Feb. 3, 1959 A. G. BODINE, JR 2,871,943

PETROLEUM WELL TREATMENT BY HIGH POWER ACOUSTIC WAVES TO FRACTURE THE PRODUCING FORMATION

Filed June 16, 1954 3 Sheets-Sheet 1

Fig. 1

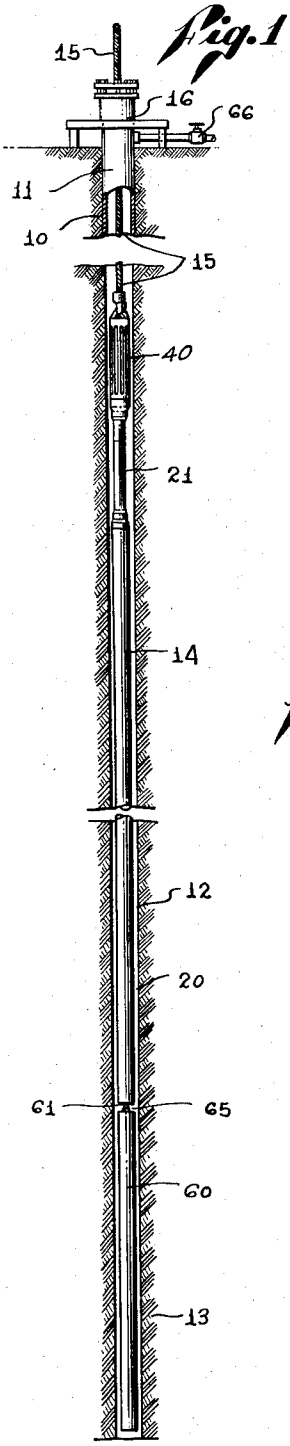
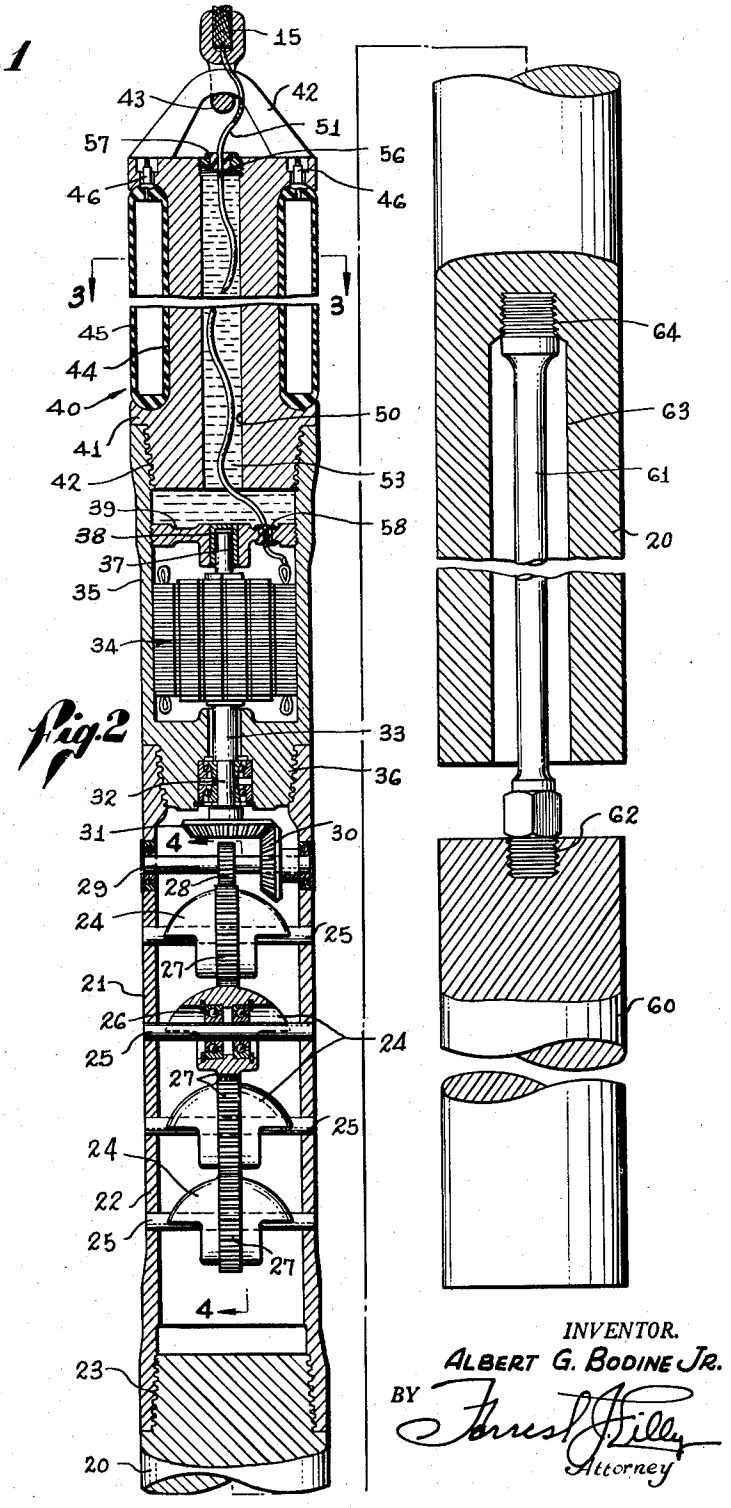


Fig. 2



INVENTOR.
ALBERT G. BODINE JR.
BY Forrest J. Filley
Attorney

Feb. 3, 1959 A. G. BODINE, JR 2,871,943

PETROLEUM WELL TREATMENT BY HIGH POWER ACOUSTIC WAVES TO FRACTURE THE PRODUCING FORMATION

Filed June 16, 1954 3 Sheets-Sheet 2

Fig. 3

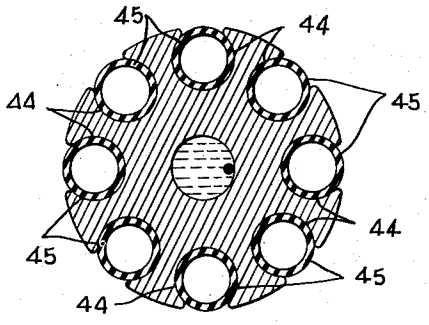


Fig. 4

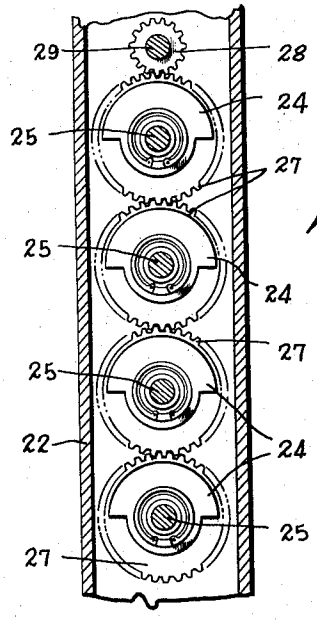


Fig. 5

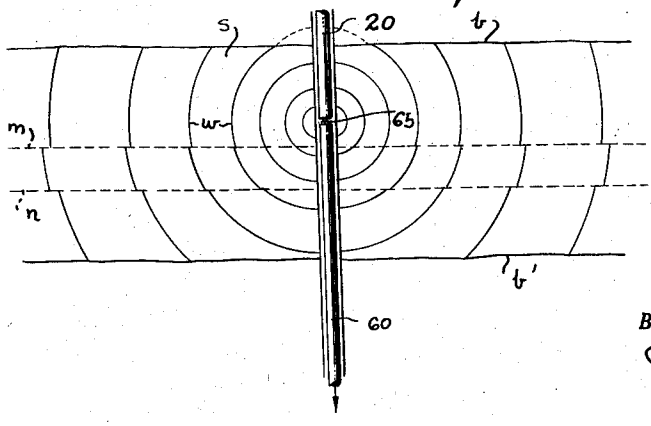
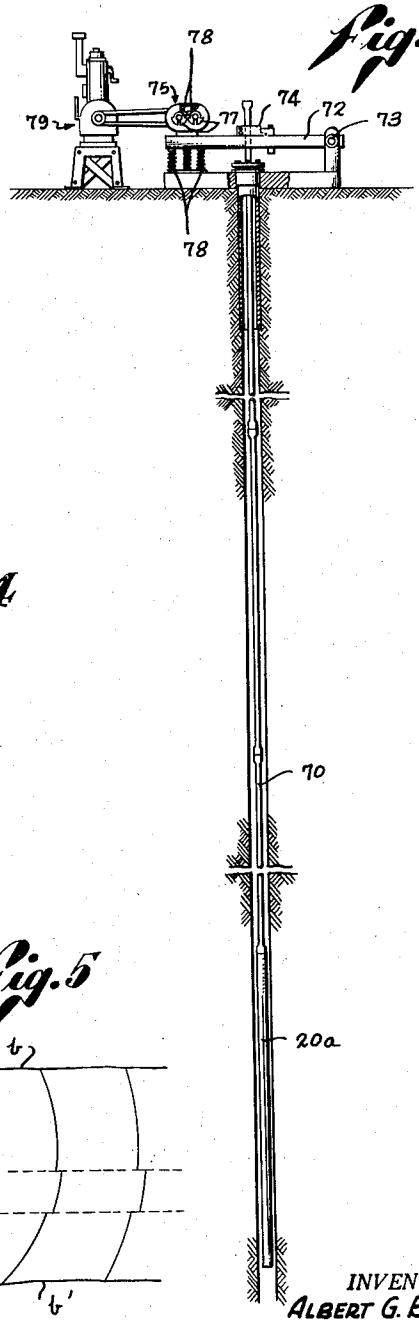


Fig. 6



INVENTOR.
ALBERT G. BODINE JR.

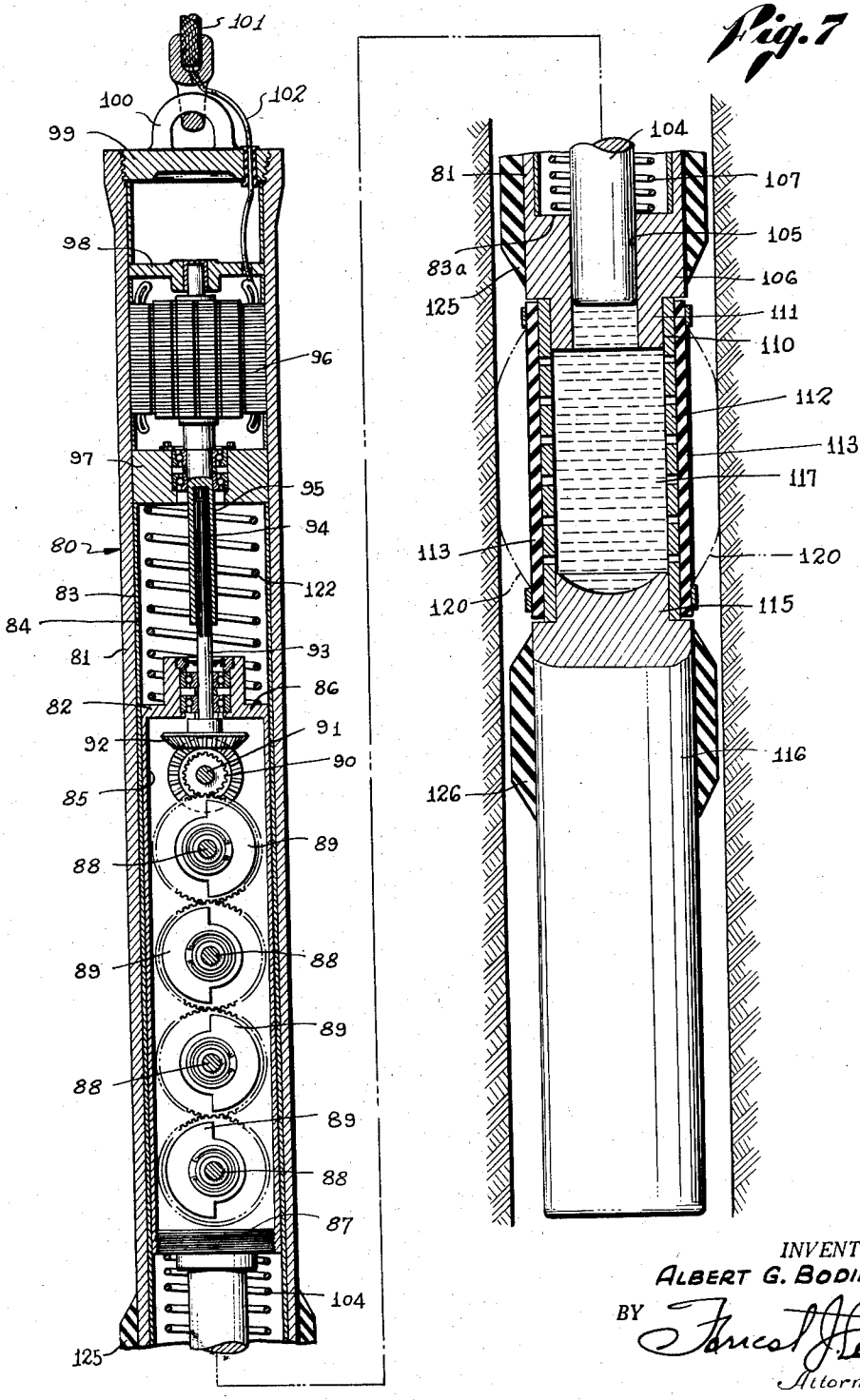
BY Forrest J. Hilley
Attorney

Feb. 3, 1959 A. G. BODINE, JR 2,871,943

PETROLEUM WELL TREATMENT BY HIGH POWER ACOUSTIC WAVES TO FRACTURE THE PRODUCING FORMATION

Filed June 16, 1954 3 Sheets-Sheet 3

Fig. 7



INVENTOR.
ALBERT G. BODINE JR.
BY Francis J. Kelly
Attorney

United States Patent Office

2,871,943

Patented Feb. 3, 1959

2,871,943

PETROLEUM WELL TREATMENT BY HIGH POWER ACOUSTIC WAVES TO FRACTURE THE PRODUCING FORMATION

Albert G. Bodine, Jr., Van Nuys, Calif.

Application June 16, 1954, Serial No. 437,078

18 Claims. (Cl. 166—42)

This invention relates generally to petroleum well treatment and more particularly to improvement of production from earthen petroleum reservoirs of low permeability by fracturing the petroleum bearing strata. The present invention accomplishes this purpose by use of acoustic waves of such extreme power as to cause the formation to undergo a periodic stress beyond its elastic endurance limit and to fail by elastic fatigue.

An oil reservoir in the ground is simply a region of porous oil-soaked rock or sand. Formation porosity refers to the total volume of voids in which oil may accumulate. Permeability refers to the ability of the formation to permit oil flow therethrough. Small pore size, and especially the absence of good joining channels between pores or voids, results in low permeability. Permeability largely determines the daily oil production rate of the well, and to a considerable degree determines how long the well will have a reasonable daily production.

A great many attempts have been made to increase artifically the production rate from a low permeability formation around a well bore. One well known process is to fire a charge of explosive in the formation to jar the formation into a state of "looseness." In some wells this "shooting" has been of moderate success; but it has various well known limitations.

Another process, with the same aim, involves the use of explosive jets. Present practice along these lines usually consists in lowering a "gun" into an oil well whereby a plurality of such jet perforating units can be fired to produce a plurality of horizontal perforations which extend into the holes in the casing and some short distance into the formation. Only limited success has been achieved with this process.

Various processes have been developed which comprise drilling a series of small horizontal bores radiating out from the main well bore like the spokes of a wheel. Here again the drainage area of the exposed rock is increased, but only to a limited extent.

It is of course well-known that the permeability near an oil well can be improved by cleaning processes. Various mechanisms for washing the perforations and the lower region of an oil well have been known for a long time. These processes are especially useful in instances where the drilling mud which was used for drilling the oil well tended to plaster over the surface of the well bore where the oil should enter. They are, however, of only limited usefulness.

In some of the oil fields the oil is produced from porous limestone. In this situation it is possible to increase the permeability by injecting acid into the well which acid attacks the limestone and increases its porosity and opens up intercommunicating channels between pores. The acid system is limited in the respect that the acid becomes neutralized as it penetrates the limestone so that it does not carry its effect as deeply as would be desired.

It has also been found that if a liquid, e. g., crude or refined oil, or a special oily fluid of high viscosity, is pumped down the well, using very large pumps with high pumping rate, it can be caused to enter the cracks and passages in the formation with sufficient hydraulic pressure (known as the "hydraulic formation breakdown pressure") that these cracks and passages are opened up by literally hydraulically "jacking" apart adjacent layers of formation. Such procedure of opening up of cracks or fissures extending out from the well is intended to expose additional surface of the rock, to provide improved drainage channels from such surfaces to the well, and to artificially breach regions of reduced permeability owing to well completion procedures. Speaking generally, these highly desirable purposes have been realized only to a limited extent, though it is recognized that some wells have been greatly improved thereby. Unfortunately, the primary result of hydraulic pumping under high pressure is to lose large amounts of oil into highly permeable regions or to enlarge already existing cracks and fissures into which the injected liquid can most easily flow. The process is therefore inherently limited in that the liquid takes the path of least resistance and tends primarily merely to the enlargement of already existing large cracks, smaller cracks and fissures and incipient fractures being largely by-passed. This process has been called hydraulic fracturing, even though it is recognized that it probably creates only incidental new fractures, and tends primarily only to enlarge existing cracks and fractures. In this system, the attainment of what is called "hydraulic formation breakdown pressure" is made known at the ground surface by an actual pressure drop as the increasingly pressurized fluid suddenly flows into the enlarged opening made in the formation. However, with the hydraulic pressure having thus fallen below "hydraulic formation breakdown pressure," it is evident that the fluid is simply being pumped into a large crevice or void, the condition for making new partings or fractures having been lost. In the effort to curtail this effect, so-called low-penetrating fluids, of high viscosity, have been used, but with only limited success.

To combat the "by-passing" effect caused by either existing or newly made large cracks or fractures, which tend to take all the fluid that can be pumped, there has been developed a system of fluid packers designed to pack off above and below an isolated region in the well bore wherein the hydraulic liquid is injected. This procedure is pursued in an attempt to reduce the chance that the injected fluid will find a path of low resistance, i. e., a large existing fracture, and therefore by-pass incipient fractures, and small and even moderate-sized existing fractures. Even with packers, however, it is generally still possible to secure the desired opening-up effect only in moderate-sized existing fractures encountered within the packed off region. The smallest fractures and the incipient fractures are still likely to be almost completely by-passed by reason of flow into such moderate-sized fractures.

It might be pointed out in passing that in some instances it has been found of advantage to include a percentage of free sand in suspension in the injected fluid so that the free sand will become lodged in what fractures have been opened, and therefore tend to hold those fractures partly open after the hydraulic pressure has been discontinued.

The general object of the present invention is the provision of a process and apparatus involving the use of high intensity acoustic waves to fracture low permeability rock, provide new exposure area, and open up new drainage channels to the well.

Rock material will of course transmit acoustic (elastic) waves, and will continue to do so indefinitely at ordinary wave amplitudes, such as are set up with certain prior processes used for various purposes. In such elastic wave transmission, alternating deformation waves of compres-

sion and expansion travel through the rock. As stated, certain prior procedures for other purposes have made use of such waves at a relatively low order of amplitude. I have discovered that if the pressure amplitude of such alternating deformation waves is very materially raised to a certain threshold level, the rock is then "cyclically overstressed," and under such conditions, fatigue failure and resulting cracking of the rock occurs within a finite time period. I have found that there is a threshold value of acoustic wave pressure amplitude for any given rock, and set of local conditions surrounding the same, at which the rock is stressed beyond its strength or endurance limit, and if the wave is maintained at such amplitude, fatigue failure and fracturing will ensue. Beyond such threshold value, fatigue failure occurs more promptly with higher and higher wave amplitudes. The present invention is based on my discovery that acoustic waves established in the formation at or above a certain threshold value place the rock media under more cyclic stress than its physical cohesive properties or tensile strength can endure, sometimes referred to herein as overstressing the rock, and that under such conditions the rock proceeds to fracture by the process of fatigue failure. I also define the threshold level of acoustic wave pressure amplitude which I have found to be necessary for fracturing of the rock by such fatigue failure as "acoustic formation-failure stress amplitude."

This present process is not to be confused with the acoustic process of "unclogging" a formation by transmitting sound waves therethrough. In my Reissue Patent No. 23,381, I disclosed and claimed an acoustic process which improves the permeability of oil bearing formations by transmission of sound waves therethrough. This process was directed to permeability improvement only, and operated by "unclogging" the formation. That is to say, the sound waves acted to displace elements or materials such as gas bubbles, clay, mud, etc. tending to clog the pores of the formation, or the flow channels between oil containing voids. This prior patent did not contemplate or suggest the present process which consists in the use of acoustic waves so powerful as to actually fracture the formation and make a physical change in the rock itself, so as to provide new surface exposure, and a multiplicity of new drainage channels to the well bore. It will be seen that the instant process, while incidentally including permeability improvement in its accomplishments (in the technical sense of improving flow through the pores of integral blocks of formation), goes far beyond such operation and, by passing the wave amplitude level at which the formation is stressed beyond its physical strength characteristics, enters the realm wherein the formation is actually fractured by the transmitted acoustic waves. To enter this field, much higher acoustic power must be delivered to the formation.

Sedimentary rocks are made up of successive relatively thick beds or strata of differing composition, such as sandstone, sand, clay, shale, limestone, etc. These thick beds usually reveal a large number of bedding planes. Thus a given bed, e. g., a sandstone, will ordinarily be composed of successive layers laid down under differing conditions, often separated by bands of clay, shale, or other material. The boundaries between successive beds of differing composition constitute planes of easiest separation, along which cracks or fractures may sometimes develop naturally, and which are most easily opened up by various so-called fracturing procedures. The successive layers are kept normally under high compression by the weight of the overburden. An aim of the present invention is to periodically elastically move or "work" these highly compressed and initially bonded layers, causing them to "fracture" and/or separate by subjecting them to extreme periodic elastic deformation stresses under the influence of powerful acoustic waves transmitted to and through them from a powerful acoustic wave radiator positioned in the bore hole. The fracturing can take place in either or both of two ways, first, separation and relative displacement of adjacent beds or layers, which of course means fracture of the bond between adjacent layers, and second, fracturing of homogeneous beds by cyclic overstress of the formation to the point of fatigue failure. The acoustic waves will, in such manner, also result in vertical cracks due to the stress geometry of a vertical bore.

According to one illustrative practice of the invention, the acoustic waves are transmitted from the radiator to the formation via a coupling liquid maintained in the well bore under a suitable hydraulic pressure. This coupling liquid contacts both the radiator and the formation, and enters all available cracks, fissures and fractures therein, so as to provide a liquid wave transmission medium between the radiator and all exposed surfaces of the formation. This coupling liquid has a specific acoustic impedance ρc (where ρ is density and c is the velocity of sound) which, while not as high as that of the formation, is nevertheless high enough that a large percentage of the wave energy transmitted through it to the formation is transmitted on into the formation. Some of the wave energy is of course reflected at the surface of the formation. At this reflecting boundary, a stress or pressure cycle is set up, acting to periodically move or reciprocate the surface of the formation through a definite displacement amplitude. Such cyclic movement of a bounding surface of the formation launches alternating elastic deformation waves which are propagated on through the formation with the speed of sound. Assuming a cyclic stress of sufficient magnitude at the point of incidence of the acoustic wave on the formation, and/or waves transmitted in the rock which are of sufficient magnitude to cyclically over-stress the rock, the rock material is subject to fatigue failure and fracture. Fracturing at the boundary planes between adjacent strata, with consequent loosening and separation of strata, is also produced. For example, the characteristic acoustic impedance of sedimentary rock has a marked discontinuity at the boundary planes between different strata, and at such planes, therefore, acoustic waves in the formation are substantially reflected rather than being fully transmitted into the adjacent strata. Accordingly, a given stratum within which a powerful sound wave is being propagated will undergo cyclic elastic deformation movements relative to adjacent strata, thus creating fractures along these bounding planes. Also, assuming the case of waves set up in two adjacent strata of different acoustic impedance, the waves will travel at differing velocities, and the resulting phase difference on opposite sides of the bounding plane results in shearing forces which separate the strata.

With respect to the above mentioned acoustic coupling liquid, it is very important that contact with the formation to be fractured be attained and that the liquid be made to follow up changes in geometry as fractures are generated, because the transmission of acoustic fracturing energy to the formation depends upon the presence of the liquid body. It is also generally desirable that the coupling liquid be maintained under a considerable hydraulic head. Every formation within the earth has what has come to be called its "hydraulic formation breakdown pressure." This is the pressure at which hydraulic liquid working into a crack in the formation will open up the crack by overcoming the pressure of the earthen overburden, the tensile strength of local earthen material at its weakest point, and various other somewhat indeterminate factors. The "formation breakdown pressure" is usually estimated as approximately equal, in pounds per square inch, to the depth of the formation in feet. It is generally somewhat less than the actual weight of the overburden. For reasons which will appear hereinafter, in my acoustic process I generally prefer that the acoustic coupling liquid be maintained at a hydraulic pressure less than "hydraulic formation breakdown pressure." The necessary pressure can often be attained by the hydro-

static head of a column of liquid filling the well hole to the ground surface. If such hydrostatic head proves to be inadequate, additional pressure can be applied by means of a suitable pressure source at the ground surface.

Assuming a hydrostatic head on the coupling liquid, as described, a pressure wave is radiated into the liquid, and it will be seen that this pressure wave will be superimposed on, i. e., will comprise alternate positive and negative pressure half cycles relative to, the maintained hydrostatic pressure. The sound wave is thus transmitted to the exposed wall surfaces of the formation, to be thence propagated through the formation. Within the formation, the sound wave involves alternate positive and negative pressure half cycles relative to the compressive pressure normally existing within the formation owing to the overburden.

An important concept of the invention is the development of elastic or acoustic wave cycles of sufficient wave-pressure amplitude to equal or exceed the magnitude which I define as "acoustic formation-failure stress amplitude." Within the coupling liquid and at the formation wall surface, this amplitude is that which will elastically vibrate the formation sufficiently to overstress it and cause it to fail by elastic fatigue. Within the formation, this amplitude is that which is sufficient to overstress the formation and cause it to fail or fracture by elastic fatigue. Thus, the acoustic waves impinging upon and/or transmitted through the formation subject the formation to a cyclic elastic stress, and when this stress is of sufficient magnitude, defined herein as "acoustic formation-failure stress amplitude," the rock is cyclically stressed beyond its fatigue strength at a frequency of many times per second, and fails or fractures as the inevitable consequence.

The feature of the foregoing paragraph may also be expressed, and the threshold limit of the present invention demarked, in terms of the "endurance limit" of the material. This expression is used by engineers to denote the maximum repetitive stress that a material will withstand indefinitely without fatigue failure, and I have found that the same concept is applicable in explaining the present invention. According to this concept, the previously defined acoustic formation-failure stress amplitude denotes a repetitive stress which exceeds the so-called endurance limit of the material. A plotted curve using repetitive stress amplitude as ordinates, and life (in cycles) to fatigue failure as abscissa, is convex downwardly and becomes horizontal or substantially so at some value of repetitive stress. This particular stress value, called the endurance limit, is taken as the value of indefinite life. The condition for the present invention is then the use of an acoustic wave of amplitude creating a repetitive stress in the structure to be fractured in excess of such value for indefinite life. Obviously, of course, it is preferable to exceed the endurance limit for the material rather substantially, so that the desired fatigue failure will occur with reasonable rapidity. To summarize, it has been noted hereinabove that the formation may, in accordance with the invention, be fractured in either of two general ways, first, fracture within the confines of a bed or stratum, and second, fracture along the interface bond between adjacent strata. It will be clear that in both cases, the acoustic waves transmitted through the formation must be of sufficient amplitude to repetitively stress the material to be fractured beyond the endurance limit thereof. In the first case, the endurance limit of the rock within a bed is to be exceeded. In the second case, the fracture is to be of the earthen material forming the interface bond; and the amplitude of the wave is accordingly to be such as to set up a stress exceeding the strength of the interface bond, i. e., of the endurance limit of the formation along this interface bond. It may incidentally be observed that when fracture of the formation does result from transmission of acoustic waves therethrough, it may conclusively be presumed that the endurance limit of the formation along the site of the fracture made was exceeded by the pressure amplitude of the wave.

It should be clear that this elastic fatigue failure is a phenomena entirely different from that of so-called fracturing by hydraulic pumping to a pressure equal to "hydraulic formation breakdown pressure." The latter refers simply to application of sufficient pressure to bodily lift the formation against the weight of the overburden. The present process consists in subjecting the treated formation to a cyclic stress of amplitude sufficient to cause formation breakdown by elastic fatigue, and this stress value may be a number which is less than hydraulic formation breakdown pressure. The physical property of the locally treated rock itself leading to fracturing in the practice of the present invention is thus its susceptibility to fatigue failure under periodic elastic stress—a property not previously made use of in formation fracturing. The defined acoustic formation-failure stress amplitude has a definite threshold value for any given rock, but it will be seen to be quite different from hydraulic breakdown pressure because, for one thing, it is not primarily a function of depth. It is sometimes feasible, depending upon local conditions, e. g., overburden pressure, geometry of formation, or power of sound wave generator, to produce pressure waves in the formation of such large swing as will develop periodic tensile stresses in the formation, leading to even more rapid fatigue failure.

The desirability of maintaining adequate hydrostatic pressure on the coupling liquid used between the acoustic wave radiator and the formation has already been mentioned. This coupling liquid is used, first, to provide an effective acoustic coupling medium between the radiator and the formation, of impedance sufficiently high with respect to that of the formation to assure adequate coupling and wave energy transmission. At this point it might be mentioned that the specific impedance of the coupling liquid may be measurably improved by incorporating therein a proportion of sand or other solid particles. It will be clear that sufficient of this coupling liquid, under sufficient hydraulic pressure, must be provided to assure that it will follow up the extensive cracks and fractures that develop in the progress of the process, so as to maintain or develop the transmission of high energy acoustic waves from the radiator to newly exposed surfaces of the formation. Maintenance of the coupling fluid under sufficient hydraulic pressure is also important from an acoustic standpoint, since the higher the mean pressure of the coupling liquid, the greater will be the amplitude of the acoustic waves transmitted through the liquid. It will be recalled that the process of the invention contemplates use of acoustic waves of amplitudes equal to or exceeding what has been defined as acoustic formation-failure stress amplitude, and this amplitude can be attained most easily, with reasonably sized wave generators, if the coupling liquid be maintained under a substantial hydraulic pressure. As already indicated, the hydraulic pressure may often be sufficient by use simply of a column of coupling liquid filling the well hole, but in cases wherein additional pressure is desired, the pressure may be elevated by means of a suitable source of pressure connected to the liquid column.

As indicated above, it is deemed preferable, even if not always essential, to employ a hydrostatic pressure on the coupling liquid which is less than "formation breakdown pressure." This is for the reason that sustained hydraulic pressure at the level of formation breakdown pressure actually lifts the formation, and tends to open up wide fissures through which the hydraulic liquid can race away. By keeping the hydrostatic head below formation breakdown pressure, this undesirable condition is avoided. Even if the level of formation breakdown pressure is periodically exceeded by the transmitted acoustic pressure wave during the positive pressure half cycles of the wave, the tendency is not to bodily lift the overburden (because the formation depth is large relative to a wave-

length), but rather to set up a periodic stress which overstrains the rock and leads to its failure. The preferred condition, i. e., a hydraulic pressure less than formation breakdown pressure, can be established by first pumping liquid down the well hole at a fast rate until formation breakdown pressure is attained, made known at the ground surface by a sudden drop in pressure and/or a suddenly increased flow rate. This condition simply means that at some locality along the exposed formation, the hydraulic pressure has equalled or exceeded formation breakdown pressure, a large crack or fissure has been opened up, and the injected liquid is racing away. Having determined the value for formation breakdown pressure, the hydraulic pressure on the liquid can then be dropped to and maintained at any desired fraction thereof.

As earlier noted, it is desired to subject the formation to acoustic waves above a certain threshold amplitude for formation failure by elastic fatigue failure, and to attain this amplitude, which is quite high, and normally out of reach, I prefer to employ an acoustic wave generator having both a high energy delivery rate, and a high output or radiation impedance, i. e., a high ratio of force to velocity at the point of drive of the liquid and/or formation by the generator.

With reference to the matter of proper positioning of the sound wave radiator relative to the formation to be fractured, several factors of interest are to be noted. To begin with, an acoustic wave radiator exerts its acoustic wave fracturing effect throughout a much more localized and concentrated region than is the case with the hydraulic system of fracturing. Accordingly, the present process contemplates a progressive lowering of the wave radiator to cover a vertically extended production interval. If the radiator should pass a region where a large old fracture exists, of the type that gives difficulty in hydraulic fracturing owing to racing away of hydraulic liquid faster than it can be pumped when such fracture is opened up by hydraulic pressure equal to formation breakdown pressure, the wave energy will not be diverted and concentrated into such fracture, because such a fracture presents, in effect, a wave guide of relatively high acoustic impedance for the pulses which enter and travel therealong. It is accordingly incapable of dissipating the available acoustic energy to the detriment of exposed areas of formation adjacent thereto.

Another feature of interest in the acoustic system is a tendency for an acoustic wave to remain within a medium bounded by other mediums of different acoustic impedance. For instance, when the wave radiator passes a particular bed in the oil bearing strata, the wave tends to stay within such bed and to travel radially outward therein, the bounding planes of the layers on each side acting to reflect incident waves, and so giving a wave guide effect. The result is that each layer of the formation is treated separately and generally within itself, so that fracturing tends to consist of a number of individual fractures distributed within a given bed as such bed is passed by the radiator. It is especially important to take note of the fact that the hydraulic coupling liquid does not necessarily, in the acoustic fracturing system, tend to race away as soon as a new crack is developed, because the hydraulic pressure can be held below hydraulic formation breakdown pressure, and the tendency to lift the formation and open up wide cracks is thus avoided in favor of forming a large number of fractures, adequate to form good petroleum drainage channels but incapable of interfering materially with the acoustic fracturing process. It is of equal importance to note that such new fractures as are developed or such cracks as are passed by the radiator do not interfere with acoustic wave transmission into the formation, since the acoustic waves are conscious only of the acoustic impedance presented by the formation, and adjacent cracks are of sufficient acoustic impedance as to have no material adverse effect. The location of the fracturing activity is easily controllable simply by positioning of the wave radiator opposite the region to be fractured. The present system, accordingly, has no need of pack-off as is required with the hydraulic fracturing process. For similar reasons, the present system is particularly well suited to the progressive and continuous treatment of long intervals of formation.

The fracturing effect of acoustic waves of high energy density may be understood by considering the extreme accelerations imparted to the coupling liquid and the formation. Taking the idealized case of a plane wave radiator (for the sake of mathematic simplicity) and investigating the acceleration "a" which will be given to the particles of an adjacent body of coupling liquid by such wave, there exists the relation

$$p=\rho c u$$

where p is the pressure amplitude of the wave, ρc is the characteristic acoustic impedance per unit area for the medium (ρ=density, c=speed of sound), and u is liquid particle vibration velocity. The particle acceleration a is related to particle velocity u by

$$a=\frac{du}{dt}=\omega u$$

where (assuming a sinusoidal wave) $\omega=2\pi$ times frequency.

Then

$$a=\frac{\omega p}{\rho c}$$

Assuming a wave radiator capable of generating a pressure wave of amplitude typical of the invention, e. g., $p=50$ atmospheres ($=50\times10^6$ dynes/cm.^{2}), $\rho c=1.4\cdot10^5$ c. g. s. units, and $f=100$ C. P. S., and substituting, we find $a=22\cdot10^4$ cm./sec.$^2=220$ g (approximately), g being the acceleration of gravity. This means that the coupling liquid is accelerated against the walls of the well hole in the formation 100 times per second and with an acceleration of the order of two hundred and twenty times that of gravity. With any reasonable degree of coupling it is possible to impart sufficient cyclic acceleration to the formation to exceed the pull of gravity locally so that the local formation literally "floats apart in space" because the return wave is never as great as the outgoing wave. The above analyzed accelerations, of course, also impart high stress fatigue conditions.

The invention will be further described with reference to the accompanying drawings showing certain selected illustrative embodiments thereof, and in which:

Fig. 1 is a longitudinal sectional view of an oil well showing a preferred embodiment of the apparatus of the invention situated therein;

Fig. 2 is a longitudinal sectional view, broken into two parts, and with sections broken away, of the embodiment of the invention shown in Fig. 1;

Fig. 3 is a transverse section taken on line 3—3 of Fig. 2;

Fig. 4 is a view taken in accordance with the line 4—4 in Fig. 2;

Fig. 5 is a diagrammatic view showing a section of formation surrounding a well bore, with the apparatus of Figs. 1–4 situated therein;

Fig. 6 is a longitudinal sectional view of a well bore showing another embodiment of the invention situated therein; and

Fig. 7 is a longitudinal sectional view, broken into two portions, of another embodiment of the invention.

Referring now to the embodiment of Figs. 1–4, and first to Fig. 1, there is shown as **10** a well bore sunk into the ground, containing casing **11**, which, however, in the illustrated case, terminates above the region of the productive formation **13**. The acoustic wave generator and radiator of the present invention is designated generally by the numeral **14**, and is, in this instance, sus-

pended by means of flexible cable 15, which runs through a conventional packer carried by casinghead 16.

The device 14 comprises essentially a long elastic steel rod 20, typically about eighty feet long, and approximately eight inches in diameter for an 8⅝ inch well bore, and a vibrator 21 adapted to generate a vertically directed alternating force and apply it to the rod 20. As here shown, this vibrator 21 includes a tubular housing 22 threaded, as indicated at 23, to the upper end of the rod 20. This tubular housing 22 incloses a plurality of vertically spaced unbalanced or eccentrically weighted rotors 24 rotatably mounted on fixed transverse shafts 25 set into the housing. The rotors 24 are mounted on shafts 25 by means of suitable bearings such as indicated at 26, and are provided about their peripheries with intermeshing spur gears 27, as shown. The spur gear 27 for the uppermost rotor 24 is driven from a pinion 28 on transverse shaft 29 rotatably mounted in the walls of housing 21, and this shaft 29 also carries a bevel pinion 30 driven from bevel gear 31 on the reduced extremity 32 of the shaft 33 of an electric drive motor 34, the latter housed in motor casing 35 threadedly joined to the upper end of vibrator casing 22 as indicated at 36. Motor shaft extremity 32 is provided with suitable bearings in lower motor housing end 36, and the upper extremity 37 of the motor shaft is received in a bushing 38, closed at its top end, and tightly mounted in a circular wall 39 threaded into the upper end portion of the housing 35.

The unbalanced rotors 24 are so phased with relation to one another that all of their unbalanced weights move up and down in synchronism with one another. The result is that the vertical components of force owing to rotation of the rotors are in phase and additive, the resultant vertically directed alternating force being transmitted to vibrator casing 21 through the mounting shafts 25, and this force being exerted on the upper end portion of the long elastic rod so as to set up longitudinally directed elastic vibrations in the latter, as presently to be described in more particular. In the illustrated embodiment, there are four of the unbalanced rotors 24, and in the gearing arrangement shown, two of these rotors turn in one direction and two turn in the opposite direction. Lateral components of force generated by these rotors are therefore balanced out.

The rotors 24 are driven by the electric motor 34 through the described gear train at a speed of rotation equal substantially to the longitudinal resonant frequency of the rod 20 considered as an elastic free-free bar vibrating in the half wavelength mode. For an 80 foot rod, this frequency is about 100 cycles per second. In this type of vibration, the longitudinal center point of the bar stands substantially stationary, while the upper and lower halves of the bar elastically elongate and contract in step with one another. Thus the upper and lower ends of the rod 20 undergo equal and opposite vibratory movements in the vertical direction. When the vibrations generated by the vibrator 21 and applied to the upper end of the rod 20 coincide substantially with the resonant frequency of the rod 20 for the described half wave mode of vibration, a longitudinal standing wave is said to be established along the rod, with a velocity node at the center point of the rod, and velocity antinodes at the two end portions thereof. With this resonant standing wave action, maximum amplitude and power can be delivered to and taken from the vibratory rod 20. The rod, vibrating at resonant frequency, is an energy storing device, giving substantial "fly-wheel" effect to the system.

With the rod 20 vibrating as described, powerful acoustic waves can be radiated from its lower end into a surrounding body of coupling liquid and efficiently transmitted through such liquid to the surrounding formation. In this way, large amounts of energy can be transmitted to the formation and propagated therein as high amplitude elastic deformation waves.

Not only does the lower end of the rod 20 generate sound waves, but the upper end of said rod may similarly tend to generate sound waves in surrounding liquid in the bore hole, with resulting energy loss. Of course, it would be theoretically possible to deliberately radiate sound waves from both the lower and upper ends of the rod 20 for transmission to the surrounding formation. It is preferred, however, to use only the lower end of the rod 20 for such purpose, since otherwise, the total power delivery from the rod must be divided between its two ends, rather than concentrated at the lower end only, and since, in addition, it is desired ordinarily to radiate the sound waves into the formation from one point only of the tool, and to gradually lower the tool to assure controlled coverage of a given interval of the formation.

To prevent any possibility of sound wave radiation from the upper end of the rod 20, or from the upper end of the vibrator connected directly to the upper end of the rod 20, I prefer to mount at the upper end portion of the tool an acoustic decoupler unit 40. A suitable decoupler is disclosed in my copending application entitled Earth Boring Apparatus With Acoustic Decoupler for Drilling Mud, filed April 3, 1951, Serial No. 219,088, now Patent No. 2,717,763. In said prior application, the acoustic decoupler fulfills a function similar to that of the present case. As shown, the acoustic decoupler 40 comprises a generally cylindrical body 41, threaded to the upper end of motor housing 35, as indicated at 42, and furnished at the top with bail 42 engaged by eye 43 on the lower end of suspension cable 15. The periphery of cylindrical body 41 is formed with longitudinal circumferentially spaced grooves or channels 44, circular in cross section, and opening through the sides of body 41, as clearly shown in the drawings. Received in these channels 44 are pneumatic cells 45 consisting illustratively of long rubber tubes fitting nicely within the channels when inflated. The cells 45 are equipped at the top with valve stems 46 for purpose of inflation.

In general, in order to properly locate the decoupler 40, it must be understood that, to be effective, the tubes 45 must be positioned substantially less than one-quarter wavelength of the generated wave, measured in the surrounding fluid column, from the point of potential sound wave generation. In accordance with well-known theory, a one-quarter wavelength distance in the fluid can be ascertained from the expression

$$\frac{s}{4f}$$

where s is the speed of sound in the liquid column, and f is the frequency of the wave, i. e., the frequency of vibration of rod 20. In the present embodiment, it is the upper end portion of the decoupler body 41, vibrating with the upper end portion of the rod 20, that is the potential source of sound wave radiation at the upper end of the tool. The pneumatic tubes 45 will be seen to be located immediately adjacent this upper end of the decoupler body 41, and are hence well within the limiting position indicated for the operating frequency of the apparatus, which, for an 80 foot rod 20, is in the general region of 100 C. P. S.

The pneumatic cells 45 of the described decoupler form yieldable bodies which yield inwardly, or are compressed, upon reception of any sound wave pressure pulse in the surrounding liquid. Any pressure pulse tending to be created in the liquid column as a result of vibratory motion of the upper end of the tool is instantly relieved by contraction of the cells 45, thus cancelling the creation of the pulse. The upper end portion of the tool has greatly enhanced freedom of vibratory reciprocation when this acoustic decoupler is used, because it is prevented from generating waves in the liquid column, such as might otherwise rob the system of a large proportion of its vibratory energy.

The described decoupler body 41 is formed with a central longitudinal bore 50 through which is passed insulated conductor 51 leading downward to one terminal of motor 34 from an electric conductor understood to be housed in suspension cable 15. The other terminal of motor 34 is grounded, and the conductor in cable 15 will be understood to be connected to a suitable source of electric power at the ground surface. Preferably, the bore 50 and space between the lower end of decoupler body 41 and wall 39 are packed with grease, as indicated at 53, to prevent chafing of the conductor 51. The upper end of bore 50 is closed by means of a threaded disc 56 in which is a rubber grommet 57 designed to form a fluid-tight seal with conductor 21, and a similar grommet 58 passes the conductor 51 through wall 39 to the motor.

The apparatus is operative as thus described, but a preferred additional feature comprises a device for increasing the output impedance of the generator-radiator combination. This feature is obtained by use of a rod 60 hung below the rod 20. The rod 60 may be of the same diameter as the rod 20, and may be, illustratively, about 10 feet in length, so as to possess fairly substantial mass. The rod 60 is here shown as suspended from rod 20 by a relatively slender elastic rod 61 threaded into the upper end of the rod 60 as at 62, and extending up into a bore 63 in rod 20 to a point about one-quarter of the length of the rod 20 up from the lower end of the latter, where it is threaded to 20, as indicated at 64. The distance between the opposed ends of the rods 20 and 60 is not critical and may be varied substantially to meet various requirements, but may well be set in the range of approximately two inches.

The operation of the system of Figs. 1–4 will first be considered with the assumption that the rod 60 is omitted. Assuming a newly drilled well, prior to completion of the well, and before the casing is run into the productive formation, a column of coupling liquid is introduced into the well bore. To obtain the desired hydraulic pressure, this coupling liquid may entirely fill the well bore. This liquid, which may be field crude oil, or refined oil, is introduced to the well bore through a pipe 66 connected into the casing at the ground surface. The liquid may desirably contain a percentage of sand or other solid material in suspension, in order to increase its specific acoustic impedance and thereby improve acoustic coupling to the formation. A source of pressure may be connected to the pipe 66 in the event that a hydraulic pressure higher than the hydrostatic head of the column in the well bore should be desired. A pump may be connected to the pipe 66 in the event that it should be desired to elevate the pressure to formation breakdown pressure, such as for purpose of testing or as a preliminary to establishing the desired hydraulic pressure below the ascertained value of hydraulic formation breakdown pressure.

The motor 34 drives vibrator 21 at the resonant frequency for half wave longitudinal elastic vibration of the rod 20. A resonant standing wave is thereby set up along rod 20, the two ends thereof vibrating vertically at the resonant frequency through an amplitude which may be of the order of ¼" to ⅜". The upper end of vibrating rod 20 will not radiate sound waves because of the acoustic decoupler 40. The lower end of the vibrating rod 20 radiates a powerful acoustic wave, which is transmitted to the surrounding formation by the intervening coupling liquid. Impinging on the formation, this powerful acoustic wave sets up a stress cycle at the boundary surface thereof. As described in the introductory part of the specification, a mass of the well liquid is moved against the formation with an acceleration of the order of 220 times the acceleration of gravity, this occurring at a frequency of approximately 100 times per second. The result is to periodically move or oscillate the exposed surface of the formation through a substantial deformation amplitude, with the result of subjecting the formation to surface applied fracturing forces, as well as setting up in the formation elastic deformation waves which subject the formation to fatigue failure as they are propagated through the rock. Viewed in another light, the acoustic coupling liquid, composed of crude oil, preferably with a percentage of included sand, is of relatively specific acoustic impedance, making a relatively good approach to the acoustic impedance of the formation itself, under which conditions a substantial portion of the acoustic wave incident on the boundary surface of the formation is transmitted into the formation and propagated therein. Some of the wave energy is of course reflected at the boundary surface of the formation, but sufficient is transmitted to produce substantial acoustic wave action within the surrounding regions of the rock. As earlier stated, the acoustic wave action must be established at a pressure amplitude of at least "acoustic formation-failure stress amplitude" to accomplish fracturing. Such amplitude varies with the nature of the rock, as well as with local conditions, including some moderate effect from pressure of the overburden, but has a fairly definite threshold value for any given set of conditions. The expression "acoustic formation-failure stress amplitude" will be understood to be used herein and in the claims to denote the necessary acoustic pressure wave amplitude to cause such a stress within any given formation under any given set of local conditions as will subject the material of the formation to a periodic stress which exceeds the endurance limit for that material under those conditions.

Considering now the operation of the apparatus of Figs. 1–4 with the inclusion of the auxiliary rod 60 hung below the vibratory rod 20, the rod 60 is designed and suspended to stand substantially still in space during the longitudinal vibration of the rod 20. To accomplish this purpose, the rod 60 is made relatively massive, and hung from the rod 20 by a slender rod 61 which functions as a spring. In such arrangement, the member 60 is mass reactive, and possesses (with rod 61) a low resonant frequency, such that the force pulses transmitted down the rod 61 are incapable of setting the rod 61 into resonant vibration. Rod 61 is attached to rod 20 well up the latter, where the amplitude of vertical oscillation is small, and such elastic deformation waves as are transmitted down the rod 61 are almost totally reflected by the rod 60, with the result that rod 60 stands substantially stationary.

Vertical reciprocation of the lower end of rod 20 then effects an oscillatory displacement of the liquid between the ends of the two rods 20 and 60, and the oscillating body of liquid is forced radially outward and then inward in turn, so as to alternately expand and then contract the region of the well bore immediately surrounding the area between the two rods. The large rods fit the well bore sufficiently closely that the tendency for sound wave transmission in the fluid surrounding the members 20 and 60 is secondary, the principal effect being a forcible alternate expansion and contraction of the well bore in step with the fluid body alternately expelled and then drawn back into the gap between the adjacent ends of the rods 20 and 60.

It will be seen that in this case, the primary tendency is not to generate acoustic waves in the coupling liquid, to be in turn transmitted to and into the formation. Instead, the primary effect here is to forcibly expand and then contact the well bore, using an oscillatory liquid body for the purpose, such liquid body or "piston" being the quantity of liquid oscillated alternately out of and then back into the gap between rods as the rod oscillates vertically relative to the rod 60. The rod 20 is thus, in this case, directly coupled through a "hydraulic piston" with the walls of the well bore, and the acoustic wave generation begins, for the most part, within the formation itself, as a consequence of the oscillatory displacement of the well walls. A device of this character has high out-

put impedance, and affords exceptionally good acoustic coupling between the generator and the formation. A generator in the nature of the half wave bar **20** has a high power output, and with a high impedance output characteristic, such as is here provided, acoustic waves establishing the necessary formation-failure stress amplitude in the formation are very readily set up in the surrounding formation.

In addition, the vertical distribution of the emitted energy is greatly reduced with the use of the rod **60**, so that application of expansive and contractive stress to the formation is highly localized and concentrated. This gives the advantage, first, of energy concentration, and therefore high stress applied to a small vertical interval of the formation around the well bore, and second, that the treatment can be confined to a formation interval between two relatively closely spaced fractures or bed boundaries.

As explained earlier, the hydraulic pressure on the coupling liquid is maintained preferably at a level below hydraulic formation breakdown pressure, while the acoustic waves acting upon the formation by impinging on its boundary surfaces and by transmission through it are established at a pressure amplitude equal to or exceeding the threshold value of the defined acoustic formation-failure amplitude.

It has been explained how the hydraulic pressure may be set at a desired value below formation breakdown pressure. The fact that the acoustic wave action is furnishing the necessary "acoustic formation-failure stress amplitude" can sometimes be detected at the ground surface, when a source of pressure is connected to the liquid column, by observance of characteristic small and momentary pressure drops, resulting from the development of fractures in the formation and the follow up of coupling liquid into such fractures. These pressure drops are not like the large and sustained pressure drops accompanying formation breakdown when hydraulic formation breakdown pressure is attained and layers of the formation are jacked apart, but, by contrast, are small, of relatively short duration, and recur with greater frequency.

In treating a given production zone, the sound wave radiator is moved progressively the full length thereof. Fig. 5 shows somewhat diagrammatically a typical application, the vibratory rod **20** and stationary rod **60** being positioned with the gap **65** therebetween positioned opposite an oil bearing formation or bed S between two joints or boundaries *b* and *b'* beyond which are assumed to be beds of differing character. The two planes indicated in dotted lines at *m* and *n* represent minor bedding planes within the more or less homogeneous production formation or stratum S, and the rock material therebetween may be understood to differ to only a small extent from the remaining portions of the bed S. In other words, the material between the planes *m* and *n* may be thought of as having been laid down under slightly different conditions, so that its wave transmission character may be generally similar to that of the remainder of the bed, but still somewhat different therefrom.

The waves generated and propagated within the bed S as a result of the operation of the sound wave generator are indicated by the circles *w* seen to radiate from the region of the gap **65**. Waves so radiated into the stratum S between the fractures or bed planes *b* and *b'* will be understood to be very largely reflected at said planes because of the substantial acoustic discontinuity caused thereby, and so kept primarily within the main stratum S which is under direct treatment, being propagated radially outward between said planes serving as wave guide boundaries. Because of the assumed close similarity of the rock material between the planes *m* and *n* to the remaining material of the bed S, together with an assumed initial bonding of the entirety of the material between the planes *b* and *b'*, the waves radiating from the region **65** are propagated horizontally outward throughout the entirety of the rock material between the planes *b* and *b'*.

It will thus be seen that the bed S may undergo cyclic deformation movements which are not propagated appreciably beyond the planes *b* and *b'*, so that the layer S is moved and worked relative to the layers beyond the planes *b* and *b'*, thus opening up or fracturing the formation (breaking the natural bond) along said planes. The material of the bed S, subjected to the described high amplitude cyclic deformation movements, fractures by elastic fatigue failure. In addition, because of inherent weakness of the bond along such bedding planes as *m* and *n*, as well as because of differences in the speed of sound in the material between and outside of the planes *m* and *n*, as indicated in Fig. 5, fractures are developed along the planes *m* and *n*. The forces operating to produce this effect will be understood when it is realized that the waves transmitted through the rock above and below the plane *m*, for instance, may have a phase difference, meaning that the elastic deformation movements on opposite sides of the separation plane are somewhat out of phase. This condition results in a shearing force along the separation plane, with resulting tendency to fracture the bond. As soon as a fracture should develop along such a plane as *m*, the radiated waves are then guided between the new boundaries *b* and *m*, for example, with materially enhanced energy concentration, and still greater and more extensive fracturing force. The vibration generator being gradually lowered, the layers formed by fracturing along such planes as *m* and *n* will be seen to be locally treated in succession. The process thus progresses, with greater energy concentration as the layers open up, always tending toward further multiplication and extension of the desired fracturing.

One practice of the invention, particularly with highly laminated formation, consists in utilizing a high hydraulic pressure in the bore hole (less, however, than hydraulic formation breakdown pressure) and then operating the generator to send a continuous elastic wave into the formation of such amplitude that the formation undergoes cyclic elastic deformation movements with an acceleration of more than one "*g*" (acceleration of gravity), in step with the wave output from the generator, with the result that the formation literally floats apart in space.

Fig. 6 shows a modified form of apparatus for carrying out the invention. Here, a vibratory rod **20***a*, like the rod **20** of Fig. 1, is suspended in the well hole by a string of drill pipe **70**, and vibratory energy is transmitted to the rod **20***a* down this pipe **70** from a vibration generator at the ground surface. The pipe string should be fairly heavy, such as drill pipe, pump tubing being too light to transmit vibratory energy of the requisite power.

The ground surface equipment comprises a beam **72**, pivotally mounted at one end **73**, having a clamp means **74** tightly engaging the upper end portion of the pipe string **70**, and carrying, at its free end, a vibration generator **75** designed to produce a vertically directly alternating force. The generator **75** is yieldingly supported by compression springs **78** under the free end of beam **72**. It comprises, illustratively, two unbalanced weights **77** on parallel shafts which are connected by spur gears **78**, one of the shafts being belt driven from gasoline engine **79**. The two weights are arranged so as to move up and down together, so that the unbalanced vertical forces which they generate will be additive, and will be transmitted to beam **72**, causing it to oscillate, and to exert a vertical alternating force on the upper end of pipe string **70**. Since the rotors turn in opposite directions, horizontal force components are cancelled.

The vertically directed alternating force exerted on the upper end of the pipe string **70** sends alternating elastic deformation waves of compression and tension down said string to the rod **20***a*, the upper end of which is acted upon by an alternating force as a result of this wave action. The speed of operation of the oscillator is

adjusted to correspond to the resonant frequency of the rod **20***a* for half-wave vibration, and the rod **20***a* is accordingly set into the same type of resonant half-wave longitudinal vibration as described in connection with the embodiment of Figs. 1–4.

Acoustic waves of high amplitude are radiated from the lower end of the rod **20***a*, and are transmitted through the liquid in the well hole to and into the formation, as earlier described. A device such as the rod **60** of Figs. 1–4 may be employed to advantage on the the rod **20***a* for any case in which higher output impedance should be required. Also, a decoupler may be used at the upper end of the rod **20***a*, if necessary as described in connection with Figs. 1–4.

Fig. 7 shows another embodiment of the invention, differing from that of Figs. 1–4 in one immediately evident respect in that the half-wave length vibratory bar forming a part of the wave generator of the earlier embodiment is in this case eliminated. The vibration generator is designated generally by numeral **80**, and comprises a tubular housing **81** containing a vertically oscillatory vibrator **82** of the unbalanced rotor type, of the same general nature as that described in connection with the embodiment of Figs. 1–4. The housing **81** has a bore **83** extending downwardly from its upper end to a shoulder at **83***a*, and fitted therein is a liner sleeve **84**. The vibrator **82** comprises a tubular housing **85** having an integral upper end wall **86** and a threaded bottom closure plug or wall **87**. Mounted therein on transverse shafts **88** are unbalanced rotors **89** similar to the rotors **24** of the embodiment of Figs. 1–4, the rotors being geared together by suitable spur gears formed therearound, and the shafts **88** being journalled in the housing **85** in the same way as described for the earlier embodiment. The rotors are driven through spur gear **90**, shaft **91** and bevel gear **92** from a vertical shaft **93** journalled in suitable bearings carried by the upper end portion of the housing **82**, as illustrated, and the shaft **93** has a splined connection at **94** with a hollow drive shaft **95** extending downwardly from electric drive motor **96**. The motor shaft is journalled below the motor by suitable bearings carried by a transverse wall **97**, and above the motor by a bushing mounted in transverse wall **98**. The upper end of the exterior housing **81** is closed by plug **99**, furnished with bail **100** suspended from lowering cable **101** containing electric conductor **102** leading to motor **96**.

The plug or wall **87** at the bottom of vibrator case **82** carries a downwardly extending plunger rod **104** which is fitted for reciprocation within a bore **105** formed in the lower end portion **106** of the housing **80**. A coil compression spring **107** is confined in the space inside the housing **81** between the shoulder **83***a* and the bottom wall **87** of the vibrator, and yieldingly supports the vibrator normally in the position illustrated. The lower end portion **106** of housing **81** is reduced, as indicated at **110**, and fitted tightly over the lower extremity **111** of member **106** is a perforated metal sleeve **112**, over which is fitted a heavy elastic sleeve **113**, preferably composed of heavy rubber. The perforated sleeve **112** and expansive sleeve **113** are fitted at their lower end over the reduced upper end portion **115** of the lower body or rod **116**, as shown. Cavity **117** inside the perforated sleeve **112** is filled to a controlled depth with a suitable liquid, preferably oil, and this cavity **117** is in open communication with the bore **105**, the liquid body extending upwardly into contact with the lower end of the plunger **104**. Downward displacement of the vibrator **82** below the position illustrated in the drawing results in displacement of the liquid body in bore **105** in a downward direction ahead of the plunger **104**, and of the liquid in cavity **117** in a radially outward direction, causing the elastic sleeve **113** to bulge. Assuming the presence of liquid in the well bore around the tool, the expanding sleeve **113** transmits an expansive force to the walls of the well bore through the intervening liquid layer. In some cases, the sleeve **113** may expand sufficiently, as indicated by the dot-dash lines **120**, as to engage and expand the walls of the well bore, but this is not essential since intervening liquid in the bore around the device is fully capable of transmitting the necessary expansive force to the well bore, without the necessity of such extreme distention of the sleeve **113**.

Preferably, rubber collars **125** and **126** are placed on the tubular housing **81** and rod **116**, respectively, immediately above and below the sleeve **113**, these collars serving to reduce the annular clearance space between the tool and the wall of the well bore. The annular clearance space that remains is of small area and consequent high acoustic impedance, so that it does not tend to dissipate up and down the bore large amounts of acoustic wave energy generated in the well fluid. This control of annular wave radiation by interposition of blocking impedance is very useful in that it conserves substantial otherwise mis-directed wave energy.

In operation, the unbalanced rotors **89** of the vibrator driven from drive motor **96** generate a vertically directly alternating force in the same manner as described in connection with Figs. 1–4. When the resultant force is in the downward direction, the vibrator housing moves downward against the supporting influence of the spring **107** and against the liquid body in the cavity **117**, expanding the sleeve **113** as described above. When the force of the vibrator is reversed and exerted in the upward direction, the vibrator housing moves upwardly, under the influence of its upwardly directed force, together with the force of the spring **107**. The weight of the vibrator prevents it from being overthrown in the upward direction, but to assure controlled operation between predetermined limits, an additional coil spring **122**, placed between the wall **97** and the upper end of the vibrator housing, can be used if desired. On the upstroke of the vibrator, the plunger **104** is of course elevated, drawing the previously displaced liquid back into cavity **117** and bore **105**, and so causing a contraction of the sleeve **113**.

The resulting operation will be seen to be an expansive force application to the walls of the well bore applied at the frequency of operation of the vibrator, causing generation of elastic deformation waves within the formation. A vibrator of the type illustrated in Fig. 7 is capable of the very powerful force application, and powerful acoustic waves are thus generated and radiated into the formation. It will be seen that while, for this case, the primary operation comprises direct periodic force application to the walls of the well bore, the use of a column of well bore liquid is still important with this form of apparatus, in that it fills into fractures as they are developed, and in that acoustic waves can be generated in the liquid surrounding the region of the expansive and contractive sleeve **113** and extending into such fractures in the formation, to be thus transmitted to newly exposed surface areas of the formation.

The apparatus of Fig. 7 will function in either of two ways, depending upon the amplitude of travel of the piston. First, assuming that the piston travel is insufficient for the piston to separate from the liquid body at any time throughout the cycle, the generated wave will be of substantially sine form, setting the formation into corresponding substantially sinusoidal undulation. Second, assuming piston travel so great as to cause separation of the piston from the liquid body on the up stroke, a condition of cavitation is brought about, and on the subsequent down stroke, a shock wave is generated having a peak positive amplitude much greater than maximum amplitude on the opposing half cycle, and much greater than the amplitude of the sine wave generated in the first case.

This last above described cyclic acoustic phenomena, consisting in repeated cavitation and shock waves, produces an asymmetrical pressure wave form characterized by periodic steep-fronted high pressure peaks of short

time duration, alternating with negative pressure swings of long time duration and moderate amplitude. Such a non-linear wave form is exceptionally well suited to the special problem of formation fracturing, its high pressure peak including high frequency components which cause high concentrated stresses greatly exceeding the endurance limit of the rock. The high pressure effect of such shock waves is primarily exerted against the region of the well bore wall immediately surrounding the sleeve 113. Cracks developing in the rock under this action fill with fluid, and form high impedance wave guides for the steep-front shock waves, with the result that the shock waves run into the cracks and exert forces on the side walls thereof like a succession of travelling wedges. Calculations show that shock waves can be generated with a peak amplitude of 50,000 p. s. i.

Shock waves owing to cavitation are known to attain tremendous pressures, and offer one of the most effective solutions to the problem of producing asymmetrical waves of extremely high peak amplitude. Other usable methods of asymmetrical wave generation are of course available, and this species of the invention is accordingly not limited to cavitation generation of the wanted high amplitude asymmetrical waves, though the cavitation method is thought to be probably the most powerful method that can be found. The use of the asymmetrical wave form in the present invention facilitates fracturing by creating stresses far beyond the endurance limit of the formation.

Another advantage of such asymmetrical wave generation is that large amounts of power can be put into the wave system even though the mean pressure be moderately low. The energy in the positive peaks is limited only by the generating apparatus. It can thus be seen that by use of a wave generator such as shown in Fig. 7, it is possible to operate with a much lower hydraulic pressure on the well fluid than is needed with the simple sinusoidal wave systems and of course this hydraulic pressure can be very much lower than formation breakdown pressure.

Another obvious advantage of Fig. 7 is that it can be moderately light in weight, thus imposing a much less strain on the cable, which is a very important consideration in deep wells.

Attention is here directed to the fact that the wave generators employed in all disclosed forms of the present invention are not of the type giving intermittent impacts, with some device or member then vibrating at its natural frequency in a damped or dying wave pattern. By contrast, I employ continuous wave generators, whose characteristic is that power is supplied on each cycle of the wave. Such continuous wave generation is necessary to deliver sufficient energy to the formation to satisfy the energy expenditure required for formation fracturing.

It will be evident from the above that various forms of apparatus may be employed in carrying out the invention. The primary requirement is a form of acoustic wave generator so powerful and a form of coupling to the formation so effective, that the acoustic waves set up in the formation establish what has been termed herein "acoustic formation-failure stress amplitude," denoting an amplitude such as overstresses the formation, i. e., stresses it beyond its endurance limit, and leads to its breakdown by fatigue failure. Rock can of course sustain an acoustic wave indefinitely without sign of fatigue failure provided the region of overstress is not approached. The present invention deals only with situations in which the waves are so highly powerul as to place the rock periodically in a condition of stress beyond its endurance limit, with fatigue failure and fracturing as the consequence.

Some of the advantages and characteristics of the acoustic process of formation fracturing may be summarized as follows: The system does not require pack-off. The apparatus can be run in on a wire line. Continuous, progressive treatment of long intervals of formation is accomplished. The actual hydraulic pressure of the fluid column need not be as high as the formation breakdown pressure, and therefore vast quantities of fluid are not injected into existing fissures or highly permeable regions. The acoustic system can attain very high fracturing pressures where needed. Finally, the acoustic wave system subjects the rock to a rapidly repeated stress of amplitude exceeding its endurance limit, and in one practice, the repeated stress wave is shaped to form a high amplitude, steep-fronted shock pulse. The rock material is thus forced to undergo rapidly repeated stresses of a nature and magnitude which it cannot endure, and it shortly breaks up by reason of elastic fatigue failure.

I claim:

1. The steps in the process of well preparation and treatment, following drilling of the well bore to and through the petroleum bearing formation, that comprises: introducing a hydraulic coupling liquid into the well bore, lowering a powerful acoustic wave radiation into said bore and coupling liquid opposite the productive formation into acoustically coupled relation to the walls of the bore hole, and operating said radiator to send through the formation acoustic waves of amplitude sufficient to create an internal stress cycle in the formation exceeding the endurance limit of the formation, whereby the productive formation is fractured by fatigue failure.

2. The steps in the process of well preparation and treatment, following drilling of the well bore to and through the petroleum bearing formation, that comprises: introducing a hydraulic coupling liquid into the well bore, positioning a powerful acoustic wave radiator in said bore and coupling liquid opposite the productive formation into acoustically coupled relation to the formation, progressively moving said radiator along the well bore through said productive formation while maintaining said acoustic coupling, and while so doing, operating said radiator to send through the formation opposite the radiator acoustic waves of amplitude sufficient to create an internal stress cycle in the formation traversed by said wave exceeding the endurance limit of the formation, whereby a vertical interval of the productive formation is progressively fractured by fatigue failure.

3. The process of fracturing oil bearing formation surrounding a well bore, that includes: maintaining a body of liquid in the well bore throughout the producing region to be treated, positioning an acoustic wave radiator in said liquid in said bore, providing an acoustic blocking impedance in said well bore so as to substantially prevent transmission of sound waves in at least one direction along said bore through said body of liquid from said radiator, and transmitting from said radiator through said liquid into and along fissures in the walls of said bore sound waves having an amplitude generating stresses in the formation above the endurance limit of said formation.

4. The process of fracturing oil bearing formation surrounding a well bore, that includes: maintaining a body of liquid in said well bore in the producing region to be treated and in continuous physical contact with the walls of said bore, coupling a sound wave radiator to said body of liquid, and transmitting from said radiator to said formation via said body of liquid sonic vibrations of an intensity to cause accelerations of the formation substantially greater than the acceleration of gravity, whereby a local region of the formation experiences separating forces greater than the pull of gravity.

5. The process of fracturing oil bearing earthen formation surrounding a well bore, that includes: coupling an acoustic wave generator to said formation, and operating said generator for producing in the formation surrounding the well bore acoustic waves of pressure amplitude exceeding acoustic formation endurance limit stress amplitude, whereby the formation is repetitively stressed beyond its endurance limit and fractures by elastic fatigue.

6. The process of fracturing oil bearing earthen for-

mation surrounding a well bore, that includes: coupling an acoustic wave generator to said formation, and operating said generator for producing in the formation surrounding the well bore acoustic waves of pressure amplitude exceeding the static pressure of the overburden, whereby travelling tensile stresses are periodically set up in the formation, and the formation fractures by cyclic fatigue endurance failure.

7. The process of fracturing oil bearing formation surrounding a well bore, that includes: maintaining a liquid column in the well bore opposite the formation, positioning an acoustic wave radiator in the well bore opposite said formation, and radiating from said radiator into the liquid acoustic waves which exert an acoustic wave pressure cycle against the exposed formation surfaces so as to cyclically and elastically deform a portion of the formation about the well hole and which are of sufficient intensity to subject the formation to an internal stress exceeding its endurance limit and thereby cause its fatigue failure.

8. The process of fracturing oil bearing formation surrounding a well bore, that includes: maintaining a liquid column in the well bore opposite the formation, positioning an acoustic wave radiator in the liquid in the well bore opposite said formation and thereby effecting a coupling between said radiator and the exposed walls of the formation, and operating said radiator to exert a cyclic pressure against the formation surfaces in such manner as to set up in the formation an acoustic wave of pressure amplitude exceeding acoustic formation endurance limit stress amplitude.

9. The process of fracturing oil bearing formation surrounding a well bore, that includes: maintaining a liquid column in the well bore opposite the formation, positioning an acoustic wave generator in the liquid in the well bore opposite said formation, thereby effecting a hydraulic wave transmission coupling through said column of liquid between said generator and the exposed walls of the formation, and operating said generator to radiate acoustic waves into said column of liquid for transmission to the walls of the formation, in such manner as to set up in the formation an acoustic wave of pressure amplitude exceeding acoustic formation endurance limit stress amplitude.

10. The process of fracturing oil bearing formation surrounding a well bore, that includes: maintaining a liquid column in the well bore opposite the formation, positioning an acoustic wave radiator in the well bore opposite said formation, effecting a hydraulic coupling through said column liquid between said radiator and the exposed walls of the formation, and operating said radiator so as to exert on said walls through said coupling liquid a pressure cycle setting up in the formation an acoustic wave of pressure amplitude exceeding acoustic formation endurance limit stress amplitude.

11. The process of claim 7, wherein said acoustic wave is established at a pressure amplitude exceeding the level of static hydraulic formation breakdown pressure.

12. The process of claim 7, wherein the liquid column substantially fills the well bore to give a high mean pressure level at the formation walls where the pressure cycle is exerted.

13. The process of claim 8, wherein an external source of pressure is connected to the column of well liquid to further increase the hydraulic pressure in the region where the pressure cycle is exerted on the formation walls.

14. The subject matter of claim 8, wherein said radiator is progressively moved along the well bore to progressively treat a given interval of the formation.

15. The process of fracturing oil bearing formation surrounding a well bore, that includes: maintaining a body of liquid in the bore in the region of the formation to be treated, introducing a finely divided solid material which is dispersed in said liquid so as to increase the acoustic inertia of said liquid, coupling an acoustic wave generator to said formation and operating said generator for transmitting through the formation an acoustic wave whose pressure amplitude creates in the formation a periodic internal stress exceeding the endurance limit of the formation.

16. An apparatus for radiating acoustic waves in liquids in a well bore, comprising: longitudinally vibratory free-free bar adapted to be suspended in the liquid in the well bore, a vibrator coupled to said bar for setting said bar into longitudinal standing wave vibration, and an acoustic wave fluid decoupler connected to the upper end of said bar, the lower end of said bar functioning as an acoustic wave radiator.

17. An apparatus for producing acoustic frequency oscillations in liquids in a well bore, comprising: a longitudinally vibratory free-free bar adapted to be suspended in the liquid in the well bore, a vibrator coupled to said bar for setting said bar into longitudinal standing wave vibration, a bar positioned below the lower end of said bar, with a gap between opposed ends of the two bars, and a yieldable elastic link connecting the last-mentioned bar to the half-wavelength bar at a point substantially spaced from the lower end thereof.

18. The subject matter of claim 5, wherein the formation comprises adjacent bonded layers of formation, and wherein the acoustic wave generator is operated to produce in the formation acoustic waves of a pressure amplitude exceeding the endurance limit of the formation along the bonded interface between said layers, whereby to cause fracture and parting of said layers along said interface.

References Cited in the file of this patent

UNITED STATES PATENTS

Re. 23,381	Bodine	June 26, 1951
2,554,005	Bodine	May 22, 1951
2,670,801	Sherborne	Mar. 2, 1954
2,680,485	Bodine	June 8, 1954