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CAVERN STORAGE FOR NATURAL GAS

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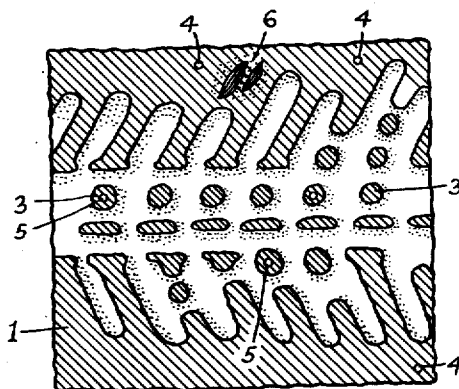
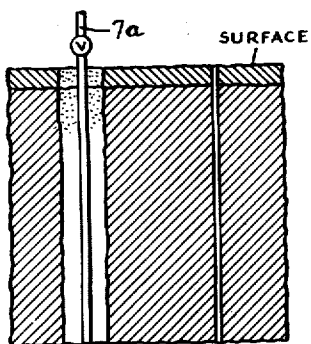


FIG. 2.

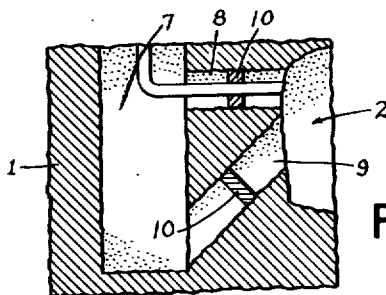


FIG. 3.

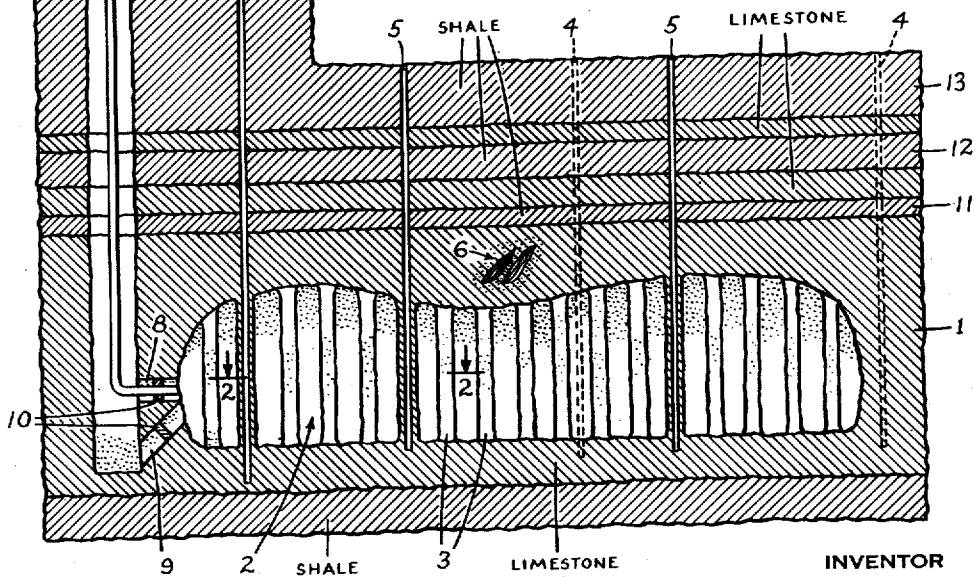


FIG. 1.

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1

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CAVERN STORAGE FOR NATURAL GAS

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6 Claims. (Cl. 61—5)

The present invention relates to methods for locating suitable sites for, and the construction of caverns for the storage of gaseous fuels such as, for example, natural gas, and to man-made caverns for the storage thereof.

The use of natural gas for heating and other purposes in locations remote from sources thereof is commonplace, and pipe lines by means of which natural gas is conveyed from such sources are now utilized to furnish such gas to relatively remote regions, such as Gulf Coast gas to the eastern seaboard and the Chicago region. Industrial and other demands for natural gas in other remote regions has, for quite sometime, occupied the serious attention of many engineers skilled in the art of gas storage and its distribution.

Where natural gas is directed for great distances through pipe lines, the heavy investment in the pipe line facilities requires, from the standpoint of sound economics, that substantially the full capacity of the line be constantly used. Inasmuch as the demand for gas in the wintertime averages four times that of the summertime, it would be prohibitively expensive to build the pipe line of a capacity sufficient to satisfy the wintertime demand and then permit the excess facilities to remain idle during the summertime. The economic utilization of natural gas at points remote from its source thus requires that storage facilities be provided whereby, in periods of sustained offpeak load (for example, in the summertime), the gas can be stored so that it is available during the wintertime to supplement the supply of gas available from the pipe line.

The accumulation of substantial quantities of gas in tanks, reservoirs, or other facilities is a difficult and serious problem in view of the vast volume of gas required to be stored in such reserve facilities and the great cost of and area occupied by such tanks and reservoirs.

In the broad problem of dealing with excess gas, it is common practice, in the older gas fields, to draw off excess gas from newer and more remote sources and direct it into existing depleted gas and oil wells and strata in order that it may be subsequently drawn therefrom when and as needed. These reserve wells and fields in which the excess gas is stored are in the general vicinity of the older markets or form of distribution of the natural gas, and thus do not offer a solution to the problem above mentioned where the gas is consumed in regions remote from such old gas fields. Moreover, the extent to which natural formations may be used varies in accordance with the natural characteristics of such formations. The permeabilities of the sands and formations comprising these gas and oil wells often limits very greatly the rate at which the gas may be drawn therefrom. Also, these natural formations frequently permit of only limited maximum and minimum pressures above which loss of gas may occur and below which objectionable inflow of water occurs.

It might also be mentioned that, in the art of mining, it is common practice to seal off one or more galleries or portions of a mine and use such portion or portions as

2

a reservoir within which air under pressure is stored for use in the mining operations. These operations utilize are under relatively low pressures and generally speaking, have involved spaces where high resistance to air leakage through the rock is not of vital importance.

In accordance with the present invention, it is proposed to provide methods by which man-made caverns may be located and constructed as well as means by which natural gas from a pipe line may be stored or accumulated at a location remote from the original sources of natural gas and adjacent the points of distribution thereof to the ultimate consumers, and an object of the present invention is to provide methods and apparatus of the above character whereby the reserve requirements of a distribution system may be satisfied with storage facilities which may be produced at relatively low cost in a small area with compressor apparatus of relatively low capacity as compared with other means of storing like volumes of gas.

The preparation and use of artificial caverns overcomes one of the most difficult problems of gas storage. For large cities, the gas storage requirements may be in the order of 20 to 30 billion cubic feet of gas at pressures of several hundred pounds per square inch gauge. The cost of above-the-ground storage tanks for such a gas volume and pressure would be enormous and, of course, the space occupied by such tanks would run into thousands of acres. This land would have no other utility and, moreover, would make the land around it undesirable or residential or business purposes, to say nothing of the very substantial hazard involved.

In accordance with the present invention, it is proposed to provide artificial caverns for storage of the gas, thus not affecting the surrounding countryside in appearance or utility, inasmuch as such caverns are far below the surface of the earth in naturally occurring masses or strata of rock, mineral aggregate or other geological formations suitable, under all the circumstances, to retain the gas without leakage therefrom. Any and all such formations will be referred to hereinafter as "strata." Such strata are selected, in accordance with this invention, to have strength and low permeability sufficient to withstand high gas pressures without appreciable leakage. From an economic standpoint, the selection of a suitable stratum, such, as for example, as, but not limited to, limestone, makes possible the production of caverns at relatively low overall cost. The rock (limestone or other material) removed by mining has a sufficiently high commercial value to offset to a large degree the cost of even deep rock mining operations.

It is essential to the present invention that the aforesaid cavern storage facilities have the property of low permeability, that is, high resistance to gas migration. In practice, such facilities would be in the form of a plurality of relatively adjacent caverns with compressor facilities and connections which permit the caverns to be charged with gas from the supply line when the load requirements fall below the available supply of gas from the supply line, and to permit the gas to be delivered from the respective caverns either under the pressure existing in such caverns or by means of the compressor facilities which draw gas from one or more of the caverns and supply it to the distribution system.

In order that the invention may be explained more fully and its advantages understood, the manner in which such cavern storage facilities may be explored or located, and then constructed will be explained with reference to the accompanying drawing, wherein the single figure is a view in somewhat diagrammatic form, showing in perspective a suitable cavern storage unit that has been made in a location that has been selected in accordance with the present invention.

At the outset it is to be observed that, other considerations being equal, it is important that the storage caverns should be located adjacent the gas distribution area in the territory to be serviced by the natural gas pipe line. The distance of the storage caverns from such a territory will depend, of course, upon available geological formations and the economics of moving the gas from the supply pipe lines to such storage facilities and to the area to be serviced.

Starting with known geological data and known methods and procedures for exploring and logging sub-surface strata, sufficiently full information of such strata or formations is obtained. The essential basic requirements of a suitable storage site include the following. The site should contain a thick stratum, massive rock, or other suitable formation having a relatively low permeability (that is, high resistance to gas migration). In practice, it is desirable to utilize formations having a permeability averaging below 0.001 millidarcy (this inherent characteristic of the formation is generally termed "primary permeability"). Minor portions of the formation may have zones of higher average permeabilities, and such formations need not necessarily be rejected because they contain, in certain portions thereof, such features as faults, fractures, or joints (generally termed "secondary permeability" features), and where such secondary permeability features exist, corrective measures must be taken as hereinafter described.

A second basic requirement is that the formation should occur at a sufficient depth below the surface to permit relatively high storage pressures.

A third important feature that should be possessed by the formation is that, if secondary permeability features exist, they should be sufficiently spaced so as to allow excavation of storage units having their outer walls a safe distance from these features.

Yet another important factor is that the material of the stratum to be excavated should have an economic value such that its sale as a commercial commodity will enable at least a part of the cost of the construction of the storage cavern to be defrayed.

Yet another important factor is that the material of the formation should be such as to afford a sufficiently strong roof rock and the rock or material of the storage horizon should have favorable physical characteristics to allow for the safe design of the caverns or storage units.

With the foregoing factors in mind, it is important adequately to sample the stratum in the storage site area so as to insure that the necessary combinations of features is available to allow for the desired high pressure cavern storage. As mentioned above, known techniques for exploring and logging sub-surface formations are utilized, and the drilling of bore holes is accomplished in such fashion as to enable cores to be obtained in as near their original state as possible.

A study of these cores, together with other information obtained by the techniques above referred to, enables the physical characteristics of the rock column overlying the storage horizon to be determined. Thus the strength, weight, permeability and the existence of secondary permeability features may be determined. In addition, inspection of the cores affords information as to the physical characteristics of the material of the stratum. These core samples may be tested for permeability, flexural strength, compression and shearing stress, and modulus of elasticity. This information enables the proper layout of the storage units to be made, as well as the determination of limitations upon size of pillars and openings and the general suitability of the horizon for the storage of natural gas under high pressures. The drill holes also furnish information as to the existence of underground water conditions, both above and below the storage horizon, and known electrical logging techniques of the bore holes will furnish additional information as to primary and secondary permeability features

of the sub-surface rocks, all in accordance with known procedures.

With the foregoing information in mind, the plan of the storage cavern is designed so that the openings formed by the mining operation are suitably spaced from the bore holes that have been made in the exploration above described, as well as from regions of secondary permeability that have been located by the exploring techniques above mentioned. In other words, the regions of these bore holes and secondary permeabilities forms the center of pillars about which the cavern opening exists after the mining operation is completed.

In the mining operation the material of the formation to be mined is removed in such fashion that the roof spans of the underground openings will be so shaped that these openings will remain stable and will permit of no spalling of the rock. Moreover, the openings will be formed so that the tension effect around the openings will be very limited in extent. The mining operation is further carried out in such fashion that a doming effect or subsidence as a result of such openings is avoided. It is also important that the barrier pillars be designed, with relation to the permeability of the material, and with respect to the thickness of such pillars, so as not to permit serious or objectionable diffusion of the gas from a storage unit that has been filled with the gas, and while a new unit is being mined in the same general area.

In this connection, it is to be observed that, depending upon the permeability of the material surrounding the cavern, there will be some diffusion of the gas in such material, the diffusion gradient sloping more or less steeply in accordance with the permeability of the material to a point at which the diffusion is substantially zero for a given pressure of gas. If the cavern opening is spaced within the material of the stratum sufficiently far, there will be no diffusion of the gas beyond the stratum, and thus there will be a satisfactory sealing of the gas therein.

In order that the invention may be more fully understood, it will now be described in connection with the accompanying drawing, wherein:

Figure 1 is a view in vertical section illustrating schematically the cavern formed in accordance with the present invention;

Figure 2 is a view in section taken on line 2—2 of Figure 1; and

Figure 3 is a view in vertical section through a portion of Figure 1 showing the plugs and pipe connections with the cavern.

With reference to the single figure of the drawing hereinabove referred to, a typical cavern for the storage of gaseous fuels, in accordance with the present invention, is illustrated as being formed within a suitable stratum 1 which may, for example, be a stratum of limestone. The cavern is illustrated generally at 2, the opening of the cavern being wholly within the stratum 1 and being formed with pillars 3 that have been designed and formed as hereinabove described. Spaced at suitably remote points about the perimeter of the property under which the cavern is formed are observation holes 4 by means of which diffusion of gas from the cavern 2 may be detected. For purposes of illustration, bore holes 5 (diamond drill holes, for example) are illustrated as existing within certain of the pillars 3 (as well as in other locations), the sides of the pillars being located sufficiently far from the bore holes to prevent diffusion of gas into the bore holes in accordance with the principles hereinabove stated. Also, for purposes of illustration, a region of secondary permeability is indicated at 6 as existing within a portion of the stratum 1. The excavation forming the opening of the cavern 2 will be seen to stop sufficiently far from the region 6 to prevent the diffusion of gas from the cavern opening into the region 6. In this connection the extent of gas diffusion will vary with several factors, such, for example, as the permeability of the material of the stratum, distance from the point of secondary permeability

5

to the cavern, pressures, etc. For example, gas diffusion along a cavern wall having 1,000 square feet of surface and subjected to 900 pounds per square inch gauge and through a barrier pillar 400 feet thick, would amount to only 4.6 cubic feet per day, provided the opposite side of the pillar were exposed to atmospheric pressure, and assuming a primary permeability of 3.5×10^{-4} millidarcies. By increasing the thickness to 1,000 feet the diffusion rate drops to 2 cubic feet per day. Both of the above rates are negligible. If, in the above circumstances, the ground is saturated beyond the pillar, then the hydrostatic head will afford a back pressure which will limit or reduce the diffusion even more, even to the extent of an approach to zero.

A shaft 7 extends from the surface of the earth down into the region of the stratum 1 wherein the cavern 2 is located, and is connected by suitable excavations 8 and 9 to the cavern 2. Plugs 10 are provided in the excavations 8 and 9 and suitable pipe connections 7a are provided in the plugs to permit gas to be charged into and withdrawn from the cavern 2. At the surface of the earth, the pipe connection 7a is provided with suitable valves and other mechanism to enable the flow of gas to and from the cavern to be suitably controlled.

In the drawing several layers of shale 11, 12, and 13 are illustrated. These strata, if of impervious shale, serve as an excellent barrier against diffusion of the gas from the cavern in the event of the existence of regions of secondary permeability that have not been located in the exploratory operations hereinabove mentioned. The size, and therefore, the capacity of the cavern 2 is determined by the nature of the service in connection with which the cavern is to be utilized provided, however, that the cavern is always located well within the outer limits of the stratum.

In designing the cavern storage development to accomplish the results hereinabove described, it is necessary to consider that the maximum stress is compression stress in the pillars and side walls due to the removal of the support that the excavated material had previously provided. The intensity and penetration of such stress is a function of depth and of density and of elasticity of the material. With high modulus of elasticity, the added stress is high, and the penetration small.

It must also be kept in mind that minimum stress results from the relief due to the existence of internal gas pressures when the cavern is charged with gas and thus the added stress due to the excavation is reduced in the proportion of the gas pressure to the pressure corresponding to the depth and density of the overburden.

Internal pressures even approaching the rock depth-density pressure will not result in wall cracks unless the initial stresses without pressure approach the stress limit of the rock, when failure may come through repeated stresses.

With the foregoing in mind, the mining operation will result in the development of openings having great stability over long periods of time, such openings being capable of resisting repeated stress variations without resulting leakage. The mining operations thus are quite different from conventional mining methods where the object is the maximum recovery of material and to accomplish such object, the roof spans and pillars are planned with this characteristic. In the formation of caverns for storage of gas, the limitations on size of mine openings, area to be undercut, and arrangement of pillars are very much more rigid than in conventional mining procedures. Moreover, barrier pillars must be provided and so designed as to prevent leakage, whereas in conventional mining operations, the operations may proceed up to property boundary lines.

To more fully realize the present invention, a plurality of caverns, formed as hereinabove described, may be provided in relatively adjacent relationship. For example, to conserve compressor capacity, one or more low

6

pressure caverns may be provided, each formed as hereinabove described, and in addition there would be provided at least one cavern which could be utilized as a high pressure cavern, also formed as hereinabove described, suitable connections between the caverns and with the supply pipe line and distribution system being provided. In this fashion operation of the system can be accomplished by maintaining the pressure in the last named cavern relatively high to serve during peak load periods. Inasmuch as gas can be pumped from the low to the high pressure caverns, suction pressures can be relatively high, thus permitting the use of compressor equipment of relatively low capacity. A further advantage lies in the fact that pumping can be done in advance of the time when its effect is needed inasmuch as gas can be pumped from the low to high pressure caverns during off-peak load periods, to be used later in the periods when peak load conditions exist.

Multiple caverns may also be utilized to advantage where permeabilities are such as to limit the extent to which pressures may otherwise be permitted in the stratum in which the caverns are formed. For example, where such permeabilities exist, the high pressure cavern may be provided centrally of one or more low pressure caverns, thus reducing the pressure differentials between barrier points to permissible limits while obtaining the above mentioned advantages of multiple cavern operation.

Suitable cavern storage facilities can be provided in strata at a depth of from 400 to 4000 feet, the advantages and disadvantages of greater depth being obvious. As above mentioned, cavern storage facilities, in accordance with the present invention, afford underground storage pressures that can be made to exceed the hydrostatic head which, heretofore, has been the limitation on natural underground storage. These pressures are dependent upon the rock column and the stress characteristics of the overlying rock. Moreover, the above mentioned cavern storage permits of the storage of much larger quantities of gas under conditions not only of higher pressure, but of greater fluctuation in pressures that heretofore have been possible. The storage facilities provided by the present invention, being subterranean, do not occupy space above ground and thus permit of substantial economies in that respect as well as the inherent economies resulting from the subterranean storage. The continued development of cavern storage facilities in a given location is thus possible in keeping with the increased load requirements that develop from year to year. Finally, storage of gaseous fuels in the cavern facilities provided in accordance with the present invention may be accomplished under such conditions as to permit of rapid unloading or discharging of the stored gas during periods of peak demand, thus adding greatly to the flexibility of operation over that of existing facilities.

While the invention has been described with specific reference to the accompanying drawing, it is not to be limited save as defined in the appended claims.

I claim:

1. A cavern for the storage of gaseous fuels under substantial pressures, comprising an excavated cavern of a desired capacity formed in a rock stratum of sufficiently low permeability to prevent substantial gas migration therethrough and at a level at least 400 feet below the surface of the earth, said cavern having supporting columns of said rock between its floor and roof, said columns enclosing and isolating the cavern from exploratory boreholes for locating said stratum and connections for introducing natural gas therein and withdrawing it therefrom.

2. A cavern for the storage of gaseous fuels under substantial pressures, comprising an excavated cavern of a desired capacity formed in a rock stratum of a permeability below 0.001 millidarcy, and at a level at least 400 feet below the surface of the earth, said cavern having

7

supporting columns of said rock between its floor and roof, said columns enclosing and isolating the cavern from exploratory boreholes for locating said stratum and connections for introducing natural gas thereinto and withdrawing it therefrom.

3. A cavern for the storage of gaseous fuels under substantial pressures, comprising an excavated cavern of a desired capacity formed in a massive limestone stratum at a level at least 400 feet below the surface of the earth, said cavern having supporting columns of said rock between its floor and roof, said columns enclosing and isolating the cavern from exploratory boreholes for locating said stratum and connections for introducing natural gas thereinto and withdrawing it therefrom.

4. A method of producing a cavern for the storage of gaseous fuels under high pressure, comprising exploring a desired area by known geological procedures including the formation of a plurality of bore holes to locate a stratum below the surface of the earth having a permeability of less than 0.001 millidarcy and to locate regions of secondary permeability in said stratum, sinking a shaft to said stratum, removing portions of the stratum spaced from the bore holes to form a cavern of a desired capacity having pillars containing said bore holes isolating said cavern from said bore holes and barrier walls isolating regions of secondary permeability to render said cavern substantially gas tight at high gas storage pressures.

5. A method of producing a cavern for the storage of gaseous fuels, comprising exploring a desired area by known geological procedures including the formation of a plurality of bore holes to locate a stratum having low permeability below the surface of the earth and to locate regions of secondary permeability in the said stratum, sinking a shaft to said stratum, and removing portions of the stratum spaced from the bore holes and regions of secondary permeability to form a cavern of a desired capacity containing substantially impermeable pillars surrounding said bore holes and substantially impermeable barriers between said cavern and said regions of secondary permeability to isolate the bore holes and regions of sec-

8

ondary permeability from said cavern thereby to render said cavern suitable for the storage of gas under high pressure.

6. A method of producing a cavern for the storage of gaseous fuels, comprising selecting by means of known geological procedures, including the formation of a plurality of bore holes, a stratum of rock of a permeability sufficiently low to prevent substantial gas migration and at a level at least 400 feet below the surface of the earth, exploring said stratum to locate regions having secondary permeability features permitting gas migration, sinking a shaft to said rock stratum, removing rock therefrom to form a storage cavern of a desired capacity, said rock being removed only from regions spaced from said bore holes and said secondary permeability features to form pillars enclosing and isolating said bore holes and barriers, isolating said secondary permeability features from said cavern.

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