IMPROVED HIGH VISCOSITY OIL-BASE FRACTURING FLUIDS

J.L. ANDERSON, P.N. BROWN, R.R. McDANIEL, and J.C. TRAINER

Byron Jackson Inc.

INTRODUCTION

Hydraulic fracturing as a well stimulation technique has been in widespread usage since its introduction to the oil industry in 1948. Lease oil was used predominantly as the fracturing fluid for the first decade. Technical advancement in developing surfactants, friction reducers, and effective gelling agents stimulated greater interest in water frac as early as 1958 and increased its popularity. Today approximately 60% of all fracturing jobs are performed with water-base fracturing fluids.

During the past two years, the economic structure of the oil industry has dictated that close attention be given to development costs. Again, lease oil comes to the forefront; it offers the advantage of being economical, provides for rapid clean-up of the well, is compatible with well fluids, and will not damage formation due to clay swelling.

New technical developments in gelling or complexing oil-based fracturing fluids strengthen the choice of operators, as evidenced in the strong comeback of oil-based fluids. Some of these new technical advances offer the following:

1. Friction reduction of oil equal to or better than that of gelled water
2. High viscosity for wider fractures
3. Deeper placement of proppants
4. Ample viscosity to carry larger mesh and high concentrations of proppants.

Two of the newest concepts in oil-base hydraulic fracturing technique are offered to the oil industry in the following systems:

1. ALLO-FRAC
2. OIL-BASE ULTRA FRAC (OBUF)

FLUID PROPERTIES OF ALLO-FRAC

Allo-Frac is classified as a non-Newtonian, viscoelastic fluid. It exhibits elastic recovery from deformations which occur during flow. The gel also exhibits a trait common to viscoelastic fluids called the "Weissenberg effect". Fluids that possess this property have a tendency to climb up a rotating shaft, making it virtually impossible to obtain accurate viscosity data of a viscoelastic fluid using a rotating bob-type viscometer. Using a Brookfield viscometer, viscosity readings of 1000 to 10,000 cps have been obtained. This range of readings results from varying the additive concentrations utilized in the gel system. The final viscosity obtained with any combination of additive concentrations is also dependent on the time the gel is left undisturbed before being pumped.

Allo-Frac will thermally thin, but subjecting it to temperatures as high as 225°F will not cause the gel to break. Figures 1 and 2 show a comparison of the effect temperature has on the flow behavior indices, n′ and k′, for Allo-Frac and a high-viscosity crosslinked guar gum. The figures show that temperature does not affect the hydrocarbon gel as greatly or as rapidly as it does the complexed water-based system. This has allowed Allo-Frac to be used in wells with bottomhole temperatures up to 250°F and still retain some of its unique gel properties.

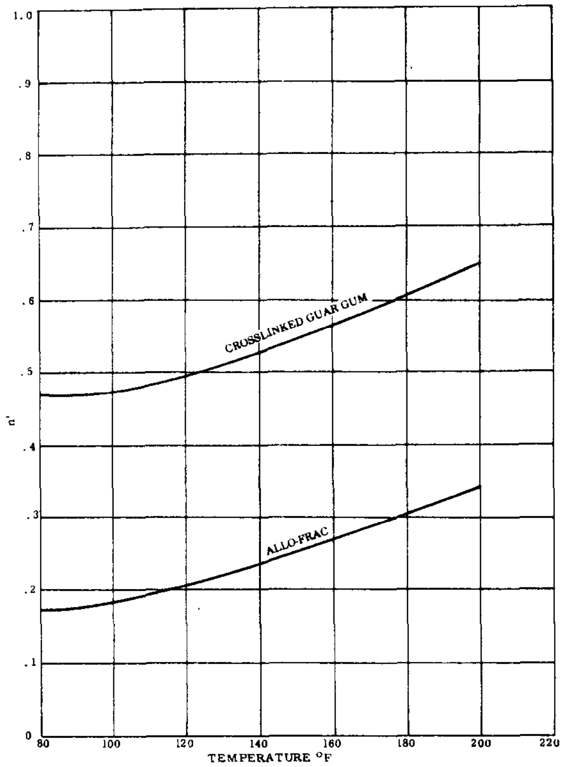


FIG. 1—FLOW BEHAVIOR INDEX (n') FOR ALLO-FRAC AND CROSSLINKED GUAR GUM VS TEMPERATURE

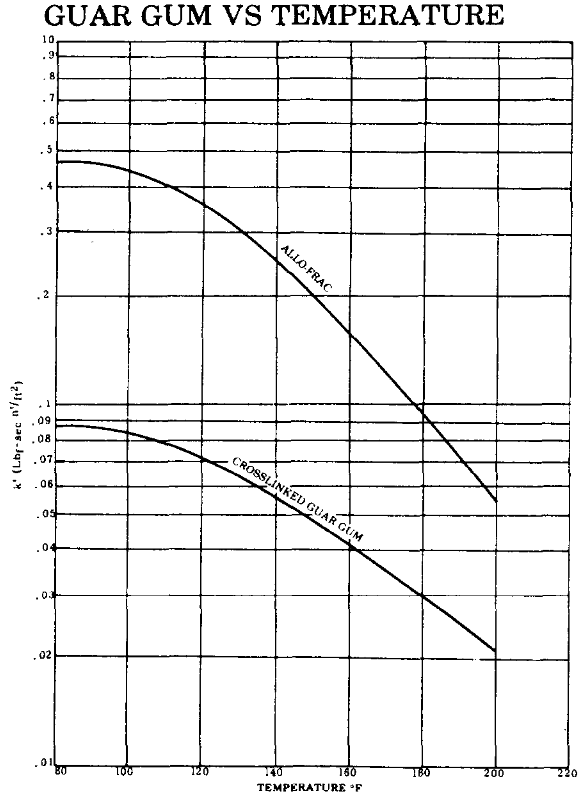


FIG. 2—CONSISTENCY INDEX (k') for ALLO-FRAC and CROSSLINKED GUAR GUM VS TEMPERATURE

The fluid is viscous, but its viscosity alone is not sufficient to insure good fluid loss control. To obtain an efficient frac fluid, it is necessary to add a fluid loss additive. The resulting fluid loss control obtained when using this system in conjunction with an additive is shown in Table 1. This table contains spurt loss, slope of the fluid loss curve, and the calculated C_{III} values at temperatures ranging from 80° to 160°F. The data presented in the table was obtained using a Baroid cell and filter paper. The test procedure was in accordance with that published in API RP 39.

TABLE 1—FLUID LOSS CONTROL OF ALLO-FRAC

Temp °F	Fluid Loss Additive Conc (lb/1000 gal)	Spurt Loss cc	M* cc/(min)½	C_{III} Ft/(min)½
80	20	2.8	1.20	8.63×10^{-4}
120	20	3.2	2.44	1.755×10^{-3}
160	20	4.0	2.60	1.87×10^{-3}

* Slope of the fluid loss curve

Friction pressure resulting from a frac fluid being pumped down tubular goods is one of the more important factors to be considered in most fracturing treatments. In many cases the use of high viscosity frac fluids results in additional friction pressure, which is wasted energy. Although Allo-Frac has one of the highest viscosities of any present-day frac fluid, it also has one of the lowest friction pressures. Tests comparing the friction pressures of this gel and kerosene, at various fluid velocities, appear in Fig. 3. The average friction pressure of Allo-Frac is 75-80% less than that of kerosene. Calculations using data obtained during actual treatments verify this friction reduction as being a realistic estimate.

A breaker is used in the fracturing fluid to change the gel from its highly viscous state to a viscosity that allows it to be produced back easily. Wells are usually shut in for a 24-hour period during which time the gel viscosity is reduced approximately 75-90% depending upon the reservoir temperature. The effectiveness

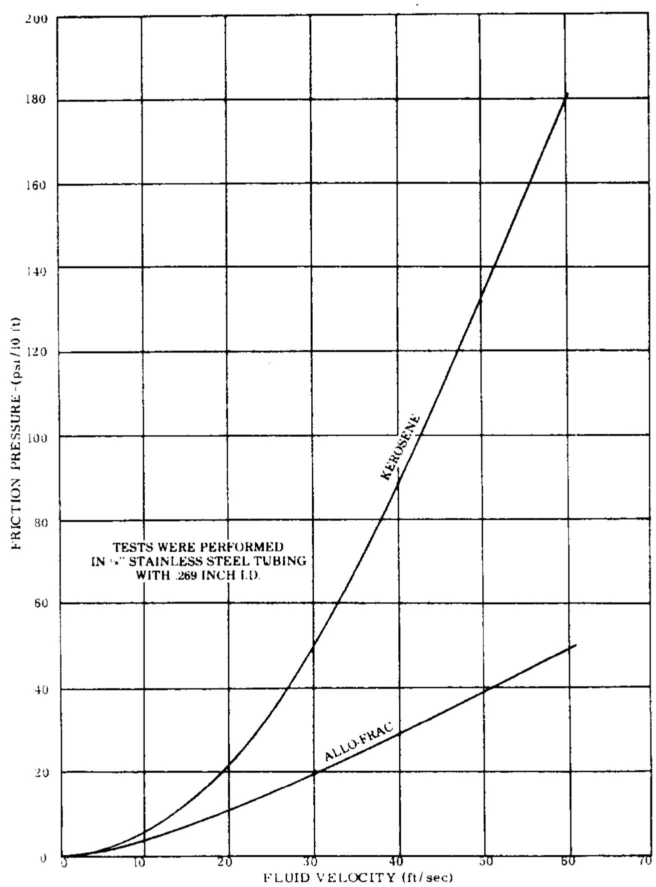


FIG. 3—FRICTION PRESSURE OF ALLO-FRAC AND KEROSENE VS FLUID VELOCITY

of the breaker improves as reservoir temperature increases. The breakout is solid-free leaving only the fluid loss additive used with the system to cause plugging of formation permeability.

Allo-Frac, unlike water-based systems, will not cause permeability damage due to the formation of stable emulsions or the swelling of water-sensitive clays. Combining these facts with its solid-free breakout makes this system ideal for treatments in which formation damage is to be kept to a minimum.

FLUID PROPERTIES OF OIL-BASE ULTRA FRAC (OBUF)

Oil-Base Ultra Frac is classified as a highly thixotropic fluid. Using a Brookfield viscometer, the viscosity was found to range from 100-5000 cps. Three main variables are responsible for this wide range of viscosities. These include the crude used, the concentration of gelling agent, and the temperature of the formation. This gelling system can be used with most any crude; however, the viscosity obtained may vary greatly depending upon the crude. Laboratory tests have shown no apparent relationship between final gel viscosity and the physical properties of the crude. Three concentrations of gelling agent are used in preparing OBUF; Fig. 4 shows the relationship between the gel viscosity obtained with each concentration and temperature.

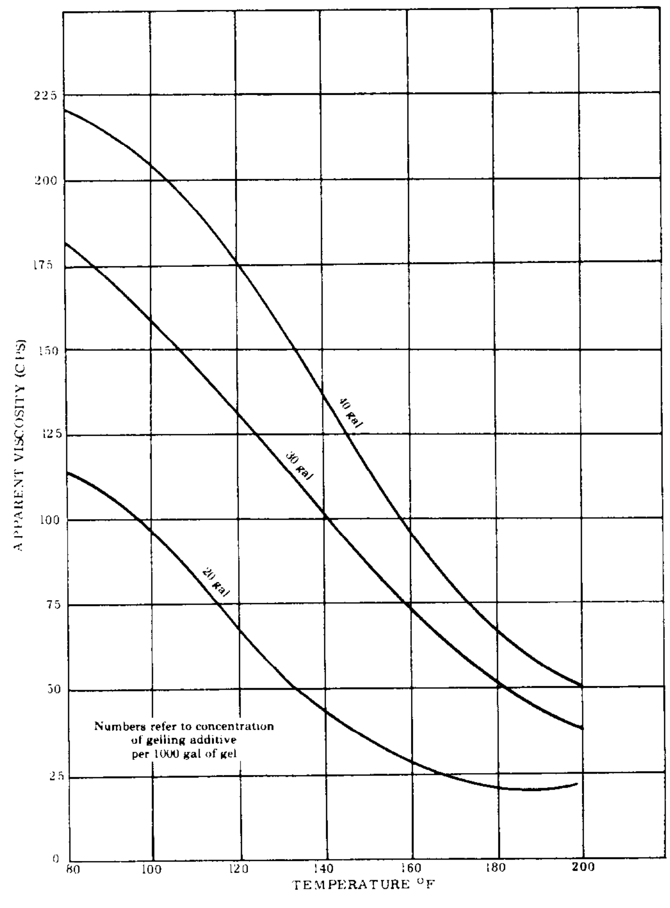


FIG. 4—APPARENT VISCOSITY VS TEMPERATURE °F OB ULTRA FRAC IN CRUDE OIL (QUEEN-API-30°)

The effect of gelling agent concentration and temperature on flow behavior indices, n′ and k′, is shown in Figs. 5 and 6. Tests confirmed that for any constant temperature, increasing the gelling agent concentration lowers the n′ value and raises the k′ value. The op-

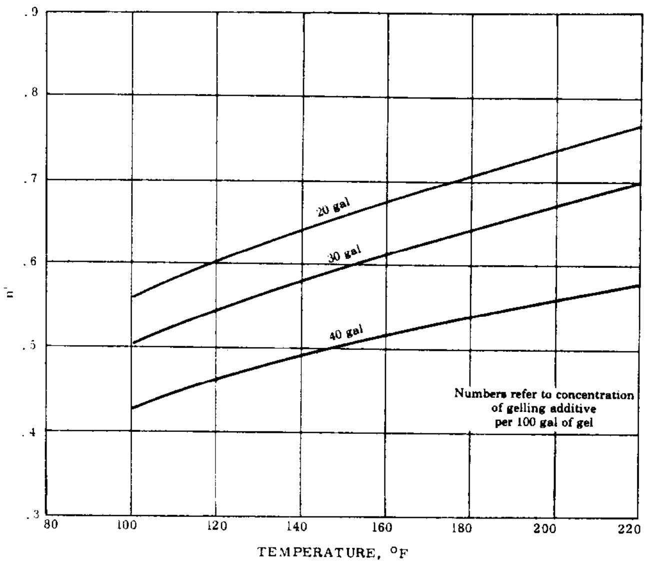


FIG. 5—FLOW BEHAVIOR INDEX (n') VS TEMPERATURE FOR OB ULTRA FRAC IN CRUDE (QUEENS)

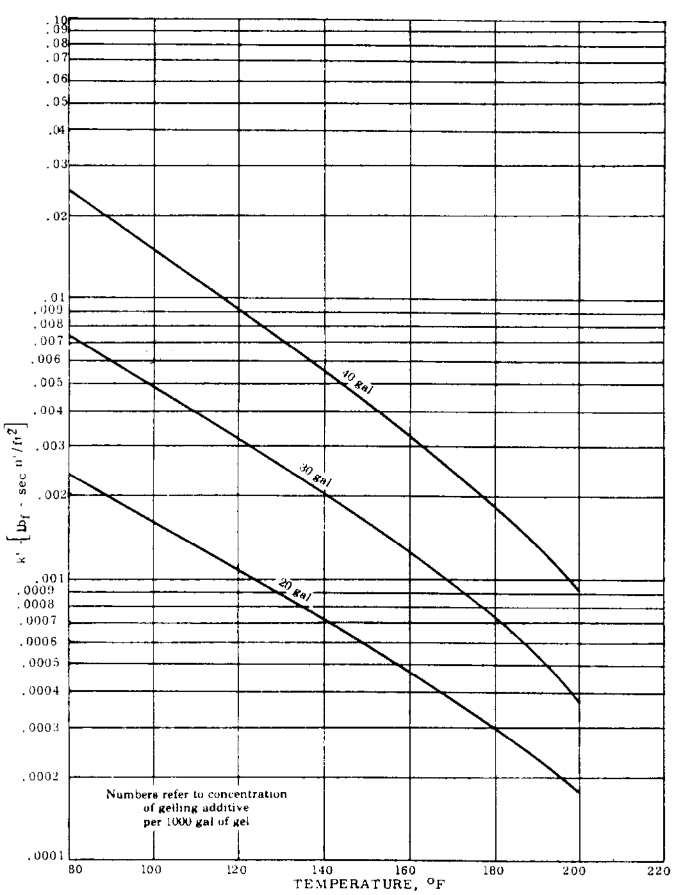


FIG. 6—CONSISTENCY INDEX (k') VS TEMPERATURE FOR OB ULTRA FRAC IN CRUDE OIL (QUEENS)

posite is true if the gelling agent concentration is held constant and temperature is increased.

Although OBUF has adequate fluid loss control, its effectiveness as a fracturing fluid may be improved with a fluid loss additive. Fluid loss tests were run in accordance with the procedure outlined in API RP 39. Table 2 contains the results of these tests in the form of spurt loss, slope of the fluid loss curves, and C_{III} values for temperatures ranging from 80-160°F. Unlike many frac fluids whose fluid loss control deteriorates rapidly with increasing temperature, these tests show the fluid loss of this system to be only slightly affected by temperatures as high as 160°F.

TABLE 2—FLUID LOSS CONTROL OF OBUF

Temp °F	Fluid Loss Additive Conc (lb/1000 gal)	Spurt Loss cc	M* cc/(min)½	C_{III} Ft/(min)½
80	25	1.0	1.36	9.78×10^{-4}
120	0	3.0	1.60	1.15×10^{-3}
120	25	1.5	1.16	8.34×10^{-4}
160	0	5.0	1.12	8.05×10^{-4}
160	25	2.2	.96	6.90×10^{-4}

* Slope of the fluid loss curve.

The friction pressure created when pumping a frac fluid down tubular goods must be minimized if the available horsepower is to be used to the utmost advantage. The relationship between fluid velocity and the friction pressures of ungelled crude and crude gelled with OBUF is shown in Fig. 7. These friction tests reveal OBUF's average friction pressure to be 50% less than that of its base crude.

A breaker is used to decrease gel viscosity and insure rapid well clean-up. Breakout tests reveal that in a 24-hour period, the viscosity is decreased by 60-80%. The exact amount of viscosity reduction is dependent upon the test temperature. As temperature increases, the effectiveness of the breaker system improves.

Tests reveal the permeability damage obtained with OBUF to be less than that of a conventional water frac containing 2% KCl and 10 lb guar gum per 1000 gal. OBUF allows formations, known to have water-sensitive clays or potential emulsion problems, to be treated with minimal permeability reduction.

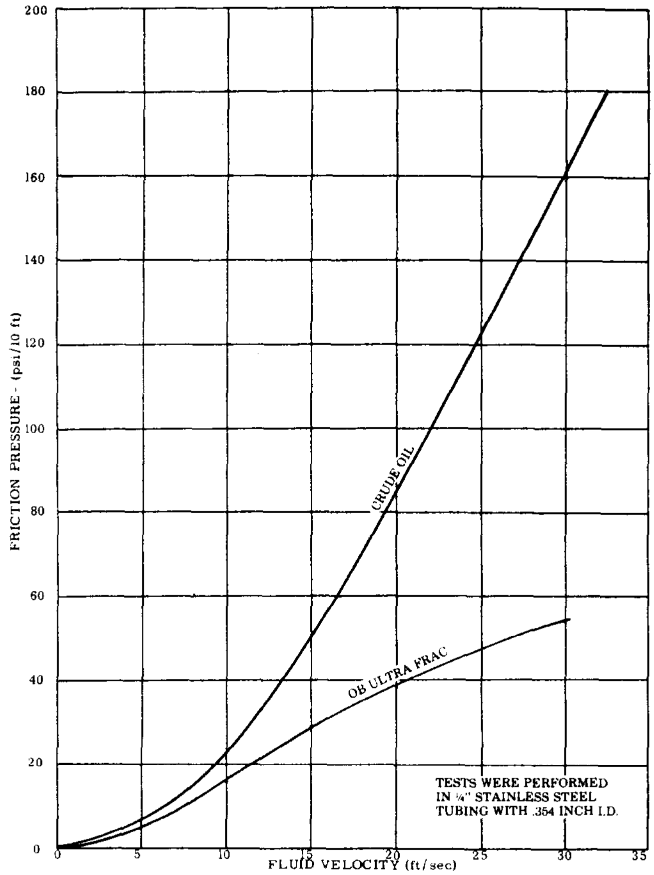


FIG. 7—FRICTION PRESSURE OF OB ULTRA FRAC AND CRUDE OIL VS FLUID VELOCITY

FRACTURE DESIGN

The primary benefits derived from applying either or both of the high viscosity oil-base systems is an increase in fluid production over that obtained with conventional systems. A fracture system properly designed to fully utilize the fluid properties of either Allo-Frac of OBUF will attain greater production results than those attained by the use of gelled water or ungelled lease oil fluids. Following is a discussion on the relationship between the final configuration of the packed fracture, the properties of the two fracturing fluids, reservoir characteristics, and injection rate.

The equations presented by Howard and Fast[1] for fracture area and those by Perkins and Kern[2] for widths, usually point out the following behavior when used to determine the description of the fracture. The fracture width is controlled by the viscosity of the fluid in the fracture and injection rate while the area or length of the created fracture is dependent on the fluid's efficiency or leak-off control.

Since the two fluids under investigation are of the non-Newtonian type, their viscosities must be defined by n' and k'; n' being the slope of the curve showing the relationship between shear stress and rate of shear and k' is the stress at 1 sec^{-1}.

The values for the fluid properties which are discussed in a preceding portion of this paper were used in a computer analysis to prepare Table 3. This table shows the predicted fracture width, during treatment, for the two oil-base fluids in a described formation. The formation used in this examination was medium hard sandstone with five md permeability. A comparison was made between Allo-Frac, OBUF, gelled water and lease oil.

TABLE 3

Fluid	Rate, BPM	Volume, gal/ft	Width, in.
Allo-Frac	20	500	.304
	40	500	.332
	20	1000	.368
OBUF	20	500	.175
	40	500	.198
	20	1000	.206
Gelled Water	20	500	.151
	40	500	.176
	20	1000	.176
Lease Oil	20	500	.141
	40	500	.172
	20	1000	.159

OBUF generally creates fracture width slightly greater than gelled water. The Allo-Frac, due to its higher viscosity within the fracture, provides approximately twice the fracture width as conventional gelled fluids. Since Allo-Frac is capable of creating large cracks, it must also have the ability to transport proppant of large diameters and in high concentration in order to obtain maximum conductivity from the fracture. Actual treatments based on computer design indicate that up to 75% of the created fracture can be packed with proppant when the fluid used is Allo-Frac.

The fracture length created during a pumping operation is primarily controlled by the fluid's ability to resist leaking off into the formation. The rate at which fluid leaks off has been shown by Howard and Fast to be dependent upon the fluid's viscosity, the efficiency of the filter cake, and the resistance offered by formation fluids. The feasibility of stimulating formations having low deliverability is determined to a great extent by the distance that proppant particles can be carried from the wellbore by the fluid. This distance often is less than maximum because of poor fluid efficiency or lack of leak-off control.

Each of the viscous oil-base gels offers substantial viscosity to aid in controlling fluid loss. Fluid loss additives may also be added to further lower the leak-off. Table 4 shows the relative effectiveness of the listed fluids, containing appropriate fluid loss additives, in creating fracture length.

TABLE 4

Fluid	Rate, BPM	Volume, gal/ft	Length, ft
Allo-Frac	30	1000	534
	30	1500	704
	40	1000	549
OBUF	30	1000	660
	30	1500	874
	40	1000	674
Gelled Water	30	1000	390
	30	1500	518
	40	1000	408
Lease Oil	30	1000	386
	30	1500	513
	40	1000	403

Because of inherent fluid loss control from the gel and its being compatible with efficient fluid loss additives, OBUF generally creates fractures 5-10% longer than Allo-Frac and 30-40% longer than gelled water or lease oil.

The ability of fracturing fluid to transport proppant is dependent upon the fluid's viscosity, density, and proppant type and size. An examination of proppant-carrying ability using the equations presented by Babcock, Prokop and Kehle[3] reveals that the viscous oil gels are better able to create a proppant bank approaching the length of the fracture created than conventional frac fluids.

The height of the fracture is usually assumed to approximate the footage of pay and to be independent of the fracturing fluid. However, the configuration in which the proppant is laid down is very much dependent upon the fracturing fluid's properties. Babcock's equations predict that the viscous fluids will produce fractures that have a relatively low packed height and the majority of the remaining interval will be propped by a mono layer or partial mono layer. On the other hand, thinner fluid will produce high sand banks and little, if any, partial mono layer.

FIELD APPLICATIONS

The final viscosity of the gelled fluid is determined by the compatibility of the gelling material to the base hydrocarbon fluid. The OBUF system will produce a medium high viscosity fluid within the 100-5000 cp* range with a wide and assorted variety of crudes. The crudes can vary from a low gravity to an extremely high gravity and still be effectively gelled by this system. The final viscosity of the fluid seems to vary with the gravity and chemical composition of the crudes. The lower gravity crudes from 10°-25° usually produce a much higher final viscosity gelled fluid than can be obtained with the higher gravity crudes.

The crosslinked system, Allo-Frac, is used to gel the higher gravity crudes (above 40° API) and distillate or condensate. These hydrocarbon gels have a final viscosity in the 1000-10,000 cp* range. This system also gels kerosene, diesel and most of the aromatic solvents.

The hydrocarbon used will need to be tested prior to the job to see if it is compatible with one of the systems. If compatible, further tests are conducted to determine rheology, fluid loss data and breakout.

OBUF is a continuously mixed system. When mixed in this method, the fluid thickness in the blender tub is in its final condition allowing for visual inspection. This method of mixing cuts down the quantity of storage tanks and the necessity to gell the pad and flush on small jobs where the fluid for the pad, the fracture treatment and the flush are all in one tank. Continuous mixing permits the gelling of only the amount of fluid needed to perform the de-

* Measured on Brookfield Viscometer #2 Spindle @ 10 RPM

sired treatment. The crosslinked system is only batch-mixed. This is due to the viscosity vs time relationship. The length of time necessary to build up final viscosity may take longer than the time required to displace the fluid. Also, there are some variations with the same basic fluid so each storage tank must be tested prior to complexing for job usage.

CASE HISTORIES

The results obtained with Allo-Frac and OBUF are shown in Table 5. The treating volumes, injection rates, treating and friction pressures, and proppant volumes are shown on the table. Notice should be taken of the results obtained with the minimum amount of treating fluid. The Allo-Frac exhibits outstanding friction reduction properties while the OBUF has large proppant volumes in small volumes of fluid.

TABLE 5—CASE HISTORIES

Treating Volume gal	Injection Rate BPM	Formation	Treating Pressure psi	Friction Pressure psi	Tubing Size in.	Proppant Volume lb	Results Before	Results After
Allo-Frac								
60,000	20	Marchand	5500	2100	2-⅞	96,000	300 BOPD	1400 BOPD
70,000	35	Marchand	4200	600	4-½	150,000	275 BOPD	1050 BOPD
40,000	28	Cottage Grove	2100	600	4-½	48,000	15 BOPD	120 BOPD
14,750	19.5	Delaware	3500	2700	2-⅞	28,000	NW	160 BOPD
30,000	27	Devonian	3700	1400	3-½	30,000	NW	100 BOPD
15,000	9	Frio	3600	600	2-⅞	25,000	500 MCFD	6,5 MMCFD
OBUF								
23,000	16	Morrow	5600	3600	3-½	30,000	37 BOPD	194 BOPD
14,000	16	Morrow	4800	2500	3-½	14,200	33 BOPD	151 BOPD
35,000	30	Simms	3500	2400	4-½	60,000	NW	300 BOPD
30,170	25	Grayburg	2400	800	5-½	32,000	33 BOPD	143 BOPD
17,630	17	San Andres	4700	1500	3-½	19,500	30 BOPD	85 BOPD
18,000	8	Conglomerate	4900	3050	2-⅜	30,000	NW	65 BOPD

STIMULATION ECONOMICS

Since producing wells have a wide range of production potential, they are stimulated with treatments whose design is influenced greatly by cost. The cost of a particular fracturing treatment can generally be subdivided into: (1) cost of equipment (HP) and (2) cost for fluid and proppant. Not included in the treatment cost are the expenses necessary to prepare the well or those for putting it back on production.

The friction pressure exhibited by either of these oil gels is less than the oil used in its preparation. Even more dramatic is the comparison of friction pressure between the gel and a Newtonian fluid of similar viscosity. When treatments are to be performed down long strings of tubing or if the well equipment has a low pressure limit, the fluid that has the least friction pressure will permit the highest injection rates.Often the saving in horsepower cost along with the increased sand-carrying ability make the viscous oil gels the most economical of the fracturing fluids.

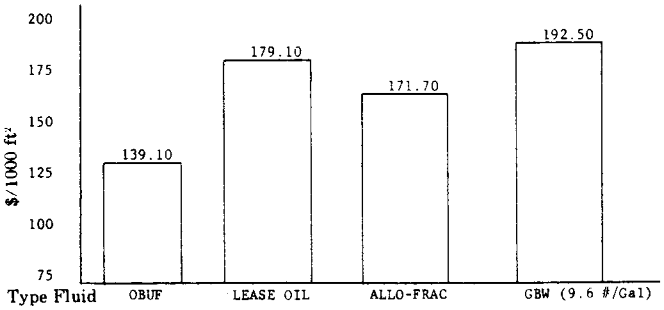
Two comparisons are made between OBUF, lease oil, Allo-Frac and gelled salt water, to show the economic-use in terms of: (1) cost per 1000 ft^2 of fracture area and (2) cost per production increase ratio. These comparisons were based on the following well information:

Type Formation	Limestone
Formation Depth	6800 ft
Vertical Extent	42 ft
Reservoir Pressure	900 psi
Nominal Pipe Size	3.5 in., 9.3 lb/ft
Permeability	2 md
Porosity	4.7%
BHT	110°F
Well Spacing	40 acres
BHFP	4900 psi
Oil Gravity	35° API

Table 6 shows cost per 1000 ft^2 of fracture area and Table 7 shows cost per production increase ratio.

Table 6 using the same fluid volume shows that the gelled oils cost less per 1000 ft^2 of fracture area than either lease oil or gelled salt water. The Allo-Frac will carry the most sand in the largest frac width while OBUF will produce the deepest penetration.

TABLE 6—COST PER 1000 SQ FT FRACTURE AREA

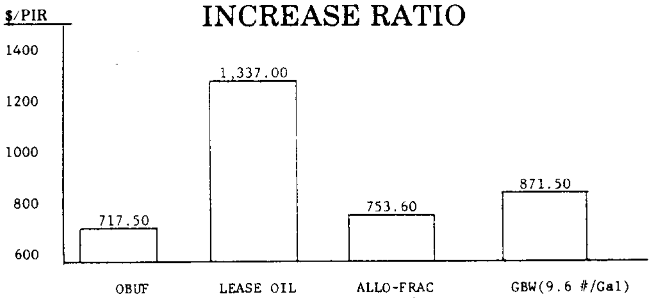


Comparison of Selected Stimulation Programs

Volume Gal	Pump Rate BPM	Propped Area, Sq Ft	Penetration PC	Settled Width, In.	HHP	Sand WT Lb	PIR	Cost* $
FLUID: OBUF + 25 lb (Fluid Loss Additive)								
20,000	15	39,851	70.2	0.180	1296.6	59,752.4	6.42	5543
FLUID: Lease Oil 25 lb (Fluid Loss Additive) + 4 Gal. (Friction Reducer)								
20,000	20	37,327	65.8	0.103	2652.0	32,014.2	5.11	6685
FLUID: Allo-Frac + 20 lb (Fluid Loss Additive)								
20,000	15	31,088	54.8	0.253	1080.9	65,508.7	6.75	5339
FLUID: GBW (9.6 lb) + 20 lb (Fluid Loss Additive) + 30 lb (Gelling Agent)								
20,000	20	14,894	26.2	0.095	1283.1	11,813.7	4.04	2868

The use of the same penetration percentage in Table 7 shows that the gelled oils cost less per production increase ratio (folds of increase) than either lease oil or gelled salt water. The Allo-Frac will give the largest production increase ratio (PIR) and frac width while OBUF will give the same frac length as the other fluids with the smallest volume of fluid.

TABLE 7—COST VS PRODUCTION INCREASE RATIO



Comparison of Selected Stimulation Programs

Volume Gal	Pump Rate BPM	Propped Area, Sq Ft	Penetration PC	Settled Width, In.	HHP	Sand Wt, Lb	PIR	Cost* $
FLUID: OBUF + 25 lb (Fluid Loss Additive)								
12,518	15	28,380	50.0	0.165	1296.6	39,091.2	5.76	4133
FLUID: LEASE OIL 25 lb (Fluid Loss Additive) + 4 Gal. (Friction Reducer)								
13,801	20	28,380	50.0	0.096	2652.0	22,728.8	4.75	6353
FLUID: ALLO-FRAC + 20 lb (Fluid Loss Additive)								
17,754	15	28,380	50.0	0.247	1080.9	58,454.9	6.51	4906
FLUID: GBW (9.6 lb) + 20 lb (Fluid Loss Additive) + 30 lb (Gelling Agent)								
45,954	20	28,380	50.0	0.112	1283.1	26,447.6	5.03	4384

* Cost does not include frac tanks, taxes or base fluid.

CONCLUSIONS

1. Both laboratory data and field tests indicate that the high viscosity oil-base gels may be applied in wells that previously would not respond well to water-base fracturing fluids.
2. Oil-base systems can be prepared from refined petroleum products such as kerosene and diesel or from produced fluids such as crude oil or distillate.
3. Computer analysis shows that the viscous oil gels are able to place higher concentrations of large mesh sand in the formation at lower cost than the conventional fluids used in fracturing.
4. Successful fracturing treatments have been accomplished on wells having a BHT of 250°F with the viscous oil-base fluids.
5. One oil-base system can be prepared using the batch-mixing process while another may be mixed continuously.
6. Friction pressure can be reduced sufficiently with Allo-Frac to permit the treating of deep formation through tubing without requiring excessive horsepower.
7. Case histories show that the cost of gelling the fluids is more than compensated for in the benefits received (PIR, frac width, small volumes, etc.).

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