Storage of Natural Gas in Salt Caverns

J. A. Istvan and C. W. Querio
PB-KBB, Inc., Houston, Texas, USA

ABSTRACT

It is now feasible to store billions of cubic feet of natural gas safely and economically in stable salt caverns. Factors that must be considered and utilized are spacing of the caverns, pillar to diameter ratios, maximum and minimum storage pressures, bottom hole temperature and the phenomenological method of evaluation. Many existing caverns would not meet the criteria necessary to assure stable and tight high-pressure, subsurface storage vessels. Therefore, it is the intent of this paper to outline the studies necessary to design and construct new large scale facilities for surge capacity and peak-shaving purposes. Elements of these studies are dependent upon elastic, viscous and plastic material behavior.

PB-KBB Inc. and affiliated companies have designed, constructed and operate several gas storage facilities and presently have others in design and construction stages. This paper does not necessarily reflect what has been proposed by others, but rather, the approach recommended by PB-KBB Inc.

INTRODUCTION

Plans for several hundred new solution-mined salt caverns for storage of hydrocarbons will be on the drawing boards in the next few years. The reason is simple: much of the presently produced natural gas, crude oil, LPG and the like, cannot find a ready market. In addition, large royalty owners are taking their share of revenue in kind, which in the case of liquids, require expensive surface storage. The problem with storing natural gas, however, is quite different. Storage can only be obtained in underground caverns, aquifers, or depleted reservoirs. Reservoir storage abounds in the world, but in certain cases "peak-shaving" gas requires high volume capability of injection and withdrawal on short notice. Depleted reservoir storage cannot usually fulfill this requirement because porosity and permeability control the procedure. Thus, the trend is toward large, accessible volumes of gas stored safely in relatively small new caverns with known limits of operational parameters.

FEASIBILITY STUDIES

Before the large drilling rig is moved on site to spud a cavern well, extensive work and study must be performed. Most of the Gulf Coast domes have been delineated by oil and gas well drilling or seismic methods. However, the only true test of whether a dome is capable of storing natural gas safely is to test drill. In the meantime, contour maps of the caprock and salt must be constructed. All known wells and brine, sulfur or storage wells must be identified and located on a map. If cores are available, it would be very useful to run tri-axial compression and strain tests on the core. Insoluble calculations from core samples, temperature gradients and geophysical log studies make up the balance of the predrilling study which is necessary to design a cavern.

Extensive study of the logs will allow a determination of the density and specific gravity of the overburden; thus allowing the pressure gradient to be determined more precisely. This pressure gradient is critical for determining the setting depths for the final cemented casing string, because the operational safety pressure factor is based upon the overburden weight. Therefore, the combination of temperature as it relates to plastic flow, pressure gradient as it relates to maximum and minimum operating pressure, spacing between caverns for stability and flexing, salt roof thickness for stability, and sufficient sump for efficient storage of insolubles are the primary criteria for safe storage.

GEOMECHANICAL ASSESSMENT OF CAVERNS

Purpose

The purpose of performing a geomechanical assessment is to ensure that the cavern spacing and layout as planned provides caverns which are structurally sound and safe to operate.

Numerical simulation and finite element analysis may help to clarify and project the direction and extent of forces acting in the area of the proposed caverns.

Consideration of operating pressures, salt characteristics, hole straightness, and depth of caverns, are only a few of the calculations necessary to determine cavern spacing (CS) and pillar/diameter (P/D) ratios. In a virgin dome, subsequent wells should be spaced according to the character of the salt found in the first well and after analysis of geophysical logs and detailed core evaluation. The plastic, elastic and viscous properties of the cores, even though they only pertain to the boreholes, will provide basic information critical to design and construction of a safe cavern.

WELL CORE &
GEOTECHNICAL INVESTIGATION PROGRAM

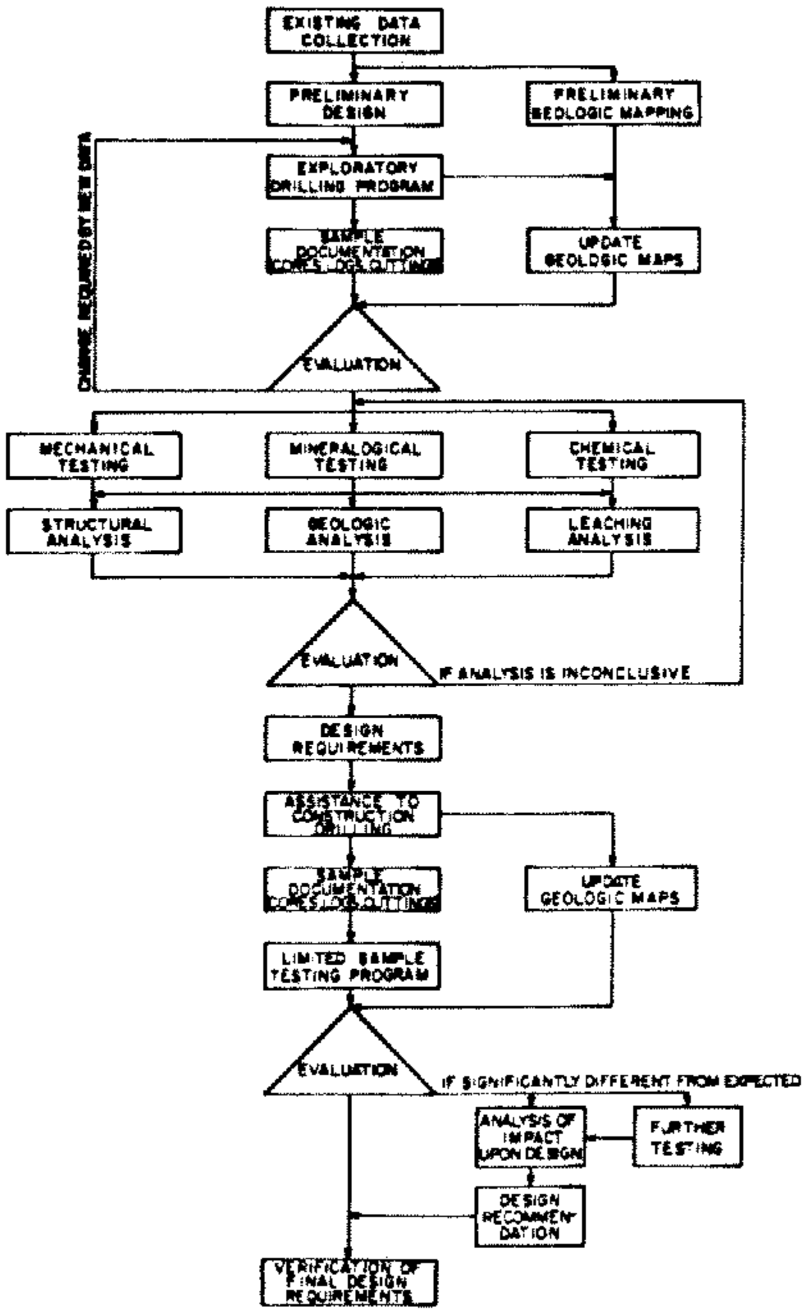

Figure 1.

An adequate stress/strain analysis would demand a numerical simulation model of the cavern geometry and geology and material laws for the involved rock strata. The laws, loading limits and stability criteria would be determined after extensive material testing of core samples in association with the theory of cavern behavior.

A geomechanical assessment of cavern design and planned cavern spacing should be prepared using empirical methods. Calculations are based on the assumptions that the salt has low compressive strength and that the overlying sediments are unable to support the load. The general thickness of salt domes permits the selection of cavern depth intervals and cavern volumes necessary for the required profitability of a project. Resulting cavern diameters and centerline separation should be conservative.

It must be recognized that salt material properties usually vary within the same deposit between positions separated by short distances. Therefore, prior to the solution mining of caverns, it is necessary to extract cores from the wells, to test this core material to establish rock mechanical properties, and to calculate stresses and strains using actual salt data. Drilling for the U.S. Strategic Petroleum Reserve at several domes in Texas and Louisiana proved the inhomogenity of salt. Adjacent wells and caverns have lenses and layers which are traceable to others within a confined area. Likewise, the converse is true.

FUNCTIONAL AND DESIGN CRITERIA

(Example, Figure 2)

Functional & design criteria include, but are not limited to:

1. Useable storage capacity
2. Number of caverns
3. Design receipt flow rate
4. Design delivery flow rate
5. Expected gas specific gravity
6. Design operating pressure of delivery pipeline
7. Distance to (delivery) connecting pipeline
8. Connecting (delivery) pipeline diameter
9. Dehydration capacity
10. Number of compressors
11. Type of compressor drive and horsepower
12. Maximum pressure at final cemented casing shoe
13. Maximum wellhead pressure
14. Top of cavern for depth and pressure calculations
15. Minimum cavern pressure
16. Total gas in place at maximum pressure
17. Cushion gas in place at minimum pressure
18. Cavern volume
19. Location of facility
20. Brine disposal and leach water supply.

From these criteria, a determination of optimum parameters for final cavern design entails a detailed analysis of the interrelationships. In addition, one of the first elements of the detailed design effort would be to verify or adjust cavern design based upon an optimization analysis. This paper is primarily generic in nature and all calculations should be re-evaluated for a specific site.

Introduction

Careful, geophysical, geological, rock mechanical, and solution mining studies are required before starting the development of a solution mined salt cavern. The design must assure that project development can be conducted in a reasonable, prudent and systematic manner and must stress physical and environmental safety and the prevention of waste. The design must also be continually reviewed throughout the construction phase to take into consideration pertinent additional detailed subsurface information from sonars and the like.

Methodology

Cavern design should be evaluated using empirical cavern design procedures.

The method provides a guideline for the depth in salt required for the planned cavern roof and the distance between cavern centerline when the caverns are located on a hexagonal grid. The salt thickness above the cavern roof and the cavern distance are determined as a function of cavern diameter and salt compressive strength.

Calculation of Stability Parameters

Strength characteristics of salt and caprock: At this time all salt material properties must be assumed. Based upon Gulf Coast experience, the following conservative assumptions are made:

- Salt of low compressive strength (unconfined). (P_z = 2600 − 4000 psi)
- Overlying sediments are incapable of providing sufficient support for the cavern roof.

Minimum salt back thickness (Figure 3). If the supporting capacity of the overlying sediments (clay, anhydrite) is not considered, then the salt in the roof region of the cavern must support the total load of the overburden. Reports of lost circulation in the caprock would tend to support the assumption that the caprock is fractured or vugular and not capable of supporting overlying sediments. A specific thickness of the salt layer (the minimum salt back thickness) must be present above the cavern roof. All elastic and plastic deformations which are caused by stress arrangements during the leaching of the cavern and gas withdrawal operations should remain within the salt and should not reach the caprock which is assumed as being unable to support overburden load.

Minimum pillar thickness. Concerning the minimum pillar thickness, PB-KBB Inc. has sufficient data from

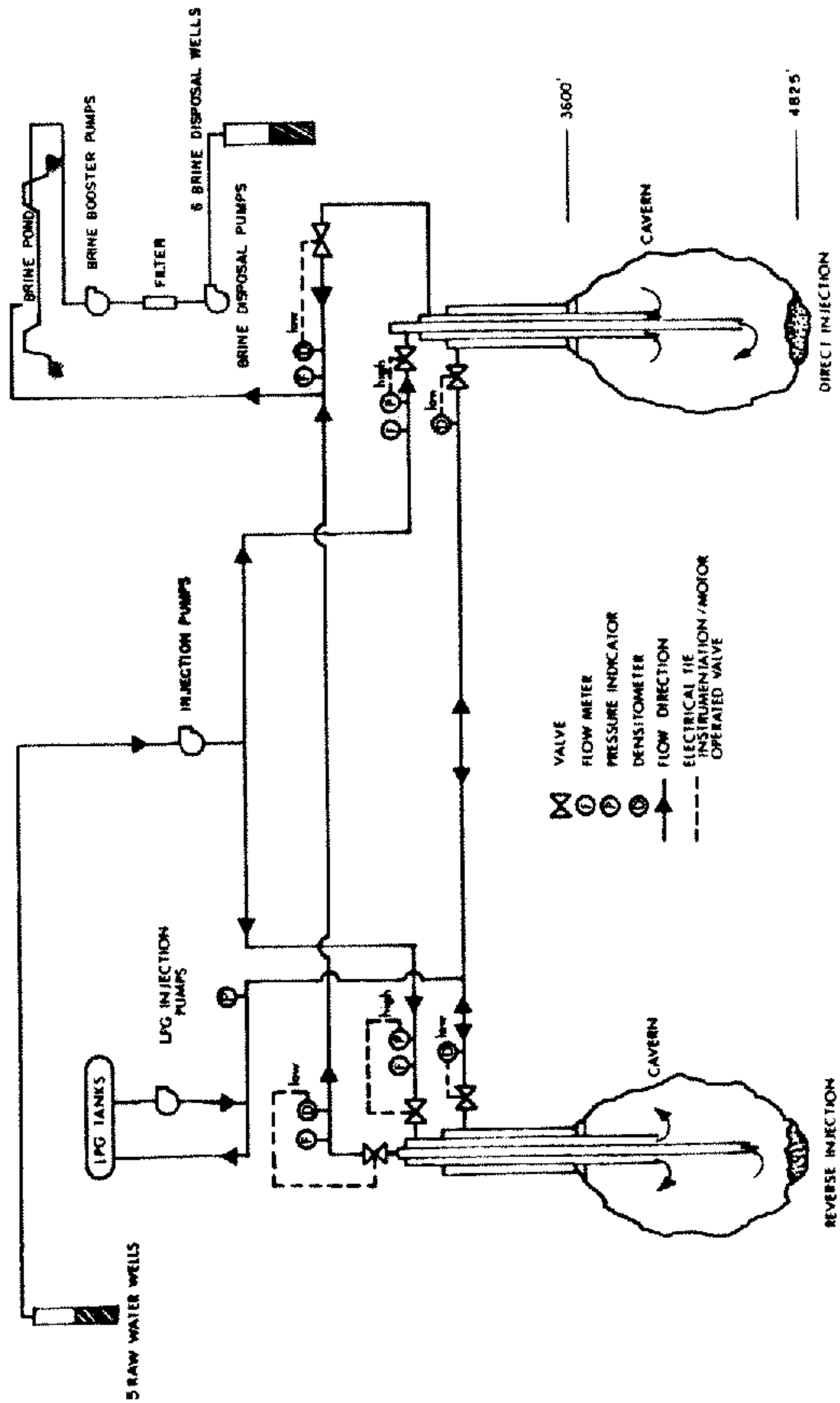
BRINE POND
BRINE BOOSTER PUMPS
FILTER
BRINE DISPOSAL PUMPS
6 BRINE DISPOSAL WELLS
INJECTION PUMPS
LPG INJECTION PUMPS
LPG TANKS
5 RAW WATER WELLS
low
high
3600'
4825'
CAVERN
CAVERN
DIRECT INJECTION
REVERSE INJECTION
VALVE
FLOW METER
PRESSURE INDICATOR
DENSITOMETER
FLOW DIRECTION
ELECTRICAL TIE INSTRUMENTATION / MOTOR OPERATED VALVE

Figure 2.

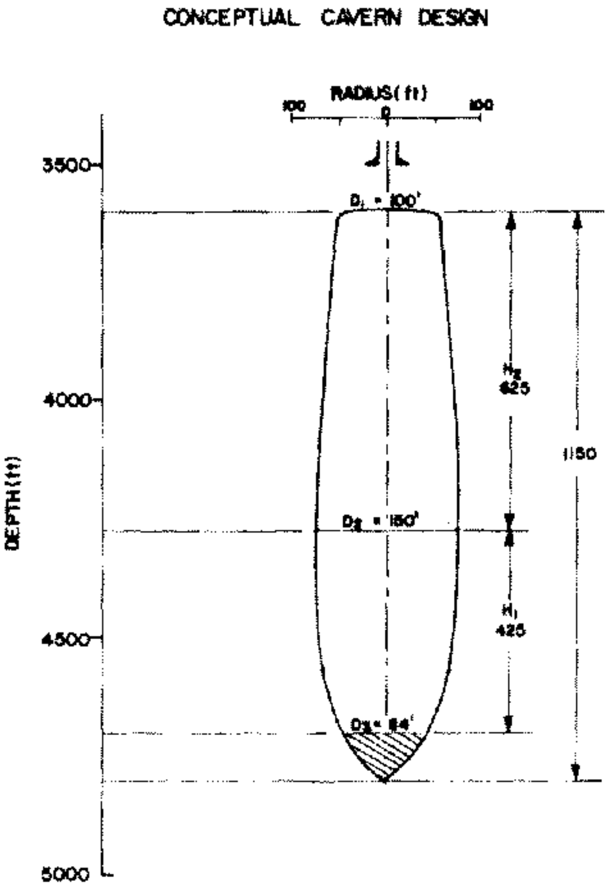

Figure 3.

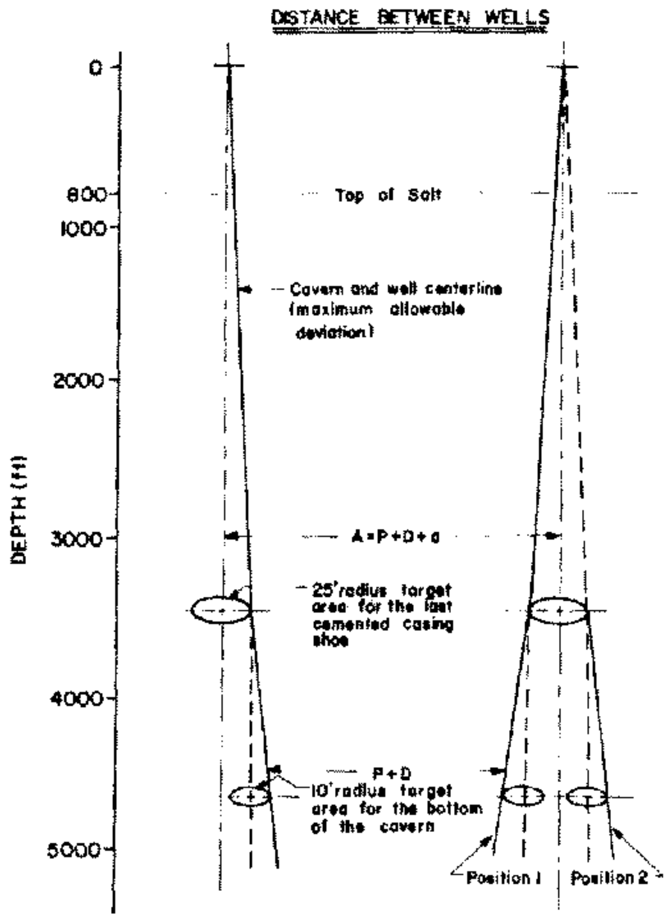

Figure 4.

both failed and tight caverns to substantiate the minimum pillar thickness as portrayed in this example.

Minimum distance between cavern wells. Two effects must be considered when determining the minimum distance between the wells:

- The effect of the well deviation. This effect is illustrated in Figure 4. According to our well control parameters, the last cemented casing shoe must fall within a 25 foot radius target area around the vertical. The bottom of the cavern must be localized within a 10 foot radius target around the new centerline determined by the extremes of the target area for the casing shoe. The most unfavorable situation will arise when both wells are deviated in opposite directions as shown in position 1 (see Figure 4). At mid-cavern depth, this will result in a 60 foot decrease of the pillar thickness between the wells.
- The effect of preferential leaching. Since salt properties vary with location, it is possible that the planned maximum diameter of 150′ is locally exceeded due to preferential leaching.

Planned Cavern Layout and Spacing

Table 1 below, illustrates possible spacing and layout for two caverns.

TABLE I

Planned Cavern Layout and Spacing

Cavern Top	3600′
Cavern Height	1050′
Widest Cavern Diameter	150′
Salt Back Thickness	2800′
Pillar Thickness	550′
Cavern Distance	700′

A salt back thickness of 2800′ results in a S/D ratio of 18.7, much higher than the calculated value of 1.7, which required a minimum salt thickness of 255′ above cavern roof.

The empirical method determines a minimum pillar thickness of 405′, thus resulting in a P/D ratio of 2.7. The planned cavern distance (center to center) of 700′ will provide a remaining salt pillar of 550′ and a margin of 145′ to allow for well deviation and localized diameter increases due to preferential leaching (see Figure 5).

Smaller P/D ratios would be acceptable only in conditions more favorable than those assumed.

If additional caverns are required, the cavern layout should conform to a 700′ hexagonal grid with the walls of the peripheral caverns no less than 275′ distant from the boundary of the property line.

Planned Concept of Operation

The caverns are designed to be operated as a high-low pressure vessel. The maximum cavern pressure was established at 80% of the theoretical overburden pressure (assuming a pressure gradient of 1 psi/ft) at the depth of the last cemented casing shoe, or $.80 \times 3{,}500 = 2800$ psi. The minimum cavern pressure (940 psi) was selected to allow free flow gas withdrawal by means of gas expansion. This minimum pressure should be increased for higher cavern temperatures.

The most extreme pressure condition is during complete cavern depressurization.

Anticipated Closure Rate

Due to the elastoplastic nature of salt, underground cavities experience reduction in volume under certain conditions of loading and temperature.

As the depth of the cavern increases, the differential stress and the temperature affecting the cavern walls also increase, causing the salt to undergo increased plastic (creep) deformation. The exact magnitude of this deformation and the related volume loss in the cavern are dependent on site-specific characteristics and cannot generically be accurately predicted.

The experience at Eminence Dome where the minimum pressure was too low and the cavern temperature high, accurately proves why a conservative minimum pressure is desirable. Closure may be minimized as well as allowing for a smaller volume of cushion gas, by at least partial displacement of gas by brine.

Previously published equations describe cavern volume closure as a function of the diameter related to the height; of the pressure load in the cavern related to the strength of the material; of the temperature; and of time.

Empirically determined coefficients and factors are de-

PLANNED CAVERN SPACING

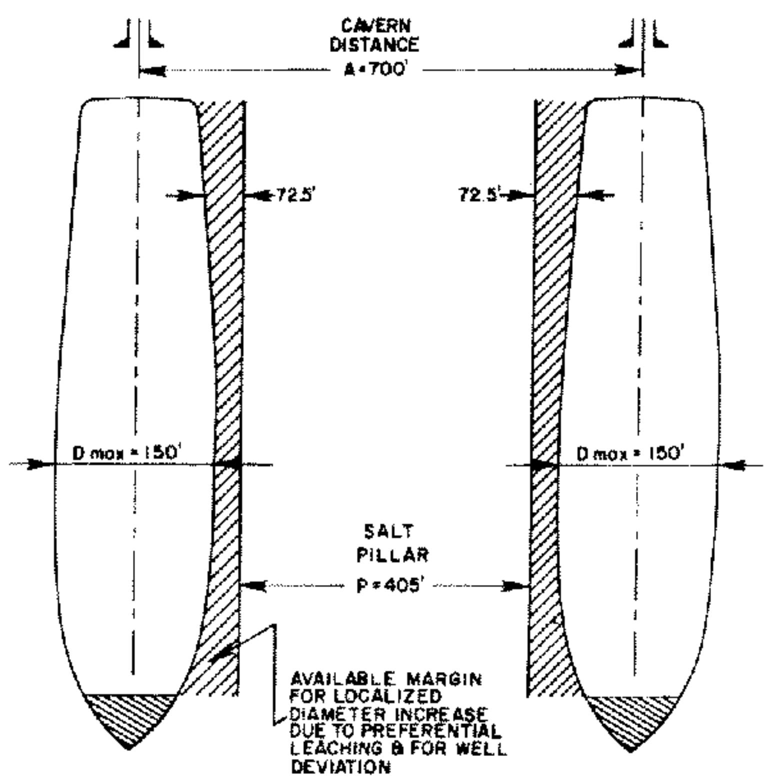

Figure 5.

pendent on salt properties and unless data on specific salt is available, state-of-the-art equations cannot be meaningfully applied.

The caverns are designed to be constructed in the 3600′ to 4825′ depth interval which is within the limit of 6000′ commonly used for salt caverns under 2°F/100′ of depth gradient. Some elastoplastic movement of the salt is expected. A loss of cavern volume on the order of 10% for the total lifetime of the project (20 years) has been assumed and factored into the initial cavern mining volume.

Anticipated Surface Impact

Reduction of the useable volume is not the only consequence of creep deformation. The construction of underground cavities causes movements and induces stress changes in the surrounding rock mass. Salt that is subject to stress, strains or temperature differences can structurally fail due to creep deformation, thus resulting in caving and rupture. These failures, when propagated to the surface, can cause subsidence.

The design of the caverns should be such that no significant surface subsidence will occur. The caverns should be deeply located in the salt body and the anticipated closure rate should have an almost unmeasurable impact at the surface.

It is, however, important to acquire information on the amount of volume reduction and the effect of subsidence movements. Subsidence survey bench marks should be installed and a program for periodic measurements should be established. The subsidence monitoring program, to be conducted over the life of the project, would involve determination at regular intervals of the precise elevation of monuments located over areas in which subsidence can potentially occur. In this manner, slow but otherwise undetected continuing movements are recorded over a period of time. The field survey should be repeated every year.

Structural Stability Analysis

During recent years numerical modeling techniques for underground openings have advanced considerably. Geomechanical assessment methods have been developed which allow cavern owners and permit agencies to judge the design objectively.

The technique of finite modeling makes it possible to establish stress and displacement fields in the rock surrounding the caverns. The models for various rock strata utilize non-linear constitutive laws that account for cavern geometry and time dependent loading.

The basis for meaningful modeling is the determination of the material behavior of the salt and the overburden. Short-term and long-term laboratory test on rock and salt samples will establish the parameters of a comprehensive constitutive law.

It is recommended that core samples be taken from the wells and tested, and that a state-of-the-art stress/strain analysis be undertaken for final cavern design.

CAVERN LIFE

After a salt well is drilled and completed, but before development commences, several tests of the final casing shoe and wellbore are necessary to allow at least 20 year life expectancy of the future cavern.

A cement bond log of the final casing is first and foremost. Good cathodic protection of that casing string is also required. Last but not least, a pressure test of the casing, casing shoe and wellbore should be performed. For liquids, a brine test for at least 72 hours has usually been sufficient. However, for gas storage, a better test would be with nitrogen, where the nitrogen is weighed when it is injected into the well to the top of the cavern. Pressure decay or lack of it should be documented for a minimum of 72 hours. This technique will verify that as long as a good cement bond is recorded and the shoe is not overpressured and the pad in the well is maintained during the leaching period, the critical points in the well will be insured as tight.

During leaching, pad elevation verification and safe operating pressures will pave the way for the final test verification that the cavern will hold gas pressure. That test is similar to the one previously described where nitrogen is weighed and injected in the well to the top of the new cavern and pressures are recorded for 72 hours.

Successful testing results in the knowledge that the operator has been prudent and probably will be successful in protecting the valuable product.

MAXIMUM STORAGE PRESSURE

Determination of this pressure is a function of several variables: normally, design specifications will stipulate a ballpark number on the basis of depth final cemented casing, regional pressure and known temperature gradients. Calculations vary from company to company and site to site, as to whether the allowable pressure gradient should be calculated from the proposed top of the cavern or the setting depth of the final cemented casing string. The ramifications of a leaky cavern from overpressuring dictate a conservative approach to the maximum allowable pressure at the casing shoe. High temperature effects are not so important for this determination, but the overburden pressure calculated from well logs is important. Likewise, salt character and determination of anhydrite, sylvite, carnallite and orientation of layers and lenses will affect the maximum allowable pressure.

MINIMUM PRESSURE

Temperature affects this parameter because the higher the temperature, the more likely creep, closure and/or spalling will occur. Higher temperature also affect the maximum allowable diameter of the caverns. Inhomogeneous salt requires a more conservative approach to calculating the minimum pressure because different minerals react differently to the temperature variations.

CONCLUSIONS

Safe operating pressures, both maximum and minimum, determined after consideration of salt rock quality and inhomogeniety, and temperature ramifications affecting the plastic nature of salt flow, are critical to a pressure and product tight storage cavern. New rules and regulations being instituted by individual states along U.S. Environmental Protection Agency guidelines, should assure fewer leaks and thus minimize loss of expensive product from the caverns.

The large volume of salt available in a dome enables the selection of a cavern depth interval that offers the best overall economy in underground storage construction and operation within the limits required for cavern stability.

Based on conservative estimates concerning the salt compressive strength (2400 psi) and the load bearing inability of the overlying sediments in our example, a minimum salt back thickness of 255′ is required, thus resulting in an S/D ratio of 1.7. Planned cavern construction should exceed this minimum ratio.

Under the previously mentioned assumptions, the empirical method determines a minimum pillar thickness of 405′, thus resulting in a P/D ratio of 2.7. The planned cavern distance (center to center) of 700′ will provide a margin of 145′ to allow for well deviation and localized diameter increases due to preferential leaching.

If additional caverns will be required in the future, the cavern layout should be designed on a 700′ hexagonal grid with the walls of the peripheral caverns no less than 275′ distant from the boundary of the property site.

No significant surface subsidence is to be expected and a loss of cavern volume in the order of 10% for the total lifetime of the project (20 years) can be anticipated if additional leaching is not performed to compensate for this loss.

The cavern design allows temporary full depressurization. For stability reasons, the condition is to be restricted to maintenance requirements and emergency situations.

The following recommendations are made:

1. Core samples from the actual solution cavern wells be obtained and tested for chemical and geomechanical properties.
2. A final sizing of the cavities be carried out by the application of both the empirical method and the finite element using actual site data.
3. A subsidence monitoring program be implemented.

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