

May 9, 1967

R. E. TENNY

3,318,380

METHOD OF FORMING FLUID-CONFINED UNDERGROUND STORAGE RESERVOIRS

Filed Aug. 26, 1963

5 Sheets-Sheet 1

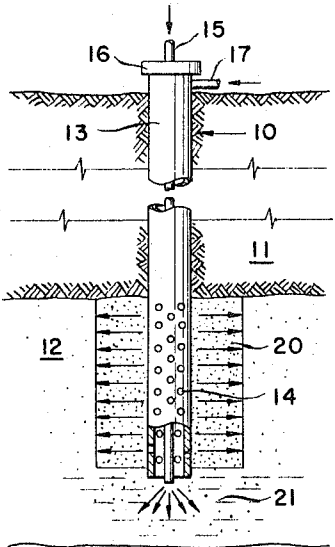


FIG. 1

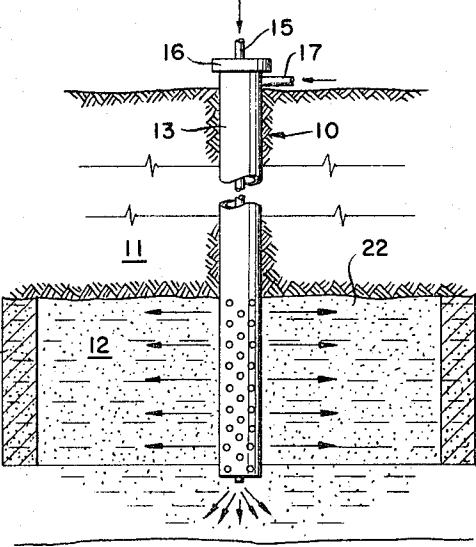


FIG. 2

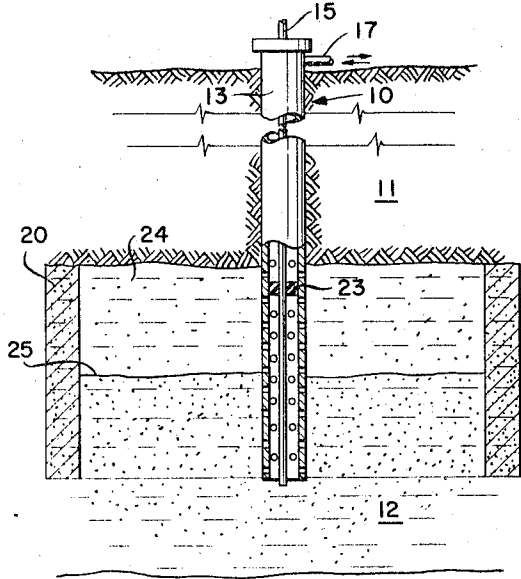


FIG. 3

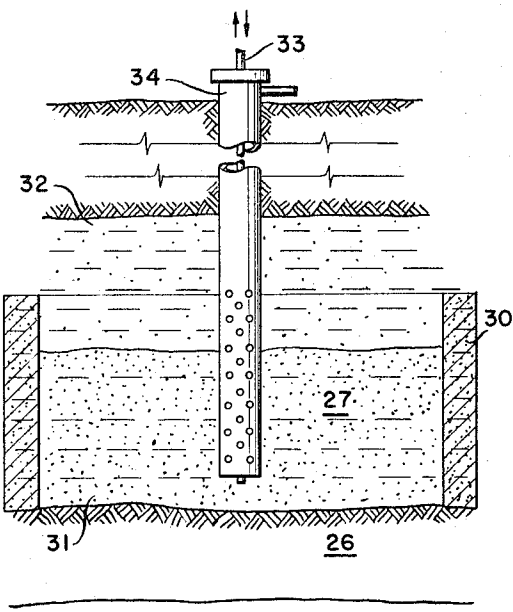


FIG. 4

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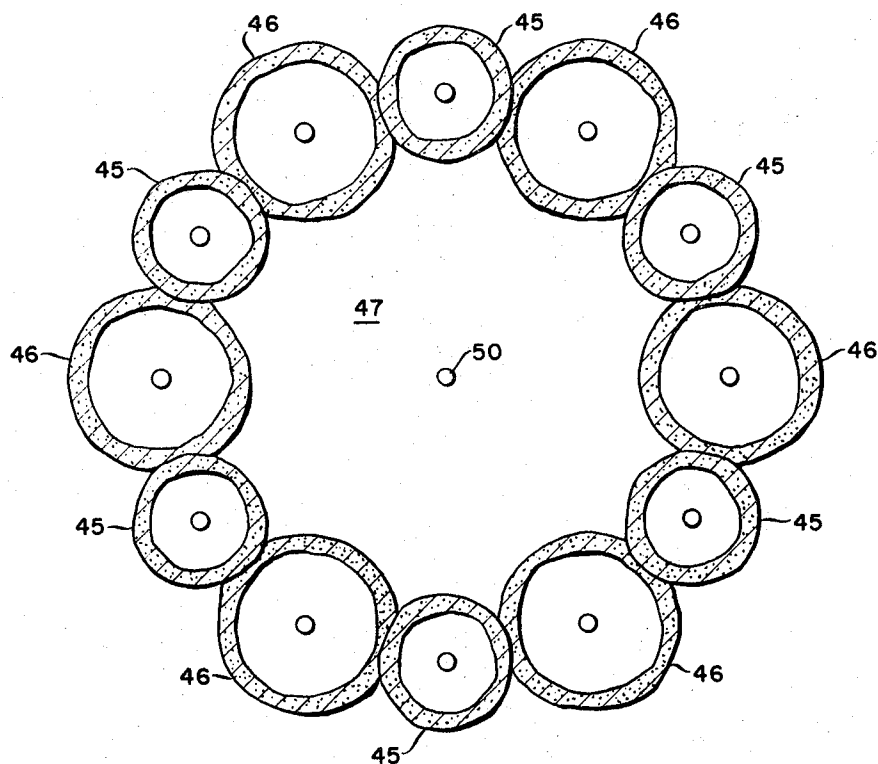
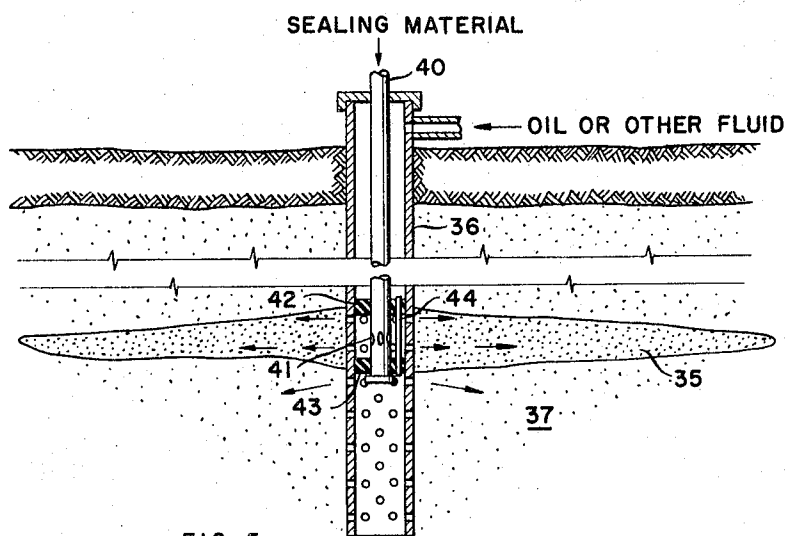
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5 Sheets-Sheet 2



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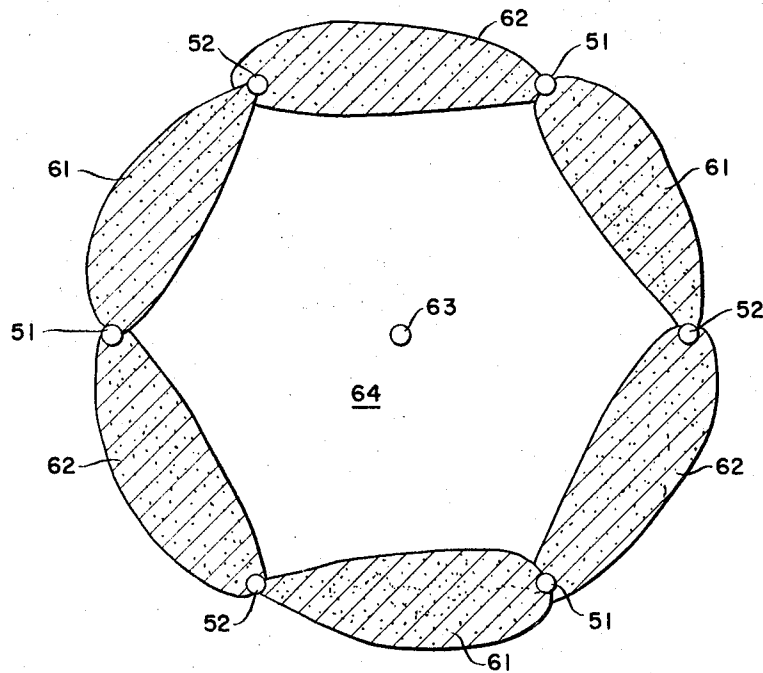
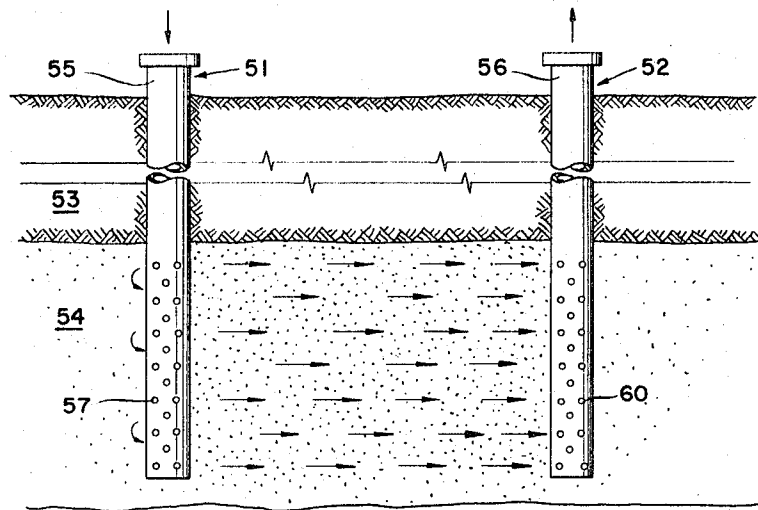
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METHOD OF FORMING FLUID-CONFINED UNDERGROUND STORAGE RESERVOIRS

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5 Sheets-Sheet 3



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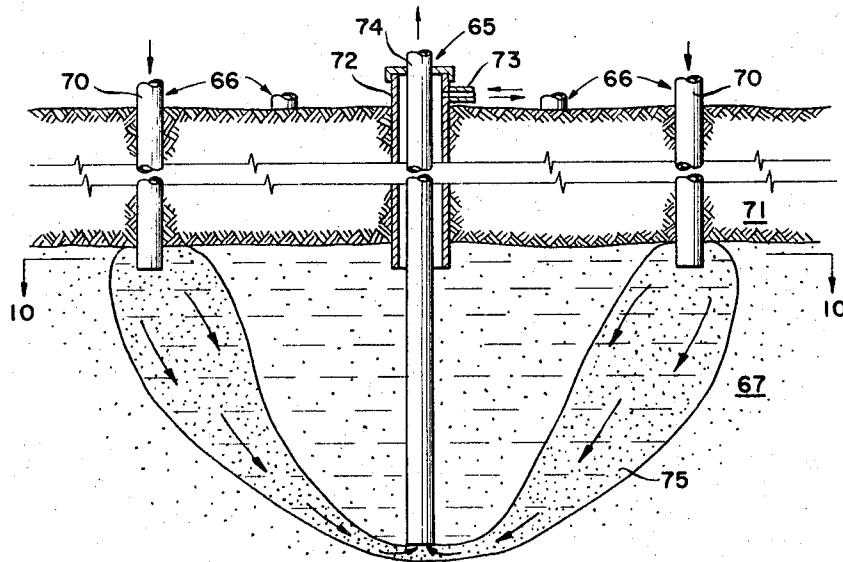


FIG. 9

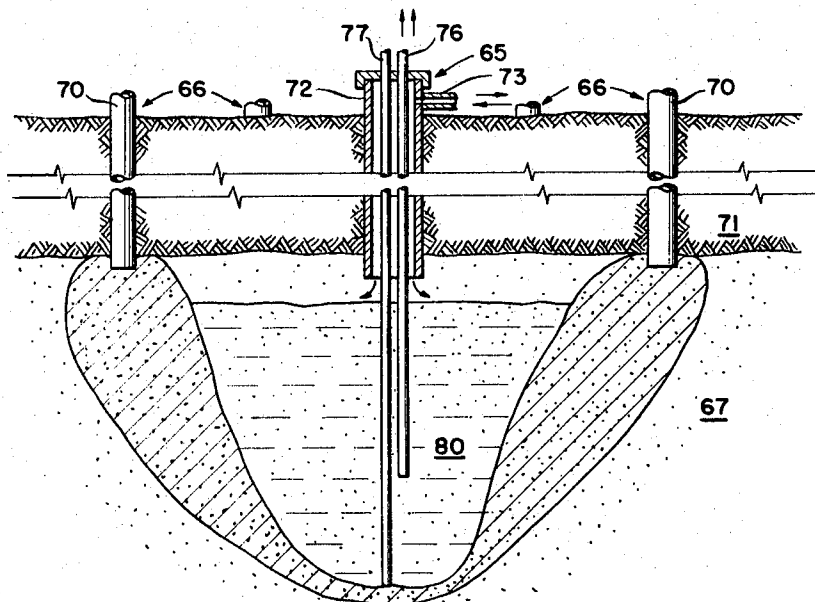


FIG. 11

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METHOD OF FORMING FLUID-CONFINED UNDERGROUND STORAGE RESERVOIRS

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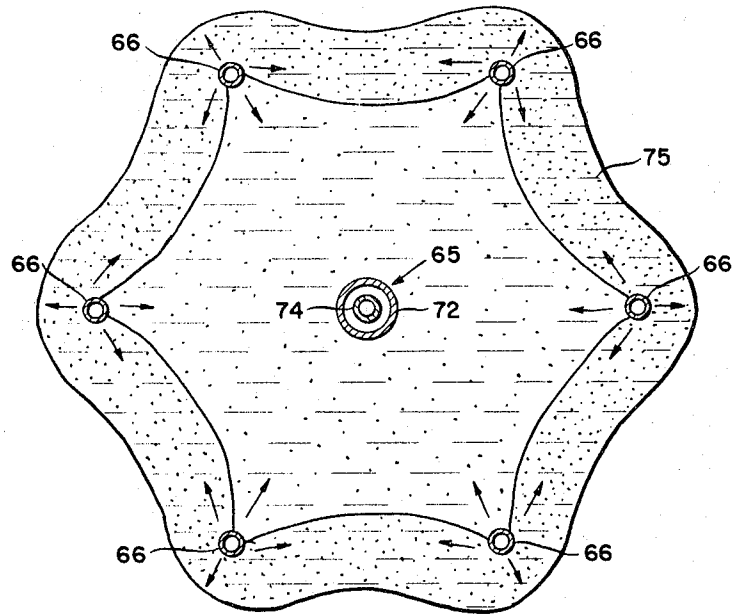


FIG. 10

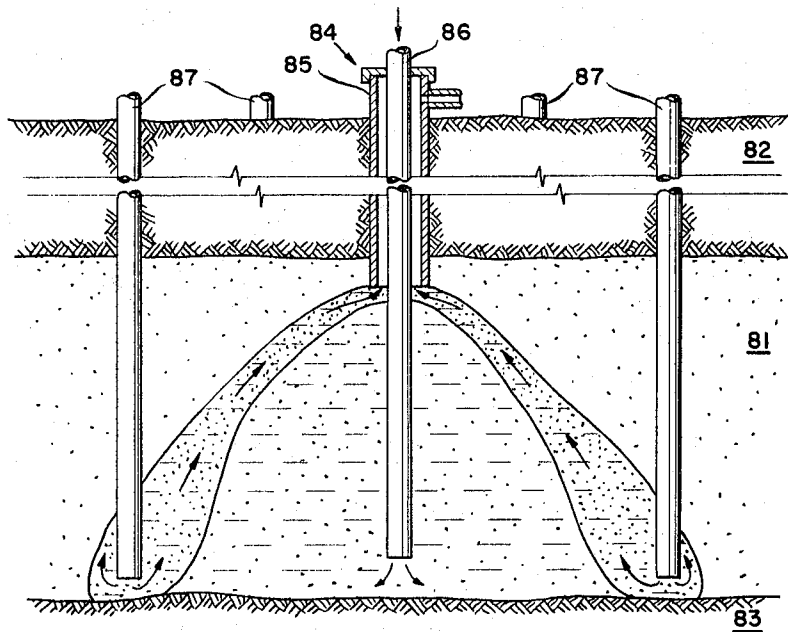


FIG. 12

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METHOD OF FORMING FLUID-CONFINED UNDERGROUND STORAGE RESERVOIRS

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Filed Aug. 26, 1963, Ser. No. 304,365
16 Claims. (Cl. 166-9)

The present invention relates to storing fluids in underground reservoir formations in which at least a part of the boundary for confining the stored fluids is positioned by the flow of fluids injected into the reservoir formation. More particularly, the invention is directed to the creation of underground storage reservoirs by positioning a confining boundary within a permeable subterranean formation. The invention is accomplished without the necessity of excavation of formation rock prior to storage.

The problem of storing petroleum products, particularly natural gas, is becoming increasingly prevalent throughout the world, particularly near the industrial and population centers of the United States. This problem results primarily from the varying loads imposed on the gas transmission and distribution industry due to seasonal variations. Such seasonal variations are particularly noticeable in the urban communities of the midwest, which includes the States of Ohio, Indiana, Illinois, Michigan, Missouri, Iowa, Minnesota and Wisconsin.

In a recent attempt to create gas storage reservoirs in the Chicago area of Illinois, subterranean sandstone beds were exploited for storage purposes. These beds appeared particularly desirable since they were capped by a relatively impermeable formation and consisted of a clean permeable formation located at a depth of about 1000 feet having an average thickness of about 200 feet. The attempt consisted primarily of creating a gas bubble in a porous sandstone formation located beneath an impermeable formation and confining this bubble with water injected therearound through injection wells. The confining water was injected into the permeable formation continuously at increasing pressures.

The above attempt to create an underground storage reservoir in a permeable sand formation has proved unsatisfactory since difficulties were encountered in injecting the confining fluid at the desired rate and the boundary of the bubble was difficult to maintain. In actual application of the attempted method, gas was lost to an extent which would make the storage method completely unsatisfactory for commercial purposes. It is believed that these losses resulted either from losses through the confining fluid, absorption into the confining fluid, or loss through the cap formation.

Although the above-described attempt to create a subterranean storage reservoir in a permeable sand formation proved disappointing, the desirability of utilizing a sand formation for subterranean storage of petroleum products is none the less desirable. Such storage is particularly attractive when compared to other subterranean storage methods, since it promises to yield substantial storage areas in locations that are not susceptible to the creation of subterranean reservoir by other known methods. Furthermore, the expenditure required for creating storage reservoirs within permeable sand formations promises to be considerably less than that required for the creation of presently known subterranean storage reservoirs. Specifically, creating a subterranean storage reservoir within a permeable sand formation has the advantage that it is not necessary to physically remove the material making up the formation through means of washing or excavation procedures.

It is an object of the present invention to provide a method of creating large subterranean storage reservoirs

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in areas where sufficient natural and/or artificially created reservoirs are not available.

Another object of the invention is to provide a method of creating subterranean storage reservoirs in permeable formations without the necessity of removing the material of the formation through excavation, washing or other physical removal procedures.

Another and more specific object of the invention is to provide a method wherein a fluid barrier may be created within a subterranean formation to confine a valuable fluid within the boundaries defined by said barrier.

Yet another object of the invention is to provide a method of displacing a fluid barrier through a subterranean permeable formation in a particular confining configuration. With respect to this object, it is also an object of the invention to provide a method of fixing a fluid barrier in position within the subterranean formation upon being established in the confining configuration.

Still another and more basic object of the present invention is to provide a method wherein fluids may be confined within naturally occurring subterranean formations and readily introduced and removed therefrom without excessive losses or expenditures.

Broadly, the method of the present invention is directed to the forming of a fluid storage reservoir in a permeable formation bounded by a horizontally extensive relatively impermeable layer. In application of the invention, a well borehole is initially formed to traverse the permeable formation. After the well borehole has been formed, a barrier fluid is displaced through the formation and around the borehole in substantially concentric relationship with respect thereto. Upon being displaced through the formation to the desired degree, the barrier fluid is established within the formation as a vertically extensive wall of closed periphery located around the borehole in a position contacting said relatively impermeable layer and spaced radially from the borehole. At this point, in order to complete the formation of the reservoir, the wall is maintained in the established position.

The specific steps utilized in the method to displace, establish and maintain the barrier fluid may vary considerably, as will be exemplified by the following detailed description. Furthermore, the relatively impermeable layer bounding the permeable formation in which it is desired to form the reservoir may be either a natural formation or an artificially created barrier layer. In addition, the reservoir may be formed either above or below the impermeable layer, depending upon the specific gravity of the fluid desired to be stored. It is to be understood, that variations in the individual characteristics of a particular application of the invention are intended to be encompassed by the generic concept of the invention.

The enumerated and other objects and the details of the inventive method will become more apparent when viewed in light of the following description and accompanying illustrations, wherein:

FIGURES 1, 2 and 3 diagrammatically illustrate vertical sections showing the sequential steps of forming and utilizing an underground storage reservoir in a permeable formation located below a relatively impermeable layer according to one embodiment of the invention;

FIGURE 4 diagrammatically illustrates a vertical section of a fluid storage reservoir formed and applied in a manner corresponding to that of FIGURES 1 to 3, but differing therefrom in that it is located in a permeable formation disposed above a relatively impermeable layer;

FIGURE 5 diagrammatically illustrates a vertical section of a permeable formation having an artificially created impermeable layer being formed therein;

FIGURE 6 schematically illustrates a sectioned plan

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view of a series of individual reservoirs, similar to those illustrated in FIGURES 1 to 4, used to define the boundaries of a relatively large reservoir area;

FIGURE 7 diagrammatically illustrates a vertical section of a formation having a curtain-like wall being formed therein to define one segment of a reservoir boundary.

FIGURE 8 schematically illustrates a sectioned plan view of a series of curtains as illustrated in FIGURE 7 utilized to completely define the walls of a subterranean reservoir;

FIGURE 9 diagrammatically illustrates a vertical section of a formation having a fluid confining reservoir being formed therein according to an embodiment of the invention wherein a dynamic fluid cone forms the walls of the reservoir;

FIGURE 10 illustrates a sectioned plan view taken on line 10—10 of FIGURE 9.

FIGURE 11 diagrammatically illustrates a vertical section of a formation having a cone formed therein corresponding substantially to that of FIGURE 9, wherein the walls of the cone have been rigidified to form a fixed barrier; and,

FIGURE 12 diagrammatically illustrates a vertical section of a formation having a reservoir formed therein corresponding substantially to that of FIGURE 9, but differing therefrom in that the cone-shaped reservoir boundaries are inverted.

Referring now to FIGURE 1, therein is illustrated a well borehole 10 extending through an impermeable formation 11 and partially traversing a permeable sand formation 12 in which it is desired to form a storage reservoir. The borehole 10 has extending therethrough a casing string 13 provided with perforations 14 at the end section thereof traversing the permeable formation 12. A tubing string 15 extends concentrically through the casing string 13 to a position wherein its open end protrudes slightly below that of the casing string. In order to provide for the introduction of fluid through both the casing string 13 and the tubing string 15, a cap member 16 closes the upper end of the string 10 and is provided with sealing means whereby the string 15 may be extended therethrough. A fluid conduit 17 extends into sealed communication with the interior of the casing string 13 below the cap 16.

In FIGURE 1, the well bore 10 is shown as it is initially utilized to inject a gel solution 20 into the permeable formation 12. The solution 20 is injected over the entire length of the perforated section of the casing string 13 and, thus extends from the impermeable formation layer 11 to the lower extremity of the casing string. At this point it is noted that the purpose of injecting the gel solution is to create an annular or ring-shaped wall around the well bore 10 at a radially spaced location with respect thereto. To affect this wall, it is necessary that the solution be capable of delayed setting-up or rigidifying within the formation. Although many alternate gel solutions having the characteristic of delayed setting may be used, particularly suitable solutions are disclosed in U.S. Patent No. 2,208,766 to Howard C. Laughton. The gel solution of the patent comprises a water soluble silicate and a gel producing reagent. Various silicates and gel-producing reagents and their respective proportions and setting times are clearly set forth in the patent.

Simultaneously, with the initial injection of the gel solution 20 into the formation 12, an aqueous fluid, such as formation brine is injected into the area of the formation 12 below the casing string 13 through the tubing string 15. In FIGURE 1, the area of this aqueous fluid injection is designated by the numeral 21. The purpose of the latter fluid injection is to maintain the area of the permeable formation beneath the casing string 13 void of the solution 20.

After the gel solution and aqueous fluid are initially simultaneously injected, as illustrated in FIGURE 1, the

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solution 20 is displaced laterally from the well borehole 10 to form an annular ring therearound. Displacement of the solution into an annular ring is affected by terminating the initial injection of gel solution and following that injection by the injection of an aqueous fluid through the perforated section of the casing string 13, as illustrated by the shaded section 22 of FIGURE 2. During both the initial injection of the gel solution 20 and the following injection of the aqueous fluid 22, injection of aqueous fluid into the portion of the formation 12 beneath the casing string 13 is continued in order to maintain this portion of the formation void of the gel solution. After the solution 20 has been displaced from the well borehole 10 by the desired distance, the injection of the aqueous fluid 22 is controlled so as to establish the solution in a relatively fixed annular ring or wall extending around the well borehole. The position of the solution 20 with respect to the well borehole 10 can be determined by various means, such as logging devices or observation wells. Upon being established in position, the annular ring of gel solution 20 reacts to form a rigid and impermeable mass and thus is permanently maintained in position.

FIGURE 3 illustrates the well borehole 10 after the gel solution 20 has reacted therearound to form an annular ring communicating with the impermeable formation 11. It is noted that in this condition the lower end of the annular ring is open to the permeable formation 12 as a result of the continuous injection of aqueous fluid through the tubing string 15. Upon establishing and maintaining the gel solution, as illustrated in FIGURE 3, aqueous fluid within the formation 12 is confined within the annular ring and functions to exert a static pressure on any fluids introduced into the formation 12 through the well borehole 10.

The well borehole 10 is equipped for the introduction of a fluid lighter than the aqueous fluid previously injected through the well borehole. Typically, the aqueous fluid injected into the formation may take the form of brine and the lighter fluid desired to be stored may be natural gas. A packer 23 is sealingly received within the space between the tubing string 15 in casing string 13 to provide for the introduction of a lighter fluid into the upper end of the formation 12 through the casing string. In the illustration of FIGURE 3, natural gas 24 is shown as having been injected into the formation 12 confined by the annular ring. As illustrated, the natural gas 24 has displaced the aqueous fluid within the annular ring downwardly to the level indicated by the line 25. With natural gas so stored within the annular ring, increased storage can be affected by forcing more gas into the confines of the annular ring, and stored gas can be exhausted from the annular ring by permitting the static pressure of the aqueous fluid within the annular ring to force gas through the casing string 13 and out of the fluid conduit 17. Thus it can be seen that a method has been provided for forming and utilizing a subterranean storage reservoir.

Referring now to FIGURE 4, therein is illustrated an arrangement differing from that described with respect to FIGURES 1 to 3 only in that the impermeable formation 26, corresponding to the formation 11, is located below rather than above the permeable formation 27 corresponding to the formation 12. The annular ring or wall of gel material in FIGURE 4 is designated by the numeral 30 and is formed in a manner corresponding identically to that described with reference to FIGURES 1 to 3.

In application, the embodiment of FIGURE 4 differs from that of FIGURE 3 in that the stored fluid designated by the numeral 31 is heavier than the aqueous fluid indicated by the numeral 32. To accommodate this difference, the introduction and removal of stored fluids are affected through the tubing string 33 corresponding to the tubing string 15. As with the formation of the reservoir in FIGURES 1 to 3, the gel solution of the annular ring 30 is initially injected and displaced through a casing string 34 corresponding to the string 13. In order

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to facilitate the formation and utilization of the storage reservoir in FIGURE 4, suitable packing arrangements are provided between the tubing string 33 and casing string 34, as are well within the province of those skilled in the well completion art.

FIGURE 5 illustrates an arrangement for creating an impermeable barrier within a permeable formation where impermeable formations are not naturally present to facilitate formation of a subterranean reservoir, such as those described with reference to FIGURES 1 to 4. It is to be understood, however, that the impermeable barrier of FIGURE 5 is not limited to the embodiments of FIGURES 1 to 4, but rather may be applied to any of the embodiments of the invention. Furthermore, an impermeable barrier formed according to the FIGURE 5 arrangement may be used where it is necessary to have an impermeable barrier either above or below a storage reservoir which is desired to be formed.

The creation of the impermeable barrier or layer, as designated by the numeral 35 in FIGURE 5, corresponds substantially to the creation of water coning suppressing disc as disclosed in U.S. Patent No. 2,784,787 to Charles S. Matthews and James W. Killian. In creating an impermeable layer 35, a casing string 36 corresponding to the aforesaid strings 13 and 34 is first run into the permeable formation 37 in which it is desired to form the layer. A tubing string 40 having a closed lower end with perforations 41 thereabove is then run into the casing string as illustrated in FIGURE 5. The perforations 41 are positioned adjacent a perforated section of the casing string 36 at the level where it is desired to form the impermeable layer. In order to concentrate this layer over a controlled depth, packers 42 and 43 are sealingly positioned between the tubing string 40 and casing string 36 above and below the perforations 41. The packers have sealingly extended therethrough a conduit 44 to permit fluids to flow from the area of the casing string above the packers to the area below the packers.

When utilizing the arrangement of FIGURE 5 to create the impermeable layer 35, it is merely necessary to inject a sealing material through the tubing string 40 while simultaneously injecting a non-sealing fluid, such as oil, through the casing string 36. The sealing material may take the form of any fluid which is capable of setting up into a mass which is both water and oil insoluble. Among the various materials that may be used are many resins, synthetic resins, plastics, synthetic plastics, and various gels and gums. Upon being injected through the tubing string 40, the sealing material is exhausted into the permeable formation 37, through the perforations 41, between the packers 42 and 43 and through the perforations of casing string 36 between the packers. The non-sealing liquid injected through the casing 36 is conveyed through the conduit 44 and exhausted into the formation 37 through the perforations in casing string 36 below the packer 43. The purpose of a non-sealing fluid injection is to prevent the sealing material injected through the tubing string from ballooning into the permeable formation in which it is desired to form the subterranean reservoir.

It is noted that in the illustration of FIGURE 5 the non-sealing fluid is injected below the area of injection of the sealing material, since the arrangement is anticipated for use when the reservoir is to be formed below the impermeable layer. However, a similar arrangement could be used where it is desired to form the reservoir above the impermeable layer. In the latter case, it would generally be desirable to provide means for injecting the non-sealing material above the area of injection of the sealing material rather than, or in addition to below. It is also noted that it may often be desirable to inject the non-sealing material both above and below the area of injection of the sealing material in order to prevent ballooning of the sealing material either upwardly or downwardly.

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FIGURE 6 illustrates a specific application for utilizing annular storage reservoirs of the type illustrated in FIGURE 3 or FIGURE 4. Whether the storage reservoirs utilized in FIGURE 6 arrangement are of the type of FIGURE 3 or the type of FIGURE 4 depends only on the specific gravity of the fluid desired to be stored. It is to be understood that the following discussion is intended to be directed to the use of either type of storage reservoir.

Referring now to the details of FIGURE 6, therein is illustrated a series of juxtaposed storage reservoirs or bottles of the type illustrated in FIGURE 3 or 4 arranged in a circular or ring-shaped pattern. The series comprises a first ring of spaced bottles designated by the numeral 45 and a second ring of bottles designated by the numeral 46 filling the spaces between the bottles of the first ring. In formation of the arrangement illustrated in FIGURE 6, the bottles 45 are first maintained in position and the bottles 46 are then established and maintained so that each of the bottles 46 sealingly engages a pair of adjacent bottles 45 to thus form a complete ring of bottles defining a wall confining a central area 47. The central area 47 so formed is confined by both the ring of sealingly contacting bottles and an impermeable layer positioned thereabove or therebelow corresponding to the layers 11 or 26, respectively, of FIGURES 3 and 4.

Thus, it can be seen that the area 47 is adapted for fluid storage similarly to the areas confined by the rings of FIGURES 3 and 4. Storage is facilitated by the formation of a central well borehole 50 therein having suitable conduit means therein for the introduction and removal of fluid from the area 47. The latter means may take a form corresponding substantially to the casing strings 13 and 34, respectively, of FIGURES 3 and 4 and the cooperating conduit structures. Furthermore, it is also possible that the bottles 45 and 46 surrounding the area 47 may also be utilized for storage purposes in the manner as was described with respect to FIGURES 3 and 4.

FIGURES 7 and 8 illustrate a method of creating a subterranean storage reservoir or bottle wherein the periphery defined by a series of connected curtains formed within a permeable sand formation. The embodiment of the invention illustrated in FIGURES 7 and 8 is similar to those described previously in that it comprises a reservoir confined by a horizontally extensive impermeable formation or layer and a ring of plugged permeable formation communicating with and extending above or below the impermeable formation. As with the previously described embodiments, the determination of whether the reservoir or bottle is formed above or below the impermeable layer is dependent upon the specific gravity of the fluid desired to be stored.

Referring now to the details of FIGURE 7, an injection well and production well are indicated therein by the numerals 51 and 52, respectively. Each of these wells extends through an impermeable formation 53 into a permeable formation 54 in which it is desired to form a subterranean storage bottle. The wells are of relatively conventional structure and include casing strings 55 and 56 extending throughout the length thereof. The casing strings 55 and 56 have perforations 57 and 60, respectively, formed in the sections thereof passing through the permeable formation 54. Preferably, the latter perforations extend over the entire length of the sections of the casing strings traversing the permeable formation 54 and are arranged relatively uniformly. Although not illustrated, it may also be sometime desirable to provide the wells 51 and 52 with tubing strings extending through the casing strings thereof, which tubing strings may be utilized to inject an aqueous fluid into the formation 54 simultaneously with the injection and production through the casing strings, as will be developed subsequently.

In operation of the arrangement illustrated in FIGURE 7, an impermeable curtain is formed between the wells

51 and 52 and in communication with the formation 53 by injecting a gel solution into the formation through the perforated casing string 55 while simultaneously producing fluid through the perforations of the casing string 56. The gel solution injected through the well 51 may take any of the forms described with reference to the application of the invention described with respect to FIGURES 1 to 3. Injection and production of the wells 51 and 52 is continued until the time when gel solution is being produced from the well 52 at a rate closely approaching that of its injection into the well 51. At this time, injection and production is terminated and the gel solution is permitted to set-up between the wells and thus form a curtain-like structure.

FIGURE 8 illustrates a plan view of a complete arrangement of wells corresponding to those of FIGURE 7, wherein the wells cooperate to form a storage reservoir or bottle. The injection and production wells 51 and 52 of FIGURE 8 correspond to those described with reference to FIGURE 7. However, in application after the wells 51 and 52 have been used for injection and production, respectively, to form a curtain of rigid material therebetween, the wells are reused in a reverse manner with the wells 52 being used for injection, while the wells 51 are used for production. The latter injection and production is continued, as was that described with reference to FIGURE 7, until a curtain of rigid solution is maintained between the wells. In FIGURE 8, the areas 61 indicate the curtains formed by the initial injection and production between the wells 51 and 52 and the curtains 62 designate the curtains formed by the reverse injection between the wells 52 and 51. Thus it can be seen that a complete circular or ring-shaped pattern of curtains can be formed to laterally confine a storage reservoir or bottle beneath, or above, an impermeable layer. The reservoir so formed is utilized by forming a well 63 into the confined area 64 thereof in order to introduce and remove fluids. The well 63 corresponds substantially to the well 10, as equipped in FIGURE 3.

FIGURE 9 illustrates yet another embodiment of the invention for forming a subterranean storage reservoir or bottle in a permeable formation disposed beneath a relatively impermeable layer. In the method of this figure, a controlled fluid cone is maintained within the permeable formation to confine fluids to be stored.

Coning, as referred to herein, is the result of the attempt of a fluid system to achieve an energy balance when a dynamic flow pattern is imposed on a two (or more) fluid system by the withdrawal of one of the fluids at a point or line of withdrawal. This phenomenon is well known both in the field and in the laboratory, as is exemplified in aforementioned U.S. Patent No. 2,784,787. In the process of the invention illustrated in FIGURE 9, fluid coning is utilized to form a dynamic fluid barrier or wall around a second fluid desired to be stored.

Referring now to the details of the FIGURE 9 embodiment, as illustrated both in FIGURES 9 and 10, the arrangement comprises a central production well 65 having a plurality of spaced injection wells 66 spaced therearound in a circular pattern. The injection wells 66 are facilitated only for the injection of fluid into the permeable formation 67 into which they extend and, accordingly, comprise only a string section 70 having an open lower end extending into the formation 67. The well 65 is, however, provided with structures to facilitate production of fluid from the lower end thereof while at the same time facilitating the introduction and removal of fluid at the portion thereof immediately below the impermeable formation 71. The structure of the well 65 includes a casing string 72 extending from the upper surface of the formation 71 to the upper portion of the impermeable formation 67, where it is open. A conduit 73 is secured in communication with the upper end of the casing string 72 and provides means whereby fluids may be introduced into and

removed from the casing string. The structure of the well 65 further includes a production string 74 extending concentrically through the casing string 72 to a level within the permeable formation 67 spaced from the impermeable formation 71 by a distance approximately equal to that of the depth of the reservoir desired to be formed.

In operation of the FIGURE 9 and 10 embodiment, a liquid such as brine is injected into all the injection wells 66, while fluids are simultaneously produced from the lower end of the well 65 through the production string 74. Upon the detection of the injected fluid in the fluid produced from the well 65, the rate of injection and production is adjusted so as to establish a cone of injected fluid having the desired confining configuration, such as that illustrated in FIGURE 9. Simultaneously, with the establishment and maintenance of the cone, the fluid desired to be stored within the reservoir defined by the walls of the cone and the lower surface of the impermeable formation 71 is injected into the upper central area of the cone through the casing string 72 and the conduit 73 communicating therewith. It is noted that the embodiment of the invention illustrated in FIGURE 9 is intended for the storage of fluids, such as natural gas, having a relatively low specific gravity. Thus, the fluids injected into the reservoir or bottle created by the fluid cone bear against the formation 71 due to their buoyant force while imparting pressure to the fluid cone designated by the numeral 75 due to their injected pressure. It can be seen that the pressure imparted to the walls of the fluid cone 75 depends on the pressure imparted to the fluid injected into the confined area of the formation 67 through casing string 72. As this pressure and the volume of gas within the fluid cone varies, so does the shape of the cone. For example, as the volume of gas within the cone is decreased, the fluid cone tends to collapse around the production string 74.

From the foregoing description of FIGURES 9 and 10 embodiment of the invention, it can be seen that it provides a subterranean fluid storage reservoir wherein the walls of the reservoir are defined by a dynamic fluid barrier having a cone-shaped configuration. The walls of the fluid cone are capable of varying with variation of volume of fluid being stored. Furthermore, the fluid injected and produced to create the dynamic fluid cone can be recycled from the production well to the injection wells, as is believed apparent. The latter characteristic is particularly desirable since the fluid used to create the dynamic barrier is often treated to increase its viscosity, decrease its solubility with respect to the stored fluid, or increase its wettability with respect to the permeable formation 67 into which it is injected.

Referring now to FIGURE 11, therein is illustrated a subterranean storage arrangement differing from that described with respect to FIGURES 9 and 10 only in that it is adapted to establish and maintain a cone as a fixed barrier rather than a dynamic fluid barrier. Accordingly, like numerals in FIGURES 9, 10 and 11 designate corresponding elements and formations. The structure of the FIGURE 11 embodiment differs from that of the FIGURE 9 embodiment only in that the casing string 72 of the well 65 has extending therethrough a pair of tubing strings 76 and 77, rather than a single string 74. The string 77 is positioned and adapted to function in a manner corresponding identically to the string 74 of FIGURE 9. Thus, fluids injected into the wells 66 can be produced through the string 77 to create a dynamic fluid cone corresponding to that of FIGURE 9. Likewise, the casing string 72 and the conduit 73 communicating therewith can be utilized to introduce fluids to be stored into the reservoir confined by the cone. The tubing string 76 is provided to introduce and remove displacing fluid to and from the reservoir created by the cone. The latter string is necessary, since, as will be developed subsequently, the walls of the cone in FIGURE 11 are not free to move with

varying volumes of stored fluids as are the walls of the fluid cone 75 in the FIGURE 9 embodiment.

In application of the FIGURE 11 embodiment, a dynamic fluid cone is initially established and maintained in a manner corresponding to that described with FIGURE 9 by injection through the wells 66 and production from the string 77. However, after the cone is so formed, it is fixed into position to maintain a frozen inflexible bottle. The latter operation is accomplished by utilizing a fluid in the fluid cone that is capable of setting-up or rigidifying and plugging the pores of the formation in which it is located. Any of the gel materials described with reference to the FIGURES 1 to 3 embodiment of the invention may be used for this purpose. Upon establishment of the fixed cone, injection and production through the wells 66 and 77, respectively, can be terminated and the reservoir confined by the wall of the cone and the formation 71 is in condition to be used for storage purposes. In the case of a light gas, the latter storage function can be accomplished by injecting the gas into the storage reservoir through the casing string 72. Removal of the gas so injected may be accomplished through its own pressure or by displacing it with a fluid, such as that designated by the numeral 80, introduced into the reservoir through the tubing string 76. It is noted that the reservoir of FIGURE 11 can also be utilized for the storage of a heavy fluid, such as the aforementioned displacing fluid 80. In this case, the fluid to be stored is injected and removed to and from the tubing string 76 and the displacing fluid is injected and removed to and from the casing string 72.

FIGURE 12 illustrates a modified version of the embodiment of the invention shown and described with reference to FIGURES 9 and 10. The FIGURE 12 embodiment differs from that of FIGURES 9 and 10 primarily in that it is adapted for the storage of fluids having a relatively high specific gravity. The structural differences between FIGURES 9 and 12 result only from those necessitated by this slightly different function.

Referring now to the specific details illustrated in FIGURE 12, therein is illustrated a permeable sand formation 81 bounded on its upper and lower surfaces by impermeable formations 82 and 83, respectively. The permeable formation 81 is penetrated by a well 84 provided with a casing string 85 communicating with the upper end of the permeable formation 81 and a tubing string 86 extending concentrically through the casing string and communication with the lower portion of the formation 81. A plurality of injection wells 87 are positioned around the well 84 in a circular configuration, corresponding to the configuration of the well 66 with respect to the well 67, as illustrated in FIGURE 10.

In the operation of the arrangement is illustrated in FIGURE 12, fluid is injected into the formation 81 through the wells 87, and is produced therefrom through the casing string 85 of the well 84. This fluid injection and production is carried out in a manner corresponding to the fluid injection and production described with reference to FIGURE 9 and thus a dynamic fluid cone is created within the formation 81. The rates of injection and production of the fluid in the cone of FIGURE 12 are controlled, as were those in FIGURE 9, to establish a cone of the desired shape. Furthermore, injected and produced fluids from the cone can be recirculated and treated for the reasons developed with respect to FIGURE 9. Upon establishing and maintaining the cone, the fluid desired to be stored therein is injected through tubing string 86. When desired, the latter tubing string can also be used to remove stored fluids from the reservoir defined by the dynamic fluid cone and the impermeable formation 83 positioned therebelow.

It is noted that the fluid cone of FIGURE 12 is similar to that of FIGURE 9 in that its configuration is adapted to change with the volume of fluid stored therein. It is further noted that the dynamic fluid cone of FIGURE 12

may be replaced with a plugging fluid, as described with reference to FIGURE 11, to form a frozen inflexible bottle of substantially the same properties as the configuration of FIGURE 11. The choice between storage reservoirs of FIGURES 11 and 12 may be dictated by the vertical relationship between the porous and permeable reservoir strata and a naturally occurring impermeable formation.

To summarize, the present invention provides an improved novel method for creating subterranean fluid storage reservoirs in permeable formations. The method, in all of its embodiments, includes displacing an annular fluid barrier through the formation around the area desired for storage, establishing the barrier as an extensive wall contacting with an impermeable layer thereabove or therebelow, and maintaining the wall in this position. The method has the advantage that it does not require the removal of material from the area in which the reservoir is created and that it is, therefore, relatively expeditious and inexpensive to execute. Furthermore, the invention is particularly advantageous since it promises to solve the ever increasing petroleum storage problems that are occurring in the large metropolitan areas in the United States.

In conclusion, it is noted that the present invention is not intended to be limited to the specific embodiments illustrated and described. For example, well patterns may vary from those illustrated and the particular fluids used to define the boundaries of the storage reservoirs may vary from the specific examples specified, so long as they possess the required characteristics. Therefore, various changes in the details of the described method may be made within the scope of the appended claims without departing from the spirit of the invention.

I claim as my invention:

1. In a well borehole traversing at least a portion of a permeable formation bounded by a horizontally extensive relatively impermeable layer, the method of forming a fluid storage reservoir in the formation, comprising:

- (a) displacing a barrier fluid through the formation from the borehole;
- (b) establishing said barrier fluid as a continuous vertically extensive wall of closed periphery located around the borehole in a position contacting said relatively impermeable layer and spaced radially from said borehole; and
- (c) maintaining said wall at said position through rigidifying of said barrier fluid.

2. A method according to claim 1 wherein the horizontally extensive relatively impermeable layer is positioned above the permeable formation.

3. A method according to claim 1 wherein the horizontally extensive relatively impermeable layer is positioned below the permeable formation.

4. A method according to claim 1 wherein the horizontally extensive relatively impermeable layer is artificially created.

5. A method according to claim 4 wherein the method of artificially creating the relatively impermeable layer comprises:

- (a) injecting a fluid water and oil insoluble sealing material into a horizontally extensive section of the permeable formation; and,
- (b) simultaneously injecting a non-sealing liquid into the permeable formation adjacent to said section in which it is desired to form the fluid storage reservoir.

6. A method according to claim 1 wherein:

- (a) the barrier fluid is a water soluble (silicate); and,
- (b) the wall is rigidified by reacting a silicate with a gel-producing reagent.

7. A method according to claim 1 wherein the displacing of the barrier fluid comprises:

- (a) injecting the barrier fluid through the well borehole and into the formation over the portion thereof traversed by said borehole; and,

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(b) injecting a fluid which is insoluble in the barrier fluid through the well borehole and into the formation over the portion thereof traversed by said borehole to force the barrier fluid to move radially away from the well borehole.

8. A method according to claim 7 wherein:

(a) the barrier fluid is a water soluble silicate; and,
(b) the wall is maintained by reacting the silicate with a gel-producing reagent.

9. In a well borehole traversing at least a portion of a permeable formation bounded by a horizontally extensive relatively impermeable layer, the method of forming a fluid storage reservoir in the formation, comprising:

(a) forming a plurality of spaced boreholes into positions traversing at least a portion of the permeable formation and in a pattern surrounding the well borehole;

(b) injecting the barrier fluid through the spaced boreholes and into the formation over the portions thereof traversed by the spaced boreholes; and,

(c) injecting a fluid which is insoluble in the barrier fluid through the spaced boreholes and into the formation over the portions thereof traversed by the spaced boreholes to force the barrier fluids injected into adjacent spaced boreholes into contact;

(d) establishing said barrier fluid as a continuous vertically extensive wall of closed periphery located around the borehole in a position contacting said relatively impermeable layer and spaced radially from said borehole; and,

(e) maintaining said wall at said position through rigidifying of the barrier fluid from which said wall is established.

10. A method according to claim 9 wherein:

(a) the barrier fluid is a water soluble silicate; and,
(b) the wall is maintained by reacting the silicate with a gel-producing reagent.

11. In a well borehole traversing at least a portion of a permeable formation bounded by a horizontally extensive relatively impermeable layer, the method of forming a fluid storage reservoir in the formation, comprising:

(a) completing a plurality of spaced boreholes into the formation in a pattern surrounding the well borehole;
(b) flowing the barrier fluid between adjacent boreholes in said pattern;

(c) establishing said barrier fluid as a continuous vertically extensive wall of closed periphery located around the borehole in a position contacting said relatively impermeable layer and spaced radially from said borehole; and

(d) maintaining said wall at said position through rigidifying of the barrier fluid from which said wall is established.

12. A method according to claim 11 wherein:

(a) the material of the barrier fluid is a water soluble silicate; and,

(b) the wall is maintained by reacting the silicate with a gel-producing reagent.

13. A method according to claim 11 wherein adjacent boreholes in the pattern are alternatively used for the injection and production of fluids to affect the flow of the

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barrier fluid into a continuous wall of closed periphery located around the borehole.

14. In a well borehole traversing at least a portion of a permeable formation bounded by a horizontally extensive relatively impermeable layer, the method of forming a fluid storage reservoir in the formation, comprising:

(a) providing the well borehole with inlet means spaced from the relatively impermeable layer by a distance substantially equal to the depth of the storage reservoir desired to be formed;

(b) completing a plurality of spaced boreholes into the permeable formation in a pattern surrounding the well borehole;

(c) providing each of said spaced boreholes with outlet means in close proximity to the relatively impermeable layer and on the same side thereof as the inlet means provided in the well borehole;

(d) injecting barrier fluid into the formation through the outlet means of the spaced boreholes;

(e) simultaneously producing fluids through the inlet means of the well borehole;

(f) injecting a fluid which is relatively insoluble in the barrier fluid into the area of the formation surrounded by said spaced boreholes at a location closer to the impermeable formation than the inlet means of the well borehole;

(g) establishing said barrier fluid as a continuous vertically extensive wall of closed periphery located around the borehole in a position contacting said relatively impermeable layer and spaced radially from said borehole; and,

(h) maintaining said wall at said position through rigidifying of the barrier fluid from which said wall is established.

15. A method according to claim 14 wherein maintaining of the wall in position is accomplished through rigidifying of the barrier fluid from which said wall is established.

16. A method according to claim 15 wherein:

(a) the barrier fluid is a water soluble silicate; and,

(b) the wall is rigidified reacting the silicate with a gel-producing reagent.

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