Cathodic Protection of Well Casing

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ABSTRACT

Despite the existence of problems, extensive field experience over the past 13 years demonstrates the effectiveness of cathodic protection in arresting external corrosion of well casing. This principle utilizes direct current which is projected through the formations to the casing from a ground bed located from 100 to 300 feet from the well. The principle current sources presently being used are either rectifiers with graphite or Duriron ground beds, or magnesium anodes. Where applicable, magnesium anodes are preferred as their lower potential minimizes the chance for stray current electrolysis on foreign structures.

This method is not limited to protection from just galvanic currents but also mitigates the corrosive action of acidic waters and anaerobic sulphate reducing bacteria. Control of these latter organisms is achieved through deposition of an alkaline film on the casing caused by ionization of the water in the various formations.

Log current potential measurements made by surface tests for determining current requirements when properly applied correlates with the down-the-hole potential drop logs.

Numerous of these tests throughout the country indicates a range in current requirements of from 0.35-16 amperes. In the same field this requirement may vary by two to four fold, often between adjacent wells.

Installation costs for the rectifier type vary from $300 to $500 per well; whereas, magnesium anode installations range from $175 to $700 per unit.

Use of Salt Solution Cavities for Underground Storage

by
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ABSTRACT

The use of solution-created cavities in salt for underground storage of hydrocarbons and other substances came about directly as a result of an invention patented in Canada and the U.S. While the solution process that operates in the creation of a storage cavity is superficially like that for brine production, the goals and techniques are necessarily different. Water plays an important role in storage in causing the effective sealing of the storage cavity in salt that is porous and permeable to some degree and might otherwise leak.

To insure the complete safety of underground storage cavities special techniques are required. Exploration drilling including coring of roof and cavity zone should usually be done. Considerable laboratory study and analysis of cores is desirable on a first project in any area. For a storage development to be made there are four principal requirements:

1. *Salt section of sufficient thickness and purity that can be rendered impermeable by the solution process.*
2. *Satisfactory roof or caprock conditions.*
3. *Sufficient depth to permit confinement and suitable section between the cavity and the surface to insure effective well completion.*
4. *Adequate surface provisions and resources for water supply, disposal, and storage.*

Appropriate field testing for safety prior to use should be done. Safety measures, observations and records during use will provide assurance of efficient recovery of stored material and elimination of possible hazards. Some control of cavity shape and dimension from a practical viewpoint now appears feasible but further experimentation will be required.

The widespread use of salt solution cavity storage will probably increase in future years as the benefits of safety and cost become evident from present operations.

INTRODUCTION

Solution cavity storage was first conceived of in Canada during World War II (1) as applied both to gases and liquid hydrocarbons. By 1949 field experimentation had been done in the U. S. and during the 1950's the use of salt solution cavities became increasingly widespread so that by the present time the annual storage issues of petroleum industry trade journals show an exceptionally widespread usage of this procedure.

Since its conception, the making of the storage cavity in the soluble salt has been visualized as an integral and desirable part of the process the use of solution and not mechanical mining. When a U. S. patent was first applied for (2) although solution as the means of making the cavity was envisioned, this apparently was not expressed sufficiently clearly in the technical language of patents to prevent possible conflict with some older European art which visualized damming up mechanically-mined openings in old potash or salt mines and storage, probably of non-volatile materials, in them. Accordingly a re-issue patent application was filed in 1954, narrowing the concepts involved and spelling out the role of solution in the storage cavity and was issued in the spring of 1957 (3). Subsequently the subject patent and re-issue patent have been dedicated to the public.

PERTINENT GEOLOGIC CONDITIONS FOR USE OF SALT CAVITY STORAGE

Generally in the world there are two types of salt occurrences, bedded rock salt and domes or similar deformed rock salt masses derived from originally bedded deposits. Typically the bedded deposits are of relatively minor thickness without interruption by impurities which are generally carbonate or sulphate rocks. Much more substantial thicknesses are found in salt domes. The general occurrence and characteristics of these types of naturally-occurring rock salt are described in more detail and their distribution indicated by Bays, Peters, and Pullen (4). This paper also describes the present concepts of the writer as to the irregularities of deposition, diagenetic effects, and geologic history of rock salt deposits, irregularities that can play a pertinent role in the development of solution cavity storage.

Another phase of the nature of most rock salt, whether bedded deposits or dome salt, is the amount of contained impurity. Most rock salt contains sufficient calcium sulphate and calcium-magnesium carbonate so that solution water becomes saturated for the conditions with these substances. When beds are logged by drillers, geologists, or geophysically, what becomes designated as "rock salt" is rarely more than 90% NaCl and often impurities on the order of 25% to 30% are not unusual.

A most significant aspect of most rock salt is its porosity and permeability. Most rock salt is dense and in a conventional sense would not be classified as a permeable and porous material, and yet like most naturally occurring substances, as for example, granite, and most dense igneous rocks, rock salt has a small but measurable porosity and permeability (5). Some salt is significantly permeable, especially in its bands of impurity. There is apparently also considerable variation in density, porosity, and permeability, as well as strength, and physical behavior from one geological environment to another (6), (7), (8). The nature of salt is such that it tends to move in such a way as to close any opening made in it. The rate and nature of the movement depend upon a number of factors to indicated later.

REQUISITE CONDITIONS FOR SALT CAVITY STORAGE

It is not feasible to install a solution cavity for underground storage everywhere that rock salt is known. While wide variety of materials could conceivably be stored in such underground solution cavities, most of the materials which are stored are volatile, flammable, and require a confining pressure to maintain liquifaction. Because of the nature of the stored material appropriate safety measures are necessary, although with underground storage of this type, far less elaborate precautions may be needed. Most systems operate with brine as the means of displacing the stored material unless additional cavity development is in process. While there are manifestly exceptions to the more general typical practices to meet special needs or conditions, these are the present normal procedures in connection with underground storage in solution cavities.

The essential requirements to provide suitable and safe underground storage are:

1. A salt section of sufficient thickness and purity to permit cavity development without significant constrictions, subsurface movements due to substantial impure interbeds, and which will be rendered impermeable to the material to be stored when a solution cavity is made therein.

2. Roof or caprock that will stand supported by the fluid buoyancy available from the brine, water or product to be stored and free of materials which are soluble in the hydrocarbon material to be stored.

3. Sufficient depth and appropriate section between the cavity and the surface to permit effective cementing and effective well construction together with the geostatic load to confine the stored material with complete certainty.

4. Suitable surface provisions and resources for water supply, disposal, and storage of water or brine to permit development and operation of the storage system.

It should be recognized that some exceptions or deviations to a degree from these requirements can be coped with by technical means, often at considerable expense, that can render a particular site usable from a practicable viewpoint. However, it is the obligation of storage operators storing flammable materials to insure 100% effectiveness of confinement for the protective measures at the surface in the event of undesirable leakage.

MATERIALS SUITABLE FOR STORAGE IN SALT CAVITIES

Although most underground storage to date has been limited to a few liquid hydrocarbons, largely classed as LPG but including ethylene and other products which require substantially high pressures, it is also evident that solution cavities in salt are appropriate for storage of other materials. The use of such cavities for natural gas, coke-oven gas, or such purified gases as oxygen or hydrogen is only commencing compared to liquid-state storage.

Generally the materials economically succeptible to such storage must be gaseous or liquid materials which are immiscible with or very slightly soluble in water or brine and non-reactive with rock salt, anhydrite, and dolomite. Those requiring pressure confinement and the range of temperature present in any province in the subsurface salt section are conditions that require an adjustment of the nature of tailor-making the storage to the stored material.

Study of the gaseous, volatile, and toxic materials which are vital to our modern industrial civilization in substantial quantity and which fill the chemical and physical requisites to be suitable for storage in salt cavities indicates many such substances could make use of this kind of storage.

Two further techniques will aid wider use of the method of storage. One is to insert an inert material between the stored substance and the underlying water-brine section of the cavity. The other is to line the solution cavity with inert materials which will prevent solution or reactivity. Both of these techniques are under development to render solution cavity storage more widely usable for specific materials which dissolve salt, react with it, or have some affinity with water or brine.

Generally the stored materials today being put into salt solution cavities fall into three categories:

1. Liquids such as gasoline, fuel oil, or crudes.

2. LPG -- low pressure liquids such as butane, propane.

3. High pressure volatiles such as ethylene.

While some gas storage has been done in solution cavities most such storage does not use this technique but depends on rock pore storage in old reservoirs or aquifers. Future usage will see a wide variety of materials considered for cavity storage strictly on the economic merits of such storage.

PHYSICAL BASIS FOR THE SOLUTION PROCESS

There are two basic means by which water introduced into a salt cavity becomes saturated. The constant process in operation is that of diffusion. Diffusion is the term applied to the ionic movement of sodium and chloride ions away from the salt-water interface, at which place transformation from solid to liquid (or dissolved) state occurs, and towards regions of lower ionic pressure. Such motion, being of an ionic, rather than a mass, nature is exceedingly slow and passage of individual ions from the salt face into the general cavity takes much time. In a simple system of solution, without considering extraneous phase relations, mass effects of accessory substances, or other influences, the rate of diffusion is susceptible to calculation (9), and although the calculations are somewhat complex it is evident that in spite of many possible variations that diffusion as a process is a very slow means of obtaining saturation.

As opposed to diffusion (ionic or molecular movement), circulation implies the existence of mass movement. Such movement brings the unsaturated fluid to the salt face where its saturation can be increased. At least three different forces contribute to this process: temperature differences, gravity segregation, and pressure gradients. Due to temperature differences between injection water and stabilized cavity water, the introduction of unsaturated fluid causes the rather well-known temperature-convection process of adjustment toward an even gradient to operate. Actually this process is a fairly rapid one as brine cavities will come to equilibrium within hours after cessation of circulation (normally 24 to 72 hours). In addition to that movement due to temperature differences, there is a gravity movement of fluids introduced into cavities that is very pronounced so that injected under-saturated (light) fluids no matter at what point they are introduced, tend to rise above or through the denser more nearly saturated fluids. It is thus nearly always characteristic that the fluid in any active brine cavity is saturated at its base, is rarely more than 10% to 15% saturated throughout much of the roof area, where the roof is not salt and may be essentially fresh at the highest point of the cavity, except for those modifications brought about by diffusion as influenced by time and temperature. The gravitational process is a very rapid one and is the most important single factor contributing to the movement of fluids within the cavity.

Another significant process in brine cavities is the response to pressure gradients established by the application of pressure in the brine lifting operation. The application of pressure has an initial effect in a new well of causing circulation of the injected fluid past the salt face at velocities that actually produce some solution; however, as appreciable size is developed, these velocities are proportionately reduced, and the circulation effects of pressure differentials become insignificant. Thus in ordinary brine cavities the fluid velocities due to pressure differentials are on the order of the imperceptible, and solution takes place only by the process of diffusion at the very slow rate which characterizes tubing injection. Under these conditions, several years could be required for the development of a cavity of sufficient size to provide a cavity of significant volume, particularly if the brine produced is near saturation.

Another instance in which applied pressure is of importance is in the dissipation of fluid from the cavity into the porous and permeable zones of the salt itself. Salt, though essentially dry, is to some degree porous and permeable. Applied pressure in cavities causes fluid to move into this porosity according to d'Arcy's law, in proportion to the applied pressure differential in atmospheres, subject to the reduction of effective permeability due to saturation of the pores of the salt with a non-brine gaseous or liquid phase that may be present. This process causes continuous outward flow into (a) the most permeable zones and (b) the zones where there is the most effective pressure application, both within the salt as well as within any exposed underlying or overlying beds and can become an important process in which the geologic sequence may significantly affect the movement of fluids to obtain saturation. Though maximum pressure is normally exerted at the base of the cavity, the zone of maximum permeability can be anywhere, and typically is not at the base of a salt section. Filtration into the permeable zones will continue until permeability is sealed by deposition from the outward-migrating fluid, usually salt or sulphate. In portions of cavities where salt and cementing agents are successively removed by ensuing solution the process is a continuing one.

A combination of diffusion and the circulation, the latter due to temperature, gravity, and pressure differences, thus produce saturation in a brine cavity. The most economic system of solution cavity development will be that which is designed to secure the advantage of having all these processes, or as many as possible, working favorably rather than disadvantageously, together with those numerous other conditions or factors which control solution. In addition, as is later indicated, if it is possible to introduce a circulation pattern that causes the solution to occur and the saturation to be obtained in a desired part of the cavity so that this is the primary means of solution, then this becomes the most satisfactory means of development.

PURITY AND TEXTURE OF THE SALT

Purity and texture are among the several factors which control the area, direction, and rate of solution of salt. Salt purity and texture relate both to original deposition of the salt beds and to their subsequent geologic history. Common impurities in salt beds are sulphate and carbonate, with occasional clay and argillaceous zones. Each salt bed or layer is normally purer in the upper part and more impure in the lower part because deposition of the bed is from bottom to top and impurities tend to be deposited in the lower part. Occasionally, particularly in thin salt beds, impurities are uniformly distributed throughout the bed.

As solution proceeds, the impurities accumulate on the floor and lower parts of the cavities and substantial voids are left in these piles of impurities. This substance blankets the lower portion of the salt and concentrates solution in the upper part of the exposed formation. Salt grain size and texture also control and direct solution. The interstices between small-size crystals or grains are the avenues by which solution proceeds. In fine-textured salt a much larger surface area is available to attack by solution than in coarsely-textured salt. Salt texture probably varies vertically from one bed to another in areas of commercially thick salt. Generally the texture reflects the deformation history of the salt beds, but depositionally is often coarsest near the base of the salt bed and finer in the upper part. This variation in texture also tends to concentrate solution of the salt toward the upper part of the bed.

In the geologic past, solution commonly took place along fracture and joint planes. These enlarged crevices were left with residual impurities released from the dissolved salt and were subsequently filled with saturated brine which, with burial and time, precipitated salt to refill these openings. This secondary filling is typically a very high purity salt of fine texture and different grain or crystal orientation than that of the salt bed enclosing it. The solution rate in this secondary salt is typically five to ten times higher than in normal bedded deposits. These secondary features are concentrated in linear patterns along joints and along the tops of salt beds. Solution will follow them preferentially.

Salt beds buried below 4000 to 5000 feet or deformed in salt domes have frequently been altered in part by "flowage" or deformation processes. In the bedded salts at such depths it is to be expected that the processes of deformation have caused partial destruction of original depositional or bedding features. Usually such destruction is zonal within the salt so that in part of a salt unit the original features are preserved and in others there has been flowage, granulation, re-crystallization, and distortion of the original texture and purity. Even in the most severe stresses of salt dome intrusion and in salt beds to nearly 10,000 feet below the surface, this process does not usually completely destroy the natural bedding but leads to the development of zones which have a preferentially high tendency toward solution. Zones of this type are readily recognizable in cores and are to be expected under most geological conditions in the United States salt basins. Where the strata are essentially horizontal at these depths, the altered beds are usually stratigraphically zoned and are represented either by zones of weakness, with respect to horizontal parting of the beds by the fracture process, or are zones of strength and recementation and must have their role evaluated in solution techniques for development of storage cavities.

EXPLORATION FOR STORAGE CAVITIES

With the ramifications of salt nature and condition, roof nature, and the necessity for insuring all of the elements of well construction and cavity development, it is evident that a very detailed knowledge of subsurface conditions is essential to design, development, and subsequent operation of a solution-cavity storage. While the drilling of conventional oil wells or brine wells could well provide the information necessary to a decision that solution cavity storage development is feasible at a particular site in bedded salt or a salt dome, the essential detail of information for design often is not available.

Exploration drilling should furnish the basis for design and development of a solution cavity storage. Where subsurface conditions are reasonably uniform, multiple cavity development will require only a reasonable amount of information initially and will permit a reduction in exploratory or preliminary information as subsequent cavities are made.

Because solubility and solution rate as well as behavior of rock materials affected by solution are so significant in the development and operation of solution cavities, core information provides the best basis for study. Where multiple salt beds are present and it is necessary to decide which bed or combination of beds is to be cavity and what strata are to comprise the roof, continuous coring of the sequence from well above any possible cavity roof is essential. It is the writer's experience that larger diameter (4 to 5 inch) diamond cores furnish the best information and often are little more expensive to secure in an over-all operable project than are slim-hole cores. This is particularly true when a hole is drilled and after the information from it is secured, it is then adapted to solution-cavity storage use. It is the writer's experience that a slim-hole exploration wells are extremely difficult to effectively plug and often could be a hazard to a successful project. If a small-diameter hole is not drilled on the actual site of a cavity but lateral to it, the information secured is not directly pertinent but is only applicable insofar as uniformity of the area will permit -- a condition often not readily ascertained. For these reasons direct drilling exploration on an actual site with appropriate adoption of the exploration hole to the operation hole at the proper stage has proven the most practicable plan.

The geophysical logs of the exploration hole -- particularly reference gamma ray-neutron logs to which all subsequent operations can be referred are an essential element of the exploration process. While electric logs, sonic logs, and other logging parameters such as hole diameter and temperature all have significant applications, the solution process and the subsurface location of stored hydrocarbons are best traced through the years of development and operation by radioactive logging techniques of those presently available.

LABORATORY TESTING

In the initial phase of storage development, exploration drilling will yield cores, which together with geophysical logging, will provide the basic data for decisions of design, testing and development.

While core description by an experienced geologist who knows what to look for in terms of distribution of soluble minerals, stratification, incipient partings and fractures, evidences of prior solution history and other lines of observation that will aid in predicting subsurface behavior is basic to the success of any project, no opportunity to supplement the judgment and experience with quantitative laboratory data should be overlooked as part of the exploration process. What the visual core examination reveals when appraised in a framework of detailed geophysical logs, drilling data, and laboratory determinations has much greater value.

In various projects there are a large number of laboratory parameters which might find use, although it is doubtful that all of them ever would be needed. The principal techniques which have been used, with brief comment as to their utility, are as follows:

Solubility Tests are commonly run on both the rock salt and roof to determine the impurity or amount of soluble material present.

Rate of Solubility Tests are frequently needed when different types of rock salt are present and it is desirable to determine what the relative effects of preferential solution might be in different beds or salt masses.

Porosity and Permeability Analyses of a conventional nature are beginning to be run more widely. However, for most operations, the permeability as a physical constant, computed in terms of water, is of little significance compared to the value of data which relate to the state of salt and roof rock under the actual saturation conditions. Some such tests are run with confining pressures to simulate the geostatic load as well as comparable saturation. Directional permeability tests are desirable for some projects.

Strength of Materials Tests are frequently run. Generally the salt compressive strength tests are run wet or dry. With the exception of non-homogeneities of deposition, most salt is remarkably uniform. Testing of tensile strength is usually done with potential roof materials; often this is done on core residues after they have been attacked by solution. Plastic deformation studies, particularly in a wet state, have been instructive in some projects. Usually these tests are used to furnish safety limits of design or to postulate plastic closure and volume changes with time, under given conditions of span and cavity size.

Simulated "Weathering" Tests, while weathering as such will not occur in a storage cavity, are frequently justified to determine the tendencies of possible roof rocks, under the conditions of solution attack, to disintegrate or foliate when unsupported. Much can be learned by the perfection of this general type of testing.

Reagent Leaching Tests are run to determine the effects of minor constituents or stored materials or brine. In such cases as the presence of hydrogen sulphide, ammonia, or organic petroliferous materials in caprock or salt, the effects of these materials on the stored substances need to be determined. Hydrogen sulphide, in particular can be a significant adulterant of stored products as well as contaminating the underlying brine to pose special problems.

Other more or less conventional laboratory tests or special adaptations thereof will find use in the study of storage of newer substances as well as refinements in the development of more efficient storage of presently stored materials.

DESIGN OF SALT-SOLUTION CAVITY STORAGE

When a well is completed to be used for underground storage in a solution cavity, the design is based on the exploration data, and the storage requirements of the operator. These will determine many of the elements of design which go to the feasibility of the system. The schedule or time-table of dissolving the cavity and bringing it into use also affect the design.

If a cavity can be totally dissolved before being brought into use, then it is feasible to operate the well with only casing and a single string of tubing. The area of the annulus outside the tubing and the cross section of the tubing are usually essentially equal to provide for equal flow rates, either in the solution process or in the displacement process of operation. When a cavity is to be partly dissolved, brought into storage use, and solution continued to increase the capacity, then a total of three strings of pipe, one casing and two tubing, are required as long as water, brine, and immiscible stored material are simultaneously involved in the well. However, some seasonal increase of storage capacity in various projects has been obtained by displacing the stored product with fresh water, which accordingly does additional solution, but without the necessity for an additional string of pipe. Thus some storage cavities have had their capacity increased intentionally by use of fresh water, with a new increment of volume added each year for the last seven or eight years. Some other cavities have had an increment of storage volume increase each year unintentionally because of the disparity between the temperature of the wintertime brine used and the natural cavity temperature. Such a condition must be anticipated in design.

The deliverability required from a solution cavity or its injectability in terms of gallons or barrels per minute will, with the use of pipe friction coefficients, determine the diameters of the pipe strings used in a storage well, when the depth and gravity differences of the stored material and water or brine are known. In some cases it is less expensive to provide pump pressure and capacity than it is to provide large hole and pipe diameters to meet a desired goal. This often depends on how frequently stored material is to be injected into or displaced from a cavity. Many operators first visualize the storage operation as a single season cycle, which it may well be in the producing areas, at considerable distances from markets which are often weather-dependent. However, in the distribution areas, LPG demand when coordinated with weather, permits multi-use of storage with numerous partial cycles, if the cavity is playing its most useful role. Usually, while some correlation with weather data and marketing studies is practicable, it is impossible to visualize the role of a storage cavity in advance and necessary to recognize in design that a market-connected storage cavity will have a variable use from year to year.

With the design determinations made from an anticipated program of usage of a solution cavity, the remaining elements of design follow rather naturally. The pipe sizes will dictate the hole diameter because a sufficient annulus, generally 2" radius or more, to insure cementing is necessary. The geologic data will determine where the casing is set. The hole diameter logs will be used to determine the volume of cement.

The physical conditions of the rocks to be penetrated usually dictate whether such holes are drilled entirely with special drilling mud or partly with salt-base or oil-base muds to prevent solution of soluble sections. Generally the best successes have been obtained with salt-base muds of low water loss which are kept properly treated for the field conditions.

Design elements of casing-heads, braden-heads, and Christmas tree components are dictated by the program and pressure requirements as well as the need for well connections. Most such design should be with as great flexibility as possible as often it is very difficult to make changes at the immediate well head after a cavity is in use without some hazard.

An important phase of design is providing for the necessary surface facilities. These will include the pumps which will provide the energy for fluid circulation during solution and for product injection or removal. Typically they will include dehydration and/or product treatment facilities. In some installations storing gases, compressors can be used to provide energy rather than pumps. Control of pressures throughout operation and development is necessary to prevent excess pressure at any stage causing fracture or formation parting (10) from pumps or compressors. It should be recognized that applied pressures at formation levels considerably below those equal to the overburden or geostatic load have been known in numerous instances to have caused fracture.

Design should provide for adequate metering, information-recording, and access for logging so that a full materials balance record of the cavity is available and occasionally, as required, steel line measurements or logging surveys can be made, under pressure when necessary.

In this discussion design is treated as the more or less creative process of specifying what a well and cavity will be and how they will operate from all of the available geological, geophysical, laboratory, and field data. It is necessary in storage cavity design to insure complete effectiveness and safety and to do this the well should be tailor-made to the site. A uniform "field practice" in a "storage farm" may be practicable in many instances; at other places lack of homogeneity and continuity make an assumption of this type of uniform cavity-making practice extremely dangerous.

One element of design in a storage "field" is the spacing between wells and cavities. To properly insure the isolation of storage cavities in salt, the role of the impurities and the behavior of the roof have to be correctly estimated. Many cavities start out or become radically different in shape than their designers may imagine. When this happens, adequate spacing to provide wet salt barriers between cavities and adequate roof support is very necessary.

WELL CONSTRUCTION

Drilling of wells for operation of storage cavities is one requiring an unusual amount of meticulous control during the process so that ultimate certainty of cementing, completion, and development is assured without leakage. Collection of field data, such as drilling time, collection of samples, mud records, and the like, are important phases of the drilling process.

Drilling mud control to prevent undesirable hole enlargement is very necessary and additives are available to prevent solution enlargement, particularly in the shoe zone where cementing and prevention of leakage are essential. Selection of the casing seat is part of the process of combined field and laboratory study of an exploration hole to assure proper cavity development and protection of roof. This particularly is true in bedded salt; in dome salts it is to be anticipated that the solution cavity will normally extend above the casing shoe either at the well or lateral to it except when the cavity solution process is operated at such rates of extraction as to only permit withdrawal of completely saturated fluid.

As is evident cementing is an important phase of well construction. Cements used must be impermeable to brine, water, and stored material. They must be non-shrinking in volume as they set. The cement should effectively bond with all the rock types present, particularly in the shoe area and any zone above at which solution conceivably could ever reach the well bore. Bonding of cements has been little studied. In order to obtain the effective cementing needed, the writer uses retarded, sulphate-resistant cements of regular grind, pre-dry-mixed with 1 1/2 % to 2 1/2% fine rock salt and 4% to 6% gel drilling mud, this then being thoroughly mixed into a slurry with saturated brine controlled by weight, usually in the range of 14.6 to 15.2 lbs. per gallon, to give a slurry that will not shrink or segregate. Such cements are relatively slow in setting and considerably more waiting time is necessary than with conventional oil-well cements.

Drilling-out of the cement shoe or float equipment and any cement left in the pipe can be a critical period in a storage well. The impact of percussion drilling conceivably can create problems as could rough heavy-weight rotary drilling. It is desirable to leave as little cement as possible in the well and in most instances to use only a single float-combination guide shoe so as to minimize the drilling-out hazards. If rotary drilling is to be used it is very necessary to weld or use permanent locking compounds on each joint of casing in the lower part of the casing string. Centralization of the casing at points selected geologically is highly desirable. Centralizers should be located in places in the hole known to be of proper diameter and in strata of high resistivity.

Casing grades selected for storage wells often desirably are of heavier weight than might be conventional for the depth in order to provide more amply for the anticipated length of life, which no one is yet able to estimate, especially in terms such as the corrosion of the casing. When the casing is made up, it is usual for thread dope to be used. Especial attention to the thread-sealing compound is needed in storage cavity wells to insure the insolubility of this material in the stored materials, brine, or water that may be in prolonged contact with the pipe during years of operation.

FIELD TESTING

To preserve the stored material and to provide safety, it is essential that the casing and shoe area be completely tight. After cement has set-up and the well is ready for completion, field testing is desirable. Such field tests should include the data necessary for reference to later observe physical changes in the cavity and include both pressure tests and logging done incidental to the completion process.

A variety of tests are feasible at this stage and under most circumstances should be done:

Pressure test of the casing string is usually desirable before any drilling out is done. This is best done hydraulically and can simultaneously be used to test the final casing head and fittings, if these are installed. The pressure test of the casing should be carried to a pressure above the probable operating or storage pressures that may be involved in the cavity operation, with a suitable margin of safety.

Repeated pressure testing of the casing shoe area at the time of drilling-out or just following drill-out is often practicable under most geologic conditions where solution-cavity storage projects are operated. Such a repetition of a pressure test with a foot or so of formation exposed below the casing shoe will provide complete assurance about safety and lack of channeling.

Cement-bond logs are useful in terranes where formation conditions have proven their applicability.

Radioactivity logs run after the casing is drilled out provide a permanent pre-solution reference record of the well which is highly desirable as the cavity is made and operation is undertaken.

Collar-locator logs on a detailed vertical scale should also be part of the reference log as they can be used, together with subsequent collar and radioactivity logs to analyze significant rock or roof movements associated with the solution cavity and to guide location of stored hydrocarbons that may migrate above the shoe area of the well.

In special cases, such as failure to obtain cement circulation or the failure of a casing string to hold pressure, special investigative techniques would be part of the field testing procedure and necessarily would employ the logging devices or other procedures especially for the problem to be resolved before further work is done with the cavity or well.

CAVITY CREATION

The making of the cavity to be used for storage requires the tubing of the tested well and initiation of the process of dissolving. A great deal is known today about the process so that the shape of the cavity and its dimension can be qualitatively predicted.

The basic geologic nature of the exposed strata as to solubility will have considerable to do with the shape of the cavity, as will the geologic dip, and interbedded impurities that do not fall to the floor which become constrictions. Blanketing by impurities will cause problems that should be recognized.

Most effective solution of salt to make a storage cavity can be done by creating a predictable circulation pattern in the cavity, using low-pressure jetting techniques, widely used for mixing in the petroleum industry, and first best described by Fossett and Prosser (11). Such low pressure jets can cause the discharged brine to have been circulated and received its salt content by movement as well as by diffusion.

In salts where natural layers are present which will cause constrictions or shelf-failure to shear-off tubing, some preparatory measures are desirable. Frequently such beds can be suitably enlarged by jetting with high-pressure jet guns, using water or acid, as needed. In some cases either explosive shattering or shooting with shaped charges in open hole have proven useful in eliminating the adverse effects of such beds.

Steel tubing lost in a solution cavity can frequently cause a serious problem. To avoid this possibility it is a good practice to doubly-suspend the tubing string used for washing at the surface and to use drillable tubing materials below the casing-shoe area of the well. Various types of materials such as plastics, cement-asbestos pipe, and readily-drillable metal alloys have been used for the lower portion of such tubing strings. Where lighter plastic materials are used, some weighting is necessary to make this portion of the string heavier than the brine.

With the use of a low-pressure jet system to attain a circulation pattern for a desirable cavity shape, it is evident that tubing injection must be used and production of brine will be from the annulus. Casing injection, with attendant widespread upper cavity, should not be considered for storage cavities.

During the entire solution operation careful volumetric and collateral records are required. These should include:

1. Metering of injection.
2. Temperature of injection fluid.
3. Metering of production.
4. Temperature of produced fluid.
5. Gravity of produced fluid.
6. Resistivity and periodic chemical analyses of produced fluid.
7. Continuous pressure records.

If other data do not indicate whether tubing is intact during dissolving frequent steel line measurements of the length of tubing are desirable.

If a cavity is to be carried to a maximum span, where roof support might become inadequate, radioactivity logging inside the tubing after considerable solution has been done will provide useful information.

The volume of salt removed from a cavity can be computed if adequate records are available. This figure often has little significance as to the volume and shape of the cavity because of the role of the impurities present and tubing strings in such solution cavities often are not maintained continuously intact to the designed bottom of the cavity. The non-homogeneities and impurities of most salts require that cavities be relatively small in diameter to insure a stable roof and minimize the hazards of failure. Some plastic shrinkage or contraction is also to be expected as a part of the process -- which will in turn aid the sealing of the cavity walls. Size of cavity to be developed for storage depends on judgment and the data collected in the solution process, but is inherently dependent first on the vertical thickness of salt present.

SHAPE OF CAVITY

Solution cavity storage should be approached on a basis that while the factors that will influence shape of cavity are recognized that complete certainty as to shape is not now possible except in very small diameter cavities. These factors of non-homogeneity of solubility, irregularly distributed impurities, geologic dip, and circulation pattern are generally known. Ideally a cavity would be cylindrical, but few approach this shape and a true "bottle" shape has been obtained only in a few salt domes where large thicknesses of very pure salt were available.

The most dependable information as to cavity shape is obtained in the smaller diameter by use of the mechanical well caliper. Such devices capable of measurements approaching 25 feet in diameter are experimentally available and have been extremely instructive especially where repeated surveys have been practicable. Further perfection of the mechanical caliper appears practicable and a most certain method of study of cavity shape.

Considerable has also been done with fill-up techniques in storage cavities after washing was completed. This procedure uses a radioactivity log tool to measure the position of the brine-product contact behind the tubing as the cavity is filled initially. This has been done by volumetrically measuring the cavity volume for each foot or each two feet in some cavities and an excellent idea of the cross section of the dissolved cavity obtained by this method. Where such studies have been correlated with geologic and solubility logs, they have been very useful in providing information to guide cavity development in subsequent wells in the same area.

Essentially the same technique to determine the cross-sectional dimension of a cavity while it is in use, after filling, and also without removing the tubing, depends on pressure equalization of liquids and careful metering as was described by Branyan (12).

The sonic methods which have had considerable use and promotion deserve consideration in some cavities as a means of ascertaining cavity shape and volume. However, the limitations and basic assumptions of these techniques need to be carefully considered in evaluating the results. These devices are based on reflection of a propagated sonic signal, generally more or less beamed at a wide angle, and depend upon recognition and timing of the travel from the instant of propagation to return to the device in the well bore.

Basically these systems then depend on the velocity of sound in brine or water. In most of the systems in use a constant velocity is assumed and all readings are based on this assumption. Actually the velocity of sound in brine or water or some gradation thereof as may be present in a solution cavity is dependent on a great number of possible pertinent conditions. Some idea of the complexity of those that may be formulated may be seen by examining a standard reference in this field such as Officer (13). Generally the velocity of sound in such cavities depends on the salt saturation or gravity, the temperature, the pressure, and the gas in solution in the fluid. All of these can cause significant and not negligible differences. In addition some other conditions are often present which influence the results of such surveys or affect the velocity of the sonic signal. A solution cavity is a volumetric cavity which has a definite cavity resonance to sonic frequencies. This has been recognized on at least one sonic survey as causing false evidences of diameter that were in fact not present on a mechanical caliper survey of the same cavity. With brine cavities, as within the ocean, sonic or salinity layering is possible and has been demonstrated to be present. This has caused both wave-guiding of sonic signals and obstructed their propagation, both common phenomena in oceanographic seismic work.

In addition it should be recognized that a sonic wave is a spherical wave which obeys the basic laws of refraction and reflection, which prevents a sonic device from "seeing" around corners or up or down, or beyond the point from which a first reflection is obtained. Where high-solubility-rate linear masses of salt are preferentially dissolved, it would only be an exceptional fortuitous relationship that would permit mapping or recognition with a sonic cavity-surveying device.

With a recognition of the conditions affecting their use and on the data obtained, the sonic surveying devices can provide information of considerable value in some storage cavity projects. They become particularly useful if all collateral volumetric and logging data are available and are used mainly in the context of one of the number of lines of information which are available for the storage operator to use in interpreting the subsurface conditions.

Some initial work with down-hole cameras and inconoscopes in solution cavities has been very promising of possible application of photographic and television techniques for use in storage cavities. However, quantitative calibration means are needed and further extensive development work is required for the systems with which the writer is familiar.

After many years of dealing with the problems of shape of solution cavities and the anxiety of operators to know the shape, and after having found out the shape of a very few cavities at considerable expense, the writer seriously questions the value of such information in a storage operation. Conservative design, limiting any hazards by now well-known techniques makes shape a matter that should be generally of little consequence to a successful and economic storage operation.

CAVITY STORAGE OPERATION

Two alternate conditions for operation may typically be desired for solution cavity storage operations. Under some conditions cavities are brought into operation before the desired volume is reached with the explicit intention of increasing the size of the cavity continuously while it is in use or by cyclic or seasonal enlargement with new solution being done by use of unsaturated fluids. The alternate is to complete the storage cavity to a maximum size desired or considered permissable and then to do all of the operation with techniques to prevent additional solution and enlargement.

When continued solution is anticipated two strings of pipe inside the casing are required, one for product, one annulus for fresh water, and the other for brine. In cavities where incremental increases in size are made, a single string of tubing is required.

As a safety measure, either permanent storage or while washing is in process, to decrease hazard of leakage it is customary for the writer to recommend the installation of a device to use the outer annulus for water or brine, providing a water seal against minute leaks. This device is sketched in the accompanying Figure No. 1, which shows the tool, used in combination with a packer and two strings of tubing, set at the casing shoe in a storage cavity, which provides a water seal around such products as LPG or aviation gasoline throughout the entire well. A similar device is practicable with single tubing and a two-fluid system to provide the same safety with a brine seal on the casing.

When operation conditions require cessation of cavity development, some additional problems may be encountered, depending on depth of storage, local ground temperatures and geothermal gradients, and other conditions of the storage. Injected fluid to provide removal of product, while saturated for the surface temperature, may be injected to an environment where it is below saturation. Heating, chemical treatment, or both may be required to prevent further solution. During this type of operation, metering and analyses, as well as frequent surveying, are all desirable to provide definitive information as to whether enlargement is or is not occurring. In one instance operations decided it was least expensive to add fine salt to injected brine, essentially in suspension for part of the trip to the cavity, to bring up saturation for the bottom hole temperature present.

An essential feature of suitable solution cavity storage operation is the maintenance of pressure supporting the roof and exerted against the side walls. By the cavity-creation process fluid pressure of water and brine replace rock and when stored product is added it is essential that it should be kept under pressure also. A desirable goal is to keep the bottom-hole or cavity pressures as near uniform as possible and to prevent unnecessary flexure of the roof. Repeated flexure of such strata could possibly cause failure with time and this realm of fatigue or flexure effects in rocks under geostatic load is one about which very little is presently known.

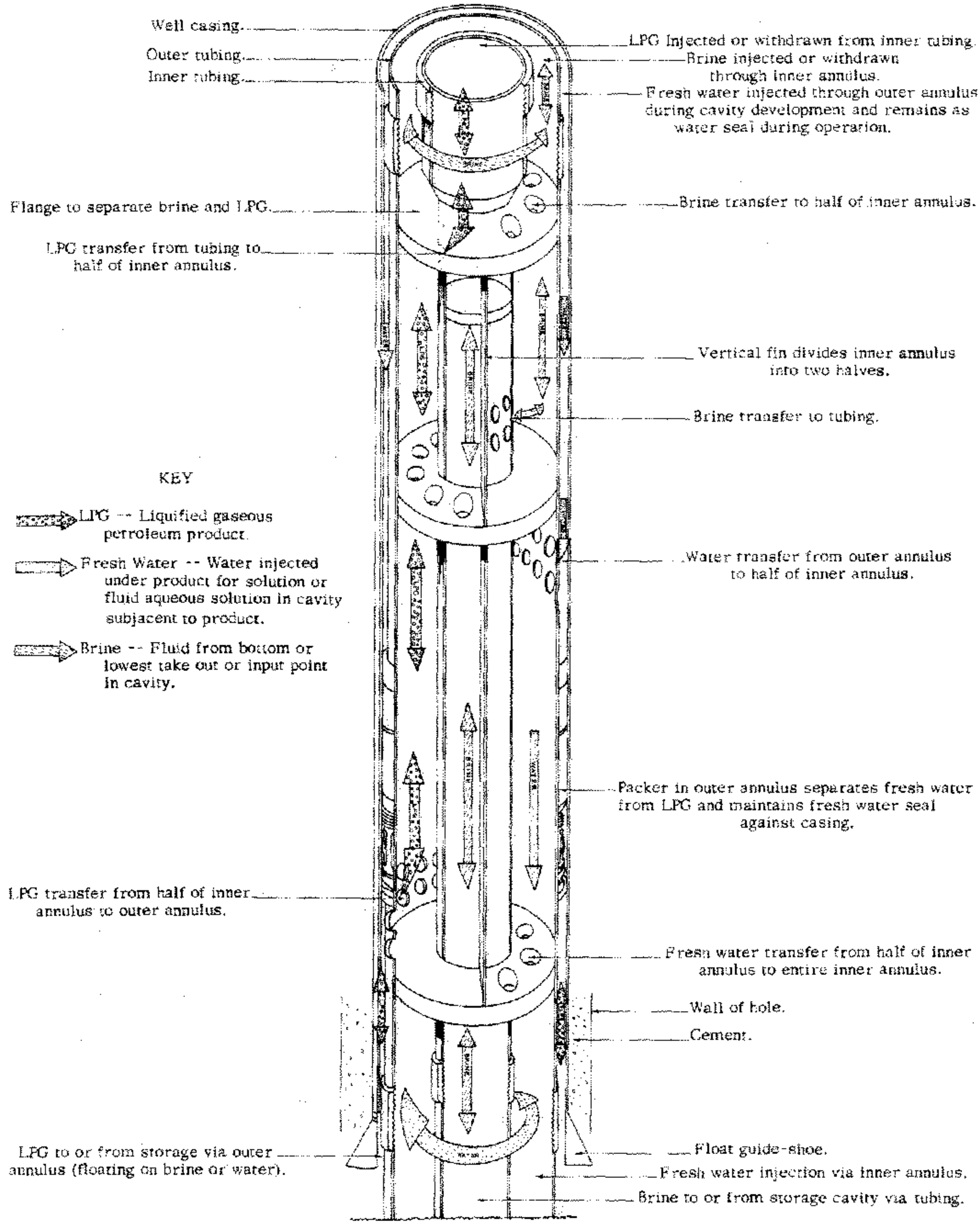

Figure 1. Device for permanent water-seal on outer casing of salt cavity storage well.

SUBSURFACE AND SURFACE MOVEMENTS

The creation of a void in the subsurface, the walls of which are water-wet salt of a highly plastic nature puts into effect compensating movements in the rock. These are counteracted by the fluid pressure of the cavity and as long as roof spans are such that elastic limits are not exceeded the movements proceed in a predictable fashion until equilibrium of geostatic pressures and fluid pressures in the cavity are reached. Usually this is within five years after creation of the relatively small volume typical storage cavity and thereafter as pressures fluctuate there is a slow responding fluctuation within the rocks.

The sagging of rocks above a cavity creates an arch relationship that can extend strain conditions well outside the cavity and if such a transfer, usually tension at a critical height above the cavity, causes failure, then adverse effects on the well or cavity can result.

It is known in one or two instances that storage cavity creation effects have reached the surface in essentially soft or unconsolidated rocks, although no leakage or escape of fluids was noted. Surface subsidence and rock movements are problems that can be expected to be associated with storage solution cavities as they become older and the trend to build larger bottles continues. Operators must be alert to these possibilities and should maintain suitable surface observations, as well as locate their storage facilities with these possibilities in mind.

PROBLEMS OF SOLUTION CAVITY STORAGE PROJECTS

While there are undoubtedly problems or failures (leakage) which have occurred during the development and operation of the numerous salt cavity projects now in use, many of them are known and most of them teach valuable lessons as to how they were caused and in some cases were corrected.

Earth movements due to inadequate support have occurred in several storage projects. These have caused loss of tubing, shearing of casing, loss of product into higher zones or the surface, and other serious consequences. In most instances they have resulted from a lack of understanding of the solution process and the way cavities develop.

Cement failures have been common due to the use of traditional oil-field mixes, the writer believes, with lack of bonding or with shrinkage and segregation in the slurry. This has been corrected by use of resin cements and salt-gel cements.

Fractures have apparently been developed by excess pressures in cementing, drilling out, or even pumping during solution operations. Frac pressure may occasionally be reached as transient pressure peaks with positive displacement pumps.

Casing leaks have apparently resulted from inadequate inspection of pipe, poor thread dope, corrosion, and similar causes. Generally they can be found with adequate inspection of casing and testing.

Occlusions of stored materials above the casing and in "pockets" of the roof of cavities has been responsible for some "loss" of stored material. In some instances where these materials can be located they can be recovered by perforation, fracturing, or both.

In most instances with which the writer is familiar, while sub-surface problems have not been uncommon, actually the principal difficulties arose from surface piping, pumps, and the common hazards of tank farm operation where trucks backed into wells or similar accidents occurred. The solution cavity generally has been a safe, effective, and economical means of storage.

CONCLUSIONS

Solution cavities in salt are becoming increasingly widespread in their use for underground storage of flammable materials. There are large terranes suitable for the development of such storage and many materials susceptible to storage by this method so that increasing use of these cavities is to be anticipated. Because of safety and economy, many materials not stored and immiscible with water or brine should use this method or adaptations thereof.

Specialized techniques of exploration and design to insure success of salt cavity storage are desirable. Data and records during development and operation will insure project safety and provide certainty of recovery. Single storage cavities of predictable general shape and dimension are possible but spacing between cavities should be adequate to provide a safety factor.

Most reasons for leakage are known and are correctable by design and developmental procedures. Suitable geologic conditions are basic to the location, creation, and operation of salt solution storage cavities.

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