This invention relates to methods and apparatus for perforating with shaped explosive charges a plurality of vertically spaced earth formations traversed by a borehole and more particularly to perforation of such formations after the bore hole has been cased, production equipment has been placed at the surface and tubing has been set in the cased bore hole.

It has become common practice to employ the well completion methods and apparatus disclosed in copending application Serial No. 209,598, filed February 6, 1951, by H. S. Robertson, for "Method and Apparatus for Perforating Well Casing and the Like," and described in an article entitled "A Method of Perforating Casing Below Tubing," by M. P. Lebourg and G. R. Hodgson, at page 303, vol. 195 (1952), Petroleum Transactions, AIME. Where these practices are followed, production equipment may be placed at the surface and tubing lowered and set in the well prior to perforating, thus simplifying well completion.

In some cases, it is desirable to obtain production simultaneously from two vertically separated formations in the well. However, the well may be under high pressure from the fluid in the first formation after perforation in accordance with the aforementioned methods and apparatus. As a result, perforation of the second formation in accordance with such methods and apparatus may be more difficult and somewhat more hazardous.

Accordingly, it is an object of the present invention to provide new and improved methods and apparatus for perforating with shaped explosive charges, in one operation, a plurality of vertically spaced earth formations with production equipment placed at the surface and tubing lowered into the well.

Another object of the invention is to provide novel methods and means whereby a plurality of vertically spaced earth formations may be separately perforated without the necessity for lowering additional equipment in the well after one of such formations has been perforated.

A further object of the present invention is to provide means for electrically coupling components of equipment in a bore hole by means of remote surface apparatus.

These and other objects of the invention are accomplished by disposing first shaped explosive charge perforating means at the lower end of the tubing opposite the upper of two formations of interest such that the open end of the tubing is free and unobstructed. Second shaped explosive charge perforating means is lowered through the tubing to the level of the lower of the two formations and is used to perforate the lower formation. The second perforating means includes means which, after perforation of the lower formation, is adapted to be positioned in the vicinity of the first perforating means where it acts upon means in the first perforating apparatus to cause detonation of the latter. More particularly, the first perforating apparatus may have an electrical detonating circuit including a winding in which voltage is adapted to be induced from a suitably energized winding forming part of the second perforating apparatus, when the two are in inductive relation. These and further objects and advantages of the invention will be more fully understood from the following description of a representative embodiment, read with reference to the accompanying drawings, in which:

Fig. 1 is a view in longitudinal section of a well which is under completion in accordance with the present invention;

Fig. 2 is a view, partially in longitudinal section of the lower end of the tubing and the shaped explosive charge perforating apparatus secured thereto;

Fig. 3 illustrates in diagrammatic form the components of a typical circuit that may be employed to discharge the shaped explosive charge perforating apparatus mounted at the lower end of the tubing; and

Fig. 4 is a schematic diagram of an equivalent circuit of the discharging circuit of Fig. 3 when the several components thereof are in the firing position.

Examining the invention in detail with particular reference to Fig. 1, a bore hole 10 has been completed in accordance with the procedure outlined in the aforementioned Robertson application and publication. Set in a well 10 is a casing 11 which traverses a plurality of potentially productive formations 12 and 13 vertically separated by the formation 14. The usual production equipment, which is not shown for simplicity, is placed at the surface of the well, and the tubing 15 is set with the aid of a conventional packer 17 so that its lower end 16 is immediately above the upper formation 13. Attached to the lower end of the tubing 16 is a firing nipple 18, to be described in greater detail hereinafter.

The hollow interior of the tubing 15 communicates with an opening 19 in the nipple 18 whereby the tubing is, in effect, open ended. A first shaped explosive charge perforating device 20 is attached to the nipple 18 by a detonating unit 29. The perforating device 20 is offset from the opening 19 and is positioned opposite the formation 12, as shown in Fig. 1.

The perforating device 20 preferably comprises a plurality of shaped explosive charges in an expendable housing, as disclosed in the aforementioned Robertson application, for example, the detonating primacord fuse for the charges terminating in an electrical blasting cap 30 in the detonating unit 29. The blasting cap 30 may have one terminal connected to ground and another terminal connected to a contact 31. Placed in the firing nipple 18 is a coil 25 wound on a magnetic core 32 placed longitudinally between two annular, magnetic pole pieces 26 and 27 having openings 34 and 35 formed therein registering with the opening 19. One terminal of the coil 25 is electrically connected to the contact 31, and the other terminal 33 of the coil 25 is grounded, as shown in greater detail in Fig. 3.

For perforation of the lower formation 13, an expendable shaped explosive charge perforating device 21, preferably of the type disclosed in the aforementioned Robertson application, is adapted to be lowered through the tubing 15 and the nipple 18 to a position opposite the formation 13 by means of a conventional cable 22 which includes an electrical conductor 43. The perforating device 21 preferably contains the electrical connections disclosed in the copending application Serial No. 322,017, filed November 22, 1952, by G. R. Hodgson for "Expansible Shaped Explosive Charge Well Casing Perforating Apparatus," and in application Serial No. 322,070, filed November 22, 1952, by J. M. Bricaud for "Bore Hole Detecting Circuit and Bore Hole Firing Circuit Utilizing a Common Transmission Channel." Now U. S. Patent No. 2,732,518, issued January 24,
Between the perforating device 21 and the cable 22 is a conventional casing collar locator 23, which may be of the type disclosed in U. S. Patent No. 2,558, 427 to H. C. Fagan, and mechanism 24 (Fig. 3) for firing the perforating device 20. The firing mechanism 24 comprises a coil 36 wound around a magnetic core 37 terminating in cylindrical pole pieces 38 and 39. The spacing between the pole pieces 38 and 39 is preferably the same as the spacing between the pole pieces 26 and 27. An appropriate A. C. source 40 at the surface selectively energizes the winding 36 through a switch 42 and conductor 43 in the cable 22, and a ground return, as shown schematically in Figs. 3 and 4.

In a representative operation, the perforating device 21 is lowered to a position opposite the formation 13 as determined by the casing collar locator 23 (Fig. 1). Setting off the perforating device 21 by closing the switch 42 results in the perforation of the formation 13 and the separation and dropping of the perforating device 21 from the head assembly including the casing collar locator 23 and the firing mechanism 24, as disclosed in the aforementioned Robertson and Hodge applications. In this manner, production of the formation 13 into the bore hole 10 is started. The firing mechanism 24 and the casing collar locator 23 are then raised until the former is in juxtaposition to the winding 25 with the pole pieces 38, 39 and 26, 27, respectively, in alignment, as accurately determined by the casing collar locator 23.

As can be seen in Fig. 4, when the firing mechanism is located in the position described above, the coil 36 comprises, in effect, the primary winding of a transformer, the coil 25 serving as a secondary winding. Close coupling between these coils will be provided in view of the magnetic path 41 provided by the core 37, the adjacent pole pieces 38 and 26, the core 32, and the adjacent pole pieces 27 and 39. The switch 42 is opened and energizing the coil 36, resulting in the induction of an A. C. potential in the coil 25 and current flow through the contact 31 to the blasting cap 30. The subsequent detonation of the shaped charges in the perforating device 20 perforates the formation 12, resulting in production into the bore hole 10 therefrom. The casing collar locator 23 and the firing mechanism 24 may then be withdrawn from the well through the tubing 15 and the well placed on production from both the formations 12 and 13.

Clearly, it can be seen that novel and highly effective methods and apparatus are provided for perforating in one operation a plurality of separate formations traversed by a well after tubing has been set therein.

It should be understood that the methods and apparatus described are illustrative only and modifications may be made thereto. For example, other suitable shaped explosive charge perforating apparatus may be substituted for the specific shaped charge devices described above. Numerous other modifications within the scope of this invention will suggest themselves to those skilled in the art. Therefore, the embodiments described above and shown in the drawing are not to be regarded as limiting the scope of the appended claims.

I claim:

1. In a method for initiating operation of apparatus for use in a well having a casing therein, the steps of setting tubing in the well with the lower open end thereof at a selected level in the well, disposing at the lower end of said tubing without substantially obstructing the opening therein a shaped explosive charge well casing perforating device including excitable operation initiating means, lowering through the tubing a second shaped explosive charge well casing perforating device to perforate the casing and earth formation at a given level in the well below said first casing perforating device, positioning the exciting means of said second well casing perforating device in exciting relation to that of said first casing perforating device, and causing the exciting means of said second well casing perforating device to excite the operation initiating means of said first well casing perforating device to initiate operation of the same.

2. In a method for obtaining production from a plurality of earth formations traversed by a bore hole having a casing therein, the steps of providing well tubing having secured at the lower open end thereof in offset relation to the longitudinal tubing axis and without substantially obstructing the opening therein a shaped explosive charge well casing perforating device including excitable operation initiating means, setting said tubing in the well with said first well casing perforating device opposite one of said formations, lowering through the tubing a second shaped explosive charge well casing perforating device including means capable of exciting said operation initiating means, causing said second casing perforating device first to perforate the well casing and earth formation at a level below the lower end of the tubing, positioning the excitable means of said second casing perforating device in exciting relation to the operation initiating means of said first casing perforating device, and causing said exciting means to excite said operation initiating means to initiate operation of said first well casing perforating device.

3. In a method for obtaining production from a plurality of earth formations traversed by a bore hole having a casing therein, the steps of providing well tubing having secured at the lower open end thereof in offset relation to the longitudinal tubing axis and without substantially obstructing the opening therein a shaped explosive charge well casing perforating device including means capable of exciting said operation initiating means, setting said tubing in the well with said first well casing perforating device opposite one of said formations, lowering through the tubing a second shaped explosive charge well casing perforating device including means to excite the operation initiating means of said first casing perforating device, and causing said exciting means to excite said operation initiating means to initiate operation of said first well casing perforating device.

4. In apparatus for use in a well, the combination of a member adapted to be mounted on the lower end of an open string of well tubing and having an opening extending longitudinally therethrough, a shaped explosive charge well casing perforating device mounted on said member offset from the longitudinal axis thereof so as not to obstruct the opening therein, an operating circuit for said perforating device and including inductance means in said member in which a voltage is adapted to be induced when exciting means is positioned in said opening, a well equipment component mounted for movement through said well tubing and out of the lower end thereof, said well equipment component being controllable from the surface for performing an operation at a selected level in the well below said tubing lower end, and magnetizable exciting means mounted in fixed relation to said well equipment component for inducing a voltage in said inductance means when disposed in inductive relation thereto, thereby to initiate operation of said perforating device.

5. In apparatus for use in a well, the combination of a member adapted to be mounted on the lower end of an
open string of well tubing and having an opening extending longitudinally therethrough, a first shaped explosive charge well casing perforating device mounted on said member offset from the longitudinal axis thereof so as not to obstruct the opening therein, an operating circuit for said perforating device and including inductance means in said member in which a voltage is adapted to be induced when exciting means is positioned in said opening, a second shaped explosive charge well casing perforating device mounted for movement through said well tubing, and magnetizable exciting means mounted in fixed relation to said second casing perforating device for inducing a voltage in said inductance means when disposed in inductive relation thereto, thereby to initiate operation of said first perforating device.

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