



- (51) **International Patent Classification:**
E21B 43/117 (2006.01) *E21B 43/119* (2006.01)
- (21) **International Application Number:**
PCT/GB2016/052330
- (22) **International Filing Date:**
28 July 2016 (28.07.2016)
- (25) **Filing Language:** English
- (26) **Publication Language:** English
- (30) **Priority Data:**
1513269.9 28 July 2015 (28.07.2015) GB
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(81) **Designated States** (unless otherwise indicated, for every kind of national protection available): AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BN, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IR, IS, JP, KE, KG, KN, KP, KR, KZ, LA, LC, LK, LR, LS, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PA, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SA, SC, SD, SE, SG, SK, SL, SM, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

(84) **Designated States** (unless otherwise indicated, for every kind of regional protection available): ARIPO (BW, GH, GM, KE, LR, LS, MW, MZ, NA, RW, SD, SL, ST, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, RU, TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, KM, ML, MR, NE, SN, TD, TG).

Published:

— with international search report (Art. 21(3))

(54) **Title:** PERFORATING GUN ASSEMBLY AND METHODS OF USE

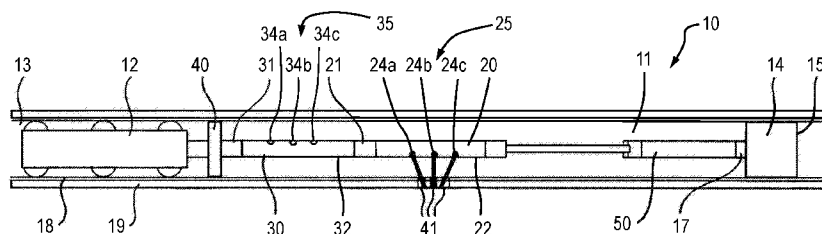


Fig. 1A

(57) **Abstract:** In one aspect, the method comprises providing a perforating gun assembly having a first group of shaped charges on a first longitudinal portion of the assembly and a second group of shaped charges on a second longitudinal portion of the assembly. The orientations of the first and second groups are rotationally offset from one another around a longitudinal axis of the perforating gun assembly. The method comprises locating the perforating gun assembly in a wellbore with the first group of shaped charges adjacent a wall of the wellbore at a perforation location, and detonating the shaped charges to form a first perforation channel in the wellbore with a defined first fracture initiation point. The perforating gun assembly is translated in the wellbore to locate the second group of shaped charges oriented towards a defined second fracture initiation point, at a desired axial position with respect to the first fracture initiation point.

1 Perforating Gun Assembly and Methods of Use

2

3 The present invention relates to a perforating gun assembly and a method of use in
4 perforating and/or hydraulic fracturing applications. In particular, but not exclusively, the
5 invention relates to a perforating gun assembly comprising convergent shaped charge
6 orientations and a method of use in a perforating operation prior to fracture initiation.
7 Aspects of the invention relate to hydraulic fracturing methods.

8

9 Background to the invention

10

11 In the hydrocarbon exploration and production industry, it is common to use perforating
12 guns to form fluid communication paths ("perforations") in a subterranean formation
13 between a hydrocarbon reservoir and a drilled wellbore that traverses the reservoir. The
14 communication paths enable the inflow of production fluids into the wellbore, and enable
15 the delivery of stimulation fluids to the formation, for example during hydraulic fracturing
16 operations. Typically perforating methods are applied to cased hole wellbores, which
17 include a casing string cemented within the wellbore to increase the integrity of the
18 wellbore and provide a flow path to surface for fluids produced from the formation. The
19 perforations extend through the steel casing, the cement on the outside of the casing, and
20 into the formation. Similar methods are used in the fields of water and geothermal
21 exploration.

1 It is conventional to form the perforations by placing a perforating gun which incorporates
2 shaped charges inside the casing string next to the formation to be perforated. A typical
3 perforating gun comprises a charge carrier and a series of shaped charges connected to a
4 detonator by a detonation cord. The perforating gun forms a part of a tool string which is
5 conveyed into the wellbore by a flexible line, drill string, coiled tubing, or other conveyance.
6 Commonly, flexible line such as wireline, electric line or slickline is used to convey the
7 perforating gun to the required wellbore depth. With the charge carriers located in the
8 interval to be perforated, the shaped charges are detonated to generate high-pressure
9 streams of particles in the form of jets. The jets penetrate through the casing, the cement
10 and into the formation. The shaped charge weights, design, and orientation determine the
11 size, depth of penetration and direction of the resulting perforation geometry.

12
13 Various factors contribute to the effect of the perforations on the productivity of the well or
14 the success of a fracturing operation. These include depth and effective diameter of
15 perforation tunnels. One technique for generating perforations with improved inflow
16 characteristics is to use groups or banks of convergent or focused shaped charges.
17 US 3,347,314, US 7,303,017, US 7,172,023 and US 7,409,992 are examples of
18 perforating devices which used convergent charge groups to create an enhanced
19 perforation cavity.

20
21 In longer perforation intervals, fracture tortuosity and multiple fracture events, both of
22 which hamper the design objective of Limited Entry, can be prevalent. The issues are
23 exacerbated in high angle or horizontal wells where regional (tectonic) stress effects
24 dominate the fracture growth pattern, with the perforation itself being a secondary factor.
25 Limiting the perforation interval to a very short section (for example as low as 1ft to 2ft or
26 0.3m to 0.6m) can have benefits towards reducing the fracture tortuosity and multiple
27 fracture events, and facilitating Limited Entry fracturing, particularly in high angle or
28 horizontal wells. Convergent charge configurations can go some way to achieving Limited
29 Entry, but disadvantages of convergent charge configurations of the types described in
30 US 3,347,314, US 7,303,017, US 7,172,023 and US 7,409,992 result from the requirement
31 for the shaped charges to operate in functional groups. This places restrictions on shaped
32 charge placement and phasing, which can have an adverse effect on production flow
33 geometry in a radial direction around the wellbore.

1 US 3,695,368 discloses a perforating method for production enhancement which uses a
2 perforator with one or more sets of longitudinally spaced charges. After a first perforation
3 is formed, the tool is axially repositioned before detonation of a second charge. The
4 second charge forms a perforation contiguous with the first perforation.

5
6 RU 2473788 describes an alternative method of forming a wellbore perforation in a two-
7 stage process for improved in-flow of production fluids. In a first perforating cycle, either
8 deep hole or big hole perforations are formed by detonation of deep hole or big hole
9 shaped charges at a particular wellbore location. The perforating tool is removed and
10 reloaded with deep hole or big hole charges (which may be the same or different from the
11 charges used in the first perforation cycle). The reloaded gun is run into hole and in a
12 second perforating cycle, the charges are detonated at the same wellbore location.

13
14 WO2013/019390 describes a fracturing method which uses a tool with multiple convergent
15 charge groups to create discrete fracture initiation sites at distinct locations, by
16 repositioning the tool between detonations.

17
18 US2014/0020896 describes a method and apparatus for conducting multiple successive
19 firings of perforating guns at a particular location in an openhole wellbore. The described
20 method places a gun with n shaped charges at a particular location in the openhole and
21 detonates the charges to create openings which penetrate the formation. The gun is
22 retrieved and a reloaded (or second) gun is run to the same location to align $n-1$ charges
23 with the openings. The method is repeated to provide relatively deep perforations which
24 bypass the near-wellbore damaged formation and which are stated to be suitable for
25 fracture initiation.

26
27 US 2,679, 898 describes an oriented gun perforating method which uses an orienting
28 means to enable two groups of perforations to be placed in a desired spaced position with
29 respect to one another.

30
31
32

1 Summary of the invention

2
3 It is amongst the aims and objects of the invention to provide a perforating gun assembly
4 and a method of use in perforating and/or hydraulic fracturing applications which is an
5 alternative to the methods and apparatus described above.
6

7 It is amongst the aims and objects of the invention to provide a perforating gun assembly
8 and a method of use in perforating and/or hydraulic fracturing applications which obviates
9 or mitigates drawbacks and deficiencies of previously proposed apparatus and methods.
10

11 It is amongst the aims and objects of the invention to provide a perforating gun assembly
12 and a method of use in perforating and/or hydraulic fracturing applications which provides
13 improved perforation connectivity and/or fracture initiation.
14

15 An aim of an aspect and embodiment of the invention is to provide a perforating gun
16 assembly and a method of use in perforating and/or hydraulic fracturing applications which
17 provides discrete fracture initiation sites with improved placement control.
18

19 Additional aims and objects of the invention will become apparent from reading the
20 following description.
21

22 According to a first aspect of the invention, there is provided a method of perforating a
23 wellbore in a hydraulic fracturing operation, the method comprising:

- 24 - providing a perforating gun assembly comprising a first group of shaped charges on
25 a first longitudinal portion of the assembly and a second group of shaped charges on
26 a second longitudinal portion of the assembly, wherein the first group of shaped
27 charges comprises at least two shaped charges arranged to generate jets oriented
28 substantially along respective axes that converge towards one another in a first
29 convergence plane, and wherein the second group of shaped charges comprises at
30 least two shaped charges arranged to generate jets oriented substantially along
31 respective axes that converge towards one another in a second convergence plane,
32 and wherein the first and second planes of convergence are rotationally offset from
33 one another around a longitudinal axis of the perforating gun assembly;
34 - locating the perforating gun assembly in a wellbore with the first group of shaped
35 charges adjacent a wall of the wellbore at a perforation location;

- 1 - detonating the shaped charges of the first group of shaped charges to form a first perforation channel in the wellbore with a defined first fracture initiation point;
- 2 - translating the perforating gun assembly in the wellbore to locate the second group of shaped charges adjacent the wellbore at the perforation location such that the position of the second group of shaped charges orients the shaped charges towards a defined second fracture initiation point; and
- 3 - detonating the shaped charges of the second group of shaped charges to form a second perforation channel in the wellbore which overlaps with the first perforation channel in an axial direction of the wellbore, which is rotationally offset from the first perforation channel around a longitudinal axis of the wellbore, and which forms a defined second fracture initiation point at a desired axial position with respect to the first fracture initiation point.

The rotational offset between the first and second convergence planes of the first and second groups of charges enables placement of perforation channels at distinct azimuthal angles, where both channels cross cut a fracture plane. The method is not limited by gun geometry or size.

The first and second convergence planes may be at any selected angle between 0 and 360 degrees. In an embodiment, the first and second planes may be phased at 180 degrees. In other words, the first and second planes may be oriented so that the respective perforation channels are phased at 180 degrees to one another. Alternatively, the first and second planes may be oriented at an angle between 0 and 180 degrees, or an angle between 180 degrees and 360 degrees.

The wellbore may be an openhole wellbore, but in preferred embodiments is a cased or lined wellbore.

The first and/or second perforation channels may be formed by the detonation of large holes in a first detonation event, and the detonation of deep penetrating charges in a subsequent detonation event. The method may comprise the step of detonating deep penetrating shaped charges to generate jets which pass through one or more large holes formed in a previous detonation event. The method may form at least two deep penetration holes in the formation adjacent the perforation location, wherein the least two deep penetration holes intersect to provide a connected channel in the formation.

1 The method may comprise forming at least one of the first or second perforation channels
2 by detonating one or more large hole shaped charges, translating the perforating gun
3 assembly, and detonating deep penetrating shaped charges to generate jets which pass
4 through one or more large holes formed by the large hole shaped charges.

5
6 The method may comprise providing a third group of shaped charges, and detonating the
7 shaped charges of the third group of shaped charges to form a third perforation channel in
8 the wellbore with a defined third fracture initiation point. Preferably the third group of
9 shaped charges is on the same perforating gun assembly as the first and second groups
10 of shaped charges. The method may comprise translating the perforating gun assembly in
11 the wellbore to locate the third group of shaped charges adjacent the wellbore at the
12 perforation location such that the position of the third fracture initiation point at a desired
13 axial position with respect to the first and second fracture initiation point. The method may
14 be repeated for fourth and/or further groups of shaped charges and fracture initiation
15 points. Therefore the method may provide a means of creating a plurality of fracture
16 initiation points at desired axial position by translation of a gun assembly between
17 detonation events. One or more of the desired axial positions may be on a preferred
18 fracture plane. The desired axial positions may be in a plane perpendicular to the main
19 axis of the wellbore.

20
21 According to a second aspect of the invention, there is provided a method of perforating
22 and fracturing a wellbore, the method comprising:

- 23 - carrying out the method of the first aspect of the invention;
24 - pumping a fracturing fluid into the wellbore to the perforation location and into the
25 perforation channels; and
26 - initiating and propagating a fracture from the first and second fracture initiation
27 points.

28
29 The terms "upper", "lower", "above", "below", "up" and "down" are used herein to indicate
30 relative positions in the wellbore. The invention also has applications in wells that are
31 deviated or horizontal, and when these terms are applied to such wells, they may indicate
32 "left", "right" or other relative positions in the context of the orientation of the well.

33
34 Embodiments of the second aspect of the invention may include one or more features of
35 the first aspect of the invention or its embodiments, or vice versa.

1 According to a third aspect of the invention, there is provided a perforating gun assembly
2 comprising:

3 a first group of shaped charges on a first longitudinal portion of the assembly, the first
4 group of shaped charges comprising at least two shaped charges arranged to generate
5 jets oriented substantially along respective axes that converge towards one another in a
6 first convergence plane;

7 a second group of shaped charges on a second longitudinal portion of the assembly, the
8 second group of shaped charges comprising at least two shaped charges arranged to
9 generate jets oriented substantially along respective axes that converge towards one
10 another in a second convergence plane;

11 a first detonator for detonating the shaped charges of the first group of shaped charges to
12 form a first perforation channel in a wellbore with a defined first fracture initiation point;

13 a second detonator for detonating the shaped charges of the second group of shaped
14 charges to form a second perforation channel in the wellbore with a defined second,
15 fracture initiation point, wherein the second perforation channel overlaps with the first
16 perforation channel in an axial direction of the wellbore;

17 an anchor for securing the perforating gun assembly in the wellbore with the first group of
18 shaped charges adjacent the wellbore at a perforation location; and

19 a positioning and alignment module configured to translate the perforating gun assembly in
20 the wellbore to a second axial position, which locates the second group of shaped charges
21 adjacent the wellbore at the perforation location such that the position of the second group
22 of shaped charges orients the shaped charges towards a defined second fracture initiation
23 point;

24 wherein the first and second planes of convergence are rotationally offset from one
25 another around a longitudinal axis of the perforating gun assembly;

26 and wherein, in the second axial position, the second group of shaped charges are
27 oriented to form a second perforation channel in the wellbore which overlaps with the first
28 perforation channel in an axial direction of the wellbore, which is rotationally offset from the
29 first perforation channel around a longitudinal axis of the wellbore, and which forms a
30 defined second fracture initiation point at a desired axial position with respect to the first
31 fracture initiation point.

32
33 The first and second detonators may form a part of a single detonation system, for
34 example a select fire detonation system, or may be separate and distinct detonators.

35

1 The first and/or second groups of shaped charges may form a part of first and/or second
2 collections of shaped charges on the first and/or second longitudinal portions respectively.
3 Each collection may comprise more than one group of shaped charges which interacts to
4 form a perforation channel.

5
6 At least two shaped charges within each group may be arranged to generate jets oriented
7 substantially along respective axes that converge towards one another. The at least two
8 groups of shaped charges of the first or the second longitudinal portions of the assembly
9 may therefore be intermeshed or interlaced in a longitudinal direction of the assembly.

10
11 The assembly may comprise at least two groups of shaped charges rotationally offset or
12 phased around the longitudinal axis of the gun module.

13
14 One or more groups of shaped charges may be arranged in a line parallel to the
15 longitudinal axis of the gun module. Preferably each group of shaped charges is arranged
16 in a line parallel to the longitudinal axis of the gun module.

17
18 In one example, the assembly comprises first and second groups of shaped charges to
19 form first and second perforation channels which overlap one another and are rotationally
20 offset by 180 degrees. In this example, the first and second perforation channels may
21 have first and second major diameters oriented substantially in the same plane.

22
23 The use of convergent shaped charges which overlap one another has benefits in
24 hydraulic fracturing applications. The perforation channels formed by the inventive
25 assembly are more closely aligned which aids fracture growth and placement control, as
26 fracture initiation points are positioned axially close to one another. An additional
27 unexpected benefit is improved gun survivability as a result of the overlapping, and
28 optional phasing, of groups of convergent shaped charges. The intermeshing of charges
29 promotes the distribution and dissipation of shock wave forces through the perforating gun
30 assembly, and increases the integrity of the perforating gun assembly and tool string
31 without compromises regarding charge placement, charge capacity, or material and
32 manufacturing costs.

33
34 Preferably the perforating gun assembly also comprises a housing, and the charge carrier
35 is disposed within the housing. The housing may comprise a substantially cylindrical

1 member, which may define a cylindrical bore in which the charge carrier is disposed. The
2 charge carrier may be co-axial with the housing.

3
4 In the context of this description, the term "housing" is used to refer to an outer housing or
5 casing of the perforating gun assembly, and the term "charge carrier" is used to describe a
6 structure to which the shaped charges are mounted (directly or indirectly) in their desired
7 groupings and/or orientations.

8
9 The perforating gun assembly may comprise an anchor for securing the assembly in a
10 cased or lined wellbore.

11
12 The assembly may comprise a positioning and alignment module configured to translate
13 the perforating gun assembly in the wellbore.

14
15 The assembly may comprise a guide shaft and a guide housing, the guide shaft being
16 movable within the guide housing to translate the perforating gun assembly in the
17 wellbore. The guide shaft may be movable from a first position, in which the first gun
18 module is adjacent the casing or liner at a perforation location; and a second position in
19 which the second gun module is adjacent the casing or liner at the perforation location
20 such that the position of the second group of shaped charges corresponds a desired axial
21 position with respect to a detonation position of the first group of shaped charges.

22
23 Preferably, the positioning and alignment module comprises one or more guide keys co-
24 operating with one or more guide keyways.

25
26 Preferably, the positioning and alignment module comprises one or more shear pins,
27 which may be configured to maintain the guide shaft in its first position. The shear pins
28 may be configured to be sheared by a force applied to the assembly.

29
30 The method may comprise assisting the translation of the perforating gun assembly using
31 a spring.

32
33 The method may comprise translating the perforating gun assembly by applying a force to
34 at least a portion of the perforating gun assembly. The force may be a motive force from a
35 downhole tractor, which may form a part of the perforating gun assembly. Alternatively, or

1 in addition, the motive force may be a tensile force or a compressive force or downweight
2 applied from surface.

3
4 The assembly may comprise at least one sealed chamber, and the method may comprise
5 breaking or rupturing a seal to the sealed chamber.

6
7 The sealed chamber, which may be pressure isolated from the wellbore, may comprise a
8 liquid filled chamber in a first condition. The liquid filled chamber may prevent translation
9 of the perforating gun assembly with respect to the anchor in its first condition.

10
11 The method may comprise breaking or rupturing a seal to the sealed chamber to enable
12 liquid to be expelled from the chamber. The method may comprise expelling liquid from
13 the chamber during translation of the perforating gun assembly with respect to the anchor.

14
15 The method may comprise breaking or rupturing a seal by detonation of the first gun
16 module.

17
18 The seal may comprise a rupture disc.

19
20 The method may comprise translating the perforating gun assembly by applying a force to
21 at least a portion of the perforating gun assembly, wherein the force is applied by exposing
22 at least a portion of the gun assembly to a wellbore pressure.

23
24 The perforating gun assembly may comprise a pressure chamber, which in its first
25 condition is sealed and isolated from a wellbore pressure, and is at a pressure lower than
26 a wellbore pressure. The pressure chamber may be filled with air at atmospheric
27 pressure.

28
29 The method may comprise exposing the pressure chamber to wellbore pressure, thereby
30 causing wellbore fluids to enter the chamber. The method may comprise exposing at least
31 a portion of the positioning and alignment module to wellbore pressure, to actuate
32 movement of the guide shaft in the guide housing, and thereby translate the perforating
33 gun assembly. The method may comprise exposing at least a portion of the positioning
34 and alignment module to wellbore pressure by detonation of the first gun module.

1 Embodiments of the third aspect of the invention may include one or more features of the
2 first or second aspects of the invention or their embodiments, or vice versa.

3
4 According to a fourth aspect of the invention, there is provided a perforating gun assembly
5 comprising:

6 a charge carrier having a longitudinal axis;

7 a first group of shaped charges comprising at least two shaped charges arranged to
8 generate jets oriented substantially along respective axes that converge towards one
9 another in a first convergence plane to a first focal point;

10 a second group of shaped charges comprising at least two shaped charges arranged to
11 generate jets oriented substantially along respective axes that converge towards one
12 another in a second convergence plane to a second focal point;

13 wherein in at least one of the groups of shaped charges, a convergence angle between
14 the orientation direction of two shaped charges within the group is selected to locate its
15 focal point at a position which is axially offset from an axial midpoint between the
16 outermost charges in the group.

17
18 Preferably, in a first group of shaped charges, a convergence angle between the
19 orientation direction of two shaped charges within the first group is selected to locate its
20 focal point at an axial position closer to a second group of charges than a midpoint of the
21 first group.

22
23 Preferably, convergence angles of charges within the group are asymmetrical.

24
25 Convergence angles of charges within first and second groups may be selected to place
26 their respective focal points closer to one another than their respective midpoints.

27
28 The at least two groups of shaped charges may be intermeshed or interlaced in a
29 longitudinal direction of the charge carrier.

30
31 Embodiments of the fourth aspect of the invention may include one or more features of the
32 first to third aspects of the invention or their embodiments, or vice versa.

33
34 According to a fifth aspect of the invention, there is provided a method of perforating a
35 wellbore in a hydraulic fracturing operation, the method comprising:

1 providing a perforating gun assembly comprising a charge carrier having a longitudinal
2 axis; a first group of shaped charges comprising at least two shaped charges arranged to
3 generate jets oriented substantially along respective axes that converge towards one
4 another in a first convergence plane;
5 a second group of shaped charges comprising at least two shaped charges arranged to
6 generate jets oriented substantially along respective axes that converge towards one
7 another in a second convergence plane;
8 wherein in at least one of the groups of shaped charges, a convergence angle between
9 the orientation direction of two shaped charges within the group is selected to locate its
10 focal point at a position which is axially offset from an axial midpoint between the
11 outermost charges in the group;
12 locating the perforating gun assembly in a wellbore at a perforation location;
13 detonating the first and second groups of charges to form first and second perforation
14 channels, having defined first and second fracture initiation points respectively;
15 wherein at least one of the defined first and second fracture initiation points is located at a
16 position which is axially offset from an axial midpoint between the outermost shaped
17 charges in its respective group.

18
19 At least one of the defined first and second fracture initiation points may be located on or
20 close to a principle fracturing plane.

21
22 Embodiments of the fifth aspect of the invention may include one or more features of the
23 first to fourth aspects of the invention or their embodiments, or vice versa.

24
25 According to a sixth aspect of the invention, there is provided a method of perforating and
26 fracturing a cased or lined wellbore, the method comprising:
27 carrying out the method of the fifth aspect of the invention;
28 pumping a fracturing fluid into the wellbore to the perforation location and into the
29 perforation channels; and
30 initiating and propagating a fracture from the defined first and second fracture initiation
31 points.

32
33 Embodiments of the sixth aspect of the invention may include one or more features of the
34 first to fourth aspects of the invention or their embodiments, or vice versa.

35

1 According to a further aspect of the invention, there is provided a perforating gun assembly
2 substantially as described herein with reference to Figures 1A, 1B, 2A and 2B of the
3 drawings.

4
5 According to a further aspect of the invention, there is provided a perforating gun assembly
6 substantially as described herein with reference to Figures 4A and 4B of the drawings.

7
8 According to a further aspect of the invention, there is provided a method of performing a
9 hydraulic fracturing operation substantially as described herein with reference to Figures 1
10 to 3D of the drawings.

11
12 According to a further aspect of the invention, there is provided a method of performing a
13 hydraulic fracturing operation substantially as described herein with reference to Figures
14 6A to 6C of the drawings.

15
16 According to further aspects of the invention, there are provided methods of performing a
17 hydraulic fracturing operation substantially as described herein with reference to any of
18 Figures 8 to 13 of the drawings.

19
20 Brief description of the drawings

21
22 There will now be described, by way of example only, a various embodiments of the
23 invention with reference to the drawings, of which:

24
25 Figure 1A is a schematic sectional view of a perforating gun assembly in accordance with
26 a first embodiment of the invention in an initial detonation position;

27
28 Figure 1B is a schematic sectional view of the perforating gun assembly of Figure 1A in a
29 second detonation position;

30
31 Figure 2A is a schematic sectional view of the positioning and alignment module of the gun
32 assembly of Figure 1A, showing internal components;

33
34 Figure 2B is a schematic sectional view of an alignment mechanism of the positioning and
35 alignment module of the gun assembly of Figure 2A;

1 Figures 3A to 3D are schematic representations of sequential steps of a perforating
2 method using the perforating gun assembly of Figures 1 and 2 in accordance with an
3 embodiment of the invention;

4
5 Figure 4A is a schematic sectional view of a positioning and alignment module of a gun
6 assembly according to an alternative embodiment of the invention, showing internal
7 components;

8
9 Figure 4B is a schematic sectional view of an alignment mechanism of the positioning and
10 alignment module of the gun assembly of Figure 4A;

11
12 Figure 5 is a part-sectional view of a charge carrier of a perforating gun assembly
13 according to an alternative embodiment of the invention;

14
15 Figures 6A to 6C are schematic representations of sequential steps of a perforating
16 method using the perforating gun assembly of Figure 5, in accordance with an
17 embodiment of the invention;

18
19 Figure 7 is a schematic representation of a prior art perforating geometry using two groups
20 of convergent charges;

21
22 Figure 8 is a schematic representation of a perforating orientation in accordance with an
23 embodiment of the invention;

24
25 Figure 9 is a schematic representation of a perforating orientation in accordance with an
26 alternative embodiment of the invention;

27
28 Figure 10 is a schematic representation of a perforating orientation in accordance with an
29 alternative embodiment of the invention;

30
31 Figure 11 is a schematic representation of a perforating geometry with two intermeshed
32 groups of charges, in accordance with an embodiment of the invention;

33
34 Figure 12 is a schematic representation of a perforating geometry with two intermeshed
35 groups of charges, in accordance with an alternative embodiment of the invention;

Figure 13 is a schematic representation of an oriented group of fracture initiation points in accordance with an embodiment of the invention.

Detailed description of preferred embodiments

Referring firstly to Figures 1A and 1B, there is shown schematically a perforating gun assembly, generally depicted at 10, located in a cased wellbore 11. Figure 1A shows the assembly 10 in an initial detonation position, and Figure 1B shows the perforating gun assembly of Figure 1A in a second detonation position, as will be described below. It is an aim of the invention to provide a perforating gun assembly for hydraulic fracturing applications, and the following embodiments of the invention will be described in that context. However, the invention has application to alternative reservoir treatment operations, and its benefits may also arise where the invention is applied to injection of other fluids, such as in water and or gas flood operations, in which breakdown (fracturing) of the formation is often (but not necessarily) a consequence of such operations.

The assembly 10 is designed to be deployed on a wireline or other flexible conveyance (not shown) with the assistance of a wireline tractor 12 located at the upper end 13 of the assembly. A lower packer 14 is provided at the lower end 15 of the assembly 10. A packer setting tool 17 connects the packer 14 to the assembly, enabling the packer 14 to anchor the assembly 10 against the casing 18 at its required depth and provide a fluid barrier in the wellbore at the lower end of the assembly.

The assembly comprises a first lower gun module 20, axially separated from the lower end 15 of the assembly, and a second, upper gun module 30, located between the lower gun module 20 and the upper end 13 of the assembly. A first detonator module 21 is associated with the lower gun module 20, and a second detonator 31 is associated with the upper gun module 30. The first and second detonation modules 21, 31 are controlled from surface and are independently switchable to detonate the first and second gun modules respectively. A centraliser device 40 provides centralisation and support for the assembly, and in this example is located between the upper gun module 30 and the wireline tractor 12.

A positioning and alignment module 50 connects the packer 14 to the lower gun module 20 via the packer setting tool 17. The positioning and alignment module 50, which will be

described in more detail below, functions to enable translation of the assembly between defined first and second detonation positions shown in Figures 1A and 1B respectively.

Each of the lower and upper gun modules 20, 30 comprises a housing 22, 32 which forms a casing for the internal components of the gun module. Each housing is a substantially cylindrical hollow tube, with an internal bore sized to receive and accommodate a charge carrier. The charge carrier functions to support a number of shaped charges 24a, 24b, 24c, 34a, 34b, and 34c (together 24 and 34 respectively). The shaped charges are ballistic elements as are known in the field of wellbore perforation and hydraulic fracturing. Each includes a housing, a liner, and a quantity of explosives between the housing and the liner. On detonation the shaped charges generate a high pressure stream of particles referred to as a jet. The jet direction depends on the orientation of the shaped charge within the gun assembly.

The charge carriers of this embodiment are substantially cylindrical hollow tubes of unitary construction which extend over an axial length of the gun assembly. Arranged over its length are a number of apertures, which extend from the outer wall of the charge carrier to a bore defined by the charge carrier. Each aperture is sized and shaped to receive a shaped charge in its desired orientation. Corresponding mounting holes are located diametrically opposite the apertures and provide a fixing point for the shaped charge in its desired orientation. The apertures and holes enable the shaped charge to be mounted at a fixed angle with respect to a plane perpendicular to the longitudinal axis L of the charge carrier. The orientation of the apertures and the mounting holes together determines the orientation of the shaped charges, and consequently the direction of jets resulting from the detonation of the shaped charges and the nature of the perforations formed.

The shaped charges 24, 34 are configured to form a hole in the casing 18 and cement lining 19. It will be appreciated that charges of different weights may be used in the first and/or second gun modules, and the invention is not restricted to configurations which have equal charge weights in the first and second sets of charges.

The shaped charges of each gun module 20, 30 are arranged in functional groups of converging charges. In upper module 30, a group of shaped charges 35 comprises shaped charges 34a, 34b and 34c, all of which are oriented in a line parallel to the longitudinal axis such that they are in the same plane parallel to the longitudinal axis

(which may be referred to as a convergence plane). Two of the charges, 34a and 34c, are oriented with their axes at angles inclined to a plane which is perpendicular to the longitudinal axis of the charge carrier such that they converge towards one another. In addition, the axis of charge 34b is oriented towards the point of intersection of the axes of charges 34a and 34c. The three shaped charges in the group are therefore oriented to converge to the same focal point in the formation.

In the first (lower) gun module 20, the large hole shaped charges 24a,b,c are also arranged in a functional group of converging charges, with orientation axes corresponding to the axes of the group of shaped charges 35, but rotationally offset, in this case by 180 degrees. The group of shaped charges 25 consists of shaped charges 24a, 24b and 24c.

The perforating gun assembly 10 also contains a detonation system which in this case comprises a pair of detonation modules 21, 31 and corresponding detonation cords (not shown) which run along the length of the bore of the charge carrier, connecting the shaped charges of their respective modules in series. Each detonation module 21, 31 is independently controllable from surface to detonate the respective gun modules. Other detonation arrangements, such as those that use different detonation sequences or timing delays, may be used in alternative embodiments and are within the scope of the invention.

Figures 2A and 2B show schematically details of the positioning and alignment module 50 of the assembly 10, suitable for use with an assembly which is deployed using a motive force, such as a wireline tractor, coiled tubing, or drill pipe. Figure 2A shows the tool 50 in longitudinal section, and Figure 2B is a cross section through line B-B¹. The tool 50 is located between the lower gun module 20 and the packer setting tool 17, and is shown in Figure 2A in a closed position. The tool comprises a guide shaft 51 extending from the lower gun module 20 into a tubular guide body 52 connected to the lower end of the assembly. An upper end 53 of the guide body 52 has an end plate 54, with an aperture 55 for receiving the guide shaft 51. A sealing ring 56 seals the end plate 54 against the guide shaft 51.

The guide body 52 defines a closed chamber 58 which is filled with a fluid. A bore 59 extending through the guide shaft 51 provides fluid communication to the lower gun module 20, which prior to operation, is sealed by a ported rupture disc sub assembly 60.

1 The bore 59 also accommodates an electrical control line 62 which passes through the
2 chamber 58 to connect the packer setting tool 17 to surface.

3
4 At a lower end 64 of the guide shaft 51 is a pair of guide keys 66. The guide keys 66
5 extend radially outward of the guide shaft 51 into keyways 68 of the guide body 52. The
6 guide shaft is therefore able to slide within the guide body in use, but is rotationally keyed
7 with respect to the guide body. The guide keys 66 are initially secured in the keyways by
8 shear pins 70, preventing movement of the assembly prior to actuation. A power spring 72
9 is disposed between the end plate 54 and a shoulder located adjacent the guide keys.

10
11 A method of use of an embodiment of the invention will now be described with reference to
12 Figures 1A, 1B, 2A, 2B, and 3A to 3D.

13
14 Referring firstly to Figures 1A and 3A, the assembly 10 is deployed on an electric wireline
15 or other flexible conveyance to its required depth in the cased wellbore. When located in
16 the required position, the packer setting tool 17 is actuated via the electrical control line 62
17 to set the packer 14 and anchor the assembly against the casing 18.

18
19 With the packer set, the lower gun module 20 is ready to be detonated. The shear pins 70
20 are intact and retain the positioning and alignment module in its spaced-out position, as
21 shown in Figure 1A. In addition, the fluid chamber 58 remains closed and pressure
22 isolated. The chamber 58 and bore 59 define a fixed fluid volume to the rupture disc sub
23 assembly 60, preventing downward movement of the guide shaft 51 and other
24 components of the assembly.

25
26 The charges of the gun module 20 are detonated, jets 29 from the shaped charges 24
27 result in the formation of perforation channel 42a which penetrates the casing 18 and
28 cement 19 to connect the wellbore with the formation immediately outside of the wellbore
29 (Figure 3B). The convergent charges of the assembly form a perforation channel 42a
30 which is substantially triangular in section and has a defined fracture initiation point at the
31 apex of the channel.

32
33 During detonation of the first gun module 20, the pressure and forces generated from the
34 explosion event are sufficient to break the rupture disc in the sub assembly 60, enabling

1 pressure communication between ports (not shown) in the sub assembly 60 and the
2 chamber 58.

3
4 The wireline tractor 12 is engaged to provide a downward motive force on the assembly
5 10, which is transferred through the guide shaft 51 to the guide keys 66 to shear the pins
6 70. The guide shaft 51 is released from the guide body 52 and the downward motive force
7 from the wireline tractor 12 causes the shaft 51 to move downwards in the guide body.
8 Movement is assisted by the power spring 72. As the shaft 51 moves downwards, fluid
9 from the chamber 58 exits through the bore 59 and the ports (not shown) in the rupture
10 disc sub assembly 60.

11
12 The shaft 51 is only permitted to move with respect to the guide body and packer by a
13 fixed predetermined distance, which is selected to position the shaped charges of the
14 second (upper) gun module 30 directly over the casing entry holes 41 formed by the first
15 detonation, as shown in Figure 1B. A consequence of the assembly being anchored to the
16 packer 14 at the lower end of the assembly is that the operation is executed from a fixed
17 depth reference. Throughout travel of the assembly to its lower position, rotation of the
18 assembly is prevented by the arrangement of guide keys and keyways.

19
20 With the assembly 10 in the second, lower position as shown in Figure 1B, Figure 3C and
21 Figure 3D, the second gun module 30 is ready to be detonated. Optionally, a latch
22 mechanism (not shown) is provided to lock the guide shaft into its lower position, so that
23 when the assembly is recovered to surface, it can be inspected to ensure that the
24 components were properly translated to their required positions before the second
25 detonation. Detonation module 31 is fired to detonate the charges 34 of the second
26 module. The charges are oriented such that they create jets 39 which form perforation
27 channels 42b adjacent the wellbore, at an azimuthal position which is rotationally offset
28 from the channel 42a (in this case by 180 degrees). The convergent charges of the
29 assembly form a perforation channel 42b which is substantially triangular in section and
30 has a defined fracture initiation point at the apex of the channel.

31
32 The described embodiment of the invention enables placement of the second perforation
33 channel 42b at an axial position of the wellbore such that it overlaps with the channel 42a,
34 as shown in Figure 3D. This enables the apex of the channel 42b, which is a fracture
35 initiation point for a hydraulic fracturing operation, to be placed at a desired axial position

1 with respect to the fracture initiation point of the channel 42a. In this embodiment, the
2 respective fracture initiation points are located at the same axial position, in the principal
3 fracture plane of the formation. When hydraulic fluid is pumped into the channels 42a,
4 42b, it is directed towards the apexes of the channels. The placement of both apexes in
5 the principal fracture plane facilitates single planar fracture growth.

6
7 In this embodiment, the preferred fracture direction is the direction of maximum horizontal
8 stress, and the wellbore is drilled predominantly in the direction of minimum horizontal
9 stress. The apexes of the channels, are the convergent points for delivery of fracturing
10 fluid, and are aligned in a single plane which is substantially aligned with the preferred
11 fracture direction (the direction of maximum horizontal stress). This arrangement
12 promotes fracture initiation from the wellbore which cross cuts both perforation channels,
13 in the preferred orientation. The perforation interval has been limited to a very short
14 section, which reduces a tendency for fracture tortuosity and multiple fracture events, and
15 facilitates Limited Entry.

16
17 With conventional perforation assemblies and methods, placement of a pair of fracture
18 initiation points in the same fracture plane is limited by the geometry and size of the
19 perforation assembly. Where convergent charge groups are used, restrictions on shaped
20 charge placement and phasing may prevent placement of two groups of charges, oriented
21 in distinct convergence planes, over the same axial position of the assembly. The
22 described embodiment addresses this issue by forming the perforation channels, and
23 fracture initiation points, during two detonation and perforation events, separated by an
24 axial shift in gun assembly position.

25
26 It will be appreciated that in a variation to the above-described embodiment of the
27 invention, a second perforation channel may be formed with its apex at a position close to,
28 but not necessarily at the same axial point of the apex of the first. The principles of the
29 system may be applied to place the second perforation and its apex at a desired axial
30 position with respect to the first. This may be the same axial position, an axial position
31 close to the first, or an axial position at a desired separation. In the latter case, it may be
32 desirable in some formations and/or wellbore orientations to place respective apexes
33 separated by a distance which places them in alignment with and/or on a principal fracture
34 plane which is not perpendicular to the wellbore. It may be desirable in some formations
35 and/or wellbore orientations, to place respective apexes separated by a distance which

1 places them at a desired angle to a principal fracture plane which is not perpendicular to
2 the wellbore.

3
4 Although the above-described embodiment has the two groups of shaped charges
5 arranged in opposed orientations, such that their rotational offset is 180 degrees, other
6 azimuthal angles of separation are within the scope of the invention. Indeed, the
7 respective groups of shaped charges may be phased at any desired angle, without being
8 limited by gun carrier geometry or size. For example, the convergence plane of a second
9 group of charges may be rotationally offset by 45 degrees, 60 degrees, 90 degrees, 120
10 degrees, or any angle suited to the formation or wellbore geometry. Apexes of the second
11 created perforations may be placed at the same axial position, an axial position close to
12 the first, or an axial position at a desired separation from the first as described above.

13
14 The above-described embodiment of the invention comprises a positioning and alignment
15 module 50 suitable for use with an assembly which is deployed using a motive force, such
16 as a wireline tractor, coiled tubing, or drill pipe. However, the principles of the invention
17 are also applicable where there is no motive force available, and Figures 4A and 4B are
18 schematic views of a positioning and alignment module 150 of a perforating gun assembly
19 according to an alternative embodiment of the invention. Figure 4A shows the module 150
20 in longitudinal section, and Figure 4B is a cross section through line B-B'. The module,
21 generally depicted at 150, is similar to module 50 of Figures 1A, 1B, 2A, and 2B and its
22 principles of operation will be understood from those Figures and their accompanying
23 description. However, the assembly 150 differs in several respects which will be described
24 below.

25
26 The module 150 is located between the lower gun module 20 and the packer setting tool
27 17, and is shown in Figure 4A in a closed position. The tool comprises a spacer shaft 151
28 extending from the lower gun module 20 and connecting to a tubular inner piston mandrel
29 152 connected to the lower end of the assembly. The inner piston mandrel 152 extends
30 into an outer piston mandrel 157. An upper end 153 of the outer piston mandrel 157 has
31 an opening 155 for receiving the inner piston mandrel 152. A sealing ring 156 seals the
32 outer mandrel against the inner mandrel.

33
34 The outer piston mandrel 157 defines a closed chamber 158 which is fluidly connected
35 with the internal volume of the lower gun module 20 via a ported sub assembly 160, and is

1 filled with air at atmospheric pressure and isolated from well pressure. A pathway
2 extending through the module provides a pathway for an electrical control line 162 which
3 passes through the chamber 158 to connect the packer setting tool 17 to surface.
4

5 At a lower end 164 of the inner piston mandrel 152 is a pair of guide keys 166 in the form
6 of lugs extending radially outward of the inner piston mandrel 152 into keyways 168
7 provided in the outer piston mandrel 157. The inner piston mandrel 152 is therefore able
8 to slide within the outer piston mandrel 157 in use, but is rotationally keyed with respect to
9 the outer piston mandrel 157. The mandrels 152, 157 are initially secured to one another
10 by shear pins 170, preventing movement of the assembly prior to actuation.
11

12 The outer piston mandrel 157 comprises reduced inner diameter portions 174, 176 located
13 at the upper end 153 and an axially separated position towards the lower end. The
14 reduced inner diameter portions define an annular piston chamber 177 between the inner
15 and outer piston mandrels. A piston flange 178 upstands from the inner piston mandrel
16 152 and carries an o-ring seal 180 to seal with the inner surface of the outer piston
17 mandrel 157. A damping spring 172 is disposed between the piston flange 178 and a
18 shoulder defined by the reduced inner diameter portion 176. An o-ring seal 182 seals the
19 inner piston mandrel 152 against the reduced inner diameter portion 176. Pressure entry
20 ports 181 connect the inside of the inner piston mandrel 152 with the piston chamber 177.
21

22 In use, a perforating gun assembly comprising the positioning and alignment module 150
23 will be operated in a similar manner to the assembly 10, and will be understood from the
24 description of Figures 1A, 1B, 2A, and 2B. The assembly is deployed on an electric
25 wireline or other flexible conveyance to its required depth in the cased wellbore. When
26 located in the required position, the packer setting tool 17 is actuated via the electrical
27 control line 162 to set the packer 14 and anchor the assembly against the casing 18. With
28 the packer set, the lower gun module 20 is ready to be detonated. The shear pins 170 are
29 intact and retain the positioning and alignment module in its spaced-out position, as shown
30 in Figure 4A. In addition, the chamber 158 remains closed and pressure isolated from the
31 wellbore.
32

33 The charges of the gun module 20 are detonated, resulting in the formation of perforations
34 which penetrate the casing 18 and cement to connect the wellbore with the formation
35 immediately outside of the wellbore. After detonation of the first gun module 20, the

1 internal volume of the gun module is exposed to well pressure, and wellbore fluids enter
2 the gun module and pass through the ported sub assembly 160 to the inside of the inner
3 piston mandrel 152. Well fluids flow under well pressure through the pressure ports 181
4 and into the piston chamber 177, and flow into the chamber until the volume is filled. The
5 force from the well fluids acts on the relatively large face of the piston flange 178 and
6 exceeds the force on the relatively small lower end 183 of the inner piston mandrel 152.
7 The net force overcomes the rating of the shear pins 170 and pushes the inner piston
8 mandrel 152 and upper assembly downwards in the outer piston mandrel 157. Movement
9 is damped by the spring 172.

10
11 As with the previous embodiment, the upper assembly is only permitted to move with
12 respect to the outer piston mandrel 157 and packer 14 by a fixed predetermined distance,
13 which is selected to position the shaped charges of the second (upper) gun module 30 in
14 the desired axial position with respect to the perforation channels formed by the first
15 detonation, in the manner shown in Figure 1B. With the assembly 10 in the second, lower
16 position as shown in Figure 1B, the second gun module 30 is ready to be detonated.

17
18 Further alternatives to the described embodiments are envisaged within the scope of the
19 invention. In one variation, the principle of creating multiple perforations which overlap
20 axially, but which are at distinct azimuthal angles, is combined with a perforating gun
21 assembly and method which uses combinations of large hole and deep-penetrating
22 charges to create each perforation channel. For example, a first gun module may
23 comprise at least one large hole shaped charge, and a second gun module may comprise
24 at least two deep penetrating shaped charges arranged to generate jets oriented
25 substantially along respective axes that converge towards one another. The method may
26 comprise locating the perforating gun assembly in a cased or lined wellbore with the first
27 gun module adjacent a casing or liner at a perforation location and detonating the large
28 hole shaped charges of the first gun module to form one or more large holes in the casing
29 or liner. The perforating gun assembly may be translated in the wellbore to locate the
30 second gun module adjacent the casing or liner at the perforation location such that the
31 position of the deep penetrating shaped charges corresponds to the position of the one or
32 more large holes; and the deep penetrating shaped charges of the second gun module are
33 detonated to generate jets which pass through the one or more large holes and form at
34 least two deep penetration holes in the formation adjacent the perforation location. The at
35 least two deep penetration holes intersect to provide a connected channel in the formation.

1 The large hole area reduces the risk of early screen out of sand, which may bridge smaller
2 entry holes, and reduces the axial extent over which the entry holes need to be formed,
3 shortening the perforation interval and enhancing fracture placement. Advantageously,
4 the single fracture initiation site may be located beyond the damaged zone and hoop
5 stress affected region of the formation. By utilising a two-stage detonation process for
6 each perforation channel, it is possible to use convergent shaped charge groups oriented
7 to intersect at a point relatively deep into the formation.

8
9 The described method and apparatus assists in achieving a Limited Entry fracturing effect.
10 Limited Entry fracturing is desirable as, by design, each perforation is in hydraulic
11 communication and contributes fluid during the fracturing treatment, and therefore offers
12 improved control over the initiation and growth of a fracture from within a given perforation
13 network. Limiting the perforation interval to a very short section (for example as low as 1ft
14 to 2ft or 0.3m to 0.6m) can have benefits towards reducing the fracture tortuosity and
15 multiple fracture events, and facilitating Limited Entry fracturing, particularly in high angle
16 or horizontal wells.

17
18 Shifting of the gun between axial positions may therefore be used (a) to place additional
19 perforations in an already-perforated zone, with a fracture initiation point at desired axial
20 and azimuthal spacing from a previously formed perforation channel, and (b) to align a
21 second set of charges with previously formed large casing entry holes, to create deep
22 penetrating channels through the large casing entry holes.

23
24 The above-described embodiments comprise distinct groups of convergent shaped
25 charges. An alternative embodiment of the invention is illustrated in Figure 5, which shows
26 a charge carrier 200 comprising first and second gun modules 220, 240. The charge
27 carrier 200 is a substantially cylindrical hollow tube of unitary construction which extends
28 over an axial length of the gun assembly. Arranged over its length are a number of
29 apertures 228, which extend from the outer wall of the charge carrier to a bore defined by
30 the charge carrier. Each aperture 228 is sized and shaped to receive a shaped charge in
31 its desired orientation. Corresponding mounting holes 230 are located diametrically
32 opposite the apertures 228 and provide a fixing point for the shaped charge in its desired
33 orientation.

34

1 In this embodiment, the apertures 228 and holes 230 are laser cut holes formed in the wall
2 of the charge carrier. The aperture 228 and its corresponding mounting hole enable the
3 shaped charge to be mounted at a fixed angle with respect to a plane perpendicular to the
4 longitudinal axis of the charge carrier. The orientation of the apertures and the mounting
5 holes together determines the orientation of the shaped charges, and consequently the
6 direction of jets resulting from the detonation of the shaped charges and the nature of the
7 perforations formed.

8
9 The shaped charges of the gun assembly are arranged in collections 216 and 218. Each
10 collection comprises multiple charges and extends over an axial length of the charge
11 carrier, and the collections 216, 218 are axially separated on the charge carrier. Within
12 each collection, the shaped charges are arranged in functional groups of converging
13 charges. In collection 216, a first group of shaped charges comprises shaped charge
14 216a, 216c and 216e, all of which are oriented in a line parallel to the longitudinal axis
15 such that they are in the same plane parallel to the longitudinal axis. Two of the charges,
16 216a and 216e, are oriented with their axes at angles inclined to a plane which is
17 perpendicular to the longitudinal axis of the charge carrier such that they converge towards
18 one another. In addition, the axis of charge 216c is oriented towards the point of
19 intersection of the axes of charges 216a and 216e. The three shaped charges in the
20 group are therefore oriented to converge to the same point in the formation.

21
22 A second group of shaped charges is formed from charges 216b, 216d, and 216f all of
23 which are oriented in a line parallel to the longitudinal axis such that they are in a plane
24 parallel to the longitudinal axis. The plane of the second group is rotationally offset or
25 phased with respect to the first group. In this case the phasing angle is 180 degrees, so
26 that the first and second groups are oriented in the same plane but in opposing directions.
27 Charges 216b and 216f are oriented with their axes at angles inclined to a plane which is
28 perpendicular to the longitudinal axis of the charge carrier such that they converge towards
29 one another. In addition, the axis of charge 216d is oriented towards the point of
30 intersection of the axes of charges 216a and 216e. The three shaped charges in the
31 second group are therefore oriented to converge to the same point in the formation.

32
33 The first and second groups of charges are intermeshed or interlaced such that they
34 overlap over the axial direction of the charge carrier; each group extends over an axial

1 portion which overlaps a perpendicular plane. This configuration of converging charge
2 groups has surprising advantages relating to gun survival and flow geometry.

3
4 Collection of charges 218 comprises two groups of convergent shaped charges (218a,
5 218c, 218e and 218b, 218d, 218f (not shown)) which are intermeshed or interlaced such
6 that they overlap over the axial direction of the charge carrier. The two groups are phased
7 by an angle 180 degrees. In addition, collection 218 is rotationally offset or phased with
8 respect to the collection 216, in this case by an angle of 90 degrees.

9
10 The shaped charges, arranged in functional groups in the charge carrier as described
11 above, are loaded into the perforating gun assembly by locating and securing the charge
12 carrier 200 into the housing 214. The housing 214 also comprises scallops distributed
13 over the surface of the housing in locations which correspond to the positions and
14 orientations of the shaped charges in the assembled gun.

15
16 A method of use of an embodiment of the invention will now be described with additional
17 reference to Figures 6A to 6C. Referring firstly to Figures 5 and 6A, the assembly is
18 deployed on an electric wireline or other flexible conveyance to its required depth in the
19 cased wellbore. When located in the required position, the packer setting tool 17 is
20 actuated via the electrical control line 62 to set the packer 14 and anchor the assembly
21 against the casing 18.

22
23 With the packer set, the lower gun module 220, consisting of a two groups of convergent
24 charges intermeshed with one another, is detonated. Jets 229a, 229b from the shaped
25 charges create perforation channels 242a and 242b which penetrate the casing 18 and
26 cement 19 to connect the wellbore with the formation immediately outside of the wellbore
27 (Figure 6B). The perforation channels 242a, 242b are substantially triangular in section
28 with apexes defining fracture initiation points which are closely spaced to one another due
29 to the intermeshed arrangement of charge groups.

30
31 The wireline tractor 12 is engaged to provide a downward motive force on the assembly,
32 to position the shaped charges of the second (upper) gun module 240 in the wellbore in an
33 axial region which overlaps with an axial region of the perforations 242a, 242b formed by
34 the first detonation, as shown in Figure 6B. Throughout travel of the assembly to its lower

1 position, rotation of the assembly is prevented by the arrangement of guide keys and
2 keyways.

3
4 With the assembly 10 in the second, lower position as shown in Figure 6B, the second gun
5 module 240 is ready to be detonated. The charges are oriented such that they create jets
6 229c, 229d which form perforation channels 242c, 242d (Figure 6C) adjacent the wellbore,
7 at an azimuthal position which is rotationally offset from the channels 242a, 242b (in this
8 case by 90 degrees). The perforation channels 242c, 242d are substantially triangular in
9 section and have defined fracture initiation points at the apex of the channels, closely
10 spaced to one another. The resulting perforation pattern places four fracture initiation
11 points on or close to a single fracture plane of the formation. The placement of all four
12 apexes in or close to the principal fracture plane facilitates single planar fracture growth.

13
14 It will be appreciated that variations to the above-described embodiments are within the
15 scope of the invention. For example, the steps of detonating a first group of charges,
16 translating the gun assembly, and detonating a second group of charges can be repeated
17 multiple times, so that multiple perforating channels can be created at desired axial
18 positions, for example aligned with or close to a principle fracturing plane. Multiple
19 perforation channels can be located close to one another with distinct azimuthal
20 orientations without being limited by gun geometry. Alternatively, or in addition, each
21 detonation event may detonate multiple groups of shaped charges which are axially
22 displaced on the perforating gun assembly, so that multiple perforating channels are
23 produced at axially displaced locations.

24
25 Variations to the methodology for translating the perforating gun assembly are also within
26 the scope of the invention. For example, in simple embodiments of the invention, the
27 perforating gun assembly may be run on a conveyance which is shifted upwards or
28 downwards in the wellbore between detonations by pulling or lowering the conveyance
29 from surface. This may simply be the pulling or lowering of a wireline, coiled tubing, or drill
30 pipe by a specified distance to place a second group of charges in the desired location for
31 the second (or subsequent) detonation step. Such a configuration may provide sufficiently
32 precise placement in some perforating or fracturing applications.

33
34 The above-described methods utilise convergent groups of charges to create perforation
35 channels, the apexes of which are determined by the convergence angles of the shaped

1 charges. Figure 7 shows schematically the orientation of two groups of convergent
2 shaped charges in a conventional arrangement 300, in which the two groups are
3 rotationally offset or phased by 180 degrees. An upper group 301 of two charges 301a,
4 301b has symmetrical convergence angles towards an apex 303, and a lower group 311 of
5 two charges 311a, 311b has symmetrical convergence angles towards an apex 313. The
6 apex 303 is located at the midpoint between the charges 301a, 301b, at an axial point of
7 the wellbore 305 and apex 313 is located at the midpoint between the charges 311a, 311b,
8 at an axial point in the wellbore 315, separated from the point 305 by an axial distance d.
9 This distance d may be acceptable in some formations and well geometries, but can be a
10 limitation on placement of the fracture initiation points in the same fracture initiation plane
11 for single plane fracture initiation. Similar (albeit significantly reduced) limitations apply in
12 the case of the intermeshed or interlaced charge groups in the configuration of Figure 5.

13
14 The present invention in one of its aspects overcomes limitations of perforating gun
15 geometry and size by selecting convergence angles in at least one group of charges, so
16 that the apex is axially offset from the midpoint of a group of charges, and is located at a
17 desired axial point of the wellbore (in most cases axially closer to another perforation
18 channel apex).

19
20 Figures 8 to 10 are a schematic representations of perforation arrangements according to
21 embodiments of the invention. In each case, the arrangement comprises two groups of
22 charges rotationally offset or phased by 180 degrees.

23
24 In the arrangement 320 of Figure 8, an upper group 321 of two charges 321a, 321b has
25 symmetrical convergence angles towards an apex 323, and a lower group 331 of two
26 charges 331a, 331b has asymmetrical convergence angles towards an apex 333. The
27 interior angle of orientation of charge 331a is increased with respect to the interior angle of
28 orientation of charge 331b, to shift the axial position 335 of the apex 333 upwards in the
29 wellbore, towards the axial position 325 of the apex 323 of the upper group of charges. In
30 this case the angle of charge 331a is approximately 90 degrees, and the angle of charge
31 331b is correspondingly reduced. The respective apexes 323, 333 are therefore more
32 closely spaced than the conventional arrangement of Figure 7, and may be placed in, or
33 relatively close to, a single fracture plane of the formation.

34

1 In the arrangement 340 of Figure 9, an upper group 341 of two charges 341a, 341b has
2 asymmetrical convergence angles towards an apex 343, and a lower group 351 of two
3 charges 351a, 351b has asymmetrical convergence angles towards an apex 353. The
4 interior angle of orientation of charge 341a is reduced with respect to the interior angle of
5 orientation of charge 341b, to shift the axial position 345 of the apex 343 downwards in the
6 wellbore, towards the lower group of charges. The interior angle of orientation of charge
7 351a is increased with respect to the interior angle of orientation of charge 351b, to shift
8 the axial position 355 of the apex 353 upwards in the wellbore, towards the axial position
9 of the upper group of charges. The respective apexes 343, 353 are therefore more closely
10 spaced than the conventional arrangement of Figure 7, and may be placed in, or relatively
11 close to, a single fracture plane of the formation.

12
13 In the arrangement 360 of Figure 10, an upper group 361 of two charges 361a, 361b has
14 asymmetrical convergence angles towards an apex 363, and a lower group 371 of two
15 charges 371a, 371b has asymmetrical convergence angles towards an apex 373. The
16 interior angle of orientation of charge 361a is reduced with respect to the interior angle of
17 orientation of charge 361b, to shift the axial position 365 of the apex 363 downwards in the
18 wellbore, towards the lower group of charges. In this case, the interior angle of the
19 lowermost charge in the group 361 is obtuse, so that the axial position of the apex 363 is
20 below the axial position of the lowermost charge. The interior angle of the uppermost
21 charge in the group 371 is obtuse, so that the axial position of the apex 373 is above the
22 axial position of the uppermost charge. The respective apexes 363, 373 are therefore
23 more closely spaced than the conventional arrangement of Figure 7, and more closely
24 spaced than the respective charge groups 361, 371. In this embodiment, the apexes are
25 located at the same axial position 365, in a single fracture plane of the formation, which is
26 perpendicular to the wellbore orientation.

27
28 Although the selection of convergence angles for apex placement is advantageous for
29 axially separated groups of convergent charges, as shown in Figures 8 to 10, similar
30 benefits apply to groups of intermeshed charges of the type shown in Figure 5. The
31 arrangements of Figures 11 and 12 each relate to perforation systems having groups of
32 three convergent charges in an intermeshed or interlaced arrangement.

33
34 In the arrangement 380 of Figure 11, an upper group 381 of three charges has
35 asymmetrical convergence angles towards an apex 383, and a lower group 391 of three

charges has asymmetrical convergence angles towards an apex 393. In the upper group 381, the interior angle of orientation of the uppermost charge is reduced with respect to the interior angle of orientation of the lowermost charge, to shift the axial position 385 of the apex 383 downwards in the wellbore, towards the lower group of charges. The orientation angle of the centre charge is selected to be aligned with the apex 383. In the lower group 391, the interior angle of orientation of the lowermost charge is reduced with respect to the interior angle of orientation of the uppermost charge, to shift the axial position 395 of the apex 393 upwards in the wellbore, towards the upper group of charges. The orientation angle of the centre charge is selected to be aligned with the apex 393. Distance D is the natural separation of the apexes for a symmetrical convergent arrangement, and distance d is the separation with the selected angles of this embodiment of the invention. The respective apexes 383, 393 are therefore more closely spaced than a symmetrical arrangement, and may be aligned with, or close to, a principal fracture plane of the formation.

In the arrangement 400 of Figure 12, an upper group 401 of three charges has symmetrical convergence angles towards an apex 403, and a lower group 411 of three charges has asymmetrical convergence angles towards an apex 413. In the lower group 411, the interior angle of orientation of the lowermost charge is reduced with respect to the interior angle of orientation of the uppermost charge, to shift the axial position 405 of the apex 413 upwards in the wellbore, away from the midpoint of the charge group and towards the upper group of charges. The orientation angle of the centre charge is selected to be aligned with the apex 413. In this embodiment, the apexes are located at the same axial position 405, in a single fracture plane of the formation, which is perpendicular to the wellbore orientation.

Although the above-described arrangements have the two groups of shaped charges arranged in opposed orientations, such that their rotational offset is 180 degrees, other azimuthal angles of separation are within the scope of the invention.

The selection of appropriate angles for desired placement of apexes and fracture initiation points as described with reference to Figures 7 to 12 may be applied in combination with the apparatus and methods of Figures 1 to 6, to provide a high degree of flexibility of fracture initiation point placement. Alternatively, or in addition, the described selection of angles may be implemented in a perforation system which uses a combination of large

1 hole charges and deep penetrating charges, where the deep penetrating charges are
2 detonated through casing entry holes formed by the large hole charges, in the manner
3 described above. Such a method may be particularly advantageous where deep
4 penetration into the formation is desirable to achieve convergence of charges at selected
5 axial points, without high degrees of asymmetry between charge angles. For example, the
6 desired axial shift of apexes and fracture initiation points may be achieved by relatively
7 small changes to convergence angles, if the convergence point is an increased distance
8 from the wellbore axis. The combination of large hole and deep penetrating hole charges
9 may facilitate convergence at these increase penetration distances from the wellbore.

10
11 In the above-described embodiments, there is focus on placement of apexes and fracture
12 initiation points in the same fracture plane, but it will be appreciated that in some
13 formations and well geometries, other perforation geometries may be desirable. Figure 13
14 is a schematic representation of a perforation arrangement 420, in which the relative
15 positions of fracture initiation points 431, 432, 433, and 434 formed by perforation
16 channels 442a, 442b, 442c and 442d respective, are arranged in a plane which is inclined
17 with respect to a plane perpendicular to the wellbore.

18
19 In some perforation arrangements, it may be desirable to arrange at least some of the
20 fracture initiation points in positions which facilitate a transition between an initial direction
21 of fracture growth, and the principle fracture plane.

22
23 The invention provides a method and apparatus for perforating a wellbore in a hydraulic
24 fracturing operation. In one aspect, the method comprises providing a perforating gun
25 assembly having a first group of shaped charges on a first longitudinal portion of the
26 assembly and a second group of shaped charges on a second longitudinal portion of the
27 assembly. The orientations of the first and second groups are rotationally offset from one
28 another around a longitudinal axis of the perforating gun assembly. The method
29 comprises locating the perforating gun assembly in a wellbore with the first group of
30 shaped charges adjacent a wall of the wellbore at a perforation location, and detonating
31 the shaped charges to form a first perforation channel in the wellbore with a defined first
32 fracture initiation point. The perforating gun assembly is translated in the wellbore to
33 locate the second group of shaped charges oriented towards a defined second fracture
34 initiation point, at a desired axial position with respect to the first fracture initiation point.

35

1 In one aspect, the method comprises providing a perforating gun assembly having a first
2 group of shaped charges on a first longitudinal portion of the assembly and a second
3 group of shaped charges on a second longitudinal portion of the assembly. The first group
4 of shaped charges comprises at least two shaped charges arranged to generate jets
5 oriented substantially along respective axes that converge towards one another in a first
6 convergence plane, and the second group of shaped charges comprises at least two
7 shaped charges arranged to generate jets oriented substantially along respective axes that
8 converge towards one another in a second convergence plane. The first and second
9 planes of convergence are rotationally offset from one another around a longitudinal axis
10 of the perforating gun assembly. The method comprises locating the perforating gun
11 assembly in a wellbore with the first group of shaped charges adjacent a wall of the
12 wellbore at a perforation location, and detonating the shaped charges of the first group of
13 shaped charges to form a first perforation channel in the wellbore with a defined first
14 fracture initiation point. The perforating gun assembly is translated in the wellbore to
15 locate the second group of shaped charges adjacent the wellbore at the perforation
16 location such that the position of the second group of shaped charges orients the shaped
17 charges towards a defined second fracture initiation point. The shaped charges of the
18 second group are detonated to form a second perforation channel in the wellbore which
19 overlaps with the first perforation channel in an axial direction of the wellbore, which is
20 rotationally offset from the first perforation channel around a longitudinal axis of the
21 wellbore, and which forms a defined second fracture initiation point at a desired axial
22 position with respect to the first fracture initiation point.

23
24 In another aspect, a perforating gun assembly comprises a charge carrier having a
25 longitudinal axis, a first group of shaped charges comprising at least two shaped charges
26 arranged to generate jets oriented substantially along respective axes that converge
27 towards one another in a first convergence plane to a first focal point, and a second group
28 of shaped charges comprising at least two shaped charges arranged to generate jets
29 oriented substantially along respective axes that converge towards one another in a
30 second convergence plane to a second focal point. In at least one of the groups of shaped
31 charges, a convergence angle between the orientation direction of two shaped charges
32 within the group is selected to locate its focal point at a position which is axially offset from
33 an axial midpoint between the outermost charges in the group.

1 The invention provides a perforating gun assembly and a method of use in hydraulic
2 fracturing applications which addresses drawbacks and deficiencies of previously
3 proposed apparatus and methods. In particular the invention in one of its aspects provides
4 a multiple stage perforating gun assembly and a method of use in hydraulic fracturing
5 applications which provides improved fracture initiation. Embodiments of the invention
6 provide discrete fracture initiation sites with improved placement control and/or improved
7 hydraulic efficiency.

8

9 Various modifications to the above-described embodiments may be made within the scope
10 of the invention, and the invention extends to combinations of features other than those
11 expressly claimed herein.

12

1 Claims:

- 2
- 3 1. A method of perforating a wellbore in a hydraulic fracturing operation, the method
- 4 comprising:
- 5 providing a perforating gun assembly comprising a first group of shaped charges on
- 6 a first longitudinal portion of the assembly and a second group of shaped charges on
- 7 a second longitudinal portion of the assembly, wherein the first group of shaped
- 8 charges comprises at least two shaped charges arranged to generate jets oriented
- 9 substantially along respective axes that converge towards one another in a first
- 10 convergence plane, and wherein the second group of shaped charges comprises at
- 11 least two shaped charges arranged to generate jets oriented substantially along
- 12 respective axes that converge towards one another in a second convergence plane,
- 13 and wherein the first and second planes of convergence are rotationally offset from
- 14 one another around a longitudinal axis of the perforating gun assembly;
- 15 locating the perforating gun assembly in a wellbore with the first group of shaped
- 16 charges adjacent a wall of the wellbore at a perforation location;
- 17 detonating the shaped charges of the first group of shaped charges to form a first
- 18 perforation channel in the wellbore with a defined first fracture initiation point;
- 19 translating the perforating gun assembly in the wellbore to locate the second group
- 20 of shaped charges adjacent the wellbore at the perforation location such that the
- 21 position of the second group of shaped charges orients the shaped charges towards
- 22 a defined second fracture initiation point; and
- 23 detonating the shaped charges of the second group of shaped charges to form a
- 24 second perforation channel in the wellbore which overlaps with the first perforation
- 25 channel in an axial direction of the wellbore, which is rotationally offset from the first
- 26 perforation channel around a longitudinal axis of the wellbore, and which forms a
- 27 defined second fracture initiation point at a desired axial position with respect to the
- 28 first fracture initiation point.
- 29
- 30 2. The method according to claim 1, wherein the rotational offset between the first and
- 31 second convergence planes orients the first and second perforation channels at
- 32 distinct azimuthal angles.
- 33
- 34 3. The method according to claim 1 or claim 2, wherein the first and second perforation
- 35 channels cross cut a fracture plane.

- 1 4. The method according to claim any preceding claim, wherein the first and second
2 convergence planes are rotationally offset at an angle between 0 and 360 degrees.
3
- 4 5. The method according to claim 4, wherein the first and second convergence planes
5 are oriented at 180 degrees.
6
- 7 6. The method according to claim any preceding claim, wherein the wellbore is an
8 openhole wellbore.
9
- 10 7. The method according to any of claims 1 to 5, wherein the wellbore is a cased or
11 lined wellbore.
12
- 13 8. The method according to any preceding claim, comprising forming at least one of the
14 first or second perforation channels by detonating one or more large hole shaped
15 charges, translating the perforating gun assembly, and detonating deep penetrating
16 shaped charges to generate jets which pass through one or more large holes formed
17 by the large hole shaped charges.
18
- 19 9. The method according to claim 8, comprising forming at least two deep penetration
20 holes through the one or more large holes.
21
- 22 10. The method according to claim 9, wherein the least two deep penetration holes
23 intersect to provide a connected channel in the formation.
24
- 25 11. The method according to any preceding claim, comprising translating the perforating
26 gun assembly by applying a force to at least a portion of the perforating gun
27 assembly.
28
- 29 12. The method according to claim 11, wherein the force is a motive force from a
30 downhole tractor which forms a part of the perforating gun assembly.
31
- 32 13. The method according to claim 11, wherein the motive force is a tensile force or a
33 compressive force applied from surface.
34

- 1 14. The method according to claim 11, wherein the force is applied by exposing at least
2 a portion of the gun assembly to a wellbore pressure.
3
- 4 15. The method according to claim 14, wherein the assembly comprises a pressure
5 chamber, and wherein the method comprises exposing the pressure chamber to
6 wellbore pressure, thereby causing wellbore fluids to enter the chamber.
7
- 8 16. The method according to any preceding claim, wherein the assembly comprises at
9 least one sealed chamber, and wherein the method comprises breaking or rupturing
10 a seal to the sealed chamber.
11
- 12 17. The method according to claim 16, wherein the sealed chamber is pressure isolated
13 from the wellbore and comprises a liquid filled chamber in a first condition, and
14 wherein the method comprises breaking or rupturing the seal to the sealed chamber
15 to enable liquid to be expelled from the chamber.
16
- 17 18. The method according to 16 or claim 17, comprising breaking or rupturing the seal
18 by detonation of the shaped charges of the first group of shaped charges.
19
- 20 19. The method according to any preceding claim, wherein at least one of the defined
21 first and second fracture initiation points is located at a position which is axially offset
22 from an axial midpoint between the outermost shaped charges in its respective
23 group.
24
- 25 20. The method according to any preceding claim, wherein at least one of the defined
26 first and second fracture initiation points is located on or close to a principle
27 fracturing plane.
28
- 29 21. A method of perforating and fracturing a wellbore, the method comprising:
30 carrying out the method according to any preceding claim;
31 pumping a fracturing fluid into the wellbore to the perforation location and into the
32 perforation channels; and
33 initiating and propagating a fracture from the first and second fracture initiation
34 points.
35

22. A perforating gun assembly comprising:
- a first group of shaped charges on a first longitudinal portion of the assembly, the first group of shaped charges comprising at least two shaped charges arranged to generate jets oriented substantially along respective axes that converge towards one another in a first convergence plane;
 - a second group of shaped charges on a second longitudinal portion of the assembly, the second group of shaped charges comprising at least two shaped charges arranged to generate jets oriented substantially along respective axes that converge towards one another in a second convergence plane;
 - a first detonator for detonating the shaped charges of the first group of shaped charges to form a first perforation channel in a wellbore with a defined first fracture initiation point;
 - a second detonator for detonating the shaped charges of the second group of shaped charges to form a second perforation channel in the wellbore with a defined second, fracture initiation point, wherein the second perforation channel overlaps with the first perforation channel in an axial direction of the wellbore;
 - an anchor for securing the perforating gun assembly in the wellbore with the first group of shaped charges adjacent the wellbore at a perforation location; and
 - a positioning and alignment module configured to translate the perforating gun assembly in the wellbore to a second axial position, which locates the second group of shaped charges adjacent the wellbore at the perforation location such that the position of the second group of shaped charges orients the shaped charges towards a defined second fracture initiation point;
- wherein the first and second planes of convergence are rotationally offset from one another around a longitudinal axis of the perforating gun assembly;
- and wherein, in the second axial position, the second group of shaped charges are oriented to form a second perforation channel in the wellbore which overlaps with the first perforation channel in an axial direction of the wellbore, which is rotationally offset from the first perforation channel around a longitudinal axis of the wellbore, and which forms a defined second fracture initiation point at a desired axial position with respect to the first fracture initiation point.

23. The perforating gun assembly according to claim 22, wherein the first and second detonators form a part of a single detonation system.

- 1 24. The perforating gun assembly according to claim 22, wherein the first and second
2 detonators are separate and distinct detonators.
3
- 4 25. The perforating gun assembly according to claim 22, wherein the first and/or second
5 groups of shaped charges form a part of first and/or second collections of shaped
6 charges on the first and/or second longitudinal portions respectively, each collection
7 comprising more than one group of shaped charges which interacts to form a
8 perforation channel.
9
- 10 26. The assembly according to claim 25, wherein the groups of shaped charges within
11 each collection are intermeshed or interlaced in a longitudinal direction of the
12 assembly.
13
- 14 27. The assembly according to claim 25 or claim 26, wherein the groups of shaped
15 charges within each collection are rotationally offset or phased around the
16 longitudinal axis of the assembly.
17
- 18 28. The assembly according to any of claims 22 to 27, wherein one or more groups of
19 shaped charges are arranged in a line parallel to the longitudinal axis of the
20 assembly.
21
- 22 29. The assembly according to claim 28, wherein each group of shaped charges is
23 arranged in a line parallel to the longitudinal axis of the assembly.
24
- 25 30. The assembly according to any of claims 22 to 29, wherein the first and second
26 groups of shaped charges are arranged to form first and second perforation
27 channels which overlap one another in an axial direction of the wellbore and are
28 rotationally offset by 180 degrees.
29
- 30 31. The assembly according to any of claims 22 to 30, wherein the first and second
31 perforation channels have first and second major diameters oriented substantially in
32 the same plane.
33
- 34 32. The assembly according to any of claims 22 to 31, wherein the positioning and
35 alignment module comprises a guide shaft and a guide housing and wherein the

- 1 guide shaft is movable within the guide housing to translate the perforating gun
2 assembly in the wellbore.
3
- 4 33. The assembly according to any of claims 22 to 32, wherein the positioning and
5 alignment module comprises one or more guide keys co-operating with one or more
6 guide keyways.
7
- 8 34. The assembly according to claim 32 or claim 33, wherein the positioning and
9 alignment module comprises one or more shear pins configured to maintain the
10 guide shaft in its first position.
11
- 12 35. The assembly according to any of claims 22 to 34, wherein the assembly further
13 comprises a downhole tractor and wherein the downhole tractor is configured to
14 provide a motive force.
15
- 16 36. The assembly according to any of claims 22 to 35, wherein the positioning and
17 alignment module comprises at least one sealed chamber.
18
- 19 37. The assembly according to claim 36, comprising a seal which is operable to be
20 broken or ruptured.
21
- 22 38. The assembly according to claim 37, wherein the seal comprises a rupture disc.
23
- 24 39. The assembly according to any of claims 22 to 38, wherein the positioning and
25 alignment module comprises a pressure chamber.
26
- 27 40. The assembly according to claim 39, wherein in a first condition the pressure
28 chamber is sealed and isolated from a wellbore pressure, and is at a pressure lower
29 than a wellbore pressure.
30
- 31 41. The assembly according to claim 39 or claim 40, wherein the pressure chamber is
32 filled with air at atmospheric pressure.
33

1 42. The assembly according to any of claims 39 to 41, wherein the pressure chamber is
2 configured to permit wellbore fluids to enter the chamber upon exposure to wellbore
3 pressure.

4

5 43. A perforating gun assembly substantially as described herein with reference to the
6 drawings.

7

8 44. A method of perforating a wellbore in a hydraulic fracturing operation substantially as
9 described herein with reference to the drawings.

10

11

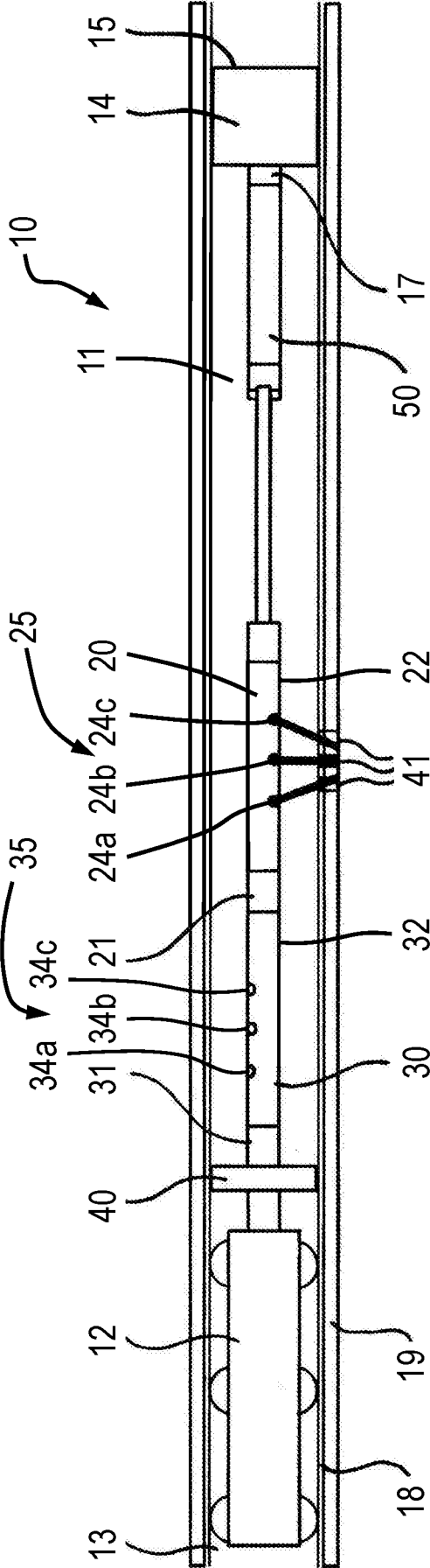


Fig. 1A

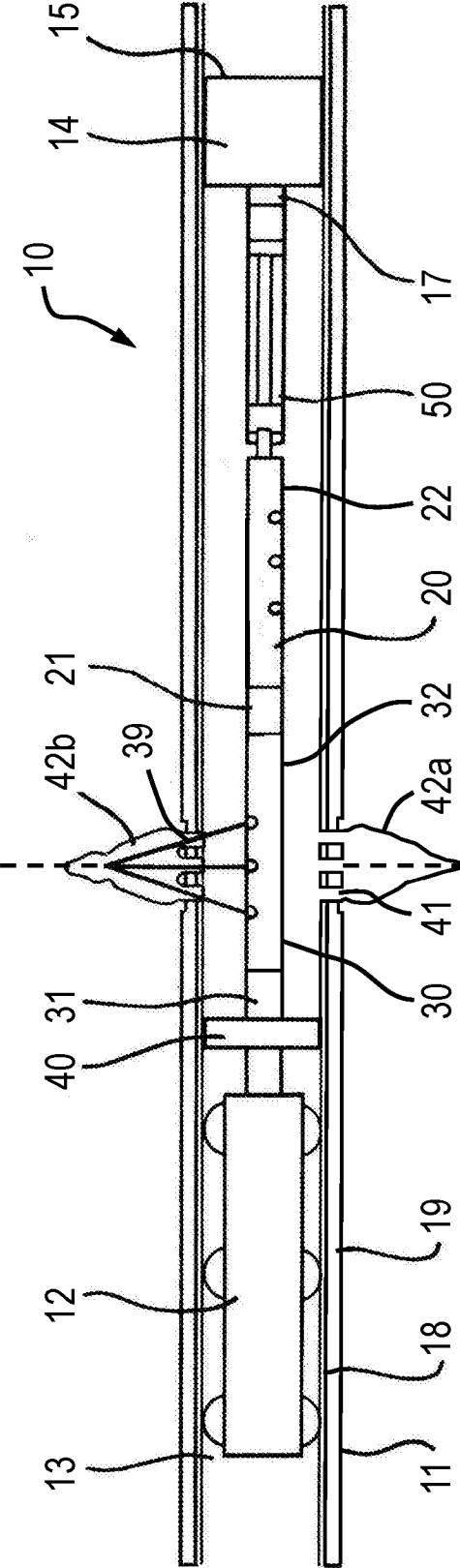


Fig. 1B

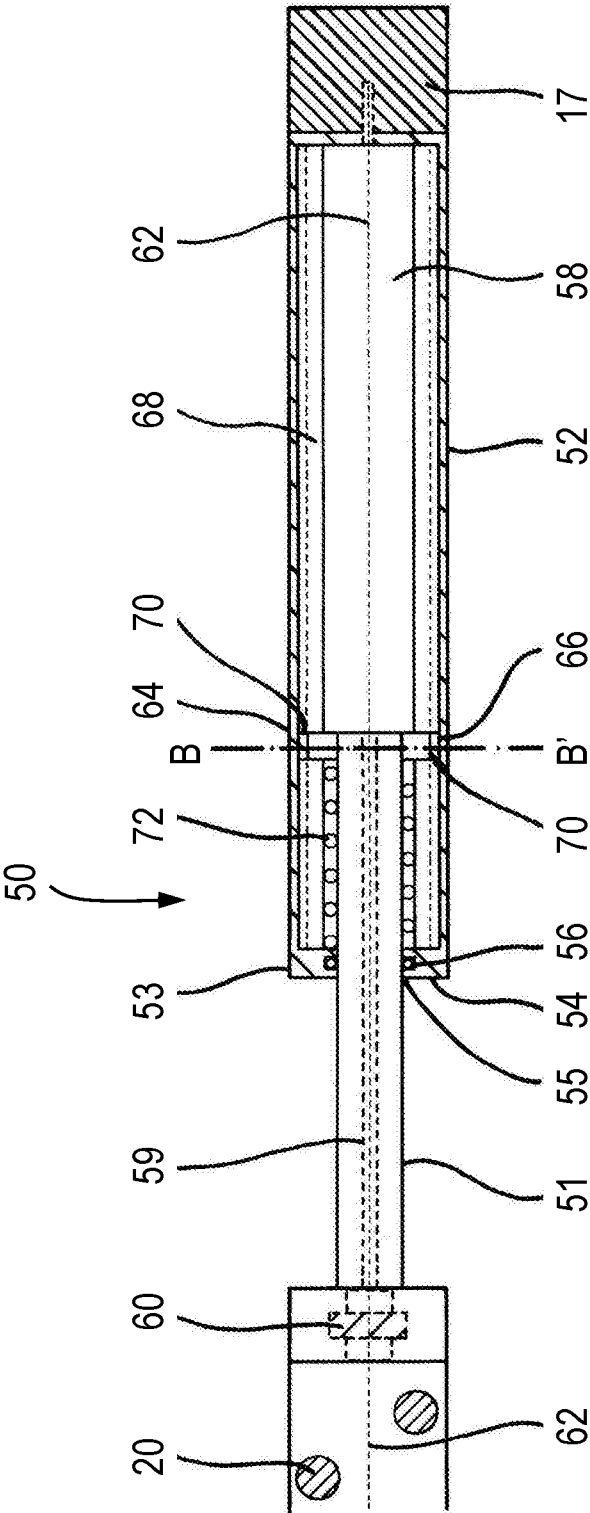


Fig. 2A

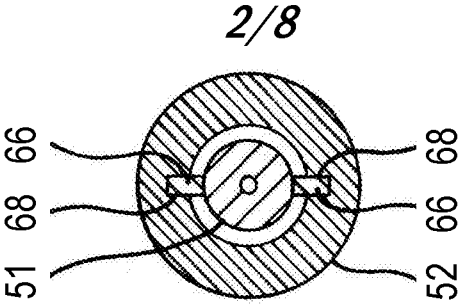
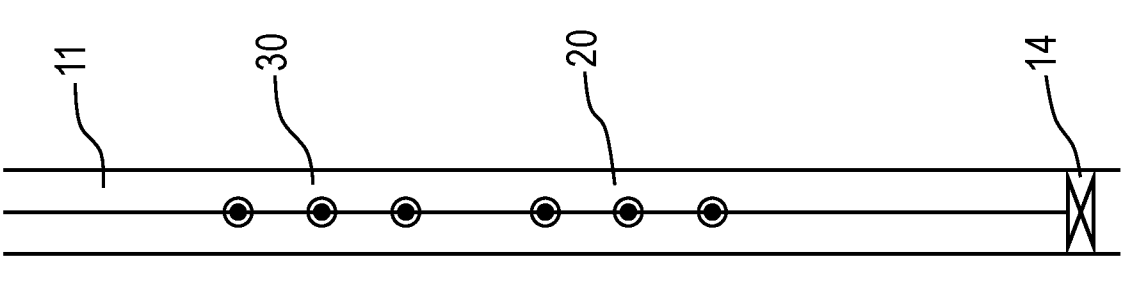
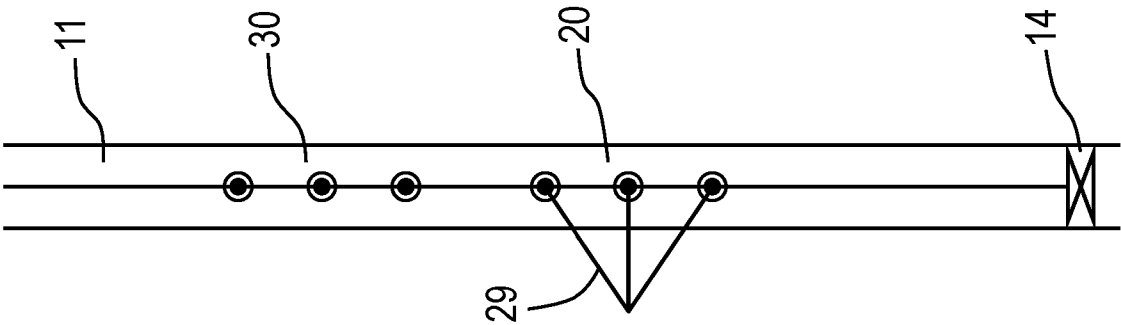
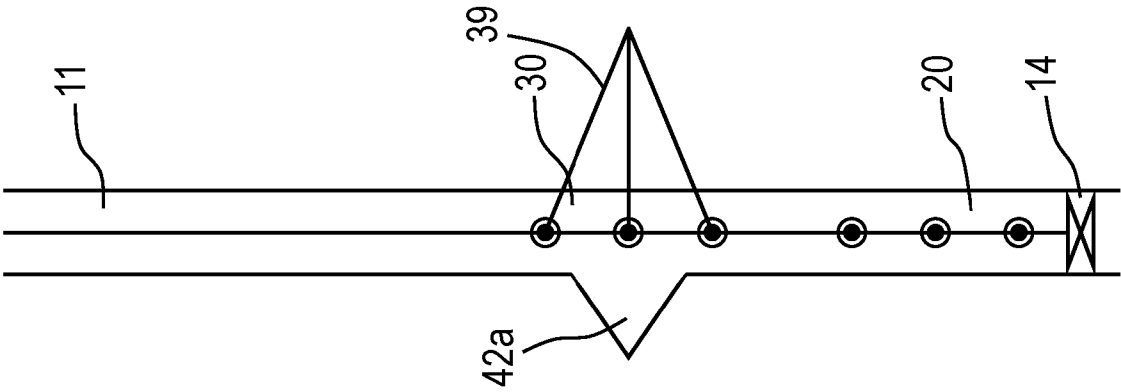
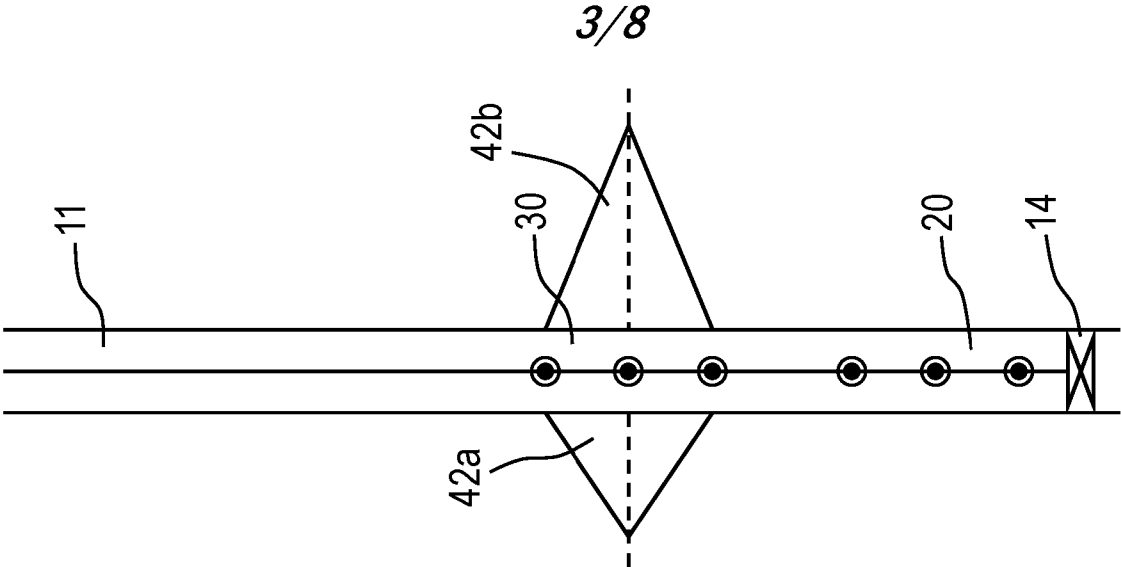


Fig. 2B



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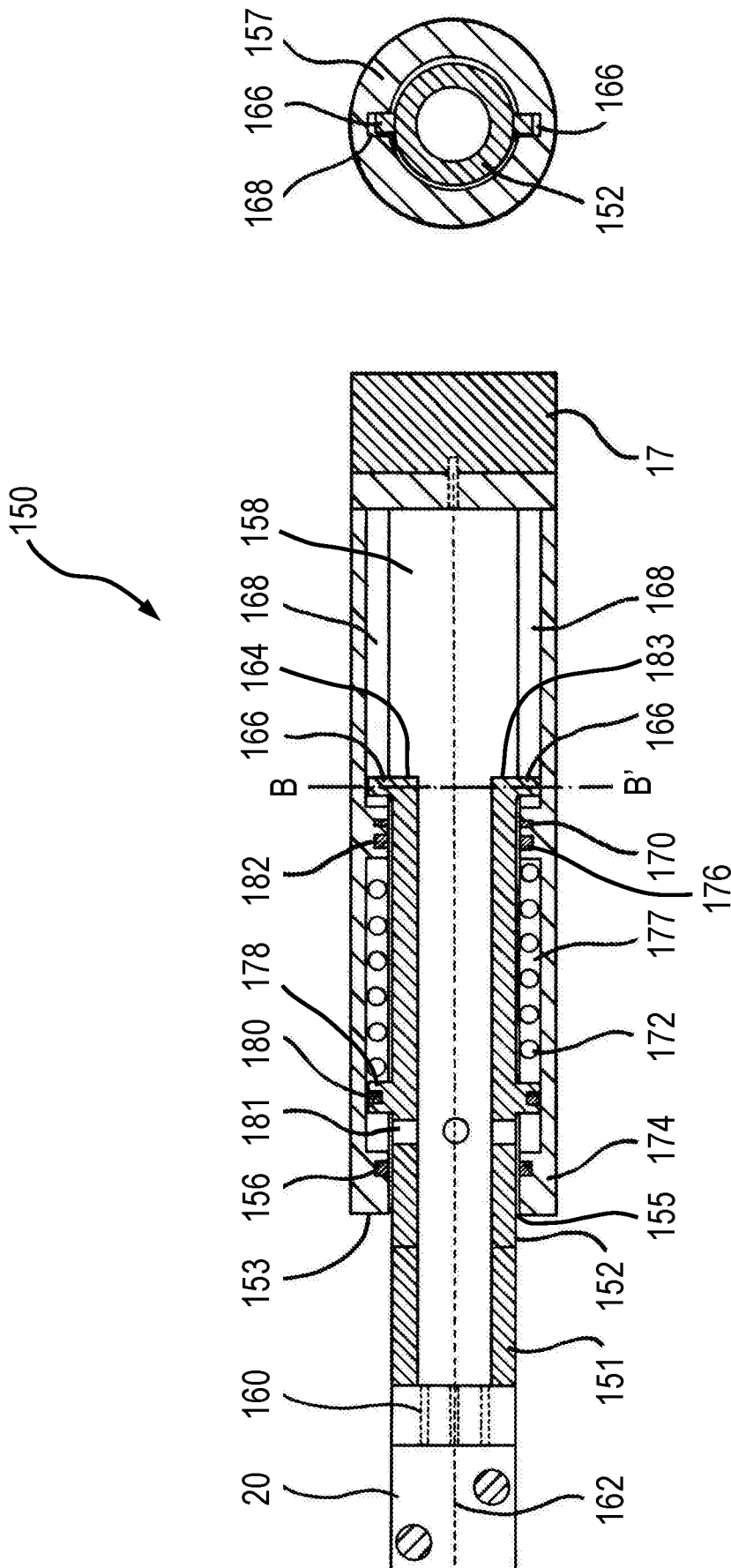


Fig. 4B

Fig. 4A

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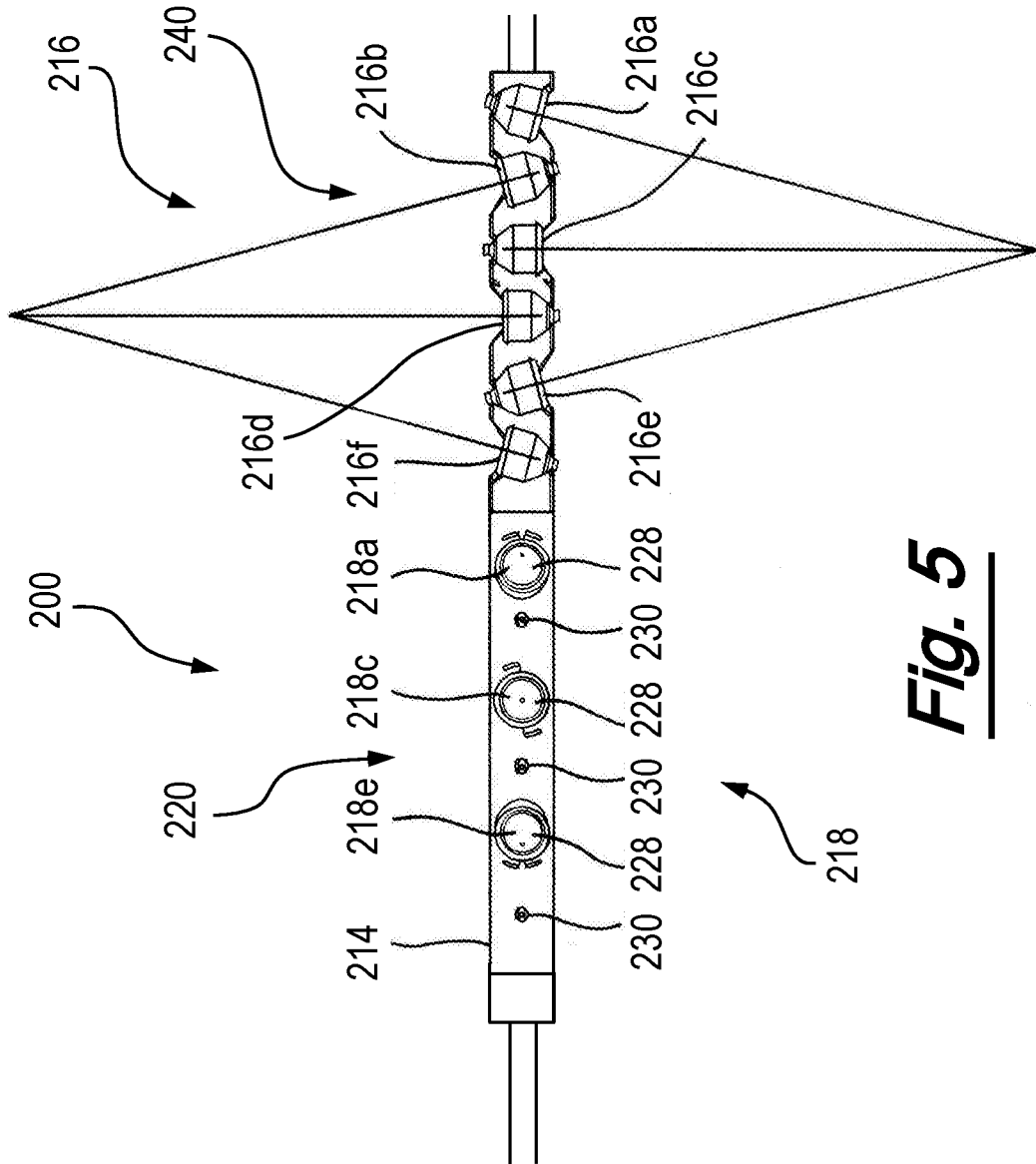


Fig. 5

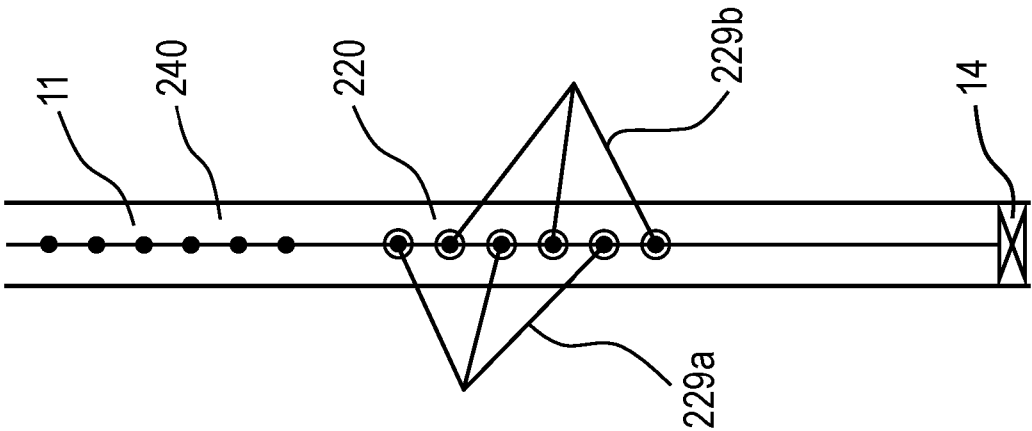


Fig. 6A

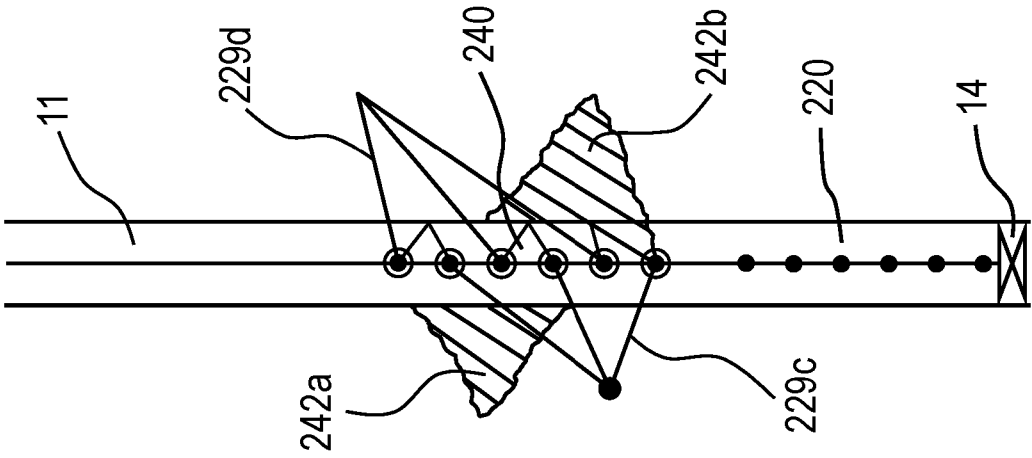


Fig. 6B

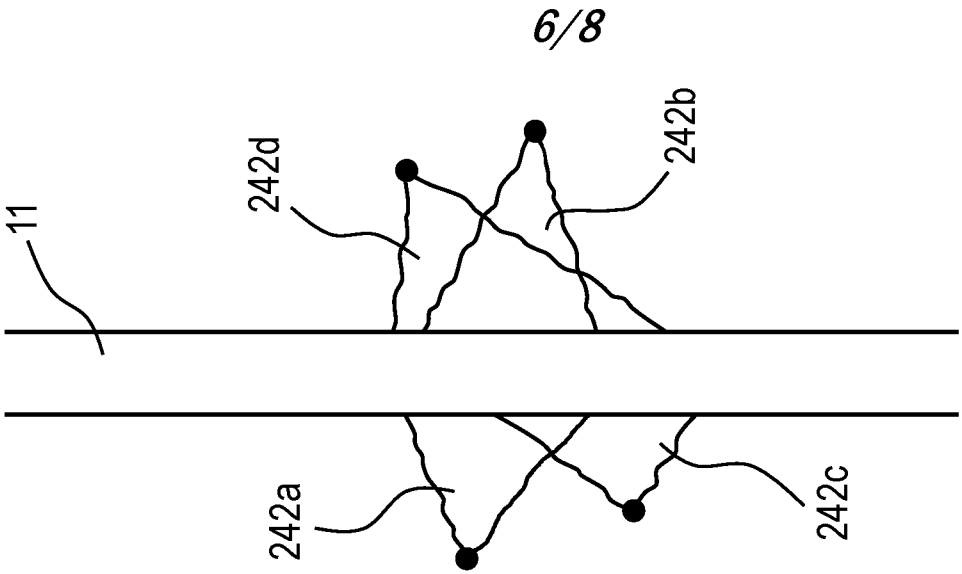
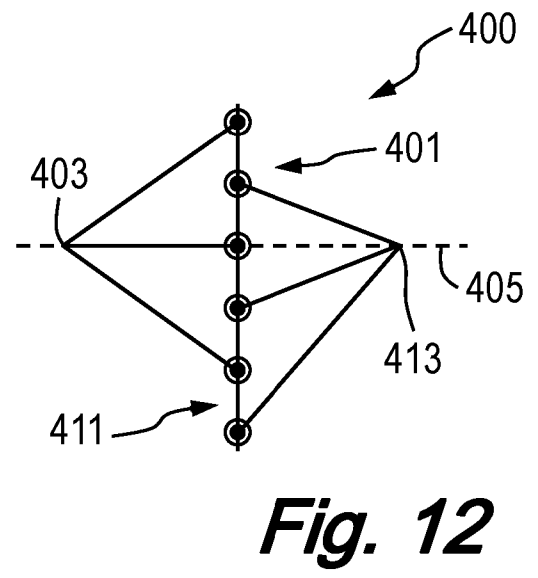
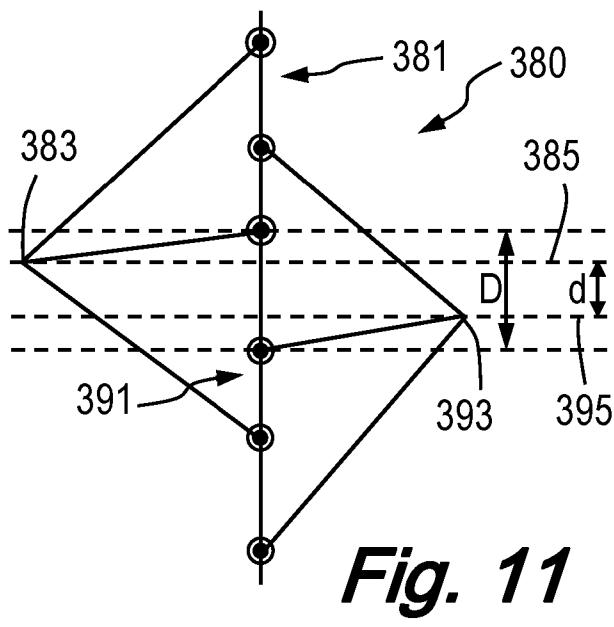
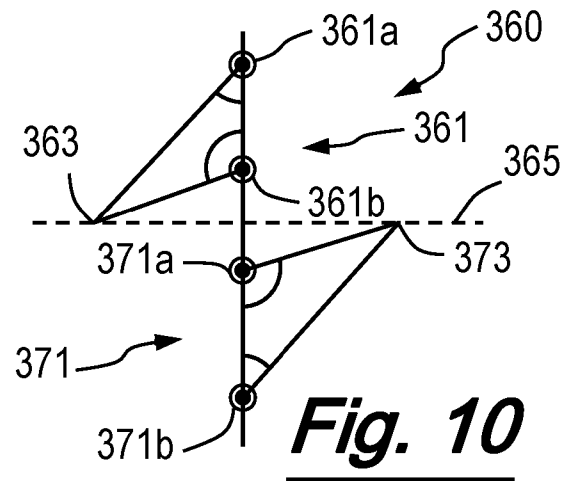
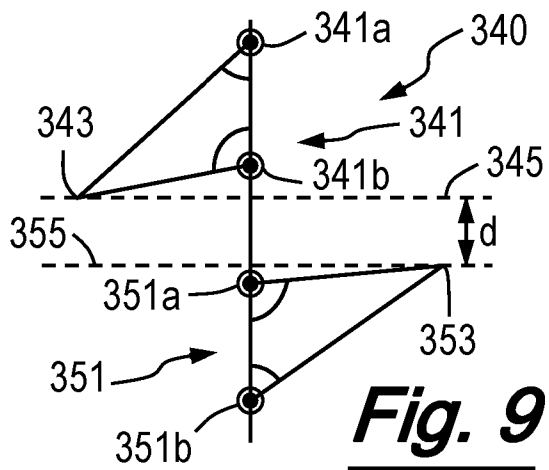
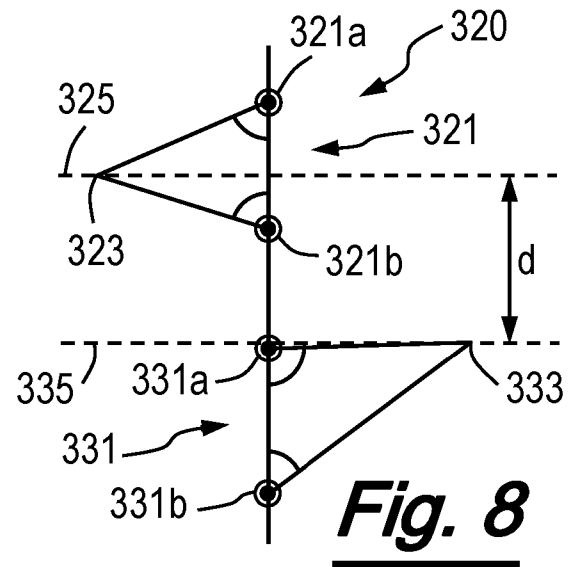
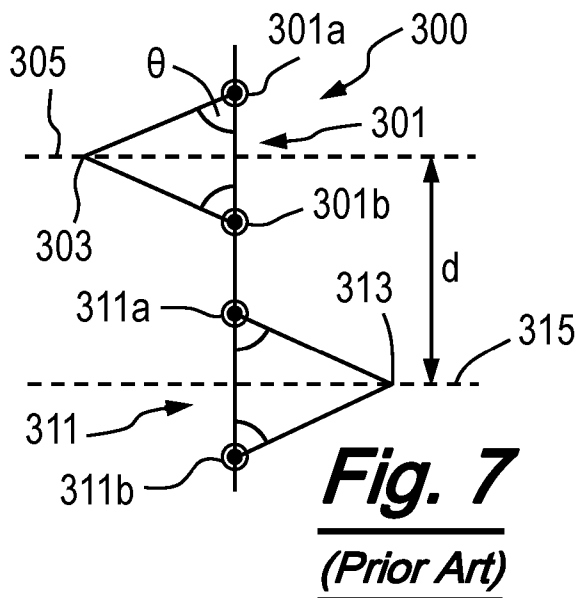
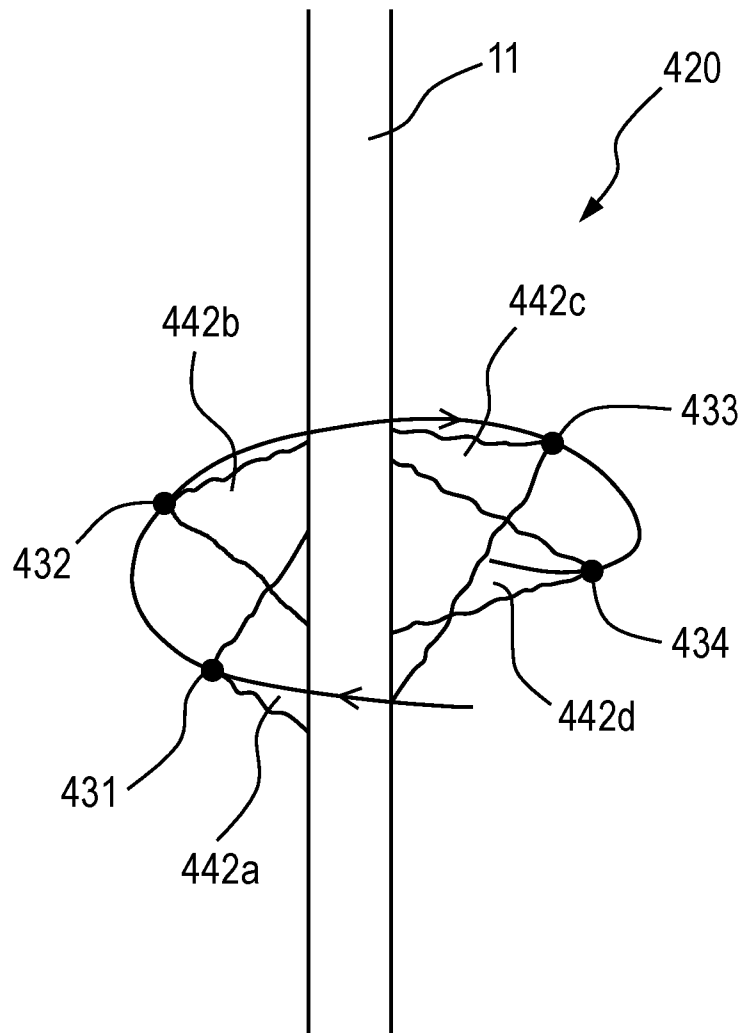


Fig. 6C

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**Fig. 13**

INTERNATIONAL SEARCH REPORT

International application No
PCT/GB2016/052330

A. CLASSIFICATION OF SUBJECT MATTER
INV. E21B43/117 E21B43/119
ADD.

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)
E21B

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)

EPO-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 2007/158109 A1 (ZAZOVSKY ALEXANDER F [US] ET AL) 12 July 2007 (2007-07-12) cited in the application	43,44
Y	paragraphs [0020] - [0026]; figures 1-7	1-11,13, 20-31
X	US 3 706 340 A (SCHUSTER NICK A) 19 December 1972 (1972-12-19)	43,44
Y	figures 1-6 column 2, line 29 - column 4, line 42 column 5, lines 016-21 column 5, line 42 - column 6, line 54 column 7, lines 41-46	1-11,13, 20-31
A	US 8 327 746 B2 (BEHRMANN LAWRENCE A [US] ET AL) 11 December 2012 (2012-12-11) figures 1,2	1,22
	----- -/--	



Further documents are listed in the continuation of Box C.



See patent family annex.

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"P" document published prior to the international filing date but later than the priority date claimed

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Date of the actual completion of the international search

21 October 2016

Date of mailing of the international search report

07/11/2016

Name and mailing address of the ISA/

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Authorized officer

Maukonen, Kalle

INTERNATIONAL SEARCH REPORT

International application No
PCT/GB2016/052330

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	WO 2013/173404 A1 (SCHLUMBERGER CA LTD [CA]; SCHLUMBERGER SERVICES PETROL [FR]; SCHLUMBER) 21 November 2013 (2013-11-21) figures 1,2,4,5 -----	1,22
X,P	WO 2016/046521 A1 (DELPHIAN BALLISTICS LTD [GB]) 31 March 2016 (2016-03-31) page 6, line 1 - page 12, line 9 page 18, lines 12-18 figures 1-6 -----	1-5, 7-18, 20-44

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No

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