May 14, 1963 G. M. CLOSS ETAL 3,089,309

SUBTERRANEAN STORAGE OF FLUIDS

Filed March 25, 1960 2 Sheets-Sheet 1

Fig. 1

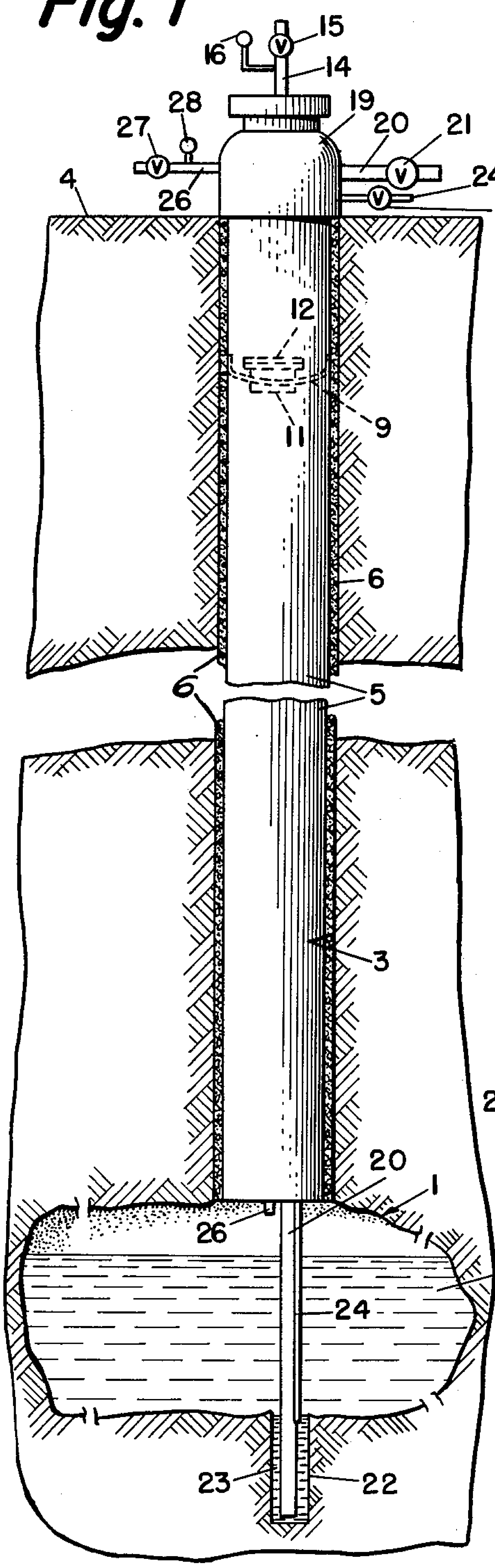
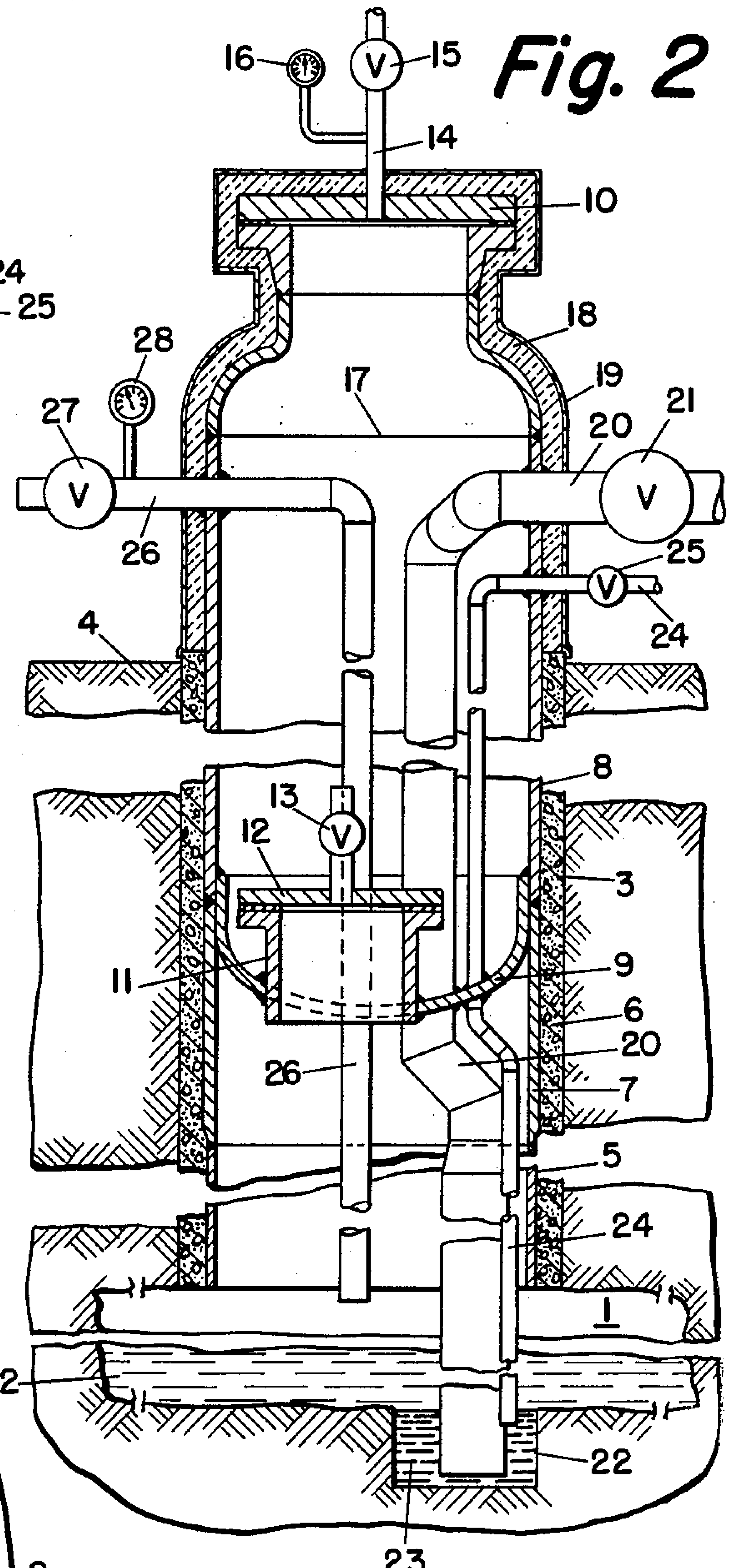


Fig. 2



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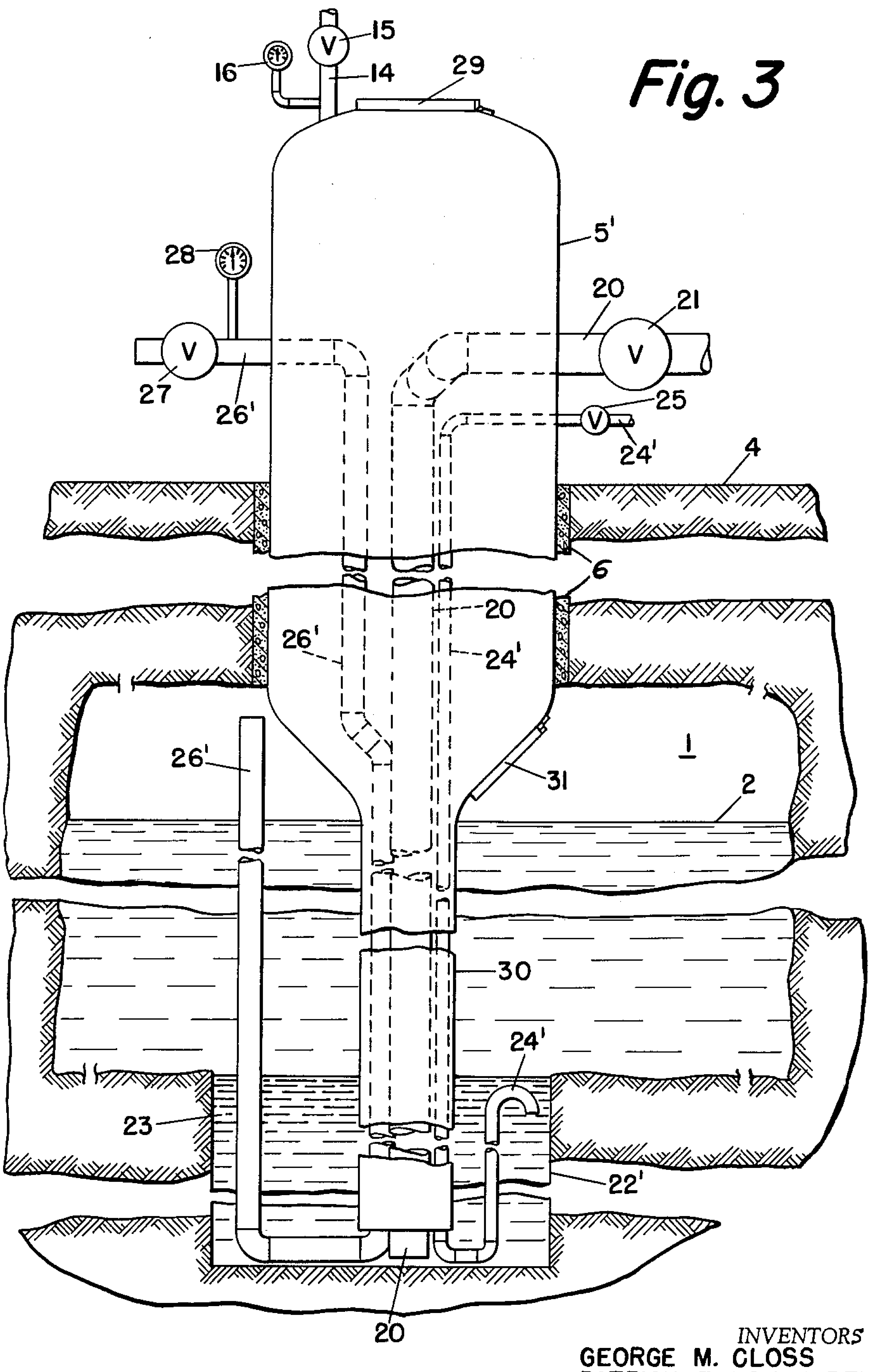

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SUBTERRANEAN STORAGE OF FLUIDS

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This invention relates to the subterranean storage of fluids under pressure, and more particularly to a mined rock cavern arrangement for the storage of such fluids.

Subterranean caverns of the aforesaid type, which may be mined in rock (granite) for example, are constructed by employing for excavation a large-diameter vertically-extending main or working shaft, through which men, materials, and equipment may be lowered to the cavern itself, and through which the rock cuttings may be raised to the surface. By way of example, such a shaft may be about forty-two inches in diameter, and the roof of the cavern (the lower end of the aforesaid shaft) may be on the order of several hundred feet below the surface. To keep this main shaft open, a casing, of forty-two inches I.D. for example, is cemented therein, in much the same way as the casing is cemented in an oil well. This casing is left in the shaft when the cavern is completed, and is used for various purposes (e.g., cavern inspection or maintenance) during the operation of the cavern. One of the main functions of this casing, during cavern operation, is to provide a convenient way for conducting the cavern fill pipe to the cavern; this fill pipe, which may for example be of six inches I.D., extends downwardly through the casing, from the surface of the earth to the interior of the cavern, in a direction substantially parallel to the longitudinal axis of the casing. Suitable valves, pumps, etc. are coupled to the upper end of the fill pipe, for pumping the fluid (which may for example be a liquefied hydrocarbon such as propane or butane) under pressure into the cavern, for storage.

The upper end of the casing may be approximately even with the surface of the earth, for example; the lower end of the casing may be approximately even with the top or roof of the mined rock cavern.

The arrangement described, for the subterranean storage of fluids at superatmospheric pressure, presents several possible fire hazards. In the first place, in the event that a fissure should develop at the top of the casing, the stored pressured fluid from the cavern would be free to gush out through this fissure, giving rise to an extremely dangerous situation from the standpoint of fire, if hydrocarbons are being stored. Additionally, in case the fill line or pipe above the surface of the earth should break, the hydrocarbon stored in the cavern could rush out through this break, resulting in a great fire hazard.

An object of this invention is to provide an improved arrangement for the underground storage of fluids such as hydrocarbons.

Another object is to provide an arrangement for materially reducing the fire hazard in connection with the subterranean (underground) storage of hydrocarbons such as propane.

A further object is to provide an arrangement, for underground storage caverns, which will positively prevent the stored fluid from leaving the cavern in the event that a crack or break should occur at the top of the casing.

A still further object is to provide an arrangement, for underground storage caverns, which will prevent the stored fluid from leaving the cavern in the event that

a break occurs in the fluid fill line, above the surface of the earth.

The objects of this invention are accomplished, briefly, in the following manner. In the preferred embodiment, a substantially cylindrical pressure vessel, on the order of twenty feet in length, is welded in lengthwise position onto the top of the casing utilized with the cavern, the arrangement being such that the lower dished head or closure of this vessel is located about ten feet below the surface of the earth, or "grade." This lower closure seals off the cavern at a point below grade. The cavern fill pipe or line passes down through this pressure vessel and through the casing; this line extends downwardly into a sump provided in the floor of the cavern, beneath the casing. In the sump there is a quantity of a sealing liquid, which would normally be water. The depth from grade to the sump is such that the vertical length of the fill pipe is somewhat in excess of the length of a column of sealing liquid necessary to counterbalance, by hydrostatic pressure, the effective pressure of the stored fluid. In another embodiment, no pressure vessel (and, therefore, no lower dished head) is used with the casing, but instead the large-diameter casing is swaged down to a smaller diameter at a level about even with the cavern roof, and this smaller-diameter portion extends down into the aforementioned sump. In this embodiment, the fill pipe passes down through the casing into the sump, as before.

A detailed description of the invention follows, taken in conjunction with the accompanying drawings, wherein:

FIGURE 1 is a schematic or overall representation of a generally preferred subterranean cavern arrangement according to this invention;

FIGURE 2 is a longitudinal section through the FIGURE 1 arrangement, drawn on an enlarged scale to show details; and

FIGURE 3 is a view somewhat similar to FIGURE 2, but showing a modified arrangement.

Referring first to FIGURE 1, which is a somewhat schematic representation of a completed cavern arrangement, a subterranean mined cavern 1 can serve as a storage container for a fluid 2 under pressure. For purposes of illustration, the cavern will be described as being utilized for the storage under pressure of propane, in a liquid state. However, it is pointed out that it can be used for the storage of other highly volatile liquefied hydrocarbons, such as butane, or the material known as "casinghead gasoline." Also, it can be used for the storage of various other fluids (either liquids or gases), whether or not they are hydrocarbons. The fluid 2 (propane, for example) is stored under superatmospheric pressure in the cavern 1, to allow storage of this material in its liquid state. Propane may be stored in such a cavern, for example, at a pressure on the order of 150 pounds per square inch, absolute. At this pressure, propane has a boiling point of about 84° F., which means that it does not boil at the temperatures ordinarily encountered in subterranean caverns.

In order to mine the cavern 1, a large-diameter main or working shaft 3 (having a diameter on the order of forty-two inches or more) is utilized for the purpose of moving men, materials, equipment, rock cuttings, etc. between the surface of the earth (denoted by "grade" level 4) and the cavern 1 proper. Shaft 3 is several hundred feet in length, and in a typical example may be about 380 feet long. In other words, the distance from grade 4 to the roof of cavern 1 may be about 380 feet. Prior to excavation or mining of the cavern proper, the casing 5 (of forty-two inches I.D., for example) is run into the shaft 3 and is cemented therein, as indicated at 6. The technique here is quite similar to that used for cementing casing strings in oil wells. Thus, the lower end of the casing 5 is located, in FIGURE 1, substantially even with the top or roof of the cavern 1, and this casing is on the order of 380 feet long. The cavern itself may be about forty feet high, from floor to roof. All of the construction so far described is quite conventional.

Now referring to FIGURE 2, the bottom or base cylindrical shell or skirt 7 of a pressure vessel 8 is butt-welded onto the top of casing 5, at a point about thirteen feet below grade 4. This pressure vessel 8 is a prefabricated vessel which has been suitably stress-relieved, and includes a bottom dished head or closure 9, and an upper removable head or closure 10. The main portion of vessel 8 is cylindrical with an I.D. of forty-two inches, tapering down to an I.D. of twenty-three inches at the top, adjacent closure 10. It may be seen, in FIGURE 2, that the bottom closure 9 is permanently sealed to vessel 8 adjacent the skirt 7; also, the vessel 8 is welded in lengthwise position onto the top of the casing 5. The closure 9 is located a distance of ten feet, more or less, below grade 4, and provides a closure which in effect seals off the casing 5 (and the cavern 1) from the interior of pressure vessel 8 and also, of course, from the atmosphere above the surface 4.

The cylindrical outer wall of a manway 11 (having a diameter of sixteen inches, for example) is sealed through the bottom closure 9; the bottom end of this manway opens into the interior of the casing 5 and the top end of this manway is sealed off by means of a removable manhead 12. The manhead 12 is provided with a vent and gate valve (for example, 1½ inches in diameter), which may be opened when desired, for venting purposes. Upon removal of the upper closure 10 and the manhead 12, access may be had, via the manway 11, for inspection and/or maintenance of the cavern. Of course, during use of the cavern 1 for storage of a fluid product 2, the manhead 12 and the upper closure 10 are in sealed position, and the valve 13 is closed.

As previously stated, the bottom closure 9 is sealed to vessel 8; the upper closure 10 is also normally sealed to vessel 8. Therefore, the interior of vessel 8 constitutes a sealed enclosure, sealed off from both the cavern 1 (and casing 5) and the atmosphere. The interior of vessel 8 is pressurized to a small positive (superatmospheric) pressure (on the order of fifty pounds per square inch absolute, for example) with inert gas. This may be done through a small (one inch diameter) pipe 14 which extends through the upper closure 10 and which is provided with a valve 15 on its outer end. The valve 15 may also be used for venting, when access to the cavern is desired. Of course, the valve 15 is closed during use of the cavern for storage purposes. A pressure gauge 16 is coupled to pipe 14, between valve 15 and closure 10, for indicating the pressure in vessel 8. This inert gas filling is used for several reasons. In the first place, it is desirable to have a non-flammable (and of course non-explosive) material at the surface of the earth, above the cavern. In the next place, the use of a small positive pressure of gas here (this pressure being less than that under which the liquid 2 is stored in the cavern), in conjunction with pressure gauge 16, will provide an indication of leaks. If the pressure, as measured by gauge 16, increases or goes up, it means that the material in the cavern is leaking into the pressure vessel 8. If this pressure decreases or goes down, it means that the vessel 8 itself is leaking.

The upper end of the vessel 8 projects above the grade or ground level 4. For example, the vertical distance between grade 4 and the upper welded seam 17 of the cylindrical portion of vessel 8 may be about three feet. The lower portion of vessel 8, from the lower end of skirt 7 to a point slightly above ground level 4, is cemented into the earth. The entire upper portion of this vessel, including the upper closure 10 is covered or lagged with an outer coating of heat-insulating material 18, and over the top of this there is a sheet metal jacket 19. As previously stated, the upper closure 10 is sealed (by any suitable well-known fastening means, not shown) to vessel 8, but is capable of being removed therefrom when desired.

In prior constructions, a portion of the casing necessarily projected or extended above the ground level, to accommodate various pipes and valves. With such constructions, if a fissure should happen to develop at the top of the casing, above the ground level, propane from the cavern (stored under superatmospheric pressure therein) would gush through this fissure, creating a very dangerous situation from the standpoint of fire. In contrast, the arrangement of the present invention entirely eliminates this possibility. It may be seen that the present construction employs a sealed closure 9 below ground level. Thus, even if a fissure should develop above ground level 4 anywhere in vessel 8 (including the upper closure 10), the bottom closure 9 seals off the cavern 1 from the fissure, so that no propane (or other liquefied hydrocarbon being stored) can escape through such fissure. The only thing that could escape under these conditions would be the inert gas contained in vessel 8, and this is of course harmless.

A fill line or fill pipe 20 (I.D. of six inches, for example), having a suitable valve 21 on its outer or upper end, is sealed through the cylindrical wall of pressure vessel 8, above the ground level 4, and passes downwardly through this vessel. This fill pipe is sealed through the bottom closure 9 and extends down into a sump 22 provided in the floor of cavern 1, beneath the lower end of casing 5. The lower end of pipe 20 is spaced slightly above the bottom of the sump. Sump 22 may be about twenty feet deep below the floor of cavern 1, and the volume of this sump is approximately 1.5 times the internal volume of the fill pipe 20, from the lower end thereof up to valve 21 above the ground level 4.

Sump 22 permanently contains a suitable sealing liquid 23, which is normally water. The characteristics which the sealing liquid 23 must have are: a specific gravity greater than that of the stored fluid, insolubility in this fluid, and immiscibility with this fluid. Water has these characteristics when the fluid is a hydrocarbon such as propane, and is desirable because it is inexpensive. The use of water as the sealing liquid in the sump would be appropriate for any cavern in which water does not affect the environmental rock structure, such as caverns mined out of granite or sandstone. However, for caverns which are mined out of shale beds, it would be necessary to use a non-aqueous hydrocarbon-insoluble liquid instead of water, since the latter would cause shale to turn into mud. Glycerine and mercury are examples of suitable non-aqueous hydrocarbon-insoluble liquids which could be used in such an environment.

When it is desired to add fluid to the cavern 1, valve 21 is opened, and the fluid is pumped, under superatmospheric pressure, through fill pipe 20 into the sump 22, from whence it flows through the water, or other sealing liquid 23 in the sump, upwardly into the cavern 1.

The fluid stored under pressure in the cavern 1 is removed or abstracted therefrom, as desired for use, in any suitable manner known in the art. For example, two deep-well pumps may be utilized, each pump being positioned in a respective sump (not shown) extending downwardly from the floor of the cavern. These pump sumps are spaced sideways or laterally from the main shaft 3. Each pump is driven by a rotating shaft from a respective source of power (e.g., a motor) at the surface. The pumps are suspended within respective outer casings by respective discharge tubings. The pump intakes are located in the respective pump sumps, and the pumps pump fluid from these sumps through the respective discharge tubings to the surface. For a more complete disclosure of such a cavern discharge arrangement, reference may be had to the copending application Serial No. 44,158, filed July 20, 1960. If two pump sumps are utilized, two small water pipes (three inches in diameter, for example; not shown herein) may be sealed through the cylindrical wall of vessel **8**, these pipes passing downwardly through this vessel and through bottom closure **9** and proceeding down to the floor of the cavern, from whence they fan out to the respective sumps wherein are located the aforementioned discharge pumps. These last-mentioned water pipes provide a safety feature, in case the pump casings should break or crack above ground. If this occurs, water can be rapidly pumped (by a low-pressure pump) through the appropriate pipe down into the proper sump and up into the pump casing until the hydrostatic pressure in the sump and casing exceeds the vapor pressure of the hydrocarbon product in storage in the cavern, creating a water seal. Once the seal is created (and this can be effected quite rapidly), the stored hydrocarbon cannot escape, it being retained in the cavern. Substantial fire hazard, and substantial loss of valuable product, are thus prevented. These water pipes also function to enable repair and inspection of the deep-well pumps, as described in the aforementioned copending application.

If only a conventional fill pipe (without the sump and the sealing liquid) were used with the cavern, in case the fill pipe should break or crack above ground, or if the valve **21** should leak, the fluid (e.g., hydrocarbon) stored in the cavern would rush out (since it is stored under superatmospheric pressure) through the break, creating a great fire hazard. However, the arrangement of this invention eliminates entirely this possibility. If the fill pipe **20** should break above ground **4**, or even if the valve **21** should leak the water (or other sealing liquid **23**) maintained permanently in the sump **22** would rise in the fill line **20** (under the influence of the pressured fluid (hydrocarbon)) in the cavern until it reached a level or height at which its hydrostatic head (plus, of course, atmospheric pressure exerted on the upper face of this sealing liquid, since the upper end of pipe **20** would then be open to the atmosphere, by way of the aforementioned break) would counterbalance the pressure of the hydrocarbon **2**. Since this last-mentioned level at which the aforesaid balance occurs is considerably below ground level **4** (as will later be explained), by way of a numerical example), no hydrocarbon can escape from the cavern by way of the broken or cracked fill pipe. The pressure of the stored hydrocarbon is insufficient to overcome the hydrostatic pressure exerted on it, and it is therefore retained in the cavern. Thus, there is no fire hazard, and no loss of valuable product.

Assuming a pressure in the cavern of 150 pounds per square inch absolute (equivalent to 135.3 pounds per square inch gauge), and assuming water is the sealing liquid, a hydrostatic head of about

$$\frac{135.3\times 32}{14.7}$$

or about 295 feet, would be needed to balance the pressure of the hydrocarbon in the cavern. This height of water is considerably less than the 380 feet or more (actually, about 440 feet) or length (below ground level **4**) provided in pipe **20**. Of course, if higher-specific-gravity liquids such as glycerine or mercury were utilized as the sealing liquid, the hydrostatic head required for balance would be even less than about 295 feet.

A small-diameter pipe or line **24** (one inch in diameter, for example) having a valve **25** on its outer or upper end, is sealed through the cylindrical wall of pressure vessel **8**, above the ground level **4**, and passes downwardly through this vessel. Pipe **24** is sealed through

the bottom closure **9** and extends down into the sump **22** but terminates at a known, predetermined level which is above the bottom end of fill pipe **20**. This predetermined level of the lower end of line **24** (relative to the bottom of sump **22**, for example) is so adjusted that when the level of sealing liquid in sump **22** is at least as high as the lower end of this line, there will be sufficient sealing liquid in the sump to perform the above-described function of balancing the pressure of the hydrocarbon (by means of hydrostatic head), in case the cavern fill line breaks. Therefore, the small line **24** can be used as a gauge line, for determining whether or not sufficient sealing liquid **23** is present in the sump **22**. During normal cavern operation, of course, valve **25** would be closed. However, when it is desired to ascertain whether sufficient liquid is present in the sump, valve **25** is opened. Let us assume that the cavern contains liquefied hydrocarbon as illustrated in the drawings. If the hydrocarbon product issues from the valve **25** when the latter is opened, it means that the level of sealing liquid is below the lower end of line **24** (such lower end then contacting the hydrocarbon); there is then insufficient sealing liquid in the sump. If no liquid issues from valve **25** when the same is opened, it means that there is sufficient sealing liquid in the sump. In this latter case, the action is similar to that occurring when a break develops in the fill line; water then raises in the gauge line **24** until it reaches a level at which its hydrostatic head balances the pressure of the hydrocarbon, and since this latter level is below the ground level **4**, nothing (except possibly gas or vapor) emerges from line **24**.

A small-diameter pipe or line **26** (three inches in diameter, for example), having a valve **27** on its outer or upper end, is sealed through the cylindrical wall of pressure vessel **8**, above ground **4**, and passes downwardly through this vessel. Pipe **26** is sealed through the bottom closure **9** and extends down into the cavern **1**, terminating about six inches beneath the roof thereof. A pressure gauge **28** is coupled to line **26**, between valve **27** and vessel **8**, for indicating the pressure in the cavern. Line **26**, in addition to its pressure-indicating function, serves as a vent line (when the cavern is being filled), and also as a gauge tube, to indicate the maximum filling point of the cavern (when hydrocarbon begins to issue from line **26**, valve **27** then being open, it is known that the cavern is full). In addition, line **26** may be used in conjunction with line **24** to determine the liquid level in the cavern.

The pressure equalizing line **26** has, of necessity, no safety feature such as that associated with the fill pipe **20**. However, even if a fissure should develop above ground level in vessel **8**, it is unlikely that pipe **26** would also break. On the other hand, if it is expected that pipe **26** might break, certain well-known design expedients could be resorted to, for reducing the possibility of breakage. One of these might be to run pipe **26** out of the vessel **8** below ground level, to encase it in concrete, and to carry it underground for several feet before it connects with other surface piping.

Although not shown in the drawings, it is desirable that all of the pipe connections to the cavern be provided with check valves.

Although not strictly necessary for sealing purposes, it is desirable that an upper closure **10** be utilized, to keep rain, debris, etc. out of the space above bottom closure **9**; also, of course, the upper closure prevents personnel from falling down into this space. Actually, the utilization of the upper closure **10** (or of a complete pressure vessel **8**, as described) allows for an inert gas filling above the cavern and casing, which is desirable. Also (and this should be obvious), the use of two separate closures **9** and **10** gives double the protection against leaks.

Although the upper closure 10 has been illustrated as being above ground or grade, this is not absolutely necessary. This closure could be below grade if desired, in which case the upper closure 10 could be covered with a pool of water, as an added safety measure.

FIGURE 3 is a view generally similar to FIGURE 2, but illustrating a modified construction. In FIGURE 3, parts the same as those previously described are denoted by the same reference numerals, while analogous parts are denoted by the same numerals, but primed. In this modified construction, no pressure vessel is secured to the casing, and therefore no bottom closure is employed, and no inert gas filling is utilized. Instead, the hydrostatic head of a sealing liquid is used to counterbalance the effective pressure of the stored hydrocarbon, when a crack occurs at the top of the casing, above ground level. This modified embodiment will now be described in more detail.

In FIGURE 3, the casing 5′ (forty-two inches I.D.) is cemented in the main shaft like casing 5, but casing 5′ is extended up above ground level 4, and is sealed off with an upper closure in which there is sealed a manway or manhead 29 with a sealed but removable cover. A vent pipe 14 is sealed through the casing cover and is provided with a valve 15, for enabling venting before access to the cavern is effected. In this case, the pressure gauge 16 is not strictly necessary, though it may be employed if desired.

The casing 5′ is swaged down to a smaller diameter (twenty inches I.D., for example) at a level approximately even with the bottom end of the main shaft. From this point, the smaller-diameter portion 30 of the casing extends downwardly into sump 22′ (provided, like sump 22, in the floor of the cavern, below the lower end of the main shaft), terminating near the bottom of the sump. The sump 22′ must be considerably larger than the sump 22, since the former must contain enough sealing liquid to provide a hydrostatic-head type seal in the large-diameter casing 5′, as well as in the reduced-diameter portion 30 of the casing.

In the FIGURE 3 arrangement, if a crack or fissure occurred at the top of casing 5′ anywhere above ground level 4 (thus opening the upper end of casing 5′ to the atmosphere), the sealing liquid 23 would be forced up the smaller-diameter portion 30 of the casing (and on up into the larger-diameter portion thereof, as well), rising to a level or height at which its hydrostatic head (plus the atmospheric pressure) would counterbalance the pressure of the hydrocarbon 2. This last-mentioned level is considerably below ground level 4. Therefore, no hydrocarbon can escape from the cavern by way of the casing crack or fissure.

In FIGURE 3, the fill line or fill pipe 20 is sealed through the side wall of casing 5′, and extends down through this casing and through the reduced-diameter casing portion 30 into sump 22′, terminating near the bottom of the sump, as in FIGURE 2. In the event of a crack or break in the fill line 20 above ground, the sealing liquid 23 rises in this line in the same manner as in FIGURE 2, until the hydrostatic head counterbalances the pressure of the hydrocarbon 2. Again, no hydrocarbon can escape from the cavern 1 by way of the broken or cracked fill line.

In FIGURE 3, the gauge line 24′ is sealed through the side wall of casing 5′, and extends down through this casing and through the reduced-diameter casing portion 30 to the lower end of this casing portion, at which point line 24′ makes a reentrant turn to proceed upwardly to its termination in sump 22′ at a known, predetermined level above the bottom end of fill pipe 20. Line 24′ is used as is line 24 in FIGURE 2, for determining whether or not sufficient sealing liquid 23 is present in the sump 22′. In FIGURE 3, it must be determined (by means of this gauge line) whether or not sufficient sealing liquid is present for the two types of hydrostatic-head seals involved in FIGURE 3.

In the modified construction, the vent and gauge line 26′ is sealed through the side wall of casing 5′ and extends down through this casing and through the reduced-diameter casing portion 30 to the lower end of this casing portion, at which point line 26′ makes a reentrant turn to proceed upwardly to its termination, about six inches beneath the roof of the cavern 1. Line 26′ serves the same purposes, and operates in the same way, as does line 26 in FIGURE 2.

A manhead or manway 31 is sealed into the transition section between the large-diameter casing 5′ and the smaller-diameter casing portion 30, this manway having a sealed but removable cover. Preferably, a vent and gate valve (not shown) are provided in the latter cover, similar to the valve 13 in FIGURE 2. Upon removal of the covers on manways 29 and 31, access may be had, via these two manways, for inspection and/or maintenance of the cavern. Of course, during use of the cavern 1 for storage, the covers on these manways would be closed and sealed.

The invention claimed is:

1. In a subterranean cavern for storing a fluid at superatmospheric pressure, said cavern having a communicating shaft extending from the surface of the earth downwardly to the cavern: a casing sealed in said shaft, a closure sealed into said casing at a point below the surface of the earth, a sump extending downwardly from the floor of said cavern, a quantity of a sealing liquid maintained permanently in said sump, said sealing liquid being immiscible with a fluid stored in said cavern and having a higher specific gravity than such stored fluid; a fill pipe for said stored fluid sealed into said casing, extending downwardly therein, sealed through said closure, and extending through said stored fluid and opening into solely the sealing liquid in said sump; and another closure sealed to the upper end of said casing, above the surface of the earth.

2. In a subterranean cavern for storing a liquid at superatmospheric presure, means providing a seal between a liquid hydrocarbon stored in said cavern and the atomsphere, a sump extending dowardly from the floor of said cavern, a quantity of water maintained permanently in said sump, and a cavern fill pipe through which only the stored liquid hydrocarbon flows into said cavern, said pipe extending from the surface of the earth vertically downwardly through said seal and through said stored liquid hydrocarbon, and opening into solely the water in said sump, the volume of said sump being at least 1.5 times the internal volume of said fill pipe, from the lower end thereof to the surface of the earth, and the vertical length of said fill pipe being in excess of the length of the column of water necessary to counterbalance, by hydrostatic pressure, the effective presure of the stored liquid hydrocarbon.

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