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(54) Title: ELONGATED PARTICLES FOR FRACTURING AND GRAVEL PACKING

(57) Abstract: A method for hydraulic fracturing or gravel packing is given in which at least a portion of the proppant or gravel is replaced with stiff, low-elasticity, low-deformability elongated particles. A pack of suitable elongated particles may have a greater permeability, and provide better sand control, than a pack of conventional spherical proppant. The size, shape, and stiffness of suitable particles are defined and specified. The size, shape, density, concentration, and stiffness of the elongated particles may vary during the treatment. The elongated particles may be resin coated. The elongated particles may be used to place a barrier to fracture growth in hydraulic fracturing.



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## **ELONGATED PARTICLES FOR FRACTURING AND GRAVEL PACKING**

### **Background of the Invention**

The Invention relates to the use of non-spherical proppants in hydraulic fracturing and sand control to improve proppant or gravel pack performance. More particularly it relates to at least partially using elongated proppants made of stiff, low-elasticity, low-deformability materials that increase proppant or gravel pack conductivity (or permeability) and decrease proppant or gravel flowback and sanding.

Hydraulic fracturing, gravel packing, or fracturing and gravel packing in one operation, are used extensively to stimulate the production of hydrocarbons, water and other fluids from subterranean formations. These operations involve pumping a slurry of "proppant" in hydraulic fracturing (natural or synthetic materials that prop open a fracture after it is created) or "gravel" in gravel packing. Conventional proppant or gravel is substantially spherical. In high permeability formations, the goal of a hydraulic fracturing treatment is typically to create a short, wide, highly conductive fracture, in order to bypass near-wellbore damage done in drilling and/or completion, to ensure good communication between the rock and the wellbore and to increase the surface area available for fluids to flow into the wellbore. Gravel is also a natural or synthetic material, which may be identical to, or different from, proppant. Gravel packing is used for "sand" control. "Sand" in this context is the name given to any particulate material from the formation that could be carried into production equipment, and should not be confused with larger sand particles that may be introduced as proppant. Gravel packing is a sand-control method used to prevent production of formation sand, in which, for example, a steel screen is placed in the wellbore and the surrounding annulus is packed with prepared gravel of a specific size designed to prevent the passage of formation sand that could foul subterranean or surface equipment and reduce flows. The primary objective of gravel packing is to stabilize the formation while causing minimal impairment to well productivity. Sometimes gravel packing is done without a screen. High permeability formations are frequently poorly consolidated, so that sand control is needed. Therefore, hydraulic fracturing treatments in which short, wide fractures are wanted are often combined in a single continuous operation

("frac and pack", "frac-pack", "frac-n-pack", stimpack, etc.) with gravel packing. For simplicity, in the following we may refer to any one of hydraulic fracturing, fracturing and gravel packing in one operation (frac and pack), or gravel packing, and mean them all; we will usually use the term fracturing.

Hydrocarbons (oil, natural gas, etc.) are obtained from a subterranean geologic formation (i.e., a "reservoir") by drilling a well that penetrates the hydrocarbon-bearing formation. This provides a partial flow path for the hydrocarbons to reach the surface. In order for the hydrocarbons to be "produced," that is to travel from the formation to the wellbore (and ultimately to the surface), there must be a sufficiently unimpeded flow path from the formation to the wellbore.

Hydraulic fracturing is a primary tool for improving well productivity by placing or extending channels from the wellbore to the reservoir. This operation is essentially performed by hydraulically injecting a fracturing fluid into a wellbore penetrating a subterranean formation and forcing the fracturing fluid against the formation strata by pressure. The formation strata or rock is forced to crack and fracture. Proppant is placed in the fracture to prevent the fracture from closing after the pressure is released, and thus to provide improved flow of the recoverable fluid, i.e., oil, gas or water.

The success of a hydraulic fracturing treatment is related to the fracture conductivity. Conductivity is a function of proppant pack permeability, the properties of the flowing fluid, and the dimensions; in this discussion, when we refer to either conductivity or permeability, we intend the term to encompass both. Numerous methods have been developed to improve the fracture conductivity by, for example, using high strength proppants (if the proppant strength is not high enough, the closure stress crushes the proppant, creating smaller particles and reducing the conductivity), large diameter proppants (permeability of a propped fracture increases as the square of the grain diameter), and high proppant concentrations in the proppant pack to obtain wider propped fractures. In addition, conductivity may be enhanced by the use of materials such as breakers, additives that help to prevent flow back, and use of non-damaging fracturing fluids such as gelled oils, viscoelastic surfactant based fluids, foamed fluids and emulsified fluids. It is also recognized that grain size, grain-size distribution, quantity of smaller particles and impurities, roundness and sphericity, and proppant density all may have an impact on fracture conductivity. It is generally understood that angular grains fail at lower

closure stresses, producing smaller particles and thus reducing fracture conductivity. On the other hand, round and uniform-sized grains result in higher loads before failure since stresses are more evenly distributed. Sand is typically suitable for closure stresses of less than about 6000 psi (41 MPa), resin-coated sand may be used up to about 8000 psi (55 MPa). Intermediate-strength proppant typically consists of fused ceramic or sintered-bauxite and is used for closure stresses ranging between 5000 psi and 10000 psi (34 MPa to 69 MPa). High-strength proppant, consisting of sintered-bauxite with large amounts of corundum is used at closure stresses of up to about 14000 psi (96 MPa). Permeability of a propped fracture increases as the square of the grain diameter. However, larger grains are often more susceptible to crushing, have more placement problems, and tend to be more easily invaded by smaller particles. As a result, the average conductivity over the life of a well may actually be higher with smaller proppants.

In an effort to limit the flowback of particulate materials (proppant and/or small particles) coming from the formation or from broken or crushed proppant) during fluid production, proppant-retention agents are commonly used so that the proppant remains in the fracture. For instance, the proppant may be coated with a curable resin, a pre-cured resin, or a combination of curable and pre-cured (sold as partially cured) resin, that is activated under downhole conditions. Different materials such as fibrous materials, fibrous bundles or deformable materials have also been mixed with conventional (spherical) proppant to hold the proppant in place and to limit the production of small particles.

Sand, resin-coated sand, ceramic particles (called synthetic proppant) and resin-coated ceramic particles are the most commonly used proppants, although the literature also mentions the use of many other materials, such as walnut hull fragments, optionally coated with bonding additives, metallic shots, or metal-coated beads that are nearly spherical but have passageways to improve their conductivity.

Many materials have been included in proppant packs. U.S. Patent No. 5,330,005 disclosed adding fibers made for example of glass, ceramic, carbon, natural or synthetic polymers or metal. They have a length of up to about 30 mm and a diameter of between 6 and 100 microns. According to U.S. Patent No. 5,908,073 flowback is prevented through the use of fibrous bundles, made of from about 5 to about 200 individual fibers having lengths in the range of about 0.8 to about 2.5 mm and diameters in the range of about 10 to about 1000 microns. U. S. Patent No. 6,059,034 disclosed blending proppant material with

a deformable particulate material such as polystyrene divinylbenzene beads. They define deformable materials as having a Young's modulus between about 0.00345 and about 13.8 GPa. The deformable particles may have different shapes such as oval, cubic, bar-shaped, cylindrical, multi-faceted, irregular, and tapered, but they preferably have a maximum length-based aspect ratio equal to or less than 5, and are typically spherical plastic beads or composite particles comprising a non-deformable core and a deformable coating. U.S. Patent No. 6,330,916 also describes the use of deformable materials having a maximum length-based aspect ratio of equal to or less than about 25 and a Young's modulus of between about 500 psi (about 0.0034 GPa) and about 2,000,000 psi (about 13.79 GPa) under formation conditions. U. S. Patent No. 6,725,930 describes the use of metallic wires having an aspect ratio of greater than 5 and making use of the properties of the metals.

There is still much room for improvement in increasing proppant pack conductivity and preventing proppant and smaller particles migration. It is an object of the present Invention to provide a new type of proppant and improved methods of propping a fracture, or a part of a fracture.

### **Summary of the Invention**

A method is disclosed of fracturing a subterranean formation involving injecting, into the formation above formation pressure, a slurry of proppant containing from 1 to 100 percent of stiff, low-elasticity, low-deformability elongated particles. The percentage of the elongated particles may be changed during the injection. The method may further include injecting a stage or stages in which the slurry contains no stiff, low-elasticity, low-deformability elongated particles. The method may also involve placing a barrier to fracture growth, the barrier made from particles including from 1 to 100 percent of stiff, low-elasticity, low-deformability elongated particles.

A method is also disclosed for gravel packing a well penetrating a subterranean formation, involving injecting, into the well, a slurry of gravel containing from 1 to 100 percent of stiff, low-elasticity, low-deformability elongated particles.

In any of these methods at least a portion of the elongated particles may be resin coated, and/or at least a portion of the proppant particles that are not elongated particles may be resin coated. In any of these methods, the slurry may include additional particles

selected from fibers having an aspect ratio greater than 25, fibrous bundles, solid acid precursors, solid degradable materials, fluid loss additives, and mixtures of these materials.

Suitable elongated particles have a maximal cross-sectional dimension,  $h_1$ , and a minimal cross-sectional dimension,  $h_2$ , of from 0.1 to 10 mm; a length,  $L$ , of from 0.1 to 20 mm; for 1D particles, a ratio  $L/h_1$  from 1.2 to 10 and a ratio  $h_2/h_1$  from 0.8 to 1; for 2D particles, a ratio  $L/h_1$  from 1 to 1.19 and a ratio  $h_2/h_1$  from 0.1 to 0.79; a curvature,  $\chi$ , of from 0 to  $2/h_2$  in units of  $1/\text{mm}$ ; for 1D particles, a stiffness,  $k$ , of from 0 to  $4.90 \cdot 10^8$  in units of  $\text{N} \cdot \text{mm}^2$ ; and for cylindrical particles, a stiffness,  $k$ , of from 0 to  $10^8$  ( $\text{N} \cdot \text{mm}$ ); a range of a particle unevenness  $d_0$  (or  $d_1$ ) is from 0 to  $0.5 \cdot h_1$  in units of mm.

The elongated particles may be a mixture of elongated particles differing from one another in at least one parameter selected from length, a cross-sectional dimension, density, curvature, and stiffness.

### **Brief Description of the Drawings**

**Figure 1** shows the wall effect introduced by elongated particles of the Invention.

**Figure 2** shows permeability as a function of closure stress for packs containing elongated rods of the invention compared to a pack containing a conventional proppant.

**Figure 3** shows the beta factor as a function of closure stress for packs containing elongated rods of the invention compared to a pack containing a conventional proppant.

**Figure 4** shows permeability as a function of closure stress for packs containing elongated rods of the invention compared to a pack containing a conventional proppant

**Figure 5** shows permeability as a function of closure stress for packs containing elongated rods of the invention mixed with a conventional proppant compared to a pack containing only the conventional proppant.

**Figure 6** shows the beta factor as a function of closure stress for packs containing elongated rods of the invention mixed with a conventional proppant compared to a pack containing only the conventional proppant.

**Figure 7** shows permeability as a function of closure stress for a pack containing elongated stainless steel rods mixed with sand compared to a pack containing only the sand.

**Figure 8** shows the beta factor as a function of closure stress for a pack containing elongated rods mixed with sand compared to a pack containing only the sand.

**Figure 9** shows permeability as a function of closure stress for a pack containing elongated rods of the invention mixed with a conventional proppant compared to a pack containing only the conventional proppant.

### **Detailed Description of the Invention**

The Invention will be described in terms of treatment of vertical wells, but is equally applicable to wells of any orientation. The Invention will be described for hydrocarbon production wells, but it is to be understood that the Invention may be used for wells for production or injection of other fluids, such as water or carbon dioxide or, for example, for injection or storage wells. It should also be understood that throughout this specification, when a concentration or amount or other parameter range is described as being useful, or suitable, or the like, it is intended that any and every concentration or amount or other parameter within the range, including the end points, is to be considered as having been stated. Furthermore, each numerical value should be read once as modified by the term "about" (unless already expressly so modified) and then read again as not to be so modified unless otherwise stated in context. For example, "a range of from 1 to 10" is to be read as indicating each and every possible number along the continuum between about 1 and about 10. In other words, when a certain range is expressed, even if only a few specific data points are explicitly identified or referred to within the range, or even when no data points are referred to within the range, it is to be understood that the inventors appreciate and understand that any and all data points within the range are to be considered to have been specified, and that the inventors have possession of the entire range and all points within the range.

Although some of the following discussion emphasizes fracturing, the elongated particles and methods of the Invention may be used in fracturing, gravel packing, and combined fracturing and gravel packing in a single operation. We have found that important proppant pack properties, such as increased conductivity, decreased beta factor, and minimal flowback, and minimal sand production, may be improved by at least partial use of elongated, non-deformable, stiff particles as proppant in hydraulic fracturing. In addition, the special properties of packs made from the elongated particles of the Invention

are particularly suitable for sand control methods such as for gravel pack, stimpack, frac&pack treatments, and the like. The main aims of sand control techniques are (1) prevention of sand production from the reservoir, (2) providing high conductivity for high production rates, and (3) bypassing near well bore damage.

Any proppant (gravel) may be used with the materials (the elongated particles) and methods of the Invention. Such proppants (gravels) may be natural or synthetic, coated (for example by resin), or contain chemicals; more than one may be used sequentially or in mixtures of different sizes or different materials. By proppant we mean any particulate material selected for a particular purpose such as propping a fracture to keep it open or gravel packing a completion to prevent or minimize production of formation particles. Proppants and gravels in the same or different wells or treatments may be the same material and/or the same size as one another. Such materials are usually called proppants when they are placed in fractures and gravel when they are placed in perforations and wellbores, but the term "proppant" is intended to include gravel in this discussion. In general the proppant used will have an average particle size of from about 100 U. S. mesh (0.149 mm) to about 10 U. S. mesh (2mm), more particularly, but not limited to 40/60 (420 $\mu$ m/250 $\mu$ m), 20/40 (841 $\mu$ m/420 $\mu$ m), 16/30 (1.19mm/595 $\mu$ m), 12/18 (1.68mm/1.00mm), 10/14 (2.00mm/1.41mm) and 8/12 (2.38mm/1.68mm) sized materials. Normally the proppant will be present in the slurry in a concentration of from about 1 PPA (119.826 kgPA) to about 25 PPA (2995.65 kgPA), preferably from about 1 PPA (119.826 kgPA) to about 16 PPA (1917.22 kgPA).

An important parameter for suitable materials for elongated proppants of the Invention is a suitable material deformability, the ability of a material to deform without breaking (failure) under the action of load. Material deformability may be measured as the degree of deformation in a large number of tests, for example tension, compression, torsion, bending etc. Preferably, the loading force is applied in such a way that uniform deformation is sustained, and the direction of the applied force does not change during the entire process of loading (the geometrically linear case). The qualitative behavior of materials in such tests is usually similar, as shown on the Fig. 10, where E. - Young's Modulus. At lower stresses ( $\sigma$ ) the behavior is elastic up to a certain value of the stress, which is called the elastic limit. Above that limit, the behavior is plastic. Plastic

deformations do not restore after the loading is off. During the plastic deformation, materials may reach their failure limits ( $\epsilon_0$ ,  $\epsilon_1$ ,  $\epsilon_2$ ) and break.

Most solid materials may be divided roughly into two major categories: brittle and plastic. Brittle materials have a relatively small range of plastic deformation; that is they fail quickly after the elastic limit has been exceeded. Examples of, brittle materials are ceramics, mica, marble, slate etc. The maximal degree of deformation for a certain material before failure is dependent upon the values of certain parameters describing the conditions and the loading process, such as the temperature and the rate of deformation. In other words, the plasticity is a state of the material; under certain conditions the material may be considered brittle, while under other conditions the material may be considered plastic. On the other hand, the Young's Modulus is a more universal characteristic of a material, and depends less on the external conditions (except temperature) or the loading process. Given this restriction, it is possible to characterize materials using their Young's this means that material deformability (the degree of deformation) may be assessed accurately only in the elastic range.

The particle deformability is not the same as the deformability of the material. The particle deformability depends upon the properties of the material and on the shape and size of the particle. Consider the following diagram on the Fig. 11: the degree of deformation  $\epsilon$ , and the displacement,  $\delta$ , are not equivalent in the two cases.

We have found in our experiments, that the shapes of particles have a large effect on the conductivity of a pack of such particles. In other words, the size (aspect ratio (AR), mesh size), and Young's Modulus,  $E$ , alone are not sufficient to determine the permeability of a pack of particles. Moreover, the overall size of a particle (AR and mesh) and its Young's Modulus do not characterize the ability of a particle to deform (bend); particles of different shapes will bend differently even if they are the same overall size and made of the same material.

Consider two simple cases: the straight rod and the slightly curved rod shown above. They may have equal overall sizes and may be made of the same material. Suppose that the particles are loaded by some bending moment,  $M$ , equally distributed along the "lengths" of the particles. From material mechanics it is known that additional curvature, due to bending (elastic behavior), may be described by the following,

$$\Delta\chi_{straight} = \frac{1}{\rho} = \frac{M}{E \cdot I} \text{ - for straight particle;}$$

$$\Delta\chi_{curved} = \frac{1}{\rho} - \frac{1}{\rho_0} = \frac{M}{E \cdot I} \text{ - for slightly curved particle.}$$

in which  $\rho$  is the radius of curvature and  $I$  is the second moment of area. The second moment of area about the x-x (y-y) axis is usually defined as an integral:

$$I_{x-x} = \int_A y^2 dA \quad (\text{or } I_{y-y} = \int_A x^2 dA).$$

Another name for the last integral is the principal moment of inertia as shown on the Fig. 12, where A is the area of a cross section, and CG is the center of gravity of the cross section. Which formula should be used in calculations depends upon the specifics of the analysis, as will be known by those skilled in material mechanics.

If the particle is significantly curved, then additional curvature may be assessed using other more complicated formulas. As will be shown below, the straight “axis” of particles has the greater influence on conductivity. Moreover, a particle should be stiff enough (non-deformable) to keep the shape under the action of some bending load and provide better conductivity. In other words, the shape of a particle is one of the main characteristics. The shape can be described by the curvature of the particle. The formulas above show that additional curvature depends upon such parameters as  $E \cdot I$ , which is called the stiffness of the straight (or slightly curved) beam at a given point on the beam axis. (This issue will be discussed in greater detail below.) Thus, a very important property of the elongated proppant particles of the Invention is the curvature. The curvature of the elongated proppant particles may be measured in different ways.

To define the curvature properly, particles are classified as follows (the descriptions are for shapes and materials having a continuous structure inside, that is structures without any pores or cavities, although particles having internal structure are within the scope of the Invention, and their shapes may be approximated by the following descriptions):

A ball is the simplest particle; it is bounded by a spherical surface.

A volume is the logical extension of a ball and the difference is in the shape of the boundary surface. The surface of a volume may be approximated by a spherical surface

with some accuracy. If the maximal deviation from a spherical surface does not exceed some value,  $d_0$ , then the particle may be treated as volumes.

A rod is the elongated particle formed by a cylindrical (or prismatic) surface and arbitrarily shaped ends (see the Fig. 13). Any rod may be decomposed into three parts: a central straight part and two ends. The important geometrical feature that characterizes the rod particle is the core. The core (or main core) is the element of a rod particle, which can be treated as a rod particle with convex cross section, and this element may be put into the arbitrary rod in a specific manner. The closed convex cylindrical surface (with elliptical cross section) which bounds the core may be considered as the core boundary, that is the largest surface of all the possible closed convex cylindrical surfaces (with elliptical cross section) that can be put into the rod without intersection with the particle surface; the area,  $A$ , of the elliptical cross section should be maximal. The length of the core is equal to the length of the straight part of the rod. Another important parameter is the maximal distance,  $d_0$ , between the core surface and the minimal overall surface. The maximal extension of the ends,  $d_1$ , may be greater than the maximal size,  $h_1$ , of the rod cross section in the straight part, but, preferably, it is not. If  $d_1 > h_2$  ( $h_2$  is the minimal size of the rod cross section), then the particle is considered complex, consisting of several elementary particles (secondary cores). The length,  $L$ , of the straight part should be equal to or greater than the maximal overall size,  $h_1$ , of a cross section, which is normal to the generatrix. A ratio of  $h_2/h_1$  of from 0.8 to 1 may be used to define particles with elongated cross section as rods, otherwise the particles may be considered as discs or plates. A rod may be considered as a particular case of a beam; moreover, a rod may be obtained as some volume swept out by a generatrix that is a straight line.

A cone is the logical extension of a rod and the only difference is in the boundary surface ( Fig. 14 ). The boundary surface is in the form of a cone; moreover, the core is in the form of a convex conical surface. As usual, the cone particle may have arbitrarily shaped ends, and all the observations elsewhere here about secondary cores apply.

A beam is a logical extension of a rod and the difference is in the definition of the boundary surface ( Fig. 15 ). In a general sense, the beam is an elementary particle, which can not be treated as can other 1D ("one dimensional") elementary particles (rods or cones). The surface of a beam may be represented (with some accuracy) as the sum of miscellaneous cylindrical and conical surfaces. Therefore, it is possible to define the

cylindrical core of the beam and the overall convex cylindrical (prismatic) surface with minimal area. There are some cases in which the core of beam can not be defined, so in such cases this particle can not be treated as an elementary elongated particle. The center of gravity (CG) of a beam particle should be in the core, otherwise the particle should be considered as complex.

A disc is a particle, which can be obtained from plane-parallel motion (or continuous sweeping parallel to some fixed plane) of some elementary rod particle ( Fig. 16 ). One of the overall dimensions of a disc is usually less or even much less than the other two dimensions.  $d_1$  is the maximal distance between the approximating ellipse and the real in-plane contour of a disc. If  $d_1$  exceeds some value, then the particle may be treated as complex, consisting of elementary particles with secondary cores. The simplest disc is an ellipse with some semi-axes  $L/2$  and  $h/2$ . The ratio  $L/h$  is specified for the disc core.

A plate is the logical extension of the disc and the beam; the difference is in the definition of the boundary surface. All definitions for plates may be done by analogy with beams. Again, observations elsewhere here about “secondary cores” should be taken into account for discs and plates.

Other particles, which can not be covered by the descriptions presented, may be treated as complex 3D particles ( Fig. 17 ).

With these definitions, it is possible to specify suitable elongated particles of the Invention. All particles may be treated as elementary particles or as sum of elementary particles. In principle, any particle may be represented as a set of balls with miscellaneous diameters, but it is not sufficient to describe the geometrical or mechanical properties of the balls, which compose some complex particles, and additional definitions are required. Particles may be categorized as “one dimensional” (1D), “two dimensional” (2D), or “three dimensional” (3D).

1D particles are:

- elementary shapes like beams, rods or cones.
- particles that can be obtained from elementary 1D shapes (beams, rods) by curving or twisting. These particles may be defined as complex 1D particles. Examples are: arc, spring, torus, screw auger, etc.

2D particles are:

- elementary shapes like discs or plates with miscellaneous boundaries.
- particles that can be obtained from elementary 2D shapes (plates, discs, etc) by curving.

3D particles are:

- all particles that can not be treated as 1D or 2D. Generally, they are complex particles with an absence of any “main” or “secondary” cores.

The gravity axis is easily introduced for an elementary 1D particle. Decompose the core of an elementary particle along its maximal length into small sections. Then the axis of gravity may be approximately described by a straight line that joins the centers of gravity (CG) of these sections. The surface of gravity may be introduced for elementary 2D particles in the following manner. The elliptical in-plane core of an elementary 2D particle is decomposed into small prismatic bodies. The surface of gravity is defined as a surface that contains the centers of gravity of all the small prismatic bodies. When the particle is curved, the curvature of the whole particle may be described by the curvature of its gravity axis (1D) or gravity surface (2D). By superimposing the centers of gravity, one may analyze and describe the displacement of the gravity axis (1D) or gravity surface (2D).

The procedure for calculation of the curvature of a complex 1D particle is as follows. (For simplicity, consider the plain curved 1D particle shown on the Fig.18.)

- 1) Define the CG curve of the particle;
- 2) Find the CG of each segment (elementary 1D particle);
- 3) Construct the perpendiculars at each CG as shown;
- 4) Define the intersection points for the perpendiculars;
- 5) Calculate an average radius of curvature for a single-curved particle or several radii of curvature for a multi-curved particle;
- 6) Calculate the set of curvatures of a set of particles.

The curvature may be assessed using the simple formula:

$$\chi = \frac{1}{\rho} = |\bar{r}''(l)|,$$

in which  $\rho$  is the average radius of curvature at each point of the gravity axis or the gravity surface. For 2D particles, the curvature may be assessed using the same formula, but to avoid any misunderstanding, the magnitude of maximal principal curvature should be assessed at a point  $P$  of double-curved surfaces ( Fig. 19 ).

It is difficult to assess the final curvature of a particle in the wellbore after placement. Therefore, only particles that maintain their shape (their curvature) after loading (stiff particles) can be known to satisfy the goals of the Invention, for example, to provide a suitable flow path (trajectory) fluids. Therefore, the stiffness (known in material mechanics) of the particle should be assessed. The inverse of stiffness is the flexibility. In other words, the flexibility is the unit deformability. Flexibility is the value of displacement under the action of a unit load applied at the point at which the displacement is measured. Bending flexibility is particularly important, but it is obvious that flexibility may be assessed for tension, compression, torsion, etc. The general formula for flexibility is:

$$f = \frac{1}{k}$$

in which  $k$  is the stiffness.

The stiffness at a given point of a 1D particle may be defined according to the formula:

$$k = E \cdot I .$$

For 2D particles, the cylindrical stiffness is widely used. There are several formulas for cylindrical stiffness. One of the formulas for the cylindrical stiffness is presented below:

$$D = \frac{E \cdot h^3}{12 \cdot (1 - \nu^2)},$$

In which  $h$  is the thickness of a disc and  $\nu$  is the Poisson ratio. Using this stiffness definitions it is possible to assess the deformability (or displacement) of particle points under the action of a given load. The flexibility in bending may be treated as the curvature that the particle attains under the action of a unit bending moment. This definition is the

physical meaning of the flexibility, and is sufficient to define the ranges for curvature of the particle in the wellbore. This curvature may be analytically assessed only for the elastic state of a particle material and for simple initial shapes of the particles. However, such particles are the most useful in creating better conductivity.

For a description of particles suitable for the Invention, it is sufficient to describe the final curvature of a particle by describing its initial shape and stiffness, assuming that its material is in the elastic state. The values that must be specified for elementary 1D and 2D particles are  $d_0$ ,  $d_1$ ,  $h_1$ ,  $h_2$ ,  $L$ ,  $\chi$ ,  $k$ , and  $D$ .

Suitable ranges for the values of these parameters are as follows: The range for  $h_1$  (and  $h_2$ ) is from 0.1 to 10 mm; the range for  $L$  is 0.1 to 20 mm. For 1D particles, the ratio  $L/h_1$  is from 1.2 to 10 and the ratio  $h_2/h_1$  is from 0.8 to 1. For 2D particles, the ratio  $L/h_1$  is from 1 to 1.19 and the ratio  $h_2/h_1$  is from 0.1 to 0.79. For the curvature, the range of  $\chi$  is from 0 to  $2/(h_{2\min})$  in units of  $1/\text{mm}$ . The range of  $d_0$  (or  $d_1$ ) is from 0 to  $0.5 \cdot h_{1\max}$ . The 1D stiffness range is from 0 to  $4.90 \cdot 10^8$  in units of  $\text{N} \cdot \text{mm}^2$ . The cylindrical stiffness range is from 0 to  $10^8$  (in units of  $\text{N} \cdot \text{mm}$ ).

An important effect of using the elongated particles of the Invention is a porosity increase. It is a well-known fact in chemical engineering that in the near wall region of a reactor having a packed bed of spherical particles a wall region having higher conductivity is observed. This region extends into the packed bed about 2-3 particle diameters. Due to this effect, the velocity profile of fluids flowing through the bed is non-uniform and there is a higher flow velocity near the reactor wall. Not to be limited by theory, but it is believed that the present Invention takes advantage of this "wall effect" to improve the permeability and conductivity of proppant, sand, and/or gravel packs by adding non-deformable, elongated (or High Aspect Ratio Particles (HARP)) particles to the packed bed. The elongated particles have the effect of adding additional surface, that is, creating additional "walls" in the packed bed. This effect is shown in Figure 1, in which (a) shows the conventional tortuous flow path of a fluid through packed spheres, and (b) shows a region of straight flow of fluid along the interface of an elongated particle and the packed spheres. However, for most materials there is an aspect ratio above which an elongated particle may bend (please see the detailed description above of the parameters that control bending, the Young's modulus and the shape). Generally, in the literature the term "fiber" is used for very long materials that can bend extensively without breaking. The term "fiber" may be

used for elongated particles suitable for the present Invention provided that it is understood that suitable particles should not bend or deform substantially or break in use.

Flows through propped hydraulic fractures at low rates are typically modeled in the petroleum industry using Darcy's law for laminar flow in porous media. Darcy's law describes the linear relationship between the filtration velocity and the macroscopic pressure gradient. This linear relationship often holds when macroscopic pressure gradients are sufficiently small so that filtration of a viscous incompressible fluid in the porous space is governed by linear Stokes equations corresponding to the low-Reynolds number limit of general non-linear Navier-Stokes equations. In other words, since the micro-scale flow of viscous fluid in the porous space is governed by linear Stokes equations, the macro-scale filtration is described by the linear Darcy's law. In cases in which flow rates are higher, the Reynolds number for the flow in the porous space is not small but is finite or even high. The flow in this case is governed by the non-linear Navier-Stokes equations, and the flow regime may be either laminar or turbulent. In these cases, Darcy's law predicts much higher flow rates than are actually observed in experiments. This is attributed to the fact that in a slow laminar flow the pressure gradient is proportional to the velocity, whereas in the flow at finite Reynolds number (this may be a laminar flow if the Reynolds number is sub-critical or a turbulent flow if the Reynolds number is above-critical) the pressure drop increases more than the proportional increase in velocity. To account for this the beta factor( $\beta$ ) has been incorporated into the modified Darcy equation, for example in the Forchheimer equation.

Modified Darcy Equation:

$$\Delta P/L = \mu V/k$$

where  $\Delta P = P_1 - P_2$  (Pa)

$L =$  Length of the proppant pack (m)

$\mu =$  Viscosity of the fluid (Pa sec)

$V =$  Superficial velocity (m/sec)

$k =$  Permeability of the proppant pack ( $m^2$ )

Forchheimer Equation:

$$\Delta P/L = \mu V/k + \beta \rho V^2$$

where  $\beta =$  Beta factor ( $Pa \text{ sec}^2/kg$ )

$\rho =$  Density ( $kg/m^3$ ) of fluid at the mean pressure of the proppant pack

Note that strictly speaking, flow in the regime not governed by the Darcy equation should be referred to as "non-Darcy" flow, rather than "turbulent" flow, because at finite Reynolds number the flow regime either may still be laminar or may already be turbulent, while Darcy's law is already inapplicable and should be replaced by a more accurate nonlinear relation. We emphasize that the flow of a viscous incompressible fluid through pores in proppant packs in subterranean fractures may not be turbulent, since the Reynolds number for such flows is finite (this is why the Forchheimer law is appropriate rather than Darcy's law) but very far from being over the critical value. However, in the case of, for example, gas filtration, the Reynolds number may be so high that the actual flow regime may turn out to be turbulent. The Invention is useful both in the case of Darcy and non-Darcy flow, since there is an increase in permeability itself (the Invention is useful in the Darcy flow regime) and a decrease of beta (the Invention is useful in the non-Darcy flow regime). The beta factor is a material property that is a function of each proppant size, shape, and type; it is essentially a measure of the tortuosity of the flow path. For comparison of the performance of different proppant or gravel packs, low beta factor means better performance and is desirable (although not essential if the permeability is lower). Reduction in the beta-factor may have a large impact on production in both oil and gas wells where non-Darcy flow limits the production. For essentially spherical proppant, the beta factor is minimized by having a high ratio of permeability to porosity, a narrow proppant size distribution, high proppant sphericity, and high proppant smoothness. It should be understood that by "conventional" or "spherical" proppant is meant proppant having particles having a roundness of greater than about 0.8 and a sphericity of greater than about 0.8.

The preferable shapes of elongated particles are rods, ovals, plates and disks; it is believed that plates may be preferred. The shapes of the elongated particles need not fit into any of these categories, *i.e.* the elongated particles may have irregular shapes. In this discussion, we may refer to the elongated particles as rods or elongated rods, but we intend those terms to include any elongated shape, for example rods, ovals, plates and disks. The maximum length-based aspect ratio of the individual elongated particles should be less than about 25. In this discussion, when we refer to elongated particles, we intend the term to refer to stiff, non-deformable particles having an aspect ratio of less than about 25.

The materials (the elongated particles) of the Invention are preferably made from ceramic materials the same as or similar to those used in conventional intermediate and

high strength ceramic proppants. However, any material may be used that has the proper physical properties, in particular Young's Modulus. Particularly suitable materials include ceramics such as glass, bauxite ceramic, mullite ceramic, and metals such as aluminum and steels such as carbon steel, stainless steel, and other steel alloys.

Suitable sizes for the elongated particles of the invention are as follows. If the particles can be characterized most straightforwardly as cylinders or fibers (with the understanding that these and other characterizations may be approximations of the shapes and the actual shapes may be irregular), then the "lengths" may range from about 0.1 mm to about 30 mm, and the "diameters" from about 0.1 mm to about 10 mm, preferably from about 0.1 mm to about 3 mm. If the particles can be characterized most straightforwardly as disks or plates, then the "thickness" may range from about 10  $\mu$  to about 5000  $\mu$  and the "diameter" may range from about 0.5 mm to about 25 mm, or the "length" may range from about 1 mm to about 20 mm and the "width" may range from about 1 mm to about 20 mm. The elongated particles of the Invention may be used with any natural or synthetic proppant or gravel. For rods (fibers) the ratio of the diameter of the elongated particle to the diameter of the conventional (spherical) proppant may range from about 0.1 to about 20; the preferred ratio ranges from about 0.5 to about 3. For plates or disks, the ratio of the diameter of the conventional proppant to the thickness of the elongated particle may range from about 1 to about 100; the preferred ratio is from about 4 to about 20; the optimal value is about 5. For plates or disks, the ratio of the diameter of the conventional proppant to the thickness of the plate or disk may range from about 1 to about 100; the preferred range is from about 3 to about 20; the optimal is about 5. For plates or disks, the ratio of the length or width of the plate or disk to the diameter of the conventional proppant may range from about 1 to about 50; the preferred range of the ratio is from about 5 to about 10.

The most important feature of the elongated proppants is that they must be stiff, low-elasticity, and low-deformability materials. The Young's Modulus should be between about 0.02 and about 1100 GPa. The dimensionless cross-sectional moment of inertia should be between about 0.1 and 0.425. Particles having a low Young's Modulus will be sufficiently stiff if they have a high enough ratio of dimensionless cross sectional moment of inertia to dimensionless length (for example rods with a large diameter and short length) although they still must have a high enough aspect ratio to produce an increase in permeability due to the wall effect.

An example of suitable elongated particles is ceramic rods that are composed of at least about 92% alumina, at least about 2% silica, and at least about 1% titania. The rods have a diameter of about 0.85 to 0.90 mm and a length of about 5-7 mm. They have a Young's Modulus of about 160 GPa, a bending strength of about 300 MPa, a specific gravity of about 3.71 g/cm<sup>3</sup> and a roundness of about 0.9.

The elongated particles of the Invention may be used without conventional proppant or gravel as the only proppant or gravel employed. The elongated particles of the Invention may also be mixed with conventional proppant or gravel. At least a portion of a fracture may be packed with 100% elongated particles. If the entire fracture is not packed with elongated proppant, then the remaining part of the fracture may be propped with conventional proppant or sand or with a mixture of elongated and conventional proppant. Such a mixture may vary from about 1 to about 99% elongated proppant and may include more than one elongated proppant shape, length, diameter, and aspect ratio. For rods, the preferred range is from about 20% to about 100% by volume for fracturing and gravel packing and the most preferred range is from about 50% to about 100%; for plates the preferred range is from about 5% to about 50% by volume for fracturing and gravel packing and the most preferred range is from about 5 to about 15%.

Mixtures of different sizes with the same shape as well as mixtures of different shapes and different sizes may be used. Improvements may be obtained from, for example, mixtures of plates and rods, and mixtures of conventional proppants and plates and rods. Mixtures of different shapes may increase flow back properties as well as provide additional conductivity and beta factor improvement.

Fracturing jobs (or fracturing and gravel packing in single jobs) are typically done in many stages, commonly with the proppant concentration, and/or the pumping rate, and/or the nature of the carrier fluid, varying from stage to stage. In the present Invention, the use of elongated particles may also vary from stage to stage. From stage to stage in a given job, in addition to varying pump rate, total proppant concentration, and carrier fluid, the size and shape of the elongated particles may vary, various mixtures of different shapes may be used, various mixtures of one or more elongated mixtures with conventional proppant may be used, and various ratios of elongated particle density and carrier fluid density may be used.

For fracturing and gravel packing in a single job, or for “conventional” fracturing (defined as jobs in which the proppant concentration in each stage is above about 1 lb/ft<sup>2</sup> (about 4.91 kg/m<sup>2</sup>)) there are four principle job designs, although other variations are within the scope of the materials and the methods of the Invention. (1) 100% conventional proppant through most of the job and 100% elongated particles tailed in for the last 5% to 50% by total weight of proppant used in the job, preferably for the last 20% to 30% of the job. (2) A mixture (or varying mixtures) of conventional proppant and elongated particles in all stages. (3) A mixture (or varying mixtures) of conventional proppant and elongated particles through most of the job and 100% elongated particles tailed in for the last 5% to 50% of the job, preferably for the last 10% to 20% of the job. (4) 100% elongated particles (or varying mixtures of different sizes and/or shapes (or both) of elongated particles) throughout the job. In any of the variations, the elongated particles at the end of the job may be resin coated.

It has also been found that elongated particles are effective in fracturing jobs done at low proppant loading (sometimes called water fracs or slickwater jobs). For example, with conventional proppants, a loading of about 1.5 lb/ft<sup>2</sup> (about 7.3 kg/m<sup>2</sup>) puts about 5 layers of proppant in a fracture. Such jobs may be performed with 100% elongated particles or with a mixture of elongated particles and conventional proppant throughout the job. In such jobs, a suitable loading of elongated particles (or mixture) may be several layers, a monolayer, or a partial monolayer. Thus, loadings of less than about 1 lb/ft<sup>2</sup> (about 4.87 kg/m<sup>2</sup>)) may be used. The absolute loading that produces the desired loading depends upon the size, shape, and specific gravity of the elongated particles and may be calculated readily by one of ordinary skill in fracturing.

Elongated particles may be placed in fractures using a variety of special techniques that have been developed to achieve various results. For example, elongated proppants may be placed in fractures in such a way as to place barriers to fracture growth, and or to fluid flow, at specific locations in the fracture. U. S. Patent No. 4,478,282 described a method for limiting fracture growth into shales above and/or below a reservoir interval including the sequential steps of (a) injecting a proppant-free pad fluid to initiate fracture generation, (b) injecting a stage containing a special material that forms a pack that blocks fluid flow, and (c) injecting conventional proppant. The fracture is narrower in the shale, so the special material bridges off there more readily. To aid in proper placement, the

carrier fluid for the special material may have a higher viscosity than the carrier fluid for the proppant. As described in U. S. Patent No. 6,705,398, the special material may have a lower specific gravity than the carrier fluid so that the special material floats to the top of the fracture, if desired, or the special material may have a higher specific gravity than the carrier fluid so that the special material sinks to the bottom of the fracture, if desired, to aid in suitable placement. Optionally, these methods may be combined to place barriers at the tip and at both the top and the bottom of the fracture. Either conventional proppant or the elongated particles of the Invention (or a mixture of elongated particles and conventional proppant or fluid loss additive at any concentration) may be used as the special material described above to form a pack to limit fracture growth or fluid flow. The best barrier may be a mixture of elongated particles and conventional proppant. The size ratio of elongated particles to conventional proppant may be optimized for the optimal permeability or impermeability. The elongated materials bridge at the desired location, and conventional proppant invades and/or plugs the bridge. However, elongated materials alone may be used for plugging. As an example, a mixture of several types of elongated particles (various shapes and sizes) may be used; the larger particles form a bridge, and smaller ones invade and/or plug. As another example, elongated particles may be used for bridging in a mixture with an encapsulated (or retarded) swelling agent that is caught in the bridge and plugs it. To form a barrier, elongated particles may be used in mixtures with 1) other elongated particles of different shape, size, or density; or 2) several types of conventional spherical proppants of various sizes and densities. Barriers may be placed using one or several stages. For example, the mixture that bridges may be pumped first, followed by another mixture that invades and/or plugs the existing bridged material, or a mixture may be prepared in such a way that it bridges and plug at the same time.

In the case of a barrier, the high permeability of particle beds containing elongated particles may be a drawback, so in this case the elongated particles may be made of a material that is responsive to the closure stress or to contact with water; under the action of such trigger this material becomes less permeable.

In other examples, elongated particles, alone or mixed with conventional proppant, may be used with solid degradable materials (such as but not limited to polymers, cross-linked polymers, sodium chloride, sodium carbonate, benzoic acid, polylactic acid, and polyglycolic acid) that may be caused to disappear under the action of a physical or chemical trigger. Such materials may initially form a filter cake or may initially be

dispersed throughout or in parts of the pack. When they disappear, they form voids that enhance permeability and fluid flow. The trigger may be closure stress, temperature, or contact with a chemical such as water, acid, base, enzyme, oxidizer and the like. International Patent Application No. WO2003023177 and U. S. Patent No. 7,178,596 give examples of such materials that may disappear and of methods of destroying them. In yet another example, elongated particles, alone or mixed with conventional proppant, may be used with solid acid precursors (such as but not limited to polylactic acid and polyglycolic acid and other materials described in U. S. Patent No. 7,166,560) that dissolve and not only leave voids but also may dissolve a portion of the surrounding formation. In yet a further example, elongated particles, alone or mixed with conventional proppant, may be used with consolidating or reinforcing materials such as the fibers described in U. S. Patent No. 5,330,005 or the fibrous bundles described in U. S. Patent No. 5,908,073. Elongated particles, alone or mixed with conventional proppant, may also be used with the method of forming strong proppant clusters in a fracture, as described in International Patent Application No. WO2007086771 and with the degradable material assisted diversion method disclosed in International Patent Application No. WO2007066254.

The elongated particles may also be used in deliberately causing a tip screen-out in fracturing to limit fracture length and height and increase fracture width. Either 100% elongated particles or elongated particles mixed with conventional (spherical) proppant at any concentration is used as a bridging agent at the fracture tip (and preferably at the top, and bottom) to stop the fracture from propagating; if injection (of bridging material or of conventional proppant) continues, the fracture widens. This is accomplished by introducing the bridging material at the early stages of the job, for example, by adding it at low concentrations during the pad, adding it as a slug during the pad, or adding it during the first proppant stage or stages. The bridging material may be introduced immediately after the pad, or the pad may be followed by conventional proppant and then the bridging material. The choices depend on the job design and on how early in the job tip screen-out is desired under the defined well conditions. Introducing the material in this way automatically results in placement of the bridging material at the fracture tip. (The fracture tip here is defined as any front of the fracture that is propagating into the matrix, so may include the top and bottom.) This approach may be optimized by selecting differing densities for the bridging material for controlling height growth in a specific direction.

This technique may also be combined with techniques, including those described above, for increasing permeability.

In gravel packing, it is most common to use the same gravel throughout a job. In the present Invention, the gravel may be 100% elongated particles (including mixtures of different elongated particles) some or all of which may be resin coated; a mixture of elongated particles (including mixtures of elongated particles) some or all of which may be resin coated, and conventional (spherical) proppant, some or all of which may be resin coated; or any of the preceding further mixed with deformable particles or with fibers. The completion may be cased hole with a screen, in which case the gravel fills the perforations and the annulus between the screen and the casing; cased hole with no screen in which the gravel fills the perforations; open hole with a screen, in which the gravel fills the annulus between the screen and the formation; or open hole without a screen, in which the gravel fills the borehole.

In fracturing, the use of elongated particles is most advantageous in reservoirs having high beta factors and/or very low permeabilities, for example tight gas wells. The elongated particles are particularly beneficial in the near wellbore region where the beta factor and well conductivity are especially important. Jobs may be designed with numerical simulators such as Schlumberger's FracCADE™ simulator, the methods disclosed in U.S. 6,876,959 issued to Pierce et al., and other pseudo three-dimensional (P3D) hydraulic fracture simulators and planar three-dimensional (PL3D) hydraulic simulators (including GOHFER™ from Stim-Lab and Marathon Oil Co.). Such simulators typically use the densities and concentrations of particles regardless of their shape. For designing barrier placement jobs in particular, it is necessary to understand the bridging behavior of the elongated particles, which bridge more effectively than spherical particles. Bridging behavior may be determined from laboratory experiments. For example, in experiments in which 6 PPA slurries were pumped at 1 ft/sec (0.3048 m/sec) through slots, it was determined that 10/14 mesh (2.00mm/1.41mm) spheres and rods having a diameter of 0.8 mm and a length of about 4 to 5 mm bridged in a 4 mm slot but not in a 9 mm slot. However, rods of diameter 0.8 mm and length of about 2 to 3 mm, and spheres of 12/18 (1.68mm/1.00mm), 16/30 (1.19mm/595µm), or 20/40 mesh (841µm/420µm) did not bridge in either slot. Similarly, laboratory experiments may be performed to determine the correlation of elongated particle (or mixture of elongated particle and spherical particle) loading to conductivity. For example, laboratory tests have shown that the conductivity of

a pack of 16/30 (1.19mm/595 $\mu$ m) [spheres is surpassed by that of a pack of elongated particles (having a length of 2-3 mm and a diameter of 0.8 mm) at concentrations up to 50% lower. This leads to another benefit of the use of elongated particles: lower loadings may be used, which translates into less material and less surface equipment.

Advantageously, the Invention is compatible with other techniques known to enhance proppant conductivity such as the use of breakers, and the use of non-damaging fracturing base fluids such as gelled oils, viscoelastic surfactant based fluids, foamed fluids and emulsified fluids. In addition, the materials and methods of the Invention may also be used with various proppant-retention agents, for example deformable particles, fibrous bundles and fibrous or fibrillated materials that form mats or nets in proppant packs. They may also be used in conjunction with curable resins coated on the proppant, pre-cured resins coated on the proppant, a combination of curable and pre-cured (sold as partially cured) resins coated on the proppant, or other sticky proppant coatings to trap proppant particles in the fracture and prevent their production through the fracture and to the wellbore. They may also be used mixed with other solid materials such as fluid loss additives and solid acid precursors.

Curable resins, pre-cured resins, combinations of curable and pre-cured resins (sold as partially cured), or other sticky coatings may also be placed on the elongated proppants of the Invention. Any such coatings that are used on conventional proppants may be used. Since the elongated proppants themselves serve to retain proppant and minimize sand production, reasons for coating conventional proppants, the principle function of coatings on elongated proppants is to increase their crush strength and prevent breakage.

The use of non-deformable, rigid, elongated particles, preferably ceramic rods, having an aspect ratio of less than about 25 for sand control by gravel packing is appropriate. Preferred elongated particles for sand control have an aspect ratio above about 5, preferably close to about 5, and have the ratio of the diameter of the elongated particle to the diameter of any spherical gravel included between about 0.2 and about 10, preferably between about 0.2 and about 4. With these criteria, both the permeability and the ability to retain sand of a pack containing elongated particles are expected to be greater than that of spherical gravel.

The present Invention may be further understood from the following examples.

**Example 1:**

Proppant packs containing 100% ceramic rods were compared to a proppant pack containing 100% intermediate strength proppant (ISP). The results for the ceramic rods were obtained in the laboratory in short term tests using API method RP-61. The ISP was CarboProp 16/30 from Carbo Ceramics Inc., Irving, Texas, U. S. A.. The data for the CarboProp 16/30 were obtained from short term experiments under the same conditions as for ceramic rods. The ceramic rods were the same size and shape, about 4-5 mm long and about 1100  $\mu$  in diameter. Type 1 rods had a specific gravity of 3.66 g/cm<sup>3</sup> and type 2 rods had a specific gravity of 3.81 g/cm<sup>3</sup>. Type 1 rods were weaker than type 2 rods; after the conductivity experiments the type 1 rods yielded about 10% smaller particles while the type 2 rods yielded only about 4% smaller particles. The laboratory experiments were designed to simulate a perforation size of 10 mm at a flow rate of 50.7 ml/min at a differential pressure of 31.2 atmospheres. There was no flowback from the packs of 100% rods. Figure 2 shows permeabilities, and Figure 3 shows beta factors, as a function of closure stress for the two types of ceramic rods and for the conventional proppant. It can be seen that the packs made up of 100% of these ceramic rods gave higher permeabilities than a pack made of 100% of this conventional proppant at all crush strengths tested, and that the ceramic rods gave lower beta factors at the lower two closure stresses. It is believed that higher permeabilities would continue to be observed at higher closure stresses. Better permeability and better beta factor were found for high strength rods type 2. Fig. 4 shows permeability as a function of closure stress for 3<sup>rd</sup> type of ceramic rods. The main difference with previous examples is higher length of ceramic rods in this case. It is easily to see that in this case permeability much higher at low closure stresses in comparison with previous examples but low at 7000 psi. The breakage of rods is higher if the length higher and it brings to permeability reduction.

### **Example 2:**

Proppant packs containing 50% by volume of either one of two types of ceramic rods and 50% by volume of CarboLite 20/40 proppant were compared to a pack containing 100% CarboLite 20/40 proppant. Again, the data for the mixtures were from the laboratory, with short term tests using API method RP-61, and the data for the 100% conventional proppant were from the supplier (Carbo Ceramics Inc., Irving, Texas, U. S. A.). The data for the CarboLite 20/40 were obtained from the 2006 "CarboLite Data Sheet" available from Carbo Ceramics, Inc., which states that the permeability and beta

factors were measured in long-term tests with a single-phase fluid under laminar flow conditions in accordance with API method RP-61. In this example, type 1 rods were about 0.8 mm in diameter and about 4 to 5 mm long and type 2 rods were about 0.8 mm in diameter and about 2 to 3 mm long. Each had a specific gravity of 3.84 g/cm<sup>3</sup>. Figure 5 shows permeabilities, and Figure 6 shows beta factors, as a function of closure stress for the mixtures of the two types of ceramic rods with conventional proppant (experimental) and for the conventional proppant alone (data from Carbo Ceramics Inc.). It can be seen that these mixtures also gave higher permeabilities at all closure stresses and lower beta factors at the lowest closure stress. Rod type 1 (50% mixture) gives higher permeabilities and lower beta factors at each closure pressure than rod type 2 (50% mixture). It is believed that higher permeabilities would continue to be observed at higher closure stresses.

### **Example 3:**

Experiments were also done with sand and with a mixture of the sand with 30% by volume stainless steel rods. The stainless steel rods were about 0.8 mm in diameter and about 4 to about 5 mm long. Each had a specific gravity of about 7.85 g/cm<sup>3</sup>. The sand was 20/40 Badger sand. Figure 7 shows permeabilities, and Figure 8 shows beta factors, as a function of closure stress for the mixture of stainless steel rods with sand. It can be seen that there was an improvement in permeability for the mixture, over sand alone, up to a closure stress of about 7000 psi (about 48.2 MPa). There was an improvement of the beta factor of the mixture over that of the sand alone up to a closure pressure of about 5000 psi (about 34.5 MPa). There was evidence of substantial crushing of the 20/40 badger sand at the closure stress of about 7000 psi (about 48.2 MPa). It is believed that the crushing of the sand may have been worse at high closure pressures in the presence of the stainless steel rods.

### **Example 4:**

Permeabilities were compared for a pack made with 50% by volume of ceramic rods and 50% proppant, with a pack made with only the proppant. The proppant was (Fores 12/18, obtained from FORES Refractory Plant, Ekaterinburg, Russia) had a mean diameter of about 1.4 mm and a specific gravity of 2.93 g/cm<sup>3</sup>. The ceramic rods were about 1.1 mm in diameter and about 4 to about 6 mm long and had a specific gravity of

3.81 g/cm<sup>3</sup>. Figure 9 compares permeabilities at various closure stresses; it can be seen that the mixture had much higher permeabilities.

**Example 5:**

In order to demonstrate the benefits of using the elongated non-deformable, rigid particles of the Invention for sand control, it is necessary to address two properties of the pack: retention and conductivity. In the following examples, the behavior of various packs of elongated particles was simulated numerically by using a sequential deposition algorithm. Cylinders were used as examples of suitable elongated particles. The sand retention properties of the packs of cylinders were calculated for the deposition of spheres onto the packs of cylinders. Spheres were defined by their radius  $r$  and cylinders were defined by their maximal and minimal semiaxes,  $L_{max}$  and  $L_{min}$ , respectively. For all cases, the sphere radius was taken to be the same. Numerical simulations were performed for  $L_{min}/r = 0.2, 0.5, 1, 1.5, 2, 3$ . Various values of  $L_{min}/r$  were obtained by varying the size of the cylinders in such a way that the cylinder aspect ratio was kept equal to 5. Perfect retention was observed for cases where  $L_{min}/r \leq 2$ . Some infiltration of spherical particles into the pack of cylinders was shown by the calculations when  $L_{min}/r = 3$ .

When the retention was good, the resulting packing consisted of three main zones: a pack of cylinders at the bottom, a pack of spheres at the top, and a middle zone containing both cylinders and spheres. The middle mixed zone and the bottom zone that consists of cylinders should be sufficiently conductive to allow the flow of reservoir fluids towards the wellbore. In cases where  $L_{min}/r = 0.2$ , the bottom zone was less permeable than the upper zone, and the permeabilities of the middle and upper zones were similar. Therefore, in this case the flow was restricted by the permeability of the pack of cylinders. For cases in which  $0.2 < L_{min}/r \leq 3$ , the permeability of the middle and bottom zones was higher than the permeability of the upper zone; therefore the flow was more restricted by the permeability of the pack of spheres (gravel). These simulations show that elongated particles are effective for sand control and provide both good sand retention and gravel permeability.

Laboratory experiments that demonstrated the effectiveness of sand production prevention were also carried out. Ceramic rods with an aspect ratio of about 5 were used in all these experiments. The first half of a cell was loaded with sand/proppant of a specific mesh size and the second half was loaded with ceramic rods. A square cell was used, with

three inlet ports and one outlet port, each having a diameter of 15 mm. The first part of the cell was loaded with small sand particles right after the inlet ports and the second half was loaded with rods; thus the two materials had a contact boundary with each other, and the sand would pass into or through the rod pack easily if it was possible. The loading used was 4 lbm/ft<sup>2</sup>. The maximum flow rate that was tested was about 12 l/min. (This flow rate has been found to be the maximum possible flow rate through a single perforation in most oil wells.) In these experiments, the flowback of sand was assessed by using the appropriate sieve size at the outlet and by visual observation of the ceramic rod pack after 10-15 min washout with closure stresses of 1000 psi (6.9 MPa) and 3000 psi (20.7 MPa). If small particles appeared at the outlet of the slot, the retention was poor.

Three different samples of sand were tested: 20/40 (~0.5 mm), 30/50 (~0.42 mm), 40/70 (~0.29 mm); the rods were 0.85-1 mm in diameter and 3.5-5 mm in length. It was found that there was no flowback of sand (or sand production) from the pack under these conditions. Sand penetration into the pack was almost negligible for all of the samples tested.

Having thus described our Invention, we claim:

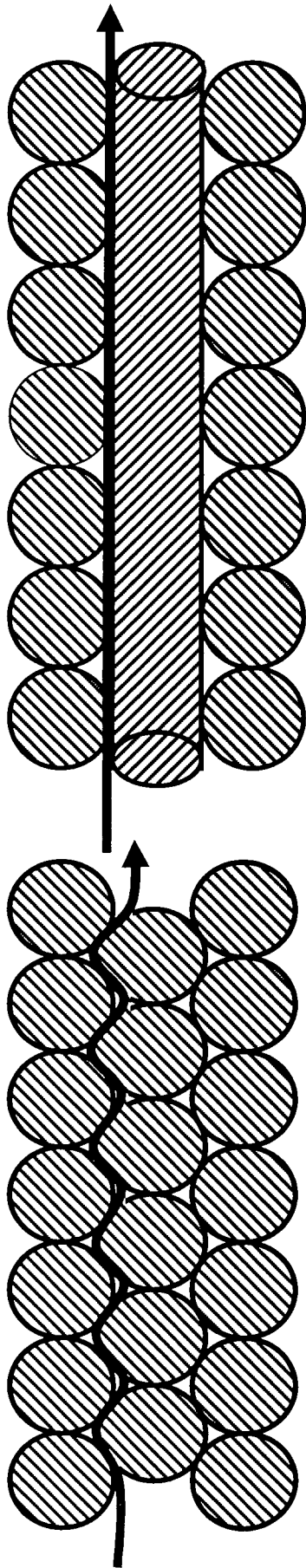
1. A method of fracturing a subterranean formation comprising injecting, into the formation, a slurry of proppant comprising from 1 to 100 percent of stiff, low-elasticity, low-deformability elongated particles.
2. The method of claim 1 wherein the percentage of the elongated particles is changed during the injection.
3. The method of claim 1 or claim 2 further comprising injecting a stage or stages wherein the slurry contains no stiff, low-elasticity, low-deformability elongated particles.
4. The method of any of the preceding claims further comprising placing a barrier to fracture growth, the barrier comprising particles comprising from 1 to 100 percent of stiff, low-elasticity, low-deformability elongated particles.
5. 5. The method of any of claim 1, claim 2, claim 3 further comprising the initiation of a fracture tip screenout in one or more fractures in the subterranean formation.
6. A method of gravel packing a well penetrating a subterranean formation comprising injecting, into the well, a slurry of gravel comprising from 1 to 100 percent of stiff, low-elasticity, low-deformability elongated particles.
7. The method of any of the preceding claims wherein at least a portion of the elongated particles is resin coated.
8. The method of any of the preceding claims wherein at least a portion of the proppant particles that are not elongated particles is resin coated.
9. The method of any of the preceding claims wherein the slurry further comprises additional particles selected from the group consisting of fibers having an aspect ratio greater than 25, fibrous bundles, solid acid precursors, solid degradable materials, fluid loss additives, and mixtures thereof.
10. The method of any of the preceding claims wherein the elongated particles have a maximal cross-sectional dimension,  $h_1$ , and a minimal cross-sectional dimension,  $h_2$ , of from 0.1 to 10 mm; a length,  $L$ , of from 0.1 to 20 mm; for 1D particles, a ratio  $L/h_1$  from 1.2 to 10 and a ratio  $h_2/h_1$  from 0.8 to 1; for 2D particles, a ratio  $L/h_1$  from 1 to 1.19 and a ratio  $h_2/h_1$  from 0.1 to 0.79; a curvature,  $\chi$ , of from 0 to  $2/h_2$  in units of  $1/\text{mm}$ ; for 1D particles, a stiffness,  $k$ , of from 0 to  $4.90 \cdot 10^8$  in units of  $\text{N} \cdot \text{mm}^2$ ; and for cylindrical

particles, a stiffness,  $k$ , of from 0 to  $10^8$  (N\*mm); a range of a particle unevenness  $d_0$  (or  $d_1$ ) is from 0 to  $0.5 \cdot h_1$  in units of mm.

11. The method of any of the preceding claims wherein the elongated particles comprise a mixture of elongated particles differing from one another in at least one parameter selected from the group consisting of length, a cross-sectional dimension, density, curvature, and stiffness.

12. The method of any of the preceding claims further comprising placing a barrier to proppant flowback, the barrier comprising particles comprising from 1 to 100 percent of stiff, low-elasticity, low-deformability elongated particles.

13. The method of any of the preceding claims wherein the elongated particles and all mentioned mixtures may contain encapsulated breaker material.



(b)

(a)

FIG. 1

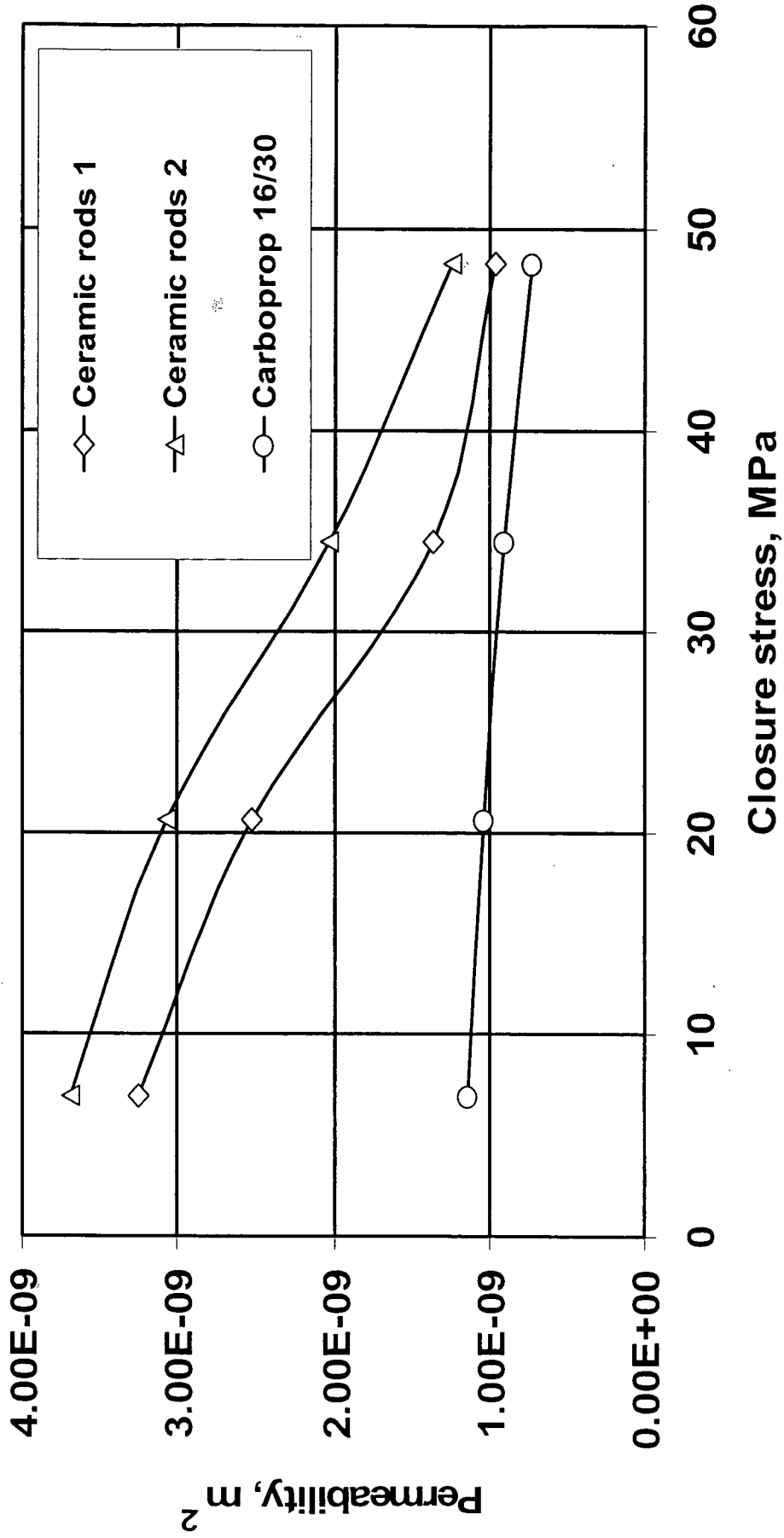


FIG. 2

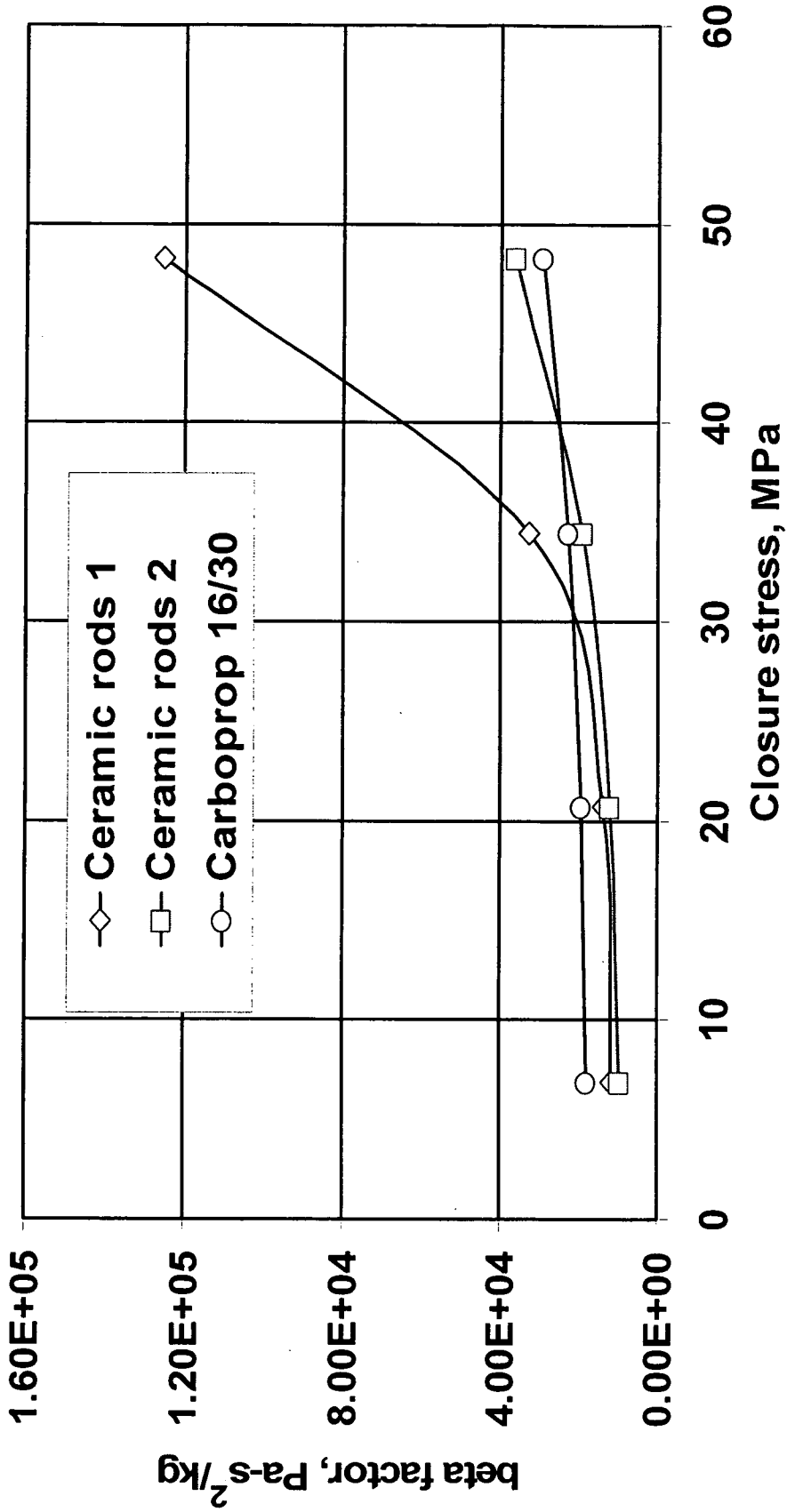


FIG. 3

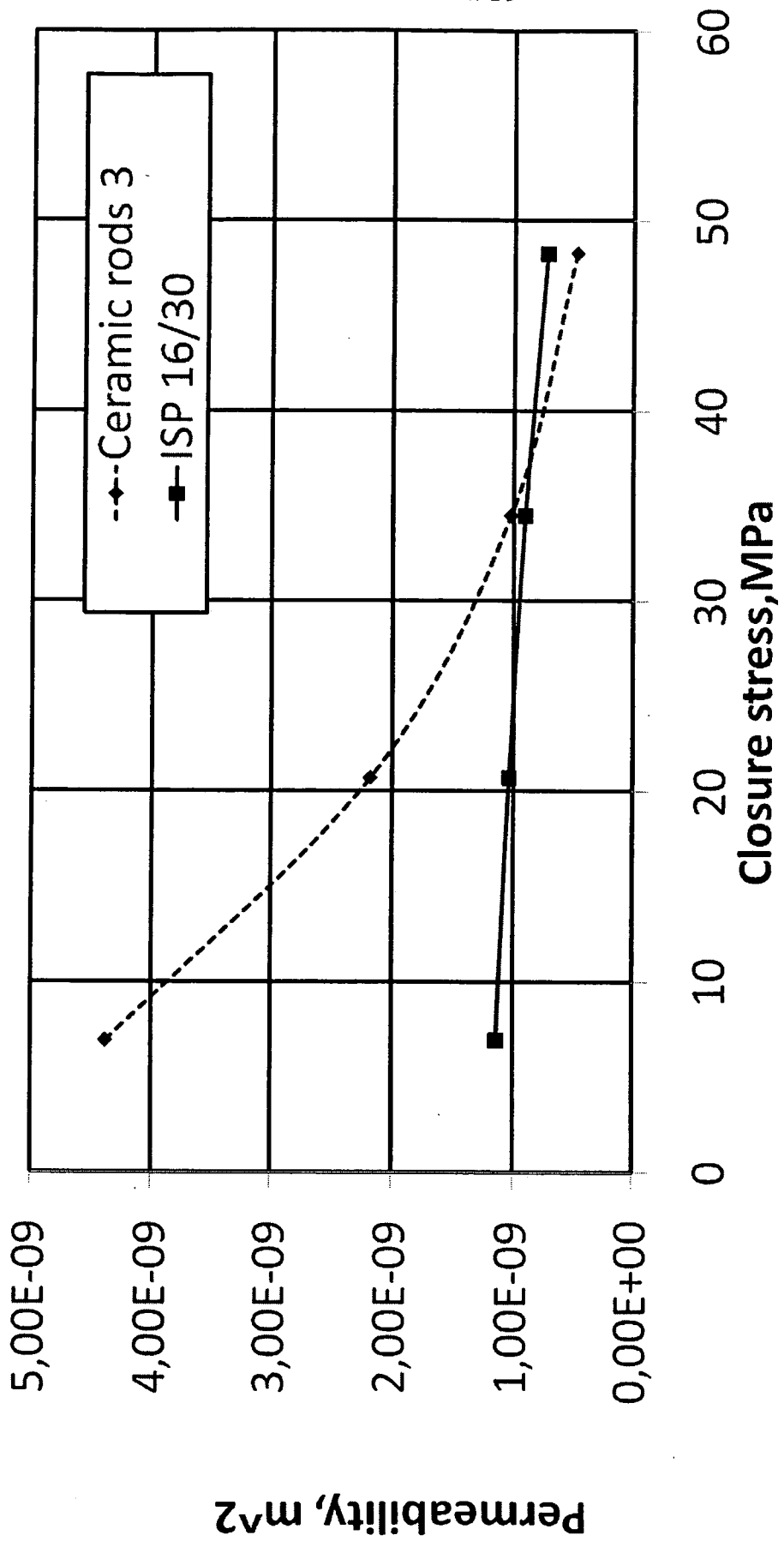


FIG. 4

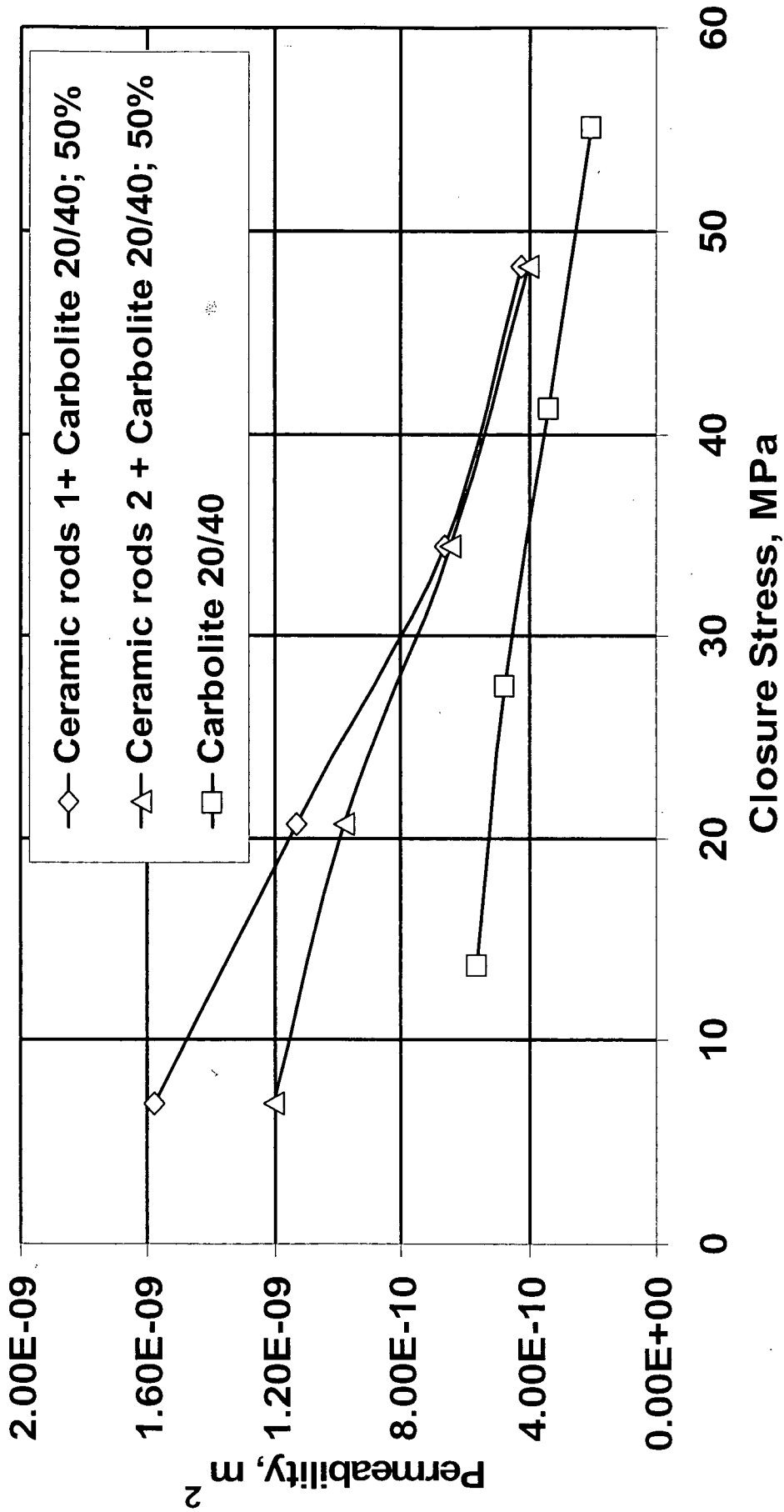


FIG. 5

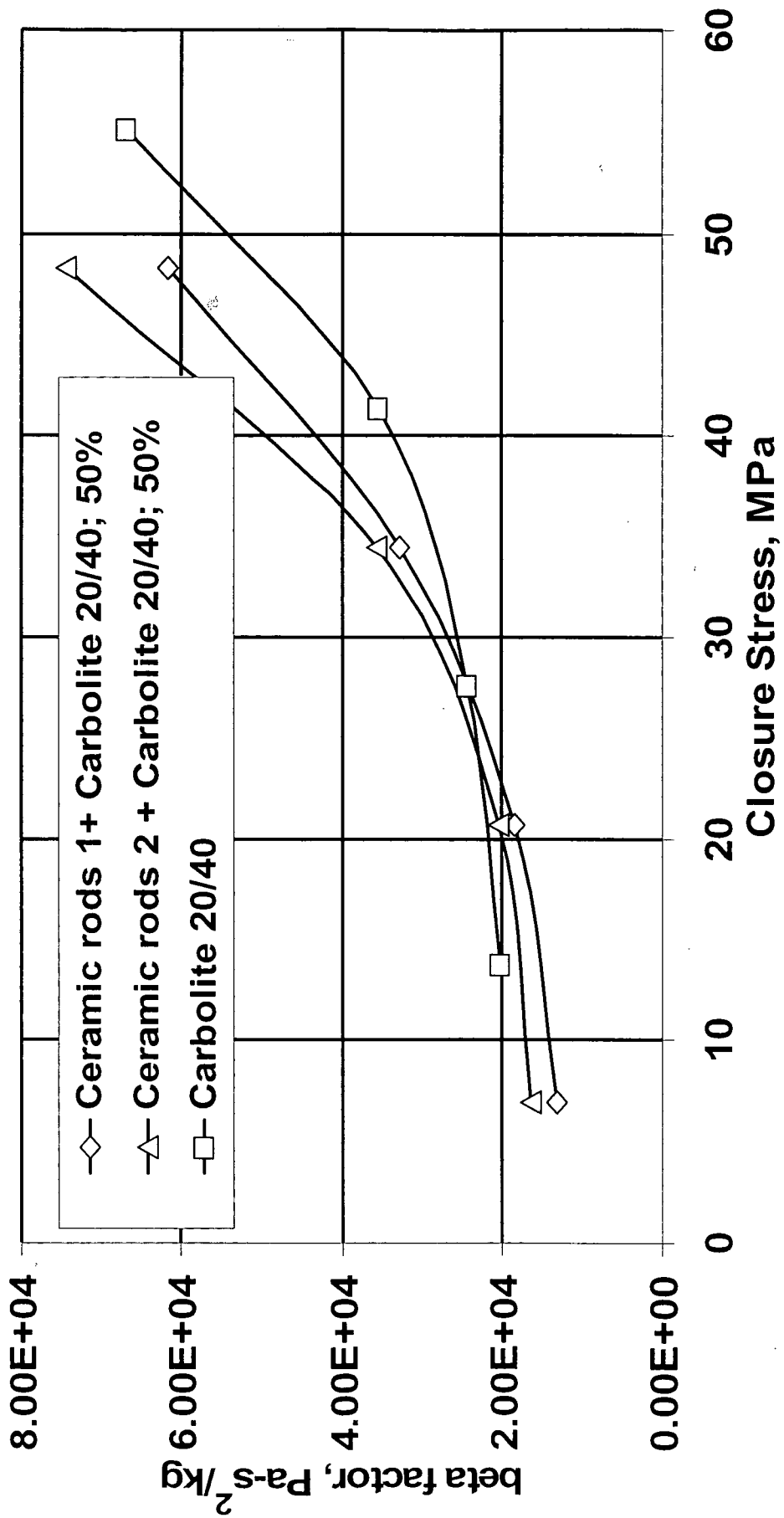


FIG. 6

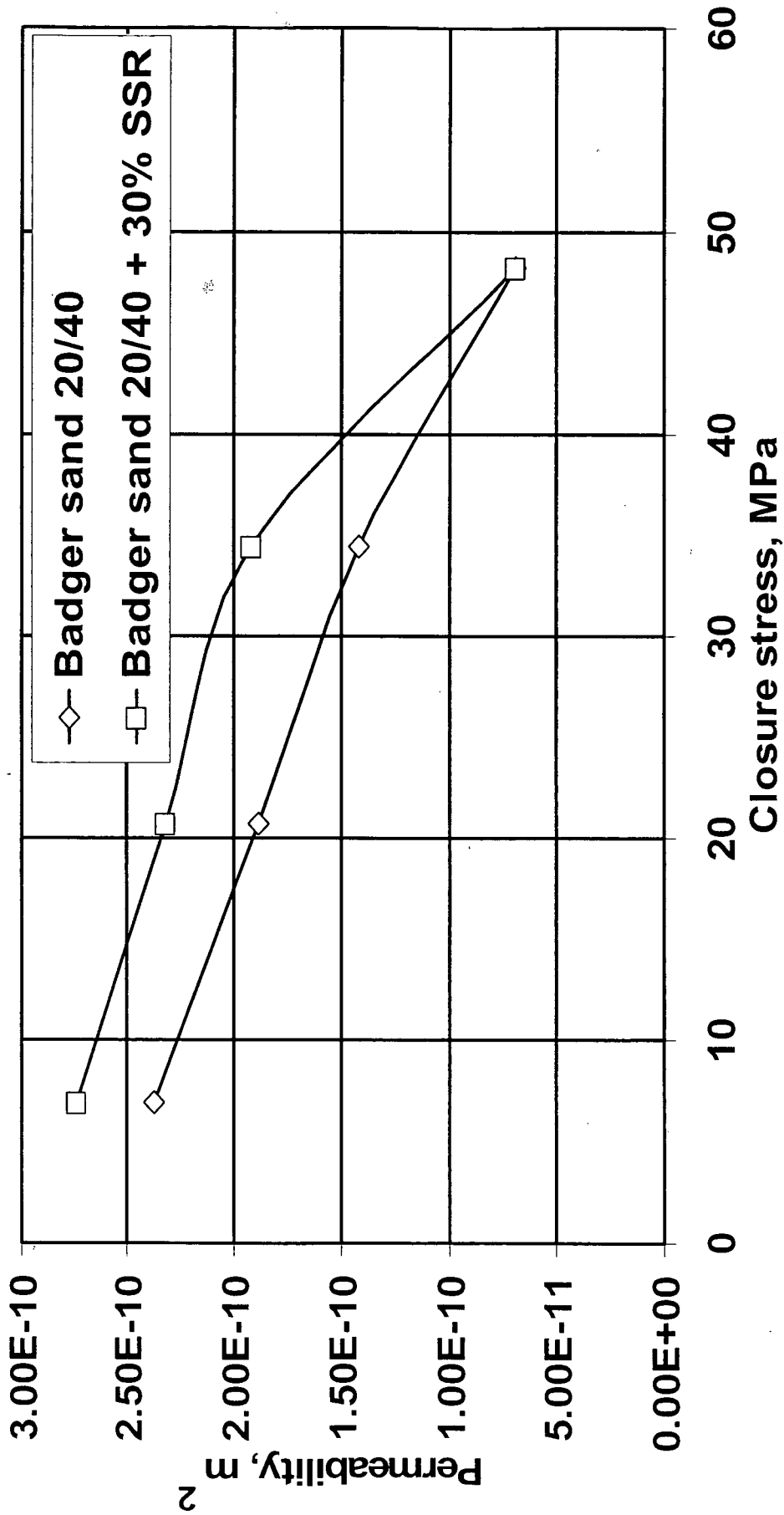


FIG. 7

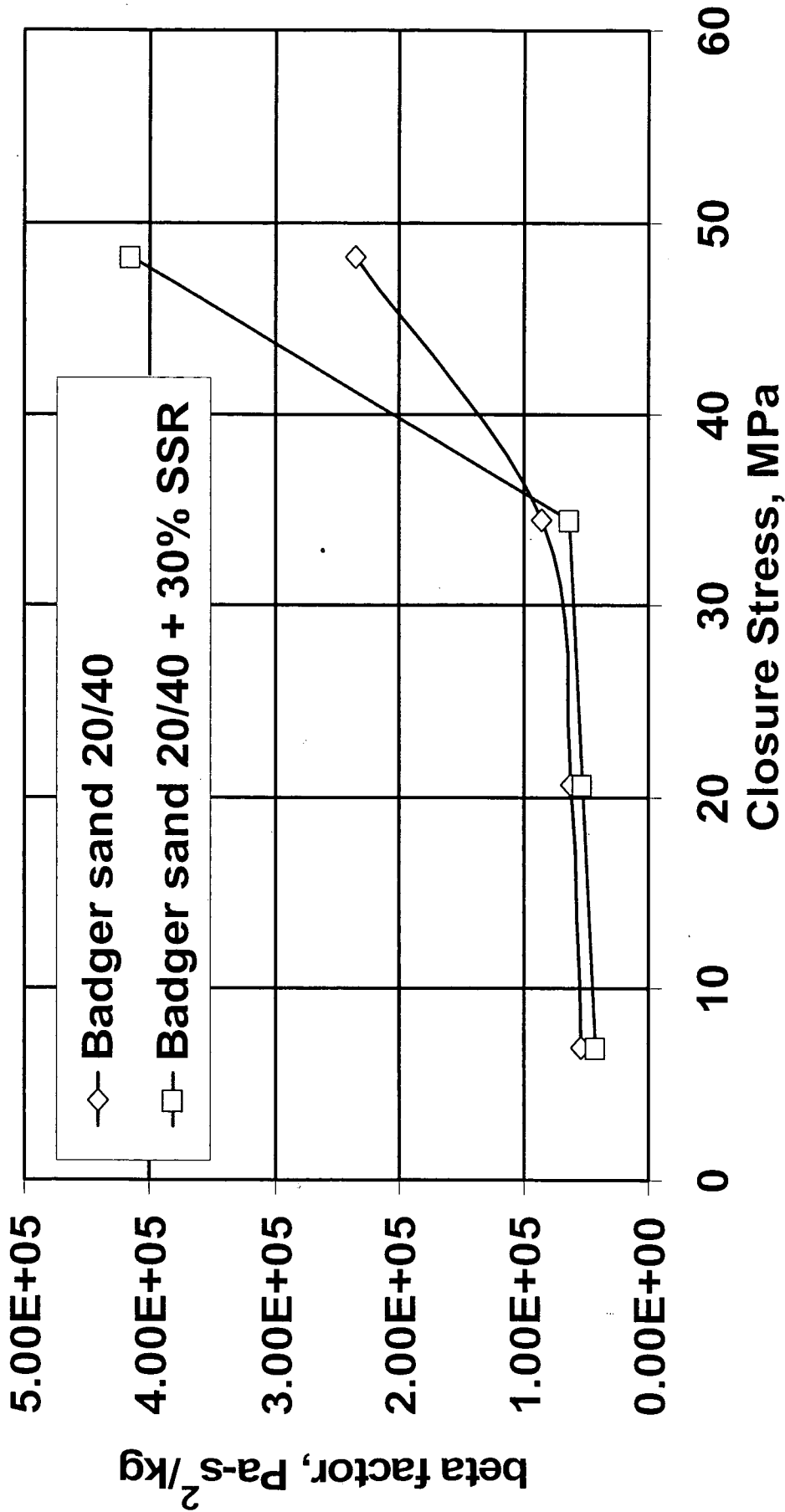


FIG. 8

9/19

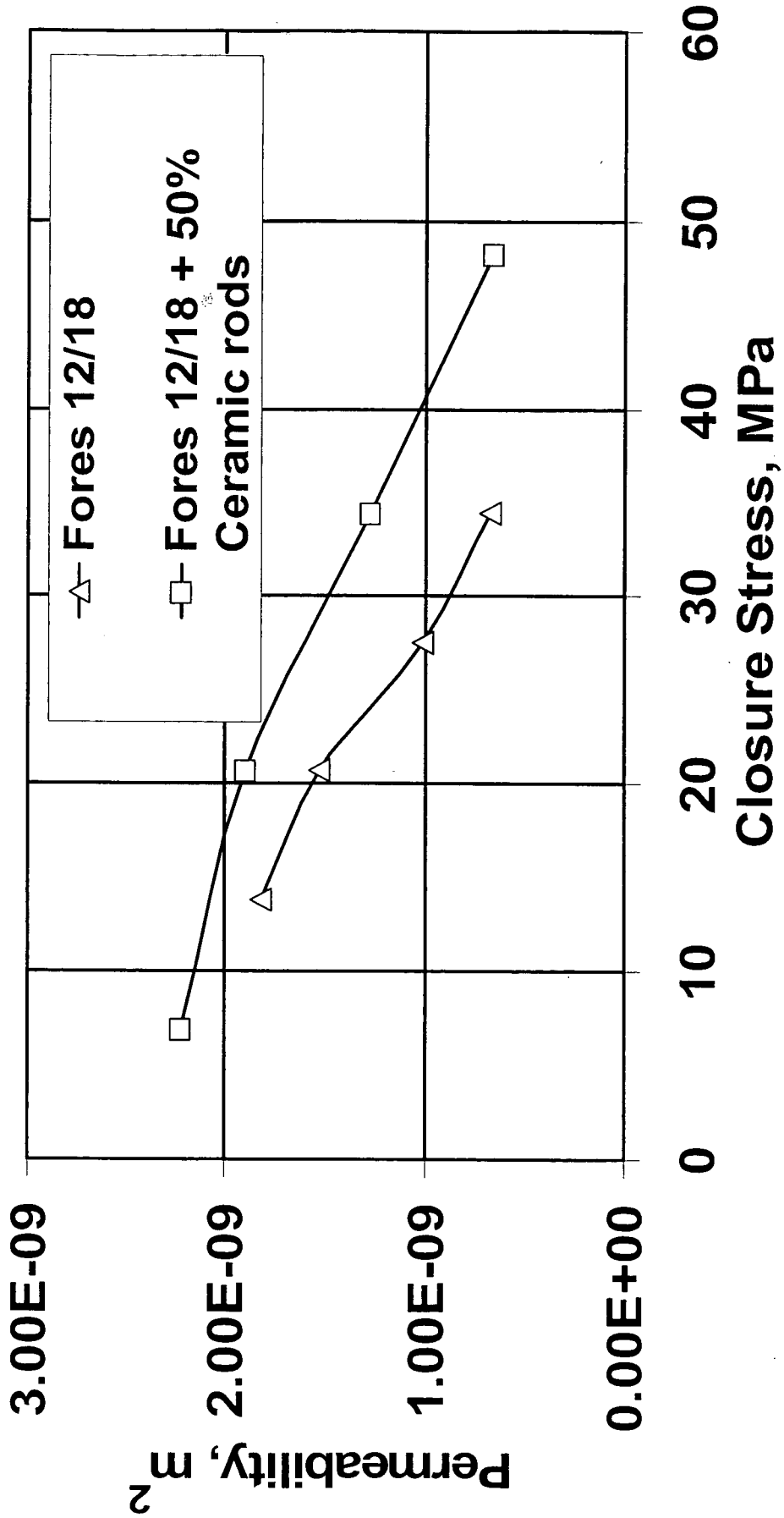
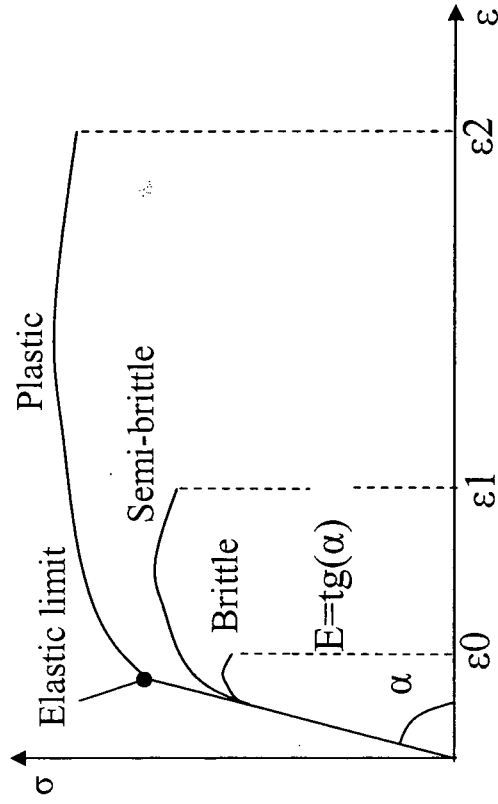
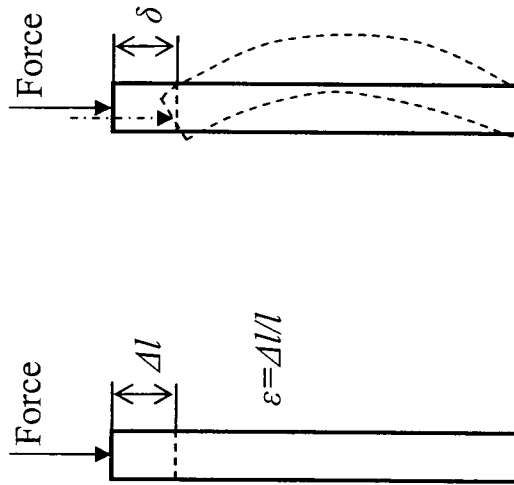


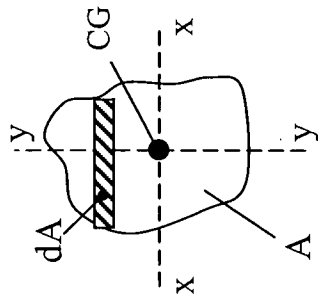
FIG. 9



**Fig. 10**



**Fig. 11**



**Fig. 12**

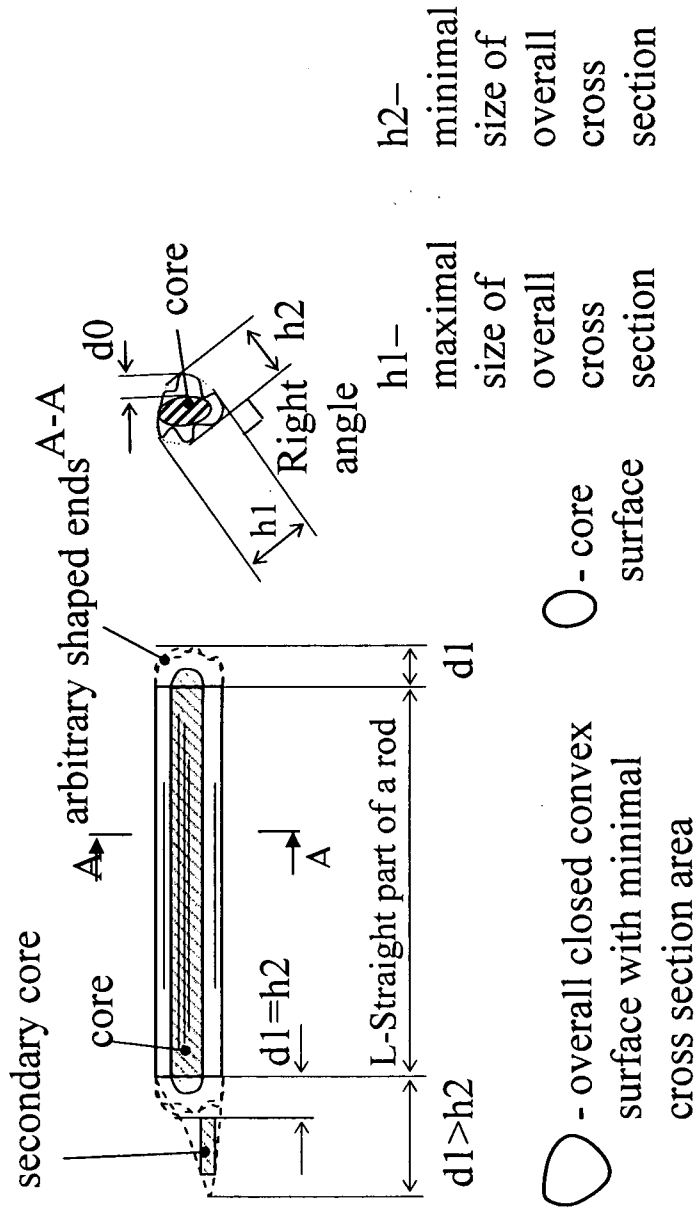
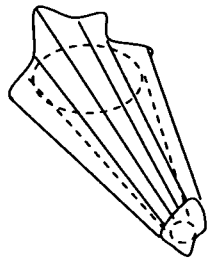
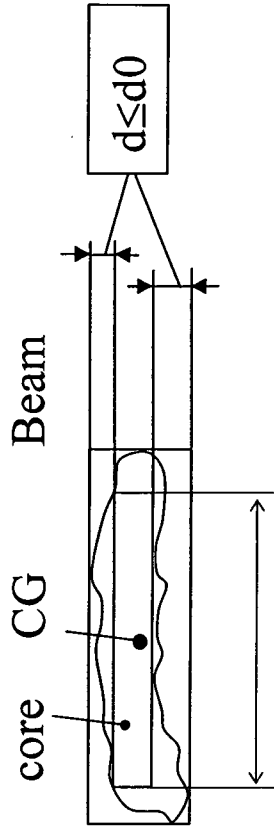


Fig. 13

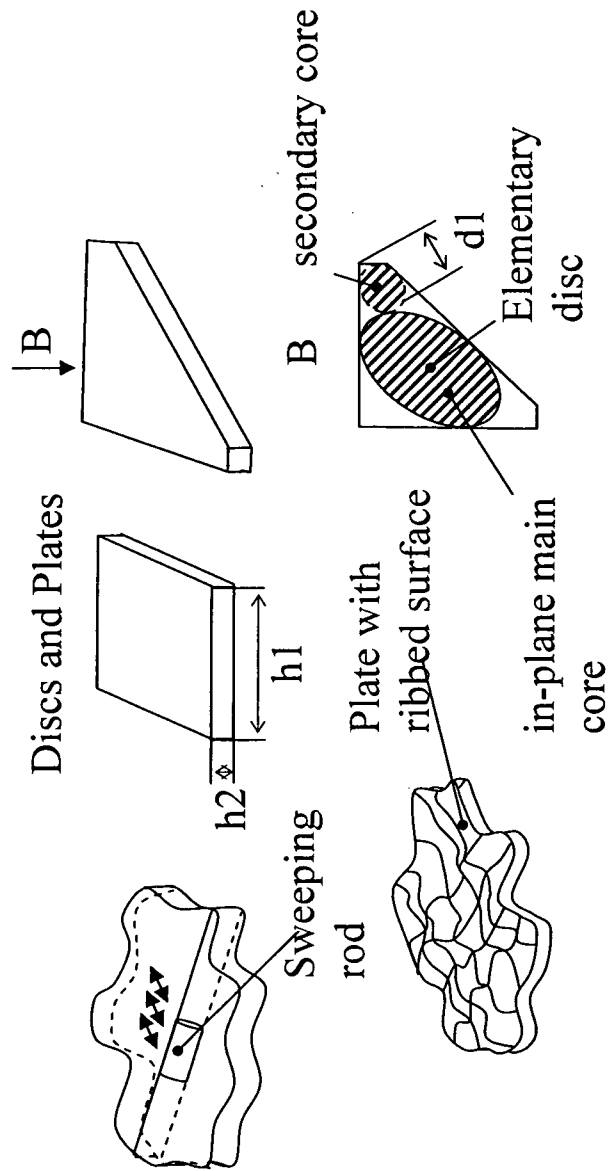


**Fig. 14**

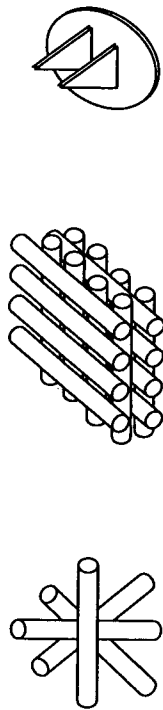


L-core part of a beam

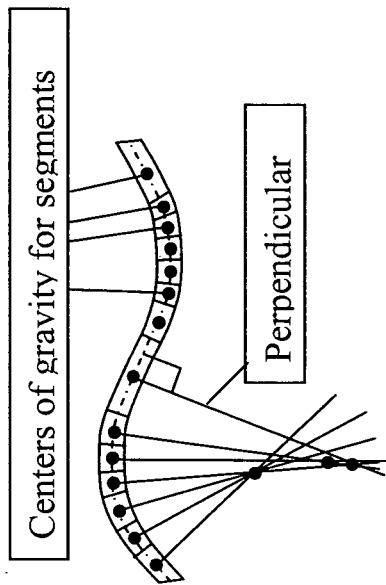
**Fig. 15**



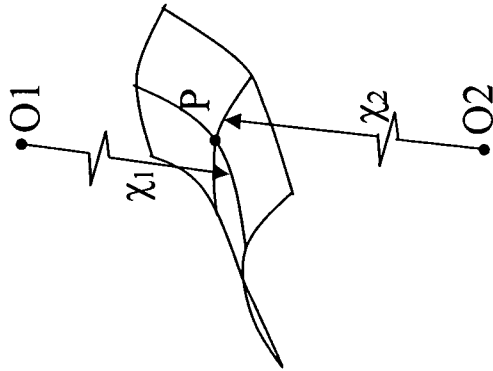
**Fig. 16**



**Fig. 17**



**Fig. 18**



**Fig. 19**

# INTERNATIONAL SEARCH REPORT

International application No. PCT/RU 2007/000753
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A. CLASSIFICATION OF SUBJECT MATTER	<b>C09K 8/80 (2006.01)</b> <b>E21B 43/267 (2006.01)</b>
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According to International Patent Classification (IPC) or to both national classification and IPC

**B. FIELDS SEARCHED**

Minimum documentation searched (classification system followed by classification symbols)

C09K 8/80, 8/80, E21B 43/00, 43/26-43/267

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

RUPAT, RUPAT\_OLD, RUPAT\_NEW, RUABRU, PatFT, EAPATIS, PAJ, PCT, Esp@cenet

**C. DOCUMENTS CONSIDERED TO BE RELEVANT**

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X Y	US 2003/0106690 A1 (CURTIS L. BONEY et al.) 12.06.2003, abstract, paragraph [0002] - [0006], [0009], [0012], [0020], [0023] - [0025], [0027], [0028], [0033], [0034], [0039] - [0041], [0042], [0044] - [0046], [0048] - [0052], [0053], claims	1-6, 8-10, 12, 13 7, 11
Y	US 2003/0196805 A1 (CURTIS L. BONEY et al.) 23.10.2003, abstract, paragraph [0012], [0019] - [0021], [0048], claims	7, 11
A	US 2003/0062160 A1 (CURTIS L. BONEY et al.) 03.04.2003, abstract, claims	1-13
A	US 5330005 A (DOWELL SCHLUMBERGER INCORPORATED) 19.07.1994, abstract, claims	1-13

Further documents are listed in the continuation of Box C.       See patent family annex.

\* Special categories of cited documents:

<p>"A" document defining the general state of the art which is not considered to be of particular relevance</p> <p>"E" earlier application or patent but published on or after the international filing date</p> <p>"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)</p> <p>"O" document referring to an oral disclosure, use, exhibition or other means</p> <p>"P" document published prior to the international filing date but later than the priority date claimed</p>	<p>"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention</p> <p>"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone</p> <p>"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art</p> <p>"&amp;" document member of the same patent family</p>
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Date of the actual completion of the international search 02 September 2008 (02.09.2008)	Date of mailing of the international search report 25 September 2008 (25.09.2008)
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