April 11, 1967 H. H. MOHAUPT 3,313,234

EXPLOSIVE WELL STIMULATION APPARATUS

Original Filed Jan. 13, 1958

2 Sheets-Sheet 1

Fig. 1.

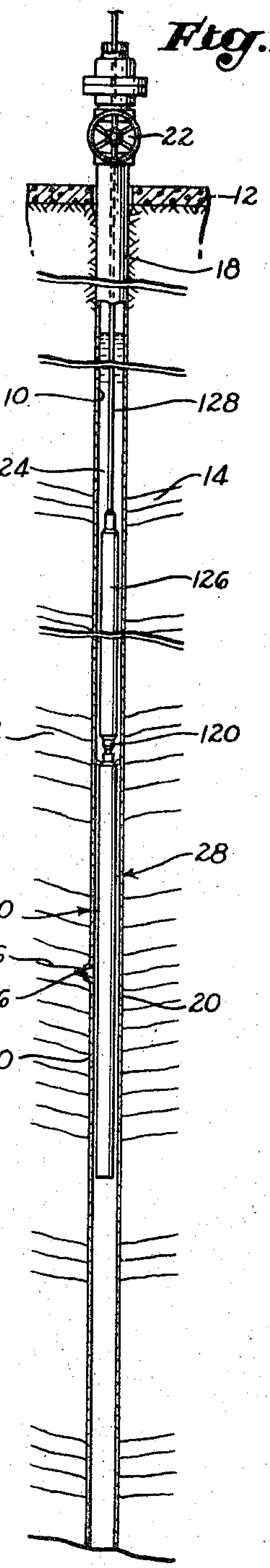

Fig. 2.

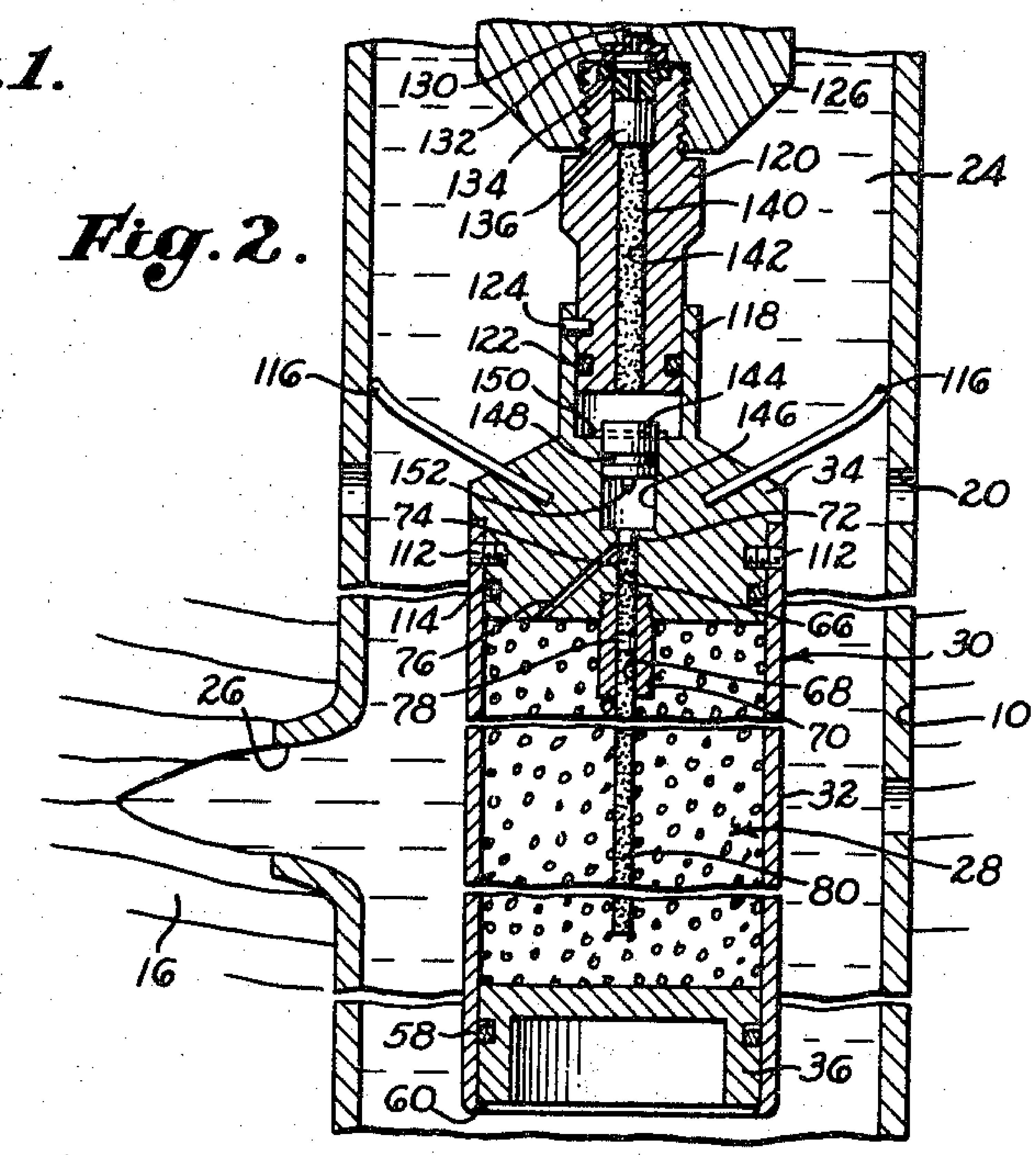

Fig. 3.

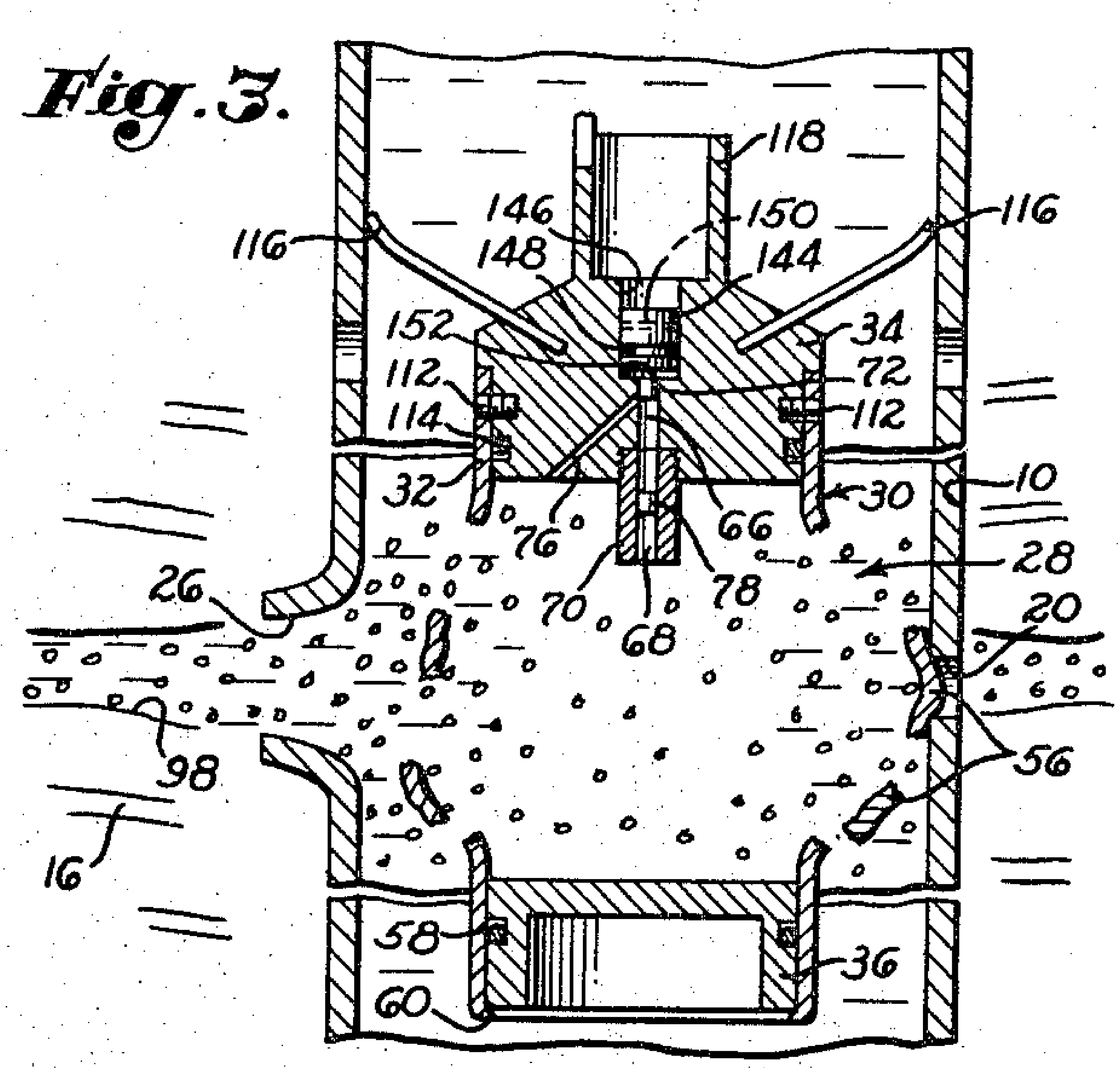

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Fig. 7.

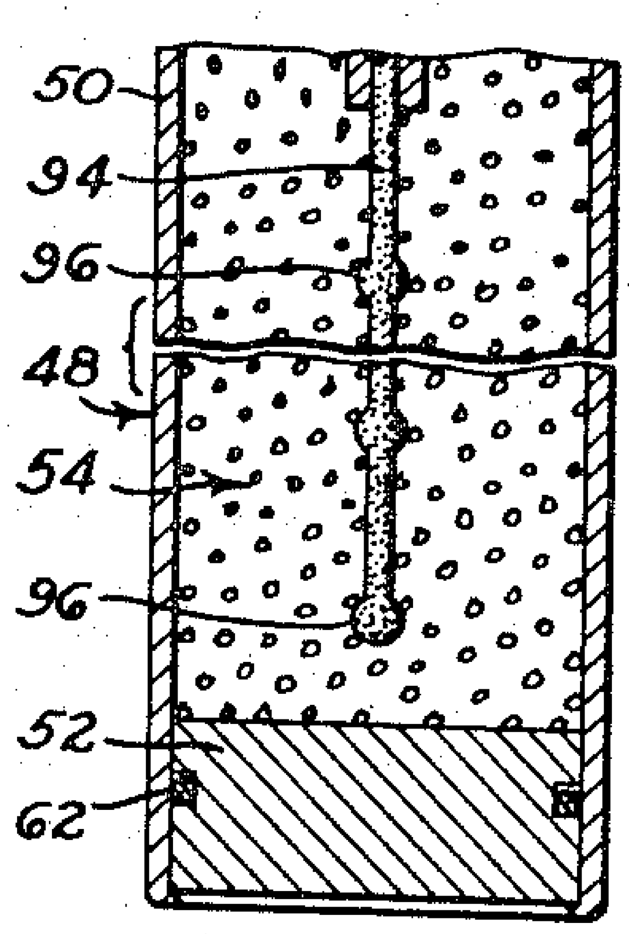


Fig. 4.

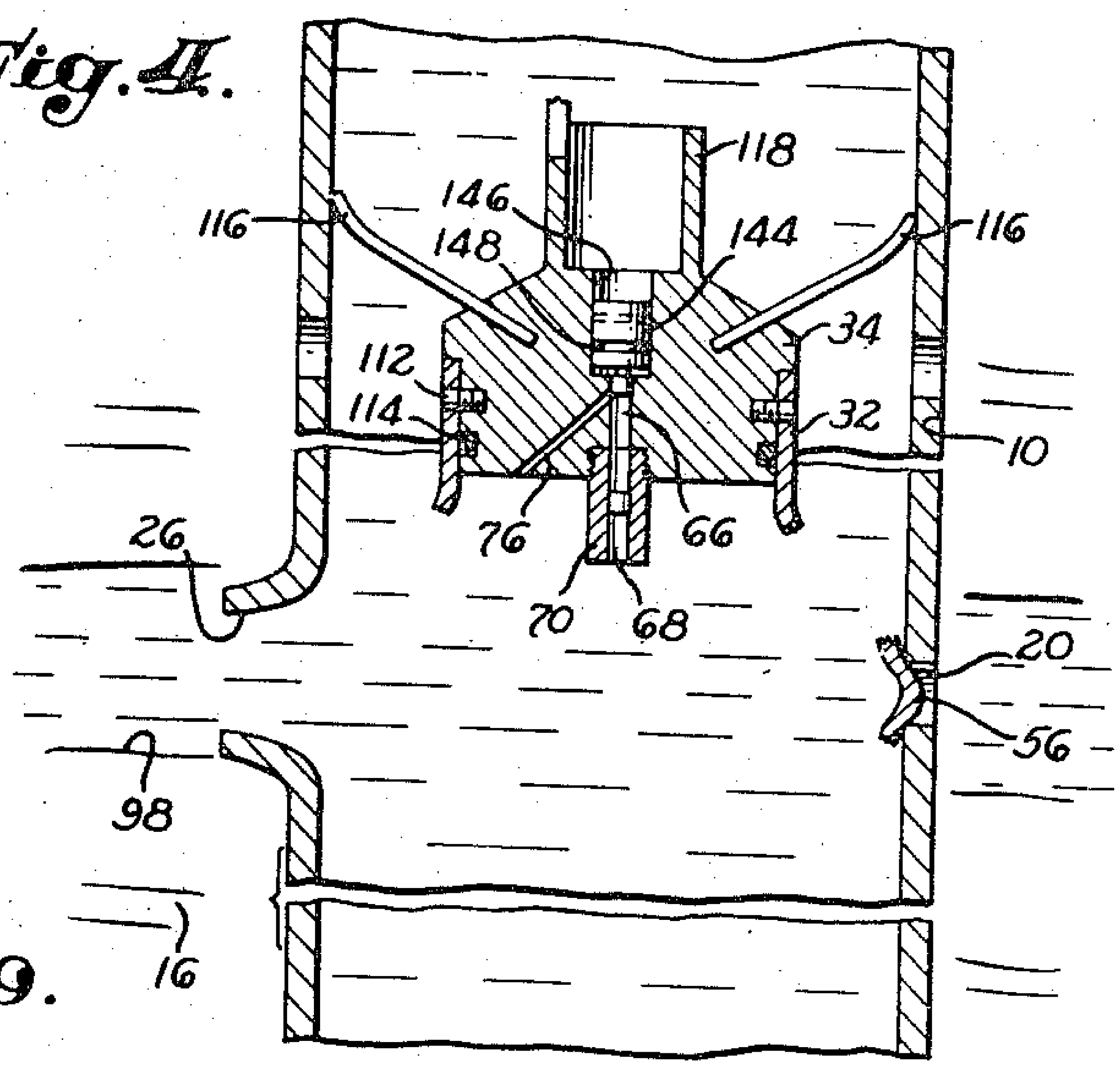


Fig. 8.

Fig. 9.

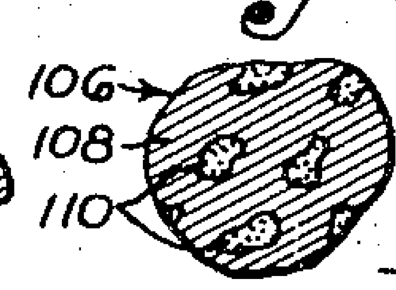


Fig. 5.

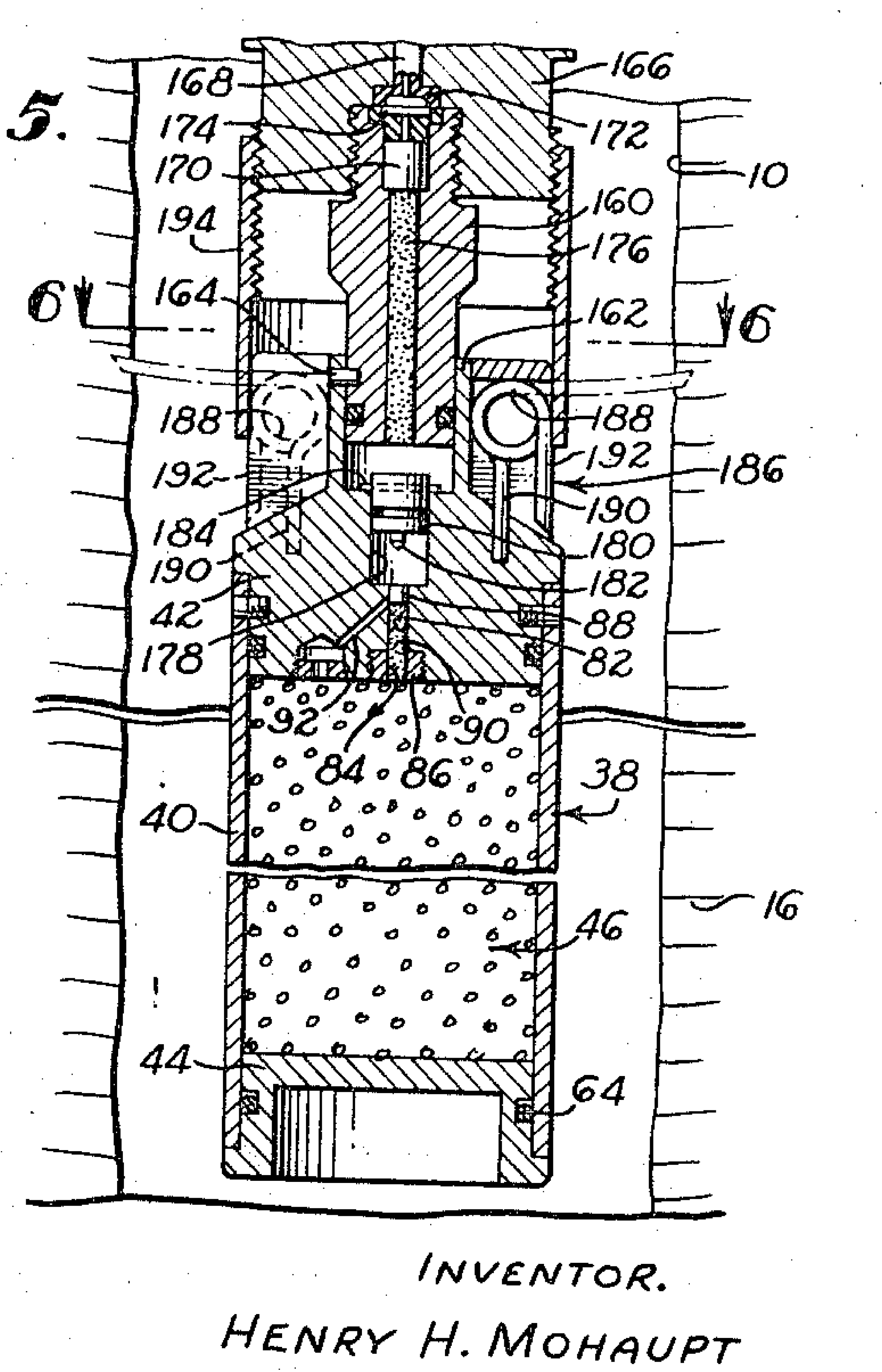


Fig. 6.

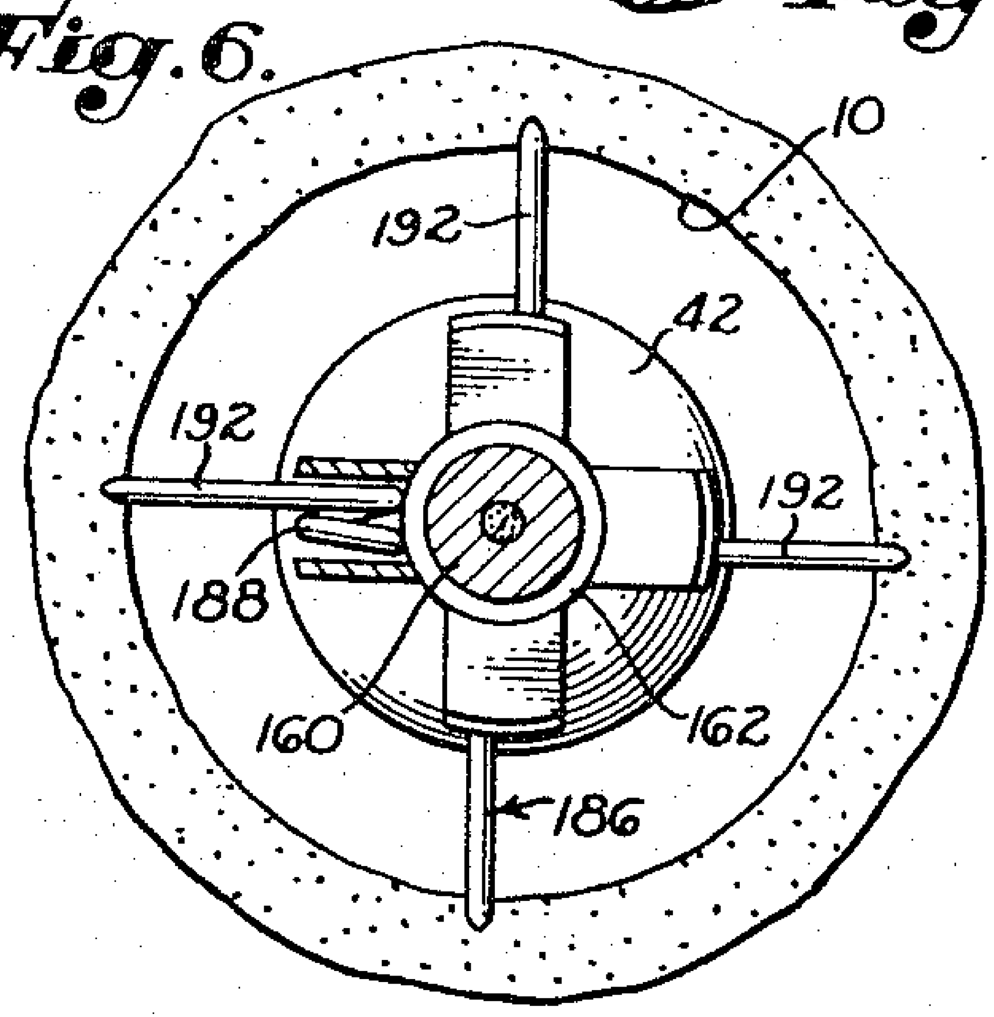
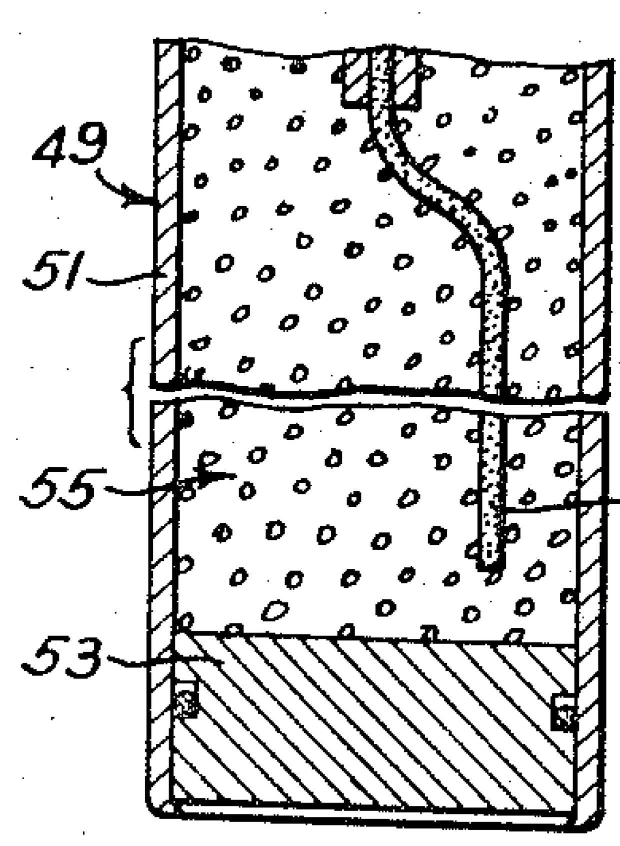


Fig. 10.



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EXPLOSIVE WELL STIMULATION APPARATUS

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Application Feb. 18, 1965, Ser. No. 433,564, now Patent No. 3,264,986, dated Aug. 9, 1966, which is a division of application Ser. No. 708,481, Jan. 13, 1958, now Patent No. 3,174,545, dated Mar. 23, 1965. Divided and this application Mar. 28, 1966, Ser. No. 537,830

3 Claims. (Cl. 102—20)

This application is a division of my co-pending application Ser. No. 433,564, filed Feb. 18, 1965, now Patent No. 3,264,986, issued Aug. 9, 1966, which, in turn, is a division of my application Ser. No. 708,481, filed Jan. 13, 1958, now Patent No. 3,174,545, issued Mar. 23, 1965.

The present invention relates in general to an apparatus for stimulating wells, such as oil wells, to increase production therefrom and, more particularly, to an apparatus for increasing the permeability of a productive formation into which a well bore extends so as to increase the flow of oil, or other fluids, from the formation into the well bore.

A primary object of the invention is to provide an apparatus which fissures the productive formation generally radially outwardly from the well bore through substantial distances in a controlled manner with little or no shattering or compaction of the formation. Thus, the invention increases the permeability of the formation to increase the productivity thereof without adversely affecting the over-all consolidation of the formation, which is an important feature.

More specifically, a primary object of the invention is to produce controlled fissuring of the productive formation by burning a submerged charge of a nondetonating explosive of the propellant type in an irregular, but controlled, manner so that, as the explosive burns, it produces in the liquid adjacent the productive formation and communicates to the formation pressure pulsations of sufficient magnitude to fissure the formation in a controlled manner, but of insufficient magnitude to shatter or otherwise destructively affect the formation.

The rapid pressure oscillations caused by the charge are transmitted directly, or through a casing, into the formation where they cause minute and repeated shiftings of the formation layers with respect to each other. The formation is simultaneously subjected to the pulsating fluid pressure which tends to force fluid into the minutely shifting interfaces of the formation. In a cased well, this occurs at the point or points where the casing has been provided with perforations of adequate diameter. This action establishes permanent breaks in the formation bond and one or more actual fissures result which are extended away from the well bore as the burning of the explosive continues, and more and more well fluid is thus forced into them. These fissures can be further extended by the application of additional charges in the vicinity of the zone. They can also be extended by acidizing or by similar methods, if desired.

Another object of the invention is to produce nonuniform combustion of the propellant explosive by igniting the charge in such a manner that the explosive is dispersed in the liquid in the well bore adjacent the productive formation in discrete form and is caused to move back and forth axially of the well bore as it burns to produce constantly shifting zones of maximum combustion intensity, thereby producing short-duration pressure pulsations in the liquid which cause minute fissures in the formation.

Another object is to control the rate of combustion of the propellant explosive by regulating the size of the explosive particles or grains, the ignition intensity and pattern, the mass of explosive, the nature of and the head of liquid in the well, and by using an inert or semi-active filler or matrix in which the explosive particles are embedded. By varying some or all of these factors, the frequency and amplitude of the pressure pulsations produced in the liquid to fissure the formation may be varied.

A further object is to provide a propellant explosive which is either granular, or which is capable of being broken up into smaller, discrete particles, so that, upon ignition of the explosive charge, mixing of the explosive with the liquid in the well bore is obtained. With such a mixture, combustion of the explosive particles takes place in localized zones, thereby creating pressure centers which cause the mixture to move back and forth axially of the well bore to create new high pressure centers and new zones of localized combustion, the over-all result being the creation of pressure pulsations in the liquid which fissure the formation in a controlled manner. In the foregoing combustion process, many of the explosive particles are ignited, extinguished, reignited, and so on, until substantially all of the particles have been burned, thereby prolonging the period during which pressure pulsations are developed in the fluid and applied to the formation to fissure it. Also, many of the explosive particles may be driven into the fissure or fissures and burned therein to enhance the fissuring action.

Another object of the invention is to obtain nonuniform ignition of the total charge by igniting it at one end only, by igniting it at its center throughout a substantial portion of its length, by igniting it at a plurality of axially spaced points, by igniting it longitudinally but non-axially, and the like.

An object of the invention in connection with a charge of propellant explosive which includes a matrix having the explosive particles or granules embedded therein is to control the length of the combustion period, and the amplitude of the pressure pulsations in the liquid, by varying the proportions of explosive and filler, combustion of progressing relatively rapidly with a low proportion of filler and relatively slowly with a high proportion of filler.

An imporant object is to submerge the charge of propellant explosive beneath a substantial head of liquid to obtain pressure pulsations of a magnitude sufficient to produce the desired fissuring of the productive formation. In order to obtain satisfactory fissuring of the productive formation, it is essential that the formation and the charge of propellant explosive be submerged beneath a head of liquid at least equivalent to 200 feet of liquid having a specific gravity in the neighborhood of one. In other words, the explosive charge should be positioned opposite the productive formation to be fissured beneath a head of at least 200 feet of oil or water, or a mixture thereof, to obtain proper fissuring, a lesser head being possible where the density of the liquid is above unity due to the presence of drilling mud, for example. The head of liquid may range upwardly from 200 feet of oil or water to several thousand feet of oil or water, or more, a head of in the neighborhood of 1,000 feet of oil or water being preferred.

With heads from about 200 feet to about 600 feet of oil or water, the liquid must be unconfined by packers, or the like, for several hundred feet thereabove so as to provide above the liquid a large reservoir of air or gas capable of absorbing excessive pressure pulsations. However, with a liquid head of more than about 600 feet, the compressibility of the liquid and the elastic deformability of the casing and the formation make non-confinement of the liquid unnecessary.

An additional object of the invention is to provide a propellant charge in the form of a long, slender cylinder having a diameter which is less than the diameter of the well bore to provide a liquid space alongside the charge for the purposes of the combustion process hereinbefore described, this liquid space being an annulus if the charge is centered in the well bore. For a well bore of about 4 inches in diameter, or more, the diameter of the propellant charge should be approximately 3 inches. The length of the charge of propellant explosive is made sufficient to accommodate the total mass necessary to produce the desired fissuring of the formation and it is essential that the length of the charge be sufficient to produce the desired axial acceleration and migration of the explosive particles incident to the combustion process hereinbefore discussed.

An important object of the invention is to utilize a propellant charge having a length-diameter ratio of at least 3:1 to obtain the desired particle migration axially of the well bore, a length-diameter ratio less than about 3:1 being insufficient to produce the necessary axial particle movement. The length-diameter ratio may run as high as 40:1 for a charge which is ignited at one end only, and may substantially exceed 40:1 if the charge is ignited substantially throughout its entire length, or at a plurality of points throughout its length. With ignition at one end only, any length-diameter ratio in excess of 40:1 tends to produce excessive migration of the propellant particles with consequent excessive pressure pulsations in the liquid. However, by igniting the charge in other places, as well as at one end thereof, zones of localized combustion are produced which limit axial movement of the explosive particles dispersed into the liquid, and which thus limit the pressure peaks produced in the liquid.

Another object of the invention is to dispose the explosive charge in a readily frangible or combustible container which minimizes the amount of junk remaining in the well bore after combustion of the charge. The container may be a thin shell of a material which breaks up into small, unobjectionable fragments in response to combustion of the propellant charge, and it may be formed of a combustible material. The explosive charge, in the latter event, may contain a material which liberates oxygen for the combustion of the container in response to heating thereof by combustion of the explosive itself. A related object is to provide a charge which requires no container, or only a very thin container, by embedding the explosive particles in a self-supporting, or substantially self-supporting frangible matrix, such as plaster of Paris, sulfur, or the like. Such matrix also acts as heat insulation preventing premature combustion of the explosive due to high well temperatures.

In instances where no matrix is used, or where a matrix which is not self-supporting is used, an important object of the invention is to provide means for equalizing the external and internal pressures applied to the container so as to permit the use of a thin combustible or frangible container.

An important object of the invention in instances wherein it is practiced in a cased well bore is to concentrate the effects of the pressure pulsations in the liquid by locating the charge opposite one or a few large holes in the casing which lead to the formation to be fissured, such hole or holes being much larger than any conventional perforations with which the casing may be equipped and being at least 1 inch, and preferably from 1½ to 2 inches, in diameter. However, the invention may be practiced with only the conventional casing perforations provided the total area of such perforations is considerably greater than that of a single hole of the size range indicated.

An important object of the invention is to provide an apparatus which includes means for lowering the charge of propellant explosive into position opposite the productive formation to be fissured and for igniting the charge in such position, and which includes means responsive to actuation of the igniting means for disconnecting the nonexpandable portions of the apparatus from the charge

itself so that such nonexpendable portions may be raised in the well bore to a position of safety, and to a position wherein they do not interfere with the combustion of the chcarge, before actual combustion of the charge is initiated.

Another important object is to provide an igniting means incorporating a time delay which permits raising the nonexpendable portions of the apparatus in the well bore prior to actual initiation of combustion of the charge of propellant explosive.

Another object is to provide an apparatus which includes a main charge of propellant explosive, means for lowering the main charge into the well bore, means engageable with the wall of the well bore for supporting the main charge therein, means including a small auxiliary explosive charge and a delaying means actuable by the auxiliary explosive charge for igniting the main charge, and means responsive for ignition of the auxiliary explosive charge for disconnecting the lowering means from the main charge so that it may be raised to a position of safety and to a position wherein it will not interfere with the combustion of the main charge, prior to initiation of combustion of the main charge.

The foregoing objects, advantages, features and results of the present invention, together with various other objects, advantages, features and results thereof which will be evident to those skilled in the art in the light of this disclosure, may be attained with the exemplary embodiments of the invention illustrated in the accompanying drawings and described in detail hereinafter. Referring to the drawings:

FIG. 1 is a vertical sectional view illustrating in a well bore an apparatus of the invention for carrying out the well stimulation method or process thereof;

FIG. 2 is an enlarged, vertical sectional view showing a charge of propellant explosive of the invention, and an igniting means therefor, positioned in the well bore;

FIG. 3 is a view similar to FIG. 2, but showing the charge of propellant explosive after ignition;

FIG. 4 is a view similar to FIGS. 2 and 3, but showing the charge after completion of combustion;

FIG. 5 is a view similar to FIG. 2, but illustrating another embodiment of the invention;

FIG. 6 is a transverse sectional view taken along the arrowed line **6—6** of FIG. 5;

FIG. 7 is a vertical sectional view of another embodiment of a charge of propellant explosive of the invention;

FIGS. 8 and 9 are fragmentary sectional views illustrating other propellant-explosive charges of the invention; and

FIG. 10 is a view similar to FIG. 7, but illustrating another propellant-explosive charge of the invention.

Referring particularly to FIG. 1 of the drawings, illustrated therein is a well bore **10** which extends from the surface **12** through overlying formations **14** into or through a productive formation **16** the permeability of which is to be increased by controlled fissuring generally radially outwardly from the well bore in accordance with the invention. In the particular installation illustrated, the well bore **10** is cased in the usual manner by a casing **18** which may be provided with perforations **20** communicating with the productive formation **16**. If desired, the casing **18** may be provided above the surface **12** with a blowout preventer **22** by means of which flow from the well may be shut off after completion of the method of the invention if necessary.

It is essential to the invention that there be in the well bore **10** above the productive formation **16** to be fissured, a body of liquid **24** providing a head at least the equivalent of a head of 200 feet of liquid having a specific gravity of about one. If there is present in the well bore **10** oil or water, or a mixture thereof, extending about 200 feet above the productive zone **16**, this will provide the necessary minimum head. Otherwise, oil, water, or other liquid must be introduced into the well bore to provide a head equal to about 200 feet of oil or water. The head of liquid above the productive formation 16 is preferably considerably in excess of 200 feet and may range upwardly to several thousand feet, or more, a preferred value being at least 1,000 feet. The liquid 24 must be unconfined to provide a surge chamber thereabove to limit the pressures developed in the liquid if the head is less than about 600 feet. The well bore 10 may be left open for this purpose but, if any blowout preventer, such as 22, or any lubricator, is used, it must be at least several hundred feet above the surface of the liquid under such conditions. With heads exceeding 600 feet, nonconfinement is not absolutely essential due to the compressibility of the fluid and the elastic deformability of the casing and formation.

In order to concentrate the fissuring action of the invention in a cased well bore, the casing 18 is provided with at least one large hole 26 opposite the productive formation 16 with any suitable apparatus, although more than one may be provided. This hole is large as compared to any perforations 20 with which the casing 18 may be provided, and must be at least 1 inch, and preferably from 1½ to 2 inches, in effective diameter to minimize throttling of surges of the liquid 24 therethrough. The term "effective diameter" is utilized to describe the equivalent diameter of a hole 26 which may not be perfectly circular. When the invention is practiced in an uncased well bore, as illustrated in FIGS. 5 and 6 of the drawings, the concentrating effect of the single large hole 26 in the casing 18 is not attained, but satisfactory fissuring of the productive formation is nevertheless achieved.

The invention further involves positioning in the well bore 10 opposite the productive formation 16, and opposite the hole 26 if the casing 18 is present, a long, slender charge 28 of a propellant explosive, the details of the charge 28 being set forth hereinafter. It is important that the charge 28, which is preferably cylindrical, have a diameter considerably less than the diameter of the well bore 10, or considerably less than the inside diameter of the casing 18, to insure the presence of liquid alongside the charge for the purpose of producing pressure pulsations in the liquid 24 in a manner to be described. The liquid alongside the charge 28 will have more or less the form of an annulus, depending upon whether the charge is centered in the well bore, or is located to one side of center. Normally, the charge 28 is supported at least approximately in the center of the well bore in a manner to be described, but irregularities in the well bore may not permit attaining exactly a centered position. In order to insure the presence of an adequate quantity of liquid alongside the charge 28, the diameter of the charge is not more than about 3 inches for a well-bore diameter, or inside casing diameter, of about 4 inches.

In order to provide the total mass or propellant explosive necessary to achieve the desired fissuring of the formation 16, and in order to provide the charge 28 with sufficient axial length to permit the necessary axial acceleration and movement of the propellant particles which will be discussed hereinafter, the charge 28 must have a length-diameter ratio, i.e., a ratio of length to diameter, of not less than 3:1. Preferably, the length-diameter ratio of the charge 28 is considerably in excess of 3:1, although it should not exceed about 40:1 where the charge is ignited at one end only, as hereinafter described. However, where the charge 28 is ignited at points other than one end thereof, as will also be described hereinafter, the length-diameter ration may exceed 40:1. Limiting the length-diameter ratio to not more than about 40:1 with one-end ignition of the charge 28 is necessary to prevent excessive migration of propellent particles axially of the well bore 10, and thus to prevent excessive pressures. However, with ignition at a point or points other than at one end of the charge 28, axial propellant migration, and thus the resulting pressure pulsations, are reduced so that, under such conditions, length-diameter ratios in excess of 40:1 may be utilized.

As previously suggested, the charge 28 comprises an explosive of the propellant type, i.e., an explosive which is slow burning and nondetonating, explosives of this type being well known in the art so that it is unnecessary to discuss specific examples herein. The charge 28 should consist of a granular propellant mass made up of small grains or particles, or, if a solid mass, it should be readily frangible by initial combustion of the charge so that the charge is immediately Jreduced to small particles, such small grains or particles being necessary to permit thorough dispersion in the liquid 24 and to permit the gases formed as a result of the combustion of the explosive to rise upwardly through the liquid 24 in the well bore 10 without substantial entrainment of the explosive particles in the rising gases.

In some instances, the charge 28 may consist of an unenclosed mass of propellant particles or grains embedded in a matrix, filler or binder which is self-supporting, but which is sufficiently frangible that initial combustion of the charge breaks it up into small pieces incapable of substantial entrainment in the rising gases. In most instances, however, the charge 28 is enclosed by a readily frangible container 30, the propellant explosive being utilized in such cases with or without a filler or matrix.

The container 30, which is shown in FIGS. 2 to 4 of the drawings, includes a cylindrical tube or shell 32 the upper and lower ends of which are closed by an upper, firing head 34 and a lower head 36, respectively. A similar container 38 is shown in FIG. 5, this container also including a shell 40 closed by an upper, firing head 42 and a lower head 44 and containing a charge 46 of a propellant explosive. FIGS. 7 and 10 illustrate other similar containers 48 and 49 comprising cylindrical shells 50 and 51 closed by upper heads, not shown, and lower heads 52 and 53 and containing charges 54 and 55 of propellant explosive. The charges 46, 54 and 55 are similar to the charge 28 and everything discussed herein in connection with the charge 28 is equally applicable to the charges 46, 54 and 55.

The shells 32, 40, 50 and 51 are formed of a frangible material which is readily broken up into small pieces, such as the pieces 56 in FIG. 3, upon initiation of combustion of the charges 28, 46, 54 and 55 in a manner to be described. The charge-containing shells may be formed of various materials, such as aluminum or plastic, which will break up into relatively small pieces with the thin shells shown, such materials being readily drillable during any subsequent drilling operations which may be performed. Alternatively, the charge-containing shells may be formed of such highly frangible materials as glass, ceramics, and the like. Such materials will shatter into very small fragments upon initiation of combustion of the charges contained therein, and are readily drillable also. As another alternative, the shells may be formed of a frangible material, such as nitrocellulose, which will burn when ignited by combustion of the charge contained therein. Still another alternative material for the charge-containing shells is a combustible plastic which may be burned by incorporating in the charge contained in such shell a material which liberates oxygen when heated by combustion of the propellant explosive. For example, such oxygen-liberating materials as nitrates, chlorates, or perchlorates, may be used.

In order to minimize the thickness of the shell 32, for example, to minimize the amount of debris left in the well bore 10, or to facilitate combustion of the shell if it is made of a combustible material, the lower head 36 is a piston which is slidable axially of the shell 32 and which is sealed relative thereto by an O-ring 58, the piston 36 being retained within the shell in any suitable manner, as by rolling or peening the lower end of the shell inwardly, as indicated at 60. As will be apparent, with this construction, as the charge 28 is lowered into the liquid 24 in the well bore 10, the piston 36 is moved upwardly by the external pressure applied to the container 30 to compress the propellant and thus tend to equalize the internal and external pressures applied to the container. Such pressure equalization, or tendency toward pressure equalization, minimizes the tendency of the shell 32 to collapse and thus permits the use of a thinner, more readily disposable shell. A similar construction is shown in FIG. 7, wherein the lower head 52 is a piston sealed with respect to the shell 50 by an O-ring 62. In FIG. 5, the lower head 44 is immovable, being sealed by an O-ring 64.

To facilitate internal and external pressure equalization, as hereinbefore discussed in connection with FIGS. 2 to 4 and FIG. 7 of the drawings, the voids in the mass of propellant grains or particles forming the charges 28 and 54 may be filled, or partially filled, with a fluid, or semifluid, filler, such as paraffin, grease, inert powder, or the like. Such fluid, or semifluid, filler facilitates equalizing the internal and external pressures.

In a charge like the charge 46 shown in FIG. 5, which is enclosed in a shell 40 provided with fixed upper and lower heads 42 and 44, the thickness of the shell 40 may be minimized by embedding the propellant grains or particles in a rigid matrix which is shatterable by initiation of combustion of the charge. For example, such a matrix may be plaster of Paris, sulfur, plastic, or the like. Alternatively, the propellant particles may be held together by a suitable cementing agent. In some instances wherein the propellant particles are embedded in a matrix of the foregoing nature, the matrix itself may be utilized to support the propellant particles without an enclosing container. For example, under such conditions, at least the shell 40 and the lower head 44 of FIG. 5 may be omitted.

As hereinbefore suggested, an important feature of the invention is that each propellant charge is caused to burn at an irregular rate, due partly to the manner in which the charge is ignited, partly to dispersion of the charge in the liquid 24 adjacent the formation 16 to be fissured, and partly to other factors which will be discussed hereinafter. Considering now the manner of ignition, the charges 28, 46 and 54 are shown as ignited in different ways, the means for igniting the charge 28 being considered first for convenience.

The upper head 34 of the container 30, which will be referred to as a firing head hereinafter, is provided with an axial bore 66 which continues as an axial bore 68 in a bushing 70 threaded into the firing head. The upper end of the bore 66 contains an ignitor 72 which is fired in a manner to be described, this ignitor setting off a delay train 74 in the bores 66 and 68. Cases formed by combustion of the delay train 74 are expanded, cooled and vented into the charge 28 through a passage 76 in the firing head 34. Ultimately, the delay train 74 reaches and fires a detonator 78 in the bore 68, this detonator, in turn, igniting a high explosive train 80 which extends along the axis of the charge 28 substantially throughout the entire length thereof. With this construction, progressive ignition of the center of the charge 28 occurs along the axis of the charge, such progressive central ignition of the charge 28 resulting in irregular ignition of the total charge and in outward expansion which fragmentizes the shell 32 and which disperses the propellant throughout the liquid 24 surrounding the charge. As a result of this dispersion, the propellant explosive is burned at an irregular rate for reasons which will be discussed in more detail hereinafter.

Referring to FIG. 5 of the drawings, the upper head 42 of the container 38, which will also be referred to hereinafter as a firing head, is provided with a bore 82 which continues as a bore 84 in a bushing 86, the bore 82 containing an ignitor 88 and the bores 82 and 84 containing a delay train 90 gases resulting from the combustion of which are vented into the charge 46 through a passage 92 in the firing head. In this construction, the

delay train 90 communicates directly with the upper end of the charge 46, only the upper end of the charge being ignited in this embodiment. Ignition of the upper end of the charge results in expansion to fragmentize the shell 40 and disperse the propellant particles forming the charge 46 throughout the liquid 24 in the well bore 10. Again, such dispersion results in irregular combustion, as hereinafter described.

In FIG. 7 is shown an igniting means which includes an explosive train 94 similar to the explosive train 80, except that it is provided at axially spaced points with nodes 96. The nodes 96 may be faster or slower burning than the explosive train 94 itself, but, in any event, they provide points of more intense ignition of the charge 54 and thus accelerate the dispersion of the charge in the liquid 24 at axially spaced points.

FIG. 10 shows an igniting means comprising a high explosive train 97 which extends longitudinally, but a nonaxially, through at least part of the length of the charge 55, the train 97 being offset relative to the axis of this charge to produce irregular ignition.

Considering the irregular nature of the combustion of the charges 28, 46, 54 and 55, these charges are all ignited nonuniformly, the ignition of the charge 28 being nonuniformed due to the fact that the explosive train 80 ignites only the propellant particles at the center of the charge, the charge 46 being ignited nonuniformly since it is ignited at its upper end only, the charge 54 being ignited nonuniformly along its centerline by the explosive train 94 and the nodes 96 thereon, and the charge 55 being ignited nonuniformly since it is ignited along one side thereof. Such nonuniform ignition of the charges results in fragmentization of the shells containing them and dispersion of the particles forming the charges throughout the liquid 24 adjacent the productive formation 16. The dispersed charges will burn more rapidly in some zones than in others, with the result that the propellant particles are caused to move axially of the well bore until they encounter pressure build-ups sufficient to create new zones of maximum combustion. For example, considering the upper-end ignition of FIG. 5, propellant particles are driven toward the lower end of this charge due to the relatively high rate of combustion adjacent the upper end thereof. Ultimately, the downwardly moving propellant particles are subjected to a sufficient pressure increase to produce burning thereof at a relatively high rate, whereupon they surge upwardly again. With the ignition system of FIGS. 2 to 4, similar back and forth axial movement of the propellant particles occurs, but not to as great a degree due to the fact that the charge 28 is ignited progressively at its center throughout substantially its entire length. In other words, with the ignition system of FIGS. 2 to 4, the axial amplitude of motion of the propellant particles is less than with the ignition system of FIG. 5, the same being true of the system of FIG. 10. The igniting means of FIG. 7 results in minimum axial movement of the propellant particles dispersed in the liquid 24 due to the fact that the more intense combustion zones opposite the nodes 96 act as barriers tending to prevent axial movement of propellant particles past a position opposite the next node in the string.

The net result of the foregoing combustion process is to produce pressure pulsations in the liquid 24 which act on the productive formation 16 to produce progressive, controlled, generally radially outward fissuring thereof, the pressure pulsations acting through the hole 26 in the casing 18 where the well bore 10 is cased. As shown in FIGS. 3 and 4, fragments 56 of the fragmentized container shell 32 tend to plug the smaller perforations 20 with which the casing 18 may be provided to intensify the action through the hole or holes 26, the latter being sufficiently large that it or they will not be obstructed by such fragments 56. During the combustion process, many of the propellant particles are ignited, extinguished, reignited, and so on, as they surge back and forth axially of the well bore between high pressure zones of maximum combustion intensity, thereby prolonging the combustion process and the period throughout which the pressure pulsations in the liquid 24 are produced. As indicated in FIG. 3 of the drawings, many of the propellant particles may be carried into the fissure, indicated by the numeral 98, formed in the productive formation 16 and may burn therein to supplement the action of the pressure pulsations in extending the fissure. The fact that the propellant particles are relatively small insures that they will not be entrained by gases rising through the liquid 24 as the result of the combustion process, and will remain in the region of the productive formation 16 until substantially all of the particles are consumed.

Carrying out the combustion process with at least the liquid head hereinbefore discussed insures the development of pressure pulsations of sufficient amplitude to fissure the formation 16 in the desired manner. At the same time, since the combustion process is prolonged as the result of ignition, extinguishment, reignition, reextinguishment, and so forth, of the propellant particles, and since the liquid 24 is unconfined to provide in effect an air or gas-containing surge chamber thereabove, the development of excessive pressures is prevented. Probably, the pressure pulsations do not exceed short-duration peak values of 50,000 p.s.i., which are sufficient to produce the desired progressive fissuring of the formation 16, but which are insufficient to damage the casing 18, or shatter or compact the formation 16.

The combustion rate may also be rendered irregular, and at the same time reduced, through the use of a filler or matrix which partially or completely encases the propellant particles. FIG. 8 of the drawings shows in fragmentary form a charge 100 composed of a matrix 102 and propellant particles 104 the bulk of which are in contact with other particles. In FIG. 9 is shown in fragmentary form a charge 106 comprising a matrix 108 having propellant particles 110 embedded therein, the majority of the particles 110 being out of contact with each other. With charges like the charges 100 and 106, initial ignition breaks up the matrices 102 and 108 to expose at least some of the particles 104 and 108 for ignition. The particles 104 and 110 thus ignited reduce the matrix pieces formed by initial ignition of the charges into still smaller pieces, and this process continues until all, or substantially all, of the particles 104 and 110 are exposed and ignited. Thus, the matrices 102 and 108 prolong combustion and result in irregular combustion rates. As will be apparent, with the charge 100, combustion proceeds less irregularly and at a more rapid rate than with the charge 106 due to the fact that, with the charge 100, combustion may proceed directly from one particle 104 to the next in most instances. With the charge 106, on the other hand, combustion progresses more slowly and is more irregular since after each particle 110 is exposed, it is not ignited until it encounters another, burning particle.

With a charge of the matrix type, such as the charges 100 and 106, any desired degree of contact between the propellant particles may be provided to produce any desired pressure-time curve. If, for example, a plaster of Paris matrix is used, the plaster of Paris in liquid form is poured into a mold, which may be the final charge container, filled with propellant particles under varying degrees of pressure. If the propellant particles are under relatively high pressure when the plaster of Paris, or other matrix material in liquid form, is poured into the mold, virutally all of the propellant particles will be in contact after setting of the plaster of Paris. On the other hand, by applying little or no pressure to the mass of propellant particles in the mold as the liquid plaster of Paris is introduced, virtually complete separation of the propellant particles by the matrix may be obtained.

An important feature of the combustion process of the invention is that the gaseous products of combustion are not forced to concentrate in the vicinity of the productive formation 16 as it is fissured, the relatively slow combustion rate resulting from dispersion of propellant particles throughout the liquid 24 adjacent the productive formation, either as free particles or as matrix-encased particles, providing ample time for the gases resulting from combustion of initially-ignited particles to rise through the liquid prior to the formation of gaseous products of combustion by subsequently ignited particles. Thus, the gases rise through the liquid 24 in a steady stream as the combustion progresses. The net result of this is that the fluid present in the vicinity of the productive formation 16 as it is being fissured by the pressure pulsations in the liquid 24 is largely liquid, and contains a relatively small proportion of gaseous products of combustion. Consequently, the fluid surging into the fissure 98 as it is progressively extended by the pressure pulsations contains a large proportion of well fluid thereby reducing the tendency to heat the exposed surfaces of the fissure to a temperature sufficiently high to fuse them, which would have a decidedly adverse effect on permeability. Thus, the combustion process of the invention, in addition to producing pressure pulsations of relatively low amplitude, also maintains the temperatures adjacent the productive formation 16 relatively low to avoid fusion damage to such formation.

The disclosure thus far has been concerned with details of the combustion process of the invention and details of the propellant charges thereof, including descriptions of the manners in which the various charges are ignited. In subsequent paragraphs, the manner in which the charge 28 is lowered into the well bore, supported therein, and the igniting means thereof actuated, will be considered.

Referring to FIGS. 1 and 2, the firing head 34, which is shown as secured to the shell 32 by screws 112 and sealed with respect thereto by an O-ring 114, carries radially outwardly and upwardly extending, cantilever springs 116 which are engageable with the casing 18, or the wall of the well bore 10, to support the charge 28 after it has been lowered into position opposite the productive formation 16 to be fissured. The firing head 34 is provided at its upper end with an upwardly extending skirt 118 into which a coupling 120 extends. The firing head 34 is sealed relative to the coupling 120 by an O-ring 122 carried by the coupling and engaging the skirt 118, and is secured to the coupling by a pin 124 located close to the upper end of the skirt 118 and extending through the skirt into the coupling.

The upper end of the coupling 120 is threaded into a sinker bar 126 having sufficient weight to force the charge 28 downwardly through the casing 18 in opposition to friction between the springs 116 and the casing 18 and in opposition to fluid resistance. Connected to the upper end of the sinker bar 126 is a wire line 128 by means of which the sinker bar and the charge 28 may be lowered into the desired position. The wire line 128 contains an electrical conductor 130, shown in FIG. 2, which extends downwardly through the sinker bar 126 and which is connected at its lower end to a contact 132. The coupling 120 carries a contact 134 which electrically engages the contact 132 when the coupling and the sinker bar 128 are assembled. The contact 134 is connected to an ignitor 136 which is fired when current is caused to flow through the conductor 130 by closure of a switch, not shown, at the surface, the ignitor being rounded to complete the circuit. Firing of the ignitor 136 results in ignition of an auxiliary explosive charge 140 in a bore 142 through the coupling 120, combustion of the charge 140 resulting in the development of pressure within the skirt 118 below the coupling 120.

Such pressure within the skirt 118 acts on the upper end of a piston 144 disposed in a counterbore 146 in the firing head 34 which is coaxial with the bore 66 therein, the piston being sealed by an O-ring 148 and normally being retained in an upper, inoperative position by a shear pin 150, or other retaining means, engaging the bottom wall of the recess defined by the skirt 118. The pressure developed by combustion of the charge 140 causes failure of the shear pin 150 with the result that the piston 144 is propelled downwardly in the counterbore 146. The piston 144 is provided at its lower end with a firing pin 152 which strikes the ignitor 72 as the piston reaches the lower end of the counterbore 146, the ignitor 72, as hereinbefore discussed, initiating combustion of the delay train 74.

The pressure produced by combustion of the charge 140 also separates the coupling 120 from the firing head 34 by rupturing the skirt 118 above the pin 124, as shown in FIG. 3. Thereupon, the sinker bar 126 is withdrawn from the well, or is at least moved upwardly therein a substantial distance above the charge 28, by means of the wire line 128, the delay train 74 providing sufficient time to permit raising the sinker bar 126 at least a distance sufficient to avoid its interfering with the rise of gas in the fluid column and to avoid excessive slackening of the wire line.

Referring to FIG. 5 of the drawings, the embodiment illustrated therein is similar to that illustrated in FIGS. 2 to 4 and includes a coupling 160 connected to a skirt 162 on the firing head 42 by a pin 164 and connected to a sinker bar 166. The latter carries a conductor 168 which is connected to an ignitor 170 through contacts 172 and 174, the coupling containing an auxiliary explosive charge 176 which is ignitable by the ignitor 170 to separate the sinker bar 166 from the firing head 42. A counterbore 178 in the firing head 42 contains a piston 180 carrying a firing pin 182 for setting off the ignitor 88. The upper end of the piston 180 is exposed to the charge 176 in the same manner that the piston 144 is exposed to the charge 140, the piston 180 being held in an inoperative position by a shear pin 184 which fails as the result of combustion of the charge 176.

The charge 46 is provided with a supporting means 186 engageable with the wall of the well bore 10, or with a casing, which includes coil springs 188 having arms 190 anchored to the firing head 42 and arms 192 frictionally engageable with the wall of the well bore. A sleeve 194 threaded on the lower end of the sinker bar 166 normally holds the arms 192 in retracted, inoperative positions, shown in solid lines, the sleeve 194 being threaded downwardly over the springs 188 to hold the arms 192 in their retracted positions after assembly of the sinker bar, the coupling 160 and the firing head 42. Upon separation of the firing head 42 and the coupling 160 as the result of combustion of the charge 176, the sleeve 194 disengages the springs 188 to permit the arms 192 thereof to fly outwardly into engagement with the wall of the well bore 10 to support the charge 46, such positions of the arms 192 being shown in broken lines. The action of the springs 188 is so rapid that the charge 46 drops but a very short distance before the arms 192 engage the wall of the well bore to support the charge in the desired position. During the time interval provided by the delay train 90, the sinker bar 166 is drawn upwardly a substantial distance, or to the surface, before ignition of the charge 46. Considering the over-all operation of the invention, with the proper head of liquid 24 in the well bore 10 above the productive formation 16 to be fissured, and after forming the hole 26 in the casing 18 in the event that the well bore is cased, the charge of propellant explosive is lowered into a position opposite the productive formation by means of the wire line and the sinker bar. The small auxiliary explosive charge in the coupling connecting the main charge and the sinker bar is then fired, which results in delayed ignition of the main charge by the corresponding piston 144 or 180, and results in detaching the main charge from such coupling. The main charge is then supported in the proper position either by the springs 116, or the supporting means 186, the latter being activated by separation of the charge from its supporting coupling and sinker bar.

As soon as the charge has been detached from its supporting coupling and sinker bar, and during the period provided by combustion of the delay train 74 or 90, the sinker bar is moved upwardly, by means of the wire line attached thereto, either to the surface, or at least to a sufficient distance above the charge to prevent damage thereto and to prevent interference by the sinker bar with upward movement of gases resulting from combustion of the charge.

Upon expiration of the desired time delay, the delay train ignites the main charge, such ignition taking place at the upper end of the charge in the case of the charge 46, taking place throughout substantially the entire length of the charge in the case of the charges 28 and 55, and ignition of the charge taking place with a maximum intensity at a plurality of axially spaced points with the charge 54. Upon ignition, the charge is dispersed throughout the liquid 24 adjacent the productive formation 16 to be fissured, the container in which the charge is disposed being fragmentized upon ignition of the charge. The propellant particles are dispersed laterally throughout the liquid 24 as a result of bursting of the charge container and then move axially in the well bore 10 away from zones of maximum combustion intensity due to the higher pressures existing in such zones, until the axial movement of the propellant particles results in pressure build-ups in new zones sufficient to create new points of maximum combustion intensity. This axial migration of the propellant particles takes place in both directions to produce constantly shifting zones of maximum combustion intensity, the axial movement of the propellant particles being a maximum with ignition of the charge at one end only, and being a minimum with the type of ignition provided by the charge 54 of FIG. 7 since the more intense ignition zones provided by the nodes 96 limit axial movement of the propellant particles. During the process of migrating back and forth, the propellant particles may be ignited, at least partially extinguished, reignited, and reextinguished many times before substantially complete combustion occurs, and some of the propellant particles may actually be swept into and out of the fissure 98 formed by the combustion process and some combustion may take place therein.

The net result of the foregoing combustion process is the creation of pressure pulsations in the liquid 24 adjacent the productive formation 16, and in the liquid-gas emulsion formed by the explosion, sufficient to form and progressively extend the fissure 98 as these pulsations act on the formation, but insufficient to shatter or otherwise destructively damage the formation. The fissure 98 is frequently extended to points many feet from the well bore to produce substantial increases in the permeability of the productive formation 16, and thus substantial increases in the production of fluid therefrom.

Due to the fact that the combustion of the propellant particles takes place while these particles are dispersed in the liquid 24 for the most part, the entire combustion process takes place without the development of excessive temperatures which would tend to detract from the permeability of the productive formation 16, as by fusing the surfaces of the fissures 98. The products of combustion resulting from burning of the individual propellant particles constantly rise upwardly through the liquid 24 and, in so doing, create a pressure reservoir which, during the final phases of the process, produces a prolonged downward flow of fluid into the fissure or fissures to further extend them. Entrainment of the propellant particles in the rising gases is minimized due to the relatively small particle sizes.

Thus, the present invention provides an apparatus for effectively increasing the production of tight productive formations by fissuring such formations in a controlled manner while at the same time avoiding damage to the well bore, or any casing therein, by avoiding excessive combustion pressures and temperatures. Although exemplary embodiments of the invention have been disclosed herein for purposes of illustration, it will be understood that various changes, modifications and substitutions may be incorporated in such embodiments without departing from the spirit of the invention as defined by the claims which follow.

I claim:

1. In combination:
(a) a main explosive charge;
(b) means connected to said main explosive charge for lowering it into a well bore;
(c) means carried by said main explosive charge for supporting it in the well bore;
(d) means including an auxiliary explosive charge carried by said lowering means for igniting said main explosive charge;
(e) means responsive to ignition of said auxiliary explosive charge for disconnecting said lowering means from said main explosive charge; and
(f) said main explosive charge including slow-burning delay train means ignitable by said auxiliary explosive charge for delaying ignition of said main explosive charge to provide time for movement of said lowering means away from said main explosive charge.

2. In combination:
(a) a main explosive charge;
(b) means connected to said main explosive charge for lowering it into a well bore;
(c) means carried by said main explosive charge for supporting it in the well bore;
(d) means including an auxiliary explosive charge carried by said lowering means for igniting said main explosive charge;
(e) means responsive to ignition of said auxiliary explosive charge for disconnecting said lowering means from said main explosive charge;
(f) said main explosive charge including priming means ignitable by said igniting means; and
(g) means for venting products of combustion from said priming means into said main explosive charge.

3. In combination:
(a) a main explosive charge;
(b) means connected to said main explosive charge for lowering it into a well bore;
(c) means carried by said main explosive charge for supporting it in the well bore;
(d) means including an auxiliary explosive charge carried by said lowering means for igniting said main explosive charge;
(e) means responsive to ignition of said auxiliary explosive charge for disconnecting said lowering means from said main explosive charge;
(f) said supporting means being movable between inoperative and operative positions; and
(g) means responsive to ignition of said auxiliary explosive charge for moving said supporting means from its inoperative position to its operative position.

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