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OBSERVATIONS ON VAPOR PRESSURE IN SPR CAVERNS: SOURCES

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ABSTRACT

The oil of the Strategic Petroleum Reserve (SPR) represents a national response to any potential emergency or intentional restriction of crude oil supply to this country, and conforms to International Agreements to maintain such a reserve. As assurance this reserve oil will be available in a timely manner should a restriction in supply occur, the oil of the reserve must meet certain transportation criteria. The transportation criteria require that the oil does not evolve dangerous gas, either explosive or toxic, while in the process of transport to, or storage at, the destination facility. This requirement can be a challenge because the stored oil can acquire dissolved gases while in the SPR. There have been a series of reports analyzing in exceptional detail the reasons for the increases, or regains, in gas content; however, there remains some uncertainty in these explanations and an inability to predict why the regains occur. Where the regains are prohibitive and exceed the criteria, the oil must undergo degasification, where excess portions of the volatile gas are removed. There are only two known sources of gas regain, one is the salt dome formation itself which may contain gas inclusions from which gas can be released during oil processing or storage, and the second is increases of the gases release by the volatile components of the crude oil itself during storage, especially if the stored oil undergoes heating or is subject to biological generation processes. In this work, the earlier analyses are reexamined and significant alterations in conclusions are proposed. The alterations are based on how the fluid exchanges of brine and oil uptake gas released from domal salt during solutioning, and thereafter, during further exchanges of fluids. Transparency of the brine/oil interface and the transfer of gas across this interface remains an important unanswered question. The contribution from creep induced damage releasing gas from the salt surrounding the cavern is considered through computations using the Multimechanism Deformation Coupled Fracture (MDCF) model, suggesting a relative minor, but potentially significant, contribution to the regain process.

Apparently, gains in gas content can be generated from the oil itself during storage because the salt dome has been heated by the geothermal gradient of the earth. The heated domal salt transfers heat to the oil stored in the caverns and thereby increases the gas released by the volatile components and raises the boiling point pressure of the oil. The process is essentially a variation on the fractionation of oil, where each of the discrete components of the oil have a discrete temperature range over which that component can be volatized and removed from the remaining components. The most volatile components are methane and ethane, the shortest chain hydrocarbons. Since this fractionation is a fundamental aspect of oil behavior, the volatile component can be removed by degassing, potentially prohibiting the evolution of gas at or below the temperature of the degas process. While this process is well understood, the ability to describe the results of degassing and subsequent regain is not. Trends are not well defined for original gas content, regain, and prescribed effects of degassing. As a result, prediction of cavern response is difficult.

As a consequence of this current analysis, it is suggested that solutioning brine of the final fluid exchange of a just completed cavern, immediately prior to the first oil filling, should be analyzed for gas content using existing analysis techniques. This would add important information and clarification to the regain process. It is also proposed that the quantity of volatile components, such as methane, be determined before and after any degasification operation.

Table of Contents

ABSTRACT **3**
CONTENTS **5**
LIST OF FIGURES **6**
LIST OF TABLES **6**
ACKNOWEDGEMENTS **7**
1. INTRODUCTION **9**
2. AN EMPIRICAL EQUATION FOR GUIDANCE **10**
3. PREVIOUS ANALYSES **12**
4. SOURCES **13**
4.1. Production and Transportation **13**
4.1.1. Production 13
4.1.2. Transportation 13
4.2. Geological Sources **14**
4.2.1. Continuous source evolution (domal salt dissolution) 14
4.2.1.1. Probable initial condition of the salt domes. 14
4.2.1.2. Release of inclusion gas through salt leaching. 15
4.2.1.3. Solution evolved gas contribution for ideal storage case. . . 16
4.2.1.4. Adsorption of gas by crude oil. 17
4.2.1.5. Brine effect on gas content of oil for ideal storage case. . . . 18
4.2.1.6. Comments on the less than ideal case. 21
4.2.1.7. Comments on the less than transparent interface. 22
4.2.1.8. Natural variation of the quantity of solution released gas. . 22
4.2.1.9. Resolution by measurement of brine gas content in construction phase. 23
4.2.2. Continuous evolution (gas release from the dome) 23
4.2.2.1. Hydrological flow of gas through the dome. 23
4.2.2.2. Creep induced salt damage adjacent to cavern. 25
4.2.3. Episodic releases (large volume gas releases from dome) 29
4.2.4. Section summary 31
4.3. Primal Sources **32**
4.3.1. Oil fractionalization during heating 32
4.3.1.1. Composition of crude oil. . . . . . 32.
4.3.1.2. Heating of oil during storage. 33
4.3.1.3. Gas release from the stored oil. 34
4.3.1.4. Reversibility of the gas obtained from heating of oil. 34
4.3.1.5. SPR standard conditions. 35
4.3.1.6. Additional caveats and simplifications. 35
4.3.1.7 Speculation. 36
4.3.2. Microbial generation 36
4.3.3. Section summary 37
5. DISCUSSION AND SUMMARY **37**
REFERENCES **38**
APPENDICES **41**
DISTRIBUTION **59**

LIST OF FIGURES

Figure 2.1. Schematic of gas release quantities according to Equation 1, ideal case. . 11
Figure 4.1. Depletion times for gas from dome into surrounding strata (from [3]). . . 24
Figure 4.2. Dilatant damage, cylindrical cavern, vs. distance/cavern diameter [19]. . 27
Figure 4.3. Gas regain (or intrusion) rates in all caverns, 2009 summary, Lord [29]. . .28
Figure 4.4. Spectum obtained from crude oil from Bryan Mound Cavern 114 [6]. . . 33

LIST OF TABLES

Table I. Oil Blanket Volume during Construction and Filling of Bryan Mound [11]. .20

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INTRODUCTION

The Department of Energy (DOE) established the Strategic Petroleum Reserve (SPR) program to develop and maintain extensive storage facilities for crude oil in selected salt domes of the Gulf Coast. This crude oil was to serve as a reserve to mitigate the impact of any future interruptions in the energy supply and to fulfill obligations of the United States under the International Energy Program [1]. Maintaining this crude oil for use in case of national emergency implies that it be available for rapid deployment through the existing oil pipeline networks to the refineries. In a practical sense, therefore, the oil itself must be maintained in a condition that meets the criteria for safe transfer from the repository to the refineries, while complying with the refinery acceptance requirements. Ability to meet these requirements is no simple task and presents significant challenge to the SPR program.

Currently, the SPR consists of some 700 MMb (million barrels) stored in solution-mined caverns among four separate facilities in Gulf Coast salt domes. While some of the storage utilized existing caverns purchased by the DOE, which facilitated prompt early storage, most of the caverns were purposely constructed by the SPR. Although there is some variation in cavern capacity, the constructed caverns are typically about 10 MMb in capacity, while the purchased caverns are of either larger or smaller capacities depending upon their history. The purchased caverns, which were solution-mined between 1942 and 1979, and acquired between 1977 and 1985, were filled with oil between 1977 and 1987, and the constructed caverns, which were solution-mined between 1980 and 1987, were filled between 1982 and 1990. Because the storage is relatively inactive, with only a few, relatively minor, withdrawals of oil over the intervening years, the dwell time of the oil in many of the caverns has been potentially a decade or more. Even though crude oil withdrawals during this period have been infrequent, a surprising number of operational events have resulted in the crude oil being exchanged between caverns, one type of crude being replaced by another, and some withdrawal of oil for readiness demonstration or for small scale oil sales during short term emergencies. Consequently, in some cases the crude oil inventory history within a cavern may be complex, and moreover somewhat difficult to follow. Of even greater interest, however, is that the stored oil can undergo changes over time which may affect the ability to meet the transport criteria. This report attempts to address the nature and cause of some of these changes.

As the crude oil is produced from an oil field, it can be both hot and pressurized. In the immediate treatment of the oil at the field, the oil will be cooled and reduced in pressure to ambient conditions, consequently, excess volatiles at this point are stripped and flared (burned), prior to transportation. Transportation is normally either by pipeline or by ship container. The stable transported product is at roughly 80°F (nominal room temperature) and 14.7 psi (1 atmosphere). These conditions are actually criteria used to assure that dangerous, explosive or toxic gases are not present during transportation. The Level 2 Criteria [2] for receipt of oil at the SPR in the “dead,” or non-gas producing, condition, which is equivalent to a “bubble point pressure (BBP)” of 14.7 psi or less, and at a temperature of 80°F or less. However, the oil may be cooled from 90°F using raw water, if it arrives at this elevated temperature, as a consequence of pipe line heating. In

addition, nitrogen and carbon dioxide inert atmospheres are often used in the shipping of the oil, primarily in vessels, some of which may be taken up by the dead crude oil.

While the transportation criteria are independent parameters, in this situation they reflect the maximum "bubble point pressure" allowable for the safe transportation of oil. When applied to the crude oil, the bubble point is the combination of the temperature and pressure where any specific oil evolves gas, and thus, the actual boiling point values may be above or below the transportation criteria. Of course, when the boiling point of the crude oil is above the safe transport values, it can no longer be transported.

Natural crude oil as it is produced from the oil field is a complex substance. It contains hydrocarbons with a range of molecular weights, indicating the chain length and bonding type of the molecules. The simplest of these molecules are methane and ethane, both of which are volatile, and explosive, components which will off-gas from the crude oil when the boiling point exceeds the transportation criteria. In addition, propane, benzene, H_2S, nitrogen and carbon dioxide are also volatile, and may be explosive or environmentally hazardous. H_2S and benzene are especially hazardous and require special removal treatments.

Significantly, while the crude oil delivered to the SPR from the production field is at or below the safe transport or SPR receipt criteria, it will not necessarily remain so. Specifically, during the storage of the oil it can acquire or produce significant amounts of dissolved gas. Because the stored oil can eventually take-up gas from the domal salt and become elevated in temperature and pressure compared to the receipt criteria, it may be necessary to periodically degas it. As noted previously, the subject of this report is the gasification process, together with limited observations and possible recommendations concerning degas operations. Only two primary sources of gas are considered: those related to external and geologic sources and those primal sources related to the oil itself.

AN EMPIRICAL EQUATION FOR GUIDANCE

While it is difficult to give a theoretical framework for the gasification of the crude oil stored at the SPR, an empirical equation based on observation can be formulated. The quantity of gas in the oil is given by:

$$Q = \Sigma Q_i^S + \Sigma Q_j^C(t) + \Sigma Q^P(T,w_n) + \Sigma Q_k^E - \Sigma Q_r^D \qquad (1)$$

Where Q is the amount of gas, Q_i^S is the time independent generation of gas by the ith solutioning and transfer process, Q_j^C is the time dependent generation of gas by creep damage release from salt adjacent to the cavern by the jth rejuvenation of creep, Q^P is the generic gas released from within the oil, Q_k^E are extraneous sources such as blanket gas, and Q_r^D is the gas removed by the rth degasification. As is apparent, only one of the terms is dependent upon time, while one term depends only (perhaps) upon temperature and the distribution of molecular components in the oil. There is thought to be little interaction between terms, except where new solutioning can rejuvenate the creep damage process by dissolving away volumes of salt that have undergone damage, to expose less damaged

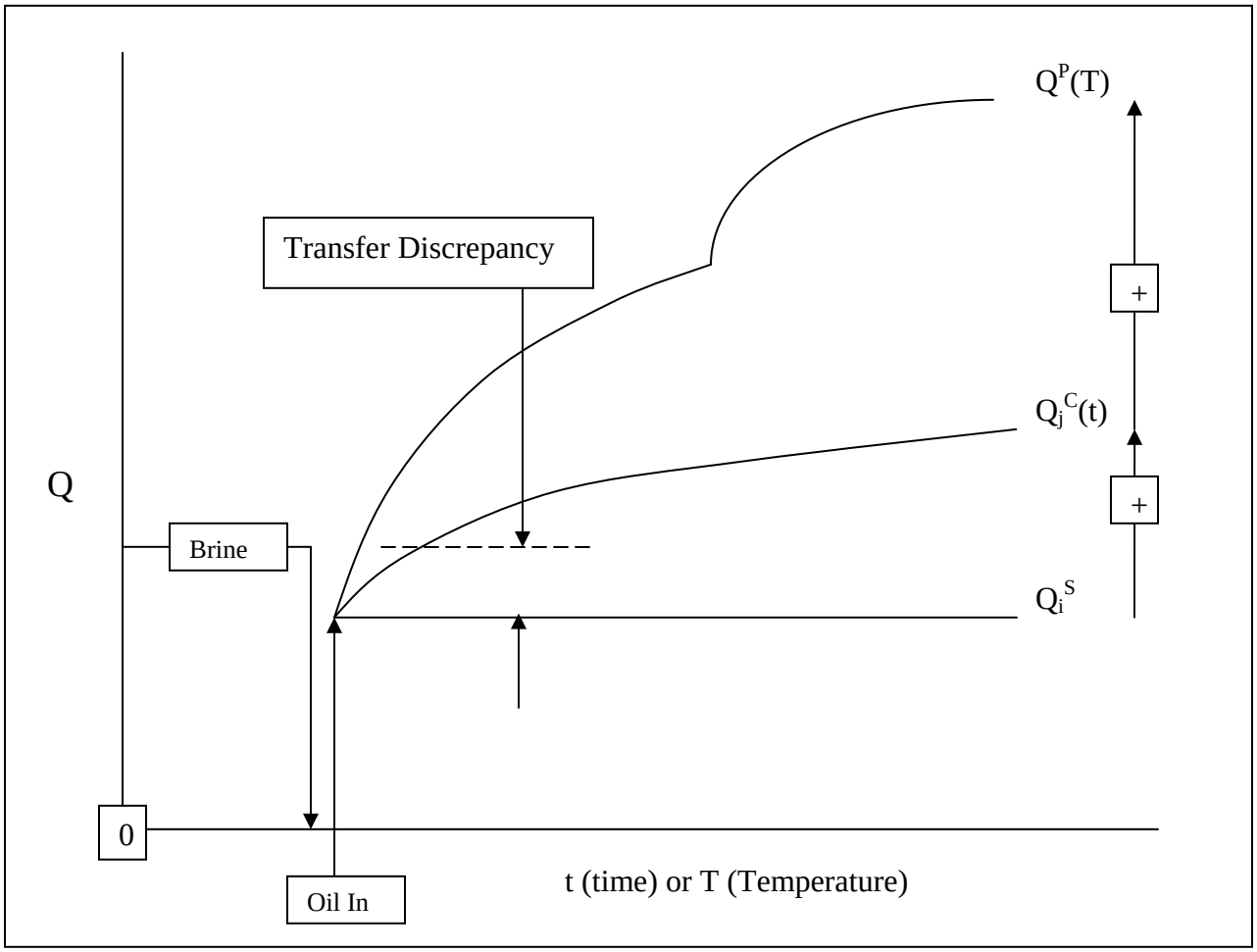

Figure 2.1. Schematic of gas release quantities according to Equation 1, ideal case.

Salt adjacent to the new cavern wall. The explicit assumption in the Q^P term is that it is dependent only on the instantaneous temperature of the oil and that the process of gas release in the oil is reversible. In a very simplistic view, Figure 2.1, a schematic, gives the possible changes in the quantity of gas available for release from the crude oil stored in the caverns.

All of this is based on a reference condition, which in the case of the SPR is the acceptance criteria of Q = 0 and T = 80°F, at P = 14.7 psi (atmospheric pressure) [2]. This is not really a standard condition, but could be. Rather it is the condition of "dead oil" required for shipment of crude oil. At the SPR, oil with a temperature of 90°F is also accepted, provided that it can be cooled to the 80°F condition.

As something of an aside, the SPR normally requires that routine analyses are made of the off-gas products obtained during systematic testing of the gases released by the crude oil before and after a degas operation. This part of the program is to assure that the deliverability criteria can be met. These analyses routinely determine the bubble point

pressure (BBP), the oil-to-gas ratio (GOR), and the spectrum of components using the TVP-95 and TVP-2000 instrument systems [3-7]. The spectral analysis by gas chromatograph (GC) is usually made of the off-gas obtained during the test. It is possible these measurements can then be related independently to each other, and expanded through an equation of state to calculate independently the component quantities in the oil.

Later we will introduce the nomenclature of exchange of fluids, which may be an important concept of the operation of the SPR and the evolution, transport and removal of gas in the oil. We should also be aware of the fact that several types of exchanges can occur during the life of a cavern. However, the most relevant exchange is the gas/oil exchange in which the oil takes-up gas. Also very importantly, the oil and oil/gas systems are closed systems, where the quantities remain fixed in the facility unless altered by a degassing operation or by an emergency or demonstration sale of oil.

PREVIOUS ANALYSES

Gas content, re-gasification, gas up-take, and gas sources issues and their bearing on the need to degas the crude oil stored at the SPR have been analyzed previously in several reports. Notably, one of the earliest reports from 1995 [3] examined extensively many of the issues identified at that time, including gas migration, geological sources, the gas content of stored oil, and predictions of gas intrusion rates. Appendices of the report examined potential creep contributions to gas intrusion, origins of the gas, etc. Later an extensive analysis of “outbursts” [4], which are the explosive release of gases from voids in the salt, usually associated with mines, was published. This was followed in 2003 [5] by a database with additional measurement data and modeling analysis of gasification and degas in all SPR caverns. Lord and Rudeen [6, 7] reported their extensive analysis of the crude oil vapor pressures at the SPR, covering in the process many issues of gasification, and again presenting a large database of cavern history. We shall make extensive use of these reports, especially the often quite definitive analyses of Hinkebein et al. [3]. There will be no concerted attempt to reexamine the analyses of these authors; rather, we hope that the current analysis presented here will enlarge on some areas considered critical to the gasification process, and suggest some modification of older concepts and significant changes in current concepts.

It is possible to identify from these reports the sources of gas that can potentially contribute to the observed gas content of the stored oil, and lead to the need to degas that oil. Without regard to the significance or viability of these sources, they can be listed: (1) Production and transportation sources [3], (2) Geological sources from inherently entrapped inclusions in the salt dome either via hydrological flow, from release by salt solutioning (leaching), or creep damage release [3, 4], (3) Enhanced gas generation within the pressurized stored oil by geothermal heating from the salt dome [6, 7] or generation by anaerobic bacterial processes [3]. We will discuss each of these sources in the context of the previous analyses, adding some new aspects, where appropriate. Most certainly, many of the fundamental insights provided by these earlier works will prove to be quite valuable.

SOURCES

As noted above, crude oil gasification has been the topic of numerous investigations within the commercial oil industry and the SPR program. There appears to be general agreement on the sources of the gases that are initially, or become, part of the complex make-up of the crude oil.

4.1. Production and Transportation

4.1.1. Production

While the oil field production of the crude oil in a strict sense does not constitute a source of additional gas, each field and well produces distinct oil in terms of the composition of the hydrocarbons and other gaseous products it contains. Although each oil composition is relatively unique, the oil is normally categorized only in the rather broad terms required by the industry. This unique composition is altered in the field during the preparation of the crude product for shipping. The pressure is reduced to atmospheric and the resultant off-gas is flared, or burned, at the initial field processing plant. Also, the temperature of the produced oil during this process is lowered at the processing plant to that required for safe transportation.

It is important to note that, in fact, the crude oil is not a continuum fluid, but it is a collection of discrete molecules, each with a distinct molecular weight and vapor partial pressure. Consequently, this composition of the crude oil can be determined indirectly by spectrographic analysis. This gives a volume fraction of each of the hydrocarbon components, as well as that of the inorganic components of oxygen, nitrogen, hydrogen sulfide, carbon dioxide, etc. During refining of the oil, these unique components can be separated by fractionation to produce the various refined liquids. However, there is perhaps an even more important aspect of the oil composition for our purposes; it should be possible to trace through the various stages of transport, storage, and degas which cause changes in the various components of the oil.

As will be discussed later, the discrete composition of the produced oil carries within itself the ability to release gases beyond those initially available under the conditions of the transportation criteria. These are the generic gaseous components of the crude oil. If, for example, any and all external sources of gas are inconsequential, or non-existent, then the spectral analysis will not only reflect the initial generic quantities of these gases but subsequent spectral analysis should trace the depletion of these gases during any degas operations.

4.1.2. Transportation

Often, especially during ship transport of the crude oil, inert atmospheres of carbon dioxide or nitrogen are injected into the head space of the containers. To some extent, the inert atmospheres probably displace the air and moisture that would logically occupy the

head space in containers. Thus, this practice helps to displace oxygen from the containers. However, it is known that the oil may take-up quantities of these inert gases, which in turn contribute to the off-gas potential of the stored oil at the SPR. It appears that these inert gases, especially nitrogen, can exacerbate out-gassing of some of the hydrocarbon molecules [8].

Although both production and transportation can influence or contribute to the gas contents of the crude oil, they are not considered the most likely or principal concerns in the gasification of stored SPR oil.

4.2. Geological Sources

Often some analysts believed the most significant sources of gas intrusion into the stored oil are considered to be those which arise from the gas inclusions contained within the salt dome, itself. There are two distinct scenarios, both based on inclusions of gas within the salt dome, but varying depending upon the size of the inclusions and their distribution in the dome. Thus, one intrusion scenario involves a more-or-less continuous evolution of gas into the oil, while the other involves discrete episodic events.

4.2.1. Continuous source evolution

In order to examine the potential for the intrusion of gas into the stored oil, we must determine the initial condition of the salt of the dome, as well as possible. Then the processes of developing the storage cavern through solution mining and the introduction of crude oil into the cavern must be described completely, and accurately. Also with such a large, operationally involved, facility such as the SPR, the history of each cavern must be known in detail.

4.2.1.1. Probable initial condition of the salt domes. The salt material of a dome is somewhat difficult to quantify, primarily because to date any sampling of the dome is through extremely limited means [9]. However, even the limited data does provide some insight. While the dome is largely relatively pure salt, it contains discrete impurity inclusions of other materials, such as other minerals (anhydrite, polyhalite, calcium carbonate, etc.) and complex soils (clays, sand, etc.). These impurities can be found in almost any quantity, governed by the depositional details of the mother salt bed, but in the Gulf Coast domes the impurities amount to a few percent of the material of the dome [9, 10]. However, because of the small amounts of these inclusions and the difficulty in sampling and analysis of a dome, the precise amounts are not well-specified, and large uncertainties could exist in the values given.

In addition to the mineral and soil inclusions, observations also show that the salt contains negative crystals encapsulating “native” brine and/or gas. We will for brevity designate these negative crystals as “pores” [10]. The gases may include methane, ethane, propane, benzene, nitrogen, carbon dioxide, light hydrocarbons, and potentially hydrogen sulphide, etc. [4], but most often are methane and nitrogen [11]. The values often given for the domal salt content of these pores is on the order of 1.0 to 5.0 % (+/-

1.0 %) by volume [3]. Here, the upper end value seems rather excessive, since this pore content would be evident to any observer of sample core. Hinkebein et al. [3] suggest a typical value for relatively pure domal salt of 0.4 %. Unfortunately, the total recovered core specimens from the drilling of a SPR well are extremely sparse, perhaps only a few feet of core from any given well. Moreover, the uncertainty associated with the domal content of these native brine and/or gas inclusions is high. However, there are some substantiating results for the lower values from other investigations. Stein [10] has determined that the bedded salt from the Waste Isolation Pilot Plant (WIPP) contains some 1.0 % by volume of included brine, which shares the porosity with gas, largely in negative crystals, but also with some gas contributions from anhydrite and clay inclusions. The usual condition of a negative crystal or pore is that it contains both brine and gas. The small amount of data suggests that the gas inclusions could also be about 1.0 % by volume. Under certain conditions, these inclusions, including the native brine and gas can be released from the massive salt body. In fact, only two mechanisms can produce such a release. One mechanism is through dissolving the salt containing the inclusions and the other mechanism is by movement of the inclusion contents through the massive salt body.

Although probably unnecessary, a visualization of the salt with gas inclusions or pores may be helpful. A 1.0 % by volume of pores can be pictured as essentially a very small pore separated from other pores by large volumes of salt. Moreover, the intervening salt mass is under a confining lithostatic pressure, the stress state of the dome, which inhibits formation of microcracks. Thus, under the domal stress conditions, it appears that the pores remain isolated, and the salt is potentially impermeable to flow of gas. For pores to become connected, development of shear stress and the reduction of the confining pressure are required to form microcracks. Such stress conditions for microcrack development may, although not necessarily, develop in the salt adjacent to a cavern.

4.2.1.2. Release of inclusion gas through salt leaching. In the development of oil storage caverns, the process begins with the solution mining or leaching of a cavern within the massive salt body. In solution mining, raw water is pumped into a borehole drilled into the salt dome, which then dissolves the salt to make brine and a cavity. The brine is pumped out of the cavity into a brine pond for eventual disposal. Introduction of raw water continues until the cavity has the desired volume. As the raw water dissolves salt, the impurities and native brine and gas inclusions are released. The impurities largely fall into the sump of the cavern, although some are transported out of the cavern into the brine pond. The native brine and gas inclusions release their content into the brine. The identity of native brine is lost, but the gas content remains. In fact, the gas, in part, is also carried out of the cavity with the brine. Anecdotally this clearly has been observed as a foaming of the brine and by a down-wind smell of the evolving gas from the brine pond. In some notable instances the production of gas caused problems during the solution mining of specific SPR caverns [11]. Bryan Mound caverns **BM111** and **BM112** had notable gas evolution, primarily methane, resulted in pressure build-up during development. In **BH114** the gas evolution was severe, involving methane and apparently some condensate, and required that it be flared or burned. Certainly, this establishes that the salt dome itself can be the source of gas, in addition to methane, the

gas may contain nitrogen, carbon dioxide, low molecular weight hydrocarbons, and perhaps even some hydrogen sulphide.

Once the input of raw water ceases, the cavern residual brine becomes saturated and any further dissolution of salt will stop. Then, no further gas from the surrounding salt mass can be released by this solution mining mechanism, until or unless raw water is once again introduced into the cavern.

4.2.1.3. Solution evolved gas contribution for ideal storage case. Because a project of the magnitude of the SPR can present a number of differing scenarios during construction and operation concerning the handling of the fluids, we will present initially the **ideal case**. For purposes of the analysis, we will define the ideal storage case as (1) the creation of a cavern by solution mining to the desired capacity and then (2) the filling of the cavern with crude oil.

The ideal case involves the clean sequential construction of the cavern by raw water solutioning, followed by the injection of crude oil. During this process, the gas evolved from the salt of the dome can be determined. However, the determination of the quantity the gas evolved has a potential uncertainty because of the uncertainty in the input parameters of the pore content of the salt and the distribution of the native brine/gas ratio. Therefore, we shall attempt to assume values of these parameters which will lead to conservative analysis results. The initial assumption is that the salt body contains 1.0 % by volume of pores filled only by gas. Overburden pressure increases at roughly 1 psi per ft. of depth below ground surface. This gas is assumed to be at the lithostatic pressure found at 4000 ft beneath ground surface (overburden), which is roughly the depth of the bottom of SPR caverns. This assumption is considered reasonable since the age of the dome would permit the equilibrium pressure in a void to be achieved at any given depth. Moreover, while this depth seems arbitrary, it is reasonable that an isolated gas inclusion in the dome will always contain the same quantity of gas, regardless of the depth. Because of the existence of the dome for hundreds of thousands of years, the bubble size will adjust to the correct depth-pressure values. The reason for this assumption will be discussed later in the report. Consequently, each 1.0 cubic ft. of salt will contain 0.01 cubic ft. of pores at a pressure of 4000 psi. When released, this gas expands to a volume of about 2.72 cubic ft. at 14.7 psi. Since a 42 gallon barrel has an equivalent volume of 5.62 cubic ft. per barrel, this results in a total of about 15.56 cubic ft. of gas per barrel of solution-mined salt. However, remember that this rather large amount of gas may be an over-estimate based on idealizing the entire pore as occupied by gas.

When we examine the solutioning process further, each gallon of salt dissolved requires about 6.1 gallons of raw water. While the solutioning process is essentially a continuous system where raw water is input into the cavern, dissolves salt to form brine, and the brine is extracted, it can be treated as though there is about a **6.1 fold exchange** of brine. With each of the initial 5 exchanges, the brine carries the gas released from the dissolved salt out of the cavern and into the brine pond. Consequently, only the last or 6th exchange of brine remains in the cavern, along with the gas released from the salt dissolved by this

exchange. ***Finally, then the amount of gas in the cavern brine in this idealized case is on the order of 2.50 cubic ft. per barrel of brine, under the assumptions used here.***

It may cause some concern that the gas from dissolution is a fixed number, and does not change with time, whereas, actual bubble point pressure and gas to oil ratio data suggests that in some caverns the gas content increases with time.

We have introduced the nomenclature of the **exchange of fluids**, which is an important concept of the operation of the SPR and the evolution, transport and removal of gas in the oil. We should also be aware of the fact that several types of exchanges can occur during the life of a cavern. These exchanges are (1) raw-water/brine, (2) oil/brine, (3) oil/oil, (4) brine/gas, and (5) oil/gas. It is important to note that the SPR tends to be a closed system for the oil involved in exchanges, since the oil once it enters the system generally remains within the system. Only occasionally during readiness withdrawals, emergency sales or customer exchanges of relatively small quantities of oil is the closed system violated. The brine and gas systems, on the other hand, are much more open systems, with quantities of brine and gas being released from the SPR operation. The brine is disposed of and the gas is reclaimed, released or flared. However, critically, if we could identify the gas released from the brine and adsorbed into the oil, that oil/gas system is also a closed system, violated only by the degasification process.

This scenario differs markedly from that proposed previously [3] wherein nearly all gas in the brine was assumed to be removed from the cavern.

4.2.1.4 Adsorption of gas by crude oil. There are two collections of oil that need to be considered for adsorption of gas. First there is the blanket oil placed at the top of the wells and caverns from the on-set of construction as the caverns are developed. And then, there is the oil injected into the cavern during filling after cavern development is complete. Each of these will contribute to the final gas content of the oil.

Since oil and brine are immiscible, there must be some mechanism for the transfer of the gas in the brine into the oil which involves an interface. Much of the transfer process therefore is controlled by the behavior of the interface, or in other words, it depends essentially upon the transparency of the interface. The transfer process is confined to the interface, where gas in the brine must move to the interface and gas in the oil must move away from the interface. It is believed that some, or possibly all, of the flow to and from the interface depends upon diffusion, with convection potentially playing a significant role. As with any other diffusion system, the flow is governed by gradients of dissolved gases through the fluids. While these diffusion rates are high, they are still finite. In one scenario, the interface is perfectly transparent, allowing uninhibited flow across it [3]. However, in another scenario, the interface is a complex system of materials a few feet thick [12] which could potentially inhibit the transfer of gas. It is thought that the complex interface develops with time, forming sludge of heavy hydrocarbons [13]. Thus, how oil takes up gas is largely determined by which type of interface exists, as well as the transmission flow dynamics.

Hinkebein et al. [3] first concentrated on the potential for the oil blanket to take-up gas from the brine throughout cavern solutioning. For the transparent interface, they have argued that because the affinity for gas is so high in the oil compared to the brine, perhaps a factor of 100, or more, that all of the gas in brine will be taken up by the oil. It has been further argued [3] that this process requires only a few days for completion, primarily because of convection cells in the raw water/brine. In particular, the raw water would impinge on the interface from beneath and then flow down the sides of the cavern, actually reducing the concentration of gas saturated brine at the interface. However, convection cell formation would seem possible only during a brine push to empty the oil from a cavern, not during oil filling. In this scenario, they used the same assumptions of 1.0 % pore content, then the small amount, 10,000 bbl, of blanket oil acquires only 14 scf/bbl of gas, even though the gas released by the solutioning is overwhelmingly large. The conclusion was that most of the gas from the dissolved salt is released to the brine pond. The gas in the blanket oil remains available for distribution as the cavern is filled with oil, but compared to the 10 MMb volume of fill oil, it is insignificant. More to the point, even if the oil blanket were to scavenge all of the gas released from the dissolution process, and then mixed into the fill oil, all of the gas would still remain in the cavern.

In the context of the oil blanket response during solutioning, Hinkebein et al. [3] evaluated the rate of the extraction of the gas by brine from an oil blanket initially containing an arbitrarily assumed 100 scf/bbl of gas attained only a lower value of 14 scf/bbl. The raw water input was from below and impinged on the interface. Based on the calculations of others [14], the time to obtain gas equilibrium between the oil blanket and the brine was stated as a “few days.” This suggests that not only is the interface quite transparent, but also that the rate of gas flow, perhaps aided by convection, through the oil and brine is rapid.

When filling a cavern, the oil is injected into the top of the cavern, where the turbulence from the injection will remain at the top of the cavern and probably does not extend downward more than a few tens of feet. Remember, these caverns are some 2000 ft. deep with diameters of some 200 ft. The injection continues to push the brine downward until the cavern is filled to within a few tens of feet of the cavern bottom [15]. It should be noted, the filling of the cavern is not a rapid process, and may take a month, or more, allowing time for the movement of gas within the system. Because of the large amounts of fluid being transferred, and the large distances involved, it is reasonable to suppose that the transfer of gas is not ideal, and that significant quantities of gas may be removed with the displaced brine through the hanging string during the cavern filling process. However if the achievement of equilibrium is as quick, as suggested, then the filling time may be adequate to assure the nearly compete transfer of gas. Clearly, however, the easiest scenario to analyze is that of the transparent interface and complete transfer of gas of the ideal storage case.

4.2.1.5 Brine effect on gas content of oil for ideal storage case.

To reiterate some of the previous points, during the solutioning process, a blanket of oil is maintained in the cavern top which prevents possible unacceptable leaching of the roof salt. Because the oil has a higher affinity for adsorption of gas than the brine, it has been

suggested that much of the gas will be transferred to the oil [3], as dictated by perhaps as much as a ratio of 100 between the methane in oil to that in brine, at equilibrium. For a transparent interface, the roof oil takes up as much as possible of the gas released during all of the brine exchanges, to achieve, we believe, equilibrium saturation with the gas in the brine. Equilibrium also requires the movement of gas in the brine to the interface and movement of gas away from the interface into the oil, processes though to be relatively quick [3].

As noted previously, the gas available in the roof oil is distributed into the fill oil. Significantly, the amount of this gas depends upon the quantity of roof oil available. As the data of Table I illustrates for Bryan Mound, the quantity of oil in the blanket is normally quite small throughout all the cavern leaching stages compared to a typical cavern final volume of 8-12 MMb. These tables for all of the SPR caverns are given in Appendix A. The blanket oil volume ranges from 500 bbl (~0.004%) up to 600,000 bbl (~5.0%). These values are similar to those summarized by Hinkebein [3]. As noted, the amount of gas in the blanket oil becomes insignificant when it is mixed into the large volume of fill oil.

The blanket oil remains in contact at a brine/oil interface layer throughout the construction of the cavern. This blanket oil remains in contract thereafter, through what could be an extended period. However, at some point during the final completion of the cavern only the gas released from solutioning during the last exchange of brine, remains in the cavern. Although the gas could be contained in the blanket oil, which is unlikely, it certainly could remain in the brine.

At some other point, either as the cavern nears the desired construction volume or when it acquires that volume, it is filled with oil. The oil enters the cavern through an inlet pipe or slick hole at the top of the cavern while brine is withdrawn by the hanging string pipe from near the bottom of the cavern. Consequently, the oil acts as a piston forcing the oil/brine interface downward as the cavern is filled. The incoming oil, if it is newly acquired dead oil, is not saturated or in equilibrium with the brine, and the affinity of the oil for the gas suggests that the gas in the brine will prefer being in the oil. Consequently, gas transfer at the transparent interface will essentially purge the brine of gas, taking up the 2.5 cubic feet of gas per barrel. Again, the time available to accomplish the transfer is the filling time of the cavern, perhaps a month or two. This transfer process, while taking place, has the natural limitations noted previously. Although a quantity of brine remains in the cavern bottom, which can vary with the cavern and operational details, the desired brine volume typically incorporates about 30 ft. of brine (or about 2% of the cavern volume) [15].

Table I. Oil Blanket Volume during Construction and Filling of Bryan Mound [11].

Cavern	Oil Blanket (bbl)					Fill-Degas*	Delta
	Sump	Chim'y	First Rev.	Second Rev.	Third Rev.		
BM001						78-83-*96*-97-**97**	14
BM002						78-85-96-96-**96**	11
BM004						77-82-	
BM005						78-86-*87*-89-	
'BM101g	630+		450	2,473,000 surge	9,808,910 fill	84-85-*97*-97-**97**	12
BM102	604+	411+	3,000	1,100	10,252,776 fill	85-	
BM103g	550+	600	1,250	809	10,033,202 fill	85-97-*97*-97-97	11
"BM104	1,014+	668+	213	1,407,000 rf/inter	10,257,027 fill	83-	
"BM105	990+	414+	830+	1,702,800 dia/inter	9,245,728 fill	83-	
"BM106	551+	1,425+	327+	5,021,367 storage	11,098,441 fill[&]	83-**97**-*00*-02	14
BM107g	520+	724+	41,000	3,100	10,258,118 fill	83-97-97-**97**	14
"BM108	770+	355+	3,000	1,294,340	10,939,562 fill	85-	
"BM109g	835+	506+	388	2,744,000 dia/inter	10,522,309 fill	83-*97*-97-**97**	14
BM110		491+	350	19,506 (46,000)	10,218,032 fill	83-*96*-97-97	13
BM111g	410+	40	580	16,000	9,961,374 fill	84-87-*97*-**97**-98	13
BM112g	350	240	6,300	8,000	9,681,996 fill	85-*97*-98-**99**	12
"BM113	14,583+	356	3,000	1,042,823	4,474,561 fill[&]	86-87-*95*-**95**-96	8
"[$]BM114	705+	2,100	2,000	1,706,264inter	7,168,403 fill[&]	87-*95*-95-**95**	8
"[$]BM115	442+	316	516	105,000	8,678,149 fill	86-*96*-**95**-95	9
"[$]BM116	225	220	300	155,000	9,425,628 fill	86-*95*-**95**-95	9

* The string of dates gives a brief history of the cavern. Numbers in red italics and underlined indicate the cavern was emptied on that date. Numbers in red bold indicate the date of cavern degas. Numbers in black show the cavern was filled on that date. An appearance of two filling dates for some early history indicates some differences or uncertainty in interpretation between references [2] and [6].

' Cavern BM101 contained some surge oil for a period of time, which was removed.

g Gas reported in the construction report in these caverns.

" These caverns all had partial filling before final cavern volume was leached.

\+ These caverns had multiple unconnected roofs initially; blanket oil is the sum of all wells.

& First note: The Mayan crude initially in Cavern BM106 was replaced by sweet crude in 2000.
Second note: The sour crude initially in Cavern BM113 was replaced by sweet crude in 1987.
Third note: BM114 partially filled, then completed, sour replaced with sweet crude in 1987.

One of the interesting aspects of the ideal process described, it that the maximum quantity of gas that can be taken up by the oil cannot exceed the quantity of gas released from the salt in the last leaching exchange, which is about 2.50 cubic ft. per barrel of cavern volume. In practice the actual quantity for the ideal case with transparent boundary layer should probably be less than this value as a result of the

rather conservative assumptions made in our calculations. However, it should be noted, interestingly, that Hinkebein et al. [3] indicate the data accumulation of measured values of gas content in the SPR oil seem to center around a value of 2.0 cubic ft. per barrel, but with considerable data scatter toward some larger values.

The other consideration that may actually control the transfer of gas is the rate of diffusion of the gas through the liquids. Liquid diffusivities are relatively slow [16], leading to diffusion rates on the order of 0.1 m per year [17]. With these slow rates of movement, the gas is essentially fixed in the brine. This is especially relevant when these times are compared to the times required for the movement of the oil, such as filling, into and out of a cavern. However, as noted previously, diffusion is not the only mechanism for transfer of liquids in the caverns, convective transfer is also present. Convection is also possible within the oil and brine, with the potential for transporting gas at a much higher rate than diffusion alone.

Even for the ideal case, the exchange of fluids during the injection of oil at the top of the cavern to replace the brine which is removed from the bottom of the cavern cannot be instantaneous. Regardless of the speed of the injection, the movement of gas in the brine toward and the movement of gas in the oil away from the transparent boundary remains a rate process. This means that as the oil injection at the top of the cavern occurs it forces brine, together with some part of the gas content out of the cavern. How much gas is lost in this oil/brine exchange is currently unknown, but it will lower the final gas content of the oil from the maximum available in the brine. In our example, this will result in the gas content of the oil falling below the 2.5 cubic ft. per barrel value.

4.2.1.6. Comments on the less than ideal case. Actually, the ideal case is not the usual or normal case because many different operational conditions and policy decisions can be imposed which alter the sequences of cavern construction and oil distribution. In Table I there is an attempt to provide a simplified history of the caverns of Bryan Mound. Approximate dates are given for the filling, emptying, refilling and degasification (under Degas I) for each cavern [2, 6], where these dates are available. Occasionally, slight discrepancies can occur in dates, which for our purposes are not significant but have not yet been resolved.

Examination of the cavern histories, in fact, shows that few caverns conform to the ideal case of first completion of construction then filling. BM102 is one that does. Frequently, as was often the practice in Degas I, the cavern was emptied of oil during degas, then degassed and the resultant oil was placed into a different cavern. At the time this was the operational practice, which was eventually changed. Thus, only the first parts of the history involved the ideal case. When the oil is removed, it contained at least the gas acquired during the final or 6th exchange of brine for oil. The degas operation, of course, again stripped out part of the gas from the oil as it was removed from the cavern. However, when the oil is placed into another cavern, it then replaces the brine which has presumably dissolved salt equivalent to the ideal case 6th exchange and this gas will then be taken up by the entering oil. Thus, the oil will again acquire the equivalent amount of gas in addition to the gas is currently carries. Potentially, here, if the degas is successful,

the degas operation produces no resultant change of the gas content of the oil, provided the only gas considered is from dissolved salt. This is an interesting result.

As is evident from the brief histories shown, the events and the manner in which oil is treated and handled becomes quite complex. For example, if the oil used to replace the removed and degassed oil of a cavern is replace by "new" oil which arrives at the facility in the "dead" condition, then the new oil will acquire only the amount of gas from the ideal case. If, on the other hand, the oil is replaced by oil from another cavern which is not degassed, and therefore, retains the gas from the initial 6th exchange of brine with oil, the replacement oil will take up additional gas. In addition, in some caverns, that were used for surge storage of oil that filled part of the cavern (BM101), underwent several partial exchanges of brine before the surge oil was removed. Further, in other caverns concurrent filling proceeded during partial exchanges of brine for cavern shaping purposes (BM104) or for other needs (BM106, among others). The permutations are many and significant. Remember, the principle of the oil and oil/gas being closed systems.

It should be noted the degas operation was later changed to a system in which the oil in the cavern is removed from the bottom of the oil volume, circulated through the degas system and returned to the top of the cavern. Consequently, the gas is removed, in part, and is not replenished from any further raw water dissolution of domal salt.

4.2.1.7. Comments on the less than transparent interface. The nature of the interface between the oil and brine has been the subject of several studies. These studies usually involved the reintroduction of brine directly into the oil rather than into the brine pool maintained in the cavern bottom. Potentially, such studies could provide insights into the transparency of the interface to the transfer of gas into the oil from the brine.

As noted previously, the brine/oil interfaces can have an appreciable thickness, perhaps as much as 3 ft. The nature of the material in the interface appears to be an emulsion of brine and oil, perhaps introduced by the initial turbulence of the injected oil when the injection point and the oil/brine interface are in close proximity. Also in the interface is a quantity of "sludge." The sludge when it is burned leaves little ash [13]. This suggests that it is composed of long-chain heavy hydrocarbons. Potentially, hydrocarbons, even ones of this kind, would still be transparent to gas transmittal.

If the only component of the interface is an emulsion, then it is unlikely that the interface is a serious impediment to the transfer of gases. It should essentially be transparent.

4.2.1.8. Natural variation of the quantity of solution released gas. As noted very early in this work, there is obvious variation in the amount of gas released by the dissolution of the salt. Some caverns released enough gas to cause a problem in construction, while others released only enough to be detected in the brine pond. This could be expected as the result of the natural variation in the gas filled pore content in the dome. Since we have argued that the salt of the dome is impermeable, these natural variations are locked into the mass of the salt, and not uniformly redistribution by Darcy hydrological flow.

4.2.1.9. Resolution by measurement of brine gas content in construction phase. **An answer to an important question is possible.** There remains considerable uncertainty in the generation and transfer of gases within the fluids in the cavern. It seems that theoretical analyses apparently have not totally resolved these uncertainties. It appears that additional experimental data would be beneficial, provided these data could be obtained. If the gas content of the resident brine in the 6th exchange could be determined, it would certainly help determine whether and how much gas is retained from the dissolution of the salt. One possible method to determine the gas content might be found in the use of the TVP techniques on brine. This could potentially supplement the existing analyses of the identity of the brine gases with quantitative measures of the gas to liquid ratios. Further, the use of spectral analysis would again identify the type and relative quantity of the evolving brine gas. Subsequent analysis of the amount of gas in the brine out-flow stream during oil filling might be instructive.

While the possibility of analyzing the brine throughout the construction and filling stages of an ideal scenario is not available for the existing caverns, any new cavern construction would seem to be an excellent opportunity to clarify this issue. In fact, the determination of gas content of the 6th exchange could lead to quantifying the composition, amount and variation of the pore entrapped gas throughout a salt dome. This would be a valuable piece of information.

4.2.2. Continuous evolution

In addition to release of gas by dissolution of the domal salt during construction of the cavern, other mechanisms potentially exist for the release of gas into the cavern. These mechanisms are (1) the flow, in a hydrological sense, of gas through the dome from the far field into the cavern based on Darcy flow and (2) the release of gas with time from the salt adjacent to the cavern through creep induced salt damage. Both of these mechanisms lead to time dependent flow or release of gas. The first of these mechanisms has been examined in detail by Hinkebein et al. [3]. The second mechanism has been often noted and analyzed using numerical methods for creep damage developed with time. This damage generated release of brine and gas was first demonstrated numerically and experimentally around a horizontal room in the WIPP [18] and then in a calculation effort that showed damage at the 4000 ft. depth in a cylindrical cavern [19], during workover conditions under well head atmospheric pressure. We shall reexamine each of these mechanisms here.

4.2.2.1 Hydrological flow of gas through the dome. Geologically speaking, hydrological flow of fluids and gases through geological media is an important consideration and it is logical to address this possibility for introducing gas into an SPR cavern. Much of the earlier work of gas transport was summarized by Ehgartner et al. [4] and included measurements of percolation through salt and capillary transport. These studies gave a variety of results, as would be expected. They are all based on the existence of a permeable salt mass.

Earlier, Hinkebein et al. [3] examined through calculations the hydrological flow of gas through a salt dome. Actually, these earlier analyses appear to be based on calculations of hydrologic flow typified by those of Ehgartner et al. [4] in which the dome was assumed to contain some 1.0 % of gas under lithostatic pressure and with nominal permeability in the range of nanodarcies (10^{-21} m^2) or larger. While these calculations lead to the movement of gas to the caverns, to produce gas quantities of several cubic ft. per barrel within the current life of the caverns, obviously, they depend directly on the chosen permeability and the far-field concentrations.

Hinkebein et al. [3], however, continued the analysis of hydrological flow through calculations, again based on far-field porosity (gas volume at lithostatic pressure) of 1.0 % and a permeability ranging from 10^{-20} to 10^{-22} m^2 in the domal salt. They chose the condition of lithostatic pressure. However, the result of the calculations depend upon the conditions in the far field, which could be either lithostatic or hydrostatic. The answer to the far field comes from studies of the surrounding strata. Independent analysis of the thermal gradients in Louisiana strata have noted an existence of gradients having two components, with a kink at a given depth between a lower gradient upper segment and a higher gradient lower segment [20, 21]. The kink depth is about 10,000 ft. in the southern parishes, and below 16,000 ft. in the northern parishes, of Louisiana. This behavior is correlated to the hydrological conditions, with hydrostatic conditions above the kink depth and lithostatic conditions below the kink depth. Consequently, the domes at cavern depths essentially are in contact with hydrostatic surroundings. As a result, gas flow would be out of the dome into the surrounding strata. Interestingly, one could conclude that hydrologic flow would not lead to a flow of gas into a cavern held somewhat above hydrostatic pressure. Rather, well before the use of the dome for storage caverns, this set of flow parameters would have caused the depletion of the gas in the dome to low levels, potentially to hydrostatic pressures, over the hundreds of thousands of years, or more, of the existence of the dome in close proximity to the hydrostatic

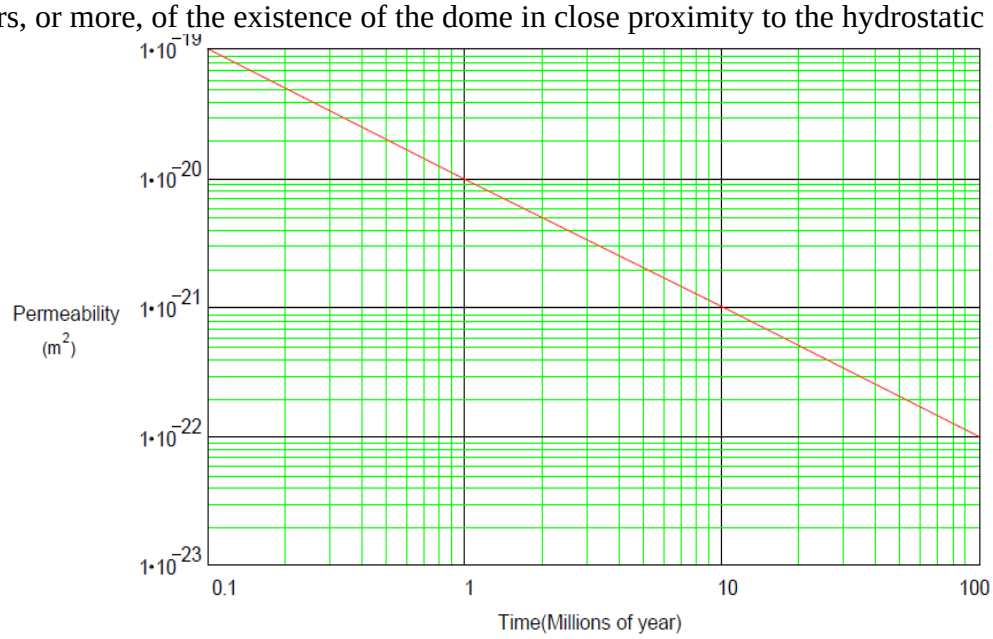

Figure 4.1. Depletion times for gas from dome into surrounding strata (from [3]).

conditions in the surrounding rocks [3]. Figure 4.1 shows the depletion of the gas in a dome, starting with the initial conditions of 1.0 % of gas inclusions, which would occur by 10 million years with the salt at a permeability of 10^{-21} m^2. The net effect is that with the life of the salt dome potentially of some millions of years, the probability of having gas at lithostatic pressure is small.
Interestingly, from these studies, Hinkebein et al. [3] concluded that salt was permeable and the flow of gas to a cavern was possible. However, this presents something of a paradox. On the one hand, the argument requires that domal salt have an inherent permeability, while on the other hand, evidence suggests that undamaged domal, or any intact salt for that matter, is actually impermeable. If the salt is permeable, then the gas content should have been depleted by the time of cavern construction, and indeed, gas should then flow into the dome away from the pressurized cavern into surrounding rock strata, which has been argued to be under hydrostatic pressure. Consequently, in fact, the paradox is resolved only if the domal salt is impermeable, which means that the inclusions of gas in the dome have remained in place unchanged over the dome history. Indeed, it is difficult to know for certain the permeability of salt, due to the range of values available [3, 4].

Sutherland and Cave [22] measured the gas permeability of salt from the bedded salt of the WIPP and found that the apparent permeability was less than 10^{-22} m^2, which was the lower detection limit of the measurement apparatus. This was determined for specimens that had been properly healed under pressure. It was found in general that any salt material obtained from the field by drilling or cutting of the salt and/or from the methods used in specimen preparation can contain deformation damage which would lead to an increase in permeability. Clearly, undisturbed and intact salt dome material has had hundreds of thousands of years, or more, under confining pressure to achieve impermeability. It was found that this undamaged condition could be reestablished for the damaged specimens through pressure/temperature healing.

In conclusion, it is believed that hydrological flow through permeable salt as a source of gas intrusion into the SPR caverns is unlikely, if not impossible, because a permeable salt would have allowed the dome to be depleted of gas into the surrounding formations over the age of the dome. As a corollary to this conclusion, the implication is that salt is indeed impermeable as suggested by laboratory tests on undamaged salt, and therefore, the gas from inclusions in the domal salt cannot move and the inclusions must retain their initial gas content over time. In fact, rather large volumes of contained gas in large voids do occur in natural salt beds and domes.

4.2.2.2. Creep induced salt damage adjacent to cavern. Deformation of the salt adjacent to the cavern through time dependent creep is an ongoing process. Whether or not this deformation is sufficient to cause the formation of microfractures (creep damage) will determine if the gas in the negative crystals or pores is released into the cavern. Many numerical calculations have been made of the stress and deformation fields around storage caverns. Typical of these were the early calculations of Ehgartner [23] for workover conditions where the operating pressure of the cavern is reduced to atmospheric. This reduction of pressure assures the maximum deviatoric stresses around

the cavern and produces the highest creep rate in the salt. Based on values of a "damage factor," a measure related to an overstress condition in excess of the criterion for dilatancy, these calculations suggest that no damage occurs around the caverns. The dilatency criterion, often used, was that of van Sambeek, et al. [24]. However, this criteria is not an actual measure of damage. Recently, somewhat more sophisticated, calculations for the Bryan Mound facility suggest that some areas around complex cavern geometries in a cavern field can become damaged using roughly the same calculational inputs [25]. However, extensive damage fields in these calculations do not occur.

As previously described, other analyses are available which have used a more detailed constitutive model to determine the extent of dilational damage in salt. In order to determine the amount of gas released from the salt, we use an example where the release of brine from around a circular room at the WIPP was determined by a creep fracture damage calculation based on the Multimechanism Deformation Coupled Fracture (MDCF) model [26] together with the application of a "snow plow" model as given by Munson et al. [18]. The minimum damage level to release the content of inclusions was 0.0001. The salt was typical WIPP salt with about 3.0 % impurities, which lowers the level of the onset of dilatancy [26, 27].

The MDCF model was also used by Munson [19] for calculations of creep damage around a cavern operating at atmospheric conditions. Again the creep damage was determined using dilatancy onset data for 3.0 % impurity content. The calculations consider a horizontal slice at a 4000 ft. depth of a cylindrical cavern, with a cavern well head pressure at 14.7 psi (atmospheric pressure). This is equivalent to workover conditions and maximizes the potential damage. The damage in **percent** is as shown in Figure 4.2 as a function of the damage propagation distance into the cavern wall, as normalized to the diameter of the cavern. This figure indicates small amounts of damage, yet potentially sufficient to release gas from the pores. At 10 years, damage ranges from about 0.315 % as extrapolated to the cavern wall to about 0.0105 % at the toe of the curve which extends into the surrounding salt to about 0.30 cavern radii. These damage levels correspond with those of 0.01 % for the onset release around the previously noted WIPP horizontal room. Extent of the damage increases with time as shown, but at an ever decreasing rate. Permeability as a function of creep induced damage levels have been quantified by Pfeifle et al. [28] and support these calculations.

For a 100 ft. diameter simulated cavern, at 10 years, the calculated curve implies the beginning of brine/gas release at a distance into the salt of 15.0 ft., i.e., the toe of the curve, and with total release at the cavern surface. We approximate roughly the volume of salt involved under this parabolic curve as the volume of salt from two-thirds the area of the parabolic damage curve with a depth into the salt of 0.1 radii, or 5 ft. The volume of gas released from this volume of salt is, for 0.01 volume percent of pores, roughly 2250 cubic ft., assuming the gas pressure in the inclusion is 4000 psi (1 psi per ft. of depth). In the same slice of cavern volume there is about 1400 bbl. of oil Therefore, we can estimate that at 4000 ft, under workover pressures, the gas content is 1.61 cubic ft. per barrel at 10 years, or about 0.16 cubic ft. per barrel per year.

However, this amount is correct only at the 4000 ft depth in the cavern. Because of the nature of the creep damage, which is related to the stress, and hence the depth in the cavern, through the 5.5 power law, the extent of the damage profile into the salt diminishes rapidly as the depth decreases. At the top of the cavern at roughly 2000 ft. the extent of the damage triangle is only 0.022 of the extent at 4000 ft.

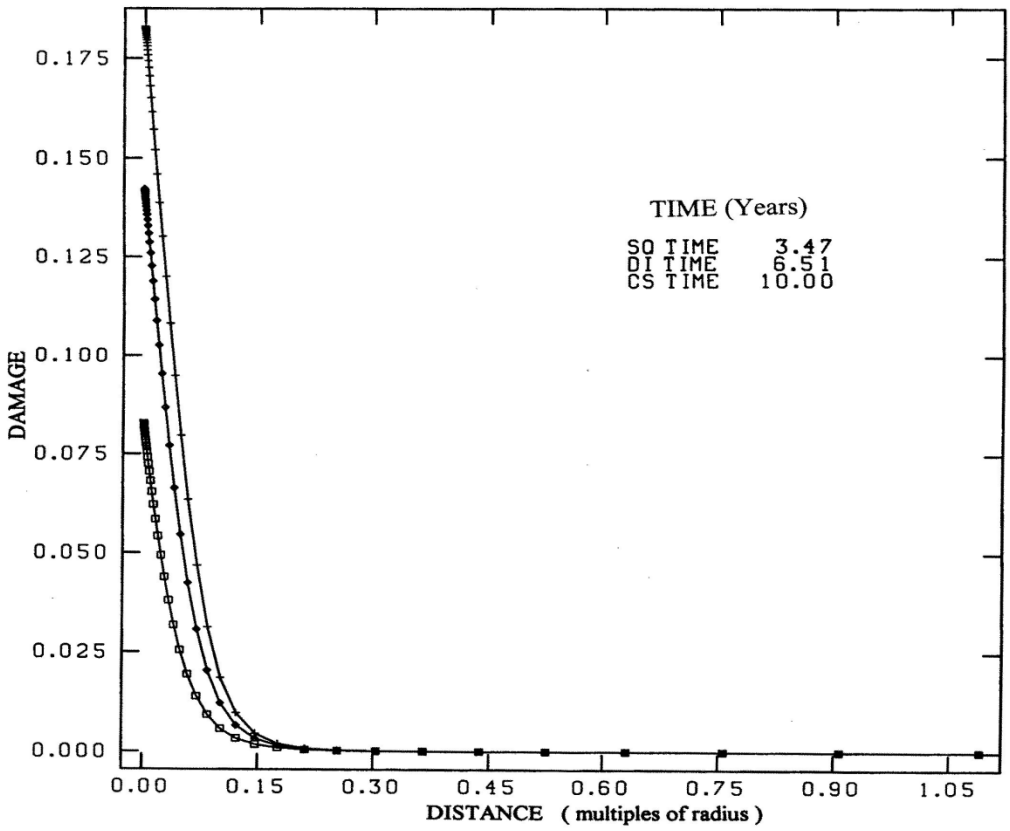

Figure 4.2. Dilatant damage, cylindrical cavern, vs. distance/cavern diameter [19].

Thus, the volume of gas becomes only 0.004 cubic ft. per barrel at 2000 ft., and at 3333 ft. (the 2/3 level) it is 0.059 cubic ft. per barrel. This creep damage release is for a cavern during a **workover** operation at a well head pressure of 14.7 psi (atmospheric).

However, **most of time during normal cavern operation** the cavern well head pressure is typically **above 600 psi**. Consequently, the creep damage release must be adjusted for this higher pressure condition, which diminishes the gas release, as noted previously. Thus, the equivalent creep related gas release must be modified to reflect an effective pressure depth of about 1400 ft, or about 0.08 cubic ft. per barrel at 10 years. Even though this estimate is very crude, it suggests that infiltration is quite limited, with **only 0.008 cubic ft. per year.**

To check whether damage generated gas is relevant, it is necessary to examine the measured "intrusion" of gas into the cavern. Normally, this infiltration is not into the brine but into the oil, since the brine is in the cavern only for a relatively short, initial, period, relative to the time required for creep damage to occur. As noted the amount of gas is about 0.008 cubic ft. of gas per barrel of oil per year. The initial acquisition of samples from the caverns to determine the infiltration was "on the order of" about 10 years. This means an accumulation of about 0.08 cubic ft. of gas, or for a typical 10 MMb cavern, somewhere around 10^4 to 10^5 cubic ft. of gas. BPP sample acquisition currently is more frequent, perhaps every one to two years.

There have been two summaries of the gas intrusion or regain rates into the SPR caverns, the most recent is that of Lord [29]. Results of this summary of all 62 caverns are shown in Figure 4.3, given in terms of the increase in the BPP. As is apparent a significant fraction of the SPR caverns (30/62 or 48%) exhibit essentially zero infiltration. However, in the other 32 caverns the regain rates were observable. Typically, however, most of the observed rates were still equal to or less than 0.1 psi/year. The exceptions, which exceeded the 0.1 psi per year, occurred in four Bryan Mound caverns (1, 111, 113, and 114), two Big Hill caverns (105 and 107), four West Hackberry caverns (6, 7, 103, and 116), and one Bayou Choctaw cavern (17).

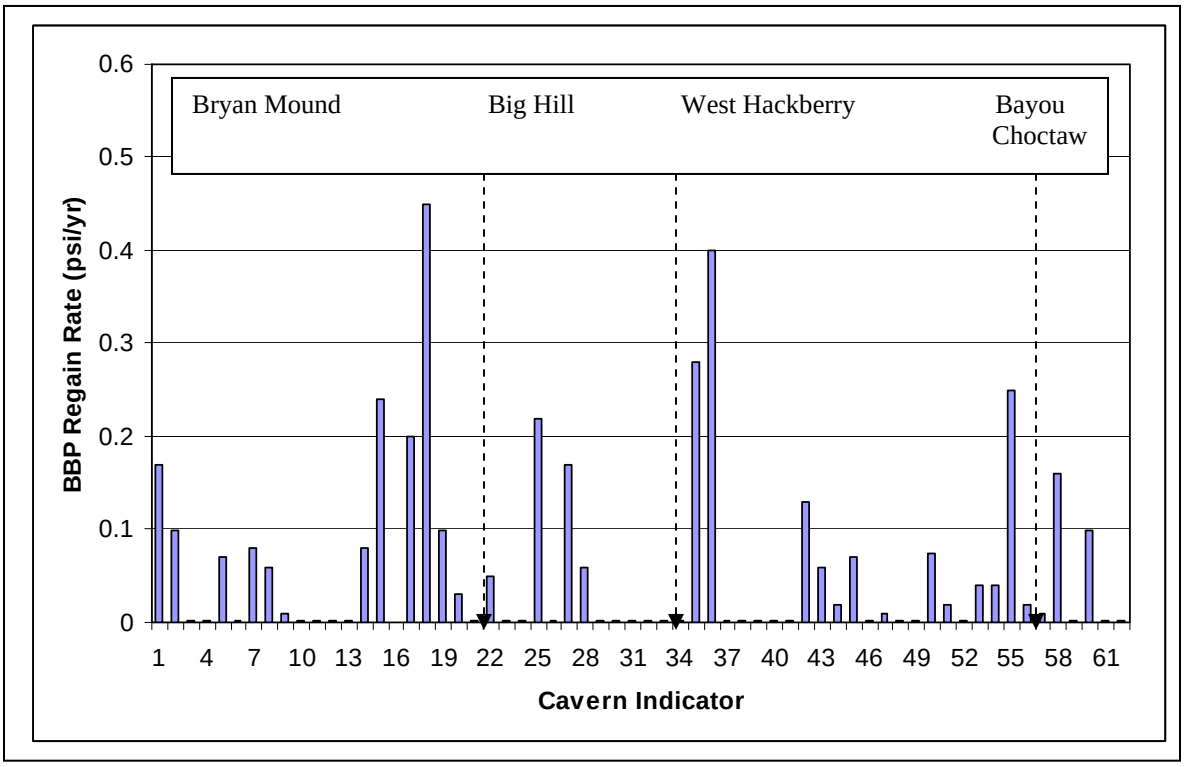

Figure 4.3. Gas regain (or intrusion) rates in all caverns, 2009 summary, Lord [29].

Clearly, the observation of a zero infiltration rate in many caverns is consistent with the very small calculated gas release rate of 0.008 cubic ft. per year. Yet, even this small rate

over the interval between oil filling and the BPP sampling could potentially yield a discernable infiltration rate. Because the amount of infiltration is time dependent, which seems not to be accounted for in the summary results, there appears to be some uncertainty in the analysis. Thus in general the measured infiltration rates and the concept of the introduction of gas through the creep damage process is certainly plausible. Never-the-less, the number of caverns, which show a much greater measured gas regain, is not explained by this process for the conditions examined in the calculation.

Although an explanation for these exceptional rates is not available, some possible directions of investigation might be suggested. While not readily apparent, as noted previously, the amount of creep damage depends upon the impurity content of the salt through changes in the onset of dilatancy curve. As a result, a greater content increases the extent of the damage zone in Figure 4.2, and to the contrary, a lesser impurity content decreases the damage zone. At vanishingly small impurity contents, there is no longer any calculated damage zone. This situation perhaps agrees with the earlier calculations of Ehgartner, et al. [3, 23] using the dilatancy curve for impurity free salt and a stress related damage factor based on the amount of overstress above the onset of dilatancy, the calculational results of which showed very limited damage, if any.

As in the case of gas released by dissolution, the natural variation in the gas filled pore content of the salt could be significant, thus individual caverns could display more or less gas evolved from the creep damage of salt adjacent to the cavern. While the dissolution process is independent of the mechanical properties of the salt, the creep damage release is directly dependent upon the mechanical behavior of the salt. Thus, we might look for potential influences of relative creep resistance of the salt to influence the generation of creep damage. To date, however, correlations of the damage variables and the regain rates have been rather difficult to make, as shown by lack of comparisons in Appendix B.

The results of this crude MDCF analysis suggests that the creep damage can release on the average about 0.08 cubic ft. of included gas per barrel of oil over 10 years, a value that increases at a diminishing rate with time as further damage occurs in the cavern wall. It should also be noted that introduction of raw water into the cavern, such as a brine push to remove the oil, will dissolve the damage zone and then the accumulation of creep damage will restart anew.

Perhaps the most important conclusion of the creep damage release of gas study is that the amounts of gas release into the stored oil is in general agreement with the measured gas regains, except, unfortunately, for some notable cases.

In an attempt to give a complete history of the regain studies, the current 2009 [29] data and the earlier data from the 1998 report by Ehgartner et al. [4] are given in Appendix C.

4.2.3. Episodic releases

On occasion, it has been noted that the gas content of the oil appears to increase abruptly [8]. Potentially, these increases are most likely the result of episodic releases of gas from

the salt during solutioning. Certainly, these episodic events are the result of outbursts of trapped gas from larger scale voids. Outbursts, or blowouts, have been studied extensively by Ehgartner [4]. These outbursts are thought to be the result of an existing stable void in the salt being exposed by mining. Mining alters the stress fields around the voids which leads to the time-dependent failure of the salt at some point adjacent to the void. Typically, the stresses around a void are also modified when the surface of the cavern approaches the void through the solutioning process. As the web between the cavern and the void decreases, shear stresses are introduced into the salt which may cause it to fail. The failure normally appears as an abrupt event, even though the actual failure is a time-dependent creep induced failure or stress rupture.

In fact, Ehgartner et al. [4] indicate a large range of possible gas volumes emitted during an outburst, from a few tens of cubic ft. of gas to possibly 50 million cubic ft. However, if we consider the size of the void required to produce the gas quantity suggested, the void size must be reasonable. In order to produce just a tenth of the 50 million cubic ft. of gas, or 5 million cubic ft., the void size at 4000 psi gas pressure, equivalent to a gas pocket at 4000 ft. depth, would have a diameter of about 150 ft. Thus, the void here would approach the size of the cavern diameter. Ehgartner et al. [4] have shown the magnitude of the "bump" in gas pressure for gas quantities from 0 to 50,000,000 cubic ft. for a 1MMb oil cavern volume. While the bump is large for these assumed conditions, the actual volume of gas released in such events is probably much more modest. Based on observations of the blowout pits remaining after a gas release in mines, the void diameter creating the blowout is probably less than 20 ft., more in the 5-10 ft. diameter range. For example, a 10 ft. diameter void again at 4000 psi would yield only 142,500 standard cubic ft. of gas. This gas would go into 10 MMb of oil or 0.014 cubic ft. per barrel. Compared to the 2.0 cubic ft. of gas per barrel often noted in the SPR oil; this is insignificant.

In order for the episodic event from a reasonable sized void is considered, the gas produced seems insufficient to be noticeable. For blowouts to produce appreciable, and noticeable, increases in the gas content or gas pressure at the SPR, many such events would have to take place nearly simultaneously. This is possible but unlikely. The exception would be an outburst near an injection pipe end, where the immediate gas release could enter the pipe and influence the gages in the pipe line.

The issue of how a sudden large quantity of gas would be adsorbed into the oil is a relevant one. Initially, the gas is a distinct phase and would exist as a "bubble' in the oil. This bubble would rise through the oil rather rapidly, perhaps to reach the top of the cavern. Since the blowout gas enters the oil rapidly, absorbing the gas may be a problem. The affinity for adsorption from the gas phase directly is high but the interface limits the rate of adsorption. Thus, adsorption into the oil may not occur rapidly enough to significantly reduce the bubble gas, unless the bubble size is initially quite small or the bubbles are distributed in the oil. Regardless, for a reasonable initial void size, the gas released would, never-the-less, represent only a small increase in the gas content of the oil, once adsorbed.

The illustrations just given assume that the suddenly released gas would be absorbed rather quickly by the oil. The more probable situation is that the released gas would form a bubble which would rise upward quickly through the oil. And, in fact, most often the gas released by the blowout does not go into the liquid but forms a gas cap, as Ehgartner et al. [4] suggests.

In conclusion, it seems any noticeable gas volume increases due to episodic events releasing gas during an outburst would not be significant in raising the gas content of the brine. Any event large enough to make a significant increase in gas content would be very evident or if from a series of events extremely unlikely.

4.2.4. Section summary

Based on the arguments presented in this section for the potential for gasification of the oil from the geological aspects of the salt dome, several observations are apparent. An important point, we believe, is that the oil/gas system is essentially a closed system, with the oil retaining the gas content as it is moved throughout the facility, unless gas is removed by a degassing operation. Also apparent: (1) When the ideal cavern solutioning scenario is assumed, then a number of simple exchanges of raw water/brine can be postulated which are required to construct the cavern. Each of these exchanges dissolves a known quantity of salt. Only the brine of the final, or 6th, exchange remains in the finished cavern, and is responsible for dissolving salt which yields about 2.5 cubic ft. per barrel of gas, assuming an initial 1.0 % by volume content of gas filled negative crystals or pores. (2) The 7th exchange of fluids is during the oil filling of the cavern. It is during this exchange that the oil is displacing the brine, and because of the greater affinity of the oil for gas, essentially sweeps the gas from the brine. The transfer of gas is assumed to be more rapid, a few days for equilibrium to occur, than the time for filling of the cavern. (3) The question of the transparency of the oil-brine interface remains open, with the potential for the interface to be a finite layer of emulsified oil-brine and hydrocarbon sludge that may decrease the rate of transfer of gas across the interface. The impediment to transfer of gas because of the finite diffusion rates is also unknown, but equilibrium seems to suggest fast diffusion rates and/or aid from convection processes. (4) Gas flow through the body of the dome through hydrological flow seems unlikely because undamaged intact salt must be essentially impermeable. (5) The release of gas from negative crystal inclusions adjacent to the cavern wall through creep induced dilatant damage is considered small at 0.08 cubic ft. per barrel at the time of 10 years. Never-the-less, the time dependent release through creep damage is compatible with the apparent "infiltration" rate in Bryan Mound caverns. (6) The possibility of gas release from very large scale voids, on the order of cavern diameters, seems unlikely. Episodic releases from more reasonably sized voids, while possible, probably would not increase significantly the quantities of gas in the brine, but may help to produce gas caps. And finally, we give a possible recommendation. The use of the TVP instruments to determine the gas to liquid (GLR) ratio in the brine of the last (6th) exchange of cavern construction could potentially be used to clarify some aspects of the gasification of oil and provide some insight for domal salt characterization.

4.3. Primal Sources

So far as is currently known, there are only two primal sources of gas in crude oil. These are the gases released during heating of the oil and the gases produced through the action of microbes (bacteria). Each of these possible sources will be treated here. However, only the fractionalization by heating of oil is thought to be a significant contributor to the observed gases in the caverns of the SPR.

4.3.1. Oil fractionalization during heating

Not surprisingly, the oil itself can be a major source of gas. One can understand this when considering the process of oil refinement. During the refining process, crude oil is heated to a relatively high temperature, vaporized, and then passed through a fractionation tower. As the oil vapors (gases) move upward through the tower, they encounter ever decreasing temperatures. Because the vapors are composed of discrete components, primarily hydrocarbon molecules, each of these components will condense-out at a more-or-less specific temperature level. Unfortunately, the level is not discrete, but is spread over some temperature range, and may overlap with other hydrocarbon molecules. Moreover, other components of the oil may retard the separation process. Never-the-less, even though the industrial refining process is currently much more complicated than this simple fractionation description suggests, it remains based on this simple concept. We shall make use of this simple description.

4.3.1.1. Composition of crude oil. As is shown by the spectral components of crude oil, the oil is composed of discrete molecules. A graph is shown in Figure 4.4 of the spectrum of components contained in the vapors obtained from a pressurized oil specimen that was “flashed” by releasing the pressure to atmospheric, which causes the volatile gas to be released [6]. Each molecule has a specific weight beginning with the smallest, short-chain, molecule and progressing to very large, long-chain, molecules. The volatile short-chain molecules are typified by methane and ethane, with the inorganic molecules of nitrogen, carbon dioxide, and others, also representative of the volatile components. For the smallest molecules, the separation between spectral peaks is quite distinct. Actually, the position of the spectral peak is fixed. More importantly, the peak is also determined by the amount of energy, heat, required to vaporize the associated molecule. As the molecular weight increases, the separation between specific molecules on the spectral distribution decreases, making it more difficult to separate these molecules by heating. Now this effect becomes important for heated crude oil. When carried out in a refinery, it leads to fractionation of the oil to produce refined products, but when it occurs in crude oil storage, it leads to gasification of the oil or an increase in the boiling point pressure (BBP) and the gas to oil ratio (GOR).

The size of a peak is an indication of the relative quantity of that component in the flash gas. From the amount of the component in the gas, it is possible to calculate through an

equation of state the amount of the component in the original oil. As noted previously, this calculation provides additional information about the crude oil.

4.3.1.2. Heating of oil during storage. It is known that the oil in the SPR is received in the dead condition, with the temperature at or below 80°F. However, it does not usually remain at this temperature. This is a consequence of the geothermal gradient that is present in the Gulf Coast [20, 21]. Typically, the gradient is on the order of 0.01°F/ft.

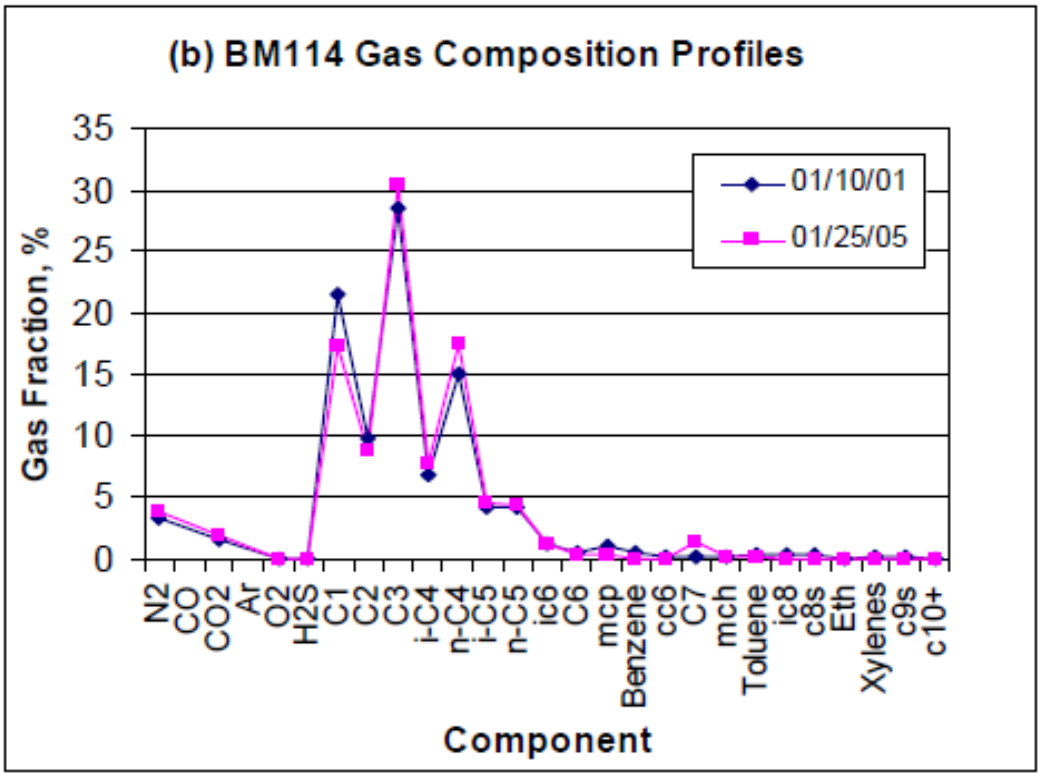

Figure 4.4. Spectum obtained from crude oil from Bryan Mound Cavern 114 [6].

[20], however, there is considerable variation as this relates to the salt domes. Never-the-less, for our purposes, it is adequate to know that the maximum temperature in the domal salt is roughly 155°F in the SPR locations [30]. In addition, the mass of the salt surrounding the cavern is probably sufficient to make it act as an infinite source of heat, except in the web area between caverns. Because the thermal transfer from the salt into the oil in a cavern is governed by thermal conduction and convection, the temperature in the oil depends upon the time interval between receipt at the SPR and the present. Usually, the thermal transfer in the salt is slower than that in the oil, so these times are certainly controlled by the thermal properties of the salt. Also, while one would assume initially that the thermal gradient in the oil would directly reflect the same gradient in the salt, the ability of the oil to form convective cells suggests that the gradient in the oil would actually become higher. The variation is the result of the possibility for convection in the oil, which causes a vertical thermal displacement. Apparently, in some cases, the

shift in temperature may be 30°F, or more. This implies further that the temperature of the oil would perhaps be more uniform. To date, the highest temperature of the oil in the SPR appears to be on the order of 135°F [3].

In practice, there can be exchanges of various amounts of oil from a given cavern over time, also with the possibility some newly received oil being added periodically. Each of these events brings various quantities of oil with differing temperatures together, with the obvious thermal changes. It appears that some of these transfers are difficult to track and to quantify.

4.3.1.3. Gas release from the stored oil. From the governing equation, the gas release from oil is related to the temperature and the specific spectral components of the oil. While there could be a number of low molecular weight components present, such as carbon dioxide or nitrogen, the most significant component would certainly be methane. As the temperature of the oil increases, the quantity of gas released increases. In fact, the temperature is the most important and critical variable, and while temperature data in the existing caverns are available, more frequent measurements should be encouraged especially during oil exchanges. Temperature must be well known, and controlled. This heating effect has been examined in greater detail by Bauer and Hinkebein [30] who determined the empirical general increase in oil temperature with time using polynomial functions. They have also used an expression for the increase in the vapor pressure to determine the state of the crude oil.

4.3.1.4. Reversibility of the gas obtained from heating of oil. There are two conditions that warrant attention. First, the implication of the governing equation is that the thermal related release of gas from the oil is reversible. Returning the temperature of the oil to 80°F should again restore it to the original dead oil receipt condition. One would have to insure that the pressure conditions were maintained at a level which would prevent intervening vaporization. If there were intervening vaporization, in theory, this vaporized oil should be adsorbed back into the oil, however, there is a problem in that the re-adsorption into the oil is more difficult. However, consequently, provided the pressure is maintained, it seems that any oil that is returned to the 80°F condition would correspond to dead oil, or at least, eliminate the vapor pressure contribution from the oil itself. The implication of this is that the final term of the governing equation becomes zero and only the geologic contributions of the initial two terms remain. As a result, only the time-independent release from solutioning and the time-dependent release from creep damage remain.

Second, potential consequences of degassing on the oil can be examined through the third term of the governing equation. While the temperature related release of gas is very relevant, it is the behavior of the components of the oil that is the key. Initially, we examine the uniqueness of the 80°F condition for dead oil. This oil has been stripped of the volatile components, at the producing field, presumably by cooling the oil to this temperature and flaring the remaining volatile gas at atmospheric pressure. Thereafter, it remains in the dead condition during transport. This suggests an interesting possibility. If the spectral analysis and fractionation process indicates that the most volatile

component comes-off between the temperatures of 80°F and, say, 135°F, then degassing the oil at 135°F or above should produce “newly dead” oil for any temperature below 135°F. Effectiveness of this process depends upon the sharpness of the temperature boundary at which the selected component is fully removed and any overlap from any next higher temperature component. There should be a distinct difference between the spectral composition of the oil before and after degasification, with the more volatile component partially removed.

There is another interesting aspect of having a reversible generation of the gases that the state equivalent to that of oil receipt can be reestablished. The receipt conditions are 80°F and atmospheric pressure. Provided that this assumption is correct, then the possibility exists that time independent and time dependent releases can be evaluated separated from those gases produced from the oil itself during the testing process.

While it is noted that the gas release from the stored oil depends only the temperature, it may appear to also be time-dependent. This only an apparent effect because heat transfer from the salt to the oil by conduction is time dependent, not the gas release.

4.3.1.5. SPR standard conditions. For the purposes of the SPR and the specifications to assure the deliverability of the stored oil when needed, important measurements of the bubble point pressure (BBP) and the gas to oil ratios (GOR) are taken periodically at various points in the cavern and cavern piping system. These involve the measurement of the true vapor pressure (TVP) and the separation of the volumes of gas and oil under very specific conditions [6]. The SPR standard conditions [3] are for the pressurized oil samples or streams to be brought to 100°F and then flash depressurized to 14. 7 psi, or 1 atmosphere. The pressure of the gas released is the vapor pressure and the amount of gas released gives the gas to oil ratio. Normally, a sample of this gas is analyzed in a gas chromatograph for the composition of up to 25 of the lighter hydrocarbons, the lumped residual heavier, long-chain, hydrocarbons, and the typical inorganic species. From these basic measurements, a number of calculations can be made to expand the information about the oil and its properties. In particular, calculations using an equation of state permit the independent evaluation of the BBP and GOR from the spectral analysis of the gas chromatograph.

As noted, the relationship between the measured components in the flash vapor and the components in the fluid oil are typically calculated for the SPR using the Soave-Redlich-Kwong equation of state. The solution involves a matrix wherein the diagonal terms can be take as the binary partial pressures, but more satisfactory results occur when off-diagonal terms are created to reflect the influence of an interaction between other components and the binary partial pressures [8].

4.3.1.6. Additional caveats and simplifications. We have already stated that our view of the gases released by crude oil is based on a very simplistic understanding. In fact, however, the organic chemistry of crude oil and refined petroleum products is quite complex. As a rule, we will usually take the measured values as preferred.

The ubiquitous nature of oil and oil products and their movement and storage around the world has resulted in considerable effort in determining the characterization and control of the vapor pressure. There are references to the absolute vapor pressure (RVP) and true vapor pressure of a liquid (TVP) which is the partial pressure of the liquid [31]. Each of these values is used in specific instances to specify and control oil and oil products. While we recognize both of these measures, the TVP, which is just the bubble point of the liquid at 1 atmosophere. and 100°F, is reported here. As a matter of information, the RVP is measured in a somewhat similar manner to that used for the TVP [31]. However, here the pressurized sample is presaturated by flashing it at 33°F and 1 atmosphere and combining the streams with water vapor and air in a ratio of 4 parts of saturated air to 1 part of liquid, while raising the temperature to 80°F. The sample is then flashed again at 100°F. This method apparently represents the transport and storage of oil products under atmospheric conditions within the head spaces of the storage or transportation system, and is the basis for many regulatory criteria. The RVP and TVP are often stated to be congruent (differ only slightly) at 100°F.

4.3.1.7. Speculation. Removal of the most volatile component, such as methane, by a degassing operation has some potentially interesting aspects. The potential exists to make a "dead-oil" at a higher temperature. While this is interesting, some portion of the "removed" volatile component remains, and retains its partial pressure. However, because the amount of the remaining component is small, it contributes little to the GOR and to the vapor pressure.

While stripping the oil of some of the volatile components could possibly permit transportation at higher temperatures, there would be a diminished caloric value of the oil. Stripped volatiles could be flared, and their value lost, or perhaps compressed and placed into gas pipe lines to recover part of their value. Under certain conditions, the volatiles might be used to heat the oil prior to degasification to assure that removal of the undesired component will be sufficient. This could lead to transportation of this newly dead oil initially at a higher temperature than the acceptance criteria for oil injected into a pipeline. Interestingly, travel over customary pipeline distances could potentially result in significant pipeline cooling [30], bringing the conditions toward or within the usual acceptance criteria.

4.3.2 Microbial generation

For completeness, it is necessary to consider the case where the oil may indeed generate the lower molecular weight hydrocarbons from the higher weight hydrocarbons. This process depends upon micro organisms that can digest the oil to produce waste which is normally methane gases. A number of the previously cited reports have treated the microbial generation of methane [3, 32]

Giles [32], while noting that the microbial generation of methane occurred in the stored oils in the permeable granite caverns in Sweden, suggested that the saline conditions of the SPR storage would preclude large numbers of microbes. He states that despite considerable study of this issue and the presence of viable bacteria in the SPR oil, there is

no apparent degradation of the crude oil. In what appears to be a very limited study, ratios of stable isotopes suggest a petrogenic (from the salt formation) rather than biogenic (from bacteria) source of the methane in the oil. The few exceptions of biogenic origin, however, were found in tests of the sludge layer at the oil/brine interface. It is possible to speculate that the interface sludge layer acquires these bacteria from the brine, which is exposed to conditions where bacteria are prevalent. Unless the interface sludge layer is intentionally mixed into the storage oil, it is unlikely that these bacteria are significant.

For the purposes of this report, we accept the conclusion of the cited study that microbial generation of methane, or short-chain hydrocarbons, is not a significant factor in the gasification of SPR crude oil.

4.3.3 Section Summary

There appear to be only two potential courses of gas release in crude oil. First, the condition of the stored oil has a major impact on the release of gas. If the assertion of Equation 1 is correct, then the generic gas release is a function only of temperature and the composition of the oil. As the oil temperature increases the quantity of gas released increases, but non-uniformly. The components of the crude oil are each representative of a distinct molecule which has a distinct (but fuzzy) range of temperature over which it is released. It is believed that the temperature dependence of gas release is reversible. Second, there remains the potential for true generation of gas in the oil through the biological digestion of oil to produce gaseous waste products. However, little evidence exists that quantities of microbes are present in the stored SPR oil for this process to occur.

DISCUSSION AND SUMMARY

The report presented here addresses the primary sources of gases which are found in the stored oil of the SPR. The initial condition of the oil, as received at the SPR facilities, is well defined as “dead oil” through the acceptance criteria. Subsequently, gases released from the surrounding salt of the dome in which the storage caverns are mined or from the oil itself. Each source is examined, with some sources found to contribute to the increase in gas content and other sources are found not to contribute.

It is apparent that this report is incomplete. It does not include discussion of the vapor pressure testing of stored oil or of the history of the measured results. Nor does the report include the methods of degasification and the production of oil streams which meet the transportation criteria. These areas of study potentially will be the subject of an expanded report in the future.

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APPENDICES

APPENDIX A(a) - - Oil Blanket Volumes and Event Sequences

Table AaI. Oil Blanket Volume during Construction and Filling Events for Bryan Mound.

Cavern	Oil Blanket (bbl)					Fill-Degas*	Delta
	Sump	Chim'y	First Rev.	Second Rev.	Third Rev.		
BM001						78-83-*96*-97-**97**	14
BM002						78-85-96-96-**96**	11
BM004						77-82-	
BM005						78-86-*87*-89-	
'BM101g	630+		450	2,473,000 surge	9,808,910 fill	84-85-*97*-97-**97**	12
BM102	604+	411+	3,000	1,100	10,252,776 fill	85-	
BM103g	550+	600	1,250	809	10,033,202 fill	85-97-*97*-97-97	11
"BM104	1,014+	668+	213	1,407,000 rf/inter	10,257,027 fill	83-	
"BM105	990+	414+	830+	1,702,800 dia/inter	9,245,728 fill	83-	
"BM106	551+	1,425+	327+	5,021,367 storage	11,098,441 fill[&]	83-**97**-*00*-02	14
BM107g	520+	724+	41,000	3,100	10,258,118 fill	83-97-97-**97**	14
"BM108	770+	355+	3,000	1,294,340	10,939,562 fill	85-	
"BM109g	835+	506+	388	2,744,000 dia/inter	10,522,309 fill	83-*97*-97-**97**	14
BM110		491+	350	19,506 (46,000)	10,218,032 fill	83-*96*-97-97	13
BM111g	410+	40	580	16,000	9,961,374 fill	84-87-*97*-**97**-98	13
BM112g	350	240	6,300	8,000	9,681,996 fill	85-*97*-98-**99**	12
"BM113	14,583+	356	3,000	1,042,823	4,474,561 fill[&]	86-87-*95*-**95**-96	8
"BM114	705+	2,100	2,000	1,706,264 inter	7,168,403 fill[&]	87-*95*-95-**95**	8
"BM115	442+	316	516	105,000	8,678,149 fill	86-*96*-**95**-95	9
"BM116	225	220	300	155,000	9,425,628 fill	86-*95*-**95**-95	9

* The string of dates gives a brief history of the cavern. Numbers in red italics and underlined indicate the cavern was emptied on that date. Numbers in red bold indicate the date of cavern degas. Numbers in black show the cavern was filled on that date. An appearance of two filling dates for some early history indicates some differences or uncertainty in interpretation between references [6] and [11].

' Cavern BM101 contained some surge oil for a period of time, which was removed.

g Gas reported in the construction report in these caverns.

" These caverns all had partial filling before final cavern volume was leached.

\+ These caverns had multiple unconnected roofs initially; blanket oil is sum of all wells.

[&] First note: The Mayan crude initially in Cavern BM106 was replaced by sweet crude in 2000. Second note: The sour crude initially in Cavern BM113 was replaced by sweet crude in 1987.

Third note: BM114 partially filled, then completed, sour replaced with sweet crude in 1987.
Cavern numbers in **bold letters** are those with greater than 0.1 psi per year regain.
Cavern numbers in *italics* are those that produced quantities of gas during construction.

Table AaII. Oil Blanket Volume during Construction and Filling Events for Big Hill.

Cavern	Oil Blanket (bbl)					Fill-Degas*	Delta
	Sump	Chim'y	First Rev.	Second Rev.	Third Rev.		
BH101	127	145	305	20,029	106,265	93-02-04	
BH102	148	230	125	12,020	130,070	93-02-04	
BH103	133	137	319	14,277	158,078	02-04	
BH104	157	152	162	12,185	118,195	02-04	
BH105	135	155	165	1,802	55,877	94-96-**97**	3
BH106	135	135	163	2,169	37,742	92-94-**97**	5
BH107	115	124	134	5,327	645,386	91-97	6
BH108			205	35,069	272,276%	91-**98**-**04**	7-4
BH109	189	193	208	2,000	46,705	96-**98**	2
BH110	125	278+	293+	11,854	870,138	96-00-04	
BH111	479+	280+	504	50,120	77,230&	96-**96**-04	0
BH112	442+	262+	290	29,479	54,725&	96-**96**-04	0
BH113	215+	270+	277	26,069	93,783&	96-**96**-04	0
BH114	260+	260+	320	33,348	84,988	02-04	

* The string of dates gives a brief history of the cavern. Numbers in red italics and underlined indicate the cavern was emptied on that date. Numbers in red bold indicate the date of cavern degas. Numbers in black show the cavern was filled on that date. An appearance of two filling dates for some early history indicates some differences or uncertainty in interpretation between references [6] and [11].

% This cavern has apparently been degassed twice.

\+ These caverns had multiple unconnected roofs initially; blanket oil is the sum of all wells.

& These caverns were apparently filled as they were being degassed

Cavern numbers in **bold letters** are those with greater than 0.1 psi per year regain.
Cavern numbers in *italics* are those that produced quantities of gas during construction.

Table AaIII. Oil Blanket Volume during Construction and Filling Events for West Hackberry.

Cavern	Oil Blanket (bbl)					Fill-Degas*	Delta
	Sump	Chim'y	First Rev.	Second Rev.	Third Rev.		
WH006						83-	
WH007						83-	
WH008						85-	
WH009						85-	
WH011						78-	
"WH101		346	334	1,162,000	9,737,980 fill	84-*01*-02	
WH102		405	330	54,637	10,391,625 fill	85-	
"WH103		312	320	1,196,506	9,908,465 fill	84-**96**	12
"WH104		322	521	2,253,745	10,861,037 fill	84-	
WH105		310	8,668	250,193	10,667,498 fill	84-	
WH106		404	605	682,014	9,855,660 fill	86-	
WH107		315	630	219,718	11,210,995 fill	84-*88*-**96**-01-05	12
WH108		312	600	30,081	8,164,174 fill	85-	
WH109		295	6,862	205,502	10,556,201 fill	88-*97*-01-05	
WH110		324	296	1,000	9,952,484 fill	85-*01*-05	
WH111		288	260	668,984	4,125,891 fill[&]	88-92-	
WH112		255	1,000	220,100	9,437,040 fill	87-	
WH113		320	517	6,396	6,291,702 fill[&]	85-*88*-**96**-05	11
"WH114		315	300	1,293,039	9,887,173 fill	85-	
WH115		286	5,503	13,200	10,292,979 fill	87-	
WH116		304	342	1,466	10,461,805 fill	85-	
WH117	190	1,730	783	50,223	10,092,655 fill	89-	

* The string of dates gives a brief history of the cavern. Numbers in red italics and underlined indicate the cavern was emptied on that date. Numbers in red bold indicate the date of cavern degas. Numbers in black show the cavern was filled on that date. An appearance of two filling dates for some early history indicates some differences or uncertainty in interpretation between references [6] and [11].

" These caverns all had partial filling before final cavern volume was leached.

[&] These caverns apparently were not filled completely.

Cavern numbers in **bold letters** are those with greater than 0.1 psi per year regain.

Table AaIV. Oil Blanket Volume during Construction and Filling Events for Bayou Choctaw.

Cavern	Oil Blanket (bbl)					Fill-Degas*	Delta
	Sump	Chim'y	First Rev.	Second Rev.	Third Rev.		
BC015A						77-	
BC017						87-**96**-97	9
BC018						80-*90*-95-**96**-03	16
BC019						81-	
BC020A						82-	
BC101	300+	300	120	94,984	10,551,373 fill	90-*91*-95-**96**-	6

* The string of dates gives a brief history of the cavern. Numbers in red italics and underlined indicate the cavern was emptied on that date. Numbers in red bold indicate the date of cavern degas. Numbers in black show the cavern was filled on that date. An appearance of two filling dates for some early history indicates some differences or uncertainty in interpretation between references [6] and [11].
Cavern numbers in **bold letters** are those with greater than 0.1 psi per year regain.

APPENDIX A(b) - - Cavern Construction, Filling, and Degas Chronology

Notes: (a) From Construction Report D506-01644-09 DOE/SPR
(b) From Lord and Rudeen SAND 2005-4322

Table AbI. BRYAN MOUND - First Facility Constructed

Cavern	Solutioned	Filled(a)	Filled(b)	Degas I	Interval	Degas II	Interval
BM001	(1942)1978	1978	??-83-***96***-96	1997	54 (18)		
BM002	(1942)1978	1978	??-85-***96***-96	1996	53 (17)		
BM004	(1942)1977	1977	??-82	--	--		
BM005	(1957)1977	1987	??-86-***87***-90	--	--		
BM101	1982-84G	1983-84	85	1996	12		
BM102	1980-84	1983-85	85		--	08	
BM103	1982-84G	1983-85	85-***97***-97	1997	12		
BM104	1980-83	1983	83	--	--	08	
BM105	1980-83	1983-84	83	--	--	07	
BM106	1980-82	1983-84	83-***00***-01	1997	14		
BM107	1980-83G	1983-85	83-***97***-97	1997	14		
BM108	1980-85	1985-87	85	--	--		
BM109	1980-83G	1983-84	83-***97***-97	1997	14		
BM110	1980-82	1984-86	83-***95***-96	1996	13		
BM111	1983-84G+	1984-87	84-***97***-98	1997	13		
BM112	1980-84G+	1984-86	85-***97***-98-***99***	1997	12		
BM113	1984-86	1985-87	87-***96***-96	1995	8		
BM114	1984-87	*1987-88	87-***96***-96	1995	8		
BM115	1984-86	*1986-87	86-***96***-96	1995	9	08	
BM116	1984-86	*1986-87	86-***96***-96	1995	9		

G indicates construction note, G+ indicates special attention required in construction.
* Previous partially filled with sour crude, replacement with sweet crude began on this date.
Date numbers in black show the cavern was filled on that date.
Cavern numbers in **bold letters** are those with greater than 0.1 psi per year regain
Cavern numbers in *italics* are those that produced quantities of gas during construction.

Table AbII. BIG HILL – Fourth Facility Constructed

Cavern	Solutioned	Filled(a)	Filled(b)	Degas I	Interval	Degas II	Interval
BH101	1988-90	1991	93-04	--		05	
BH102	1987-90	1991	93-94-04	--		06	
BH103	1987-90	1991	02-04	--		05	
BH104	1987-90	1991	02-04	--		05	
BH105	1987-90	1991	94-96	1996	2		
BH106	1987-90	1991	92-95	1997	2		
BH107	1987-90	1991	91	1997	6		
BH108	1987-90	1991	91	1997	7	04	
BH109	1987-90	1991	96	1997	7		
BH110	1987-90	1991	96-04	--		06	
BH111	1988-90	1992	96-04	1996*	0		
BH112	1988-90	1992	96-04	1996*	0	05	
BH113	1988-90	1992	96-04	1996*	0	04	
BH114	1988-91G+	1992	02-05	--		06	

G+ indicates special attention required in construction, including flaring of gas.
* These caverns apparently degassed as they were being filled?
Cavern numbers in **bold letters** are those with greater than 0.1 psi per year regain.
Cavern numbers in *italics* are those that produced quantities of gas during construction.

Table AbIII. WEST HACKBERRY – Second Facility Constructed

Cavern	Solutioned	Filled(a)	Filled(b)	Degas I	Interval	Degas II	Interval
WH006	(1946)1978	1978	83	--			
WH007	(1946)1978	1978	??-83	--			
WH008	(1946)1978	1978	??-85	--			
WH009	(1947)1978	1978	??-85	--			
WH011	(1962)1978	1978	78	--			
WH101	1981-83	1984	84-***01***-02	--			
WH102	1982-83	1984-86	85	--			
WH103	1981-84	1984	84	1996	12		
WH104	1981-84	1984	84	--			
WH105	1981-84	1984	84	--			
WH106	1984-87	1987-89	86-87	--			
WH107	1981-84	1985-86	84-***88***-88	1996	12		
WH108	1982-84	1984-86	85	--			
WH109	1984-87	1988-90	88-***97***-03	--			
WH110	1982-85	1985-86	85-***01***-04	--			
WH111	1982-88	1988-89	88-92	--			
WH112	1983-87	1988-89	87	--			
WH113	1982-85	1985-88	85-***88***-04	1995	10		
WH114	1982-85	1987	85-87	--			
WH115	1984-87	1988	87	--			
WH116	1982-85	1987-89	85	--			
WH117	1985-88	1989	89	--			

Date numbers in black show the cavern was filled on that date.
Cavern numbers in **bold letters** are those with greater than 0.1 psi per year regain.

Table AbIV. BAYOU CHOCTAW – Third Facility Constructed

Cavern	Solutioned	Filled(a)	Filled(b)	Degas I	Interval	Degas II	Interval
BC015A	(1953)1980	?	??-87	--			
BC017	(1955)1985	1987	??-87-97	1996	41		
BC018	(1967)1978	1978	80-***90***-93	1996	28		
BC019	(1970)1978	1978	81	--			
BC020A	(1979)1978	1981	82	--			
BC101	1987-90	1990	90-***91-95***-96	1996	5		

Date numbers in black show the cavern was filled on that date.
Cavern numbers in **bold letters** are those with greater than 0.1 psi per year regain.

APPENDIX B - - Correlation Attempts to Miscellaneous Data

Table BI. -- Bryan Mound Regain vs. Insolubles, Closure Rates, and Cavern Locations

Cavern	Regain psi/yr.	Insol %	Closure %/yr.	Wells	Falls	Remarks	Location
BM114	0.45	3.50	0.120	2	0	Very Irreg	S. Dome Edge
BM111	0.24	5.78	0.020	2	1	Flutes Irreg	N. Outer Ring
BM113	0.20	3.50	0.125	2	2	Irreg	S. Dome Edge
BM001	0.17			2	0	Irreg	
BM002	0.10			2	0	Short Irreg	
BM115	0.10	3.31	0.150	2	0	Irreg	S. Dome Edge
BM103	0.08	4.39	0.150	2	5	Smooth Lump	N. Outer Ring
BM110	0.08	3.40	0.020	3	0	Flutes	Central
BM101	0.07	4.40	0.025	2	2	Smooth	N. Inner Ring
BM104	0.06	-	0.025	3	0	Flutes Str	N.C. Inner Ring
BM116	0.03	4.27	0.085	2	2	Smooth Irreg	S. Dome Edge
BM105	0.01	5.30	0.025	2	0	Flutes Irreg	Mid Inner Ring
BM004		0.00		3	0		
BM005		0.00		3	4	Dbl Cylinder	
BM102	0.00	1.00	0.020	2	2	Smooth Lump	N. Inner Ring
BM107	0.00	-	0.025	3	8	Smooth	Mid Inner Ring
BM108	0.00	4.20	0.020	3	5	Flutes Irreg	Mid Outer Ring
BM109	0.00	-	0.050	3	7	Flutes Irreg	S.Mid Outer Ring
BM106	Ind.	-	0.030	3	10	Smooth	S. Outer Ring
BM112	Ind.	4.31	0.020	2	5	Smooth Irreg	S. Outer Ring

Cavern numbers in **bold letters** are those with greater than 0.1 psi per year regain.
Cavern numbers in *italics* are those that produced quantities of gas during construction.

Table BII. -- Big Hill Regain vs. Insolubles, Closure Rates, and Cavern Locations

Cavern	Regain psi/yr.	Insol %	Closure %/yr.	Wells	Falls	Remarks	Location
BH105	0.22	4.15	0.125	2	0		Center Left
BH107	0.17	7.90	0.075	2	0		Low Crp SE
BH108	0.06	5.71	0.15	2	0	Smoth Wings	Wings
BH102	0.05	6.34	0.17	2	0		Right Center
BH101	0.00	5.12	0.14	2	0	Smoth SF Pit	Far Left
BH106	0.00	5.52	0.09	2	0	Smooth	SE Area
BH109	0.00	4.29	0.125	2	0		Right Center
BH110	0.00	2.36	0.125	2	0	Dis. Pits	Far Left
BH113	0.00	4.29	0.15	2	0		Wings Low Cent.
BH114	Ind.	4.95	0.125	2	1	Smooth	Left Low Edge
BH111	Ind.	5.23	0.07	2	0		Right Low Edge
BH112	Ind.	5.28	0.11	2	0		Right Low SE
BH103	Ind.	2.94	0.19	2	1	Smooth Stria.	Center Center
BH104	Ind.	5.61	0.135	2	0	Smooth	Upper Center

Cavern numbers in **bold letters** are those with greater than 0.1 psi per year regain.
Cavern numbers in *italics* are those that produced quantities of gas during construction.

Table BIII.--West Hackberry Regain vs. Insolubles, Closure Rates, and Cavern Locations

Cavern	Regain psi/yr.	Insol %	Closure %/yr.	Wells	Falls	Remarks	Location
WH007	0.40			3	0		
WH006	0.28			3	0		
WH116	0.25	2.34	0.200	1	0	Smooth	N.W. Outer Ring
WH103	0.13	5.38	0.110	1	3	Smooth	Central
WH111	0.075	3.10	0.150	1	0	Smooth	N. Outer Ring
WH106	0.07	-	0.090	1	0	Smooth	S. Outer Ring
WH104	0.06	3.84	0.120	1	0	Smooth	Central
WH114	0.04	3.51	0.120	1	0	Smooth	N.W. Outer Ring
WH115	0.04	3.49	0.120	1	0	Smooth	N. Central
WH105	0.02	2.67	0.135	1	0	Smooth	S. Central
WH112	0.02	4.18	0.125	1	0	Smooth	S.E. Outer Ring
WH117	0.02	3.84	0.175	2	0	Rough	S. Central
WH108	0.01	4.11	0.130	1	2	Rough	S. Outer Ring
WH008	0.00			1	0		
WH009	0.00			3	0		
WH011	0.00			3	0		
WH109	0.00	-	0.090	1	2	Smooth	N. Central
WH101	0.00	4.68	0.125	1	0	Smooth	Central
WH107	0.00	5.36	0.140	1	1	Smooth	Central
WH110	0.00	-	0.230	1	1	Smooth	N. Outer Ring
WH102	Ind.	5.68	0.120	1	1	Smooth	Central
WH113	Ind.	4.24	0.175	1	1	Smooth	N.W. Outer Ring

Cavern numbers in **bold letters** are those with greater than 0.1 psi per year regain.

Table BV. -- Bayou Choctaw Regain vs. Insolubles, Closure Rates, and Cavern Locations

Cavern	Regain psi/yr.	Insol %	Closure %/yr.	Wells	Falls	Remarks	Location
BC017	0.16			2	0		
BC019	0.10			2	0		
BC015	0.01			2	0		
BC020	0.00			2	3		
BC101	0.00	1.47	0.060	2	2	Very Rough	S.E. Central
BC018	Ind.			2	0		

Cavern numbers in **bold letters** are those with greater than 0.1 psi per year regain.

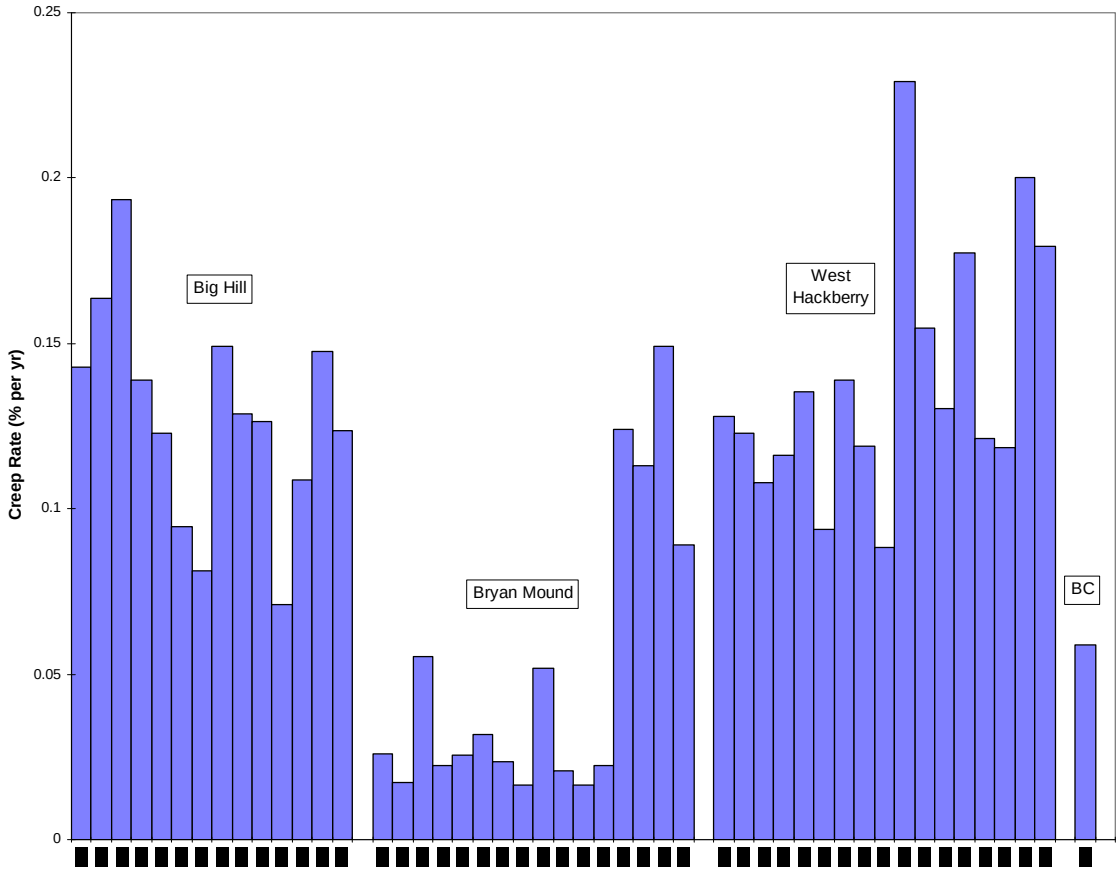

Figure B1. Relative creep closure rates of constructed SPR caverns [18].

APPENDIX C - - 2009 Regain (Intrusion) Summary - Graphs

Notes: From [29]. Lord, D., and D. Rudeen, 2009. Updated Vapor Pressure Regain Tables: *Results from June 2009 data review session*, Memo to Gerard Berndsen, DOE, SPR, dtd July 17, 2009 from Sandia National Laboratories, Albuquerque, NM.

Figure C5. From [4]. Ehgartner, B.L, J.L. Neal, and T.E. Hinkebein, 1998. "Gas Releases from Salt," SAND98-1354, Sandia National Laboratories, Albuquerque, NM.

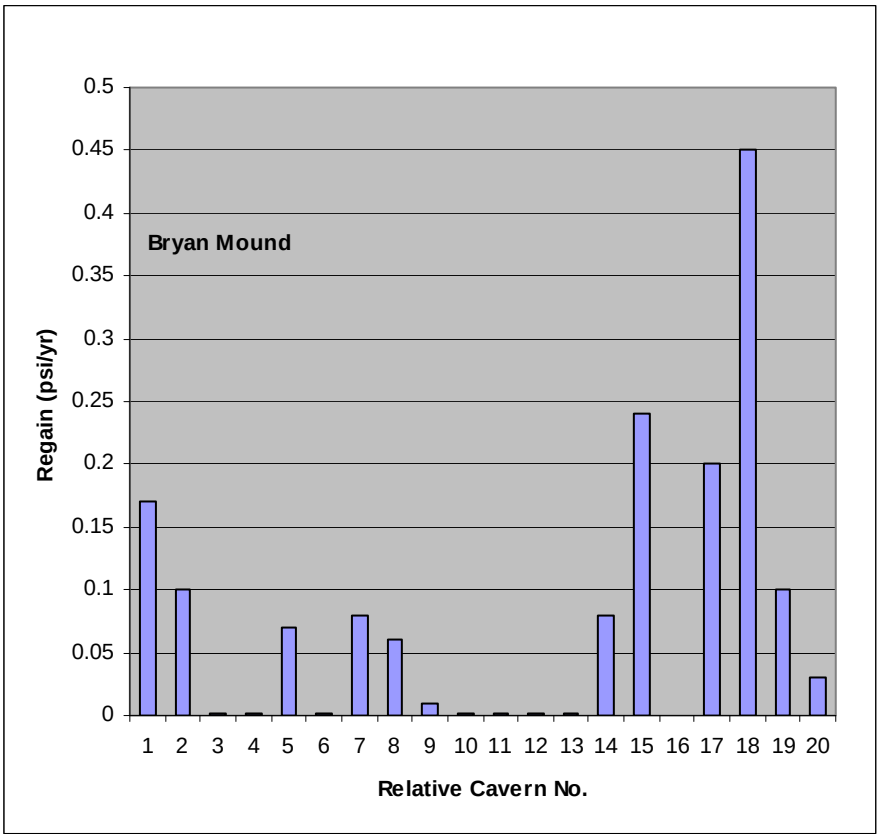

Figure C1 Measured regain rates in 2009 in caverns at Bryan Mound [29].

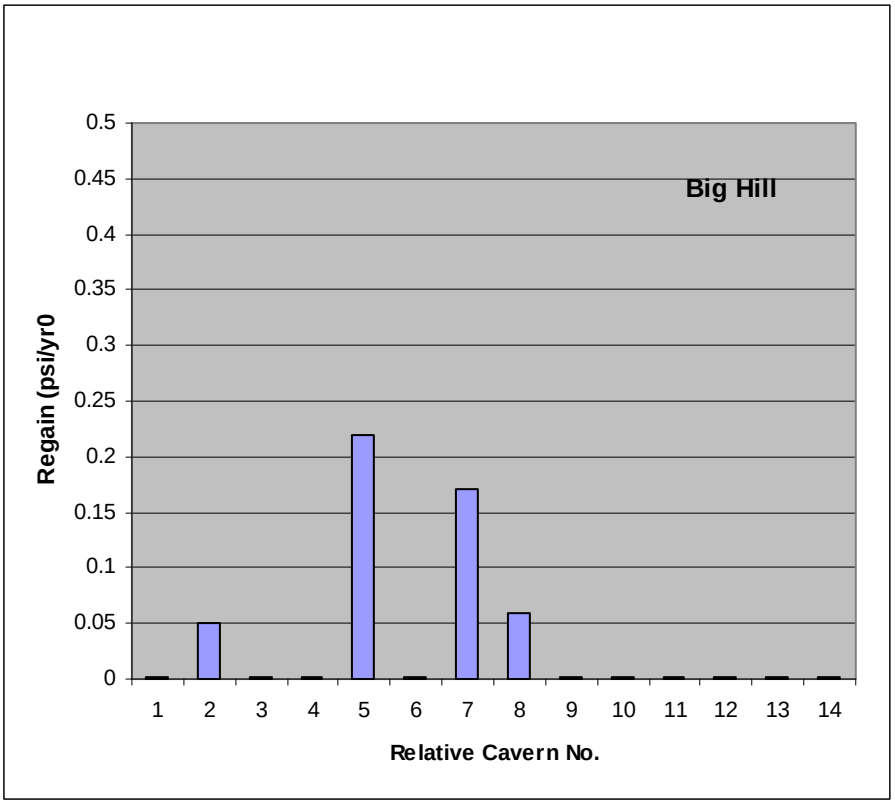

Figure C2. Measured regain rates in 2009 in caverns at Big Hill [29].

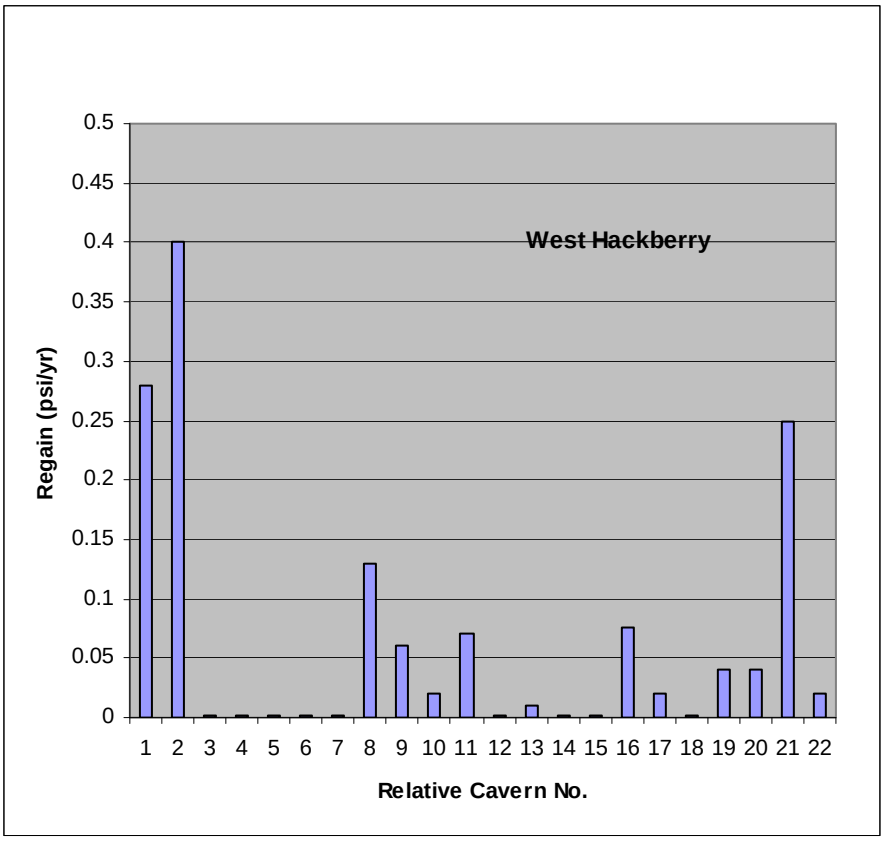

Figure C3. Measured regain rates in 2009 in caverns at West Hackberry [29].

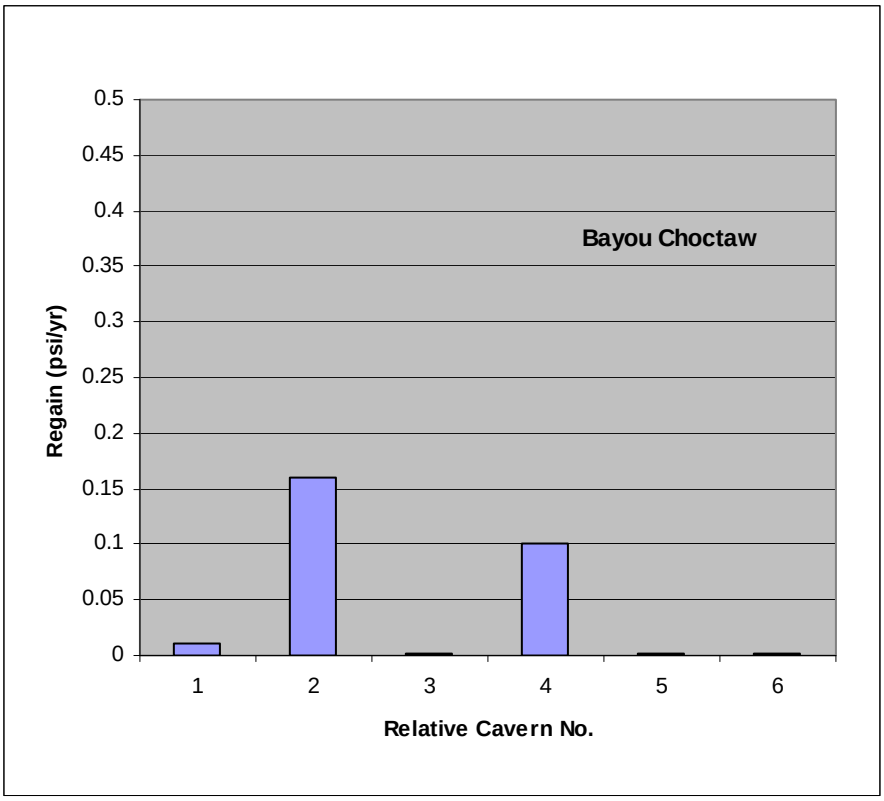

Figure C4. Measured regain rates in 2009 in caverns at Bayou Choctaw [29].

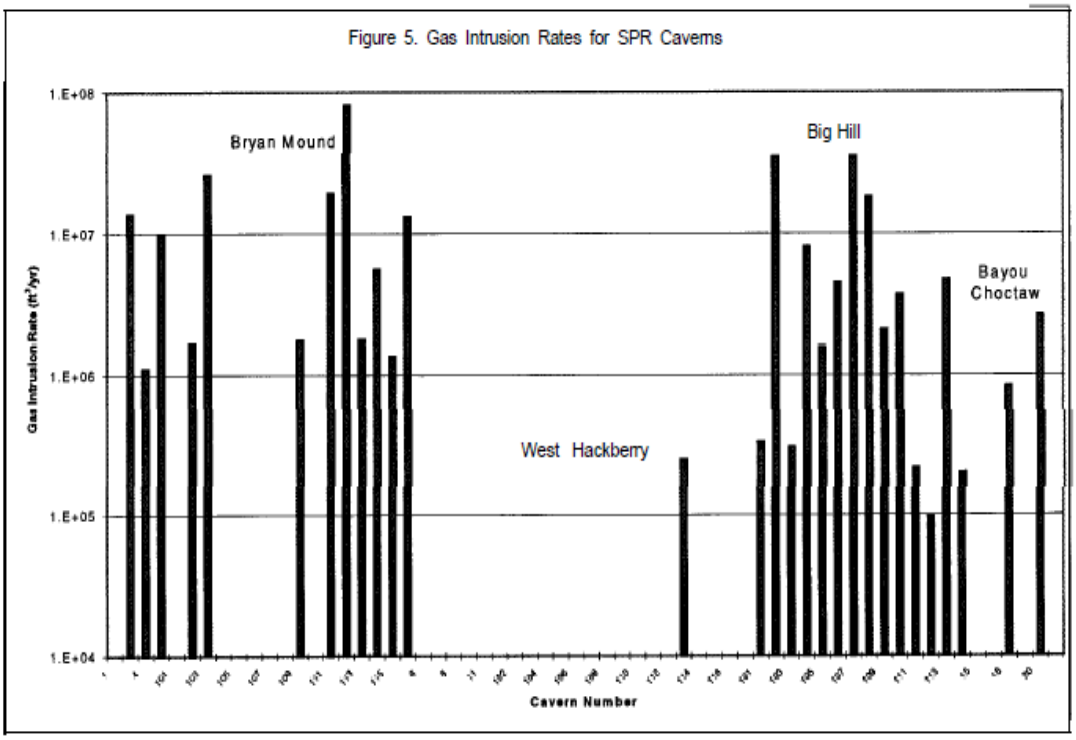

Figure C5. Intrusion rates from an early 1998 report by Ehgartner et al. [4].

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