FIELD APPLICATIONS OF A HIGH-STRENGTH FRACTURE PROPPANT

CLAUDE E. COOKE
Exxon Production Research Company

and

JOHN L. GIDLEY AND DEAN H. MUTTI
Exxon Company, U.S.A.

INTRODUCTION

Hydraulic fracturing has been a very effective well-stimulation process in the oil and gas industry for a number of years. Experience has shown that the benefits of fracturing are, however, reduced in deeper wells. The reason for this decrease is known: the proppant is subjected to higher stress with increasing depth. Silica sand, the most commonly used propping material, is not sufficiently strong to resist a large amount of crushing at closure stresses encountered in deep formations. The crushing creates fine particles that can greatly reduce the fluid conductivity of the fracture when the well is produced. To achieve optimal fracturing results, a material that does not crush in deep well fractures is needed.

Exxon Production Research Company (EPR) developed a laboratory procedure for testing propping materials under conditions that closely simulate reservoir conditions.[1] Continuing research resulted in sintered bauxite particles that show greatly improved resistance to crushing over any material available in the past.[2] Sintered bauxite has now been tested in over 20 wells, all of which have been deeper than 10,000 feet.

Any proppant considered as a replacement for silica sand will likely cost more and must have benefits that more than offset the increased cost. Detailed economic analyses of the costs and benefits of a high-strength proppant have been developed as a part of the field testing of sintered bauxite. These analyses have shown that the economic benefits of a high-strength material are appreciable. The field results have shown that the benefits predicted from laboratory studies can be realized.

This paper briefly summarizes the laboratory studies that have led to the development of the new, high-strength bauxite proppant, describes field applications of the proppant, and discusses the results of a detailed economic analysis for a particular field. We expect that wide-spread use of the new proppant will be economically justified in the future.

SUMMARY OF LABORATORY DEVELOPMENT

The conductivity of a fracture packed with silica sand is greatly decreased by crushing of the sand grains. To prevent crushing, a material that is not extremely brittle and is not susceptible to the effects of brine is necessary.[1] If the proppant particles deform slightly at point-to-point contacts, stress concentrations will be reduced. Of course, the material must also have high strength. The search for new proppant materials has centered around materials from which tough, inert grains could be manufactured at the lowest possible cost. Sintered bauxite has the properties needed.

Graded sintered bauxite proppant samples were tested with EPR's laboratory equipment,[2] and results like those in Figure 1 showed that the samples retained most of their permeability at stresses up to 10,000 psi. The permeability of sand tested in the same manner decreased rapidly. The tests were performed by measuring permeability to brine at a temperature of 315°F.

Another type of test was used to measure fracture conductivity directly (instead of permeability). Results obtained with different concentrations of sintered bauxite particles at stresses varying from 3000 to 10,000 psi are shown in Figure 2. These

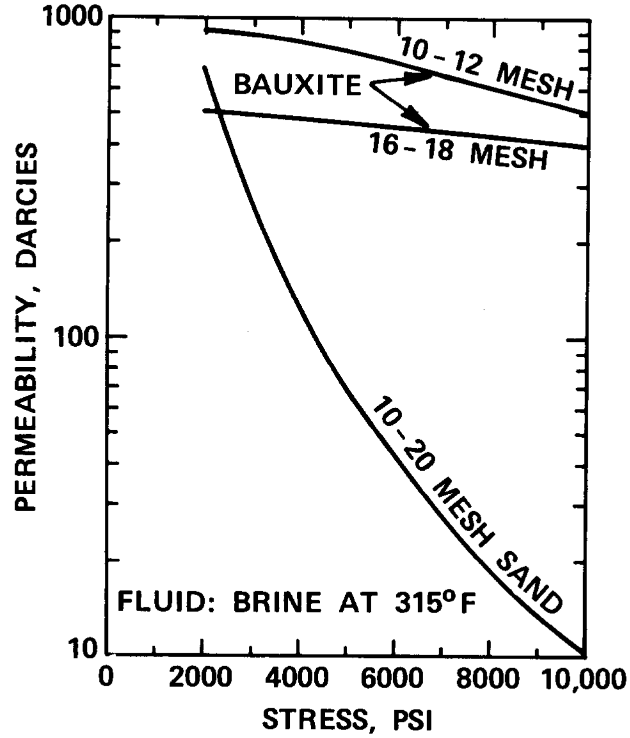

FIG. 1—EFFECT OF STRESS ON PERMEABILITY OF SINTERED BAUXITE PARTICLES AND SAND.

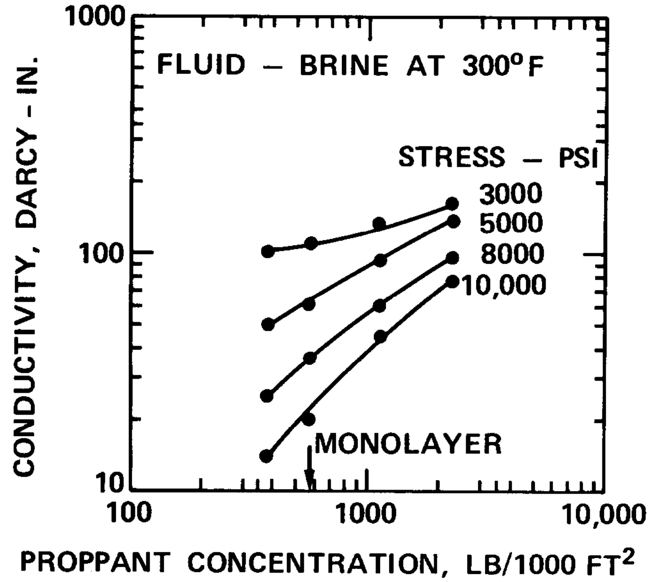

FIG. 2—EFFECT OF PROPPANT CONCENTRATION AND STRESS ON THE CONDUCTIVITY OF 10-12 MESH SINTERED BAUXITE PARTICLES BETWEEN MORROW SANDSTONE SLABS.

results were obtained at a temperature of 300°F in brine, with the proppant placed between Morrow sandstone cores.[2] At a stress of 8000 psi, the conductivity of the fracture propped with sintered bauxite was about 50 times greater than a fracture containing the same amount of sand.

Different sizes of proppant are available and have been tested in the laboratory over a range of stress values and temperatures. Aging tests have shown no appreciable effect of time and temperature on the proppant. These and other data developed in the laboratory and in field tests are used to design a treatment for a particular well.

FIELD APPLICATIONS

Although the sintered bauxite proppant was thoroughly tested in the laboratory, several questions remained that could be answered only by pumping the proppant into deep wells. Potential problems remained in the handling and pumping the higher density, abrasive, tough particles. Also, verification was required that a real fracture propped with bauxite would have a higher conductivity than it would when propped with sand or other materials. Field trials found that the bauxite worked very well, and there were no problems with handling and pumping. Results of field use to data are summarized below.

DESCRIPTION OF TESTS AND RESULTS

Over 20 wells have been fractured with the sintered bauxite proppant since it was first field tested, and a total of over 1,000,000 pounds of the new proppant has been pumped. Table 1 lists the results of 17 field tests performed in Exxon Company USA and other operators' wells in Texas and Mississippi. Well depths range from over 10,000 to 16,400 feet with reservoir temperatures ranging from 190°F to 360°F. The proppant has been successfully tested in both sandstone and limestone reservoirs.

All of the treatments have used conventional fracturing equipment. Seven of the treatments used pressure-intensifier pumping units. Most fracturing fluids used to carry the proppant have been either polymeremulsion or two-component, cellulose-based polymers in water. Fracture gradients measured during the treatments ranged from 0.75 to 1.0 psi/ft, with the corresponding maximum closure stress on the proppant calculated to be from 7,000 to

TABLE 1—SINTERED BAUXITE PROPPANT FIELD APPLICATIONS

Well	Location	Operator	Depth(ft)	Formation	Temp(°F)	Lbs. Proppant Sand	Lbs. Proppant Bauxite	Production Data Before Rate(MMCFD)	Before FTP(psi)	After Rate(MMCFD)	After FTP(psi)
A	South Texas	Exxon USA	10,330	Vicksburg	260	-	25,000	0.09	400	0.12*	475
B	South Texas	Exxon USA	10,880	Vicksburg	270	-	24,000	0.40 (61 BC/D)	1,600	2.7 (230 BC/D)	3,100
C	South Texas	Exxon USA	11,330	Frio	260	-	46,000	0**	-	1.1 (55 BC/D)	3,500
D	South Texas	Exxon USA	12,900	Frio	290	-	34,000	0.20	100	0.9	8,000
E	South Texas	MGF/Exxon USA	13,550	Edwards	360	-	111,000	Not Tested		1.0	1,500
F	South Texas	MGF/Exxon USA	13,500	Edwards	360	-	111,000	Not Tested		1.1	4,165
G	Texas Gulf Coast	Exxon USA	10,360	Wilcox	285	-	17,000	1.90	1,400	7.7	1,300
H	Texas Gulf Coast	Exxon USA	10,300	Wilcox	285	17,000	8,500	2.00	800	13.4	1,415
I	Texas Gulf Coast	Exxon USA	10,020	Wilcox	275	21,000	5,500	0.30	-	2.9	1,325
J	East Texas	Exxon USA	12,000	Haynesville	295	99,000	35,000	0.10	100	0.37	1,100
K	East Texas	Exxon USA	11,890	Haynesville	290	-	57,000	Not Tested		2.5	2,000
L	West Texas	Exxon USA	10,950	Wolfcamp	190	-	39,000	1.00	100	4.5	2,700
M	West Texas***	Exxon USA	10,950	Wolfcamp	190	-	58,000	.90	50	Not Yet Evaluated	
N	Mississippi	Union	14,980	Hosston	275	-	6,500	0.23 (78 BC/D)	550	0.32* (123 BC/D)	1,325
O	Mississippi	Fla. Gas Expl.	16,060	Hosston	285	-	90,000	0.90	700	5.0	3,250
P	Mississippi	Inexco	16,400	Hosston	280	-	74,500	0.40	100	1.3	400
Q	Mississippi	Fla. Gas Expl.	15,480	Hosston	280	-	74,500	0.38	2,000	1.8	1,600

*Mechanical failure left proppant in wellbore.
**Buildup of rock in wellbore prevented production before fracturing.
***Well was refractured after screen out on initial treatment.

10,000 psi. The incremental benefits of the high-strength proppant over sand at these stress levels are significant.

South Texas Area. The first fracturing treatment with the sintered bauxite proppant was done in a South Texas well (well A, Table 1) at a depth of 10,330 feet. The well had been produced for several years from an abnormal pressure zone. A pressure-buildup test indicated a very low reservoir permeability. The major questions to be answered in this first test concerned the handling and pumping of the new material. Tests were performed by the service company prior to the treatment to determine that the normal proppant handling equipment would function, and pressure intensifiers were used to minimize any problem that might be caused by excessive pump-valve wear. The surface treating pressure was 10,000 psi, and examination of the valves afterward showed only normal wear. Thus, no special equipment is needed to pump the new material. A tubing failure occurred while pumping this first treatment, and about 7,000 pounds of proppant was left in the wellbore. Because of mechanical conditions in the well, removal of the proppant was too difficult. This prevented a valid test of well stimulation.

The next three treatments (wells B, C, and D in Table 1) were also performed on low-permeability, abnormal-pressure sandstone reservoirs. In these wells, before fracturing, it was necessary to limit the production rates to prevent excessive pressure drawdown at the formation face. In well C, pieces of the formation had been pulled into the wellbore as a result of excessive drawdown. Use of sintered bauxite proppant generated good production increases from all three wells. Both well B and well C produce appreciable amounts of condensate, so the increases in condensate production are also shown in the table. Production rates and flowing pressures have remained essentialy constant on all three wells after several months of sustained production. Unfortunately, pressure buildup tests were not made before fracturing these wells, so evaluations of the treatments are therefore limited. Because of the high fracture gradient (0.8 to 1.0 psi/ft), the maximum stress applied to the proppant in the formation during cleanup and production is estimated to be about 7,000 psi for wells B anc C. The benefits of the high-strength proppant are appreciable at this stress level. The benefits should be even greater in well D, which is deeper than the other two, when the pressure is drawn down under long-term production.

The two MGF/Exxon USA wells (E and F, Table 1) are completed over a large gross interval in the Edwards Limestone. These wells have the highest reservoir temperature (360° F) of the wells treated to date with the high-strength proppant. The gas produced from this formation contains a small amount of H_2S and CO_2. Production data on both wells are from short-term flow tests after fracturing. In well E, excessive water production from a lower, wet zone has limited the gas production rate. Buildup tests run on well E and on an offset well indicated that the formation has low permeability. The buildup test on well E obtained after the treatment showed substantial formation stimulation.

Well F, which was fractured down the casing string with 111,000 pounds of the high-strength proppant, had the largest treatment that has been performed without intensifiers. (The other large treatments, four jobs of 74,500 pounds or more, all employed pressure-intensifier pumping units. Inspection of the pumps after the treatments showed no increased wear over that experienced with sand.) The after-frac production rate from well F was deliberately held at a reduced rate to obtain a more nearly constant rate for buildup test evaluation. The closure stress on the proppant in these wells during cleanup and the short-term production tests is estimated to be about 7,000 psi.

Texas Gulf Coast Area. Three treatments (wells G, H, and I) were performed in a field in the Texas Gulf Coast area at a depth just below 10,000 feet. The fracture gradient in this field is about 0.75 psi per foot; therefore, the stress on the proppant is less than in the wells in other areas and the incremental benefits over the use of sand are lower than in the South Texas wells just described. In two of the treatments performed in this field, sand was injected first, followed by the high-strength proppant. Pressure buildup tests available for these wells were used to predict the effect of sand and the effect of the high-strength proppant in increasing production. The interpretation of these tests was limited by the accuracy of the data and the small size of the treatments; the best interpretations possible showed that the higher fracture conductivity for the high-strength proppant was realized in the reservoir. The large increases in the production rates of the wells were partly attributed to near-wellbore damage removal in this sandstone reservoir.

East Texas Area. Two treatments (on wells J and K) were performed in an East Texas limestone reservoir where acid fracturing had been used previously. The treatment in well J followed an unsuccessful acid-fracturing treatment. The sintered bauxite proppant was used at the end of the treatment after 99,000 pounds of sand had been injected. Production rate data before fracturing indicated a very low reservoir permeability. Log analysis indicated that the productive interval in well K was about the same quality as that in well J.

West Texas Area. Two wells (L and M) in the Wolfcamp formation in a West Texas field were treated with the high-strength proppant. The treatment on well L, as judged by short-term production tests appeared to be very successful despite a screen-out that prematurely terminated the treatment. Well M was fractured a second time with the new proppant after a screen-out occured on the initial treatment. The two sintered bauxite treatments performed on well M followed an unsuccessful acid treatment. The last treatment, only recently performed, has not been evaluated.

Mississippi Area. Four treatments on which we have data were performed in wells of operators not affiliated with Exxon. These wells are in Mississippi (wells N, O, P, and Q). Depths ranged from 14,980 to 16,400 feet. Prior fracturing results with other proppants in the deep sands in this area were not satisfactory. Surface treating pressures on these wells during the injection of sintered bauxite proppant ranged from 10,000 to 14,000 psi, and pump rates were in the range of 10-16 bbl per minute. Table 1 shows the results in well O, P and Q have been excellent. In well N, mechanical failure with the pumping equipment left about 3500 pounds of proppant in the wellbore. After flow-testing well N, a wireline survey indicated that proppant covered the entire perforated interval, thus preventing a valid interpretation of the effectiveness of the treatment.

After nearly a year of production, the production rate from well O has dropped off only slightly from the initial rate immediately after treatment. A pressure buildup test before fracturing allowed the results to be interpreted; significant reservoir stimulation was indicated. Water production has limited gas production in wells P and Q, but the high rates of liquid production during cleanup of the wells and the increases in gas rates showed that very conductive fractures are present at depth of 16,400 and 15,480 feet. The maximum stress on the proppant in these wells was estimated to be about 10,000 psi. Laboratory data show that the sintered bauxite proppant at this stress level has a much greater conductivity than any other proppant available.

PREDICTING INCREMENTAL BENEFITS OF HIGH-STRENGTH PROPPANT IN GAS WELLS

Predicting the incremental benefits of placing a high-strength proppant in a fracture-stimulated gas well required consideration of several phenomena: fracture geometry, unsteady-state flow, cleanup of fracturing fluid from the fracture, and non-darcy flow phenomena of gas in the fracture. Exxon Company USA models fracture geometry with EPR's hydraulic-fracturing computer program. This program estimates the length and width of the propped fracture and the permeability of the proppant at the estimated maximum closure stress. The effects of unsteady-state flow and turbulence in the fracture are then predicted with EPR's reservoir simulator computer program. Tannich's methods are used to predict liquid cleanup and early-time production rates.[3] Combining the fracture geometry, permeability, net pay thickness, porosity, pressure, temperature, and well spacing, the program arrives at a prediction of gas and condensate production rates for a period of several years is made for sintered bauxite, sand, and acid if a limestone reservoir is being analyzed. The production-flow streams generated can then be evaluated by applying economic data for investment and operating costs, taxes, and product price forecasts to compare the present-value profit at an appropriate discount rate for a sintered bauxite treatment in a successful well to other types of stimulation treatments of comparable cost.

Figures 3 and 4 show the information generated by an economic analysis of a deep Exxon USA gas field in East Texas. EPR's proppant and acid-fracturing computer programs were used to predict the geometry and properties of fractures generated by several different sizes of sintered bauxite, sand, and acid-fracturing treatments. Sizes of the various treatments ranged from 22,500 to 180,000 pounds of sintered bauxite, 100,000 to 400,000 pounds of sand, and 15,000 to 120,000 gallons of acid. The predictions were entered into the reservoir simulator program, along with the properties of the reservoir in this deep, low-permeability gas field. Maximum closure stress on the fracture in this field was calculated to be about 9,000 psi during cleanup and long-term production.

Cumulative production forecasts generated by the reservoir simulator program for treatments using 45,000 pounds of sintered bauxite, 200,000 pounds of sand, and 30,000 gallons of acid are shown in Figure 3. In this particular reservoir the incremental benefits of using sintered bauxite are very significant; during the first 10 years with sintered bauxite, the additional production is approximately 0.75 Bscf more than an equal-cost sand fracture treatment and over one Bscf more than an equal-cost acid-fracture treatment.

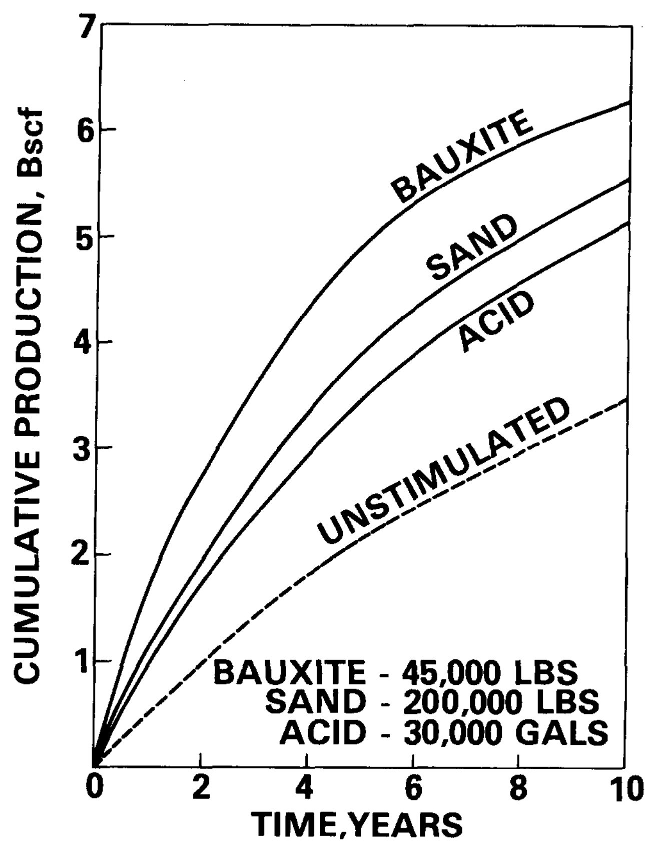

FIG. 3—CUMULATIVE PRODUCTION FORECAST FOR DEEP EAST TEXAS AREA GAS FIELD.

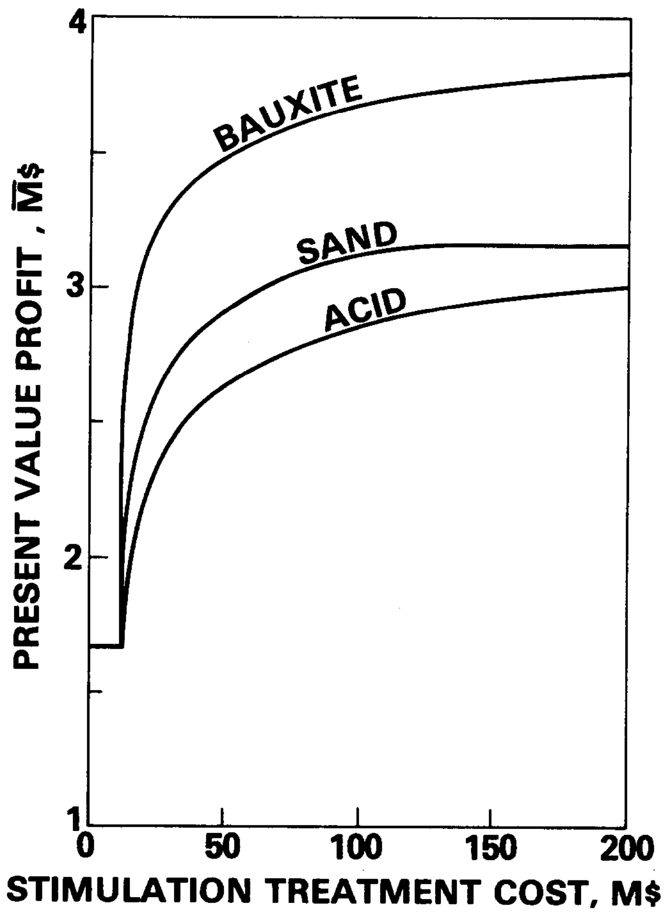

FIG. 4—PRESENT-VALUE PROFIT FOR DEEP EAST TEXAS AREA GAS FIELD (12% DISCOUNT RATE).

Figure 4 shows the present-value profit generated by the different treatments, taking into consideration the cost to drill, complete, and treat the successful wells, plus standard tax rates, operating expenses, and sale of the gas to an intrastate pipeline. The incremental benefits derived from the high-strength proppant are substantial for all sizes of treatments performed. The most economically attractive treatment in this particular field is a sintered bauxite treatment of about 60,000 to 100,000 pounds. These results apply only to the specific set of reservoir conditions and economic factors encountered in this field, so they should not be applied to all operating areas.

CONCLUSIONS

1. A new, high-strength sintered bauxite propping material has been developed.
2. The new proppant can be pumped with the same equipment used to pump sand.
3. Field results using the sintered bauxite proppant in deep wells have been very good, confirming the laboratory results.
4. Detailed economic analyses, using a reservoir simulator and reservoir and economic parameters for a deep, low permeability Exxon USA gas well in the East Texas area illustrate the large economic benefits that are expected from use of the sintered bauxite proppant under applicable conditions.

REFERENCES

1. Cooke, C.E.: Conductivity of Fracture Proppants in Multiple Layers, *J. Pet. Tech.* (Sept. 1973) 1101-1107; *Trans.* AIME, 255.
2. Cooke, C.E.: Hydraulic Fracturing with a High-Strength Proppant, SPE 6213, presented at Fall meeting, SPE of AIME, Oct. 1976.
3. Tannich, J.D.: Liquid Removal from Hydraulically Fractured Gas Wells, *J. Pet. Tech.* (Nov. 1975) 1309-1317.