Conditions: Temperature ------------- 110°F
Pressure ---------------- 1500 psi
Closure Pressure -------- 1000 psi

| Etching Time (Minutes) | Fracture Flow Capacity (md-ft) | Core Removed (inches) |
|---|---|---|
| Test No. 1: 200 ml/min 28% HCl | | |
| 9 | 9,691 | .044 |
| 18 | 12,960 | .056 |
| 27 | 26,691 | .068 |
| 36 | 40,255 | .088 |
| Test No. 2: 20 ml/min 28% HCl | | |
| 9 | 4,833 | .058 |
| 18 | 6,990 | .074 |
| 27 | 7,535 | .091 |
| 36 | 28,409 | .109 |
| Test No. 3: 180 ml/min $N_2$ + 20 ml/min 28% HCl + 1% Foamer B | | |
| 9 | 17,533 | .066 |
| 18 | 12,329 | .084 |
| 27 | 70,000+ | .130 |
| 36 | 70,000+ | .153 |

+ Maximum reading of instrument.

TABLE 7—EFFECT OF FOAM QUALITY ON ACID ETCHED FRACTURE FLOW CAPACITY

Conditions: Temperature ------------- 110°F
Pressure ---------------- 1500 psi
Closure Pressure -------- 1000 psi

| Etching Time (Minutes) | Fracture Flow Capacity (md-ft) | Core Removed (inches) |
|---|---|---|
| Test No. 1: | 180 ml/min $N_2$ + 20 ml/min 28% HCl + 1% Foamer B 90 Quality Foam | |
| 9 | 17,533 | .066 |
| 18 | 12,392 | .084 |
| 27 | 70,000+ | .130 |
| 36 | 70,000+ | .153 |
| Test No. 2: | 80 ml/min $N_2$ + 20 ml/min 28% HCl + 1% Foamer B 80 Quality Foam | |
| 9 | 8,613 | .037 |
| 18 | 21,537 | .070 |
| 27 | 70,000+ | .139 |
| 36 | 70,000+ | .175 |
| Test No. 3: | 47 ml/min $N_2$ + 20 ml/min 28% HCl + 1% Foamer B 70 Quality Foam | |
| 9 | 12,392 | .036 |
| 18 | 41,464 | .074 |
| 27 | 36,026 | .096 |
| 36 | 27,259 | .120 |
| Test No. 4: | 30 ml/min $N_2$ + 20 ml/min 28% HCl + 1% Foamer B 60 Quality Foam | |
| 9 | 14,678 | .030 |
| 18 | 28,977 | .075 |
| 27 | 38,443 | .097 |
| 36 | 37,234 | .120 |

+ Maximum reading of instrument.

TABLE 8—EFFECT OF FOAM QUALITY AND FOAM STABILITY ON ACID ETCHED FRACTURE FLOW CAPACITY

Conditions: Temperature ------------- 110°F
Pressure ---------------- 1500 psi
Closure Pressure -------- 1000 psi

| Etching Time (Minutes) | Fracture Flow Capacity (md-ft) | Core Removed (inches) |
|---|---|---|
| Test No. 1: | 47 ml/min $N_2$ + 20 ml/min 28% HCl + 1% Foamer B 70 Quality Foam | |
| 9 | 12,392 | .036 |
| 18 | 41,464 | .074 |
| 27 | 36,026 | .096 |
| 36 | 27,259 | .120 |
| Test No. 2: | 47 ml/min $N_2$ + 20 ml/min 28% HCl + 1% Foamer B + 4% Foam Stabilizer - 70 Quality Foam | |
| 9 | 11,314 | .048 |
| 18 | 30,126 | .067 |
| 27 | 70,000+ | .076 |
| 36 | 70,000+ | .087 |
| Test No. 3: | 30 ml/min $N_2$ + 20 ml/min 28% HCl + 1% Foamer B 60 Quality Foam | |
| 9 | 14,678 | .030 |
| 18 | 28,977 | .075 |
| 27 | 38,443 | .097 |
| 36 | 37,234 | .120 |
| Test No. 4: | 30 ml/min $N_2$ + 20 ml/min 28% HCl + 1% Foamer B + 4% Foam Stabilizer - 60 Quality Foam | |
| 9 | 30,695 | .037 |
| 18 | 70,000+ | .054 |
| 27 | 70,000+ | .063 |
| 36 | 70,000+ | .070 |

+ Maximum reading of instrument.

TABLE 9—ACID ETCHED FRACTURE FLOW CAPACITY WITH CONVENTIONAL AND FOAMED 28% HC1

Conditions:
- Temperature ------------- 105°F
- Pressure ---------------- 1250 psi
- Closure Pressure -------- 1267 psi
- Formation --------------- Kansas City Limestone

| Etching Time (Minutes) | Fracture Flow Capacity (md-ft) | Core Removed (inches) |
|---|---|---|
| Test No. 1: 200 ml/min 28% HCl | | |
| 9 | 632 | .036 |
| 18 | 3,096 | .060 |
| 27 | 12,408 | .084 |
| 36 | 55,912 | .098 |
| Test No. 2: 180 ml/min $N_2$ + 20 ml/min 28% HCl + 1% Foamer A 90 Quality Foam | | |
| 9 | 4,788 | .032 |
| 18 | 25,958 | .052 |
| 27 | 61,894 | .080 |
| 36 | 84,328 | .086 |

TABLE 10 - Acid Etched Fracture Flow Capacity With Conventional and Foamed 28% HCl

Conditions:
- Temperature ------------- 110°F
- Pressure ---------------- 1250 psi
- Closure Pressure -------- 1312 psi
- Formation --------------- Viola Limestone

| Etching Time (Minutes) | Fracture Flow Capacity (md-ft) | Core Removed (inches) |
|---|---|---|
| Test No. 1: 20 ml/min 28% HCl | | |
| 20 | 3,636 | .032 |
| 40 | 48,198 | .036 |
| Test No. 2: 180 ml/min $N_2$ + 20 ml/min 28% HCl + 1% Foamer A 90 Quality Foam | | |
| 25 | 140,000+ | .072 |
| 50 | 140,000+ | .106 |

+ Maximum reading of instrument.

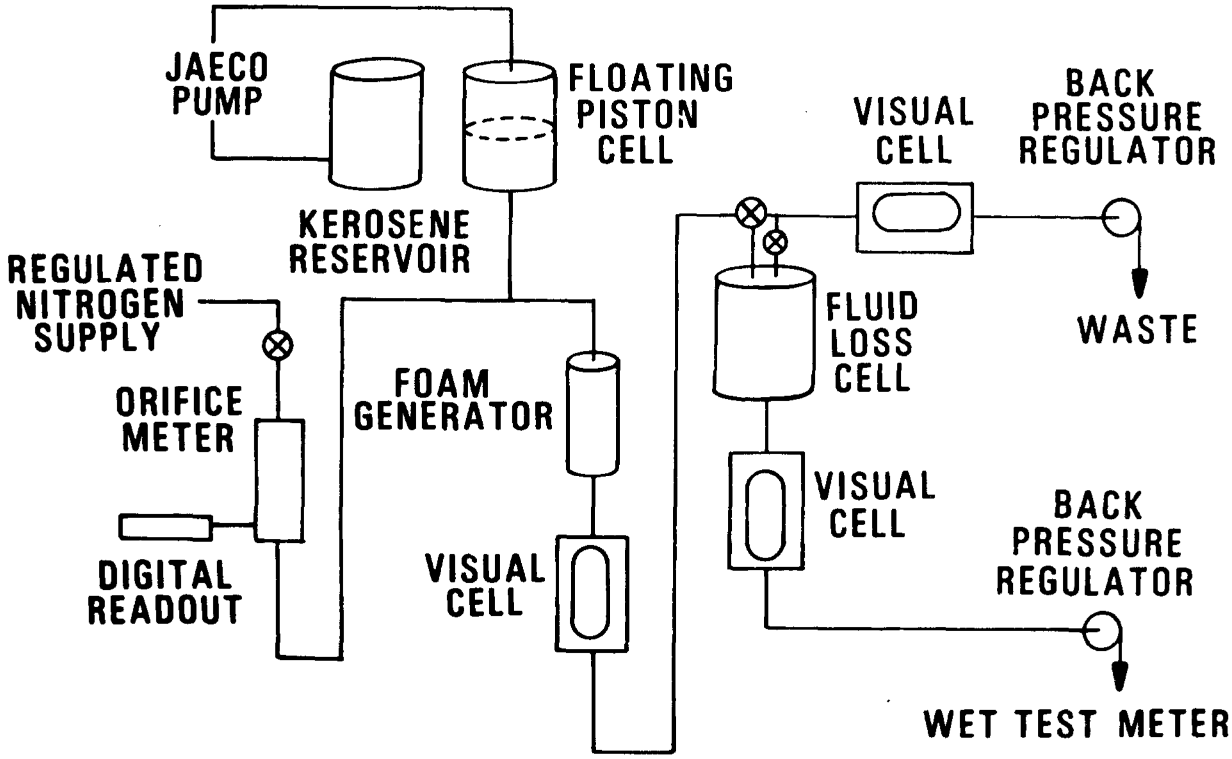


FIGURE 1—TEST SYSTEM SCHEMATIC