國內炭化水素化合物 地下貯藏計劃

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韓國科學院

Plan for Hydrocarbon Underground Storage in Korea

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要 約

오늘날 탄화수소화합물을 大量 地下 貯藏하는 것은 가장 經濟的인 貯藏方法으로 알려지고 있고, 他國에서는 많이 盛行되고 있다. 그러나 回收難으로 Light hydrocarbon만을 取扱한다. 一般的으로 枯渴된 油田을 地下 까스 貯藏庫로 轉換하여, 地下水가 그 貯藏量을 調整하고 있다. 本論文에서는 實 貯藏 例 들의 記述과 工業設計 및 分理를 記述하려고 한다. 國內에서도 까스의 大量備蓄問題가 臺頭하고 있어, 이러한 地下 貯藏 方法의 應用이 時急하여 지고 있다. 여기서는 三個의 地下貯藏案을 考察하였다. 첫째 石油 資源開發 試錐에서 남은 dry hole을 活用하는 것이며, 이 경우 shale과 aquifer의 存在가 必要하다. 두째 같은 假定下에서 地下熱回收後 溫水井을 작은 地下貯藏庫化하는 것이다. 셋째로는 濟州島萬丈窟을 LPG 備蓄에 利用하자는 것이다. 그러나 이상의 제안을 현실화하자면 여러가지 不確實性과 工學的難點이 있기 때문에, 充分한 研究開發을 하여야만 할 것이다.

Abstract

The underground storage of hydrocarbons is the most economical engineering method known to store a large volume of hydrocarbons and has been widely practiced else where in the world. Because of the recovery difficulties, however, this storage technique is confined to light hydrocarbons.

Usually, depleted oil and gas reservoirs are converted to underground gas storages where the underline aquifer behavior controls the storage volume and the pressure. Actual case study examples are described in this paper together with the engineering design and model analysis.

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Because of the growing Korea's need for bulk volume gas storage, development plans are necessary to apply some of these techniques to Korea. Three different underground storage possibilities are proposed. The utilization of dry holes resulted from petroleum exploration work is a possibility for gas storage if an impermeable rock structure extends over an aquifer. Alternatively, the low temperature geothermal well could similarly be converted to a small gas storage under same assumptions, after a successful energy recovery operation for a moderate economic gain. Lastly, the Jejudo Manjanggool natural cave is a good prospect for a constant volume LPG storage. Because of the many uncertainties and engineering difficulties, sufficient development work must be carried out before attempting to put these into actual practices.

Introduction

Bulk storage of hydrocarbon has been a serious engineering and military problem during the 20th century, and many different types of storage have been practiced. Surface tank storage is an obvious one but is limitted to small volume of gases at less than 30 psig because of the structural instability. It is a common practice to store LPG in spherical and cylindrical pressure tanks and various forms of surface storage are reported for petroleum products and chemicals. The short-comings of the surface tank storages are the limitation on the storage capacity necessary.

The most economical system is the underground storage, but it is limited to light hydrocarbons. Recently, since the 1973 energy crisis, large scale ocean surface storage, and ocean bottom storage systems have also been known. LPG was stored in an artificial salt dome after considerable cavity creation work. Out of all these variations, nothing seems to be more comfortable than the bulk storages in underground.

One of the oldest underground storage structures was tapped with about 80 wells and was located at a depth less than 1,000 feet covering a sand area of about 30 square miles. The types of gases stored were natural gas and coke oven gas from steel mills. During the 1920 depression period in USA, the mills had to reduce the production capacities and were shut down often; and the coke oven gas was wasted because the gasholder construction was uneconomical. A large underground storage could store in the order of 10 billion cubic feet of gas. With a pressure draw-down of 50 psig, 100 million cubic feet per day of gas could be withdrawn, governed by the back-pressure equation and the reservoir physical constants. The gas storing sand was located at a depth of about 1,000–10,000 feet, with approximately 5–150 feet in thickness and had a pososity of about 20 percent.

The underground storage concept can not be applied to heavy hydrocarbons because of the excessive recovery difficulty and the low percent recovery e.g. 40%. Total recovery at critical condition was speculated in recent years but it is still far from realization. If and when this difficulty is overcome, the secondary and tertiary recovery problems would be solved naturally. Thus, the underground storage concept is at best applied to the bulk storage of light hydrocarbons where the amount of cushion gas (50 psig well head pressure for 2,000ft gas field) is relatively small and easily recovered. Commonly, depleted oil and gas reservoirs are converted to underground gas storage systems[4]. But since 1960s with the advancement of engineering techniques for analyzing the underground storage behavior, aquifer storage has been successfully practiced where only water existed[5,6].

For the development of an underground storage system in Korea, a non-oil & gas producing nation, it is essential that the underground aquifer behavior must be fully understood before one can attempt to make any plans to exploit the possibilities of underground storage.

Physical System Model Study

A typical underground storage system can be visualized as a gas bubble breathing on a large aquifer which can be of an infinite extent as shown in *Fig.* 1.

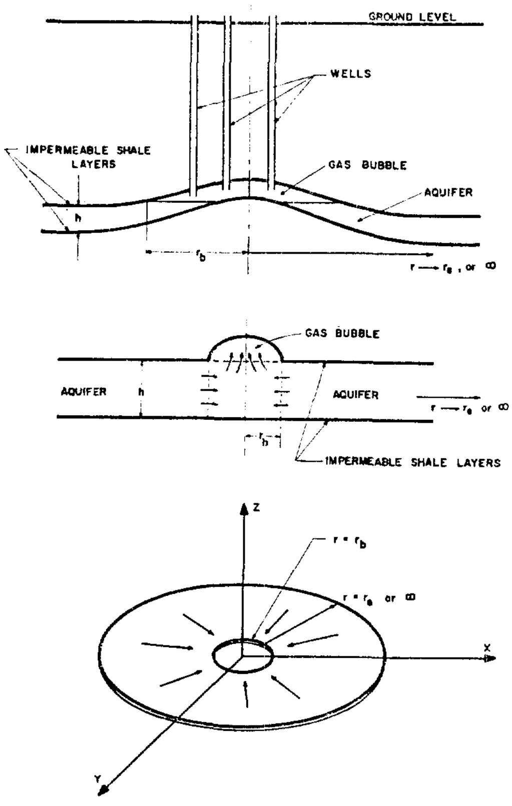

Fig. 1. Underground storage–Radial flow model.

Aquifer is an underground water bearing formation, bounded on the top and bottom, sandwiched by impermeable rock or shale and extending many miles horizontally. And the water movement due to the high pressure must be determined, as it determines the reservoir pore volume available to gas. When the gas pressure is increased, the water is compressed and pushed out of the gas reservoir, and the reverse takes place when decreased.

The governing partial differential equation describing the radial flow of brine through porous media is follows:

$$\frac{\partial^2 P}{\partial r_D^2}+\frac{1}{r_D}\frac{\partial P}{\partial r_D}=\frac{\partial P}{\partial t_D} \qquad (1)$$

where $t_D=\frac{k\theta'}{c\phi\mu r_g^2}$, $r_D=\frac{r}{r_g}$.

The boundary conditions for pressure case are:

$$P[1,\ t_D]=G[t_D], \qquad (2)$$

$$P[\infty,\ t_D]=O,$$

$$P[r_D,\ O]=O.$$

Its Lapace transform or transfer function can be shown to be the following:

$$Q_{tD}[s]=g[s]\left\{\frac{s\cdot K_1[\sqrt{s}]}{s^{3/2}\cdot K_0[\sqrt{s}]}\right\}=g[s]\ \{s\cdot f_1[s]\} \qquad (3)$$

and the time domain solution can be expressed to calculate the cumulative water influx or efflux or the reservoir volume change as:

$$W=[2\pi r_g' h]\frac{k}{\mu}\int_0^{\theta}\left(\frac{\partial P}{\partial r}\right)_{r_g}d\theta=2\pi r_g'^2 hc'\phi Q_{tD}. \qquad (4)$$

where $$Q_{tD}=\int_0^{t_D}\frac{dG}{d\tau}\cdot Q'_{tD}\,[t_D-\tau]d\tau \qquad (5)$$

The inversion of *Eq.* (3) or the step response Q'_{tD} are found in the literature in a tabular form[3].

Similarly, the rate case solution can be obtained to calculate the pressure change from the production rate data:

$$P[r,\ \theta']=\left(\frac{\mu}{2\pi kh}\right)\cdot\ P_{tD}[r_D,\ t_D] \qquad (6)$$

where $P_{tD}[r_D,\ t_D]=\int_0^{t_D}\frac{dE}{d\tau}\cdot P'_{tD}\ [t_D-\tau]d\tau$ (7)

The rate case step response P'_{tD} are also found in the literature[3]. For the volume case the problem can be formulated and solved likewise[5]. The convolution integrals can be computed by

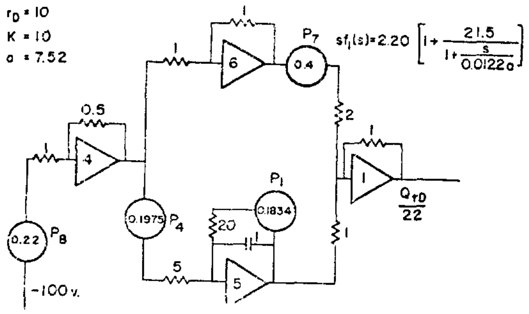

Fig. 2. LM 10 (Electronic differental analyzer) circuit diagram for $r_D=10$ to get cumulative-flux function.

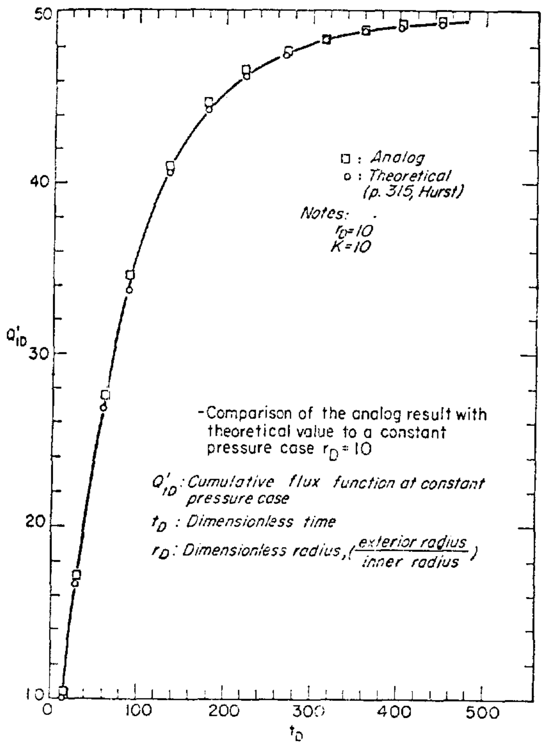

Fig. 3. Comparison of the analog result with theoretical value to a constant-pressure case, $r_D=10$.

a digital computer[2] or the curve fitted transfer function can be simulated on an analog computer to obtain equivalent time domain solution readily for engineering design purposes[5]. Also graphical integration method is known though tedious to handle[4]. For $r_D=10$ limitted aquifer case, the pressure step response transfer function can be obtained, and its analog simulation circuit is presented in *Fig.* 2, and the results are compared in *Fig.* 3 with the theoretical values of the literature[5].

Detail Example of Case Study:

The developed mathematical model and the technique of engineering analysis can then be applied to field case study. If Field A is subjected to a prescribed pressure variation, one can determine the storage volume variations. *Fig.* 4 shows the generated analog computer input and the function to be generated for the actual Field A. For the specified input, the output response volume variation has been obtained for the limitted reservoir model developed. The results are compared with those from a digital compter in *Fig.* 5. The similar study can be made to improve the understanding of other aquifer behaviors such as field inter fer ences[5]. An aquifer storage can also be analyzed by studying a radial flow moving boundary problem[6]. A typical solution to a sinusoidal input is shown in *Fig.* 6. And this computer

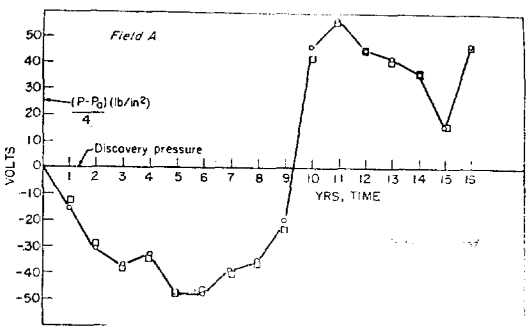

Fig. 4. Specified pressure variation in field A and the generated function.

solution should be modified a little to have a form such as *Fig.* 17, dry hole aquifer storage operation. An actual aquifer gas storage Field B was studied, and the results are presented in *Fig.* 7 along with the field data.

For the conversion of a nearly depleted oil field

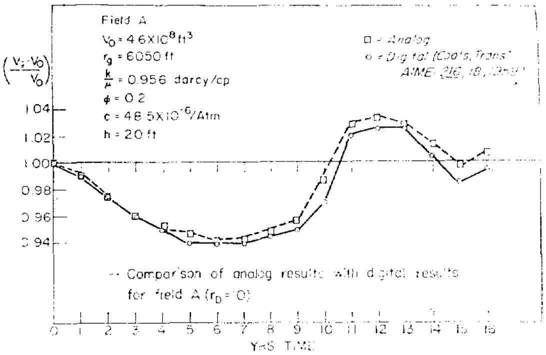

Fig. 5. Comparison of analog results with digital results for field A (r_D=10).

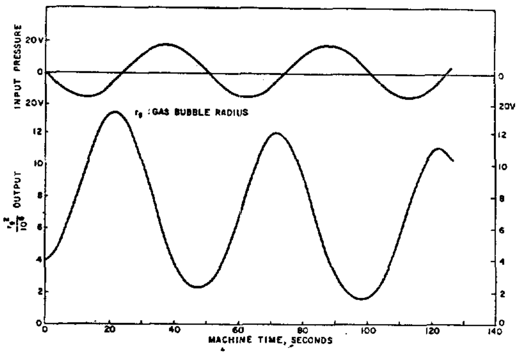

Fig. 6. Solution to a sinusoidal input case by moving-boundary method.

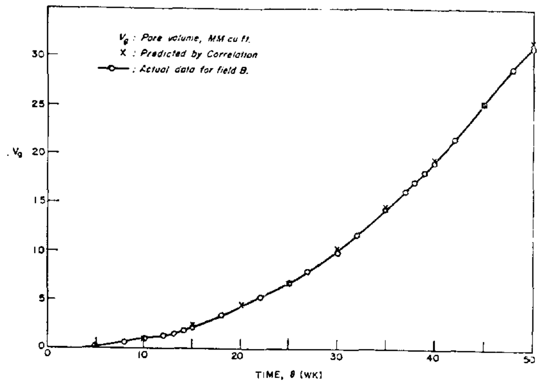

Fig. 7. Gas reservoir pore volume variation for field B. (Aquifer Storage)

to an underground gas storage, a numerical calculation can be made when the production-pressure data are available to determine the water encroachment coupled with the oil reserve estimation material balance method[4].

Addititional Theoretical Model Studies:

The technique can be extended for various other cases to obtain particular solutions. Some of the results are included in this paper for which the analytical solutions are not readily available in the literature.

Fig. 8 shows an approximate gas bubble growth which can be used for crude gas storage design estimation. At the water-gas interface, it is expected that an additional flow resistance can exist due to the twilight zone. The model then needs to be modified as in *Fig.* 9, for which the approximate error range is estimated in *Fig.* 10. When the boundary movement is rapid, it is likely that the flow resistance would be time-varying including an irreversible hysteresis effect, and this can be simulated on an analog computer even if nonlinear and time-varying. Often fault model as shown in *Fig.* 11 needs to be considered, whose solutions are presented *Fig.* 12 and *Fig.* 13. Similar solutions are also given in *Fig.* 14 and *Fig.* 15 for 3 identical reservoirs on a delta sitting on a common aquifer. Carslaw & Jaeger's point and

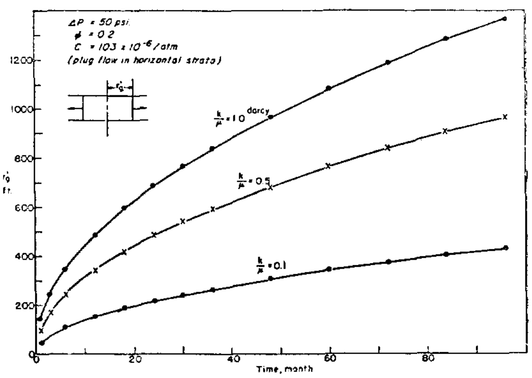

Fig. 8. Approximate gas bubble growth with time for constant pressure case of infinite aquifer.

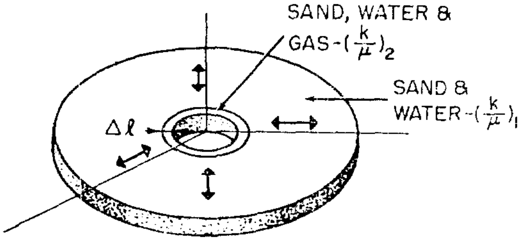

Fig. 9. Radial flow model with twilight zone resistance.

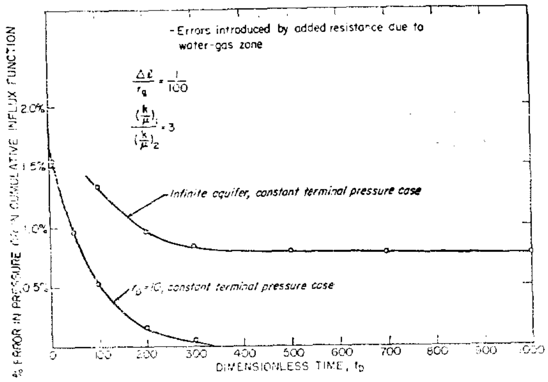

Fig. 10. Errors introduced by added resistance due to water-gas zone.

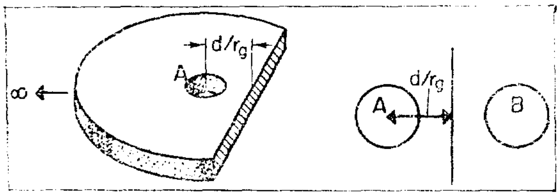

Fig. 11. Radial flow model with a fault at$\left(\frac{d}{r_g}\right)$

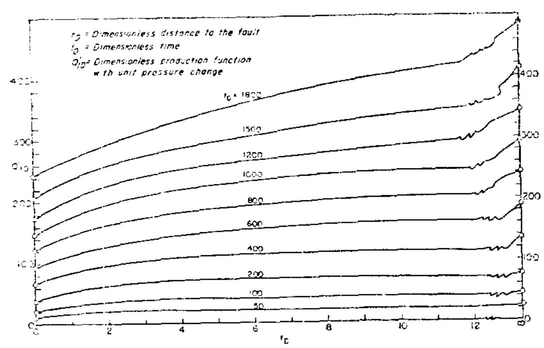

Fig. 12. Constant pressure case solution with fault at r_D.

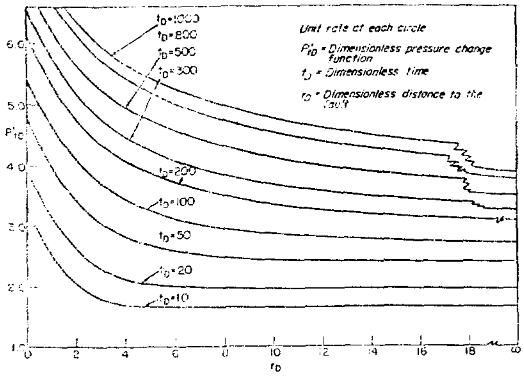

Fig. 13. Constant rate case solution with a fault at r_D.

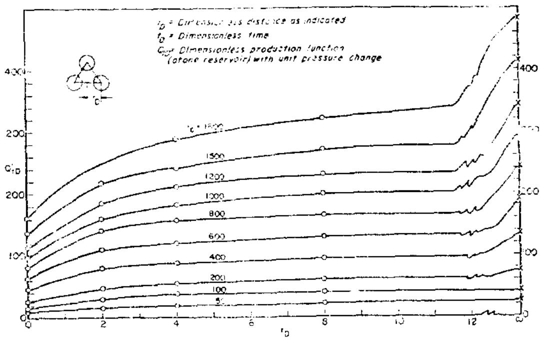

Fig. 14. Constant pressure case solution for three identical reservoirs

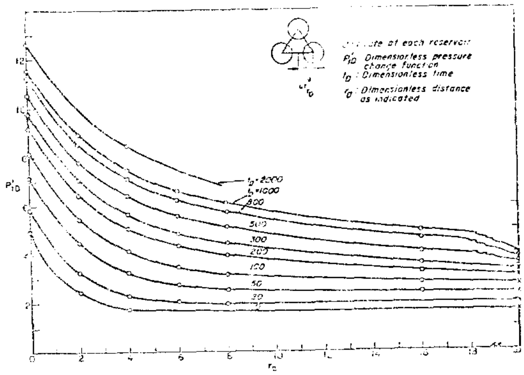

Fig. 15. Constant rate case solution for three identical reservoirs on a delta.

line solutions[1] can be utilized to synthesize other solutions, such as growing disk model[5]. Elliptical & spherical flow models are also studied, and their solutions are available in the literature. The nonlinear gas flow resistance can be considered, but it is usually small compared to that of liquid flow resistance as indicated by the small pressure distribution within a gas field.

The basic concept can be applied to any other complex underground operations, where the phase equilibrium phenomena and chemical reactions play significant and important roles in addition to the transport phenomena.

Plans in Korea

Korea is now beginning to face with the large volume gas storage problems, together with the rapid industrial development plans. Some of these examples are the bulk storage of city gas, revaporized natural gas from the imported LNG which is now being considered, the future domestic production of off-shore natural gas and the recovery operation of the geothermal low temperature energy. Unfortunately, very little or no information is available about the Korea's underground geological structure and the physical constants. The off-shore data up to 10,000 feet below the ocean bottoms are being obtained and compiled by the major foreign operating firms. Within the inland, the Pohang drilling work up to 6,000 feet in 1976 was the only historical occasion. During the 4th 5 year Economic Plan about to begin many drilling operations are planned which can uncover many of the uncertainties about the underground structure in Korea.

With the limitted information on hand, proposals have been made as to how Korea too can adopt the underground gas storage techniques practiced around the globe.

Utilization of Dry Holes:

Several dry holes are already developed below the sea bottom by the off-shore operations and also in-land at Pohang totalling about 8. Except the fact that there are no gas and oil, the structure is somewhat like the aquifer storage. It is the oil drilling practice to seek for shale structures such as shown in *Fig.* 16, at least the top portion. It is considered that the existance of bottom shale structure is not an absolute requirement and the existance of sand-water formation must be assumed for a gas storage development. The utilization of dry hole would be very much equivalent to an aquifer storage development, so far as the uncertainties and the engineering analysis method are concerned. The hole exists up to 10,000 ft with casing and top shale structure with permeability less than 10^{-5} -10^{-7} md covered over a sand-brine formation must be assumed. The extent of the shale structure is an uncertainty that remains to be uncovered. Since it is only possible here to develop a single well storage system, the initial development study does not have to rely on infinite aquifer. Usually, impervious dolomite or limestone can provide a tight caprock structure. Thus it is considered that the dry hole can develop into an aquifer storage system, which is a moving boundary problem.

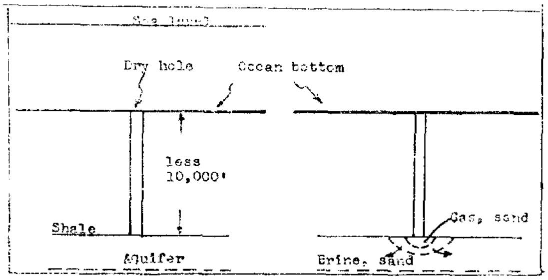

Fig. 16. Dry hole utilization

At the moment, all the dry holes are idled. Some of them are abandoned, and the casings are withdrawn. No special maintenance or development work are conducted. If the utilization of dry hole becomes successful upon confirming the geological structure and the model,

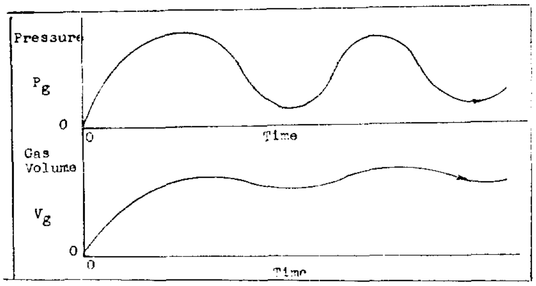

Fig. 17. Dry hole aquifer storage operation.

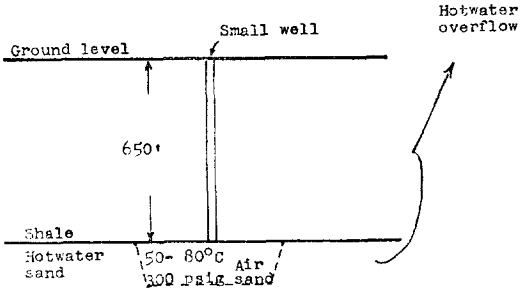

Fig. 18. Geothermal well operations.

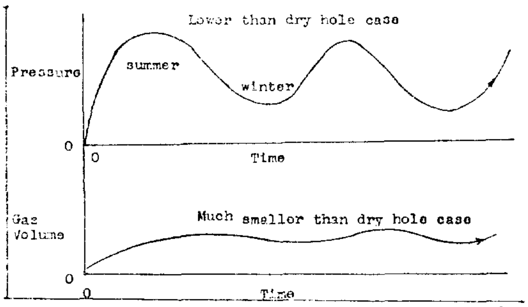

Fig. 19. Conversion to gas storage and Geothermal energy recovery-air injection.

the dry hole storage operation would be like *Fig.* 17. Even though it is a single well operation, the storage volume would be fairly large because of the depth and the high pressure operation permissible. However, the gas hydrate formation possibilities should be carefully avoided under such high pressures.

Development of a Geothermal Well:

In Korea, there are no high temperature geothermal wells, but there are many low temperature (30-80°C) wells (about 16). Engineering studies are being made to recover the energy by injecting air during the summer and with-drawing the hot air during the winter (*Fig.* 18 & 19). Of course for this operation too, the similar assumptions on the structure such as dry hole case must be made. In the absence of the shale structure the permissible operating pressure would be very low since the well depth is shallow, e. g. 650 ft. Single well storage capacity operating at a pressure of 300 psig would perhaps be in the order of 1/50th of a full grown gas storage system.

It is proposed that air injection be made during the summer at a small well hoping that the large flat shale plate covers over sand-hotwater system. Should the hotwater overflows at a ground level point, this would be equivalent to gas drive recovery of hotwater, which can be utilized equally advantageously. The hot air can be withdrawn during the winter months for direct community heating purposes after treatment of the air. The geothermal energy recovery can offer some economic incentives to develop this sort of system. When the recoverable energy is depleted, the overflow leaks could be permanently cemented to convert the system to a small gas storage reservoir. About this time, the engineering design and the geological structure should be well confirmed to safely convert to a gas storage. However, the purging of the residual air from the pore volumes should be carried out before hydrocarbon injection, so that the oxygen-hydrocarbon mixture will never exceed the explosion limit under any circumstances. For the geothermal well storage model, it is possible that the model can assume geometries other than previously mentioned radial flow model.

Considering the fact that Korea has many drilling proposals under the 4th 5 year Economic Plan, there is little doubt that some of these drillings will result in geothermal wells of considerable depth, offering the chances of developing geothermal energy recovery and gas storage conversion without having to work extra from the petroleum exploration task.

Adaptation of Natural Cave:

While studying the possibility of developing variable volume underground storage system, one should not overlook the possibility of utilizing the natural caves--constant volume natural storage tank. In Korea, there are very large number of caves which can be used as industrial storage purposes, though most of them are small. The Jejudo Manjanggool, for example, is considered as a good candidate for LPG storage upto 800,000bbls enough to store 130 day supply of LPG. Currently, Korea has excess LPG because of the government suppression policy for safety and chemical usage, which is considered as a transient phenomena. And there is a strong necessity because of military reasons as well. This natural cave is located at the southern tip of the nation's largest island, just a mile from the shore for easy unloading from tankers. It probably is not suitable for crude oil storage or for gases because of the limitted volume.

This sort of constant volume storage does not require extensive engineering analysis; instead it requires good safety precautions, venting and pumping works. This type of storage has nothing to do with the aquifer behavior. In US, artificial caves were developed and used for this purpose but Korea has definite advantages in this regard.

The so called artificial Frozen Earth Storage built by Phillips Petroleum Company has a capacity of 160,000 bbls and required $5 investment per barrel with all the necessary safety features, insulation, compressor and condenser. The details of the Frozen Earth Storage system is shown in *Fig.* 20 and the utilization of Manjaggool cave will require similar installations as shown in this figure.

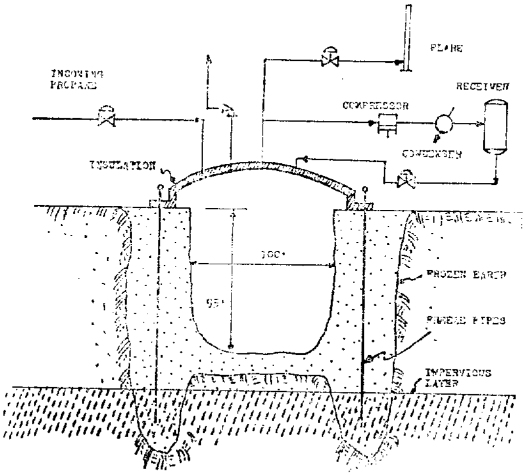

Fig. 20. Scheme for Woods Cross frozen earth storage shows a refrigeration system using the stored products as the refrigerant.

Conclusions

The subject of hydrocarbon underground storage is introduced to Korea, and typical examples of foreign practices are reviewed to illustrate the techniques and the underline principles.

Efforts have been made to make specific plans as to how such underground storage system can be developed in Korea. Utilization of dry holes, development of low temperature geothermal wells and adaptation of Jejudo Manjanggool natural cave have been proposed.

Serious development studies must be made to fully explore the commercial realization possibilities for the gas or LPG underground storage systems in Korea.

Nomenclature

h aquifer sand thickness
r_b, r_g gas bubble radius
P, P_g pressure
r_D dimensionless radius
t_D dimensionless time
θ, θ' time
c compressibility
φ porosity
μ viscosity
k permeability
K_1, K_0 Bessel function of second kind 1st and zero order respectively
s Laplace transform variable
Q_{tD} dimensionless cumulative flux function
W cumulative water influx or efflux
G pressure function
τ dimensionless time
P_{tD} dimensionless cumulative pressure change function
E rate function
K computer time scale factor
a voltage scale factor
Q'_{tD} dimensionless cumulative flux function, constant pressure case
P_0 discovery pressure
V_0 initial reservoir pore volume
V_g reservoir pore volume
Δl twilight zone thickness
d distance to fault
P'_{tD} dimensionless cumulative pressure change function, constant rate case

References

1. H. S. Carslaw, & J. C. Jaeger, "Conduction of Heat in Solids", Clarendon Press, Oxford, England, 1974.
2. K. H. Coats, D. L. Katz, and M. R. Tek, *AIME Petro Trans.*, **216** (1959), 18.
3. W. Hurst, and A. F. Van Everdingen, *AIME Petro Trans.*, **186** (1949), 305.
4. H. D. Yoo, D. L. Katz, M. R. Tek, and R. R. White, *Petro Engr*, B27-B31, No. 9 (1959).
5. H. D. Yoo, D. L. Katz, and M. R. Tek, *AIME-SPE Journal*, No. 12 (1961), 287-297
6. H. D. Yoo, *AIChE Symposium Series*, **58**, No. 37 (1962), 75-82.
7. PID Report Series #59 (1974).