

[54] STORAGE OF GAS IN UNDERGROUND EXCAVATION

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[51] Int. Cl. **F25d 23/12**

[58] Field of Search **61/5; 137/236; 62/260, 62/54; 165/45**

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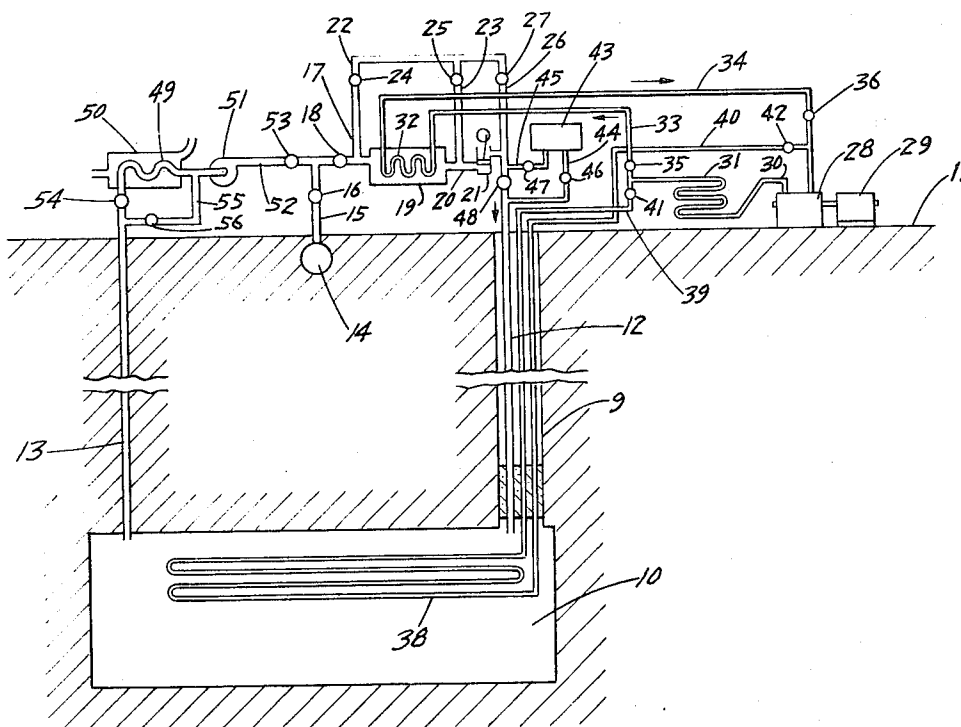
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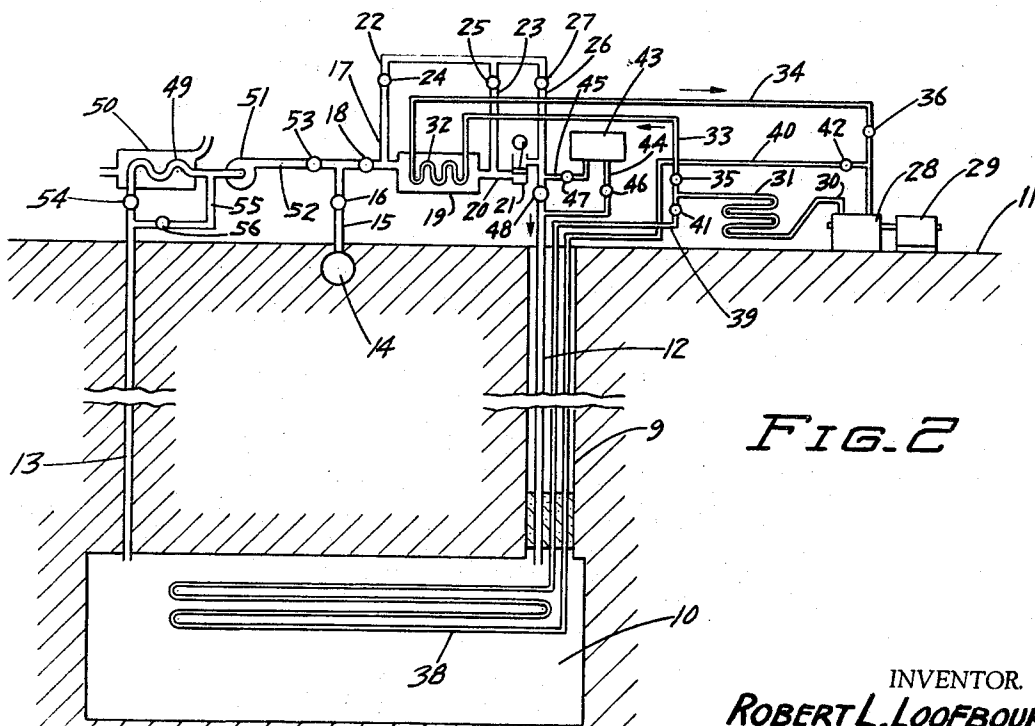
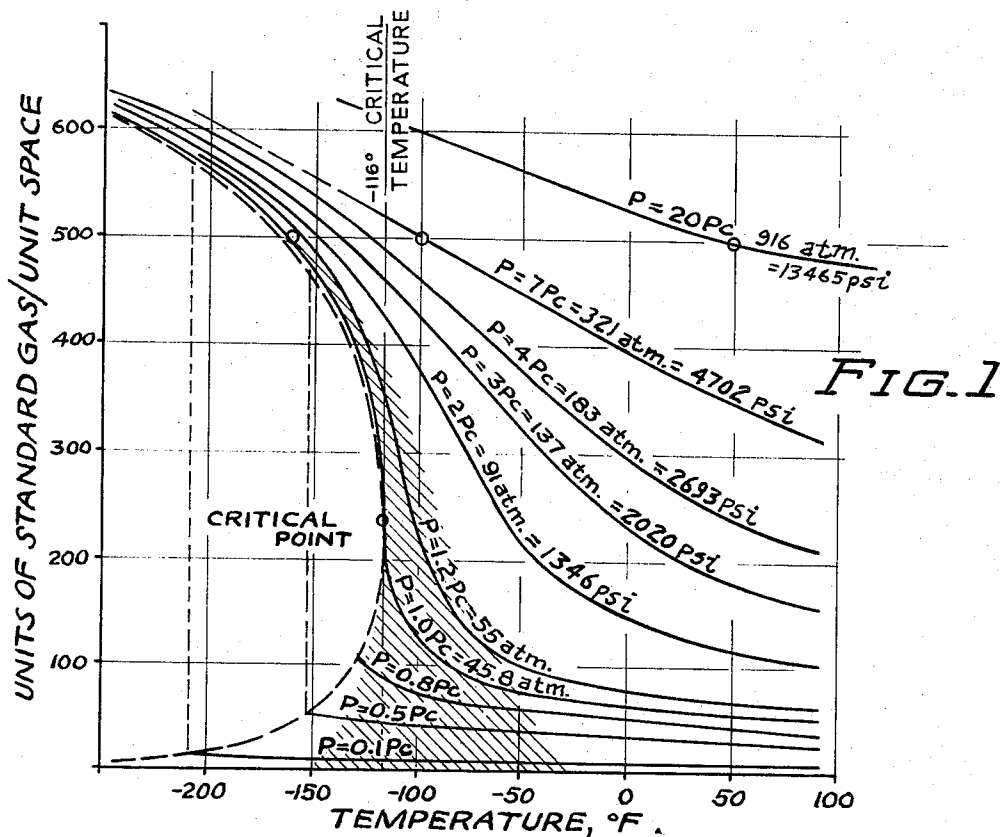
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[57] ABSTRACT

Methods and systems for storing large volumes of gas, such as natural gas and the like, as commonly received from pipelines or tankers, in deep underground cavities under near-critical conditions of pressure and temperature. Part of the total gas received may be used to meet current requirements and the remainder stored during times of less than average demand, for use when demand is higher. Capital and operating costs of storing gas in ways disclosed make large scale storage attractive. As more gas is delivered from greater distances by more costly means, the need to accumulate gas in storage near markets, for use in emergencies and to keep the transportation system working at capacity, continually increases. This invention provides for this need, not only at attractive costs but also it provides a type of storage which can be built near many large markets where more conventional storage cannot; it requires little land and little surface construction. Gas is stored with maximum security and delivered with greatest availability.

7 Claims, 6 Drawing Figures





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FIG. 3

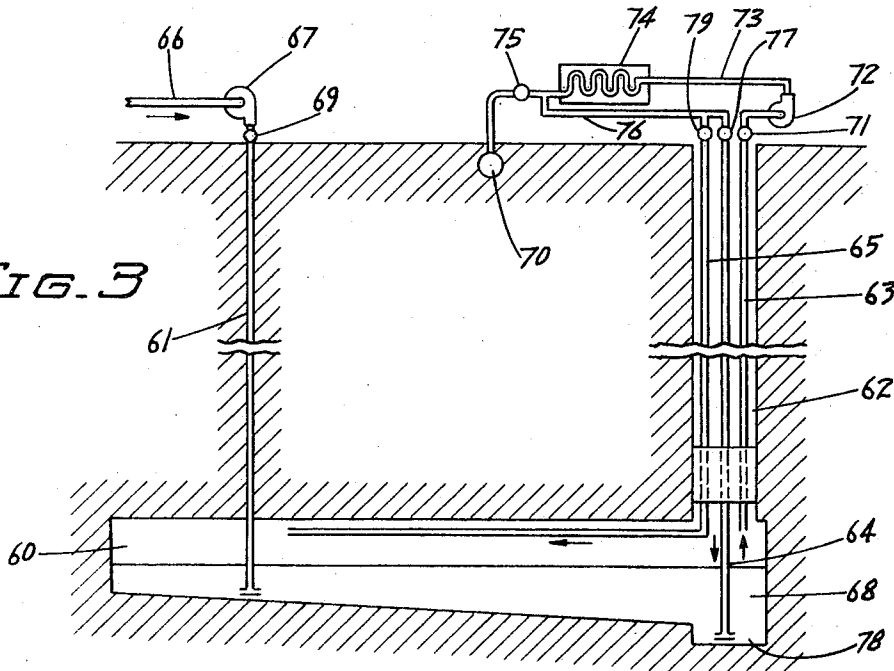


FIG. 4

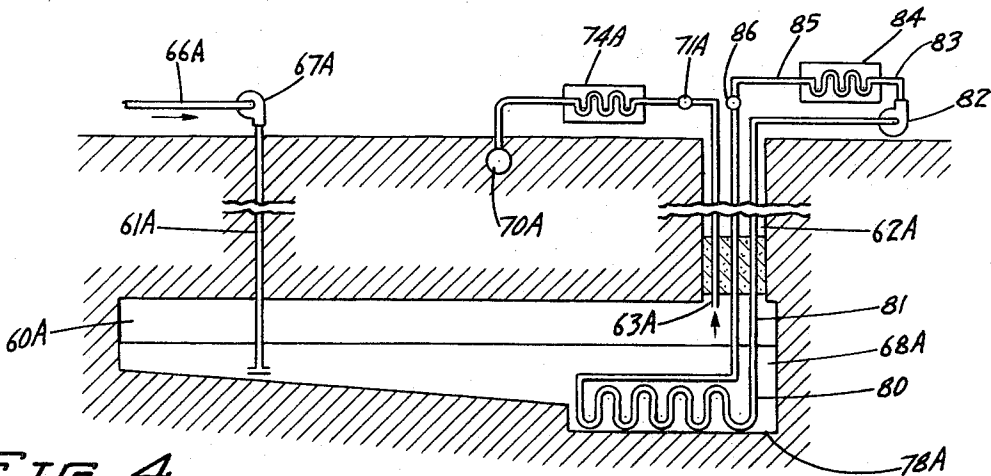
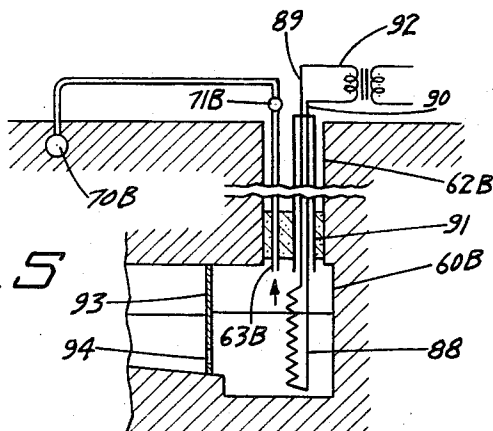
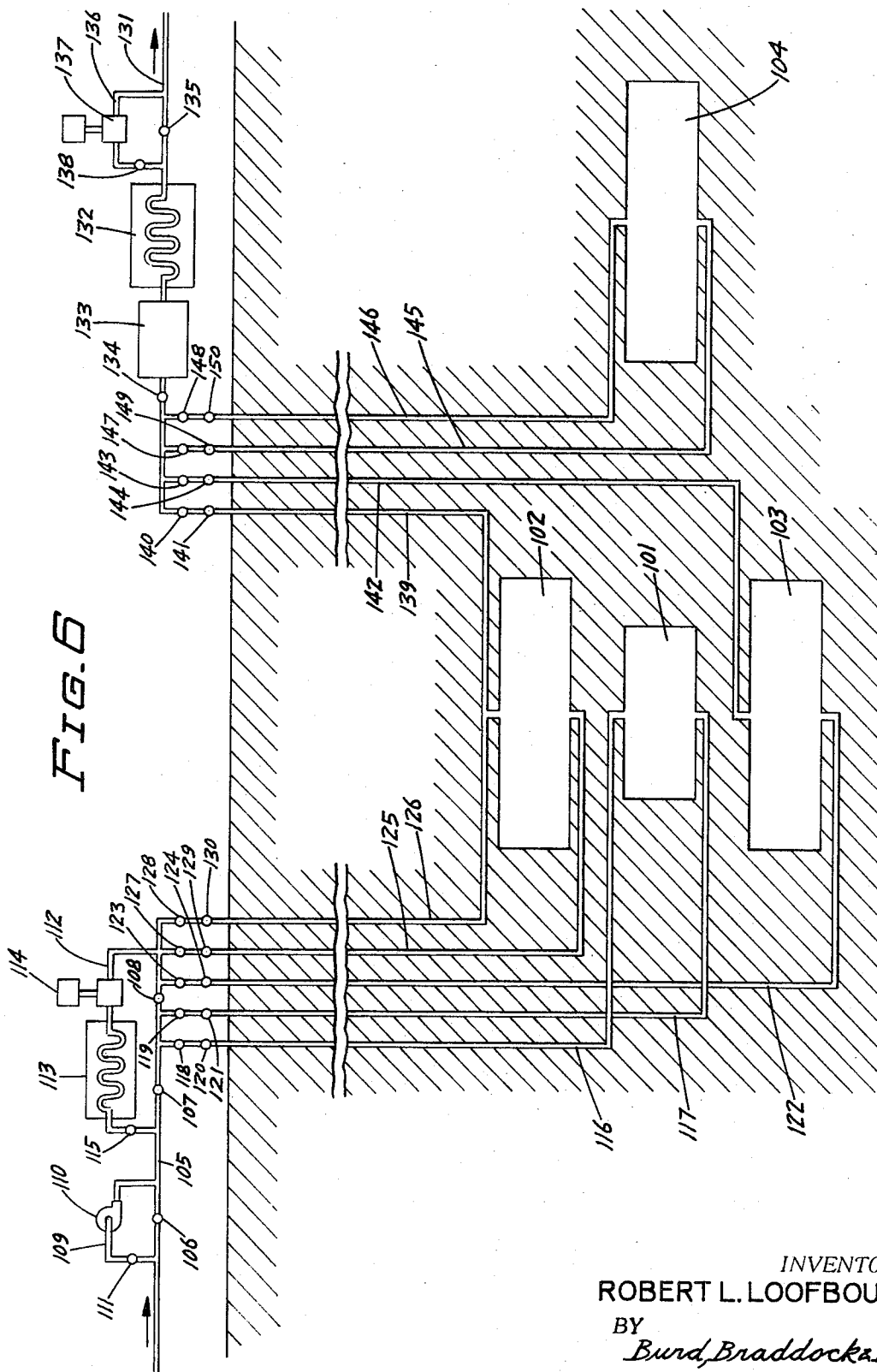


FIG. 5



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FIG. 6



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STORAGE OF GAS IN UNDERGROUND EXCAVATION

This invention relates to the storage of gas in underground chambers and more particularly to the underground storage of gas at near-critical conditions.

Thermodynamically, the critical temperature of a gas is the temperature above which it cannot be liquefied at any pressure. The critical pressure is the pressure of the saturated vapor at the critical temperature or the pressure at which the gas and liquid coexist at the critical temperature. Gases and their mixtures deviate from the classic gas laws (which show the relation between pressure, volume and temperature for an imaginary "perfect" gas) in that under some conditions more gas can be stored in a unit space than the gas laws indicate. This deviation and its rate of change are most favorable to gas storage at the critical temperature and pressure.

The "compressibility factor" of a gas is the measure of this deviation. For various elemental gases and gaseous chemical compounds, each at its critical temperature and pressure, the compressibility factor is between 0.3 and 0.19, that is, the volume of space occupied by a unit volume of gas at critical conditions is between 0.19 and 0.30 of the volume which a "perfect" gas would occupy at the same temperature and pressure.

The present invention is directed to the utilization of these properties for the advantageous storage of gases and mixtures of gases under economically feasible conditions. The principal object of this invention is to provide a storage system for large volumes of common and economically useful gases which can be built underground and used where natural underground reservoirs do not exist. The invention is directed especially to the storage of large volumes of pure or mixed gases having critical temperatures lower than the freezing point of water. Data for some of these gases are shown in Table I, appended.

The invention is illustrated in the accompanying drawings in which corresponding parts are identified by the same numerals and in which:

FIG. 1 is a diagram showing the number of units of standard methane gas which are contained in a space having a volume of one unit for a range of volume-pressure-temperature relationships;

FIG. 2 is a simplified and diagrammatic sectional view of an underground storage system for the storage and temperature control of gas received at relatively high pressures and ambient temperatures;

FIG. 3 is a similar diagrammatic sectional view of a storage system for gas received liquefied at near atmospheric pressure and low temperature;

FIG. 4 shows a similar system with a warming coil in the storage chamber to gasify the stored liquid;

FIG. 5 is a partial sectional view showing immersion heating means in the storage chamber; and

FIG. 6 is a diagrammatic sectional view of an excavated storage to receive liquefied natural gas and warm it by natural heat exchange.

Whereas other known types of storage of these and similar gases utilize (a) high pressure to cram gas at ambient temperature into storage spaces such as pressure tanks and conventional underground gas storage reservoirs, or (b) extreme low temperature to keep the gas liquid at nearly atmospheric pressure, this invention provides means of storing gas at optimum temperature

and pressure, thereby enabling much more gas to be stored in a unit space and at moderate pressure. Whereas storage of these and similar gases in liquefied form requires facilities for liquefaction and revaporization, this invention provides a means of storing nearly the same amount of gas in a unit space without the costly facilities and energy consumption required to convert the stored gas to liquid and back again to gas. The inflexible requirement of extreme low temperature is also avoided.

The percentage of methane in natural gas is generally more than 85 percent and may be 95 percent or more. When a mixture of gases is cooled and compressed sufficiently, liquid will condense. It will contain most of the components of the gaseous mixture but their proportion in the liquid will not be the same as in the gas. Before natural gas has been brought to the ultra-dense condition here contemplated for storage, most of the impurities with relatively high boiling points will have been liquefied. Small percentages of butane, propane, ethane and carbon dioxide may be present in the gas supplied by a pipeline and are representative of this group. Depending on the composition of the gas as received, provision may be made to separate any fractions which liquefy as the gas is cooled. Impurities with relatively low boiling points, such as nitrogen, oxygen, hydrogen, helium and argon will not condense, though small amounts of these gases may dissolve in any liquids which do separate.

For purposes of illustration, methane is used as an example, but it is evident that the same means can be used to store other gases, including those shown in Table I and others of similar properties.

Referring to the drawings, FIG. 1 shows the number of cubic feet of "standard" methane which can be stored in one cubic foot of space under a range of actual storage temperatures and pressures. "Standard" gas is gas at standard conditions, 60° F and 14.7 psia. Study of these curves will show advantageous conditions for the storage of gas at a maximum pressure of about 50 atmospheres and within a temperature range from about -100° to about -180° F, or perhaps a little lower. Storage at this moderate pressure is especially useful because generally greater storage pressures require that underground storage excavations be at greater depths, which adds to construction cost and time. Note that 500 standard cubic feet can be contained in each cubic foot of excavated space at about 50 atmospheres and at -160° F (Point A, FIG. 1), whereas if the temperature were only 60° higher, that is -100° F, the pressure would have to be increased to 320 atmospheres, if the same amount of gas were to be contained in the same space (Point B). Further, if the temperature were 50° F, the storage pressure would have to be about 920 atmospheres to accomplish the same result (Point C). (The data on the chart of FIG. 1 is after Matschke, Donald E. and Thodos, George, The PVT Behavior of Methane in the Gaseous and Liquid States, Jour. of Petroleum Tech., Oct. 1960, pp. 67-71).

The solid line curves of FIG. 1 represent data in the gaseous phase. The curved dashed line through the critical point separates this from the liquid phase. Unless this dashed line is crossed, there is no change in state and only sensible heat, that needed to warm or cool the gas as such, rather than to vaporize or condense it, is involved.

One principal object of this invention is to provide a type of storage for large volumes of methane and similar gases, which can be built and used where conventional reservoirs do not exist. Underground storage systems for the storage of gases at or near their critical temperatures and pressures afford a number of advantages as compared with other types of storage facilities which can be built at such places. Other and equally important objectives are (a) to provide an efficient way to receive gas as liquid in large quantity rapidly, as from tankers; (b) to warm a part of the gas received and send it out more or less continuously for consumption; and (c) hold other gas in dense form to meet emergency or peak requirements.

1. The costs of construction and operation can be moderate because:

a. Many units of gas, made dense by low temperature and moderate pressure, can be stored in a unit of space without requiring the high pressures and consequent great depths that would be needed if gas were stored at ordinary temperatures. Where rock is reasonably favorable, this enables the storage excavations themselves to be made at costs favorable as compared to the heavily insulated tanks of special metals or alloys or insulated covered pits which may be used to store liquefied gas at the surface. With favorable conditions it is possible to make space for 1/5 or even 1/10 of the cost of insulated tanks. The effect of large capacity in reducing the unit cost of underground excavations is greater than in reducing those of surface storage tanks or pits.

b. Heat exchange and more common refrigeration units or compressor units of moderate capacity are substituted for the complicated large liquefaction plants which are required where gas is to be liquefied for storage as a liquid at approximately atmospheric pressure. To reduce the temperature of a pound of methane gas from 60° F to -180° F at 1,000 psi requires the absorption of 280 BTU. To reduce its temperature to -258° F at atmospheric pressure and liquefy it, requires the absorption of 384 BTU. Conversely the same amounts of heat must be restored in each case to return the gas to 60° F. Heat exchange equipment for use with the dense gas will be comparatively compact.

c. Vaporizers are not needed if gas is stored as such. Where it is stored as liquid at nearly critical temperature, the work of vaporizing the liquid is less than if liquid has first to be vaporized and then warmed from the temperature of liquid storage at atmospheric pressure (about 140° F below the critical temperature).

2. The critical temperatures of these gases are such that the walls of the excavations in which they are stored are surrounded by a thick shell of rock which remains below the freezing point of water, and some other possible contaminants, as long as the storage is in use. Any moisture in rock pores and fractures is frozen, sealing any possible leakage through the rock. In the unlikely event that rock at a chosen storage locus is both permeable and dry, water or another suitable sealing material can be placed in the rock through boreholes from the surface. As a consequence, this type of storage can be built in many locations which would be questionable or unsuited to the construction of under-

ground excavations for the storage of gas under ordinary temperatures.

3. Like other types of deep underground gas storages, including the very useful conventional recharged natural gas reservoirs, this type of storage affords a degree of security distinctly superior to that of any storage requiring extensive plant installations and storage tanks or pits at the surface.

4. Storage can be designed for expansion of capacity without interruption of service, if and when required. Reference to FIG. 1 shows that the quantity of gas which can be stored in unit space at a temperature of -120° F (235 standard cubic feet per cubic foot of space) may be more than doubled if the storage temperature is reduced to -160° F with no significant change of pressure (500 standard cubic feet per cubic foot). Necessary but minor facilities, such as underground piping, can be built in anticipation of the change so that the only major addition would be the installation of additional heat exchange and refrigerating equipment on the surface.

Depending on the manner in which gas is delivered to the storage, and hence on its condition at delivery, it is desirable that the equipment provided and even the design of the storage excavations be varied. Two cases are described under which it is assumed that gas is delivered as:

1. Compressed gas, ordinarily delivered from long distance pipelines at about 700 to 1,200 psi and about 40° F to 80° F, and

2. Liquefied gas, which may be delivered from tankers specially fitted out for the purpose, at substantially atmospheric pressure and about -260° F.

EXAMPLE 1 - STORAGE OF GAS RECEIVED AS COMPRESSED GAS

In FIG. 2, there is shown schematically a system for the storage and temperature control of gas received at relatively high pressure and ambient temperatures. Most long distance pipe lines deliver gas at pressures of 700 to 1,200 psi at temperatures from about 40° F to 80° F. According to the system of the present invention, such gas is cooled at the surface to below its critical temperature and then charged to the excavations at pressures which increase to the maximum storage pressure as the excavations fill. At maximum charge the pressure is slightly above the critical pressure. It is to be noted that the gas as it leaves the pipeline is likely to be at a pressure greater than the storage pressure; compression is therefore unnecessary. Because gas is stored as such, only sensible heat is involved; none is required for liquefaction or vaporization.

While gas is in storage some heat will come toward the storage excavations from the surrounding rock mass. In order that the storage operate as planned, the temperature of the stored gas must be controlled, not so closely at the beginning and end of the storage cycle when the amount of the charge is relatively small, but narrowly near mid-cycle when the charge is high.

Referring again to FIG. 1, allowable conditions within the storage are represented by the shaded area. While the storage contains less than half the gas it may ultimately hold, conditions need not be controlled rigidly, but while the storage contains more than half its ultimate charge, conditions must be kept between the maximum working pressure of 50 to 55 atmospheres and the dashed line marking the border between gas

and liquid phases. The latitude of temperature at lower pressures has several advantageous consequences: (a) the heat exchanger-refrigeration plant does not need to have capacity to cool gas to the lowest storage temperature at the highest charging rate; charging conditions may follow any irregular path within the area indicated, and (b) if the storage operates for a number of years within the area of greater latitude, it should be possible to determine the heat conductivity of the walls of the excavations rather closely and so to select any additional heat-exchanger-refrigeration equipment with confidence.

Referring now to FIG. 2, there is shown a storage excavation 10 deep in the earth which is connected to the surface 11 by means of an input casing 12 which extends through shaft 9 and a discharge casing or shaft 13. The incoming gas is received through a pipeline 14 which is connected by means of a pipe 15 valved at 16 and by another pipe 17 valved at 18 to a refrigerating chamber 19. Another pipe 20 connects the refrigerating chamber 19 with the input pipe 12, through expansion engine 21. Alternatively, the gas may bypass chamber 19 through pipes 22 and 23, valved at 24 and 25, respectively, or bypass chamber 19 and expansion engine 21 through pipes 22 and 26. Pipe 26 is valved at 27. Obviously, the gas may also be passed through chamber 19 while bypassing expansion engine 21.

An independent refrigerating system is provided at the surface comprising a compressor 28 driven by a suitable motor 29. The compressed refrigerating gas from the compressor is conducted through a suitable conduit 30 to a condenser or cooling tower 31. A refrigerating coil 32 in the chamber 19 is connected to the refrigerating plant by means of pipes 33 and 34 which are fitted with valves 35 and 36, respectively. Valve 35 is an expansion valve. The cooling effect of the expanding gas flowing through the coil 32 in countercurrent flow against the incoming gas serves to cool the gas to be stored as it is charged into the storage excavation.

A further refrigerating coil 38 is optionally provided in the storage excavation 10. Coil 38 is connected to the refrigerating plant at the surface by means of pipes 39 and 40 passing down through shaft 9 and fitted with valves 41 and 42, respectively. Valve 41 is an expansion valve. The cooling effect of the expanding gas flowing through coil 38 functions to control the temperature in the excavation. Further temperature control means are provided in the form of a small liquefaction plant 43 connected to the input pipe 12 by means of a suitable conduit 44 and connected to pipe 20 from the refrigerating chamber by conduit 45. Conduits 44 and 45 are fitted with valves 46 and 47, respectively.

A main valve 48 controls flow to input pipe 12. The discharge pipe 13 from the storage excavation is connected to a heater coil 49 housed in a furnace 50 or other heating chamber connected to a compressor 51 which in turn is connected by means of a pipe 52 provided with a valve 53 to connecting pipe 15 to the pipeline 14 which may also serve to distribute the stored gas from the excavation upon discharge. Optionally, discharge pipe 13 may be valved at 54 and bypass 55, valved at 56, is provided to bypass the heat exchanger and pass gas directly to the pump.

In the normal operation of the gas storage system of FIG. 2, gas received from pipeline 14 passes through pipe 15 and valve 16, through pipe 17 and valve 18,

through chamber 19 where its temperature is lowered, and thence through pipes 20, 23 and 26 and valves 25, 27 and 48 through input pipe 12 to the storage excavation 10. In response to demand, the stored gas is discharged through pipe 13. Optionally it is rewarmed in coil 49 in chamber 50. The discharging gas is pumped through compressor 51, pipe 52, valve 53, pipe 15 and valve 16 back into pipeline 14 for distribution.

During the storage cycle the temperature of the gas in the storage excavation may be controlled by several means used either singly or in combination. These are as follows:

1. Gas may be circulated by being withdrawn from the storage excavation 10, pumped up through pipe 13 through bypass 55 and pump 51, pipes 52 and 17 and valves 53 and 18, recooled in the heat exchanger refrigeration unit 19 and pumped back through pipe 20 and valve 48 and pipe 12 to the storage excavation. The design must be such that the gas circulates through all parts of the storage and should preferably permit the direction of circulation to be reversed.

2. A refrigerated fluid from the surface is circulated through coil 38 and pipes 39 and 40, using natural convection alone or with forced circulation. Although coil 38 is shown as connected to a refrigerating plant for circulation of refrigerating gas, the same system may optionally be used for circulating a cooled fluid, such as brine, or the like.

3. A small portion of the stored gas discharged from the refrigerating chamber 19 on the surface is liquefied in the liquefaction plant 43 and injected as a liquid to evaporate in the excavation and cool it.

4. In anticipation of gradual warming of the stored gas, depending on the heat conductivity of the wall, to compensate for gradual warming, gas is introduced somewhat less than the critical temperature, to an extent that storage temperature will slightly exceed the critical temperature as the critical pressure is approached. Conversely, after somewhat more than half the gas has been withdrawn, the storage pressure will drop, the remaining gas will be cooled by expansion countering the heat naturally conducted through the walls, thus reducing the requirements of temperature regulation as no large change of temperature results.

5. During the period of charging, and especially the early part of it when the pressure in the storage is low, gas to be charged is circulated through engines 21, not only to recover power but to gain the maximum cooling effect from the expansion. As the amount of gas in storage approaches its maximum and the storage pressure is closer to the pipeline pressure, gas is first cooled and then expanded through an engine.

6. The described means of temperature control may be supplemented by insulating all or parts of the walls of the storage excavation as may be desirable or necessary in view of the storage cycle and the nature of the rock mass surrounding the storage excavation.

7. The rock formation itself may contribute to temperature control where the excavations are made in cellular or other rock having less than average conductivity. Sites may be selected with this in mind.

8. Some temperature control is achieved by use of compact storage chambers in order to reduce the ratio of rock surface to storage volume.

EXAMPLE 2 - STORAGE OF GAS RECEIVED LIQUEFIED

The choice between storing natural gas as high density gas or as liquid and gas depends on the condition of the gas as received by the owner of the storage and in view of the heat transfer characteristics of the rock at the site or sites available. If gas is received as liquid, as from tankers, and charged to storage as liquid at only a little more than atmospheric pressure and at about -260°F , the natural inflow of heat will gradually raise this temperature. While both liquid and gas exist in the storage chamber, the pressure must equal the vapor pressure of the liquid at the temperature existing. If the storage is fully charged and then shut in for a long period, pressure might have to be controlled so that the planned working pressure would not be exceeded. However, all rocks are poor conductors of heat, some indeed being rather good insulators. Normal gas withdrawals, even at low seasonal rates, may keep storage temperature undesirably low. The natural heat inflow is allowed to warm the stored liquid so that it will vaporize, or may be vaporized more readily as required for withdrawal.

In FIG. 3, there is shown schematically a system for the storage and temperature control of gas received as liquid at nearly atmospheric pressure. The storage excavation 60 deep in the earth is connected to the surface by means of an input casing or shaft 61 and a discharge shaft 62 through which a plurality of discharge pipes 63, 64 and 65 extend. The incoming gas delivered from a marine or vehicular tanker is pumped rapidly through pipe 66 by pump 67 into the storage chamber 60 through inlet 61. The liquefied gas may exist in the chamber both in liquid form, as at 68, and in gaseous form. Inlet 61 is valved at 69.

The gas from storage is introduced for distribution to a pipeline 70. Gas in the vapor phase is withdrawn through pipe 63, which is valved at 71, by pump 72 through pipe 73 to a heat exchanger 74 where the gas is warmed, and thence to the pipeline. For temperature control of the storage chamber, valve 75 may be closed and the warmed gas from heat exchanger 74 circulated back through pipe 76 either through pipe 64, which is valved at 77 and extends to a sump 78 in the liquid phase of the stored gas, or through pipe 65, valved at 79, into the vapor phase of the storage, both for the purpose of vaporizing more liquid for circulating through pipeline 70.

The following means, singly or in combination, may be used for vaporizing gas in the storage chambers, or bringing it up to the desired storage temperature:

1. Warm methane, or any desired diluting gas is circulated into the gaseous or liquid phase. Circulation should be through all parts of the storage and preferably the direction of circulation should be reversible.

2. A warmed fluid from the surface is circulated through heat exchanging coils in the storage, the same coils being available for cooling, if necessary, as shown in FIG. 4.

A warm or cooling coil 80 is disposed in sump 78A in the liquid phase 68A of the stored gas in chamber 60A. The structure for the introduction of gas into the storage and withdrawal of gas from the storage is shown in somewhat simplified form as described in connection with FIG. 3 with the suffix A added to the reference numerals. Coil 80 is connected by means of a pipe 81 to

pump 82 and pipe 83 to heat exchanger 84. Heat exchanger 84 may be for the purpose of either heating or cooling and is connected to coil 80 through pipe 85 and valve 86. The heating or cooling fluid, as necessary, is circulated in a closed system for heating or cooling the storage facility.

3. Electrically powered immersion heaters are placed through cased bore-holes into the liquid. As shown in FIG. 5, one or more immersion heating units 88 are disposed in the chamber 60B at least partially submerged in the liquid phase of the stored gas. Heater 88 is connected by conductors 89 and 90 extending through a closed casing 91 to an electrical heat generating source 92 at the surface.

4. To make heating most effective, its effect may be confined by baffles, as also shown in FIG. 5. Vertical baffle 93 having one or more openings 94 adjacent the floor of chamber 60B confines the heat of heater 88 to the compartment adjacent the discharge 63B to distribution pipeline 70B while still permitting inflow of colder stored gas to that compartment.

5. The pressure on the stored liquid may be reduced, thus lowering the temperature at which it vaporizes.

6. Sites may be sought in granite or other more than normally conductive rock.

7. Storage chambers may be designed to afford a high surface to volume ratio, consistent with other design conditions.

It is also possible to displace liquid methane from the storage excavations to the surface and vaporize it there. This can be done readily by pumping warm methane gas into the storage, thus increasing the pressure sufficiently to raise a column of liquid to the surface, or simply by warming the storage to increase the pressure therein. The density of methane is: at -116°F and 45.8 atmospheres, critical temperature and pressure, specific gravity of liquid and gaseous methane is 0.162, density is 10.1 lbs. per ft^3 which produces a head of 70 psi for each 1,000 feet of vertical height.

at -263°F and 1 atmosphere specific gravity of liquid methane is 0.415, the density is 25.9 lbs. per ft^3 which produces a head of 180 psi for each 1,000 feet of vertical height.

The storage of large volumes of natural gas and similar substances at low capital and operating costs can be further improved by the use of the following additional means:

- a. A number of separate storage chambers are provided as shown schematically in FIG. 6, which are so proportioned, oriented, disposed and so connected as to facilitate the maintenance of low temperature in a main storage chamber or chambers. A further means of cooling and maintaining low temperature in the main storage is possible by circulating cold gas or other fluid through chambers which are adjacent to but separate from the main storage chamber. This cold gas may be the exhaust from an expansion engine or other gas being prepared for sending out and the chamber through which it is sent may be below the main storage to intercept heat flowing toward the surface.

- b. Pipe from each chamber is generally brought through the shafts to the surface but where convenient cased bore-holes are used which can be drilled and connected to chambers without difficulty while the storage is in use.

- c. For ease of operation and servicing, control valves are placed near the surface, preferably in closed pits.

For safety, excess flow valves are installed below the control valves.

d. Generally, for convenience in transferring gas, a slight pressure drop is maintained between chambers through which gas moves, through pumps or compressors can be installed for use where this may not be desirable. For most dependable delivery, pressure in the final or sendout chamber should be higher than needed to move gas into the sendout pipeline.

e. Generally, gas-retaining bulkheads are placed in shafts and to reduce the pressure difference on them, they are filled above with sand, gas under pressure or similar.

f. If incoming gas contains gases of higher boiling point than natural gas, such as LPG, which tend to liquefy and separate in the storage chamber, a small pipe and pump is provided to remove the excess periodically. However, within the range of conditions maintained in the storage, the existence of a certain amount of LPG will increase the capacity of the space to hold natural gas, which it absorbs. Either by allowing LPG to accumulate or by adding it, we have another way of increasing capacity. If any substantial amount of LPG moves through a storage system, there may be advantage in having a fractionating tower or other stripping device in the line between the first and second storage chambers as well as a separate small diameter pump column from a sump in the first chamber.

Where gas is supplied as a liquid at approximately atmospheric pressure and about -260°F , as from large tankers, these additional means are to be used:

g. The storage site is located as near as possible or practicable to deep water. This will decrease the cost of high capacity, specially built pipeline through which tankers are unloaded and also facilitate barge shipment of stone. Beyond the storage, ordinary pipe can be used and because it can be used continuously, its hourly capacity can be much smaller.

h. Where there is objection to charging LNG directly into storage, it may be vaporized in the pipeline, sent through a grid of pipe buried in earth a few feet or submerged in a pond, sent through a coil in a storage chamber, or through a heat exchanging boiler with heat supplied from warmed gas circulated from storage.

i. A number of separate chambers are provided through which gas is circulated successively, being warmed gradually by natural heat flow, the chambers designed, oriented, connected and arranged to warm the gas most efficiently. The chambers are spread out horizontally to increase heat exchange.

j. Natural warming is supplemented by providing heat exchangers on the surface in any part of the system.

k. A final tempering chamber is provided from which gas can be sent out to consumption with least possible conditioning.

Referring now to FIG. 6, there is shown diagrammatically a storage system utilizing some of the above enumerated means and especially designed to receive liquefied natural gas for storage and to warm the gas by natural heat exchange. The excavated storage includes a plurality of spaced apart chambers 101, 102, 103 and 104. The first three of these chambers are spaced verti-

cally one above the other. The last is spaced horizontally from the others. Liquefied gas is delivered periodically, as from tankers, for rapid unloading in line 105. Line 105 is provided with control valves 106, 107 and 108, as indicated. For use when needed, a line 109 containing pump 110 and control valve 111 is provided to facilitate delivery of the liquefied gas. A bypass line 112 including a heat exchanger 113, compressor 114 and control valve 115 is provided where, for example, it may be desired that the gas be vaporized or compressed before charging to the storage chambers.

Storage chamber 101 is connected to the delivery line 105 through lines 116 and 117 fitted, respectively, with control valves 118 and 119, and preferably, for safety, with excess flow valves 120 and 121. Chamber 103 is connected with delivery line 105 by means of line 122 fitted with control valve 123 and excess flow valve 124. Chamber 102 is connected with the delivery line by lines 125 and 126 fitted, respectively, with control valves 127 and 128 and excess flow valves 129 and 130.

The gas from storage is circulated to a distribution line 131. The distribution line includes a heat exchanger 132 and desirably a dehydrator 133, and is fitted with control valves 134 and 135. A bypass line 136 connected to an expansion engine 137 and fitted with control valve 138 is provided for use when desirable. Chamber 102 and charging line 126 are connected with the distribution line 131 by means of line 139 fitted with control valve 140 and excess flow valve 141. Chamber 103 is connected with the distribution line through line 142 fitted with control valve 143 and excess flow valve 144. Chamber 104 is connected with the delivery-distribution system through line 131 and lines 145 and 146 fitted, respectively, with control valves 147 and 148 and excess flow valves 149 and 150.

Ordinary routing of the liquefied gas is in sequence to chamber 101 and then to chambers 102, 103 and 104. By pumping, pressure in chamber 101 may be kept the highest. However, valving and compressors allow flexibility. For more rapid warming, chamber 102 may be spaced horizontally from chamber 101 instead of vertically.

Various alternative procedures are possible. The liquefied natural gas may be pumped directly to chambers 101, 102 or 103 or to the heat exchanger 113 and compressor 114 and then to chambers 101, 102 or 103. Gas from chamber 101 may be drawn directly to chamber 102 or to chamber 103. Gas from chamber 101 may be transferred directly or through the heat exchanger-compressor to chambers 102 or 103 or returned to chamber 101. Gas from chambers 102 and 103 may be transferred to the dehydrator 133, heat exchanger 132 and expansion engine 137 to distribution to a distribution system or gas from chambers 102 or 103 may be transferred to chamber 104. Gas from chamber 104 may be transferred to the dehydrator-heat exchanger-expansion engine to distribution.

It is apparent that many modifications and variations of this invention as hereinbefore set forth may be made without departing from the spirit and scope thereof. The specific embodiments described are given by way of example only and the invention is limited only by the terms of the appended claims.

TABLE I

CRITICAL DATA FOR VARIOUS GASES ¹					
	Crit. Temp. ° F.	Crit. Pres. Atmos.	Crit. Vol. Cu. Ft./per lb.	Std. ² Vol. Cu. Ft./per lb.	Ratio Std. Vol./Crit. Vol.
Argon	-187.7	48.0	0.03	9.50	317
Carbon Monoxide, CO	-220.3	34.5	0.053	13.57	256
Hydrogen	-399.8	12.8	0.516	188.6	365
Methane, CH ₄	-116.5	45.8	0.099	23.6	239
Nitrogen	-232.8	33.5	0.053	13.57	256
Nitric Oxide, NO	-136.7	65.0	0.031	12.66	408
Oxygen	-181.8	49.7	0.037	11.87	320
Air	-220.3	37.2	0.0457	13.08	286
Natural Gas ³	1 - 87.4	46.1			
	2 - 96.3	45.7			
	3 - 118.6	45.3			

¹ Marks, Mech. Engrs. Handbook, 6th Ed., pp 1-20, 4-26, and Amer. Gas Jour. Handbook 1938, p. 60-61
² At 60° F. and 14.7 psia
³ These are "pseudo critical" values calculated for mixtures considered representative of natural gas

The embodiments of the invention in which an exclusive property or privilege is claimed are defined as follows:

1. A method of storage of pipeline gas received as compressed gas from a pipeline at pressures between about 700 to 1,200 psi and temperatures between about 40° to 80° F in an excavated underground storage facility including at least one excavated underground rock chamber, which method comprises:
 - A. cooling said gas to about -50° to -150°F and charging to said storage facility at pipeline pressures,
 - B. when said facility contains about one half of its maximum capacity, increasing the pressure and maintaining at moderately elevated level up to about 2,500 psi,
 - C. maintaining the facility at reduced temperature between about -50° and -150° F, whereby the gas is maintained for storage predominantly in the gaseous state and is densified to store between about 75 and 475 cubic feet of gas to each cubic foot of storage space,
 - D. circulating stored gas to heat exchangers at ground surface to cool the gas to maintain the storage temperature,
 - E. discharging said stored gas upon demand, and
 - F. after the quantity of stored gas has been reduced to about one half of its maximum, decreasing the pressure while maintaining the temperature between about +50° and -150° F.
2. A method according to claim 1 further characterized in that the stored gas is cooled by absorption of heat in said heat exchangers by expansion of incoming gas from pipeline pressure to sendout trunkline pressure.
3. A method according to claim 1 further characterized in that the stored gas is cooled by absorption of heat in said heat exchangers by expansion of incoming gas being charged to storage from pipeline pressure to storage pressure.
4. A method according to claim 1 further characterized in that gas is withdrawn from the top of said chamber and cooled gas is reintroduced at the bottom of said chamber.
5. A method according to claim 1 further characterized in that:

- A. said storage facility comprises a plurality of storage chambers connected in series, and
- B. the pressure in each of said storage chambers downstream from the first chamber is maintained at a level lower than the pressure in the next adjacent upstream chamber.
6. A method according to claim 1 further characterized in that:
 - A. said gas to be stored is natural gas,
 - B. a small amount of liquefied petroleum gas (LPG) is maintained in said storage chamber, and
 - C. a portion of said natural gas is absorbed in said LPG, thereby increasing the capacity of said chamber.
7. A method of storage of pipeline gas received as compressed gas from a pipeline at pressures between about 700 to 1,200 psi and temperatures between about 40° to 80° F in an excavated underground storage facility comprising at least one excavated underground rock storage chamber and a plurality of other chambers adjacent to but separated from said storage chamber, which method comprises:
 - A. cooling said gas to about -50° to -150°F and charging to said storage chamber at pipeline pressures,
 - B. when said storage chamber contains about one half of its maximum capacity, increasing the pressure and maintaining at moderately elevated level up to about 2,500 psi,
 - C. maintaining the storage chamber at reduced temperature between about -50° and -150° F, whereby the gas is maintained for storage predominantly in the gaseous state and is densified to store between about 75 and 475 cubic feet of gas to each cubic foot of storage space,
 - D. circulating a heat exchanging fluid through said other separated chambers to maintain the storage temperature within said storage chamber,
 - E. discharging said stored gas upon demand, and
 - F. after the quantity of stored gas has been reduced to about one half of its maximum, decreasing the pressure while maintaining the temperature between about +50° and -150° F.

* * * * *

UNITED STATES PATENT OFFICE
CERTIFICATE OF CORRECTION

Patent No. 3,848,427 Dated November 19, 1974

Inventor(s) Robert L. Loofbourow

It is certified that error appears in the above-identified patent and that said Letters Patent are hereby corrected as shown below:

In the title, "EXCAVATION" should be pluralized.

Column 7, line 61, "warm" should be --warming--.

Column 9, line 5, "through" (second occurrence) should be --though--.

Signed and sealed this 14th day of January 1975.

(SEAL)
Attest:

McCOY M. GIBSON JR.
Attesting Officer

C. MARSHALL DANN
Commissioner of Patents