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Rawson

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[54] **METHOD FOR EXCAVATING BY EXPLOSIONS**

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[73] Assignee: **Gulf Oil Corporation**

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[52] **U.S. Cl.** **102/23,** 166/247, 299/13

[51] **Int. Cl.**.....**F42d 1/00**

[58] **Field of Search**.....102/20–24; 166/247; 299/13

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[57] **ABSTRACT**

A method for excavating by means of explosions is described wherein two or more explosive devices or charges are placed at selected depths and relative distances and are detonated with a predetermined time relationship. Various charge positions and detonation timing patterns are described for producing explosions in which the effects of one explosion are enhanced by the other in order to achieve excavations having desired configurations.

7 Claims, 8 Drawing Figures

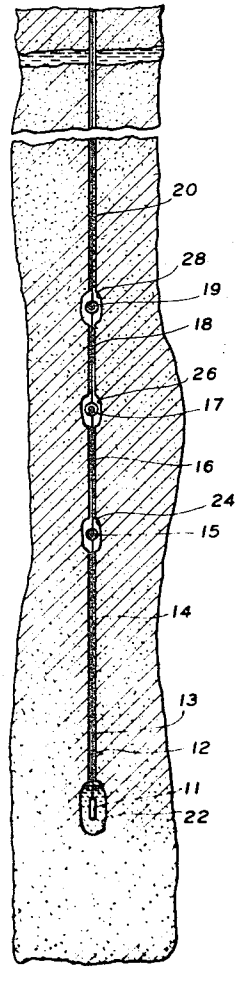


FIG. 1.

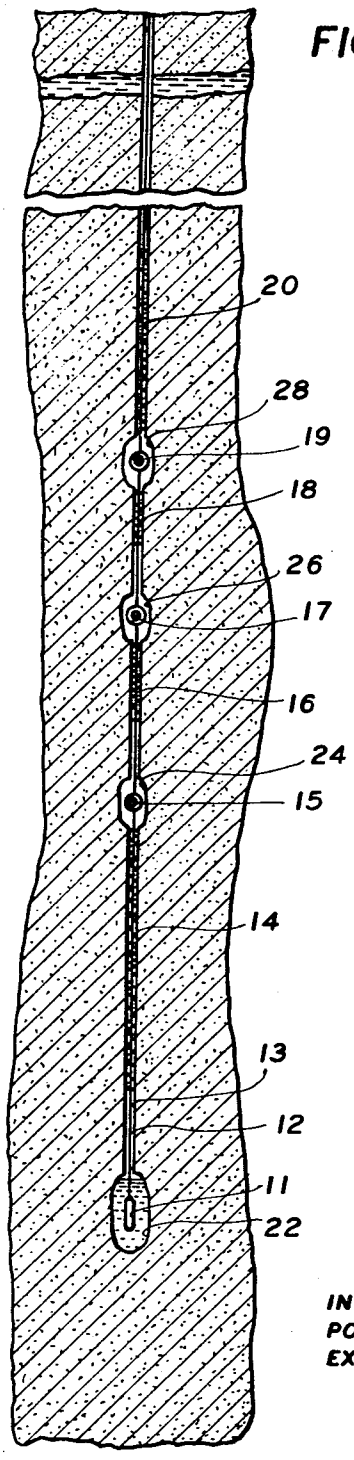
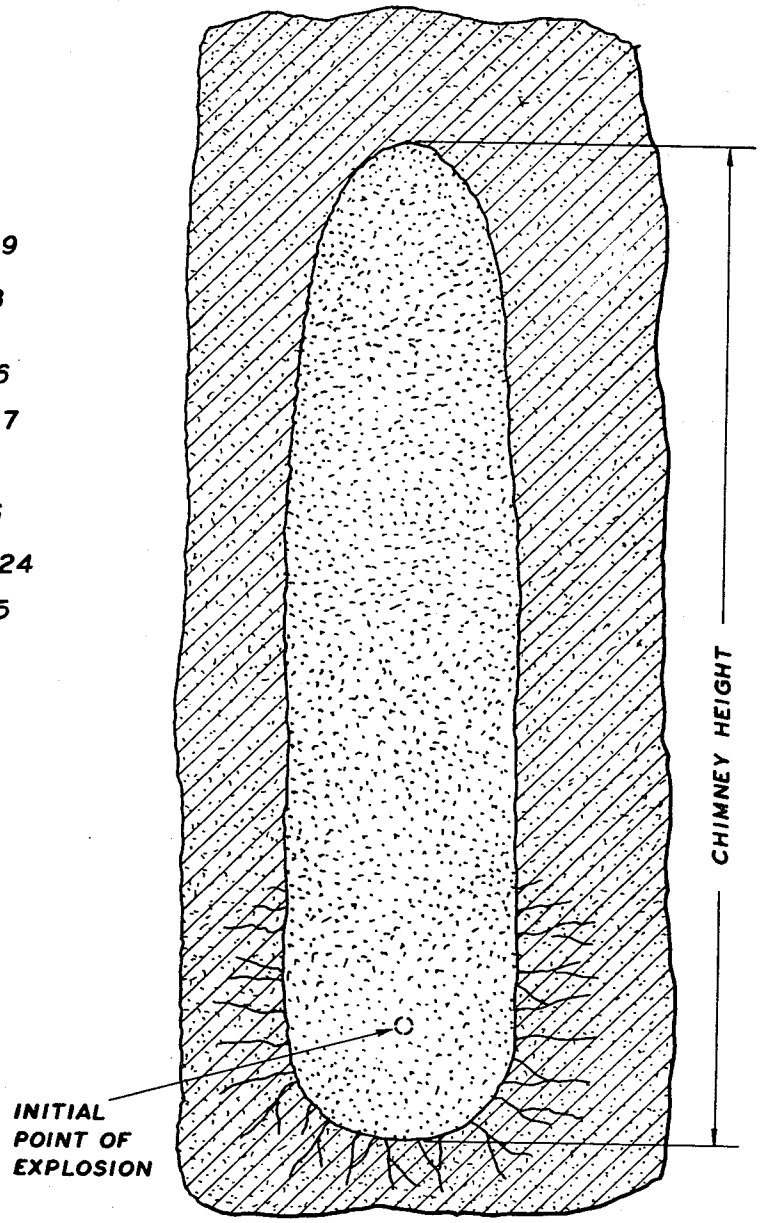


FIG. 2.



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FIG. 7.

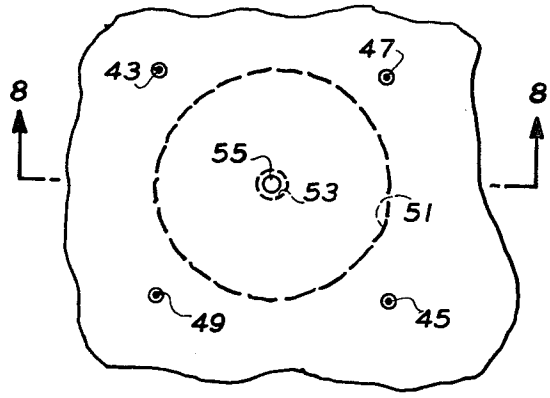


FIG. 3.

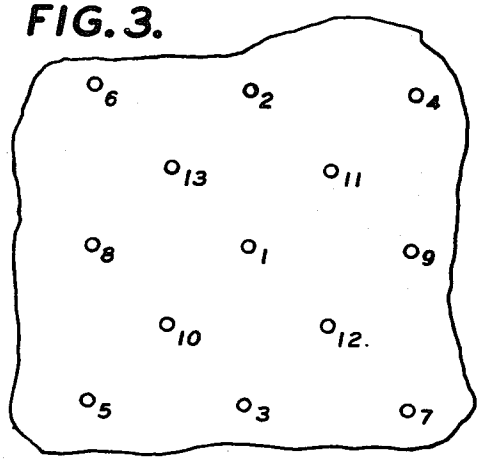


FIG. 8.

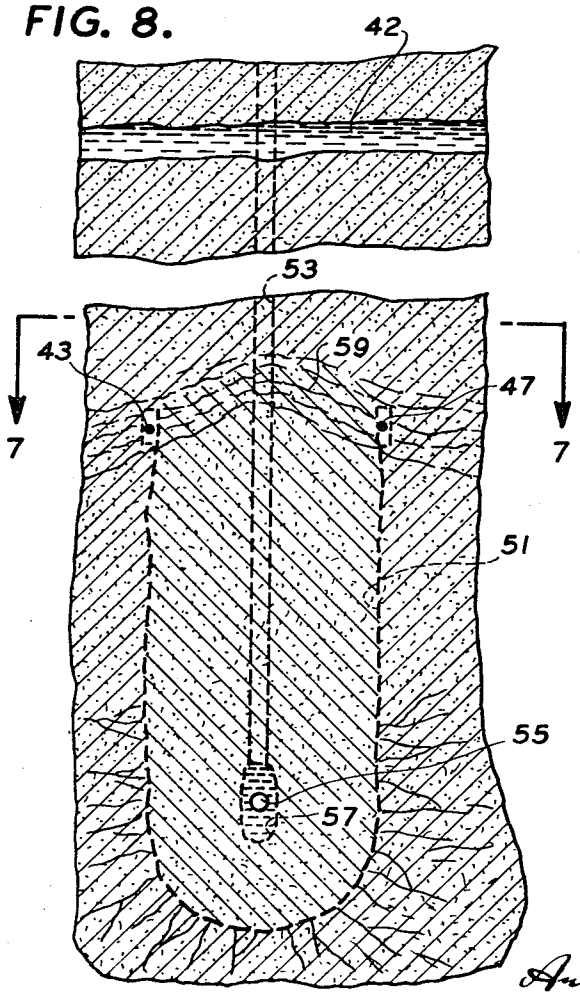
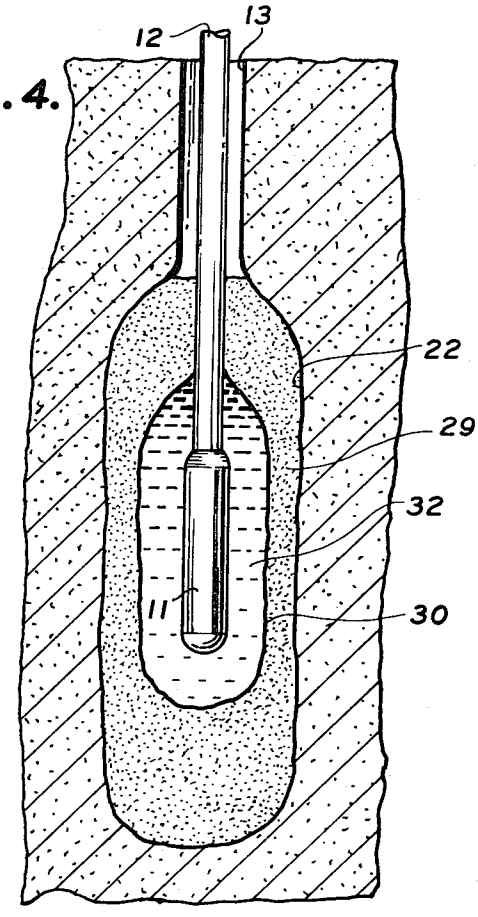


FIG. 4.



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FIG. 5.

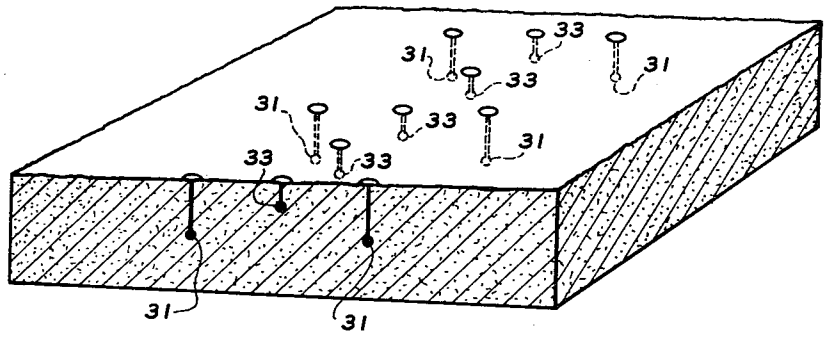
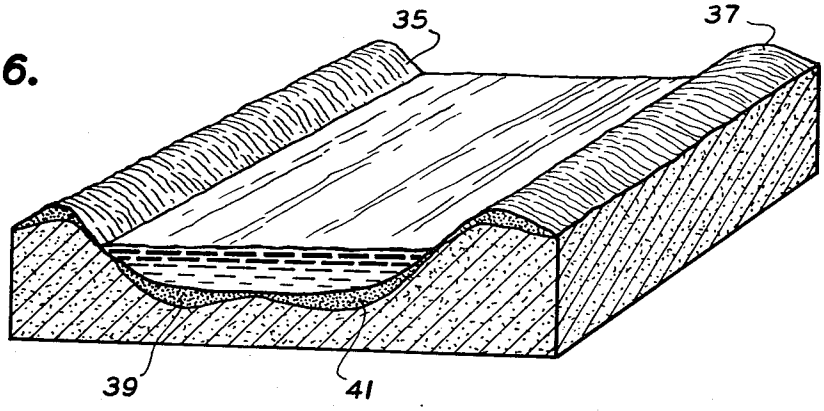


FIG. 6.



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METHOD FOR EXCAVATING BY EXPLOSIONS

This invention relates to the use of explosives for excavating and, more particularly, to the use of a plurality of explosive devices or charges emplaced and detonated in a predetermined relationship to produce mutually enhancing explosion effects.

In recent years, a considerable amount of scientific research has been directed toward exploring possible civil and industrial applications of nuclear explosives. The Plowshare Program of the U.S. Atomic Energy Commission has been a major promoter of such research. This activity in the nuclear area has at least partially stimulated work in the development of improved chemical explosive techniques. Such research has not only included projects concerning the use of explosives ancillary to conventional excavation techniques, but has also concerned the use of explosives for producing a desired excavation without any further ancillary excavation.

In this specification and claims, the term "excavate" and the term "excavating" are used in a broad sense to include not only making hollow or digging by removing material, but also producing an underground cavity and/or merely changing the characteristics of a given zone by loosening or fracturing the material therein and thus creating a region which is more porous and which is capable of receiving a fluid which permeates the interstices. Such a region is defined herein by the terms "permeable region" and "permeable zone".

Among the civil applications of excavation by means of explosions, the digging of canals, aqueducts, and reservoirs are important examples. In industrial applications, explosion excavation techniques may be employed to produce underground voids for the storage of solids or fluids in either a void region produced by the explosion or explosions or in the void interstices of a fractured zone produced by the explosion or explosions. In many cases, storage takes place in both void regions and fractured zones which are contiguous with the void regions. The production of such an underground excavation can also be advantageous in collecting oil or similar fluids contained within the rock structure at a given level. By fracturing the rock structure, seepage of fluids into a collection cavity can take place and the fluids then may be withdrawn. Such techniques are of importance in the production of oil and natural gas from strata in which more conventional removal techniques are unsatisfactory. Descriptions and data on experiments under the A.E.C. Plowshare Program relating to the above described civil and industrial applications, such as those projects conducted under the names GNOME, DUGOUT, SEDAN, HARDHAT, GAS BUGGY AND DANNY BOY, are available from the A.E.C.

Excavating by means of explosion is not without some attendant difficulties. For example, some methods have been devised for producing underground cavities or rubble columns which are elongated in the vertical direction, sometimes referred to as "chimneys". Frequently, difficulty has been encountered in achieving the desired chimney dimensions in that desired elongated configuration does not result. Occasionally, it is desired to maintain the chimney below a certain depth in order to avoid fractured zones intersecting certain strata. Again, difficulties have been experienced in accomplishing this aim. In the case of nuclear devices, particularly those of the fission type, a large number of neutrons are released, resulting in irradiation of the surrounding earth and possible detrimental effects from slowly decaying irradiated elements.

Accordingly, it is an object of the present invention to provide an improved method for excavating by means of explosions.

Another object of the invention is to provide a method of excavating by means of explosions by which elongated underground chimneys are readily achieved.

A further object of the invention is to provide a method for excavating by means of explosions wherein the upper limits of underground chimneys are readily controlled.

Still another object of the invention is the provision of a method for excavating by means of nuclear explosions in which the effects of the release of neutrons are controlled.

It is another object of the invention to provide an improved method of surface excavating by means of explosions.

Other objects of the invention will become apparent to those skilled in the art from the following description taken in connection with the accompanying drawings wherein:

FIG. 1 is a diagrammatical section view illustrating one form of practicing the invention;

FIG. 2 is a diagrammatical section view illustrating the results of the method as practiced in FIG. 1;

FIG. 3 is a diagrammatical plan view of another form of practicing the method of the invention;

FIG. 4 is an enlarged vertical section view of a lower portion of FIG. 1;

FIG. 5 is a diagrammatical perspective view illustrating another form of practicing the method of the invention;

FIG. 6 is a diagrammatical perspective view, similar to FIG, 5, illustrating the results of the method of the invention as practiced in FIG. 5;

FIG. 7 is a diagrammatical plan view illustrating still another form of practicing the invention; and

FIG. 8 is a sectional view taken along the line 8-8 of FIG. 7.

Very generally, one form of practicing the method of the invention as illustrated in FIGS. 1 and 2 involves emplacing at least two explosion producing means 11 and 15 at selected depths and at a distance apart no greater than would result in contiguous permeable zones after detonation. At least one of the explosion producing means 15 is insensitive to the degree of shock which results from the explosion of the other explosion producing means 11. One of the explosion producing means 11 is detonated to produce an explosion. Thereafter, the shock insensitive explosion producing means 15 is detonated to produce an explosion after a time delay of between about one-tenth second and 1 second.

One important application of nuclear energy is in the use of nuclear explosions completely contained underground for hydrocarbon storage and recovery. Nuclear explosives are utilized to increase the effective radius of the bore hole of a well by forming a region of enlarged diameter. When such regions are of substan-

tial height with respect to their diameter, they are often referred to as "chimneys". The formation of underground chimneys is particularly useful in gas and oil bearing formations of low permeability where conventional production techniques are uneconomical. By producing a chimney of 100 feet or more in diameter, gas and oil recovery from certain types of geological structures may become economical where more conventional recovery techniques are not.

At this point it may be noted that the enhancement of recovery of natural gas or oil by the use of underground explosions and the production of volume underground for storing fluid materials does not necessarily require the creation of an actual void space. The extensive fracturing of low permeability rock or shale can produce sufficient space within the fractures themselves as to provide substantial volume. Where these fractures extend through otherwise low permeability rock, seepage of oil or natural gas through the fractures may take place into the well bore and from there the fluid may be recovered by conventional pumping techniques.

To enhance recovery of oil from oil shale, retorting may be done underground rather than in surface pilot plants as in now know. By producing temperatures of 300°–600°C, oil shale may be made to decompose so that the oil therein is released. Retorting underground in a chimney may be accomplished by introducing sufficient oxygen to maintain burning. Underground retorting techniques are known and have been described in a number of publications in connection with the Plowshare Project. Accordingly, further detailed explanation will not be provided in this specification.

In a contained underground nuclear explosion, the total energy of the nuclear device may be released in less than microsecond following detonation. A strong shock wave of spherical configuration moves radially outward against the surrounding material. The energy of the shock wave, as it is absorbed by the surrounding material, causes the surrounding material to heat up and to be worked, resulting in displacement, cracking, crushing, vaporizing, and melting of the surrounding rock. Since some of the surrounding material is vaporized by the shock wave, the vapor forms a gas bubble which expands and displaces the surrounding material to create a cavity. The expansion continues until the gas pressure is approximately balanced by the pressure of the surrounding material. The size of the cavity formed by a nuclear explosion may be about 100 or 200 feet in diameter and is typically lined with molten rock and filled with gas at a few thousand degrees Centigrade. As temperatures drop, the vapors begin to condense and the pressure in the cavity drops. A pool of molten rock may collect in the base of the cavity. At some time after the cooling begins, which may be as long as several hours, the roof of the cavity typically collapses to form a cylindrical chimney of fragmented rock. Some materials are very uniform, plastic and unfractured, such as in a salt dome. Such materials are more stable and may collapse very slowly or not at all.

In order to enhance recovery of fluids, it is desirable in many instances to make the chimney extend a substantial distance vertically. In this way, the chimney cuts across a number of different strata and increases the volume into which fluids in the strata can seep. However, for some types of rock, such as those characterized by high-density, low-porosity, high-strength, and brittle failure, chimney heights result which are equal or less than the radius of fracturing by the explosion. This is because such rock, due to brittle failure, tends to bulk significantly upon breakage during the development of the chimney. Moreover, some rock that responds plastically, such as salt, may not form substantial chimney height. Where the charge is to be buried very deeply, with a greater overburden and hence a greater pressure at the depth, the chimney height tends to be less for a given set of conditions.

It is therefore desirable, under some conditions, to enhance the development of the chimney produced by an underground nuclear explosion. In accordance with the invention, a nuclear device **11** which may be either a fission device or a fusion device, is placed at the lower end of a bore hole **13** at the end of a support tube **12**. A series of delay charges **15**, **17** and **19** comprising suitable chemical blasting agents are emplaced at different lesser depths above the nuclear device **11** and along the bore hole **13**. Regions of enlarged diameter, **22**, **24**, **26** and **28** are provided for accommodating the explosives. Such regions are formed in a manner described below. Suitable plugs **14**, **16**, **18** and **20** are placed in the bore hole between the respective charges and the nuclear device. In order to prevent premature detonation, the chemical charges **15**, **17** and **19** are either of a type which is insensitive to shock from the nuclear blast or are packaged with a shock absorbent material to provide such insensitivity. One way of doing the latter is described subsequently in the specification. The chemical charges **15**, **17** and **19** are set off in sequence with a delay of less than a second total from the time of the detonation of the nuclear device **11**. The delay time is selected to permit full cavity growth as a result of the explosion of the nuclear device but which is less than that time in which the material would collapse into the cavity of its own accord.

In selecting the lower limit of the delay times, as mentioned above, the cavity growth time resulting from the detonation of the nuclear device **11** should be determined. Information is presently available through publications of the Plowshare Program in which cavity growth times for various types of nuclear explosions and for various types of rock are available. Typically, cavity growth takes place in about **100** milliseconds for soft rock such as alluvium soil or volcanic tuft and for low explosive yields, such as those at less than 10 kilotons. The maximum growth time is typically around 500 milliseconds for large yield explosions in the 50 to 500 kiloton range and for hard rock. For most applications, to simplify time delay selection, a delay time of at least 500 milliseconds may be selected for satisfactory results. In this manner, it may be assured that the second explosion will be working against minimal effects of the first explosion.

The upper limit of the delay time is selected to be less than the time in which the roof of the cavity produced by the nuclear explosion would collapse of its own accord As previously explained, this may vary from a few seconds to several hours or not at all. Moreover, the determination of this particular time may be extremely difficult since so many unknown factors have an effect. As a general rule, it is probably best that the delay time

not exceed one second because certain unknowns in the rock structure may cause early collapse or may cause a reduction in cavity size due to resilience of the surrounding material.

In the example illustrated in FIG. **1**, where the rock is hard and brittle, the chemical device **15** may be set with a 200 millisecond delay after the first detonation, the device **17** set with a 250 millisecond delay after the first detonation, and the device **19** set with a 300 millisecond delay after the first detonation. In this way, the material loosened from the detonation and explosion of the immediately lower chemical charge is given added impetus downward to improve the compaction of lower material. Also, less rotating and jumbling of the material occurs because everything is moved together rather than piecemeal as would occur in natural collapse. By enhancing the development of the chimney in this manner, the resulting chimney may be observed in FIG. **2**. Such a chimney is typically one-third again longer than a chimney resulting from the detonation of a single nuclear device and the resultant natural formation of the chimney. Moreover, because the chemical delay charges cause additional rock breakage and force compaction of the chimney rubble, bromine **85** and selenium **85** are quenched to inhibit the development of krypton **85** and thus reduce concentrations of that gaseous fission product in the chimney gas.

Selection of the charge size and the distance at which the charges are spaced depends on the depth at which the charges are placed, and the strength and compressibility of the rock at that depth. It is, of course, preferable to consider interacting effects of the distribution and orientation of natural weaknesses in the rock, the extent of new fractures produced from the explosion, the surface topography, the reinforcement of shock waves, and also the coalescence of cavity gas between charges, in selecting charge size and spacing. In determining the particular charge size and spacing required, helpful reference may be had to data in relation to conventional large scale quarry blasting such as is available in the *Blaster's Handbook* published by E.I. Du Pont De Nemours & Company, Inc., 1969 Edition.

In some circumstances, particularly for large volume production, it is preferable to produce a plurality of underground chimneys spaced from each other throughout the oil or gas bearing strata. It is very desirable, and probably an economic necessity in such an arrangement, to develop intensive permeable fracturing in the regions between the chimneys. By packaging explosives, either chemical charges or nuclear devices, to survive shock loading of up to about 1 k bar, the detonation of the various devices may be delayed in order that the effects of each explosion may be enhanced by the effects of the delayed explosion. Thus, the later detonated charges can break toward the cavity produced by the earlier detonated charge after that cavity has expanded to its maximum development, as explained above. For example, at a given level a plurality of nuclear devices may be spaced out over an area of a total of about one-half mile square spaced in a face centered distribution pattern where the spacing is approximately equal to the expression $320\ (w/4)^{1/3}$, where W is the yield of the device in kilotons and the spacing is in feet. Firing of the device may be in any suitable pattern to produce the desired breakage, depending upon the particular mature of the underground strata, to optimize fracturing between the resulting chimneys. Delay may be of the order 200–400 milliseconds. One potentially suitable firing pattern is illustrated in FIG. **3**. By detonating the devices in the sequence indicated by the numbers, and with 200 to 400 milliseconds delay between shots, the illustrated breakage pattern produces extensive fracturing in the horizontal direction, thereby producing a very large permeable region. Spacing between charges of 40 kilotons yield is about 700 feet, with the corner charges being spaced about one-half mile apart. In this way, the effects of each explosion are enhanced by subsequent explosions.

Another technique for producing large volumes underground involving fewer explosive devices is illustrated by the pattern of charges **1, 2, 6, 8** and **13** in FIG. **3**. The center position **13** may be initially detonated with the charges **1, 6, 2** and **8** being detonated in that order after delays of several hundred milliseconds. In this way, the delay charges can be detonated after the central cavity has expanded to its maximum. By placing the delay charges sufficiently close to the central cavity, a large underground void space may be created. Naturally, placement of the devices for a given yield would be closer where a large void space is desired rather than where a fragmented zone between chimneys is desired.

Returning now to FIG. **1**, it is desirable that the chemical delay charges **15, 17** and **19** be of substantial strength. This may require the use of a substantial volume of chemical explosive. Thus, the regions **24, 26** and **28** along the shaft **13** where the chemical charges **15, 17** and **19** are emplaced, are enlarged so that the available volume is sufficient for the strength of the explosion desired. In order to enlarge such regions, generally referred to in the art as "hole springing", any suitable technique may be utilized. For example, the region desired to be enlarged may first be underreamed over a short vertical section, loaded with a few tens of tons of chemical explosive or blasting agent, shot, and cleaned out by an appropriate technique for the removal of fragments, such as reverse circulation or a "poor boy" bucket. Hole springing techniques are well known in the art, and some of such techniques are explained in the following publications:

The Modern Technique of Rock Blasting, Langfors and Kihlstrom 210, John Wiley & Sons 1963

Blaster's Handbook, Ch. 15, E.I. Du Pont De Nemours & Company, Inc. 1969 Ed.

A similar technique may be employed to make the cavern or cavity **22** of sufficient size and enable the nuclear device **11** to be surrounded with a large quantity of a solid or fluid. In this manner, the fireball chemistry may be altered to a desired degree. Thus, where the device is surrounded by water, the neutron absorbing properties of the water can be used to control the release of neutrons into the surrounding material. Moreover, the cavity volume is enhanced at a given explosive yield because the working gas produced by vaporized rock is boosted due to the vaporization of the surrounding water. Thus, a much larger gas bubble is produced with a consequently larger displacement of rock. Although tritium is produced by neutron absorption by the water, the production of tritrium from deu-

terium in water is about a factor of 10^{-6} below tritium production from lithium in rock.

Referring particularly to FIG. **4**, the details of the cavern or cavity **22** at the lower end of the shaft **13** are more clearly illustrated by enlargement. The nuclear device **11** is contained within the cavity **22** at the end of the supporting tube **12**. Various tubes may be inserted down the hole **13** adjacent the support tube **12**. Such tubes may include sampling tubes and firing cables. When inserted in the hole, the explosive canister may be surrounded by water merely by filling the hole, or a flexible bag **30** of expandible material may be placed around the canister and filled with water through a tube until the bag expands and contains the desired amount of water.

Other materials besides water may be used to provide shock absorption (for example, an expanded polystyrene) or to alter the fireball chemistry. In this manner the device may be made insensitive to shock, or some radioactive species that are biologically hazardous may be modified and controlled, or both. For thermonuclear explosives that produce large quantities of tritium, the fireball may be made oxidizing so that all hydrogen and thus all tritium end up in the form of water. Although the presence of tritium in hydrocarbons introduced into the chimney is not eliminated, the technique just described changes the contaminating processes from direct gas mixing to a slower chemical exchange process. Since the tritium in the water is diluted by water having normal hydrogen atoms, there is less tritium that can exist as water vapor to exchange directly with added hydrocarbon gases.

An excellent oxidizing agent which can be added to water and which is low in cost is ammonium nitrate (NH_4NO_3). Such a substance can be mixed with water and, if desired, can be formed in a jell by the use of cross-linking agents. After the satisfactory cavity size is cleared out, the slurry of ammonium nitrate in water can be added to the emplacement cavity prior to the introduction of the nuclear device. This is shown in FIG. **4** where the ammonium nitrate slurry fills the region at **29**. By delaying insertion of the canister, the contact time of the ammonium nitrate slurry, which is somewhat acid, with the canister, is minimized. The canister, however, should preferably be corrosion resistant. Since carbon **14** and tritium are produced by neutron activation of ammonium nitrate, the first foot or two immediately surrounding the nuclear device is preferably shielded by pure water. This may be accomplished by a suitable supplemental enclosure, such as the flexible bag **30**, the water **32** being contained therein.

Since the ammonium nitrate is itself a blasting agent, and since the nuclear explosive itself acts as a primer, the reaction takes place as follows:

$2\,NH_4NO_3 \rightarrow 2N_2 + 4H_20 + 0_2$. The additional water produces a large quantity of working gas which replaces much of the vaporized rock produced in the situation where no surrounding fluid is present. Because the addition of nitrogen and oxygen gas due to the presence of ammonium nitrate reduces the amount of rock vapor present in the working gas, and because water is an efficient heat exchanger, the cavity gas temperature drops rapidly upon chimney collapse. By utilizing one or more delay charges as described previously to enhance chimney development, the chimney collapse thus induced speeds up the drop in temperature and can cause the radioactive tin and antimony to be trapped in the glass that solidifies from the molten silicate of the rock. It is therefore more probable that the decay product iodine **131** is restricted to the solidified glass.

Referring now to FIGS. **5** and **6**, use of the method of the invention in connection with surface excavation is illustrated. In surface excavating, a charge may be placed beneath the surface a distance sufficient to raise a substantial amount of material and displace it to either side to create a cavity. In connection with nuclear explosives, some experiments have been carried out in the Plowshare Project. One difficulty which arises is that if the excavation is to be of substantial depth, a correspondingly large explosion is required to move the material out of the desired region. Moreover, in any explosion of this type, a substantial amount of material is displaced directly upward and merely falls back into the cavity. Thus, for a given explosive yield, there is a limitation on the achievable depth of the resultant excavation.

In accordance with the invention, delay charges are utilized to enhance the effect of the first excavation explosion and thereby increase the depth of the resultant excavation. Referring to FIG. **5**, a technique for producing a ditch or canal is illustrated. One or two rows of main charges **31** are emplaced at a suitable depth to displace the necessary amount of material upwardly. A row of delay charges **33** is provided intermediate the two rows of main charges **31** or above the one row of main charges and at a lesser depth. The delay charges are cushioned against shock either by placing them in a cavity filled with a shock-absorbent material or by constructing them of a suitable shock insensitive explosive. In either case, the delay charges are delayed a time sufficient for the detonation of the main charges to produce the required expansion and displacement of the material. The delay charges are then detonated to produce a secondary explosion along the row above or between the rows of main charges. This results in an outward displacement of the material initially displaced upward by detonation of the main charges to throw it away from the center of the ditch or canal and thereby prevent it from falling back into the cavity. Thus, the use of the delay charges forms a canal having a general configuration as shown in FIG. **6**. In this case, the high banks **35** and **37** on either side of canal result from the piling up of the displaced material along the edges of the cavity. As may be noted, some material is broken up in or returns to the bottom of the cavity in the regions **39** and **41**. The quantity of such material, however, is substantially less than would be the case were the secondary delay charges not utilized.

Under certain conditions, it may be important to terminate chimney growth below a certain level to reduce the development of permeable paths to overlying aquifiers or to the atmosphere. Referring to FIGS. **7** and **8**, the invention is employed to terminate the upward development of a chimney by pre-splitting a region where it is desired to halt chimney development. Chimney development is halted below the underground stream **42**, as an example. In accordance with the invention, chemical explosives are employed in the re-

gions **43**, **45**, **47** and **49** just outside of the upward extension of the outer perimeter of the expected chimney **51**. The bore hole **53** is shown in phantom extending vertically downward and a nuclear device **55** is placed in a suitable cavity **57** as previously described. The cavity is preferably filled with water to enhance the development of the cavity and to absorb neutrons. The charges are detonated in their numerical order, **43**, **45**, **47** and **49** with about a 25 milliseconds delay. Once firing has occurred, the bore hole **53** and the water boost cavern **57** are cleaned out and the nuclear device **55** is emplaced.

The result of the detonation of the four charges as previously explained produces a generally conical region **59** having little or no tensile strength due to the fracturing produced by the chemical detonations. This region or zone has the effect of terminating the propagation of rock failure induced by the subsequent detonation of the nuclear device **55**. The techniques utilized to provide sufficient volume for emplacement of the chemical charges and for emplacing water around the nuclear device may be the same as those previously described.

It may therefore be seen that the invention provides an improved method for excavating by means of explosions. Placement of a plurality of explosive devices and detonation thereof is accomplished in a manner which causes the resulting explosions to enhance the effects of each other. A greater change for given yields can be expected than from heretofore known techniques. The use of chemical explosives together with nuclear explosives is feasible and in some cases preferable, in that the resultant radioactivity from the nuclear explosion is substantially reduced. Further reduction of radioactivity is accomplished by the invention through the utilization of a surrounding water-filled cavity for the nuclear device. Fireball chemistry may be altered through the production of additional gas by the provision of a surrounding water-filled cavity, or other chemicals may be utilized in the cavity to produce other types of fireball chemistry. In this manner, many harmful affects of radiation may be substantially altered, reduced, or eliminated.

Various modifications of the invention in addition to those shown and described herein will become apparent to those skilled in the art from the foregoing description and accompanying drawings. Such modifications are intended to fall within the scope of the appendant claims.

What is claimed is:

1. A method for excavating by means of explosions, comprising: drilling a hole to a predetermined depth, enlarging a region at the terminus of said hole, placing a nuclear device in the enlarged region, filling the enlarged region with a solid or fluid, plugging the hole a distance above said enlarged region, placing an explosive chemical charge in the hole above the plug at a distance from the nuclear device no greater than would result in contiguous permeable zones after detonation, providing means for rendering said chemical explosive charge insensitive to shock resulting from explosion of the nuclear device, detonating the nuclear device to produce an explosion, and detonating the explosive chemical charge to produce an explosion after a delay time of between about one-tenth second and 1 second.

2. A method according to claim **1** wherein said delay time is about one-half second.

3. A method according to claim **1** for excavating wherein the later detonated explosion producing means is positioned above the first detonated explosion producing means such that the second explosion forces material fractured by the first explosion downwardly toward the bottom of the void produced by the first explosion and in addition forces some of the material outwardly preventing it from falling back into the void.

4. A method according to claim **1** wherein the enlarged region is filled with water.

5. A method according to claim **1** wherein the fluid material is enclosed within a flexible membrane surrounding the nuclear device.

6. A method according to claim **1** wherein at least some of the material in the enlarged region is ammonium nitrate.

7. A method according to claim **1** wherein the size of the enlarged region is sufficient to provide at least one foot of water immediately surrounding the nuclear device.

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