(19) Europäisches Patentamt
European Patent Office
Office européen des brevets

(11) Publication number: 0 246 800 A1

(12) EUROPEAN PATENT APPLICATION

(21) Application number: 87304213.9

(22) Date of filing: 12.05.87

(51) Int. Cl.³: B 01 F 3/04
E 21 B 43/26

(30) Priority: 16.05.86 US 864621
19.05.86 US 864696

(43) Date of publication of application: 25.11.87 Bulletin 87/48

(84) Designated Contracting States: DE ES FR GB IT NL

(71) Applicant: HALLIBURTON COMPANY
P.O. Drawer 1431
Duncan Oklahoma 73536(US)

(72) Inventor: Edgley, Kevin Dale
912 West Elm
Duncan Oklahoma 73533(US)

(72) Inventor: Stromberg, James Lynn
Route 5 Box 649L
Duncan Oklahoma 73533(US)

(72) Inventor: Harris, Phillip Carroll
2002 Woodrock
Duncan Oklahoma 73533(US)

(74) Representative: Wain, Christopher Paul
A.A. THORNTON & CO. Northumberland House 303-306
High Holborn
London WC1V 7LE(GB)

(54) Particle-containing foams.

(57) A foam comprising liquid, gas and particulate matter has a foam quality and a particulate matter concentration as defined by the area enclosed by the trapezium, A, B, C, D, in Figure 3. Such a foam is particularly useful as a fracturing fluid or the like having very high ratios of proppant particulate material to the liquid phase of the foam. These ratios can be substantially higher than even the theoretical maximum ratio available when the proppant is introduced into a foaming apparatus as a proppant/liquid slurry. This is accomplished by a dry sand foam generation process wherein the sand or other particulate material is introduced into a foam generator apparatus as a dry particulate material in a stream of gas which is subsequently mixed with a second liquid stream.

EP 0 246 800 A1

./...

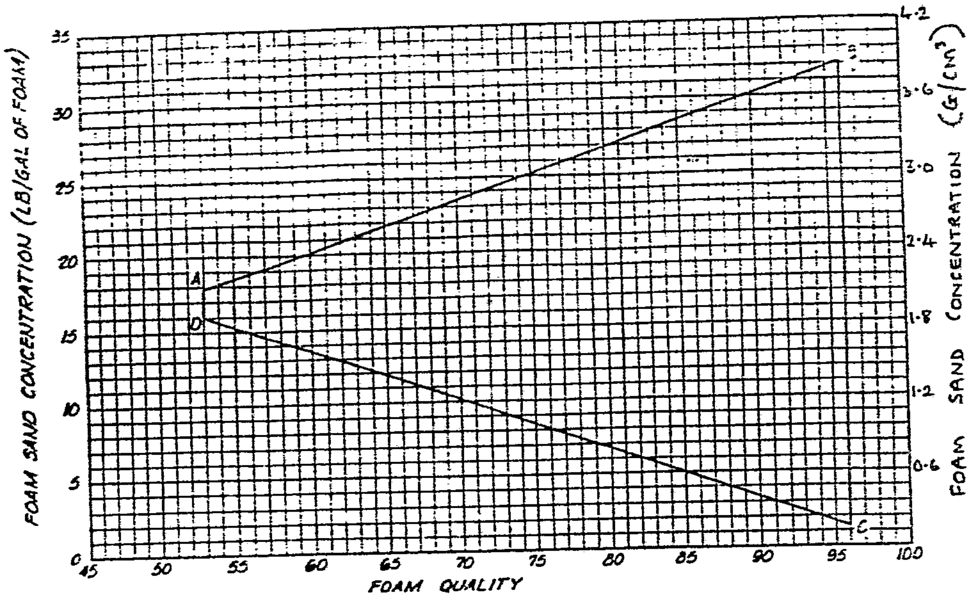

FOAM SAND CONCENTRATION (LB/GAL OF FOAM)
35
30
25
20
15
10
5
0
4·2
3·6
3·0
2·4
1·8
1·2
0·6
FOAM SAND CONCENTRATION (G/CM³)
A
B
C
D
45
50
55
60
65
70
75
80
85
90
95
100
FOAM QUALITY

FIG. 3

PARTICLE-CONTAINING FOAMS

This invention relates generally to particle-containing foams and particularly, but not exclusively, to foamed fracturing fluids carrying high concentrations of proppant material.

During the completion of an oil or gas well, or the like, one technique which is sometimes used to stimulate production is the fracturing of the subsurface producing formation. This is accomplished by pumping a fluid at a very high pressure and rate into the formation to hydraulically create a fracture extending from the well bore out into the formation. In many instances, a proppant material such as sand is included in the fracturing fluid, and subsequently deposited in the fracture to prop the fracture so that it remains open after fracturing pressure has been released from the formation.

In recent years, it has become popular to utilize a fracturing fluid which has been foamed. There are a number of advantages of foamed fracturing fluids which are at this point generally recognized. For example, one advantage is that they have low fluid loss characteristics resulting in more efficient fracture treatments and reduced damage to water sensitive formations. Another advantage is that foamed fracturing fluids have a relatively low hydrostatic head, thus minimizing fluid entry into the formation and its resultsing damage. Also, foamed fracturing fluids have a high effective viscosity permitting the creating of wider vertical fractures and horizontal fractures having greater area. Furthermore, foamed fracturing fluids typically have a high proppant carrying capacity, allowing more proppant to be delivered to the site of the fracture and more proppant to remain suspended until the fracture heals.

Currently available foamed fracturing fluids do have at least one major disadvantage, and this pertains to the proppant concentrations available with currently practiced foam generation techniques. Typically, current techniques involve blending a mixture of proppant and liquid containing a suitable surfactant. The mixture is pumped to high pressure after which a gaseous phase, typically nitrogen or carbon dioxide, is added to produce the foamed proppant-laden fracturing fluid.

This technique involves an inherent proppant concentration limitation due to the concentration limitation of the proppant/liquid mixture. The theoretical maxmium concentration of a sand/liquid mixture is approximately 34 lb of sand per gallon ($4.1 g/cm^3$) of liquid. This corresponds to a liquid volume just sufficient to fill the void spaces of bulk sand. In common practice, this maximum is further limited by the blending and pumping equipment capabilities and lies in a range of 15 to 25 lb/gal (1.8 to $3.0 g/cm^3$).

Typically, foams are produced which have approximately three unit volumes of gaseous phase per unit volume of liquid phase corresponding to a foam quality, that is a gaseous volume fraction, of 75%. Herein lies the problem: when the liquid phase is foamed, the gas expands the carrier fluid to approximately four times its original volume. A sand concentration of 25 pounds of sand per gallon ($3.0 g/cm^3$) of liquid in a sand/liquid slurry is reduced to approximately 6 pounds of sand per gallon ($0.7 g/cm^3$) of carrier fluid, that is foam, by the process of foaming. Even the theoretical maximum sand concentration of 34 lb/gal ($4.1 g/cm^3$) in the sand/liquid slurry would only produce an 8.5 lb/gal ($1.0 g/cm^3$) concentration in a 75% quality foam.

The concentration of proppant in the fracturing fluid is of considerable importance since this determines the final propped thickness of the fracture. A fracturing fluid with a sand concentration of 34 pounds of sand per gallon ($4.1 g/cm^3$) of carrier fluid could theoretically prop the fracture at its hydraulically created width.

Another problem encountered with many fracturing fluids including foam also involves proppant concentration and this pertains to the fracturing fluid's compatibility with the formation core and formation fluids particularly in gas wells. For example, many formations contain clays which swell when contacted by water base fluids resulting in reduced formation permeability. Foamed fracturing fluids reduce this problem due to their low fluid loss and low hydrostatic head characteristics, both of which result in less fluid entering the formation. However, even with foamed fracturing fluids, the theoretical maximum sand concentration is 34 pounds of sand per gallon ($4.1 g/cm^3$) of liquid phase of the foam and, as previously mentioned, the current practical limit is about 25 pounds per gallon ($3.0 g/cm^3$). A foamed fracturing fluid with a greater concentration of sand to liquid would be highly desirable for water sensitive formations since a given amount of sand could be delivered to the formation with less liquid in the carrier fluid.

Prior to the present invention, one approach to these problems of the inherent limitation of sand concentration in foam, created by the limitations on the proportion of sand which can be carried by the liquid prior to foaming, has been to concentrate the sand in the sand-liquid slurry prior to foaming.

One example of a foam sand concentrator of that type which also generally explains the inherent limitations in the prior art foaming processes, is shown in U.S. Patent No. 4,448,709 to Bullen. Bullen indicates that the physical limitation of the high pressure pumps utilized in his process limits the sand concentration in the initial liquid/sand slurry to about 10 pounds of sand per gallon (1.2g/cm^3) of liquid. When such a slurry is foamed to a 75% quality, the resulting foam carries 2-1/2 pounds of sand per gallon (0.3g/cm^3) of foam, if no concentration is used. The Bullen concentrator is stated to be capable of removing about 50% of the liquid from the slurry, thus doubling the proppant concentration in the subsequent foam to a maximum of about 5 pounds per gallon (0.6g/cm^3) of 75% quality foam, that is 20 pounds per gallon (2.4g/cm^3) of liquid in the resulting foam.

Other examples of devices which concentrate sand in the slurry prior to foaming are disclosed in U.S. Patent Nos. 4,126,181 and 4,354,552. Such processes have utilized mechanical devices such as centrifugal separators or cyclone separators to remove a portion of the liquid present in the solids-containing slurry prior to foaming of the concentrated slurry. In general, these processes provide proppant concentrations in the slurry of no more than about 20 pounds per gallon (2.4g/cm^3) of liquid.

Thus, it is apparent that although the prior art has recognized the problem of the inherent limitations on sand concentration in foamed proppant carrying fracturing fluids, no satisfactory solution to the problem has been provided prior to the present invention.

The present invention provides foamed compositions in which sand concentrations many times greater than even the theoretical maximum sand to liquid concentration of sand-containing slurries of 34 pounds sand per gallon ($4.1 g/cm^3$) of liquid phase can be achieved. Tests have produced stable foams having sand to liquid ratios up to 100 pounds of sand per gallon ($12 g/cm^3$) of liquid phase in the foam.

According to the present invention, there is provided a foam composition containing a foam comprising liquid, gas and particulate matter, characterised by a foam quality and a particulate matter concentration as defined by the area enclosed by the trapezium A,B,C,D in Figure 3 of the accompanying drawings.

These compositions of the present invention can be produced by introducing sand at high pressures with a gas stream into a mixing vessel, and introducing a high pressure liquid stream separately into the vessel, thus mixing the gas, liquid and sand at high pressure in the foam generator vessel. This process avoids the inherent sand carrying limitation present when the sand is introduced in a sand/liquid slurry.

In order that the invention may be more fully understood, reference is made to the accompanying drawings, wherein:

FIG. 1 shows a sectioned elevation view of a dry sand foam generator in combination with a schematic illustration of associated equipment utilized with the foam generator, in one embodiment of the process of the invention;

FIG. 2 is a graphical illustration of the compositions of the present invention as well as the theoretical maximum sand concentrations of the prior art wet sand foam generation techniques as a function of foam quality. On the left-hand vertical axis of Fig. 2, the foam sand concentrations are expressed relative to the volume of foam, and on the right-hand vertical axis, the liquid sand concentrations are displayed relative to the volume of liquid phase contained in the foam.

FIG. 3 is a graphical definition of the compositions of the present invention as a function of foam quality and particulate concentration.

Referring now to the drawings, and particularly to Fig. 1, a system generally designated by the numeral 10 is illustrated for producing foamed fracturing fluids carrying high concentrations of proppant material in accordance with the principles of the present invention. The system 10 is based upon the use of a dry sand foam generating apparatus generally designated by the numeral 12.

Although the invention is described in the context of the production of a proppant carrying foam for hydraulic fracturing of a well, the invention is also useful in other areas utilizing foamed fluids, such as foamed gravel packing wherein sand or the like is packed in an annulus surrounding a well casing. Further, while specific reference to a particulate material comprising sand will be discussed, it is to be understood that any other particulate may be utilized such as, for example, sintered bauxite, glass beads, calcined bauxite and resin particles, as well as any other conventionally known particulates for use in the treatment of subterranean formations.

The foam generating apparatus 12 has a body 14 with a straight vertical main flow passage 16 disposed therethrough. Main flow passage 16 has an inlet 18 at its upper end, and an outlet 20 at its lower end.

Foam generating apparatus 12 includes an upper first nozzle insert 22 threadably engaged at 24 with an upper threaded counterbore 26 of body 14. Nozzle insert 22 has an inner end 28 received in the body 14 and adjustably positioned relative to an annular conically tapered first seat 30 surrounding main flow passage 16.

Inner end 28 of nozzle insert 22 has a conically tapered annular surface 32 defined thereon. The conical taper of surface 32 is complementary with that of annular seat 30, that is, the taper on both the surface 32 and seat 30 are substantially the same. In the example shown, surface 32 and seat 30 are each tapered 60° from the horizontal.

An annular conical first flow path 34 is defined between tapered surface 32 and seat 30 and has width defined vertically in Fig. 1 which is adjustable by adjustment of the threaded engagement 24 between insert 22 and body 14.

Below the threaded engagement 24, insert 22 has a reduced diameter cylindrical outer portion 36 closely received within an upper cylindrical bore 38 of body 14 with a seal being provided therebetween by O-ring 40.

Below cylindrical portion 36 is a further reduced diameter nozzle end portion 42 of insert 22.

An upper annular plenum 44 is defined between nozzle portion 42 of insert 22 and upper bore 38 of body 14, and surrounds the main flow passage 16.

A transverse liquid inlet passage 46, which may generally be referred to as a second flow passage 46, is disposed in the body 14. Inlet passage 46 has an outer inlet end 48, and an inner second end 50 which is communicated with the annular plenum 44.

As is further explained below, liquid inlet passage 46 is utilized to introduce a liquid stream, generally a water-based liquid including surfactant, into the foam generating apparatus 12. The liquid stream also may contain other additives such as a viscosifying agent, crosslinking agent, gel breakers, corrosion inhibitors, clay stabilizers, various salts such as potassium chloride and the like which are well known conventional additives to fluids utilized in the treatment of subterranean formations.

The viscosifying agent can comprise, for example, hydratable polymers which contain in sufficient concentration and reactive position, one or more of the functional groups, such as, hydroxyl or hydroxyalkyl, cis-hydroxyl, carboxyl, sulfate, sulfonate, amino or amide. Particularly suitable such polymers are polysaccharides and derivatives thereof, which include but are not limited to, guar gum and derivatives thereof, locust bean gum, tara, konjak, tamarind, starch, karaya, tragacanth, carrageenan, xanthan and cellulose derivatives. Hydratable synthetic polymers include, but are not limited to, polyacrylate, polymethacrylate, polyacrylamide, maleic anhydride-methylvinyl ether copolymers, polyvinyl alcohol and the like.

Various crosslinking agents for the above-viscosifying agents are well known and include, but are not limited to, compounds containing titanium (IV) such as various organotitanium chelates, compounds containing zirconium IV such as various organozirconium chelates, various borate-containing compounds, pyroantimonates and the like.

A lower second nozzle insert 52 is threadably engaged at 54 with an internally threaded lower counterbore 56 of body 14.

Second nozzle insert 52 is constructed similar to first nozzle insert 22, except that its upper inner end has a radially inner conical tapered surface 58 which is complimentary with a downward facing conically tapered second annular seat 60 defined on body 14 and surrounding main flow passage 16. In the example shown, surface 58 and seat 60 are each tapered 15° from the horizontal.

Although the tapered annular openings associated with seats 30 and 60 are each tapered downwardly in Fig. 1, the apparatus 12 can be inverted with the seats 30 and 60 then being tapered upwardly so that the conical fluid jets ejected therefrom are directed against the downward flow of gas and sand through flow passage 16.

A lower second annular plenum 62 is defined between second nozzle insert 52 and lower counterbore 64 of body 14.

A transverse supplemental gas inlet passage 66 is disposed in body 14 and communicates a supplemental gas inlet 68 thereof with the second plenum 62.

As is further explained below, transverse gas inlet passage 66 and the adjustable lower nozzle insert 52 are utilized to provide supplemental gas, if necessary, to the proppant carrying foam. In some instances, however, such supplemental gas may not be necessary, and the transverse gas inlet passage 66 will not be used. In fact, the methods of the present invention can in many instances be satisfactorily performed with a foam generator in which the lower second nozzle insert 52 and the associated transverse gas inlet passage 66 are eliminated.

The main flow passage 16 can generally be described as including an upper portion 70 disposed through first nozzle insert 22, a middle portion 72 defined within the body 14 itself, and a lower portion 74 defined in second nozzle insert 52.

Also schematically illustrated in Fig. 1 are a plurality of associated apparatus which are utilized with the foam generating apparatus 12 to produce a proppant laden foamed fracturing fluid.

A high pressure sand tank 76 is located vertically directly above the foam generating apparatus 12. Sand tank 76 is substantially filled with a particulate material such as sand 78 through a sand fill inlet valve 80.

The sand tank 76 is then filled with high pressure nitrogen gas from a nitrogen gas supply 82 through primary nitrogen supply line 84. A pressure regulator 86 and other conventional equipment (not shown) for controlling the pressure of the gas supplied to sand tank 76 are included in supply line 84. While gas supply 82 is disclosed herein as comprising nitrogen, many other gases are suitable for use in generating a foam according to the method and using the apparatus of the present invention. Such other gases include without limitation air and carbon dioxide, as well as any inert gas, such as any of the noble gases.

As the sand tank 76 is filled with sand 78, it is pressurized with nitrogen gas to a relatively high pressure, preferably above 500 psi (3.45 MPa) for reasons that are further explained below.

This dry sand 78 is introduced into the foam generating apparatus 12 by opening a valve 88 in sand supply line 90 which extend from a bottom 92 of sand tank 76 to inlet 18 of main flow passage 16 of foam generating apparatus 12. The sand supply line 90 preferably is a straight vertical conduit, and the valve 88 is preferably a full opening type valve such as a fully opening ball valve.

When the valve 88 is opened, a stream of gas and sand is introduced into the main flow passage 16 of apparatus 12 through insert 22. The dry sand 78 flows by the action of gravity and differential gas pressure downward through sand supply line 90 into the vertical bore 16 of foam generating apparatus 12.

A water based liquid 94 is contained in a liquid supply tank 96. A high pressure pump 98 takes the liquid 94 from supply tank 96 through a suction line 100 and discharges it under high pressure through a high pressure liquid discharge line 102 to the inlet 48 of transverse liquid inlet passage 46.

The liquid 94 in supply tank 96 will have a sufficient concentration of a suitable surfactant mixed therewith in tank 96, so that upon mixing the liquid 94 with gas and sand in flow passage 16, a stable foam will be formed. Suitable surfactants are well known in the art, and include, by way of example and not limitation, betaines, sulfated or sulfonated alkoxylates, alkyl quaternary amines, alkoxylated linear alcohols, alkyl sulfonates, alkyl aryl sulfonates, C_{10} - C_{20} alkyldiphenyl ether sulfonates and the like.

The liquid and surfactant flow through the transverse liquid inlet passage 46 into the annular plenum 44. The liquid and surfactant then flow from the annular plenum 44 in the form of a self-impinging conical jet flowing substantially symmetrically through the first annular flow passage 34 and impinging upon the vertically downward flowing stream of gas and sand flowing through main flow passage 16.

This high pressure, high speed, self-impinging conical jet of water based liquid and surfactant mixes with the downward flowing stream of gas and dry sand in a highly turbulent manner so as to produce a foam comprised of a liquid matrix of bubbles filled with nitrogen gas. This foam carries the sand in suspension therein.

If supplemental gas, in addition to the gas introduced with the dry sand from sand tank 76, is required to achieve the desired foam quality, that gas is supplied from nitrogen gas supply 82 through a supplemental gas supply line 110 having a second pressure regulator 112 disposed therein. Supplemental gas supply line 110 connects to supplemental gas inlet 68 of transverse gas inlet passage 66 so that gas is introduced into the second annular plenum 62 and then through the conical flow passage defined between conically tapered surface 58 on the inner end of lower nozzle insert 52 and the tapered annular lower set 60 of body 14.

In the testing of the foam generating apparatus 12 which has been done to date, however, it has been determined that in many instances sufficient gas can be introduced with the dry sand 78 from the sand tank 76, and that the desired foam quality can be controlled by controlling the amount of liquid introduced through transverse liquid inlet passage 46.

The proppant laden foam generated in the foam generating apparatus 12 exits the outlet 20 and is conducted through conduit 114 to a well 116. As will be understood by those skilled in the art, the foam fracturing fluid is directed downwardly through tubing (not shown) in the well 116 to a subsurface formation (not shown) which is to be fractured.

When conducting a hydraulic fracturing operation, the pressure of the fracturing fluids contained in conduit 114 when introduced into the well head 116 are substantially in excess of atmospheric pressure. Well head pressures in a range from 1000 psi to 10,000 psi (6.89 to 68.9 MPa) are common for hydraulic fracturing operations.

The delivery rate of dry sand 78 into the foam generator 12 is controlled by the differential gas pressure between the sand tank 76 and the bore 16 of the foam generator apparatus 12. For a given sand delivery rate, flow rate of the liquid jet entering transverse liquid inlet passage 46 determines the liquid sand concentration, that is, the pounds of sand per gallon of liquid phase in the carrier fluid, of the generated foam. The volume rate of gas through sand supply line 90 required to deliver the dry sand together with the volume rate of supplemental gas, if any, supplied through transverse gas inlet passage 66 determine the quality, that is, the gaseous volume fraction of fluid phases of the generated foam.

If it is desired to vary the flow rate of dry sand 78 into the foam generating apparatus 12, that will generally be accomplished by varying the nitrogen pressure supplied to the sand tank 76.

If it is desired to vary the flow of liquid to the transverse liquid inlet passage 46 of foam generator 12, that will be accomplished by varying the pumping rate of pump 98.

The setting of the threaded engagement of upper nozzle insert 22 with body 14, permits adjustment of the width of annular flow passage 34. This adjustment generally is utilized for the purpose of achieving an appropriate mixing energy and, thus, a satisfactory foaming of the materials which are mixing within the main flow passage 16.

Although not shown in Fig. 1, suitable flowmeters may be placed in lines 84, 102 and 110, if desired. Flow of sand out of tank 76 can be measured by measuring a change in weight of the tank 76 and its contents.

Referring now to Fig. 2, a graphical representation is presented of the theoretical maximum sand concentration of a foam as a function of foam quality, both for wet sand foam generation such as has been practiced in the prior art where the sand is introduced in a sand/liquid slurry, and for dry sand foam generation as disclosed in the present application wherein the sand is introduced with a stream of gas. There are two sets of data displayed in Fig. 2. Foam sand concentration, e.g., the pounds of sand per gallon of foam, is displayed vertically on the left side of the graph. The values displayed on the right-hand vertical axis of Fig. 2 are for liquid sand concentrations, e.g., pounds of sand per gallon of liquid phase of the foam.

Looking first at the foam sand concentrations displayed on the left-hand vertical axis of Fig. 2, the theoretical maximum foam sand concentration for a wet sand foam generation process like that utilized in the prior art is shown by the dashed line 118 and is seen to be a decreasing linear function of foam quality. The plotted maximum concentrations for the wet sand foam generation process as represented by line 118 are obtained by adding sufficient gas volume to the liquid occupying the void volume of bulk sand to obtain a given foam quality.

The theoretical maximum foam sand concentration for the dry sand foam generation process of the present invention is represented by the solid line 120 and is seen to be an increasing linear function of foam quality. The plotted maximum concentrations for the dry sand foam generation process as represented by straight line 120 are obtained by adding sufficient liquid to the gas volume occupying the void volume of bulk sand to obtain a given foam quality.

It is noted that the theoretical maximum lines 118 and 120 intersect at a point 122 corresponding to a 50% foam quality. At a 50% foam quality, both the wet sand foam generation process represented by line 118 and the dry sand foam generation process represented by line 120 would provide an identical foam since they both contain equal volumes of gas and liquid and an identical amount of sand. It must be remembered, however, that the values shown in Fig. 2 are theoretical maxima which differ substantially from the practical maxima which can be obtained in wet sand foam generations processes.

It is generally desired that the foam composition produced by the present invention have a "Mitchell quality", that is, a volume ratio of the gaseous phase to the total gaseous and liquid phases and disregarding the volume of the particulate solids, in the range from about 0.53 to 0.99 during at least some portion of the treatment of a subterranean formation with such foam composition. This can also be expressed as a quality in the range from about 53% to about 99%. A general discussion of the Mitchell quality concept can be found in U.S. Patent Nos. 4,480,696 to Almond et al; 4,448,709 to Bullen and 3,937,283 to Blauer et al.

For the purposes of the present invention, it is preferred that an upper limit of foam quality be about 96% because the properties of the foam become somewhat unpredictable at higher quality levels where the foam may convert to a mist. Thus, the generally preferred range of quality for foams generated by the dry sand foam generation process of the present invention is in a range from about 53% to about 96%.

Referring now to the liquid sand concentrations displayed on the right-hand vertical axis of Fig. 2, the theoretical maximum liquid sand concentrations for the prior art wet sand foam generation process and for the dry sand foam generation process of the present invention are shown by dashed line 124 and solid line 126, respectively.

For the prior art wet sand foam generation processes, line 124 shows a constant 34 lb/gal (4.1g/cm^3) theoretical maximum liquid sand concentration. As previously explained, this is determined by the volume of liquid required to fill the void spaces in tightly packed sand.

However, for the dry sand foam generation process of the present invention as represented by solid line 126, the maximum liquid sand concentration is unbounded as the foam quality approaches 100%.

As is apparent from the graphical comparisons shown in Fig. 2, the potential for achieving high sand concentrations in a proppant carrying foam utilizing the dry sand foam generation techniques of the present invention is many times greater than that using prior art wet sand foam generation techniques.

With the methods of the present invention, proppant carrying foamed fracturing fluid compositions can be produced which contain a ratio of sand to the liquid phase of the foam, that is, a liquid sand concentration such as that represented on the right-hand vertical axis of Fig. 2, substantially in excess of both the theoretical maximum ratio of particulate material to liquid which could have been contained in the liquid, such as 34 lbs/gal (4.1g/cm^3), and the somewhat lower practical maximum ratio, such as 15 to 25 lbs/gal (1.8 to 3.0g/cm^3), which could have been contained in the liquid as a result of limitations on pumping equipment and the like. In this regard, referring now to Fig. 3, the compositions of the present invention are those denoted by the trapezoidal region defined by the points A,B,C and D.

A number of laboratory tests, which are described below, have been performed with the dry sand foam generation process of the present invention, and it has been determined that with the apparatus illustrated in Fig. 1, it is desirable that the process be performed with a nitrogen gas pressure within the sand tank 76 at least equal to about 500 psi (3.45 MPa). At such supply pressures, the pressure drop between tank 76 and bore 16 of foam generating apparatus 12 is only about 5 psi (34.5 kPa), so that the pressure at which the foam is generated in bore 16 is also equal to at least about 500 psi (3.45 MPa).

Tests have been conducted utilizing a gas pressure in sand tank 76 ranging from about 50 psi (345 kPa) up to about 1,000 psi (6.89 MPa). At nitrogen pressures in sand tank 76 lower than about 500 psi (3.45 MPa), it has been observed that there is an excess of gas present in the foam generating apparatus 12, and a continuous uniform foam is not produced; instead, the fluid exiting outlet 20 has intermittent slugs of gas contained in the foam.

With nitrogen gas pressures in sand tank 76 in excess of about 500 psi (3.45 MPa), a continuous substantially uniform foamed fluid is produced.

The tests to date have all been run with water based fluids, varying from plain water up to a viscosified fluid containing 40-pounds of derivatized guar per 1000 gallons of water (4.8g/cm^3), all with satisfactory results.

All tests to date have been run utilizing a surfactant sold under the trade name "Howco Suds", a water-soluble biodegradable surfactant blend, which can be obtained from Halliburton Services in Duncan, Oklahoma.

Example 1

An early test was conducted utilizing a pressurized air source at 82 rather than pressurized nitrogen. The sand tank 76 was pressurized to approximately 75 psi (520 kPa) with compressed air. The differential pressure between sand tank 76 and main flow passage 16 of the foam generator was about 50 pst (345 kPa). The test was run until a five-gallon bucket (1.9 x 10^{-2} m^3) was filled with foam exiting outlet 20. The weight of sand delivered from sand tank 76, and water delivered from supply tank 96 were determined, and converted on a volume basis. In that manner it was determined that the five gallons (1.9×10^{-2} m^3) of foam collected included 1.32 gallons (5.0×10^{-3} m^3) of sand and 0.37 gallons (1.4×10^{-3} m^3) of water. The remaining volume of the five gallons (1.9×10^{-2} m^3) of foam, such as, 3.31 gallons ($1.3 \times 10^{-2} m^3$) was comprised of air. From this data, a foam quality of 89.9% was calculated. The liquid sand concentration was calculated to be 74.9 pounds of sand per gallon (9.0 g/cm^3) of water in the foam, which corresponds to 7.53 pounds of sand per gallon (0.9 g/cm^3) of foam. In this test, the liquid was actually introduced through passage 66 rather than passage 46, so that the liquid entered flow passage 16 as a concentric conical jet tapered downwardly at an angle of 15° to the horizontal. The foam generating apparatus 12 utilized in this test had a bore 16 with a diameter of 3/8 inch (9.5mm).

Example 2

A later test was run, again using a foam generator with a 3/8-inch (9.5mm) bore. In this example, the liquid stream was injected into passage 46 so that it entered the main flow passage 16 at a downward angle of 60° to the horizontal. Air pressure supplied to the top of tank 76 was at 69 psi (475 kPa). Air pressure measured in line 90 immediately above the apparatus 12 was 50 psi (345 kPa). A liquid flow rate through line 102 of 0.34 gallon (1.3×10^{-3} m^3) per minute at a pressure of 175 psi (1206 kPa) was measured. A total weight of sand injected was measured to be 41.64 pounds (18.9 kg). Again, the test was run until a five-gallon (1.9×10^{-2} m^3) can of foam was produced. The sand volume in the foam was calculated to be 1.89 gallons (7.2×10^{-3} m^3). The liquid volume in the foam was calculated to be 0.42 gallon (1.6×10^{-3} m^3). This left an air volume in the foam of 2.69 gallons (1.0×10^{-2} m^3). From this a quality of 86.5% was determined. A liquid sand concentration of 99.9 pounds of sand per gallon (12.0g/cm^3) of liquid phase of the foam was calculated. This foam was observed to be a good stable foam.

In both of Examples 1 and 2 described above, it was observed that there was substantial excess air present in the process, as slugs of air were intermittently produced from outlet 20 between slugs of foam.

Substantial further testing was conducted and modifications were made to attempt to eliminate this excess air. Testing was done utilizing centrifugal separators to separate the foam from the excess air.

Finally, later testing showed that the problem of excess air was eliminated when the pressure of gas supplied to sand tank 76 exceeded about 500 psi (3.45 MPa). This is shown in the following Example 3.

Example 3

This test was run using a foam generator with a 5/8 inch (15.9mm) bore. The liquid stream was injected into passage 46 so that it entered the main flow passage 16 at a downward angle of 60° to the horizontal. The test apparatus was modified to allow the generated foam to be collected in a receiver vessel (not shown) at approximately the same pressure at which it was generated. The volume of generated foam was determined by measuring a volume of water displaced from the receiver vessel. An average nitrogen pressure in sand tank 76 was 756 psig (5.2 MPa gauge). Average pressure in the bore 16 of foam generating apparatus 12 was 750 psig (5.2 MPa gauge). Average pressure in the foam receiver vessel was 730 psig (5.0 MPa gauge). The test was run for 5.0 minutes. Total sand weight delivered was 292 lb. (133 kg) for a sand rate of 58.4 lb/min (26.5 kg/min). Total liquid supplied was 3.0 gal (1.1×10^{-2} m^3) for a liquid rate of 0.60 gallons per minute (2.3×10^{-2} m^3 per minute). The gas flow rate of the apparatus 12 was calculated to be 55.7 standard cubic feet (1.56 m^3) per minute. Total foam generated was 57.37 gal (0.22 m^3). From this data, a foam quality at the foam generator 12 of 93% was calculated. A liquid sand concentration of 97.3 pounds of sand per gallon (11.7g/cm^3) of liquid phase of the foam was calculated. This corresponds to a foam sand concentration of 6.8 pounds of sand per gallon (0.8g/cm^3) of foam. A volumetric rate of foam production at the generator was 11.26 gallons (4.3×10^{-2} m^3) per minute.

Finally, it has been determined subsequent to the testing described above, that at high gas supply pressures, e.g., 900 psi (6.2 MPa), it is not necessary to direct the liquid phase into the foam generator as a self-impinging conical jet; instead a simply "tee" can be used to mix the liquid with the gas and dry sand.

Thus, it is seen that the apparatus and methods of the present invention readily achieve the ends and advantages mentioned as well as those inherent therein. While certain preferred embodiments of the invention have been illustrated for the purposes of the present disclosure, numerous changes in the arrangement and construction of parts and steps may be made by those skilled in the art, which changes are encompassed within the scope and spirit of the present invention.

CLAIMS:

1. A foam comprising liquid, gas and particulate matter, characterised by a foam quality and a particulate matter concentration as defined by the area enclosed by the trapezium A,B,C,D in Figure 3 of the accompanying drawings.

2. A foam according to claim 1, wherein the gas is one or more of air, nitrogen, carbon dioxide and the noble gases.

3. A foam according to claim 1 or 2, wherein the particulate matter comprises at least one of sand, sintered bauxite, calcined bauxite and glass beads.

4. A foam according to claim 1,2 or 3, which also includes a viscosifying agent.

5. A foam according to any of claims 1 to 4 which has been produced by:

(a) introducing a quantity of liquid into a vessel,

(b) introducing a gas and a particulate material into said vessel,

(c) mixing said liquid with said gas and particulate material and thereby forming a foam composition as defined.

6. A foam according to claim 5, wherein in process step (a), said liquid is introduced as a first stream into an annular plenum surrounding a cylindrical bore of said vessel and communicating with said bore by an annular opening surrounding said bore; and in process step (b) said gas and particulate are admixed and introduced as a second stream into said cylindrical bore of said vessel; and in process step (c), said liquid first stream flows

radially inward through said annular opening to impinge upon said second stream.

7. A foam according to claim 5 or 6, wherein the process steps (a), (b) and (c) are performed at pressures of at least about 500 psi (3.45 MPa).

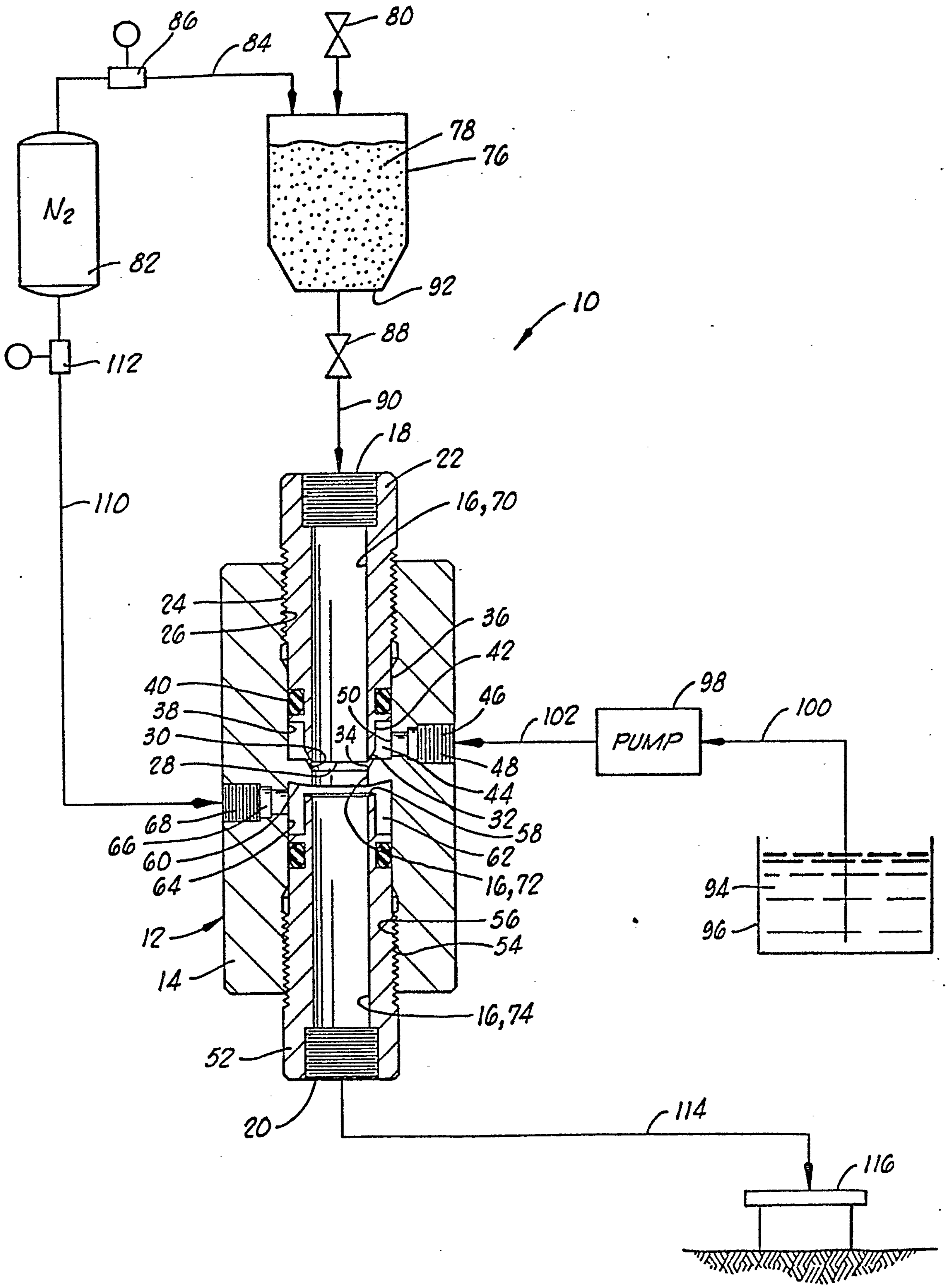

86
84
80
78
76
N2
82
92
10
88
112
90
18
22
16,70
110
24
26
36
42
40
38
30
28
50
34
46
102
98
PUMP
100
48
44
32
58
68
66
60
64
62
16,72
94
96
56
54
12
14
16,74
52
20
114
116

FIG. 1

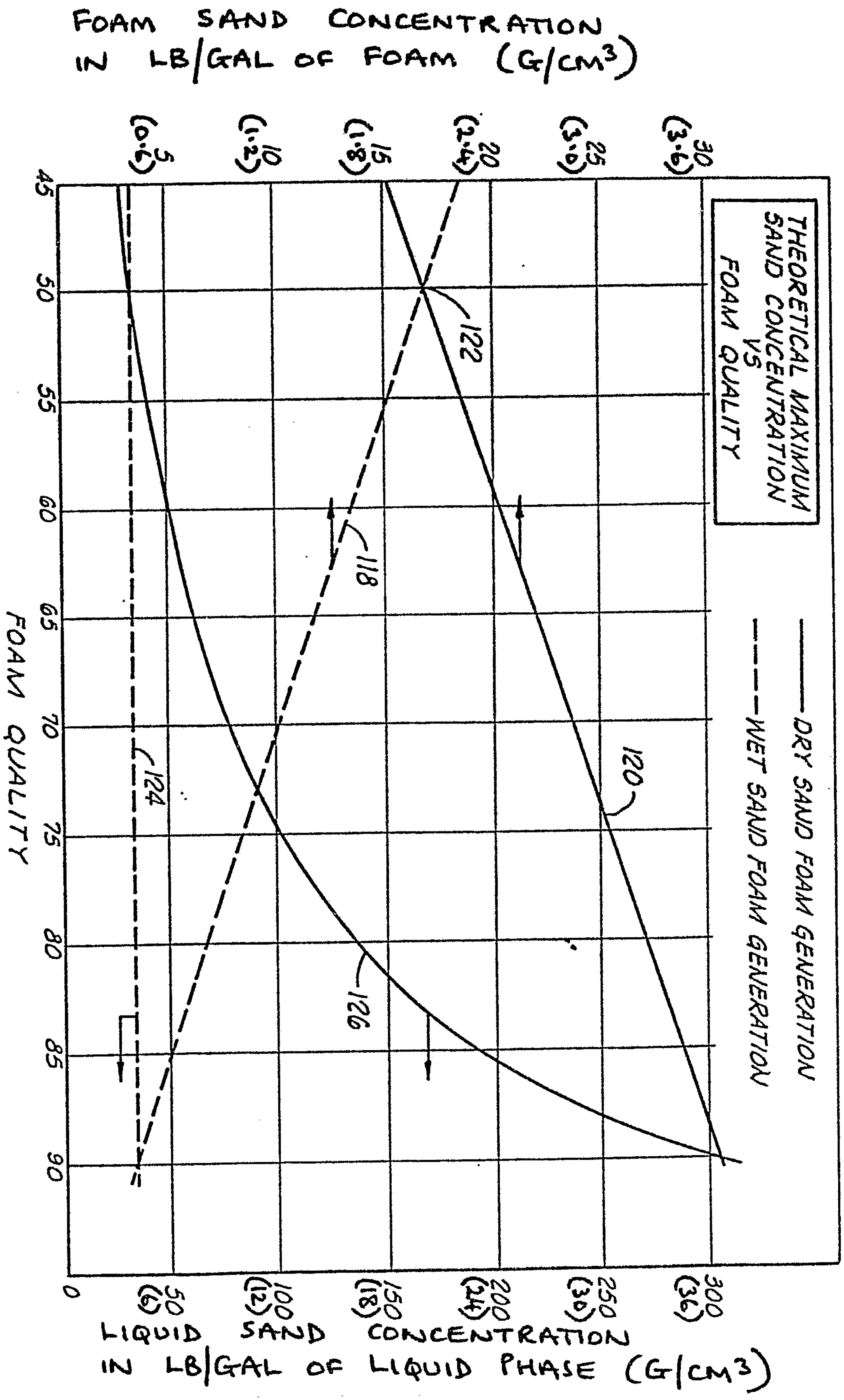
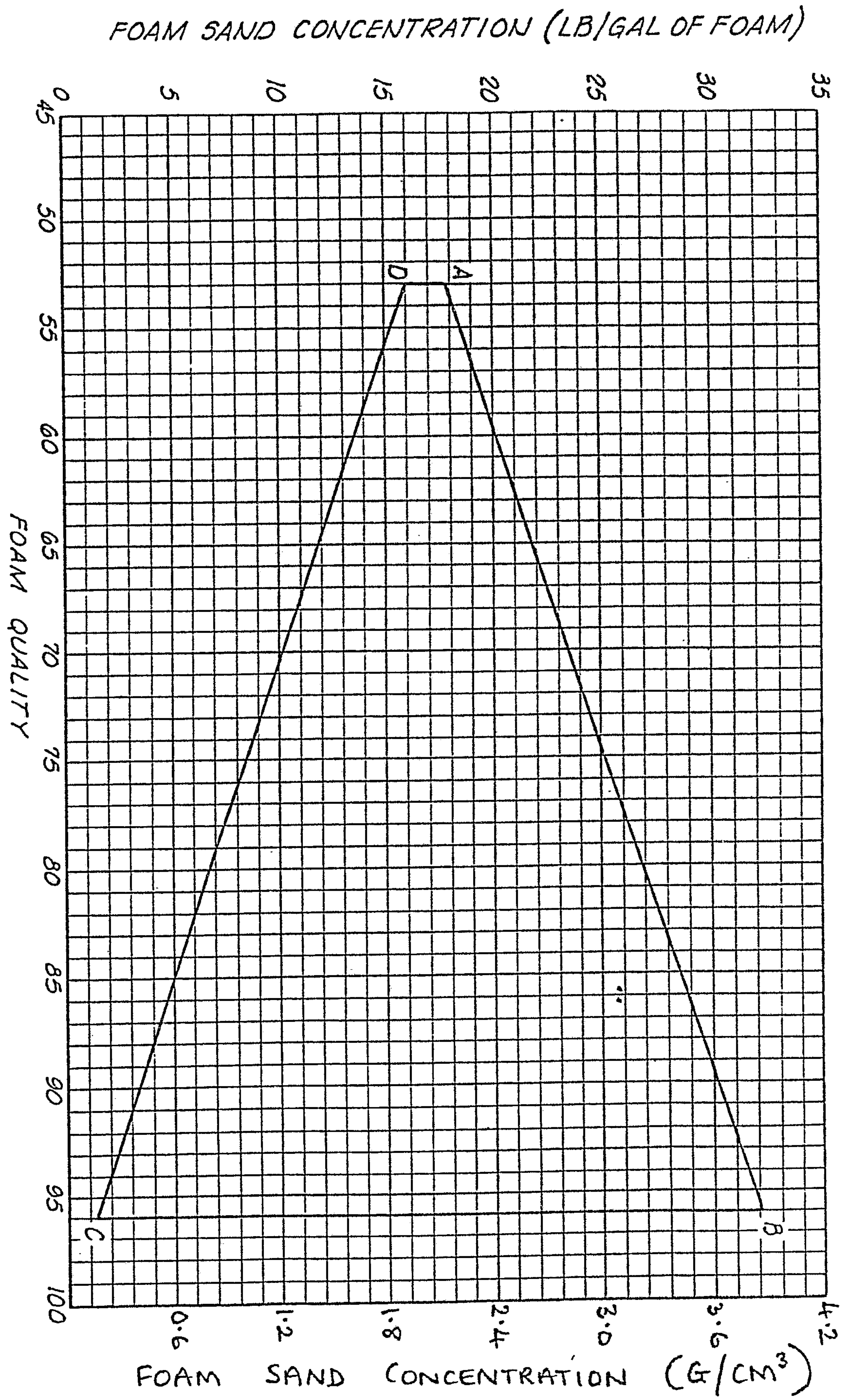

FOAM SAND CONCENTRATION
IN LB/GAL OF FOAM (G/CM3)
5 (0.6)
10 (1.2)
15 (1.8)
20 (2.4)
25 (3.0)
30 (3.6)
THEORETICAL MAXIMUM SAND CONCENTRATION VS FOAM QUALITY
DRY SAND FOAM GENERATION
WET SAND FOAM GENERATION
45
50
55
60
65
70
75
80
85
90
FOAM QUALITY
122
118
120
124
126
0
50 (6)
100 (12)
150 (18)
200 (24)
250 (30)
300 (36)
LIQUID SAND CONCENTRATION
IN LB/GAL OF LIQUID PHASE (G/CM3)

FIG. 2

0246800


FOAM SAND CONCENTRATION (LB/GAL OF FOAM)
0
5
10
15
20
25
30
35
FOAM QUALITY
45
50
55
60
65
70
75
80
85
90
95
100
A
B
C
D
0·6
1·2
1·8
2·4
3·0
3·6
4·2
FOAM SAND CONCENTRATION (G/CM³)

European Patent Office

EUROPEAN SEARCH REPORT

Application number

EP 87 30 4213

DOCUMENTS CONSIDERED TO BE RELEVANT

Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (Int Cl 4)
A	PETROLEUM ENGINEER INTERNATIONAL, vol. 57, no. 1, January 1985, pages 50,53-54,56-58,60, Dallas, Texas, US; S.N. SHAH et al.: "Ultrahigh sand concentrations boost Oklahoma production" * Page 50, column 1 *	1-3	B 01 F 3/04 E 21 B 43/26
A,D	US-A-4 448 709 (BULLEN) * Column 4, line 61 - column 5, line 12 *	1	
A,D	US-A-4 126 181 (BLACK) * Column 2, line 53 - column 3, line 18; column 4, lines 16-21; column 5, lines 19-23 *	1-3	
A	EP-A-0 145 227 (HALLIBURTON CO.) * Abstract; figure 1 *	5	TECHNICAL FIELDS SEARCHED (Int Cl 4) B 01 F E 21 B
A	FR-A-2 521 869 (DEBRECENI MEZOGAZDASAGI GEPGYARTO ES SZOLGALTATO VALLALAT)	6	

The present search report has been drawn up for all claims

Place of search	Date of completion of the search	Examiner
THE HAGUE	04-09-1987	ASHLEY G.W.

CATEGORY OF CITED DOCUMENTS

X : particularly relevant if taken alone
Y : particularly relevant if combined with another document of the same category
A : technological background
O : non-written disclosure
P : intermediate document

T : theory or principle underlying the invention
E : earlier patent document, but published on, or after the filing date
D : document cited in the application
L : document cited for other reasons

& : member of the same patent family, corresponding document