United States Patent

Nordyke

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[54] **NUCLEAR EXPLOSIVE METHOD FOR STIMULATING HYDROCARBON PRODUCTION FROM PETROLIFEROUS FORMATIONS**

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[52] **U.S. Cl.** **166/247**
[51] **Int. Cl.** **E21b 43/26**
[58] **Field of Search** 166/63, 247, 299; 102/21, 23

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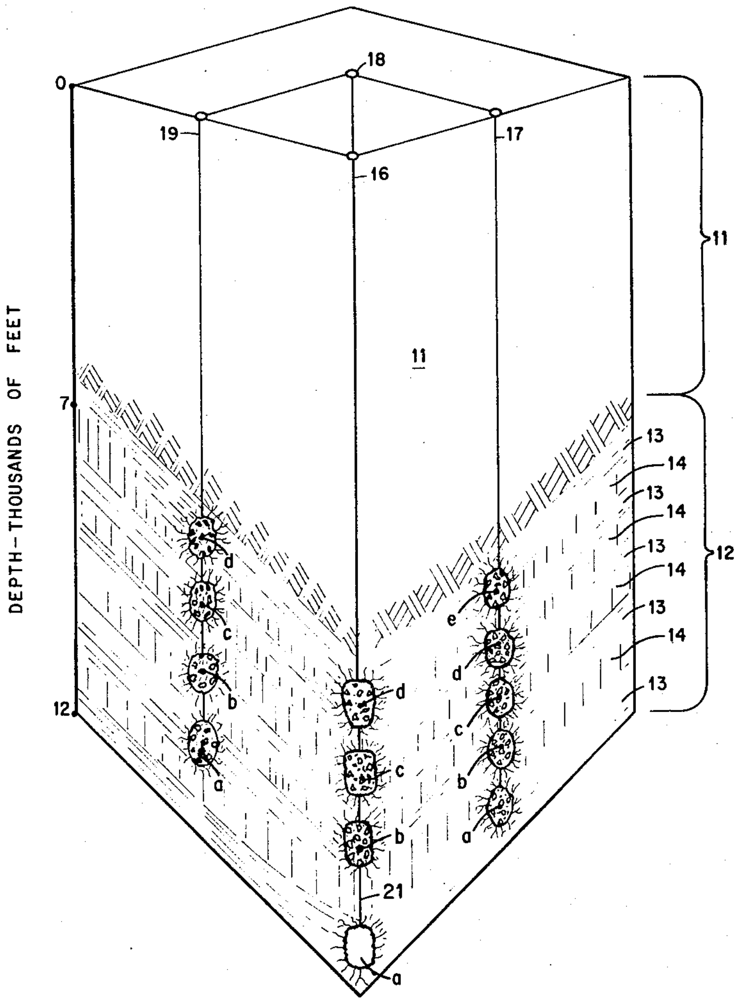
[57] **ABSTRACT**

Multiple nuclear explosive devices are emplaced and detonated sequentially at spaced locations in a borehole in a petroliferous formation. The explosive size, relation spacings, depths of burial and sequential timing are selected and arranged to minimize and limit seismic surface effects as well as to optimize fracturing of the formation with consequent more economical stimulation of petroleum hydrocarbon especially in low-permeability reservoirs.

7 Claims, 3 Drawing Figures



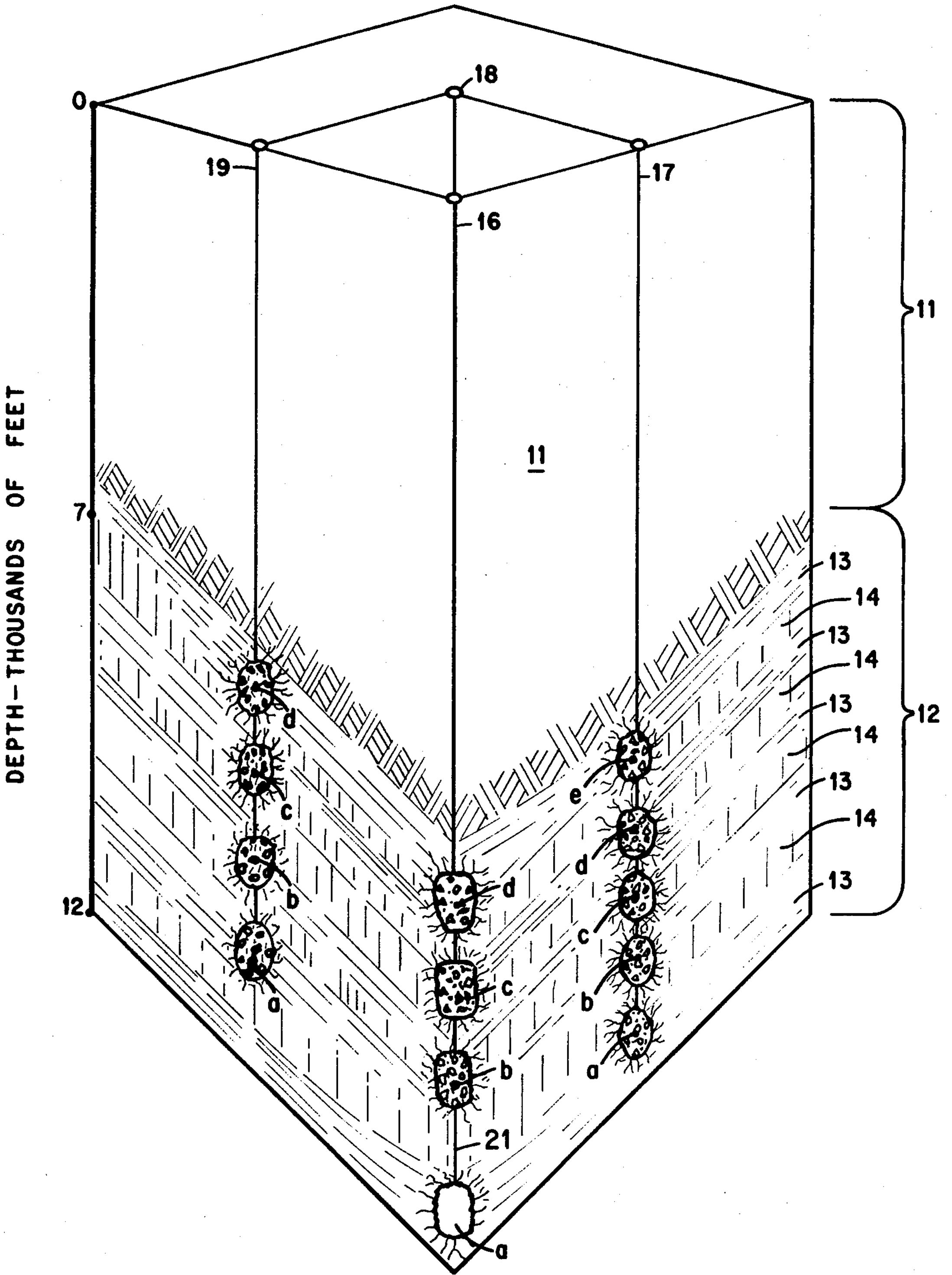


Fig. 1

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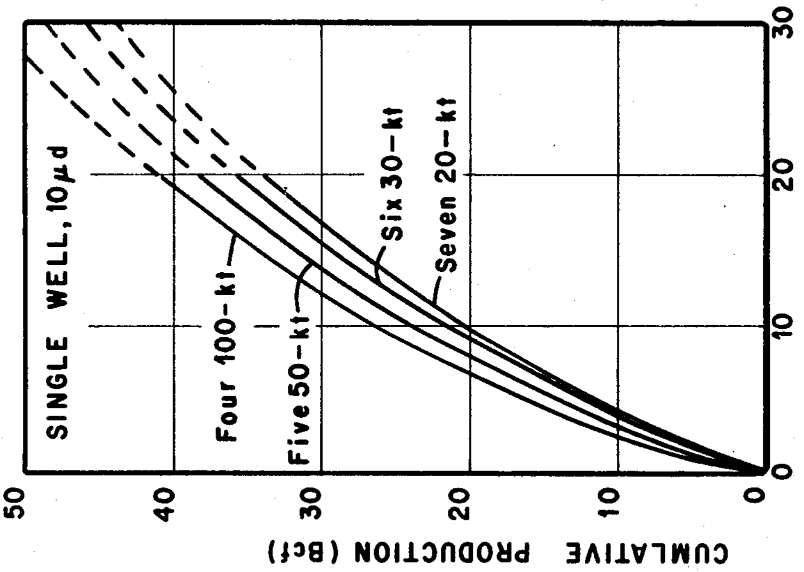

Fig. 3

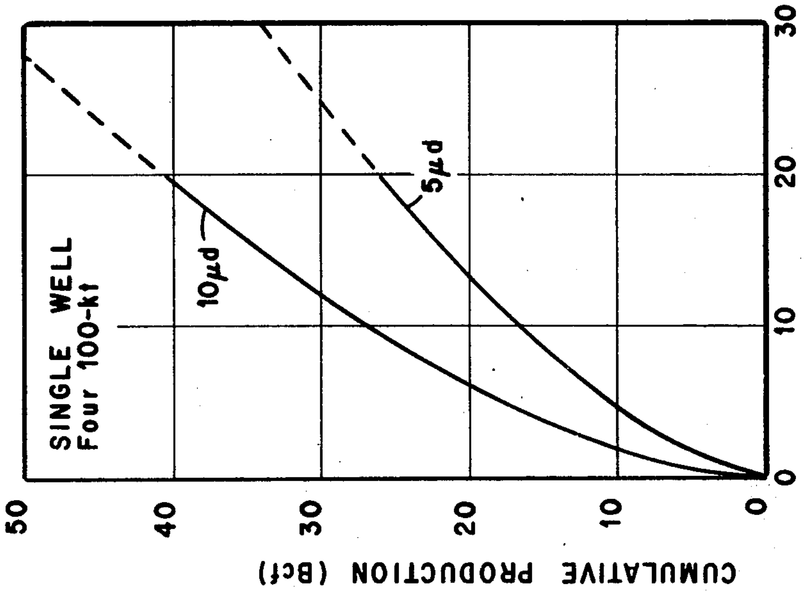

Fig. 2

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NUCLEAR EXPLOSIVE METHOD FOR STIMULATING HYDROCARBON PRODUCTION FROM PETROLIFEROUS FORMATIONS

BACKGROUND OF THE INVENTION

This invention was made in the course of or under AEC Contract No. W-7405-ENG-48 with the United States Atomic Energy Commission.

Domestic natural gas is being consumed in ever increasing quantities for producing power and heat, in chemical and metallurgical industries, etc. The rate of consumption is rapidly approaching the limit which can be produced economically from known reserves by conventional practices, i.e., from gas reservoirs having adequate permeability throughout a sufficient volume to permit a continued high rate of production using a reasonable number of wells. The possible areas in which favorable gas reservoirs may be found are rapidly diminishing. However, very large quantities of hydrocarbons including natural gas are known to exist in low permeability ("tight") reservoir formations. The gas is present in the pores of the formation but the pores are so poorly connected that the rate of flow through such minute fractures and other pathways as may exist is too low to satisfy production requirements or even to amortize the investment in production facilities under current or projected circumstances. Larger diameter conventional wells would increase production at relatively insignificant rates compared to the cost in providing same. Production from some low permeability reservoirs has been made economically feasible by chemical explosive, by hydraulic fracturing, by chemical treatments, and by other methods; however, such procedures do not appear technically or economically feasible with a major portion of such "tight" reservoirs. Moreover, relatively permeable reservoir lens portions may in some cases be enclosed by impermeable layers so as not to permit escape of the gas.

For example, the Wind River, Green River, Uinta, Piceance and San Juan Basins situated in Wyoming Utah, Colorado and New Mexico have characteristics and reserves which are believed potentially recoverable using nuclear explosives as set forth in the following table:

TABLE

Estimated increase in reserves of natural gas in four major Rocky Mountain basins assuming effective use of nuclear explosives.

basin*	aerial extent		number of known gas-bearing formations	total sand thickness, ft	productive thickness, ft	increased recovery NE, trillion cubic ft
	with productive potential mi²	assumed productive area, mi²				
Uinta	8,900	1,800	4	1,700	680	61
Piceance	3,900	800	4	1,200	480	19
Green River	19,000	4,000	7	2,500	1,000	199
San Juan	10,600	2,000	3	1,100	440	38
					Total:	317

c.f. C. H. Atkinson "Nuclear Fracturing Prospects for Low Permeability Hydrocarbon Reservoirs in the United State," U. S. Department of the Interior, Bureau of Mines, Bartlesville, Oklahoma.

Various procedures have heretofore been proposed for implantation and detonation of nuclear explosive devices in certain formations to stimulate production of hydrocarbons therefrom. Moreover, two experiments, i.e., Gasbuggy and Rulison have been conducted, in which production testing is still continuing, in which single nuclear explosive devices have been emplaced in thick, low-permeability formations to stimulate gaseous hydrocarbon production therefrom. c.f. "Gasbuggy in Perspective," pp. 662–697, "Proceedings" American Nuclear Society Symposium on Engineering with Nuclear Explosives, Jan. 14–16, 1970, LasVegas, Nevada. See also "Project Rulison, A Preliminary Report," pp. 597–620 of said Proceedings.

Generally, as proposed heretofore, an individual well is utilized to emplace each single explosive device whether the devices are to be detonated singly, successively at relatively long spaced intervals or simultaneously at horizontally spaced locations to provide enhanced fracturing by shock wave interaction. For example, as disclosed in U.S. Pat. No. 3,409,082, issued Nov. 5, 1968, two or more such devices can be substantially simultaneously detonated in horizontally spaced locations adjacent the lower portion of the formation to provide a much greater horizontally radial fracturing effect. Consonant therewith, in considering the use of nuclear explosives to stimulate hydrocarbon production, the importance of obtaining horizontally extending fractures of the maximum extent has heretofore been emphasized. Otherwise, it is often proposed to employ larger explosive yield devices. Such concern for the radial fracturing effect is reflected in the use of terms such as the "effective well radius" which is utilized in calculations employed to predict recovery rates. This perspective, of course, is a carry-over from traditional oil and gas well practice and the methods used therein to increase recovery and is not particularly suited for application in thick low permeability hydrocarbon (gas) bearing reservoir formations. In such formations the gas-bearing formations may be thousands of feet thick or may comprise similar formation thicknesses including several hydrocarbon bearing zones of up to hundreds of feet thick interspersed with barren or even impermeable layers therebetween. Accordingly, a major proportion of the potentially productive formation, above and/or below the fracture zone, would not be effectively interconnected therewith and the hydrocarbons therein cannot be recovered by such prior art methods. The use of multiple wells would, of course, increase the cost in direct relation to the number of explosives used and such cost would most often be prohibitive. Increasing the explosive yield would increase the height of the fractured zone somewhat; however, seismic effects limit the permissible explosive yield to levels far below those that would be necessary to fracture requisite thicknesses of the formation.

Surface seismic effects, as well as the formation fracturing, detonation cavity and chimney size and other effects are directly related to the explosive yield. While formation effects vary with depth of burial, the seismic effects may not vary greatly with depth and particular formation characteristics may greatly enhance the effect, e.g., at considerable distances, in a manner that cannot easily be predicted with a high degree of certainty. This consideration generally requires that the explosive yield of the device be made small to assure minimum seismic damage which requirement generally rules out the possibility of using a single, large yield explosive device, to interconnect the various layers. Moreover, horizontal fracturing of the layers would be very ununiform, being greatest near the central level and negligible at uppermost and lowermost positions. Also with large yield devices the possibility of inadvertent venting with consequent release of radioactivity and of gaseous hydrocarbons is enormously increased.

Accordingly it may be seen that a need exists for nuclear detonation procedures which are capable of effectively stimulating hydrocarbon production from the several portions of low-permeability formations of relatively great thickness or of those in which several productive zones may be interbedded with impervious layers over relatively great cumulative thickness. Especially needed are procedures which minimize cost, maximize production and minimize seismic and other hazards.

SUMMARY OF THE INVENTION

The present invention relates generally to the use of nuclear explosive detonations for stimulating production of hydrocarbons from low-permeability petroliferous formations or reservoirs and, more particularly to a procedure wherein a plurality of nuclear devices with an explosive yield within permissible seismic limits are disposed in a single borehole and are detonated sequentially in such a manner as to interconnect productive strata over a relatively great vertical dimension as well as to obtain enhanced fracturing with an attendant increase in formation permeability so as to stimulate hydrocarbon production therefrom.

Generally speaking, in accordance with the present invention, a plurality of nuclear explosive devices are disposed in vertically spaced locations at appropriate positions in a relatively thick petroliferous formation of the character described. Placement of the devices is preferably accomplished by completing a cased or uncased borehole, as appropriate, and of a suitable diameter to accommodate the devices and firing mechanisms. Conventional well drilling practice or the well drilling practice developed for underground nuclear explosive testing can generally be employed. The explosive devices are positioned within separate formation layers from which stimulated production is desired or adjacent, i.e., proximate the lower portion of such a layer to utilize the explosive force of the detonation most effectively. The spacing between the devices may be determined to assure that the fractured zones, i.e., chimney and associated fracture zone produced by the individual explosions, intersect to provide intercommunication therebetween. The explosive size, i.e., the yield of a single device or the sum of any such as may be detonated simultaneously, is selected to produce seismic surface motion within the permissible limit and the spacing is adjusted to provide the permeability effect described in the foregoing.

With such arrangement, a certain characteristic effect which is associated with nuclear explosive detonations in a geological formation is exploited. More particularly, the fracture zone which includes the detonation chamber, chimney and associated fracture system is quite assymmetric in dimension, being relatively highly elongated in the vertical direction as compared to the horizontal dimension. Consequently, permeability is enhanced to a greater proportion in the vertical as compared to the horizontal direction. Moreover, due to reflection of shock waves by the fractured zone produced by a previously fired explosive fracturing is enhanced over a greater formation thickness permitting a spacing greater than that predicated on fracturing produced by a single detonation conducted in the conventional manner. Furthermore, it has been found that the effective production rate, related to the effective well radius provided by the several successively detonated nuclear detonation fracturing decreases at a relatively slowly varying rate with decreases in the explosive yield, e.g., in the 100 kt (kiloton) to 5 kt or less range. Accordingly, the present procedure permits the use of relatively smaller explosives and accordingly less occasion for seismic and other undesired damage effects and yet to provide for most effective stimulation of hydrocarbon, especially gaseous production, from very thick low-permeability reservoirs of the character described. The present invention provides for more economical emplacement and detonation and for using particular nuclear explosive effects more effectively, especially as applied to gas field stimulation and therefore should assist in adding the known large quantities of natural gas in tight formations to the critically short reserves of recoverable gas now known.

Accordingly it is an object of the present invention to provide improved methods for stimulating the production of hydrocarbons from low-permeability formations using nuclear explosive detonations.

Another object of the invention is to provide a method for stimulating production of petroleum hydrocarbons from a low-permeability formation wherein a plurality of nuclear explosive devices are emplaced in a single borehole and are generally detonated sequentially to increase the permeability of the formation.

Still another object of the invention is to provide a method for stimulating the flow of petroleum hydrocarbons from a thick low-permeability formation wherein a plurality of nuclear explosive devices are emplaced in a single well borehole and in which the explosive power of any of the devices is below a permissible seismic effect limit.

A further object of the invention is to provide a method for stimulating the flow of petroleum hydrocarbons from a thick low-permeability formation wherein a plurality of nuclear explosive devices of a size generally below a seismic effect limit are employed in a vertically spaced array and are detonated, at least in some instances, in a sequential pattern to maximize vertically oriented chimney and fracturing permeability increasing effects within the formation while providing adequate fracture zone diameters for effecting improvement in hydrocarbon production from all or selected areas in such a formation.

Other objects and advantageous features of the invention will be apparent in the following description and accompanying drawing, in which:

FIG. 1 is a perspective sectional view of a typical thick low-permeability gaseous hydrocarbon reservoir illustrating use of multiple nuclear explosive devices to stimulate hydrocarbon production therefrom;

FIG. 2 is a graphical illustration of cumulative natural gas production from the formation of FIG. 1, over a period of years, as calculated to be achieved for detonation of four 100 kiloton explosives in two formations of representative different low-permeability characteristics, i.e., 5 and 10 microdarcy units; and

FIG. 3 is a graphical representation of cumulative natural gas production from the formation of FIG. 1 as calculated for selected numbers of various size nuclear devices in a formation with a permeability of 10 microdarcy units.

DESCRIPTION OF THE INVENTION

The process of the invention is generally applicable for increasing or stimulating production of petroleum hydrocarbons, especially gaseous hydrocarbons from thick, low-permeability formations. Several such formations, in which very large quantities of natural gas is present but which cannot be produced economically, are enumerated hereinbefore and still others are known to exist or may be discovered and identified by further exploration. For purposes of describing the invention, particular reference will be made to the Green River Basin formation which has characteristics considered to be generally representative of such thick formations or other formations amenable for practice of the invention. The in situ permeability of the gas-bearing (or hydrocarbon bearing) zones in such a formation may be indicated by representative low values of the order of, 0.005 to 0.10 millidarcy (md); however, it is considered that "tight" formations having permeabilities over an even greater range, not usually capable of producing economic flows of product, i.e., about 0.001 **md to about** 0.100 md can effectively be treated in accordance with the invention. Hydrocarbon, i.e., gas bearing regions of such formations may extend to several thousand feet in thickness either as a reasonably continuous zone or as discontinuous low-permeability zones separated by barren impermeable regions with aggregate thicknesses of several thousand feet. The gas bearing zone is generally overlain by several thousand feet of relatively barren formation and the gas bearing formations may reach depths of ten to fifteen thousand feet. The hydrocarbons are generally present in substantially closed pores or in pores poorly interconnected as by minute channels or microfractures. The porosity of the gas bearing zones is generally below about 10 percent but "tight" in which the gas and/or other hydrocarbon is disposed. Formations of higher porosity may exist. The pressure of the hydrocarbon therein, i.e., the formation pressure may approach hydrostatic or lithostatic levels and be of the order of thousands up to several tens of thousands pounds per square inch as measured under static flow equilibrium conditions.

The method of the invention may be applied for recovering hydrocarbons from the Green River and other equivalent formations using a well arrangement such as that illustrated in FIG. hydrocarbon of the drawing. Such formations have extensive regions which have similar characteristics so that a repetitive pattern based on standard well spacings, e.g., 320,640 acres, etc., as in conventional oil and gas field practice may be used. In the present instance the completed "well" will include a series of vertically linked chimney and associated fracture patterns of increased permeability formed by detonation of spaced nuclear explosives in the formation. As illustrated in FIG. 1 of the drawing, a typical portion of such a hydro-carbon bearing, i.e., petroliferous formation, may include an upper, substantially barren composite formation series **11** comprising shales, silty layers, sandstones, carbonaceous layers such as coal, generally of sedimentary origin of which lower portions, at least, may serve as an impervious caprock. Such formation layer series **11** may range from 1 or 2 thousands of feet in thickness to at least about 6 to 10 thousand feet in thickness. Below series **11** may lie a separate petroliferous formation series **12** comprising at least one low-permeability stratum **13**, e.g., sandstone, limestone or other hydrocarbon permeated layer. Quite characteristically the petroliferous series may be in the form of lenses, etc., interbedded with intervening impervious or barren strata **14** with the composite petroliferous zone extending over formation regions of up to several thousand, e.g., 2,000 to 5,000 feet in thickness. For purposes of the invention, it will be appreciated that the minimum composite thickness, to be treated will exceed that in which a single nuclear detonation of seismically permissible size would provide requisite permeabilities. Suitable thicknesses may then usually be above about 300 to 500 feet in thickness corresponding to a relatively "thick" formation in the context of which such term is employed herein. The method of the invention may usually be employed to more advantage with formations having a thickness of at least about 800 to 1,000 feet and particularly those in which expected seismic effects limit the explosive size to less than that required to produce the desired permeability and which would have a greater quantity of gas "in place" for a given area.

Emplacement of the nuclear explosive devices is accomplished by drilling a series of wells, e.g., **16**, **17**, **18** and **19**, at spaced positions appropriate for the selected acreage spacing by conventional procedures used in oil and gas field and/or underground nuclear explosive device practice. The latter procedures are disclosed, for example, in a paper entitled "Emplacement and Stemming of Nuclear Explosives for Plowshare Applications," page 974, et. seq., of the aforesaid ANS Proceedings. See also, "Hearing before the Joint Committee on Atomic Energy," Congress of the United States, Jan. 5, 1965, page 287, et. seq.

For purposes of the invention a plurality of at least two and usually more explosive devices are disposed in vertically spaced relation in a region in the formation in which it is desired to provide permeability enhancement and interconnection over a thick portion of the formation. In the formation shown in FIG. **1**, such a formation interval lies generally between 7,000 and 12,000 feet; however, it may be noted that potentially productive strata are distributed differently from place to place in the formation. In the case of wells **17** and **19**, fairly uniform distributions exist between about 7,500 to 10,500 feet and between about 7,500 to 11,500 feet, respectively. In such a case an explosive device spacing and explosive yield may be selected to produce a continuous chimney-fracture zone system interconnecting the gas-bearing strata **13**. In the case of well **16**, a similarly distributed zone exists between about 7,500 to about 10,000 feet; however, a relatively thick, i.e., about 1,000 feet thick barren region intervenes between a lower gas bearing zone, i.e., that which is situated between about, 11,000 and 12,000 feet and the above potentially productive interval. To interconnect such a separated zone, one or more nuclear explosives might be disposed in the barren strata and detonated in the same manner of those in the continuous productive regions. In such a case it may be more economical to interconnect the lowermost zone with that above by using a porous stemming material such as incompressible balls, e.g., of steel disposed in the well bore section **21** as c in the copending application of Richard A. Heckman, Ser. No. 32,678(70) filed Apr. 28, 1970 issued as U.S. Pat. No. 3,627,041 on Dec. 14, 1971. Otherwise the well might be stemmed with a fluidic composition such as drilling mud which is sufficiently incompressible to prevent collapse of the drill casing.

The dimensions of the fracture zone, both horizontally and vertically are related to the size of the cavity formed by the explosion by well known factors. The radius of the cavity R_c produced by an underground nuclear explosion is a function of the yield and the depth of burial as determined by the empirical relation

$$R_c = C\frac{W^{1/3}}{[\rho h_B]^{1/4}}$$

where W is the explosive yield in kilotons, ρ is the bulk density of the overlying rock, h_B is the depth of burial of the explosive in feet and C is a constant. The constant C varies with rock type with values of **281** for rock salt and **342** for volcanic tuff containing 20 to 25 percent water. A constant of about **350** is considered a reasonable approximation for a petroleum hydrocarbon bearing formation. A bulk density value (ρ) of about 2.34 may be used. (c.f. Journal Petroleum Technology, May 1964, cited above and Report UCRL-14311, dated Aug. 5, 1965, Lawrence Radiation Laboratory, Livermore California)

The fracture zone produced by a nuclear detonation, insofar as it affects nuclear stimulation is believed to extend to at least about 2.5 times the cavity radius, R_c, in a horizontal direction, to 4.4 R_c in a vertically upward direction and to about 2.4 R_c in a vertically downward direction from the shot point. These values correspond to data obtained from "Gasbuggy" involving explosion of a 29 kiloton (kt) explosive buried to a depth of 4,240 feet in the San Juan Basin formation in New Mexico as well as from other available data (c.f. Report No. UCRL-72175 (1970), Lawrence Radiation Laboratory, Livermore). Thus a 100 kt explosive would produce a cylindrical zone of very high permeability with a radius of about 220 feet, extending about 385 feet above and about 215 feet below the shot point. These data therefore indicate that the spacing between adjacent nuclear explosive devices should be of the order of 6.8 R_c if the devices are of equivalent yield. If the devices are of different yields the respective R_c factors are used to determine the spacings. As a conservative estimate it would require four 100 kt explosives spaced uniformly to provide requisite permeability in a formation thickness of about 2,400 feet. Due to enhancement effects described hereinafter three 100 kt explosives spaced somewhat farther apart could suffice.

The determination of seismic effects and the setting of permissible yield limits requires a complex analysis, or may be determined by seismic exploration and study techniques as described, inter alia, in several papers presented in the aforesaid ANS Proceedings. The permissible limit is generally determined by the allowable stress of the repeated detonations exerted on engineering, habitable, natural and other structures, the magnitude of which is related to proximity and/or shock wave transmission and reflective characteristics applicable to each formation.

Using the present method explosive yields may be selected over a wide range permitting great flexibility in selecting a yield of permissible size as determined by seismic effects. Yields as low as 1 kt or less to as high as at least 100 kt may be used. In selecting an appropriate yield, it is desirable to select yields above about 1 kt, e.g., 5, 10, 20 kt or more since cost of the device increases rather slowly with size and the volume fractured increases proportionately so that cost per unit volume fractured decreases. However, it is usually desirable, to minimize seismic hazards to limit the maximum yield, e.g., to 100 kt or below. On the other hand from the standpoint of explosive cost and emplacement complexity it is desirable to use as few explosive devices as feasible which tends to require larger yields. The seismic limit may then often serve to select the optimally largest yield permissible which reduces the number of explosives required to a minimum. For example, four 100 kt, five 50 kt, six 30 kt or seven 20 kt (kiloton) devices can be used substantially equivalently in a formation of about 2,400 feet thickness. Other combinations of explosive yield and spacing can be determined from the relations given above. In the event that two or more of the explosives are to be detonated simultaneously the additive yield is used as determined by the seismic limit.

To minimize seismic effects it is generally preferred that the nuclear explosives be detonated sequentially with a time delay period of at least about 1 to 5 minutes therebetween to allow explosive and seismic effects in the formation and distant structures to subside and to allow chamber collapse and chimney formation to occur. Similar effects would be obtained with longer time period of indefinite length. To accomplish such sequential firing a first explosive device (not shown) may simply be lowered to shot point level, a, in any of wells **17**, **18**, **19**, etc., and the well bore thereabove stemmed, e.g., with packers, saltcrete, or the like in the case of wells **17** and **19**, for example, in the manner used, e.g., in Gasbuggy or Rulison operations, to a level somewhat above the height of the expected fracture zone. Shot point, a, will generally be located about **2.4** R_c above the lowest stratum level in which stimulation is desired. In the case of well **16** shot point, a, may be located in a similar fashion in the gas bearing zone beneath stratum **21**.

Following detonation of the first shot, e.g., in wells **17** and **19**, a second explosive (not shown) may be lowered to a shot point, *b*, of about 2.4 R_c above the boundary of the fracture zone, produced by the first shot, which boundary would be about 4.4 R_c above shot point, a, with stemming again being accomplished as described. In the case of well **16**, shot point, *b*, may be located about 2.4 R_c above the terminus of the porous communication means or fracture zone created in the thick impervious layers as described above. Detonation may then be effected and the procedure repeated as many times as necessary to provide the desired height of the fractured zone as at shot points, *c*, *d* and *e*, in the respective wells. It will be appreciated that emplacement and detonation of a series of nuclear explosives as described results in the formation of a series of interconnected chimney-fracture zones which will generally occupy a relatively elongated generally cylindrical region of the gas bearing portions of the formation. The effective permeable diameter of the cylindrical region should be increased somewhat over that of a single shot due to the additional shock wave effects. From the subsequent shots related to reflection from the chimney and fracture zone of earlier shots to which the formation is subjected. It is generally preferred that all of the explosives be emplaced simultaneously as by arrangement as a composite string of explosives, seal and stemming units, etc. Sequential timing arrangements can then be used to time the detonations. Use of a series of successively emplaced and detonated explosives in the manner described provides certain advantages in that the emplacement hole can be smaller and explosive devices and techniques similar to those used heretofore can be used. The successive detonations can provide highly enhanced fracturing since the chimney and previously fractured zone reflects the shock wave generated by the later shot to provide additive effects. Moreover, detonation of a second shot disposed above a previously fired shot should promote an increase in chimney height in the first cavity particularly where chimney formation may not have fully developed in the previous shot.

However, certain problems may arise in carrying out such a procedure especially where the number of shots become quite numerous since gas pressure may increase to cause problems, the emplacement hole may be damaged and the extensive period of time required for preparing the additional emplacements may prove burdensome. It is therefore preferred to utilize a technique in which a substantial number, usually all of the explosive devices, are emplaced initially. A first explosive device (not shown) may be lowered and anchored at shot point (a) with appropriate stemming then being disposed thereabove. It will be appreciated that at least a fire control cable or similar means (not shown) will extend from the explosive to the surface. The remainder of the explosives are emplaced similarly and finally the well bore above the uppermost device is sealed with removable stemming, packers, etc., and the well casing is preferably closed with a high pressure production device similar to those used in conventional practice. Otherwise a "string" of such devices may even more be preferred.

The nuclear explosive devices employed in the foregoing preferred emplacement procedures, except for the first to be detonated, should be constructed to withstand the effect of shock waves and other phenomena to which they may be subjected in practicing such procedure. Ruggedized explosive devices constructed, e.g., in the manner used for nuclear artillery shells or delayed detonation impact aerial bombs or missiles may be employed to withstand the shock waves and/or a shock minimizing suspension may be used. With up to several hundred feet of stemming material or formation being disposed between the successive shot points deleterious effects from neutron and/or other radiation should be minimal. However, if needed dense gamma and x-ray shielding materials and/or neutron absorbers such as boron containing materials may be arranged about the devices as in conventional shielding practice. Magnetic field pulses or disturbances can possibly be a source of difficulty. To offset the effect of such magnetic fields the devices may be shielded by inclosing the devices in a ferramagnetic canister and by using conductive shell shields in which eddy current generation prevents penetration of rapidly rising magnetic fields. Nonmagnetic well casings can also be used. Moreover, the firing cable or other penetrations of the shield may be provided with means for closing or severing the connection following transmission of a firing signal to prevent entry of electrical current pulses which might be generated, e.g., in the firing cable by the magnetic field pulse caused by a detonation.

The sequential order in which the nuclear explosives is detonated is of considerable importance in determining the results achieved. As discussed above, detonation of a device disposed sequentially above the chimney-fracture zone of a previously detonated device promotes vertical fracturing therebetween and enhanced chimney formation therebetween. This effect may be sufficient to permit spacing of the explosives from 0.5 to 1 R_c further apart than would results achieved with single detonations might seem to dictate. Now consider a firing order in which an uppermost explosive, e.g., at shot point, *d*, in wells **16** or **17**, or, e, in well **17**, is fired first and the next lower explosive is fired later, i.e., after a delay of at least about 1 to 5 minutes as discussed above. A chimney-fracture zone complex is formed by the first explosion so that on explosion of a second device therebelow reflection of the shock wave from the first fracture zone enhances fracturing therebetween. Some enhancing effect on chimney formation may be provided although it is expected to be less than when a superposed explosive is used in the described reversed firing order described above. One additional beneficial effect is obtained with such a downward firing order in that reflection of the shock wave downward reduces the seismic effect at the surface. Accordingly, a smaller yield explosive, well within the seismic or depth of burial limit may be employed at the uppermost shot point and a progressively larger yield device at the lower shot points than when permissible single or simultaneously fired devices are used. It is conceivable that a selected pair of the emplaced devices, with a combined yield below the permissible limit could be fired simultaneously so that the shock waves would interact along a horizontal plane therebetween to produce a fractured zone (not shown) which is of wider diameter than those of singly detonated devices. This procedure might be of use for stimulating production under certain conditions or might serve to link up adjacent well units. It might be noted that reflection can also occur with shock waves travelling horizontally from one well to another. Indeed it is conceivable that shock sensitive structures situated, on the opposite side of an array of such nuclear stimulated wells, from additional wells would in effect be screened since the shock wave might well be reflected and diminished by interactions. In such a case larger yields might be employed.

For carrying out the upward firing order sequence separate suitably armored firing cables might be used with firing signals or initiating signals being applied from the surface at intervals of say 5 minutes when effects of the previous detonation have subsided. Such a system can not be used with the second, sequentially downward firing order since arrangement of separate firing cables which would not be disrupted by initial blasts would be very difficult. Accordingly, a system may be used in which firing time delay mechanisms, e.g., clockwork, are provided in all but the first to be fired device. Such mechanisms would be set to fire after selected time intervals corresponding to either of the described firing orders and would be actuated in common with the firing signal applied to the first to be exploded device. Suitable time delay devices which may be used may be constructed in a manner similar to those used in delayed action artillery shell or aerial bomb practice or liquid explosive fracturing practice. Moreover, electrically or mechanically actuated sequence and time delay switching devices may be employed with self-contained, power sources to provide arming and initiating functions. Sequential detonating systems used with conventional explosives, suitably modified, may also be employed.

Once the array of nuclear explosives emplaced as described have been fired reentry is made preferably through the residual portion of the emplacement well. Otherwise, if appropriate a second well may be drilled to interconnect with the fracture zone or chimney. If the horizontal fracturing effect is used to interconnect with a previously completed well, nothing else need be done. Reentry through the residual portion of an emplacement well may be accomplished by removing packers and stemming materials and be redrilling as necessary. Provision of a drillable casing section, e.g., of aluminum alloy in the region just above the fracture zone would facilitate such reentry. After a suitable time period has elapsed the well may be interconnected with other similar wells and to a distribution system as in usual practice.

Further details relating to the method of the invention will be made apparent in the following examples:

EXAMPLES

Using a typical region of the Green River Basin having properties set forth below a variety of explosive sizes and number of detonations are considered relative to the effects produced.

Reservoir Properties	
Reservoir thickness	2,400 ft
Depth to midpoint	11,000 ft
Effective in-Situ permeability	0.010 and 0.005 millidarcy
Viscosity	0.017 centipoise
Gas-filled porosity	5%
Gas field pressure	6,000 psi
Bottom hole pressure	750 psi
Gas in place	70 MMcf/gross ft of height
Gas in place per section per 2,400 ft	170 Bcf
Well spacing	One well square mile

Nuclear Properties					
Number of explosives	4	5	6	7	3
Yield per explosive, kt	100	50	30	20	100
Cavity radius, ft	88	70	59	52	88
Horizontal fracture radius for production calculation, ft	220	175	148	129	220
Vertical height above shot, ft	385	305	257	225	515
Vertical height below shot, ft	215	170	143	126	285

In the first four examples using **4, 5, 6** and **7** nuclear explosives the parameters are calculated on the basis that the fracture zone, insofar as natural gas stimulated production is concerned, extends 2.5 R_c in the horizontal direction, 4.4 R_c in a vertically downward and 2.4 R_c in a vertically upward direction. In the last case, the enhanced fracturing expected to occur in the vertical direction by reflection of the shock wave from previously fracture zones is taken into account. Knowing what explosive size limit is imposed by seismic effects, predicted or determined as indicated above, it is generally preferred to use the larger yield devices since the amount of fracturing obtained per unit cost is reduced. This is because nuclear explosive cost relative to yield increases at a diminishing rate.

Calculations were made assuming simple Darcy permeability flow of the gas from a 0.010– or 0.005–md rock into a cylindrical chimney-fracture region of varying size having infinite permeability, at a pressure of 750 psi. The horizontal fracture radii were selected to be less than the observed fracture radius, to compensate for the real variation of permeability with radius that occurs in practice. FIG. **2** presents cumulative production from the formation as a function of time, as a result of using 100–kt explosives for the two values of permeability. At almost all times, the 0.010–md case produces about 60 percent more gas than the 0.005–md case. FIG. **3** shows the variation in cumulative production vs time for the four different yields, all at 0.010–md. It can be seen that the total variation between the 100– and 20–kt cases is only about 12 percent. It can be seen that substantially similar results are obtained using the required additional number of smaller yield explosives. The total cost of the nuclear explosive is somewhat increased but by using a single emplacement hole and proceeding as described the cost per unit of explosive used decreases greatly over that of emplacing and detonating a similar number of explosives in individual boreholes.

While there have been described in the foregoing what may be considered to be preferred embodiments of the invention modifications within the skill of the art may be made therein without departing from the teachings of the invention and it is intended to cover all such as fall within the scope of the appended claims.

What I claim is

1. A process for recovering hydrocarbons from a thick relatively impermeable hydrocarbon bearing formation comprising:

drilling a well bore into said formation;

emplacing and detonating a plurality of nuclear explosive devices at spaced locations in said well bore within said hydrocarbon bearing formation, said nuclear explosives having an explosive yield determined to be below that permissible with relation to seismic effects and with at least several of said nuclear explosive devices being emplaced contemporaneously and being detonated sequentially, said nuclear explosive devices being spaced at a generally vertical distance at which at least the fracture zone created about the detonation chambers and associated chimneys by the respective detonations intersect thereby providing a vertically elongated generally cylindrical region of high effective permeability in said formation;

establishing a production well bore communicating said generally cylindrical region of interconnected fracture zones, associated chambers and chimneys zone with production facilities at the surface; and

producing hydrocarbons from said formation by withdrawing at least gaseous hydrocarbons therefrom through said generally cylindrical region into said well bore to said surface production facility.

2. A process as defined in claim 1 wherein said subterranean formation has a permeability in the range of about 0.001 millidarcy to about 0.100 millidarcy.

3. A process as defined in claim 1 wherein at least two adjacent nuclear explosive devices are detonated substantially simultaneously so that shock waves from the detonations collide and interact along a generally planar region therein providing a fractured zone of increased diameter therealong and extending into said formation.

4. A process as defined in claim 1 wherein the maximum spacing between said nuclear explosive devices is of the order of the sum of 4.4 R_c for the lowermost device plus 2.4 R_c for the uppermost device, where the term

$$R_c = C \frac{W^{1/3}}{[\rho h_B]^{1/4}}$$

wherein W is the explosive yield in kilotons, C is a constant appropriate to the particular rock type, ρ is the bulk density of the overlying rock, h_B is the depth of burial in feet and R_c is the radius in feet of the cavity produced by the detonation.

5. A process as defined in claim 4 wherein adjacent nuclear explosives are detonated sequentially wherein the maximum spacing between said nuclear explosive devices is of the order of the sum of 4.4 R_c for said lower most device plus 2.4 R_c for the uppermost device plus a distance in the range of about 0.5 to about 1.0 R_c and wherein the reflection of shock waves from the second fired explosive from the fractured zone and chimney of the first fired explosive device provides enhanced fracturing extending at least between the fractured zones of the respective detonated explosives.

6. A process as defined in claim 4 wherein the explosive yield of said nuclear devices is in the range of about 1 kiloton to about 100 kilotons.

7. A process as defined in claim 6 wherein the permeability of said formation is in the range of about 0.005 millidarcy to about 0.10 millidarcy.

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