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METHODS OF DETERMINING THE DIMENSIONS OF UNDERGROUND CAVITIES

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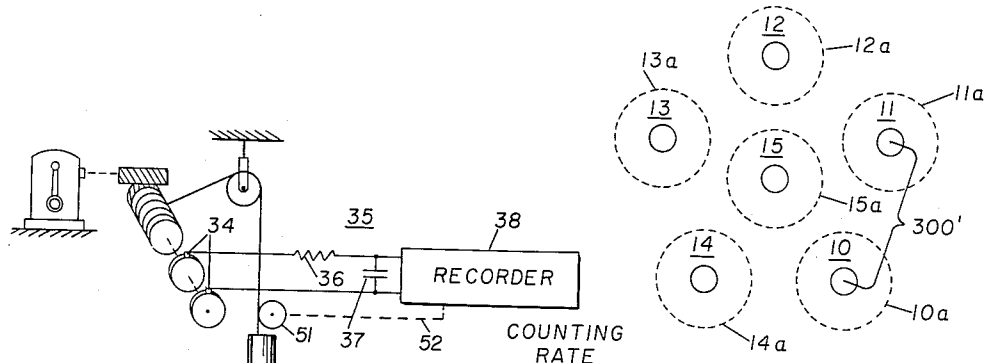
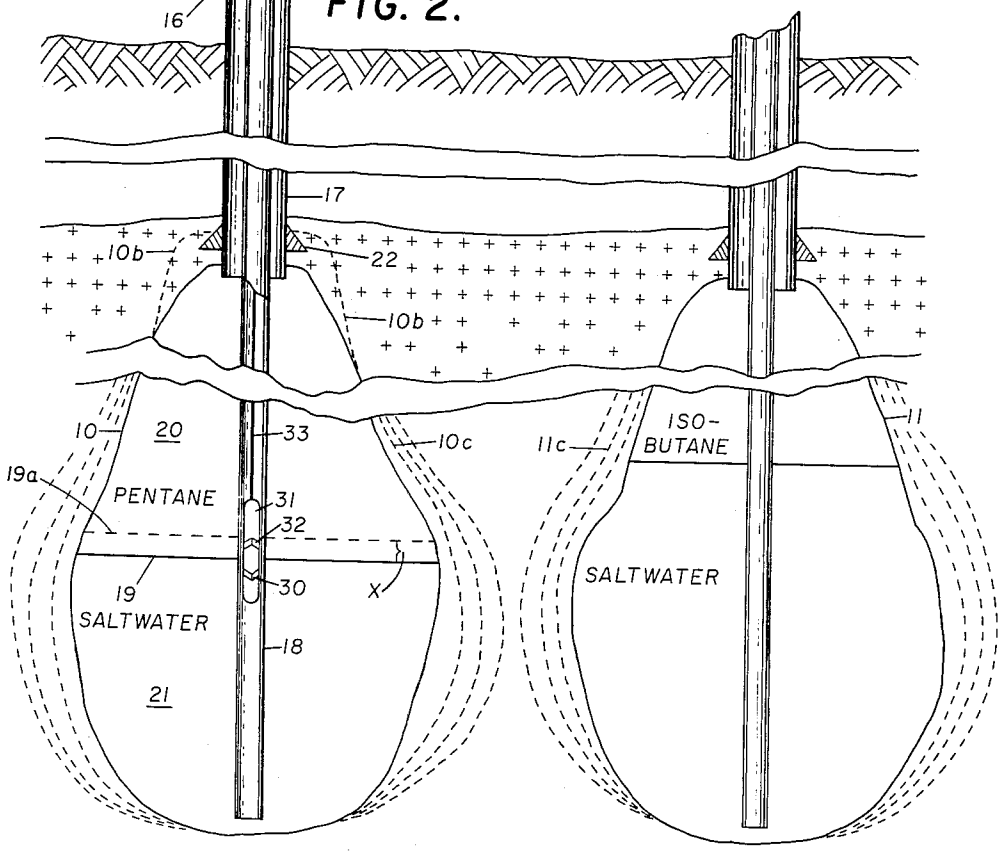


FIG. 1.

FIG. 2.



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METHODS OF DETERMINING THE DIMENSIONS OF UNDERGROUND CAVITIES

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This invention relates to the storage of liquefied petroleum products in storage wells formed in salt formations in the earth and, more particularly, to methods for determining the vertical cross section of storage wells and has for an object the provision of a reliable, simplified method of determining the dimensions of an underground storage cavity.

Use is now being made of storage facilities formed in salt formations in the earth for the large quantity storage of petroleum products. Usually, a plurality of storage wells or cavities are located in the same salt formation a relatively short distance one from the other. As is well-known in the art, the size of a storage well or cavity formed in a salt formation will increase with use over a period of time. Therefore, it becomes important to know when the enlargements of proximate wells become excessive so as to result in the merger of the storage wells beneath the earth and the mixing of the products stored therein.

The vertical cross section of a storage well is similar to a teardrop, that is, narrow at the top and wide at the bottom. But this only occurs under ideal conditions of uniform solubility of a salt formation. Such conditions seldom exist and therefore a true configuration of the storage well is unknown. Accordingly, the horizontal dimensions of the storage well at various depths, important when trying to avoid merger of adjacent wells, can no longer be determined by merely measuring the volume of liquid contained in the well.

Without information as to the size of the well, further problems arise. In the manufacture of a storage well, a shoe or seal is usually provided around the pipes extending into the well to create a pressure vessel in order that the petroleum products, usually liquefied petroleum gas, may be stored in liquid form in the well. Should too much of the petroleum product be withdrawn from the well, the water will begin to erode the roof of the cavity and by a leaching action of the salt around the shoe or seal may eventually erode away the roof of the cavity. It will then be impossible to maintain pressure within the well and the petroleum products will vaporize and be lost to the atmosphere through the porous earth structure above the salt formation.

Accordingly, it is a further object of the present invention to maintain the vapor-tight integrity of storage wells formed in salt formations.

In accordance with one aspect of the present invention, there is provided a method whereby the interface between the petroleum product, usually liquefied petroleum gas, and the salt water may readily be determined. More particularly, the method comprehends the generation of gamma rays and the detection of scattered rays at a point spaced from the point of generation of the gamma rays. By moving the points of generation and detection through the storage well, there will be observed a pronounced change in the detection rate of the scattered gamma rays when the interface is traversed.

Employing this aspect of the present invention, it is

possible then to determine, in accordance with another feature of the present invention, the vertical cross section of the underground storage well or cavity and changes therein. More particularly, the liquid interface is initially located in accordance with the previous method and fluid input to the cavity or storage well is metered. The new position of the interface is determined and from this information it is possible to determine the horizontal cross section of the storage well as a function of depth. A plot of the horizontal dimensions with respect to depth will produce a vertical cross section of the storage well.

For other objects and advantages of the present invention, reference may be had to the following detailed description taken in conjunction with the accompanying drawing in which:

Fig. 1 illustrates a storage well arrangement in a salt formation, and

Fig. 2 schematically illustrates a system suitable for practice of the present invention.

Referring now to the drawings, and more particularly to Fig. 1, there is illustrated a series of storage wells **10–15** located in a salt formation. The boundaries of each of the wells **10–15** are illustrated by the dotted lines **10***a*–**15***a*. Each of the wells is employed for storage of a liquefied oil product, usually some form of liquefied petroleum gas, hereinafter referred to as LPG. For example, the well **10** may have stored therein, pentane, while isobutane will be in well **11**; normal butane in well **12**; propane in well **13**; a raw mixture of pentane, isobutane, normal butane, and propane in well **14**; and normally gaseous olefins in well **15**.

The wells **10–15** may be formed by employing conventional well drilling apparatus to bore a hole into the depths of a salt formation. Thereafter, water preferably warm water, is circulated by way of pipes **17** and **18** to erode the surrounding walls of salt and form a cavern within the salt formation similar to the cavities **10** and **11**, Fig. 2. Thereafter, the product to be stored, for example, pentane, will be pumped from a source, not shown, through pipe **16**, thence through the outer concentric pipe or casing **17** and into the storage well **10**. The salt water is displaced and travels back to the surface by way of the inner concentric pipe **18**. The LPG, being of lighter density than the salt water, rides on top of the water, and being immisible therewith, creates with the water a well-defined liquid interface **19**.

In order to remove the stored pentane, a reverse process is employed, namely, salt water is pumped into the storage well **10** by way of pipe **18**, displacing by positive pressure the stored LPG or pentane to the surface for distribution over pipe lines for use at a refinery or for direct transmission to a market.

With continued use of the storage facilities, the size of each well will increase as illustrated by the dotted lines **10***c* and **11***c* due to erosion of the wall structure of the storage wells by the salt water. This is explained by considering the operation required to withdraw the petroleum product from a well. Salt water from the surface is pumped down through pipe **18** and is heated to the temperature of the surrounding salt formation. With increased heat, the water is able to take more salt into solution until saturated conditions exist at the temperature in the well. Now when the petroleum product is added to the well, this saturated salt water is removed and placed in storage at the surface. If the saturated salt solution be permitted to decrease in temperature, salt will be precipitated out; and when the same water is again used to drive the petroleum product out of storage, the condition of erosion above-described will be repeated. While some erosion is desirable in order to obtain an increase in the size of the storage cavity, un-

controlled erosion can prove quite costly. Should the wall structure separating wells 10 and 11 be completely eroded, the product of well 10 will be mixed with the product of well 11, resulting in considerable expense to the operator. For example, storage wells of the type represented by wells 10 and 11 are usually large enough to hold approximately 250,000 barrels of product. Accordingly, should the pentane in well 10 be mixed with the isobutane in well 11, it would be necessary to transfer 500,000 barrels of product to the refinery for the costly operation of reseparating the pentane and isobutane. In accordance with the present invention, it is now possible to record changes in the cross section of the storage wells so that steps can be taken for a controlled erosion of the wall surfaces of the wells or for elimination of erosion by suitable measures, such as, raising the temperature of the salt water and saturating it completely with salt before injection into the storage well.

In accordance with the present invention, the position of the interface 19 initially is determined. A measured amount of fluid, either water or LPG, is added to the well and causes interface 19 to move to a new position 19*a*. The new position of the interface is then determined. The horizontal area of the well may be determined at a known depth of the well from the information comprising the measured amount of fluid and the distance *x* which the interface has moved. The information as to well area is useful in determining the storage capacity of the well. If the well be assumed symmetrical about the pipe 18, the well radius may be determined at a given depth in the well. The assumption of symmetry is not unreasonable since earth strata are usually uniform in a horizontal direction. By repeating the above steps and from the information thereby obtained, it is possible to plot a vertical cross section of the well and thereby study the extent of well enlargement due to the leaching process.

The method of the present invention may be practiced with a system including a source 30 of gamma rays movable by way of a logging tool 31 along the length of the pipe 18 and through the storage capacity of the well 10. The gamma rays emitted by the source 30 are scattered by the salt water or by the LPG, and these scattered gamma rays are detected by a suitable detecting means 32 supported by and spaced from the source 30 in the tool 31. The detector 32 produces a series of pulses proportional to the number of gamma rays scattered from the surrounding medium, either salt water or LPG; and these pulses are transmitted uphole over the cable 33 and are applied by way of commutators 34 to an integrator 35. The integrator 35, comprised of resistor 36 and capacitor 37, produces a D.C. signal proportional to the gamma rays detected downhole by the detector 32; and this D.C. signal is applied to a null-balance recorder of the strip-chart type 38. The recorder 38 produces a record, a portion 39 of which is illustrated, comprising a trace 40 representative of the signals generated downhole by the detector.

The chart is driven as by way of sheave 51 and mechanical connection 52 to move the strip-chart 39 proportionally to the movement of the tool.

Since the number of gamma rays reaching the detector is a function of the density of the scattering material, the record 39 will indicate whether the tool is adjacent the LPG or the salt water. And, further, since the counting rate decreases with increasing density of the surrounding material, the counting rate will be higher as represented by the portion 41 of trace 40 when the tool is opposite the LPG and lower as represented by the portion 42 of trace 40 when the tool is opposite the salt water. When the tool traverses the interface 19, there results a sharp change in the counting rate as illustrated by the trace 40; and by reference to the length of chart 39, the operator will immediately know the location of the interface 19.

In one embodiment of a system suitable for carrying out the method of the present invention, the source of gamma rays was six millicuries of cobalt-60, and the detector was separated from the source and shielded therefrom with lead absorber a distance of 24 inches. The detector 32 was a sodium iodide crystal coupled to a photo-multiplier tube. A suitable logging tool 31 for carrying out the method of the present invention may be obtained from Well Reconnaissance Incorporated, of Dallas, Texas.

While the fluid input may be either salt water or LPG product, there is illustrated in the arrangement of Fig. 2 a meter 45 connected to the input pipe 18 for measuring the amount of water added to the well. Meter 45 may be of the type to integrate the amount of fluid added to the well. Where the meter is of this type, the cross-sectional area may be determined in the following manner. A fixed amount of fluid, for example, 10,000 barrels, will be added to the well by way of pipe 18. Prior to the addition of this fluid, the position of the interface 19 will have been located and recorded as the trace 40 on the chart 39. Now, after the fixed amount of fluid has been added to the well 10, the interface 19 will move to a position 19*a*. The new interface 19*a* will be located in the manner above-described and will appear on the chart 39 as trace 40*a*. The distance *x* between the traces 40 and 40*a* will be a measure of the total displacement X of the interface from position 19 to position 19*a*. Knowing the total change in the interface position and the amount of fluid added to the well, it will be simple to compute the cross-sectional area of the well 10.

Should the operator discover that the well 10 is getting too large, i.e., there is a possibility that the contents of wells 10 and 11 may merge, steps may then be taken to prevent the further enlargement of the well 10. This can be accomplished, for example, by heating water to be added to the well to well temperature and saturating it with salt so that further erosion of the walls of the well will not take place.

It is of further importance in the operation of storage facilities formed in salt formations that the well be maintained under sealed conditions. For this reason in the formation of such a well a roof of salt is always maintained over the cavity and a seal or shoe 22 provided to act as a packer or seal between the casing or outer pipe 17 and the salt roof of the well.

Because of the ever changing sizes of the storage well, it becomes difficult to maintain a record of the amount of petroleum product in storage. Accordingly, when there is a large demand for the stored product, it will be desirable to withdraw as much of the product from the well as possible. However, if too much of the product is withdrawn, the salt water will begin eroding the roof of the cavity or storage well causing enlargements as illustrated by the lines 10*b* which if permitted to continue would break the seal of the well. Thereafter the well would be useless for future storage of liquefied petroleum products because any product added to the well would no longer be under pressure and would leak through the porous earth formations above the salt formation and to the atmosphere.

In accordance with another aspect of the present invention, it is now possible to maintain a record of the position of the interface between the salt water and the stored petroleum product. In such a record the interface position can be referenced from the earth's surface but preferably, and for reasons of greater accuracy, the reference may be from the location or position of the shoe or seal 22. From the discussion above, it will be apparent that a major consideration in determining the position of the interface is the prevention of leaching of the roof of the well and thereby the maintenance of the seal around the shoe 22. The location of the shoe can be determined from the drilling record. On the other hand, the location of the shoe may be noted from a log similar

to the portion reproduced in Fig. 1. The shoe 22 is formed of material more dense than the surrounding salt. Accordingly, as the radioactive source and detector are moved past the shoe, a distinctive change in signal level will be observed at a recorded depth on the chart. Knowing the location of the shoe and, therefore, the roof of the storage well, it is now possible to withdraw a maximum amount of the stored petroleum product without endangering the seal.

In accordance with that method, the position of the water-oil product interface is accurately determined, despite changes in storage capacity of the well due to continued erosion of the storage well by unsaturated salt water, by moving a source of gamma rays along a path traversing the depth of the storage well. The gamma rays are directed into the liquid stored in the well and surrounding the source. At a point spaced a predetermined distance from the source, the gamma rays scattered by the liquid are detected and a signal representative of the number of scattered gamma rays is recorded with respect to the depth of the source. The position of the interface is noted as above-described upon a sharp change in the recorded values of scattered gamma rays. A portion of a typical chart indicating the position of the interface 19 is represented by chart 39 and trace 40.

In the practice of the present invention it has been found that the positions of the LPG-salt water interfaces may be located with an accuracy of between one or two feet, depending upon the interpretation of the log produced on the record or chart 39 and upon the sharpness of the break between the portions 41 and 42 of the trace 40. Such accuracy is adequate for purposes of aiding operators in locating the interface in order to determine the cross-sectional area of the well to prevent mixing of products stored in adjacent wells and to prevent the eroding of the seal around the casing shoes of such wells. Thus, the present invention provides a simple, accurate, and inexpensive method of obtaining information necessary to the proper operation of storage facilities within salt formations.

What is claimed is:

1. The method of determining as a function of depth the horizontal cross section of a petroleum product storage well in a salt formation subject to water erosion in which the liquid petroleum product forms with salt water liquid in the storage well an interface and in which a casing for the addition and removal of salt water liquid extends from the surface toward the bottom of the well, comprising the steps of moving a source of gamma rays through a column of salt water in the casing and thus along a path substantially traversing the depth of the storage well, directing gamma rays out of said salt water column and through the casing into the liquid stored in the storage well and surrounding the casing, at a point a predetermined distance from the source and within said salt water column and inside said casting detecting the gamma rays scattered by the liquid outside the casing, generating a signal representative of the number of scattered gamma rays detected at said point, recording the signal with respect to depth for indication of the location of the interface between the salt water outside the casing and the petroleum product, adding from the surface a known amount of one of the liquids to the storage well and removing at the surface a like amount of the other of the liquids to displace the position of the interface, and repeating the above steps to record the new position of the interface.

2. The method of determining the cross section of a storage well formed in a salt formation in which a liquid petroleum product is stored with salt water liquid in the storage well and forms therewith an interface and in which the position of the interface previously has been located and further in which a casing for the addition of and the removal of salt water liquid extends from the surface toward the bottom of the well, comprising the steps of adding from the surface a known amount of one of the liquids to the well while removing at the surface a like amount of the other liquid from the well to move the interface to a new position, moving a source of gamma rays through a salt water column within the casing and along a path substantially traversing the depth of the well and directing gamma rays into the liquids surrounding the casing, detecting at a point spaced a predetermined distance from said source and within the salt water column and the casing the gamma rays scattered by liquid surrounding the casing, recording with respect to a depth function the number of gamma rays scattered and detected, and repeating the above steps to produce a record suitable for the determination of a full profile of the cross section of the storage well.

3. In a liquid petroleum storage well formed in a water-soluble salt strata in the earth in which salt water is present to the extent necessary with the petroleum product to fill the storage capacity of the well thus to form with the liquid petroleum product an interface and in which a casing extends from the surface of the earth toward the bottom of the well for the addition of and the removal of salt water liquid, the method of determining the position of the interface despite changes in the storage capacity of the well due to continued erosion of the salt strata by unsaturated salt water, comprising the steps of moving a source of gamma rays through a salt water column within the casing and along a path substantially traversing the depth of the storage well and directing gamma rays beyond the salt water column and through the casing into the liquid stored in the well and surrounding the casing, at a point spaced a predetermined distance from the source and within the salt water column and the casing detecting the gamma rays scattered by the liquid outside the casing, generating a signal representative of the number of scattered gamma rays detected at said point, and recording the signal for indication of the interface.

4. In a liquid petroleum product storage well formed in a water-soluble salt strata in the earth in which salt water is present to the extent necessary with the petroleum product to fill the storage capacity of the well thus to form with the petroleum product an interface and in which a casing extends from the surface of the earth toward the bottom of the well for the addition to the well and the removal from the well of salt water liquid, the method of determining the position of the interface despite changes in storage capacity in the well due to continued erosion of the salt strata by unsaturated salt water, comprising the steps of moving a source of gamma rays through a column of salt water within the casing and along a path substantially traversing the depth of the storage well and directing gamma rays beyond the column of salt water and through the casing into the liquid stored in the well and surrounding the casing, generating and recording a function related to the position of the source within the casing, at a point spaced a predetermined distance from the source and within the salt water column and the casing detecting the gamma rays scattered by the liquid outside the casing, generating a signal representative of the number of scattered gamma rays detected at said point, and recording the signal with respect to said recorded function for indication of the location of the interface.

5. The method of withdrawing liquefied petroleum gas stored in a well formed in a salt formation in which the liquefied petroleum gas forms an interface with salt water liquid in the storage well and in which a casing for the addition of and the removal of salt water liquid extends from the surface toward the bottom of the well, comprising the steps of moving a source of gamma rays through a salt water column within the casing and along a path substantially traversing the depth of the well and directing gamma rays into the liquids stored in the well and surrounding the casing, recording the position of the source as it is moved along said path, at a point spaced

a predetermined distance from the source and within the salt water column and the casing detecting the gamma rays scattered by liquid surrounding the casing, generating a signal representative of the number of scattered gamma rays detected at said point, stopping movement of the source upon the generation of a signal sharply deviating from a previously generated signal and indicative of the position of the interface, removing liquefied petroleum gas from the well, following with the source the change in the position of the interface, and stopping the withdrawal of liquefied petroleum gas from the well when the interface has attained a predetermined position from the top of the well.

6. The method of removing liquefied petroleum gas stored in a well formed in a water-soluble salt strata in the earth in which salt water is present to the extent necessary with the petroleum product to fill the storage capacity of the well and to form with the liquefied petroleum gas an interface and further in which a casing for the addition of and the removal of salt water extends from the surface toward the bottom of the well, comprising the steps of predetermining a position along the depth of the casing as a limit of the liquefied petroleum

gas to be withdrawn from the well, positioning a source of gamma rays in a salt water column within the casing and at said point and directing gamma rays into the liquid stored in the well and surrounding the casing, at a point within the salt water column and within the casing and spaced a predetermined distance from the source detecting the gamma rays scattered by the liquid outside the casing, generating a signal representative of the number of scattered gamma rays detected at said point within the casing, removing liquefied petroleum gas from the well, and upon the generation of a signal sharply deviating from previously generated signals and indicative of the arrival of the interface at the vicinity of said source stopping the removal of the liquefied petroleum gas from the well.

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