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METHOD OF SEALING UNDERGROUND CAVITIES

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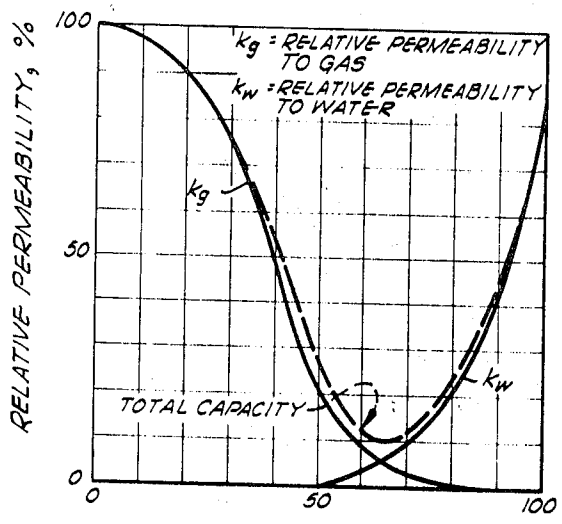


Fig. 1

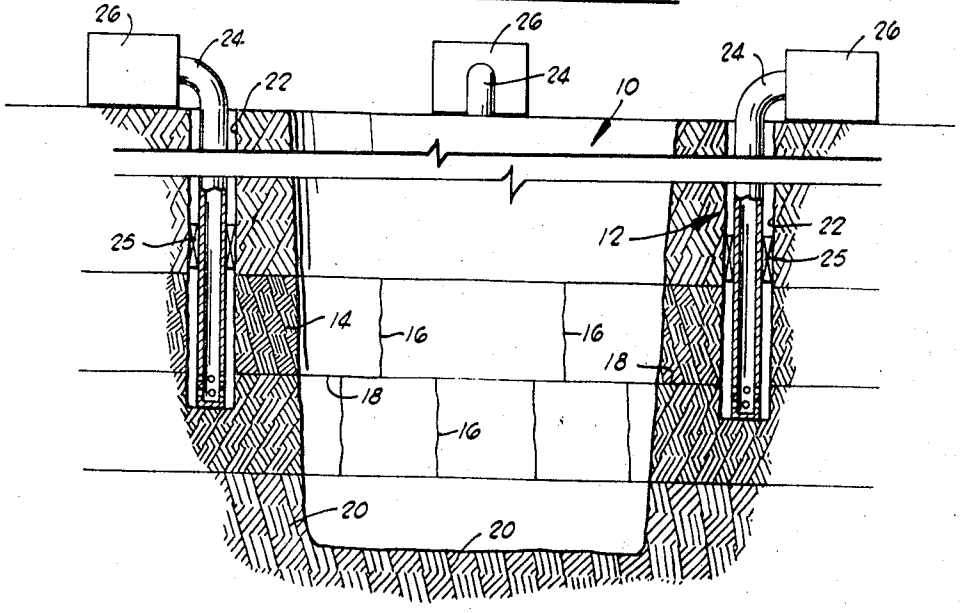


Fig. 2

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METHOD OF SEALING UNDERGROUND CAVITIES

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U.S. Cl. 61—.5 9 Claims

ABSTRACT OF THE DISCLOSURE

Method of reducing the flow of liquids through the earth immediately adjacent a subterranean cavity comprising drilling at least one well into this portion of the earth and injecting via this well at a depth at or below the area through which fluid flow occurs, a gas at a pressure sufficient to displace at least a portion of these liquids.

This invention relates to a method for shutting off connate liquids flowing into an excavation from the surrounding earth. More particularly, but not by way of limitation, the invention relates to a method of excluding from an underground cavity, ground water tending to enter the cavity from the surrounding earth.

Liquid and liquefiable petroleum products and materials such as anhydrous ammonia have recently been stored with increasing frequency in underground cavities. Subterranean storage in natural or artificial cavities provides certain advantages over surface storage, including greater economy of construction and maintenance, inherently greater structural strength, and greater safety. One of the disadvantages of storage in some types of subterranean facilities resides in contamination of the stored material by the influx of ground waters or other connate liquids from the surrounding earth through permeable formations in which the storage facility is located, or conversely, loss of a portion of the stored material from the facility due to seepage into the permeable surrounding formations.

Various methods have been proposed for preventing such contamination or seepage loss, and usually involve the establishment of some type of barrier which blocks the flow of liquids at the face of the surrounding formation which defines the cavity. Thus, it may entail lining the face of the earth around the cavity with cement, or filling the cavity with a plugging agent or with air and forcing these materials under pressure into the pores and interstitial spaces of the surrounding formation to reduce its permeability. It has also been proposed to freeze the earth and the connate water therein in a region around the cavity and, by this means, prevent ground water from flowing into the cavity. Finally, it has been proposed to block the inflowing ground water by drilling small holes into the earth around the cavity and injecting cement into the permeable earth around the cavity via these holes.

The present invention provides a more economical and more expeditiously practiced method of preventing ground water from entering subterraneon storage facilities than most of the described previously used methods. Broadly described, the method of the present invention comprises drilling at least one hole into the earth which surrounds the underground storage facility, then injecting into such hole, a material which is at least partially gaseous and which reduces the total flow capacity of the earthen formation which surrounds the facility, and thereby reduces or eliminates inflowing connate liquids, and renders the formation substantially impervious so that loss of the

stored liquid through seepage is reduced or eliminated. In a preferred embodiment of the invention, a plurality of holes are drilled into the earth surrounding the cavity and air, either alone, or mixed with a plugging or foaming agent, is injected into the several holes and forced therefrom into the formation. In this way, either the absolute permeability or the water permeability of the rock or soil surrounding the cavity is reduced, with a commensurate reduction in flow of water into or from the cavity.

The described procedure affords several advantages over the techniques previously most widely used, including the ability to more selectively, and therefore economically, introduce the sealing material into the earth, the greater economy of using air as compared to cement or the like, and the independence of the sealing or plugging operation from activities involved in excavation of the cavity, or in depositing in the cavity the liquid to be stored therein. The air or gas employed in the invention also is capable of more complete penetration into the formation than cement or various relatively viscous liquids.

An important object of the invention is to provide an improved method for preventing the influx of connate liquids to an underground cavity from the surrounding soil.

A further object of the invention is to provide a method of controlling flow of liquids through the soil immediately adjacent a subterranean cavity by the use of an instrumentality applied entirely externally of the cavity.

Another object of the invention is to provide a more economical, and more easily controlled, method for excluding ground water from an excavation.

In addition to the foregoing described objects and advantages, additional objects and advantages will become apparent as the following detailed description of the invention is read in conjunction with the accompanying drawing which illustrates the invention.

In the drawing:

FIGURE 1 is a graph illustrating the way in which the total flow capacity, relative permeability and water saturation characteristics of a formation are interrelated.

FIGURE 2 is a schematic illustration of the manner in which one embodiment of the invention is practiced.

Before referring specifically to FIGURE 2 of the drawings, some general considerations relative to the theory and practice of the present invention will aid in its understanding. The problems which the invention undertakes to solve occur in several ways and are due to at least two different subterranean conditions. First, when excavating an earthen cavity for the storage of liquids, such as liquefied petroleum gas or anhydrous ammonia, formations are frequently traversed which contain connate liquids—most often water. In many instances, the formation is permeable, or is at least capable of conveying fluids through fracture and joint sets or fault zones. Occasionally no connate liquids may have accumulated in the vicinity and the earth traversed by the excavation may be relatively dry.

Where the excavation does traverse a formation which contains percolating waters, the digging operations are rendered more difficult, and sometimes must be interrupted in order to pump water from the cavity, or one of the known means for preventing seepage into the cavity must be employed. Although it will usually be endeavored to form the storage cavity in a relatively impermeable formation, such as igneous and metamorphic rocks, even in such impermeable strata, ground water can flow through fault zones and through fracture and joint sets occurring at rock unit interfaces since the permeability along such interfaces is generally substantially greater

than the average absolute permeability of the formation. It is in a formation of this type, and during an excavation operation of the type described, that the present invention is of greatest utility in preventing influx of ground water into the cavity.

Upon completion of the storage cavity, even though the seepage of connate water may not have been sufficient to warrant preventative action during the excavation, problems still may be posed by the permeability characteristics of the earthen environment of the cavity. Thus, if a low density liquid is stored in the cavity at a temperature above the freezing point of water and is accumulated therein only to a relatively slight depth, water may still be forced into the cavity from the formation and undesirably contaminate the stored liquid. Alternatively, if the stored liquid is allowed to nearly completely fill the cavity, it may be forced into the surrounding formation by the hydrostatic head developed, resulting in an undesirable loss.

Under any of the described conditions, the present invention undertakes to impose a barrier greatly reducing or eliminating the flow of liquids through the earth immediately adjacent the subterranean storage cavity. The mechanisms upon which the process of the invention are based can be described as including the ability of the gas to infiltrate or enter much smaller pores in the formation than solids or liquids, the greater selectivity and improved control which can be obtained by using one or more small peripheral holes for introducing such gas at predetermined locations in the earth around the cavity, and the reduction in the total flow capacity of the formation which results from the mutual interference to flow established when the gas and water (or other liquid) commingle in the formation. These mechanisms will be referred to further as the description of the invention proceeds.

In practicing the invention, the initial step is, of course, to prepare the subterranean storage cavity. Except where a natural or existing cavity is to be used, this will, of course, entail excavating the earth to the desired depth and horizontal dimensions. In any case, where connate liquid influx or stored liquid seepage becomes a problem, optimum practice of the invention will next entail gaining some knowledge of the lithology of the earth surrounding the cavity. This can be obtained in the course of the excavation, or where water influx becomes severe and requires correction before the cavity has been excavated to its full depth, can be obtained by retrieving cores from the formation extending to the total depth which is to characterize the completed cavity. The lithological knowledge will permit the permeability characteristics of the formations which surround the cavity to be known, including the depths at which fault zones and fracture and joint sets are located. In this way, the primary routes of inflowing connate liquids can be known, and the most efficient plan of treatment formulated.

Given such an understanding of the water flow regimen which the lithological data will provide, one or more gas injection holes of relatively small diameter, say one to six inches, are drilled through the earth around the periphery of the cavity, and are extended to a selected depth so as to preferably terminate in, or immediately below, the region of high permeability through which the ground water is flowing in the formation. In most instances, it will be preferable to provide a plurality of small gas injection holes ringing the cavity in order to more completely arrest the flow of water into the formation. It should be noted, however, that the diffusion and penetration characteristics of the gaseous blocking medium employed in the invention permit a relatively large zone of the formation to be penetrated by gas injected from each of the gas injection holes, and for this reason, the present invention is not only more effective, but more economical than many procedures heretofore in use. In almost all situations, it will be necessary to inject the gas through tubing or pipes positioned in the holes, and frequently it will be desirable and often necessary to use one or more packers around the tubing and above the point where the gas is injected into the formation. The packers are preferably positioned opposite or above formations which are characterized in having a low vertical permeability. This reduces the possibility of high losses of gas occurring as a result of by-passing the packer and re-entering the hole at a higher location where the hole is in communication with the atmosphere.

Where a permeable rock constitutes the source of the inflowing ground water, the gas injection wells should preferably be drilled to at least the depth which is to characterize the completed storage cavity, and most preferably, slightly deeper. This will result in gas injected via such holes flowing upwardly and outwardly in the earth into the lower pressure regions, with such upward and outward flow being accompanied by an expansion of the injected gas to occupy a substantially greater volume at the reduced pressure. This is a desirable result in that it permits a greater percentage of the pore spaces of the rock to be filled with the injected gas, and thus enhances the mutual interference mechanism hereinafter described.

If the rock is impermeable but ground water is reaching the cavity through regions of relatively high permeability at the horizontal rock unit interfaces in a jointed system, upward flow of gas through the formation cannot readily occur, and the gas injection holes should terminate at, or very slightly below, the particular fault zone or joint set.

The gas injection holes are subject to considerable variation in their horizontal spacing from the wall of the cavity. Many variables enter into the determination of this spacing, including lithological uniformity, permeability, porosity, depth of the water table below the surface, and, of course, whether the blocking function of the injected gas is intended for use primarily during excavation of the empty cavity or after the cavity is filled with the liquid to be stored. In general, however, the gas injection holes should be positioned at a distance of from ¼ to 1 cavity radius from the hole with this distance increasing within this range as the radius of the cavity increases. Variations from this range may be dictated by the concurrence of extremes in several of the variables mentioned.

Once the gas injection wells have been located in the manner described, a gas-containing blocking medium is injected into the formation through the holes. This blocking medium may be a pure gas which is relatively inert chemically with respect to connate liquids and also to the material to be stored in the cavity, or it may be such an inert gas having entrained therein a plugging agent which sets up to a hardened state upon contact with the connate liquid to be excluded from the cavity. As yet another alternative, a foaming agent can be added to the gas to provide certain advantages of flow obstruction.

The mechanism by which the gas reduces or suppresses the flow of water into the cavity is illustrated in FIGURE 1. If enough of the gas is forced into the pores of the rock, water is displaced therefrom, the relative permeability of the formation to gas, k_g, increases, and the water saturation approaches zero. No water will then flow through the formation to the cavity. If gas is forced into the formation in an amount sufficient to reduce the water saturation to about 65 percent, the relative permeability of the formation to both water and gas is reduced to about 5 percent due to the mutual interference to flow which the two immiscible phases produce. The total flow capacity of the permeable portion of the formation is also greatly reduced and very little water will flow through the pores into the formation.

It should perhaps be pointed out at this point that an ancillary advantage of the invention occurs when it is used to prevent the influx of water into cavities used for cryogenic storage in that heat flow into the cavity is re-

duced due to the relatively low heat capacity of the gas as compared to water.

Maximum efficiency of gas injection is obtained by injecting enough of the gas to decrease the water saturation over a substantial area around the formation to about 50 percent, then closing or shutting in the gas injection holes and waiting for the gas to bleed into the cavity to the extent that the water saturation builds up to about 70 to 75 percent. The formation is then repressurized by injection of additional gas to again reduce the water saturation to about 50 percent. This type of cyclical gas injection, alternated with pressure equalization and bleed off, is most economical, and is the preferred procedure for use to prevent influx of water during excavation, even though a minute amount of ground water can still enter the cavity. If the particular problem to be overcome requires complete water stoppage, such as the elimination of contamination during filling of the cavity with the liquid to be stored therein, continuous gas injection at relatively high pressure is employed in order to completely eliminate the influx of water.

In terms of the actual gas pressure used during injection, this pressure should, of course, be lower than the pressure at which the formation or overburden will fracture. This upper limit of pressure generally corresponds to about 1 p.s.i.g. per foot of depth, thus increasing as the depth at which the gas is injected increases. At the other extreme, the gas pressure during injection should exceed the pressure of the connate liquids resulting from hydrostatic head. This latter pressure, in the case of water, will be equivalent to about 0.433 p.s.i.g. per foot of hydrostatic head. Thus, the depth at which the water table source of ground waters is located will, in most instances, establish the lower limit of actual gas pressure which should be employed, but in any event, injection of the gas at a pressure in the range of from 0.4 p.s.i.g. multiplied by the depth at which the gas is injected, to 1 p.s.i.g., also multiplied by this depth, will usually provide the desired results.

The gases which are useful in the practice of the invention are those which are relatively inexpensive and which are relatively inert, both with respect to the particular connate liquid to be blocked, and to the liquid to be stored. Air will often comprise the optimum gaseous material, but in some instances, such relatively inert materials as carbon dioxide or nitrogen may provide certain advantages. In addition to the use of gas alone for blocking the influx of connate liquids, the invention also contemplates the entrainment of suitable plugging agents in the gas for the purpose of sealing off some of the relatively larger water-bearing fractures. The type of plugging agents which can be used are those which are frequently used in oil and gas production for the purpose of reducing the permeability of the formation at one or more locations, and include, for example, silica tetrafluoride, methyl trichlorosilane, colloidal silica compounds, water soluble starch materials, finely divided clay, methyl cellulose, and various polyacrylimides. Gases or volatile liquids which form a solid hydrolysis product upon contact with water are preferred. In general, such plugging agents function to reduce the permeability by setting up to a relatively hard state after they have been injected into the pores or fractures and have there been contacted by the connate water. When set up in this manner, the plugging agent actually forms a physical obstruction to water flow and reduces the absolute permeability of the rock. In using plugging agents entrained in the injected gas to reduce or completely suppress water influx, gas injection is initially established through the air injection holes so as to clean out these holes and push the water back away from the walls of the hole. Then, while the gas is continuously injected, the plugging agent is intermittently entrained therein to successively plug all parts of the fracture system. In some instances, it may be preferable to inject pure gas, then gas carrying entrained plugging agent, then pure gas, and finally terminate the injection to permit the pressure to equalize or bleed off. This allows better contact of the water with the plugging agent.

Another embodiment of the invention contemplates the entrainment of foaming agents in the injected inert gas. Materials of this type develop a foam or froth upon contact with the connate liquids of the formation and are generally well known in the art of air drilling of oil and gas wells, as well as in other technologies, such as the detergent industry. The inclusion of the foaming agent in the injected gas offers the dual advantages of two phase flow interference hereinbefore described, and physical obstruction reducing the absolute permeability of the formation. Typical foaming agents which can be employed include, but are not limited to, alkyl benzene sulfonates, alkyl sulfonates, aryl sulfonates, ether sulfates, sulfated ethoxylates of normal, primary alkanols, ammonium alcohol ether sulfates, the alkali metal salts of lauryl mercaptan ethoxylate sulfates and high molecular weight fatty quarternary ammonium salts. Other suitable materials can be selected from published lists of surfactants.

As a final consideration, it should be pointed out that under some conditions, the most effective blocking of connate liquid influx may be obtained by using in alternating sequence, periods of pure gas injection and periods in which gas carrying plugging or foaming agents are employed. It may also frequently be desirable to precede the gas injection with the use of conventional cement grouting in a fracture zone to seal off as many of the large fractures as possible and thus reduce the total amount of gas which must be injected to reduce the flow of connate liquid to an acceptable level.

A specific example of the practice of the invention, as illustrated by reference to FIGURE 2 of the drawings, will further aid in understanding the steps employed. A cavity **10** is excavated in the earth **12** for purposes of storing liquefied petroleum gas. The cavity is to be 100 feet in depth and 75 feet in diameter at the surface of the ground. In the initial removal of earth, the type of strata encountered is an impermeable clay. At a depth of about 40 feet, however, a relatively impermeable metamorphic rock sequence **14** is encountered consisting of gneiss and shist. The metamorphic rock strata **14** is layered and is transected by a regular and nearly vertical system of joint sets. The traces **16** of the joints which appear at the exposed face of the cavity are illustrated in FIGURE 2.

As the excavation traverses a bedding plane **18** located at a depth of about 60 feet, a rapid influx of ground water into the cavity **10** commences to occur through the conchoidal surface structure at the rock unit interface. In order to control this water flow and permit excavation to continue, it is decided to provide a plurality of peripheral gas injection holes around the cavity. A test hole is drilled in order to obtain soil cores to the proposed total cavity depth of 100 feet. From the cores thus obtained, it is determined that the metamorphic rock **14** terminates at a depth of about 80 feet and is underlain by an impermeable slate **20**. No other water-conveying fault, fracture or bedding plane structures are perceived to be located below the bedding plane **18** located at a depth of 60 feet in the metamorphic rock.

On the basis of the lithological data obtained from the cores, a plurality of holes **22** each having a diameter of five inches are drilled downwardly from the surface at circumferentially spaced intervals around the cavity **10** and about fifteen feet therefrom, and pipes **24** perforated at their lower ends are extended downwardly into the holes so that their lower ends are located at, or immediately below, the bedding plane **18** in the metamorphic rock **14**. Packers **25** are set around the pipes **24** at a depth of about 37 feet to block the flow of air up the holes **22**. Compressors **26** are connected to the pipes **24** to supply air to the pipes at a variable pressure of from about 20 p.s.i.g. to about 75 p.s.i.g. Air is initially intermittently injected

into the formation from the pipes **24** at a pressure sufficient to reduce the flow of water into the cavity to a negligible rate. The compressors **26** are periodically shut off and air pressure in the formation is allowed to bleed off until water influx into the cavity increases substantially. The compressors **26** are then restarted and the cycle is repeated. Excavation of the cavity **10** is then continued until the desired depth of 100 feet is attained.

What is claimed is:

1. The method of reducing liquid flow below the surface of the earth through a permeable formation immediately adjacent and in fluid communication with a subterranean cavity comprising:

drilling at least one hole from the surface into or extending to a location immediately below and in fluid communication with said permeable formation adjacent the cavity; and

injecting a relatively chemically inert with respect to said flowing liquid gaseous material alone into said hole and from said hole into said permeable formation around said hole or above said location and adjacent at least a portion of the cavity at a pressure sufficient to reduce the flow of liquid through said permeable formation into which said gas is injected.

2. The method defined in claim **1** wherein said gaseous material is selected from the class consisting of air, nitrogen and carbon dioxide.

3. The method defined in claim **1** wherein the injection of gaseous material is carried out by

(a) initially injecting gaseous material through said hole at a pressure and volume sufficient to substantially reduce the flow of liquid through the permeable formation adjacent the cavity, then

(b) terminating the injection of the gaseous material for a period of time sufficient to permit the flow of liquid to increase; then

(c) resuming the injection of gaseous material at the initial pressure and volume to substantially reduce the flow of liquid through the permeable formation adjacent the cavity; and

(d) alternately commencing and terminating the injection of gas as described in steps (a) and (b) to maintain a low average rate of liquid flow through the permeable formation adjacent the cavity.

4. The method defined in claim **1** wherein a plurality of holes are drilled and said holes are each horizontally spaced from the cavity by a distance equivalent to from about ¼ to about 1 cavity radius.

5. The method defined in claim **1** wherein said gaseous material is injected into the permeable formation at a pressure of from about 0.4 p.s.i.g. to about 1 p.s.i.g. multiplied by the depth in feet at which the gaseous material is injected.

6. The method defined in claim **1** wherein the gaseous material injected is selected from the class consisting of air, carbon dioxide and nitrogen, and the gas is injected in an amount and at a pressure such that the total fluid flow capacity of the permeable formation adjacent the cavity is reduced to a minimum as a result of mutual interference between the injected gas phase and the liquid in said permeable formation.

7. The method defined in claim **1** wherein the gaseous material is injected at a point below and in communication with the main channels of the permeable formation through which the liquid flows.

8. The method of preparing a subterranean liquid storage facility comprising:

excavating earth to provide a cavity in the earth having the desired dimensions for storage;

extending holes from the surface of the earth to a permeable soil adjacent and below the excavation and in fluid communication with said excavation,

after commencing said excavation, injecting alone a gaseous blocking medium selected from the class consisting of air, nitrogen and carbon dioxide into the permeable soil adjacent and below said excavation through the holes, said blocking medium being injected at a pressure sufficient to substantially reduce influx of connate liquids into said excavation through said adjacent soil; stopping said injection until said reduced influx increases; and

continuing said injection at least at periodic intervals to regulate said reduced influx of said liquids into the excavation of said cavity.

9. The method defined in claim **8** wherein said gaseous blocking medium is initially injected into the soil after the excavation is completed.

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