

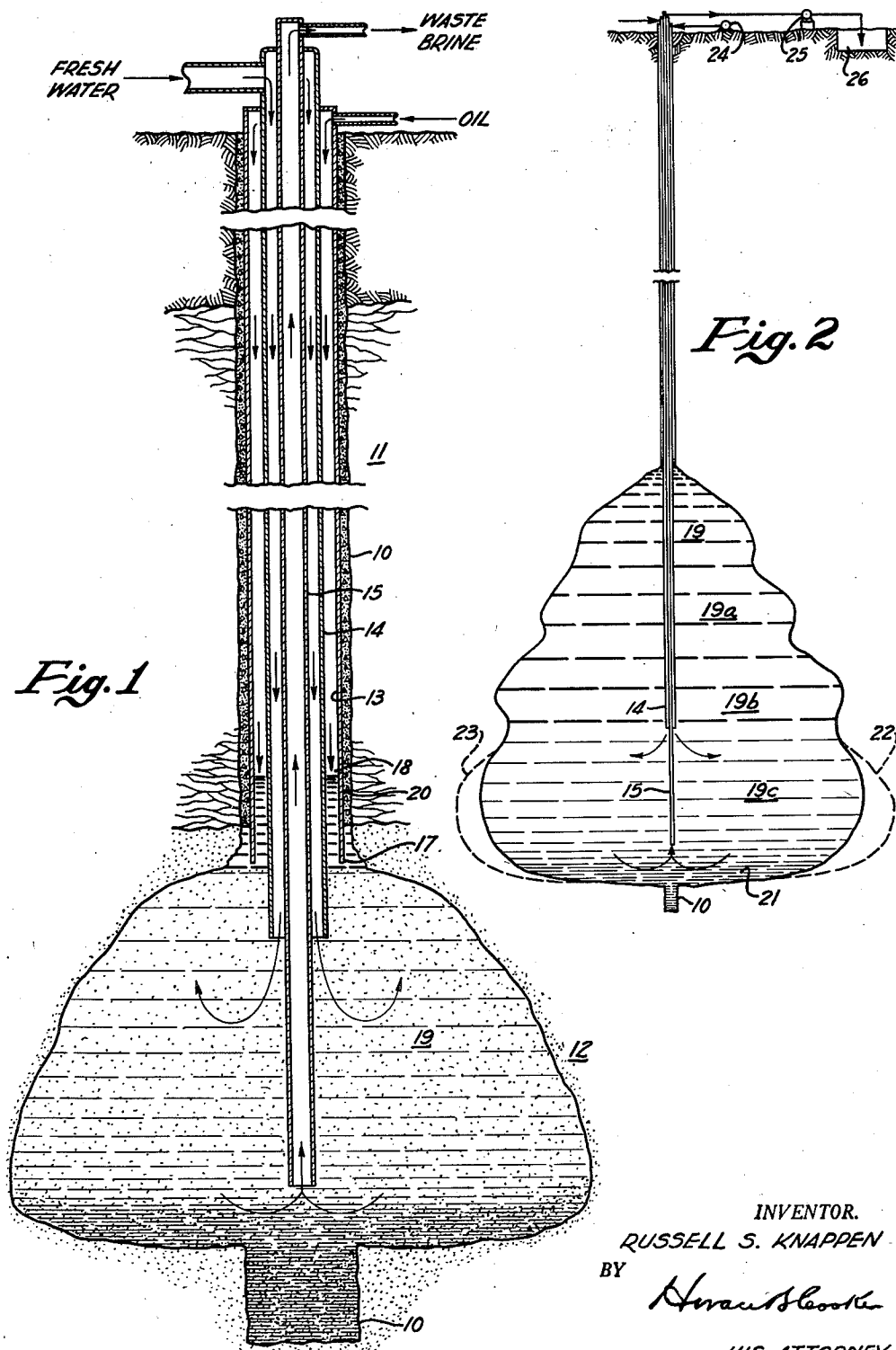
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METHOD FOR DEVELOPING CAVITIES IN SALT OR OTHER SOLUBLE ROCK

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1

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METHOD FOR DEVELOPING CAVITIES IN SALT OR OTHER SOLUBLE ROCK

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This invention relates to a method of forming underground reservoirs for the storage of gases or liquids, particularly petroleum products, such, for example, as liquefied petroleum gas. The invention has particular reference to a method for forming underground storage cavities in soluble-rock formations by dissolving the rock with a suitable solvent.

It is known that, generally speaking, underground storage reservoirs should preferably be of roughly conical form for the purpose of providing a structurally strong reservoir and one in which the overburden will prevent loss of materials stored under high pressure. A conical form also provides the strongest roof as a protection against roof collapse. In other instances, other shapes, e. g., a hollow sphere, may be preferred.

It is an object of the present invention to provide a method of forming shaped reservoirs in soluble-rock formations for the storage of liquids or gases.

Briefly stated, my invention comprises the method of forming a shaped underground reservoir in which a well hole is drilled into a soluble-rock formation, casing is set in the hole down to a point between a substantial distance above, and a substantial distance below, the top of the soluble-rock formation, e. g., usually about ten but possibly several hundred feet, the casing is cemented, at least one outlet and one inlet tubing, preferably concentric, are lowered into the hole and to a depth below the casing seat, non-dissolving sealing liquid is forced down through the space between the casing and the contained tubes to below the casing seat, a solvent that is immiscible with and heavier than the sealing liquid and which will dissolve rock of the formation is then pumped down the inlet tubing, and, after dissolving rock of the formation is withdrawn or forced out through the outlet tubing as a solution of the material forming the soluble-rock formation. Dissolving or leaching is continued until a cavity of predetermined size is produced. The tubing is then lowered in the borehole into position for solution of another section of the activity. Sealing liquid is then pumped into the first section of the cavity preferably through the space between the tubes and the casing, until the immiscible liquid almost completely displaces the solvent in this cavity, above the depth of the shorter of the inlet or outlet tubing. This solvent is forced back up the outlet tube. Introduction of solvent is resumed, and solution of a second section of the cavity begins. This section of the cavity can be made larger in area than the first section of the cavity by continuing the dissolving until a larger amount of dissolved rock is carried to the surface. In similar manner this section of the cavity can be smaller than the preceding section of the cavity by dissolving the formation for a shorter time before introducing sealing liquid to displace the solvent and prevent further dissolution of the walls and roof of the cavity.

2

A saturated solution of solvent is substantially higher in specific gravity than the more dilute solvent being introduced into the cavity and saturated solvent will tend to lie on the floor of the cavity and protect it from further solution. In other words, there will be some tendency for the solution to stratify in the cavity being formed and solution will proceed primarily in a lateral direction or at least more rapidly in a horizontal than a vertical direction thus making it possible to form cavities of vast area. This effect is considerably increased if the solvent outlet tubing is extended to a level much lower than the solvent inlet tubing.

It is a feature of my invention so to dispose the relative positions of the open ends of the inlet and outlet tubing in order to govern the shape of the cavity being formed, a lower outlet tubing forming cavities with larger horizontal dimensions and a lower inlet tubing cavities with greater vertical dimensions. The open ends of the inlet and outlet tubing are preferably maintained at least 10 feet apart.

Although reservoirs can be dissolved out of formations such as dolomite or limestone by using an acidic aqueous solution according to the method of my invention, I especially contemplate forming underground reservoirs in rock salt formations or salt domes in which the solvent employed can be fresh water or a dilute salt water and the sealing liquid an oil.

In the accompanying drawings which serve to illustrate a preferred embodiment of my invention,

Fig. 1 illustrates a borehole, sealed casing, inlet and outlet tubing, and associated apparatus for forming shaped reservoirs, and

Fig. 2 is an elevational cross sectional view showing a partially completed reservoir, the remainder of the reservoir being shown in dotted outline.

Referring specifically to Fig. 1, to illustrate a specific example of drilling a well and forming a shaped reservoir, a borehole 10 is drilled by the usual rotary drilling equipment (not shown) down to cap rock which is reached at 870 feet and thence through the cap rock formation 11 into a salt formation 12 which is reached at a depth of about 2100 feet. Drilling is continued for another 1800 feet into the salt formation. A casing string 13 is then set into the well to a depth which extends into the salt formation 12.

The casing is fixed in position by forcing cement down through casing 13 and up through the annular space between casing 13 and borehole 10. Drilling fluid in the hole below the end of the casing prevents important downward movement of cement, which must rise toward the surface. A plug is pumped down the casing to force most of the cement out of the casing. Pumping is stopped before the plug is forced out of the casing. After the cement sets, the plug in the casing is drilled out. Two concentric strings of tubing, 14 and 15, are then lowered into the well. The outer tubing 14 is lowered to a depth below the casing shoe 17 and the inner string of tubing 15 is lowered to a depth of about 200 feet below the bottom of the outer tubing 14. The above depth differential of 200 feet is selected to form the first and uppermost section 19 of a conical cavity. Four repeated settings and dissolving steps are required to form the entire cavity, as shown in Fig. 2. A seal is formed by introducing an oil, or other water-immiscible liquid having specific gravity less than water, into the annulus 18 between the outer tubing string and the casing 13. This liquid is pumped down the annulus 18 and will flow out of the bottom of the casing and will rise up into any annular space between the casing 13 and the

3

borehole 10, which was not filled by cement. The oil or water-immiscible liquid is pumped into the cavity to displace any water which stands in the hole above the bottom of the outer tubing string 14. This oil will prevent any subsequent solution of salt above the lower level of the oil or water-immiscible liquid.

The importance of the seal of water-immiscible liquid between the open hole and the casing and the outside string of tubing was strikingly demonstrated in one instance where no seal was employed in leaching out a cavity with an unsaturated brine. The dissolving of salt around the casing created a cavity having a volume of more than 400,000 gallons. The hydrocarbons which subsequently occupied this cavity when the reservoir was put in use could not be recovered except by perforating the casing and, in addition, this uncontrolled leaching left a long length of unsupported casing extending into the cavity.

About 5,000 barrels per day of fresh or slightly salty water are pumped into the hole through the outer string of tubing 14 and are returned, except for that amount of solution which remains to displace dissolved salt, to the surface for disposal or sale. At this rate of leaching with fresh water, a 50,000 barrel reservoir can theoretically be formed in about sixty days. After allowance for interruptions and inefficiency and rate of solution, a 50,000 barrel cavity should be formed in 150 days. When the uppermost section 19 of the cavity has been substantially completely formed as shown in Fig. 1, the tubing strings 14 and 15 are then lowered into the borehole 10 and oil is pumped down through the outer annulus 18 until the brine which had occupied the cavity 19 is displaced upwardly through the tubing string 15. A seal is again formed by the oil and leaching proceeds beneath the seal in the same manner as occurred in the leaching of the cavity section 19. This process is repeated until four sections are formed as shown in Fig. 2. Any desired number of sections can be removed to form a cavity of the size and shape desired.

Fig. 2 is an elevational view of the entire cavity showing the successively formed sections 19, 19a, 19b, and 19c. Section 19c is incompletely formed, the process of solution of the rock not having been entirely completed. During the time that section 19c is being formed, an oil seal extending down through and filling sections 19, 19a, and 19b prevents further solution by the water of these upper sections of the cavity. The tendency of dense, saturated brine to settle at the bottom of the reservoir forms a protective layer 21 which prevents further leaching downwardly. Outer tubing string 14 serves as an inlet pipe for solvent and concentric inner tubing string 15 for the flow of brine to the surface. After leaching has continued in the section 19c until the cavity has been increased in size to approximately the dimensions indicated by dotted lines 22 and 23, additional oil is pumped by the pump 24 down through the annular space between the casing 13 and the tubing string 14 until the brine in section 19c has been substantially completely forced out of the cavity. Brine removed from the cavity 19c is pumped by pump 25 to pit 26 and to conventional means (not shown) for disposal.

Circulation of the leaching fluids can be reversed so as to introduce dilute solvent through inner string 15, and withdraw saturated solution through the annular space between the tubing strings 14 and 15.

When the leaching process is completed the tubing strings 14 and 15 can be pulled and a string of large tubing (not shown) of, for example, about 5½ inches in outside diameter can be run in and suspended or bottomed at substantially total depth in the reservoir shown in Fig. 2. A frame or derrick or pulling mast varying from 65 feet to 140 feet in height and a pulling machine are employed for running, adjusting, and pulling the above mentioned tubing strings.

4

In forming a shaped reservoir by the continuous method, the outer tubing string (inlet string) is lowered gradually down the well hole. The rates of dissolving and of lowering (and relative position, as aforesaid, of the inlet and outlet tubing) determine the lateral dimension of the cavity provided by leaching, wider cavities being formed when the injection of solvent is more rapid and when tubing string moves more slowly. As the outer tubing string is moved progressively downwardly the inner tubing string may be lowered at substantially the same rate and the seal of solvent-immiscible liquid is pumped into the well at a rate such that the interface between the sealing liquid and the leaching solvent will travel downwardly at substantially the same rate as that of the tubing. It is necessary that the bottom open hole of the outer tubing remain at all times below the said interface. An oil seal can consist of a hydrocarbon that is to be stored in the well so as to avoid having to pump out the sealing liquid after the cavity has been formed.

When the cavity has been formed and filled with stored fluid, this fluid can be withdrawn from storage by various methods. If the stored fluid is a gas, or will become a gas on relief of pressure, the fluid may be withdrawn by merely reducing pressure at the casing head, which is the top of the casing cemented in the overlying formation. If the fluid is desired in liquid form, but will gasify upon release of pressure, the fluid may be recovered by injecting saturated brine through tubing 15 extending to a point near the bottom of the cavity and forcing the stored fluid under pressure to the surface through tubing 14 or through casing 13, or both. If the stored fluid will not gasify upon release of pressure, it may be pumped by ordinary oil-field-pumping methods through tubing 15. Alternatively, the fluid may be forced to flow to the surface through tubing 15 by injecting a gas under sufficient pressure into the upper part of the cavity through tubing 14 or through casing 13, or both. Alternatively, saturated brine may be injected into the bottom of the cavity through tubing 15, thereby forcing the lighter stored fluid to rise to the surface through tubing 14 or casing 13, or both. Saturated brine must be used in cavities in salt to avoid further solution of the cavity walls and roof, with resulting destruction of the preferred conical or other formed shape of the cavity. The positions of the lower ends of tubing strings 14 and 15 will normally be adjusted to secure the results desired with a minimum of agitation of the stored fluid and a minimum of mixing of injected and withdrawn materials.

My method and the reservoirs formed thereby are especially well adapted to the storage of hydrocarbons or gases under high pressures, since among other shapes, conical shapes can be produced which will provide the strongest possible roof shape for maintaining the cavity intact and resisting the pressure of fluids stored in the cavity.

Having described my invention, I claim:

1. A method of forming shaped underground reservoirs in soluble-rock formations, the said method comprising: drilling a well through an overburden and into a soluble-rock formation; cementing casing in the well, the casing seat being located at a point between a substantial distance above, and a substantial distance below, the top of the soluble-rock formation; introducing a tubing string into the cased well and running it to a substantial depth below the open bottom end of the said casing; running another tubing string into the well to an even greater depth; pumping a sealing liquid, that is relatively a non-solvent with respect to the soluble rock formation, into the well and permitting the sealing liquid to flow into open hole below the casing and rise up around the casing; pumping a solvent that is immiscible with and heavier than the sealing liquid down through one of the said tubing strings; introducing the solvent

5

into the well and thus bringing it into contact with the soluble-rock formation and dissolving rock of the said formation; forcing a solution of the rock in the solvent upwardly to the surface through the other of the said tubing strings; after a period in which a cavity of a predetermined capacity and approximate lateral dimension has been excavated by said dissolving, introducing additional sealing liquid into the well and thus lowering the seal that is formed by the sealing liquid; also lowering the tubing strings in the well and repeating the dissolution process until another, lower cavity of a predetermined capacity and approximate lateral dimension has been formed; and continuing a repetition of the foregoing steps while varying the period of dissolving to obtain cavities of predetermined approximate lateral dimension until a shaped reservoir has been formed.

2. In a method of forming shaped underground reservoirs in soluble-rock formations, in which a borehole is drilled ultimately to total reservoir depth, casing is cemented in the borehole to a depth which includes some fluid-impermeable rock, and tubing strings are run in, one to a depth in the soluble-rock formation below the casing, and another to a greater depth, the steps of: pumping a non-solvent sealing liquid downwardly through space between the casing and tubing strings to and beyond the bottom of the casing; pumping a solvent that is heavier than and immiscible with the sealing liquid down through one tubing string into contact with the soluble-rock formation and thus dissolving rock of the formation; forcing solvent containing dissolved rock upwardly to the surface through another tubing string; after a selected period in which a cavity of a predetermined capacity and approximate lateral dimension has been so excavated, introducing additional sealing liquid into the well thus lowering the seal formed thereby; lowering the tubing strings and repeating the dissolution process at a lower point in the well; and continuing a repetition of the foregoing steps until a shaped reservoir has been formed.

3. A method of forming underground reservoirs in soluble-rock formations for storage therein of fluids, the said method comprising: drilling a well through overburden and an impermeable rock formation into soluble rock formation; setting casing into the impermeable rock formation to a depth within the said impermeable formation; cementing the casing in the so-formed open hole; running at least two strings of tubing into the cased well, one to a depth slightly below the bottom of the casing, and another to a substantial depth below the bottom of the other tubing; pumping a sealing liquid that is immiscible with and of lower density than solvent used in leaching the soluble-rock formation into the well and to and beyond the bottom open end of the casing; pumping solvent down through one tubing and into dissolving contact with soluble rock in the open well; by said pumping of solvent, forcing solvent and dissolved rock upward through a second tubing to the ground surface; after a period in which a cavity of a predetermined capacity and approximate lateral dimension has been so excavated, introducing additional sealing liquid into the well and thus lowering the seal that is formed by the sealing liquid; also lowering the tubing strings in the well and repeating the dissolution process until another, lower cavity of a predetermined capacity and approximate lateral dimension has been formed; and continuing a repetition of the foregoing steps, while varying the period of dissolution to obtain cavities of predetermined approximate lateral dimension, until a shaped reservoir has been formed.

4. A method of continuously forming shaped underground reservoirs in water-soluble salt formations, the said method comprising: drilling a well ultimately to total reservoir depth; setting casing into the resulting borehole and cementing the same; introducing tubing

6

string into the cased well and running it to a substantial depth below the bottom open end of the said casing; running another tubing string into the well to an even greater depth; pumping an oil into the annular space between the well and the tubing strings; lowering the tubing strings, while introducing water through one of the strings and removing water, containing dissolved salt, through another, at a rate of advance such as will provide a lateral cavity of approximate predetermined dimension; and continuing to introduce oil at a rate to form an interface traveling downwardly at substantially the rate of lowering the tubing strings to seal from further dissolving action the surfaces of the already formed reservoir.

5. The method of claim 4 in which the tubing strings are concentric, water is pumped into the well through the outer, shorter tubing and water containing dissolved salt is removed through the inner, longer tubing.

6. A method for forming underground reservoirs of generally conical shape in water-soluble salt formations comprising drilling a borehole into the salt formation; cementing a casing in the borehole to prevent upward movement of fluids outside of the casing; running at least two strings of tubing down through the casing into the borehole below the lower end of the casing, one of the strings of tubing being longer than the other and extending deeper into the borehole than the other; pumping water down one of the strings of tubing into the salt formation to dissolve the salt and force brine formed by dissolution of the salt up the other string of tubing; pumping a water-immiscible sealing fluid having substantially no solvent effect on salt and a density lower than water down the casing into the borehole and cavity formed by dissolution of the salt formation to form a water-immiscible fluid-brine interface above the ends of the strings of tubing; removing brine containing a predetermined amount of salt from the salt formation; lowering the strings of tubing to a deeper position in the salt formation; pumping additional water-immiscible fluid into the borehole and cavity to lower the water-immiscible fluid-brine interface substantially the same distance the strings of tubing were lowered; and repeating the steps of pumping water into the formation, to remove a predetermined amount of salt, lowering the tubing and lowering the level of the water-immiscible fluid brine interface; the amount of salt removed per foot of lowering of the strings of tubing being greater as the tubing is lowered deeper into the salt formation.

7. A process as set forth in claim 6 in which water is discharged from the shorter string of tubing into the salt formation and brine is delivered from the salt formation through the longer string of tubing.

8. A method for forming underground reservoirs of generally conical shape in water-soluble salt formations comprising drilling a borehole into the salt formation; cementing a casing in the borehole to prevent upward movement of fluids outside of the casing; running at least two strings of tubing down through the casing into the borehole below the lower end of the casing, one of the strings of tubing being longer than the other and extending deeper into the borehole than the other; pumping water down one of the strings of tubing into the salt formation to dissolve the salt and force brine formed by dissolution of the salt up the other string of tubing; pumping a water-immiscible sealing fluid having a density lower than water down the casing into the borehole and cavity formed by dissolution of the salt formation to form a water-immiscible fluid brine interface above the ends of the strings of tubing; removing brine containing a predetermined amount of salt from the salt formation; lowering the strings of tubing to a deeper position in the salt formation; pumping a volume of water-immiscible fluid substantially equal to the volume of salt removed in the preceding dissolving step into the cavity in the salt formation to lower the water-immiscible fluid brine interface substantially the same distance the strings of

tubing were lowered; and repeating the steps of pumping water into the formation, to remove a pre-determined amount of salt, lowering the tubing and lowering the level of the water-immiscible fluid brine interface; the amount of salt removed per foot of lowering of the strings of tubing being greater as the tubing is lowered deeper into the salt formation.

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