BRIDGING EFFECT OF PROPPING AGENT PARTICLES IN PERFORATIONS, PERFORATION TUNNELS, AND CROSSCUT CHANNELS

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ABSTRACT

The transport of propping agent particles through the perforations, down the perforation tunnels, and into the fracture via the crosscut channels connecting the perforating tunnels and the fracture present special flow problems during hydraulic fracturing operations. Hydraulic fracturing treatments are commonly performed in the field, yet surprisingly little experimental or analytical work is available to guide engineers in selecting operating conditions to ensure that propping agent particles are transported efficiently from the casing into the fracture. This paper describes how propping agent particles are transported from the casing into the fracture. Presented in the paper is a procedure for predicting proppant agent transport from the casing into the fracture, and how the technique can be utilized to more effectively employ the hydraulic fracturing process.

INTRODUCTION

It is common practice in the oil and gas industry to effect the completion of oil, gas, and water wells by setting and cementing casing through the formations of interest and perforating the section of casing opposite the desired intervals by means of a perforating gun lowered into the well on a cable or on the tubing. Perforating has been used for nearly 60 years for generating a flow channel between oil, gas, and water reservoirs and the well bores of oil, gas, and water wells. The first well reported to have been perforated was a Union Oil Co. of Calif. well in the Montebello Field, Los Angeles, Calif., in 1932.[1] The well was perforated using a bullet perforator, and the perforation operation was performed by W. E. Lane and W. T. Wells who later formed the Lane-Wells Co.[1] The shaped jet perforator came into use in 1946, shortly after World War II and stemmed from the principles of projectiles and rockets that were used during the war in the bazooka weapon and shaped charge grenades.[2] The first jet perforating operation was performed by Well Explosives, Inc., the parent company of Welex which is now Halliburton Logging Services, Inc.[2]

Jet perforating essentially replaced bullet perforating, which was the mainstay of perforating operations for many years prior to that time. The development history of the shaped jet charge entailed two phases which are listed below.[3]

1. The first phase was concerned with the aspects of refining gun and charge designs to improve the operational aspects and increase penetration and hole size.

2. The second phase pertained to laboratory testing for determining and predicting the flow properties of perforations.

The majority of hydraulic fracturing treatments performed in the oil and gas industry are conducted through perforations. These perforations are usually created by shaped jet charges that penetrate through the casing, through the cement sheath, and several inches into the formation. Each perforation has an entry hole diameter of approximately 0.25 to 0.90 in. and a carrot like cylindrical shaped perforation tunnel of a length of approximately 5.0 to 30.0 in.

Although the art of hydraulic fracturing is a matter of routine in petroleum operations today, knowledge is scarce concerning the behavior of propping agent particles in the fluid stream as they move from the casing, through the perforations, down the perforation tunnels, and into the fracture via the crosscut channels connecting the perforation tunnels and the fracture. Refer to Fig. 1 for a schematic of propping agent particle transport from the casing into the fracture. Examination of Fig. 1 shows the sketch to be fairly self-explanatory and only tortuosity of the perforation tunnels and crosscut channels needs some additional explanation. The values for perforation tunnel and crosscut channel parameters obtained experimentally are often higher than simple perforation tunnel and crosscut channel geometry would lead one to expect. In an effort to account for the high values, certain formulae have been derived to account for the "tortuosity concept". Tortuosity of the perforation tunnels and crosscut channels is described by the following equation.[4]

$$\text{Tortuosity Factor} = \frac{\text{Length Of Tortuous Flow Path}}{\text{Bulk Length Of Porous Medium}} \quad \text{...........(1)}$$

The tortuosity factor appearing in Equation 1 is not directly measurable. The values of the tortuosity parameter reported in the literature[4,5,6] range from 1.44 to 1.58 with and average of 1.51. The actual value of the tortuosity factor may vary with the type of porous medium, but no guidance is available as to a preferred value for the parameter; therefore, use of the 1.51 value should be acceptable.

One reason for the scarcity of knowledge concerning the transport of propping agent particles from the casing into the fracture is that it is extremely difficult to apply a mathematical approach in expressing the flow behavior of solid particles in a liquid under these conditions. The dilemma of expressing slurry flow in the physical configuration of the perforations, the perforation tunnels, and the crosscut channels by mathematical models makes it very difficult to completely solve the problem unless many simplifying assumptions are made. Particle trajectory studies have been made under these simplified conditions[7]; however, the results cannot be easily applied to downhole configurations as they are encountered in the oil and gas industry today. Torrest and Savage[8], Haynes and Gray[9], and Guesbeck and Collins[10] designed and performed experimental techniques to eliminate most of the problems associated with solving the problem. Their experimental results can be used in solving the problem of propping agent particle transport through the use of scale-up factors. Little experimental or analytical work is available in the petroleum industry today to guide engineers in selecting operating conditions which ensure that solid particles are transported efficiently from the casing into the fracture. This portion of sand transport theory is usually neglected in the design of hydraulic fracture treatments.

The purpose of this paper is as follows:

1. Describe how propping agent particles are transported from the casing into the fracture.

2. Present a procedure for predicting propping agent particle transport from the casing into the fracture.

3. Present how the technique can be utilized to more effectively employ the hydraulic fracturing process.

Basic Considerations

The problem of determining if a propping agent particle will be transported by the carrier fluid into a perforation or whether it will settle below the perforation depends primarily on the relative magnitudes of particle inertia and fluid drag. The inertia of the propping agent particle causes it to resist following the fluid path into the perforation; however, fluid drag tends to move the propping agent particle in the direction of fluid flow. The shape of the propping agent particle and the turbulence level of the carrier fluid determines the extent of the propping agent particle movement along the primary direction of travel of the carrier fluid. By intuition, two extremes of propping agent particle transport are obvious:[9]

1. At zero rate, no propping agent particles can be transported into the perforations because the carrier fluid is not moving and not directed toward the perforations, and fluid drag forces in the horizonal direction are zero.

2. Practically all propping agent particles are transported if the fluid viscosity and flow rate are high enough to prevent propping agent particle settling. High viscosity and high flow rate minimize propping agent particle inertia and maximize fluid drag.

When propping agent particles are transported from the casing into the perforations during hydraulic fracturing operations, inertia and gravity forces cause fracturing slurries to increase in propping agent concentration below the perforations. The increase in propping agent concentration can result in incomplete packing of voids outside the casing for the following reasons:[10]

1. Propping agent particles can bridge at the entrance of the perforation tunnels.

2. Highly concentrated fracturing slurries may not be transported through the perforations. Instead, the propping agent particles form a bed in the casing until an equilibrium velocity is reached. At this velocity, the concentrated fracturing slurry can then be moved into the perforations.

According to Guesbeck and Collins[10], two conditions were observed in their experiments of propping agent particle transport through perforated casing. The two conditions are:[10]

1. At the start of injection, some propping agent particles bypass the perforations and fall into the rat hole below the perforations, forming a propping agent particle bed.

2. As injection continues, the height of the propping agent particle bed increases until some equilibrium height is established. This equilibrium bed height, which might be above the bottom perforation, depends on the total volumetric flow rate. If a flowing system is operating at equilibrium conditions and if the total volumetric flow rate is increased, the equilibrium bed height will decrease until a new equilibrium state is established. If the total volumetric flow rate is increased sufficiently, the top of the equilibrium propping agent particle bed may be slightly below the bottom perforation.

BRIDGING IN PERFORATIONS

Perforation Entry Hole Size

Illustrated in Fig. 2[10] and tabulated in Table I is the minimum perforation diameter required to prevent sand bridging. Examination of Fig. 2 shows the following:[10]

1. If the perforation diameter is two to three times the sand grain diameter, bridging of the perforation occurs at sand concentrations of approximately 0.5 to 1.0 lb/gal (0.022 to 0.043 gal sand/gal slurry).

2. If the perforation diameter is four to five times the

sand grain diameter, bridging of the perforations occurs at sand concentrations of approximately 2.0 to 3.5 lb/gal (0.083 to 0.136 gal sand/gal slurry).

3. If the perforation diameter is greater than six times the diameter of the sand grain, bridging of the perforation does not occur even at sand concentrations of 30.0 lb/gal (0.580 gal sand/gal slurry).

4. The ratio of perforation diameter to sand grain diameter at which bridging occurs is fairly insensitive to the viscosity of the carrier fluid. The diameter ratios were virtually the same when either tap water or 100 cp hydroxyethyl cellulose solution was used as the carrier fluid.

   Even though the ratio of perforation diameter to propping agent particle diameter at which bridging occurs is not greatly affected by the carrier fluid viscosity, the size of the propping agent particle node that forms in the casing around a bridged perforation increases with increasing viscosity. If the propping agent nodes form on opposite sides of the casing and if the nodes are sufficiently large, a propping agent particle bridge can form across the casing and prevent fracturing slurry from being transported downstream of the nodes.

Coberly[11] investigated bridging of sand grains on circular holes. He found that a stable bridge was formed when the size of the opening was less than three times the grain size of the sand, and the upper limit of bridging was on holes having a diameter as great as 4.5 times the sand grain diameter. Coberly[11] and Guesbesk and Collins[10] findings are in fairly close agreement. The slight difference in the results can probably be attributed to how the testing was done. Coberly used dry sand and Guesbeck and Collins used sand slurries composed of sand and tap water and sand and 100 cp hydroxyethyl cellulose solution.

Examination of Table I shows the following:

1. The minimum perforation diameter required to prevent sand bridging varies with sand concentration and sand mesh size.

2. When the perforation diameter is six times the sand grain diameter, bridging never occurs regardless of sand concentration and sand mesh size.

Based on the data contained in Fig. 2[10] and Table I, recommended minimum perforation diameters are outlined in Table II.

In order to compare propping agent particle diameters with perforation diameters, it is necessary to know the sieve sizes of the propping agent particles. The U.S. standard screen scale is used for this purpose. Sieves of the U.S. standard screen scale are tabulated in Table III[12,13] for mesh designations of 2.5 to 400. Table III[12,13] may be used to determine the size of the propping agent particles of the mesh designations in use in the petroleum industry.

Perforating Gun Standoff

The basic methods and procedures used in the design of perforating systems have been reported, discussed, and explained fully in detail. As a result of this work, the oil and gas industry adopted in 1962 a standard procedure for the evaluation of well perforators and published the results in API RP 43 bulletin.[14] Perforating systems require careful manufacture and design for optimum downhole performance. For almost any requirement, a perforating system can be selected that will yield the most effective and efficient results. Perforation gun standoff is one of the perforating parameters affecting bridging of propping agent particles and, in turn, perforating results.

The diameter and penetration of jet perforating charges are affected by the distance between the charge and the casing wall. This distance is referred to as "gun standoff". All jet charges have an optimum standoff where the charge will produce the desired perforation diameter and penetration. The relationship between gun standoff and perforation diameter and penetration is a complex function of the following:

1. Casing size, weight, and grade.

2. Cement type and strength.

3. Formation type, strength, pressure, and temperature.

4. Perforating fluid type, amount, and pressure.

5. Perforating gun type, size, and geometry.

6. Jet charge type, strength, and geometry.

In most perforating operations, hole size and penetration seem to vary, with optimum values occurring at lower clearances. Varying gun clearances are common since most guns tend to eccenter in the casing due to well deviation. In addition, many guns are multi-phased and designed to fire in several directions. Variations in hole size and penetration can also be expected between shaped jet charges of the same type and size due to quality control of the charges. Fig. 3[2] illustrates how charge performance can vary with gun positioning in the wellbore. Refer to Fig. 4[3] for the effect of gun standoff on hole size and penetration of a hollow carrier 3

3/8 in., 90 degree phased gun fired in 7.0 in., 23.00 lb/ft, J-55 casing. Examination of Fig. 4[3] shows the following:

1. The optimum gun standoff is approximately 0.5 in. which results in a perforation hole size and penetration of approximately 0.48 in. and 15.0 in., respectively.

2. The worst possible gun standoff would result from decentralizing the gun and produce the maximum gun standoff of approximately 3.0 in. A gun standoff of 3.0 in. would result in a perforation hole size and penetration of approximately 0.25 in. and 14.0 in., respectively.

   Decentralizing the gun would also result in gun standoff of approximately 1.2 in. and 0.0 in. A gun standoff of 1.2 in. results in a perforation hole size and penetration of approximately 0.39 in. and 14.0 in., respectively. A gun standoff of 0.0 in. results in a perforation hole size and penetration of approximately 0.43 in and 15.0 in., respectively.

3. Centralizing the gun would result in a gun standoff in all directions of approximately 1.5 in. which results in perforation hole size and penetration of approximately 0.35 in. and 14.0 in., respectively.

The problem of gun clearance becomes acute when considering small diameter perforating guns in large diameter casing. Centralizing the perforating gun has been suggested as a solution to varying clearance. While practical for large diameter guns, it is impractical for small diameter guns where the problem is most severe. Centralizing of the perforating gun results in high clearance on all shots. Performance is then reduced on all shots. It has also been observed that poor quality irregular shaped perforation holes are obtained at high gun clearances as compared to low gun clearances. If there is an appreciable difference between the gun outside diameter and the casing inside diameter, the gun can be zero phased and decentralized for maximum penetration and maximum hole size. Magnetic and mechanical gun decentralizers are available for this purpose.

Even though decentralized zero phased perforating results in maximum penetration and maximum hole size, it also results in the perforations being in line down one side of the casing. This can result in the fracture being formed along the side of the casing instead of directly from the center of the casing.[15] Phasing of perforating shots should be 60 degrees or 90 degrees to avoid fracture formulation along the side of the casing. Perforating should be done using a centralized hollow carrier gun of a diameter that will result in optimum standoff for the perforating conditions. Avoid small diameter guns in large diameter casing where possible.

Perforating Gun Phasing

In addition to gun standoff, gun phasing also greatly affects bridging of perforations, perforation tunnels, and crosscut channels. Phasing for current day commercial perforating guns is listed below in order of the best to the worst phasing.

1 60 degrees.

2. 90 degrees.

3. 120 degrees.

4. 180 degrees.

5. 0 degrees.

The performance of 60 degree to 180 degree phasing is very close. Zero phasing results in poor performance. 180 degree phasing is 20.0% better than zero phasing, and the optimum phasing of 60 degrees is 30.0% better than zero phasing. Perforating should be done using 60 degree or 90 degree spiraled perforating charges.

Frac Sand Erosion Of Perforations

The effect of frac sand erosion on perforation shape is illustrated in Fig. 5. The perforation shapes shown in this figure were obtained from imprints on Lynes' soft rubber formation packers that were ran before and after high sand concentration fracturing treatments. Before the fracturing treatment, the perforation shapes are very irregular and have a diameter of approximately 0.5 in. After the fracturing treatment, the perforation shapes were still very irregular; however, the perforations then had a width of approximately 0.5 in. and a length of approximately 1.0 in. The perforations had approximately the same width, but the length had approximately doubled. The perforation shapes after fracturing are probably the result of the notching effect of the high sand concentration slurry as it turned the corner and exited the casing via the perforations into the fracture. Retreatment of wells containing frac sand eroded perforations, where selectivity is to be accomplished by utilizing ball sealers, might not be very effective due to the size and shape of the ball sealers and the eroded perforations.

Transport Efficiency

Haynes and Gray[9] conducted experiments and studied sand particle transport in perforated casing in an effort to determine the effect on transport efficiency of the following parameters.

1. Flow rate.

2. Sand size.

3. Sand concentration.

4. Sand sphericity and roundness.

5. Perforation pattern.

Transport efficiency is the mass fraction of propping agent particles that are transported through the perforations relative to the total mass of propping agent particles injected.[10] To express the success of transporting propping agent particles through the perforations, the following equation can be used.[9]

$$\text{Transport Efficiency} = \frac{\text{Propping Agent Particles Transported Into The Perfs}}{\text{Total Propping Agent Particles Injected}} \quad \text{...........(2)}$$

Flow Rate, Sand Size, and Sand Concentration

The relationship between transport efficiency and flow rate, sand size, and sand concentration is shown in Fig. 6[9]. Examination of Fig. 6 shows the following:[9]

1. Transport efficiency improves with an increase in flow rate.

2. A decline of gain in transport efficiency is shown by the reduction in slope of the curves at the higher flow rates.

3. The curves for the 10/20 mesh sand have a more positive slope throughout the range of flow rates compared to 40/80 mesh sand. This is caused by the effects of the particle inertia of the sand. Particle inertia effects in the 40/80 mesh sand are overcome by fluid drag forces at a relative low flow rate, hence flattening of the curves in the high flow rates.

4. Transport efficiency increases as the sand size becomes smaller. 40/80 mesh sand has higher transport efficiencies than 20/40 mesh sand, and 20/40 mesh sand has higher transport efficiencies than 10/20 mesh sand.

5. Transport efficiency decreases with an increase in sand concentration. For all sand sizes (10/20 mesh, 20/40 mesh, and 40/80 mesh), each curve for low sand concentration (1.0 lb/gal) lies slightly above the

corresponding curve for high sand concentration (10.0 lb/gal).

Sand Sphericity And Roundness

A description of the geometric form of a propping agent particle involves several separate but interrelated concepts. Several methods have been used to report propping agent particle shapes and geometric identities. Some require visual comparisons and some involve tedious measurements. All require considerable skill and judgement on the part of the person evaluating the propping agent. The most common propping agent particle shape parameters that are used for evaluating propping agents are sphericity and roundness.

Sphericity is a measure of how close a propping agent particle approaches the shape of a sphere. Propping agent sphericity is expressed in a three dimensional manner by comparing the volume of the propping agent particle to the volume of a circumscribing sphere around the propping agent particle. Sphericity can be determined from the following equation.[16]

$$\text{Sphericity} = \sqrt[3]{\frac{\text{Volume Of Propping Agent Particle}}{\text{Volume Of Circumscribing Sphere}}} \quad \text{..........(3)}$$

Roundness is a measure of the curvature of the propping agent particle corners and edges. Propping agent roundness is expressed in a two dimensional manner by arranging a propping agent particle so that the maximum projection area is visible. Propping agent particles are arranged with the shortest intercept approximately verticle and the longest and intermediate inserts showing from above. The propping agent particle is then photographed or traced to obtain a better image for measurement. The radius of the curvature of the propping agent particle corners and edges are then compared with the radius of the largest circle that can be inscribed in the propping agent particle image. If the propping agent particle corners and edges are sharp; their average radius is small, the roundness value approaches 0.1, and roundness is low. When the average radius of the corners and edges approaches that of the inscribed circle; the roundness value approaches 0.9, and roundness is high. Roundness can be determined from the following equation.[16]

$$\text{Roundness} = \frac{\text{Average Radius Of Corners And Edges}}{\text{Radius Of Maximum Inscribed Circle}} \quad \text{............(4)}$$

A person can be trained to estimate propping agent particle sphericity and roundness fairly accurately by simply viewing the propping agent particle and comparing the visual estimation to a set of sphericity and roundness images. Fig. 7[16] is a chart for visual estimation of sphericity and roundness of propping agent particles. Frac sand should have a sphericity of 0.6 or greater and a roundness of 0.6 or greater.[17] Intermediate and high strength proppants should have a sphericity of 0.7 or greater and a roundness of 0.7 or greater.[18]

The relationship between sand sphericity and transport efficiency is shown in Fig. 8[9] . Examination of Fig. 8 shows the following:[9]

1. Transport efficiency increases with sphericity for course particles (10/20 mesh and 20/40 mesh), but remains essentially constant for fine particles (40/80 mesh).

2. The effect of sand particle sphericity on transport efficiency was determined by comparing an angular sand having a sphericity factor of approximately 0.75 with that of Ottawa sand with a sphericity factor of approximately 0.95. The test data, plotted in Fig. 8[9], indicate that a significant increase in transport efficiency results from using the more spherical sand, but the advantage disappears as the sand size becomes smaller.

Perforation Pattern

Radial perforation orientation is somewhat inexact in everyday oil and gas completion operations; therefore, the effect of perforation pattern on transport efficiency is largely academic. It is still necessary and of interest to investigate the effect, however. The relationship of perforation patterns on transport efficiency is shown in Fig. 9[9]. The perforation patterns included in Fig. 9 are illustrated in Fig. 10 and listed below.[9]

1. Inline perforations.

2. Opposite perforations.

3. Staggered perforations.

4. Spiral perforations.

Examination of Fig. 9 shows the following:[9]

1. For all perforation patterns, transport efficiency improves with an increase in flow rate.

2. A decline in gain in transport efficiency is shown by the reduction in slope of the curves at the higher flow rates.

3. The differences in transport efficiencies of the perforation patterns are extremely close and are within the over-all accuracy of the experimental procedure; therefore, perforation pattern has virtually little or no effect on transport efficiency.

Bridging In Perforation Tunnels And Crosscut Channels

Bridging of propping agent particles in perforation tunnels and crosscut channels is as severe as bridging in perforations. Refer to Fig. 11 for a schematic of propping agent particle bridging in perforation tunnels and crosscut channels. Bridging of perforations can be over come by applying perforating techniques designed to eliminate perforation bridging. Eliminating bridging in perforating tunnels and crosscut channels can best be accomplished by selectively acidizing each perforation with 50 to 100 gal of acid using straddle packer assemblies similar to Halliburton's PPI packer. Acidizing using ball sealers for selectivity can also be used; however, the procedure is not nearly as effective as the straddle packer technique. The type and strength of the acid utilized depends on the characteristics of the formation containing the perforation tunnels and the crosscut channels.

If a screenout occurs and the wellbore is packed with proppant, the perforation tunnels and crosscut channels are also probably packed with proppant. Packing the perforation tunnels and crosscut channels with proppant will create a severe restriction and reduce the producing capacity of the well. When a screenout occurs, the well should not be repressured. This will only further crush the proppant and reduce well capacity more. The pressure should be released, and the well should be flowed back immediately. This procedure may move some of the proppant back into the wellbore and reduce the perforation tunnel and crosscut channel restriction. If the well does not respond, reperforating may be necessary before the well is restimulated and/or put on production. The reperforating process has been successfully used for several years by the writer, and the process is fairly well known to the oil and gas industry, since it has been previously reported in the literature.[19,20]

SUMMARY AND CONCLUSIONS

The experimental and theoretical works described in this paper have given some insight into propping agent particle transport from the casing into the fracture and have enabled us to derive some useful conclusions, which are as follows:

1. Transport efficiency improves with an increase in flow rate.

2. Transport efficiency increases as the sand size becomes smaller.

3. Transport efficiency decreases with an increase in sand concentration.

4. Transport efficiency increases with sphericity for course particles (10/20 mesh and 20/40 mesh), but remains essentially constant for fine particles (40/80 mesh).

5. Transport efficiency is not effected by perforation pattern alone.

6. The minimum perforation diameter required to prevent propping agent bridging varies with propping agent concentration and mesh size.

7. If the perforation diameter is two to three times the propping agent particle diameter, bridging of perforations occurs at proppant agent concentrations of approximately 0.5 to 1.0 lb/gal (0.022 to 0.043 gal sand/gal slurry).

8. If the perforation diameter is four to five times the propping agent particle diameter, bridging of perforations occurs at proppant agent concentrations of approximately 2.0 to 3.5 lb/gal (0.083 to 0.136 gal sand/gal slurry).

9. If the perforation diameter is greater than six times the diameter of the propping agent, bridging of perforations does not occur even at propping agent concentrations of 30.0 lb/gal (0.580 gal sand/gal slurry).

10. Eliminating bridging in perforation tunnels and crosscut channels can best be accomplished by selectively acidizing each perforation with 50 to 100 gal of acid using straddle packer assemblies. Acidizing using ball sealers for selectivity can also be used; however, the procedure is not nearly as effective as the straddle packer technique. The type and strength of the acid utilized depends on the characteristics of the formation containing the perforation tunnels and the crosscut channels.

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Table I

Minimum Perforation Diameter Required to Prevent Sand Bridging

Sand Conc. (Lb/Gal)	Diameter Ratio (Dim.)	Minimum Perforation Diameter (In.)							
		6/12 Mesh**	8/16 Mesh**	12/20 Mesh*	16/30 Mesh**	20/40 Mesh*	30/50 Mesh**	40/70 Mesh*	70/140 Mesh**
0.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.5	2.25	0.30	0.21	0.15	0.11	0.07	0.05	0.04	0.02
1.0	2.90	0.38	0.27	0.19	0.14	0.10	0.07	0.05	0.02
2.0	3.85	0.51	0.36	0.25	0.18	0.13	0.09	0.06	0.03
3.0	4.65	0.61	0.44	0.31	0.22	0.15	0.11	0.08	0.04
4.0	5.20	0.69	0.49	0.34	0.24	0.17	0.12	0.09	0.04
5.0	5.45	0.72	0.51	0.36	0.26	0.18	0.13	0.09	0.05
6.0	5.65	0.75	0.53	0.37	0.26	0.19	0.13	0.09	0.05
7.0	5.75	0.76	0.54	0.38	0.27	0.19	0.13	0.09	0.05
8.0	5.85	0.77	0.55	0.39	0.27	0.19	0.14	0.10	0.05
9.0	5.90	0.78	0.55	0.39	0.28	0.20	0.14	0.10	0.05
10.0	5.95	0.79	0.56	0.39	0.28	0.20	0.14	0.10	0.05
30.0	6.00	0.79	0.56	0.40	0.28	0.20	0.14	0.10	0.05

* - API Primary Mesh Designation For Sand
** - API Alternate Mesh Designation For Sand

$$\text{Diameter Ratio} = \frac{\text{Perforation Diameter}}{\text{Sand Grain Diameter}}$$

6/12 Mesh - Maximum Sand Grain Diameter = 0.1320 In.
8/16 Mesh - Maximum Sand Grain Diameter = 0.0937 In.
12/20 Mesh - Maximum Sand Grain Diameter = 0.0661 In.
16/30 Mesh - Maximum Sand Grain Diameter = 0.0469 In.
20/40 Mesh - Maximum Sand Grain Diameter = 0.0331 In.
30/50 Mesh - Maximum Sand Grain Diameter = 0.0232 In.
40/70 Mesh - Maximum Sand Grain Diameter = 0.0165 In.
70/140 Mesh - Maximum Sand Grain Diameter = 0.0083 In.

Table II
Minimum Perforation Diameter Required to Prevent Propping Agent Bridging

Propping Agent Mesh Size (Dim.)	Maximum Propping Agent Particle Diameter (In.)	Diameter Ratio (Dim.)	Minimum Perforation Diameter (In.)
4/8	0.1870	6.00	1.12
6/12(2)	0.1320	6.00	0.79
8/12	0.0937	6.00	0.56
8/16(2)	0.0937	6.00	0.56
10/20	0.0787	6.00	0.47
10/30	0.0787	6.00	0.47
12/20(1,3)	0.0661	6.00	0.40
16/20(3)	0.0469	6.00	0.28
16/30(2)	0.0469	6.00	0.28
18/35	0.0394	6.00	0.24
20/40(1,3)	0.0331	6.00	0.20
30/50(2)	0.0232	6.00	0.14
30/60	0.0232	6.00	0.14
40/60	0.0165	6.00	0.10
40/70(1,3)	0.0165	6.00	0.10
70/140(2)	0.0083	6.00	0.05

(1) - API Primary Mesh Designation For Sand.
(2) - API Alternate Mesh Designation For Sand.
(3) - API Primary Mesh Designation For Intermediate And High Strength Proppants.

Table III
Sieves of the U.S. Standard Screen Scale

Mesh Designation (Dim.)	Sieve Opening (In.)
2½	0.3150
3	0.2650
3½	0.2230
4	0.1870
5	0.1570
6	0.1320
7	0.1110
8	0.0937
10	0.0787
12	0.0661
14	0.0555
16	0.0469
18	0.0394
20	0.0331
25	0.0280
30	0.0232
35	0.0197
40	0.0165
45	0.0138
50	0.0117
60	0.0098
70	0.0083
80	0.0070
100	0.0059
120	0.0049
140	0.0041
170	0.0035
200	0.0029
230	0.0024
270	0.0021
325	0.0017
400	0.0015

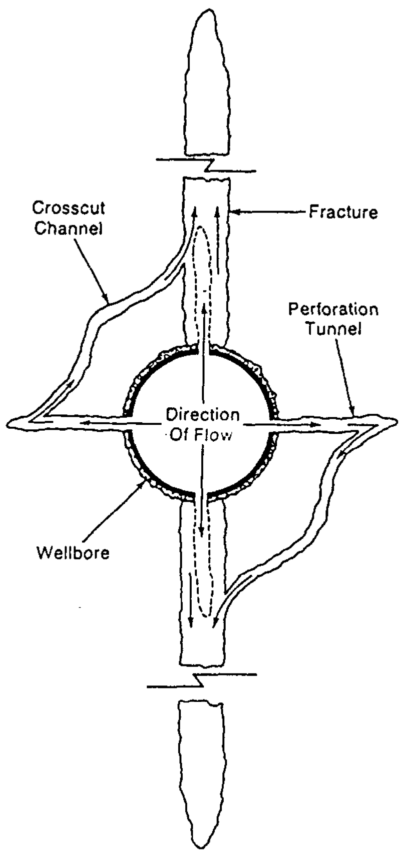

Figure 1 - Schematic of propping agent particle transport from the casing into the fracture

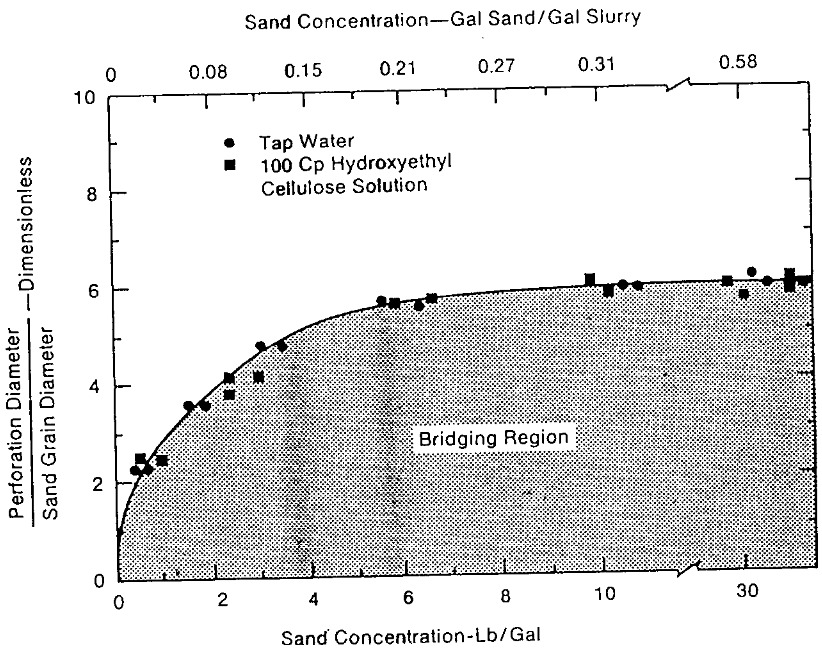

Figure 2 - Bridging of sand grains in perforations

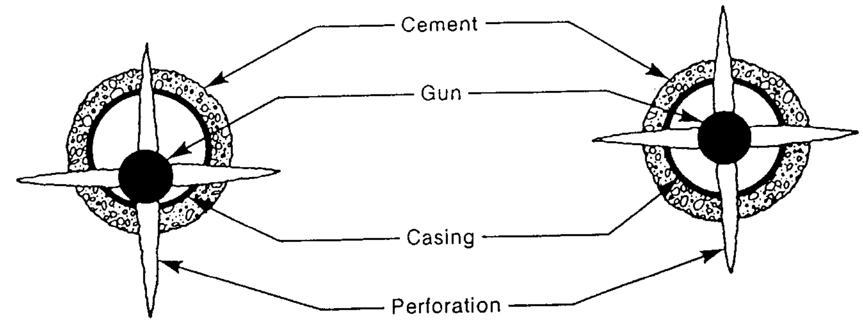

Figure 3 - Effect of perforating gun positioning in the wellbore on perforation hole size and penetration

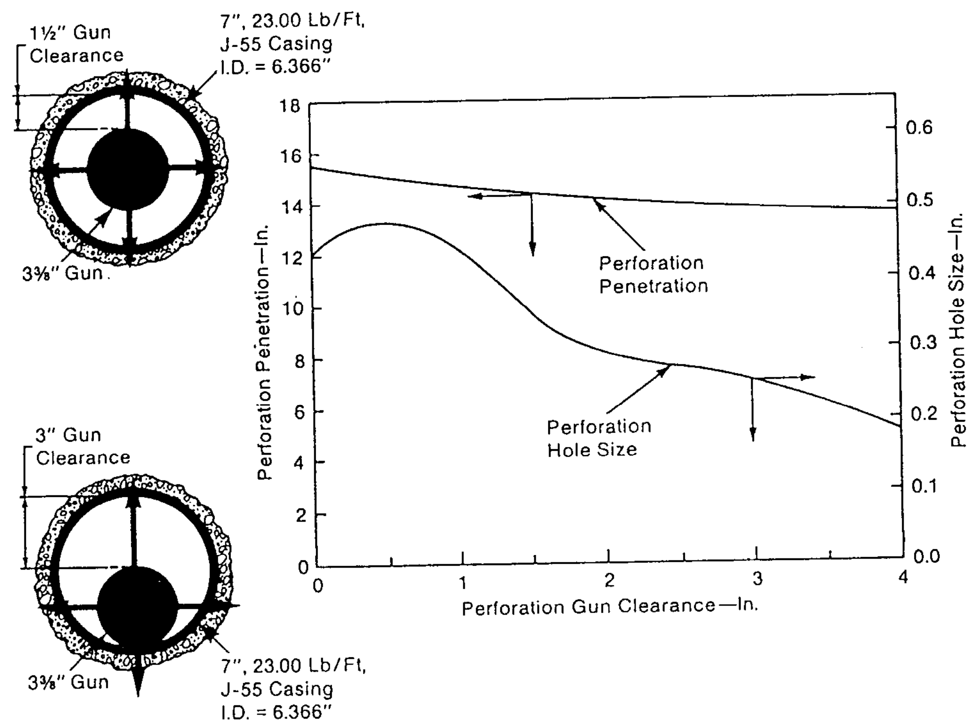

Figure 4 - Effect of perforation gun clearance on perforation hole size and penetration

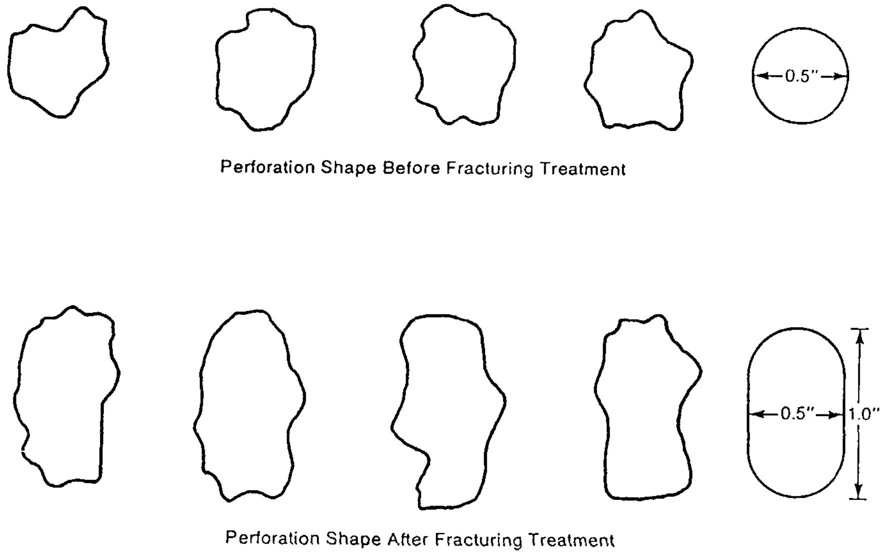

Figure 5 - Effect of frac sand erosion on perforating shape

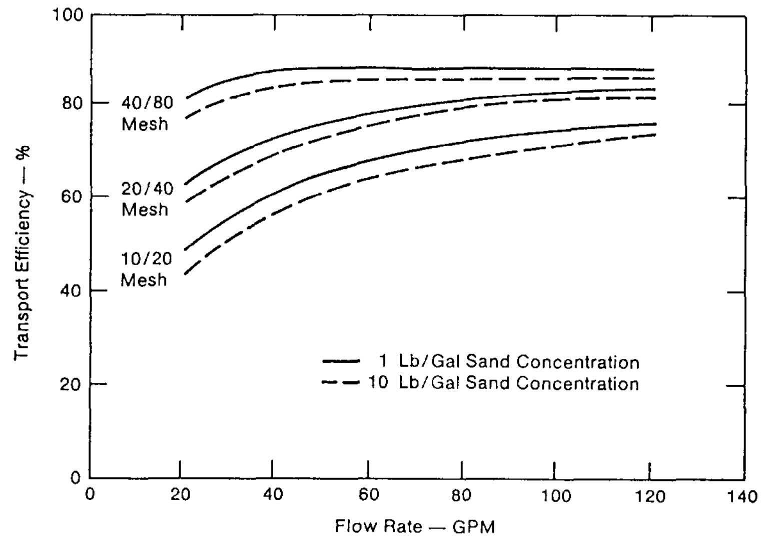

Figure 6 - Effect of flow rate, sand size, and sand concentration on transport efficiency

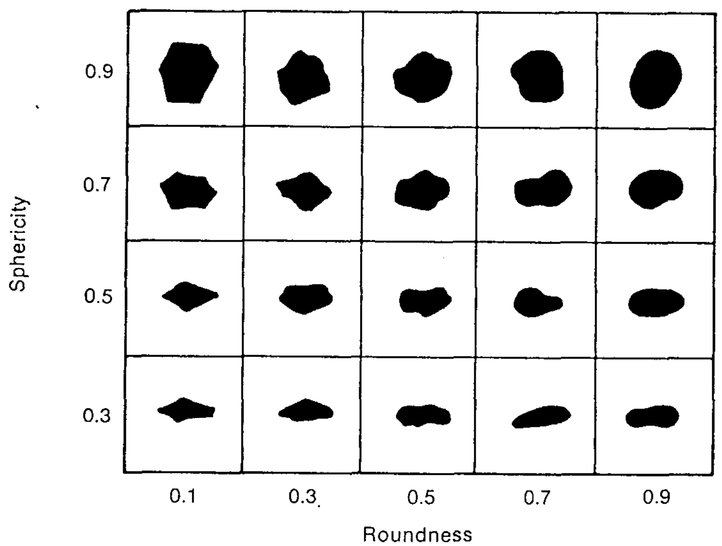

Figure 7 - Chart for visual estimation of sphericity and roundness

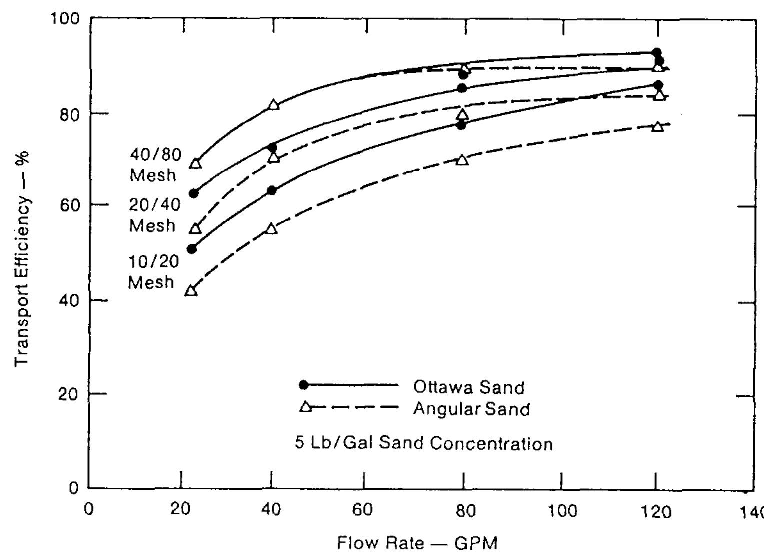

Figure 8 - Effect of sand sphericity on transport efficiency

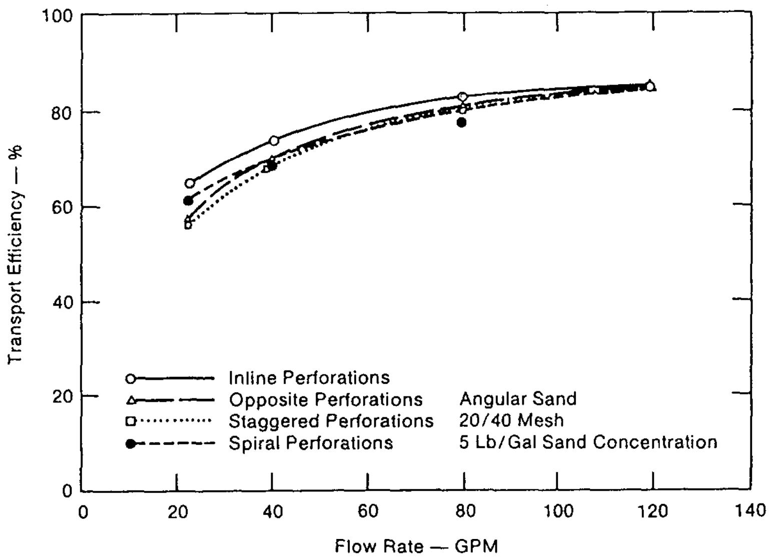

Figure 9 - Effect of perforation patterns on transport efficiency

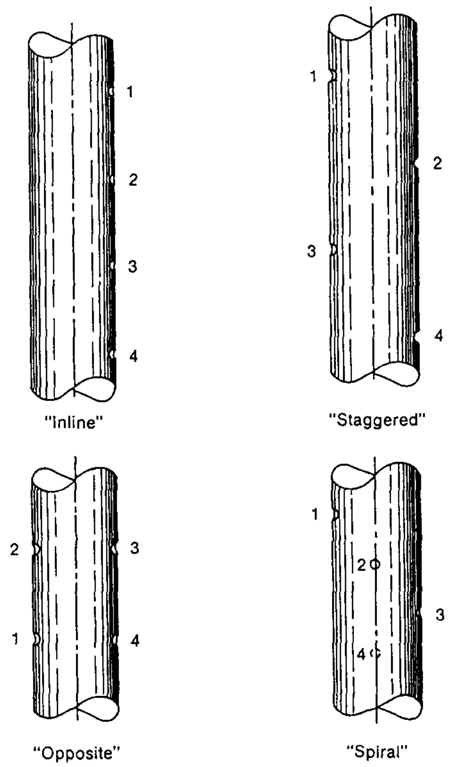

Figure 10 - Perforation patterns

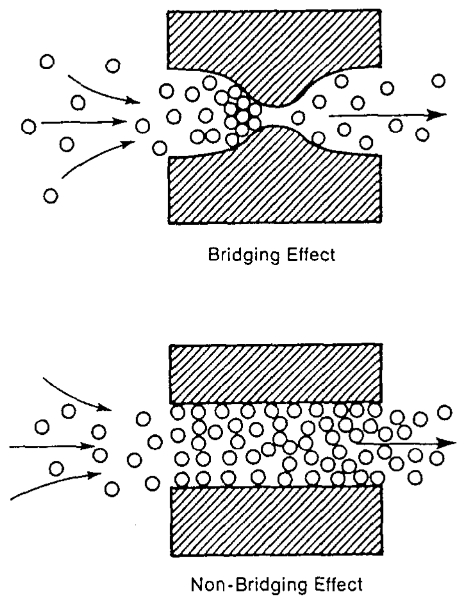

Figure 11 - Schematic of propping agent particle bridging in perforation tunnels and crosscut channels