April 8, 1969 D'ARCY A. SHOCK ET AL 3,436,919

UNDERGROUND SEALING

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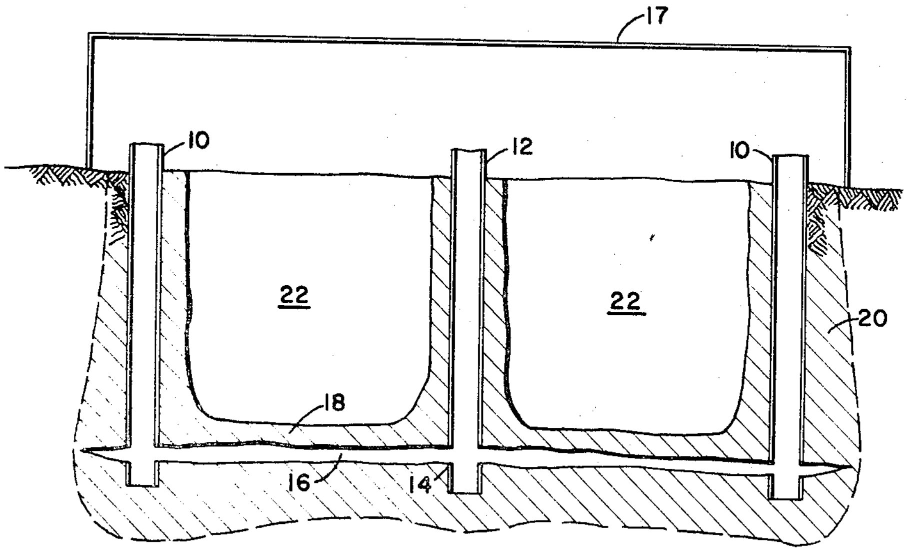

FIGURE 2

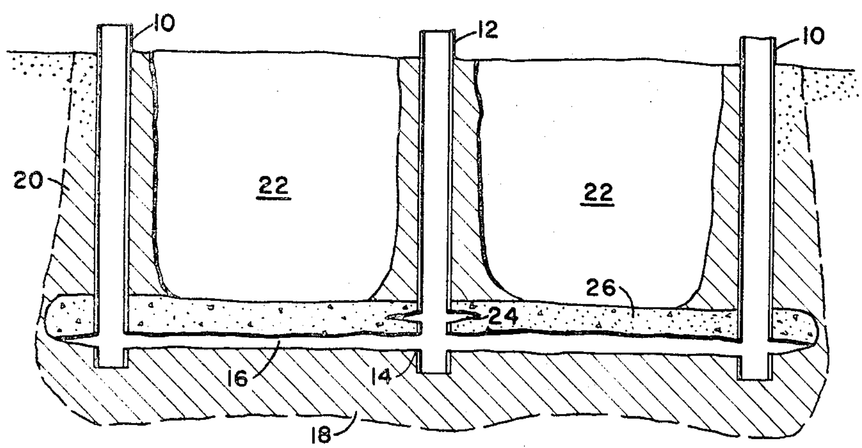

FIGURE 3

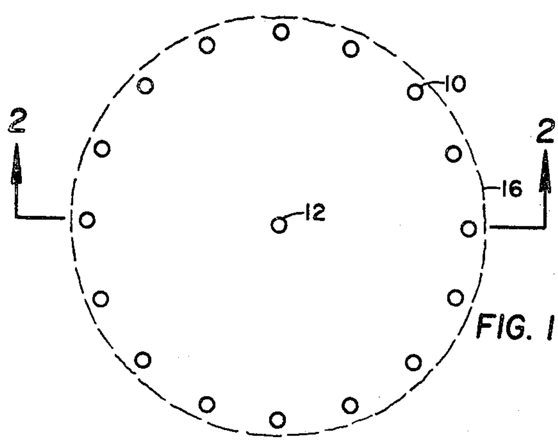

FIG. 1

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UNDERGROUND SEALING

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Continuation-in-part of application Ser. No. 156,855, Dec. 4, 1961. This application May 9, 1966, Ser. No. 548,499
Int. Cl. B65g 5/00; E21f 17/16
U.S. Cl. 61—.5 7 Claims

ABSTRACT OF THE DISCLOSURE

A method for forming a bottom seal for frozen earth storage tanks and the structure of the tanks are disclosed. A central well is positioned amidst a number of surrounding freeze wells and a horizontal fracture is propagated between the central and surrounding wells. A refrigerant is circulated through the fracture at a temperature sufficient to freeze connate water in the areas adjacent the fracture. A frozen impermeable horizontal bottom is thus formed. Side walls are frozen by circulating refrigerant through the surrounding freeze wells thereby forming an enclosure. In soft formations, a consolidating agent is injected between the central and peripheral wells to form a horizontal consolidated layer which in itself may be sufficiently impermeable to form a closure in combination with the frozen side walls. If not, a fracture is propagated underneath or through the consolidated layer and refrigerant forced therethrough to for ma frozen sealed bottom.

This application is a continuation-in-part of the copending application of the present inventors, entitled "Underground Sealing," Ser. No. 156,855, filed Dec. 4, 1961, now abandoned.

This invention relates to underground sealing. More particularly, but not by way of limitation, the present invention relates to a method for sealing an underground area against the influx of connate waters, and against the dissipation of a liquid stored in the cavity into the surrounding earth.

The tremendous current production in this country of liquefied petroleum gases as well as other liquefied gases exerting high vapor pressures has presented a serious problem of providing suitable storage facilities to accommodate such fluids. This is particularly true during the seasons of the year when such fluids do not find a readily available market. The difficulty which is often encountered in providing suitable storage facilities for fluids of the type mentioned is the requirement that tanks and containers which are constructed for this purpose must be very massive and therefore quite expensive in order to withstand the high vapor pressures developed by such fluids.

One solution to the problem of storing liquefied petroleum gas, and other volatile liquids such as liquefied natural gas and ammonia, has been the provision of either natural or artificial subterranean storage caverns. One type of such cavern is that which is formed in impermeable rock formations such as shale and limestone. However, naturally occurring formations which lend themselves to the construction of such caverns are difficult to find, and, of course, do not always accommodate themselves to storage of such liquids in the most desirable locations. Also, expensive lining are frequently required to make such natural or artificial caverns absolutely impermeable to the liquids that are to be stored therein, or to ground waters which may infiltrate the cavern and contaminate the contents thereof.

More recently, it has been proposed to form the

underground storage cavern in a permeable, water-bearing formation. In this case, the water in the cavern walls is frozen to render the walls impermeable to the fluids stored, and also to the connate waters surrounding the cavern. One of the methods which has been proposed for forming such storage caverns in impermeable water-bearing formations is the so-called "ring freeze technique." According to this method, a plurality of wells is drilled in circular formation around the perimeter of the area of earth which is to be excavated to form the underground cavern. A refrigerating medium is then pumped down into the wells to freeze the water in a ring of earth surrounding the portion of the ground which is to be excavated. The earth is excavated within the frozen perimeter, and a protective covering or roof is placed over the excavation to prevent the loss through volatilization and evaporation of the liquefied petroleum gas or other fluid which is to be stored therein. Although tests of this technique have demonstrated its basic feasibility, a major difficulty which, until the present invention, remained unsolved in the ring freeze technique of underground liquid storage is the difficulty in providing an effective seal at the bottom of the cavern. This is particularly true when the depth of the cavern is increased so that the head exerted upon the bottom of the cavern by the surrounding connate waters is relatively great.

In one embodiment the present invention provides a method for forming a bottom seal for frozen earth storage tanks which are constructed by the ring freeze technique. The method is also applicable to the provision of a bottom seal in storage tanks having side walls formed by other methods than the ring freeze technique.

According to one embodiment of the invention, an injection well is drilled in a predetermined relationship to a plurality of surrounding freeze wells. The freeze wells are completed by perforating the casing near the bottom of the well, by leaving the bottom of the well uncased, or by other methods. The underground formation adjacent the injection well is then notched or perforated at, or near, a zone of weakness adjacent the bottom of the injection well.

After the surrounding formation is notched by a known technique, such as by plane perforating or sand cutting, a fracture is then initiated and extended into the surrounding formation by injecting a hydraulic fracturing fluid into the formation via the injection well and notch. The pressure of the hydraulic fluid is increased until it exceeds the breakdown pressure of the formation. The formation then fractures along the zone of weakness until the fracture has been extended to intersect and communicate with all of the ring wells as indicated by an increase in pressure in the wells. A channel of fluid communication is thus established between the injection well and the surrounding freeze wells by means of the connecting fracture.

The hydraulic fracturing fluid is then withdrawn from the injection well and is replaced by a refrigerating medium which is pumped through the injection well into the fracture which has been propagated in the formation near the bottom of the injection well and thence up through the surrounding ring wells intersected by and communicating with the periphery of the fracture. The temperature of the refrigerant is sufficiently low to freeze interstitial water in the formation to form a layer of ice adjacent the faces of the fracture. After the refrigerant has been circulated from the injection well through the fracture and up through the peripheral ring wells a sufficient time to freeze the connate water for a considerable distance on each side of the fracture, a wall of ice next is formed around the perimeter of the area which is to be excavated.

The wall of ice can be formed in any of several ways. The circulation of refrigerant from the centrally located well through the fracture and up the peripheral well bores can be continued until the connate water surrounding the freeze wells freezes into a solid wall extending from the frozen area around the fracture to ground level. Refrigerant can be circulated in each freeze well by injecting refrigerant down an open ended tubing extending to the bottom of the well and returning the fluid to the surface through the annulus between the tubing and the well bore. These two methods can obviously be combined if such is thought desirable. The wall of ice formed will extend downwardly to and be combined with the layer of ice which has been formed on either side of the fracture; at least a portion of the earth enclosed by the ring wells and the frozen area adjacent the fracture can then be excavated to provide an underground storage cavern for the accommodation of the liquefied petroleum gas or other fluid which is to be stored. The injection well will be removed after completion of substantially all of the excavation, and following the introduction of the relatively low temperature liquid to be stored in the cavity. By the described method, a continuous, impermeable seal is effected at the bottom of the cavity which is formed. The seal functions to prevent connate water from infiltrating into the liquid stored in the cavity, and conversely, prevents the seepage or dissipation of stored liquid into the surrounding porous formation.

It is to be noted that the formation of the frozen bottom seal is not limited to situations in which the use of a wall of ice formed by the use of ring wells is contemplated. In other words, a concrete wall, or wall of similar impervious material might be utilized in conjunction with a bottom formed by a frozen layer of ice instead of the wall of ice formed by use of the ring wells, if this should be desired.

From the foregoing discussion of the invention, it will be appreciated by those skilled in the art that the method of the invention, as thus far described, is limited to utilization in those types of earth formations where the formations are consolidated sufficiently to permit fracturing thereof. Formations of this type include, but are not limited to, shale and limestone. On the other hand, where the formation is composed of loosely packed sand or the like, it will not usually be sufficiently consolidated to yield a fracture upon application of the high pressure hydraulic fluid. In this event, the method of the invention is modified to first consolidate the formation sufficiently to permit it to be fractured.

In such modified method, the ring wells and injection well are completed as heretofore described. The next procedure, however, is to perforate the well casing, prefferably of the injection well, some distance from the bottom of the well and pump a composition having the property of consolidating the sand, or other loosely packed material, into the formation adjacent such perforations. The flow of the consolidating material into the formation is continued until communication is established with all of the ring wells surrounding the injection well. A semi-horizontal impermeable zone communicating with the surrounding ring wells is thus established. The ring wells are then flushed clean of the consolidating composition, and made ready for the subsequent freezing steps of the method.

In some situations, the use of the consolidating material may alone provide a sufficient bottom seal to obviate the necessity of further sealing by freezing. If appropriate testing shows, however, that the consolidating material has not sufficiently sealed the bottom, the consolidated formation is then perforated from the injection well and fractured in the manner described above to form a fracture extending from the injection well and intersecting and communicating with the peripheral wells. The refrigerating medium is circulated from the injection well, through the fracture, and into and up through the peripheral wells as heretofore described. It is preferable in many instances to perforate and fracture just beneath the consolidated formation, since, in this way, a thinner consolidated strata may be formed and the procedure effected more economically. After the bottom seal is formed, either by consolidation or by consolidation and freezing, the enclosing side wall is formed by circulating refrigerant through the ring wells, until the wall of ice is formed as described above; at least a portion of the enclosed earth is then excavated to complete the cavity.

From the foregoing description, it will be apparent that a major object of the present invention is to provide a novel seal for a portion of an underground formation.

Another object of the present invention is to provide a novel method for forming an effective bottom seal for an underground storage tank used for storing low temperature liquids having a high vapor pressure.

An additional object of the present invention is to provide a method for forming a bottom seal for an underground storage tank which is formed in a porous, unconsolidated formation.

An additional object of the present invention is to provide a method for quickly, and relatively inexpensively, forming a frozen earth storage tank for storing liquefied petroleum gases and other liquefied, normally gaseous materials.

Other objects and advantages of the present invention will become apparent upon a reading of the following disclosure in conjunction with a perusal of the accompanying drawings which illustrate our invention.

In the drawings:

FIGURE 1 is a plan view of the arrangement of ring wells and central injection well as the same appear when viewed from above the surface of the ground.

FIGURE 2 is a schematic view in section taken along the line **2—2** in FIGURE 1 through the center of an earth formation which is being subjected to the process of the present invention for the purpose of forming an underground frozen tank for storing liquefied petroleum gas or other low temperature liquids.

FIGURE 3 is a view similar to FIGURE 2, but illustrating a modified embodiment of the invention by which underground storage tanks may be formed in unconsolidated earth formations.

Referring now to the drawings in detail, and particularly to FIGURE 1, a plurality of wells **10** are formed in relatively closely spaced relation to each other around a closed perimeter which encloses the earth which is to be excavated in forming the underground storage cavern. Although in most instances it will be preferred to form the wells **10**, hereinafter referred to as ring wells, around the circumference of an imaginary circle, the method of this invention is not limited to this arrangement, since in some instances irregular geometric formations of the ring wells may be desirable or necessary. Moreover, it will not always be necessary to form a completely closed geometric figure. Under some extraordinary circumstances, it is possible that there will be impervious areas, such as a dike or a tilted sill, which could conceivably form one portion of impervious wall **20**. Located within the area enclosed by the ring wells **10** is an injection well **12**. While under normal conditions injection well **12** will be located at the approximate center of this area, it is to be understood that under certain conditions it may be necessary or desirable to locate this well off center. Both the ring wells and injection wells should usually be drilled to approximately the same depth, although varying depths may be utilized if it should prove more desirable.

After injection well **12** and ring wells **10** have been drilled, the formation adjacent the lower end of injection well **12** is perforated or notched as indicated by reference character **14** by any suitable notching technique, such as by plane perforating or sand cutting. Following the notching of the formation, a hydraulic fracturing fluid is passed into injection well **12** and the pressure of the hydraulic fluid is then increased until it exceeds the breakdown pressure of the formation adjacent perforation 14. After the pressure of the hydraulic fluid exceeds the breakdown pressure of the formation, the formation will fracture along a bed plane or other zone of weakness adjacent notch 14, and the continued impress of the hydraulic fluid will cause fracture 16 to be propagated until it reaches and intersects ring wells 10 surrounding injection well 12, thereby providing a channel for fluid from the fracture into the ring wells 10. The radial advance of fracture 16 from injection well 12 to ring wells 10 will be indicated by an increase in the pressure in each of the ring wells.

Following the extension of fracture 16 to each of the ring wells 10, the hydraulic fluid is withdrawn from the fracture and injection well 12 and is replaced by a suitable refrigerating medium whose temperature is lower than the freezing point temperature of water in the formation. The refrigerating medium circulates downwardly through injection well 12, into and through fracture 16, and from thence into and up through the surrounding ring wells 10. After a sufficient period of time, the connate water in the earth on each side of the fracture will become frozen. In this manner, a sheet of ice 18 is formed around fracture 16. Additional refrigerating medium is likewise circulated in each of the ring wells 10 either coincident with the injection of refrigerant through the fracture or subsequent thereto so that a wall of ice 20 is formed which completely surrounds the earth which is to be excavated in forming the cavity. The apparatus for circulating refrigerant within each of the wells 10 is not depicted since such is well known in the art. It will be apparent from the discussion thus far that ring wells 10 should be spaced sufficiently close to each other that wall of ice 20 is continuous in nature. The refrigerating medium which is utilized for forming layer of ice 18 and wall of ice 20 may be any suitable refrigerant such as brine, liquefied ammonia, or the liquefied gas which is to be stored in the subterranean cavern.

Upon completion of the formation of layer of ice 18 and wall of ice 20, at least the earth enclosed by the vertical wall of ice is excavated. This results in the formation of a doughnut-shaped exacuation around the injection well 12 and inside the ring wells 10. When the excavation has been completed to the desired size, a suitable cover or roof 17 is placed over the excavation to prevent loss of the fluids stored therein due to volatilization or evaporation.

Several alternate procedures may be followed in placing the covering over the excavation and in storing the fluids therein. In some instances, where the fluid is highly volatile, it may be preferable to allow the injection well to remain in place and to provide a central opening through the covering to accommodate the piping leading to the injection well. In other instances, the fluid may be placed in the excavation, the injection well then removed, and finally, the covering placed over the excavation. In yet other situations, it may be preferable to place the fluid to be stored in the excavation after placing the cover thereon, and then removing the injection well 12 as the final step in the procedure.

As has been previously indicated, the fracturing technique utilized in the preferred embodiment of the method of the present invention may sometimes be impossible to perform due to the unconsolidated or loosely packed nature of the earth formations in which it is proposed to form the subterranean storage facility. Under such circumstances, a modified method of the type illustrated in FIGURE 3 may be employed. According to the modified method of the invention, the casing of injection well 12 is initially perforated at some distance above the bottom thereof as at 24, and a consolidating medium is forced outwardly into the surrounding strata of loosely packed, unconsolidated material.

A number of materials capable of consolidating the loosely packed sand or other formation substance are well known, and the choice of the consolidating material will depend upon the conditions of the location and the economics of the situation. Generally, such consolidating materials are pumpable slurries which set up to a hardened state upon standing quiescently in the formation. In many cases, the slurries are gell-like materials having thixotropic properties. Examples of suitable consolidating materials are concrete, asphalt emulsions, and gel formers.

In FIGURE 3, the portion of the formation which has been consolidated by injection of the consolidating composition thereinto is represented by reference character 26. It will be noted that such consolidation is extended to intersect ring wells 10 after which the ring wells are flushed clean of the consolidating composition. After the consolidating composition has set up to a hardened state, the wall of ice 20 is formed by circulating the refrigerating medium within each of the ring wells 10 as above described. The permeability of consolidated strata 26 is then tested; and, if sufficient impermeability is demonstrated to meet the requirements of the fluid to be stored in the cavity, no further processing before excavation of the earth surrounded by the ring wells is required.

On the other hand, if the consolidated strata is not impermeable to the degree required, it is then necessary to form a horizontal layer of ice to function as the bottom seal of the excavation. This may be accomplished by notching consolidated strata 26 and forming a horizontal fracture in the manner hereinbefore described, extending from the injection well 12 to intersect the ring wells 10, followed by circulation of the refrigerating medium through the injection well, fracture, and ring wells to freeze the connate water. Where only a thin or shallow consolidated strata is formed in order to more economically use the consolidating composition which is employed, the fracturing may be more effectively accomplished by perforating or notching the earth at a point in the injection well just under the consolidated strata and then fracturing at this point although the process of the instant invention is not limited to this practice. This procedure has been followed in the situation depicted in FIGURE 3 so that fracture 16 there shown actually lies along the lower boundary of consolidated strata 25. The water in the portion of consolidated starta 26 which immediately overlies fracture 16 is therefore frozen and becomes a part of ice layer 18 when the refrigerating medium is circulated through fracture 16.

From the foregoing description, it will be apparent that the present invention provides a novel method for forming an efficient bottom seal in an underground storage tank for storing low-temperature, volatile liquids. The method may be employed in pervious, water-bearing formations, whether or not the same is consolidated sufficiently to permit fracturing thereof. Moreover, although the method has been described, for illustrative purposes, as it is used to form the bottom seal in an underground storage tank having walls of ice formed by the ring freeze technique, other procedures and materials of construction, such as concrete, may be used in forming the side walls is desired.

Throughout the specification, primary interest has been centered upon the use of the instant process for forming underground storage tanks having a top open to the atmosphere or covered by an artificial cover. The process is not, however, limited to this type of a storage installation. It is within the scope of this invention to form totally enclosed underground caverns, for instance, both a bottom and top seal could be formed by fracturing between an injection well and a periphery of wells and circulating a refrigerative material at two different places from injection well 12 through the two fractures. The intervening material could then be removed by standard shaft mining methods and the outer walls could be formed either by freezing or by other methods which are mentioned in the specification. In addition to the use of this process in a totally enclosed underground storage facility, it is contemplated that embodiments of this invention may find utility in other phases of endeavor. For instance, if for some reason it was desired to form an impervious area about a mine shaft, a portion of the mine shaft wall could be frozen by using the novel fracturing method as taught by this invention. The necessity for a plurality of freeze points would thus be overcome.

Other innovations may be made in the described procedure without departure from the novel, basic principles which underlie the invention.

We claim:

1. A method for constructing an underground liquid-containing chamber in a formation containing interstitial water and having a plurality of wells penetrating therein which comprises the steps of:

(a) extending a fracture through said formation containing interstitial water from one of said plurality of wells to intersect the remainder of said plurality of wells, the plane of said fracture remaining within said formation containing interstitial water;

(b) flowing through one of said wells, through said fracture in said water-bearing zone, and thence into the remainder of said wells, a refrigerating fluid having a temperature while flowing through said fracture less than the freezing point temperature of the interstitial water present in said formation adjacent said fracture, which freezes interstitial water in the formation to ice in the region adjacent the fracture to form a liquid-impervious continuous layer of ice in said formation; and

(c) forming a liquid-impervious side wall extending from and at an angle to said liquid-impervious layer of ice of (b) thereby forming a liquid-impervious walled and bottomed enclosure.

2. The method claimed in claim 1 wherein said water-impervious side wall is formed by circulating a refrigerating medium whose temperature is less than the freezing point temperature of water present in the earth through the earth along a path extending from and at an angle to said fluid-impervious barrier of (b).

3. A method for forming within a formation containing interstitial water a liquid-impervious layer of ice contiguous with and coextensive with a horizontal fracture communicating with a plurality of wells penetrating said formation containing interstitial water comprising the steps of:

(a) extending a horizontal fracture from one of said plurality of wells through said formation containing interstitial water to intersect the remainder of said plurality of wells, the plane of said horizontal fracture remaining within said formation containing interstitial water; and

(b) circulating through said wells and said intersecting fracture a fluid which is at a sufficiently low temperature as it passes through said fracture to freeze the interstitial water present in said formation adjacent said fracture into a liquid-impervious sheet of ice contiguous with and coextensive with said horizontal fracture.

4. A method for forming a liquid-impervious sheet of ice within an unconsolidated water-bearing earth formation having a plurality of wells penetrating said water-bearing earth formation which comprises the steps of:

(a) forcing a consolidating medium from one of said plurality of wells into and through the water-bearing earth formation and to intersect the remainder of said plurality of wells thereby forming a consolidated stratum at a depth corresponding to the desired location of said sheet of ice;

(b) extending a fracture from one of said plurality of wells to intersect the remainder of said plurality of wells, said fracture being extended beneath said consolidated strata of (a); and

(c) circulating through said wells and said intersecting fracture of (b) a fluid which is at a sufficiently low temperature to freeze liquid within the formation adjacent said fracture thereby forming a liquid-impervious layer of ice in said formation adjacent said fracture.

5. The method of storing a low temperature liquid in a water-bearing earth formation which comprises:

(a) drilling a plurality of wells into said water-bearing earth formation at spaced intervals around a perimeter to define an enclosed area;

(b) drilling an additional well into said water-bearing earth formation inside the area enclosed by said wells of (a);

(c) initiating and propagating a horizontal fracture in the water-bearing earth formation from said additional well of (b) until said fracture intersects said wells of (a) the plane of said fracture lying within the water-bearing earth formation;

(d) circulating a refrigerating medium whose temperature is less than the freezing point temperature of water present in the earth adjacent said fracture through said fracture between said wells of (a) and (b) to freeze interstitial water within said water-bearing formation into a layer of ice adjacent said fracture and intersecting said plurality of wells of (a) and said well of (b);

(e) circulating a refrigerating medium whose temperature is less than the freezing point temperature of water present in the earth in said wells of (a) to freeze the interstitial water in the earth adjacent these wells and thereby form a wall of ice extending from the surface of the earth to the layer of ice of (d) adjacent said fracture;

(f) excavating at least a portion of the earth inside said wall of ice and above said layer of ice adjacent said fracture to form an earthen cavity open at the top and enclosed on other sides by ice; and

(g) placing said low temperature liquid in said cavity.

6. The method of claim 5 wherein a cover is placed over said cavity to prevent contamination and excessive evaporation of low temperature liquid stored therein.

7. The method of storing a low temperature liquid in a cavity in a water-bearing earth formation which comprises:

(a) drilling a plurality of wells at spaced intervals around a perimeter to define an enclosed area within said water-bearing earth formation;

(b) drilling an additional well in the area enclosed by said wells of (a);

(c) perforating the water-bearing earth-formation adjacent said well of (b) at a level corresponding to the desired location of the bottom of said cavity;

(d) pumping a liquid which sets up to a hardened state into said water-bearing earth-formation via said well of (b) and perforations of (c) to consolidate the earth-formation sufficiently to permit fracturing thereof;

(e) fracturing the water-bearing earth-formation from said well of (b) in said consolidated earth-formation until a fracture intersects said wells of (a);

(f) circulating a refrigerating medium whose temperature is less than the freezing point temperature of water present in said consolidated water-bearing earth-formation through said fracture of (e) between said wells of (a) and (b) to freeze interstitial water thereby forming a layer of ice in the earth-formation adjacent said fracture;

(g) circulating a refrigerating medium whose temperature is less than the freezing point temperature of water present in the earth-formation in said wells of (a) to freeze the interstitial water in the earth-formation adjacent these wells and thereby form a wall of ice extending from the surface of the earth to the layer of ice of (f) adjacent said fracture;

(h) excavating at least a portion of the earth formation inside said wall of ice and above said layer of ice adjacent said fracture to form an earthen cavity open at the top and enclosed on other sides by ice; and

(i) placing said low temperature liquid in said cavity.

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