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Strategic Petroleum Reserve Caverns Casing Damage Update 1997

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Abstract

Hanging casing strings are used for oil and brine transfer in the domal salt storage caverns of the Strategic Petroleum Reserve (SPR). Damage to these casings is of concern because hanging string replacement is costly and because of implications on cavern stability. Although the causes of casing damage are not always well defined, many events leading to damage are assumed to be the result of salt falls impacting the hanging strings. However, in some cases, operational aspects may be suspected. The history of damage to hanging strings is updated in this study to include the most recent events. Potential general domal and local operational and material factors that could influence the tendency for caverns to have salt falls are examined in detail. As a result of this examination, general factors, such as salt dome anomalies and crude type, and most of the operational factors, such as geometry, location and depressurizations, are not believed to be primary causes of casing damage. Further analysis is presented of the accumulation of insolubles during cavern solutioning and accumulation of salt fall material on the cavern floor. Inaccuracies in sump geometry probably make relative cavern insolubles contents uncertain. However, determination of the salt fall accumulations, which are more accurate, suggest that that the caverns with the largest salt fall accumulations show the greatest number of hanging string events. There is good correlation between the accumulation rate and the number of events when the event numbers are corrected to an equivalent number for a single hanging string in a quiescent, operating cavern. The principal factor that determines the propensity for a cavern to exhibit this behavior is thought to be the effect of impurity content on the fracture behavior of salt. A conceptual micromechanical model of creep and fracture suggested these factors as the primary cause of the generation of microfractures and spalls and subsequent salt falls. Although the predicted microfracture locations are encouraging, the model shows insufficient amount of microfracture to generate spalls for the simple cavern shapes assumed.

Acknowledgments

The authors would like to acknowledge the continued support of Bob Myers, DOE SPRPMO, who initiated this study. Also, the discussions and inputs of Harry Lombard (now retired), Jim McHenry, and Ken Mills, all of DynMcDermott Petroleum Operations, were of great benefit.

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Strategic Petroleum Reserve Caverns Casing Damage Update 1997

Executive Summary

Throughout the history of Strategic Petroleum Reserve (SPR) storage caverns, a number of events have occurred in the caverns causing damage or loss of pipe from the hanging strings used for crude oil and brine filling and recovery. To date, in excess of 33,400 ft of casing has been lost as a result of these events. Such events are of concern because casing damage and loss of hanging strings represent a near-term expense and a long-term concern for the stability of the caverns. Inspection of the casing retrieved from some of these events seem to define three categories [Shourbaji, 1997]: damage due to salt falls; damage potentially due to salt falls; and, damage potentially due to operational factors, not related to salt falls. Many of the events are thought to be in the first category and it is these events that are the dominant focus of this report. These hanging string events are believed to be direct evidence of salt falls from the walls, and possibly roofs, of the caverns. While all SPR cavern facilities have currently experienced these events, Bryan Mound has experienced a substantially greater share of events. This report has as a principal task to update and summarize the events experienced at all facilities. However, in accord with its technical nature, it predominantly concentrates on those events thought to be due to salt falls. It also examines the relative importance of possible material and operational factors that may cause the salt falls. This evaluation process is made more difficult by the relatively large number of possible factors compared to the rather small number of events experienced to date. An examination of factors that may contribute to the development of salt falls is presented. It appears that specific local, rather than general, factors govern the propensity for a given site or cavern to experience salt falls. The dominant local factor appears to be the impurities contained within the salt.

The objectives of this study on casing damage and salt fall events in the storage caverns of the Strategic Petroleum Reserve (SPR) were two fold:

(1) to update the history of hanging string events and failures within the SPR caverns; and,

(2) to reevaluate the possible causes of these events and failures, where appropriate, in terms of salt falls.

All of the SPR sites were reviewed and the number of hanging string events (damage) and hanging string failures (loss of string) were compiled. To the date of this report, Bryan Mound has the greatest propensity with 54 events and 43 string failures, West Hackberry is second with 11 events and nine hanging string failures, Bayou Choctaw has experienced five events with two string failures, and Big Hill has had only one event. Examinations of recovered joints and couplings of hanging string pipe strongly suggest that the damage was potentially the result of impacts from blocks of salt; these blocks may have attained appreciable velocities after spalling from the cavern walls.

In an attempt to isolate the principal cause of these events and failures, all major factors potentially involved in the creation of salt falls were examined. These factors included:

(1) the natural factors of anomalous zones, creep properties and fracture properties; and,

(2) imposed factors of crude type, leaching method, operating pressure, location in dome, cavern depth and cavern geometry.

Even though the number of events is limited, logical evaluation of each of these factors suggested that only the fracture properties of the domal salt could be a principal cause of salt falls. The other factors were, at best, secondary in their effect. While the fracture is influenced by stress and cavern geometry, in the geometrically similar Phase II and III caverns, it is most directly influenced by the impurity content of the salt. Because the impurity concentration varies within the individual domes and from dome to dome, the tendency for a cavern to form salt falls is a property peculiar to a given cavern. For example, Bryan Mound Cavern 106, which has the greatest accumulation rate (in ft/year) of salt spall, also has the greatest number of hanging string events.

A model of the formation of a salt fall is based on the gradual development of microfractures during the stress induced creep of salt. This eventually leads to the formation of salt spalls which fall to the cavern floor. For a fixed salt-impurity content, the development is time-dependent and depends upon the stress (depth of cavern), the changes in stress (depressurization), and geometry (stress field). Multiple hanging strings increase the probability of hanging string impacts.

A number of suggestions are made which might reduce hanging string events. Cavern operating pressure should be maintained at the highest possible level, cavern depressurizations should be minimized, and the number of hanging strings in a given cavern should be reduced where possible. A study of the vertical location of hanging string damage and string loss compared to the oil/brine interfaces and oil inventory suggests that some hanging strings could be shortened; this shortening would place them above the danger zone and inventory could be rearranged with the same purpose in mind.

1.0 Introduction

In the Strategic Petroleum Reserve (SPR) Program, the crude oil storage caverns are placed in salt domes. In these caverns, events occur wherein the casings of the hanging strings (access piping used for filling and removal of crude oil and brine) can suffer damage with potential separation and loss of pipe. To date, in excess of 33,400 ft. of casing has been lost as a result of these events. Such events are of obvious concern because casing damage and loss of hanging strings represent a near-term expense and a long-term concern for the stability of the caverns. Inspection of casing retrieved from some of these events seem to define [Shourbaji, 1997] three categories: damage due to salt falls; damage potentially due to salt falls; and, damage potentially due to operational factors, not related to salt falls. Many of the events are thought to be in the first category and it is these events that we focus on in this report.

Although, as noted, there are several potential sources of the casing damage, the principal cause of many these destructive events is thought to be the result of salt falls from the sides, and possibly the roof, of the cavern. Evidence that the hanging strings have been impacted by a substantial mass of salt can be seen in bent sections within a string of recovered pipe [Munson, 1997a]. The concave side of the bent pipe sections are associated with abrasion and impact indentation which is typical of the observed damage. If the impact is severe enough, the moment introduced into the tapered thread coupling may deform it sufficiently to permit the threads to disengage and the pipe to uncouple (bottle capping). However, typically, the threaded coupling seal is broken; this permits oil to enter the casing, displacing the brine, which eventually discharges into the brine pond. In fact, it is the appearance of oil in the brine pond and pressure increase in the brine string that normally indicate damage to the casing. These events, and hence salt falls, are of importance to the SPR Program because replacement of hanging strings is both expensive and time-consuming. Additionally, salt falls may be an indication of gradual deterioration of the cavern with time and may be a concern for cavern stability and current life-extension programs. As a result, this study was initiated with two basic purposes:

(1) to update both the history of hanging string events and hanging string failures within the SPR Program; and,

(2) to reevaluate the possible causes of casing damage and the potential for salt falls.

There have been a number of earlier studies of the geological, geophysical, and/or geotechnical characteristics of the individual SPR storage cavern facilities. These facilities are located at sites in four of the salt domes of the Gulf Coast. Because these domes are significant natural geological structural features, the previous characterization treatments have been primarily from the geological view point. Neal et al. [1994] characterized the physical and geological features of the Bryan Mound salt dome and the SPR caverns in the dome, specifically listing the known hanging string failures. A similar site characterization study, but without evaluation of hanging string events and failures, was prepared by Magorian et al. [1991] for the West Hackberry salt dome and SPR caverns. The general characterization studies of the remaining sites, Bayou Choctaw [Neal et al., 1993a] and Big Hill [Magorian and Neal, 1988], have been reported, again without identifying hanging string failures. The principal thrust of these works has been the geological setting, the stratigraphy of the dome and the surrounding bedded sediments, and the general hydrological situation. Where available, individual cavern geometries and locations were given. Other factors, such as environmental concerns, seismicity, flooding and potential cavern locations are discussed. As noted, casing damage events and salt falls were treated only in the Bryan Mound characterization because, at the time of these studies, nearly all of the events occurred at this facility. In a brief analysis of salt falls, no acceptable correlation could be discerned from a number of possible factors, including the type of crude, solutioning method, mode of operation, depressurization, anomalous zone influence, heterogeneous salt, and other factors.

A slightly different approach to the problem of salt falls is taken in this report, evoking more of the structural mechanics aspects of the salt response to postulate possible causes of the salt falls. Because the caverns are constructed in the very large natural system which comprises the salt dome, available knowledge and analysis capabilities are not currently adequate for prediction of such detailed response as the creation of a salt fall. In addition, the very size of these immense caverns compounds the problem. With the limited knowledge base which now exists of cavern conditions, application of the general constitutive model for evolution of fracture in salt and the geometric condition of the caverns are both insufficiently detailed to predict individual salt falls. For such large systems, it is often necessary to make simplifications to the system before analysis is possible, and then to draw inferences from the simplified analysis on the behavior of the actual system. Nevertheless, such analysis can lead to improvement of the general knowledge of those situations that create a propensity for salt falls.

In general, a rather large body of knowledge of the mechanical behavior of salt has been developed over the last two decades. This available knowledge includes sophisticated constitutive descriptions for both creep and fracture. The Multimechanism Deformation (M-D) model of salt creep by Munson [1997] and the Multimechanism Deformation Coupled Fracture (MDCF) constitutive model by Chan et al. [1989, 1991, 1994] for the creep and fracture of salt were chosen for this study. It is thought that these models provide acceptable generic descriptions of salt materials.

This report is essentially divided into sections dealing with the purposes of the study. It begins with a review of site characterizations and an update of the known hanging string events and salt falls at each individual site. First, the relevant site characteristics of each site are reviewed, with emphasis on the known characteristics of the salt body and mechanically important features of the salt. Second, and perhaps most importantly, the factors thought to be relevant to the salt fall problem are stated and a preliminary analysis is presented based on these factors. Clearly, in the selection of the factors, only those considered as potentially major in their influence are included. Third, logical arguments and analysis are used to determine the relative importance of the factors. Then, a conclusion is drawn as to the possible controlling factor, which is the influence of impurities in the salt on fracture development. In view of the very limited available database, other investigators may arrive at different conclusions. As a result, it is recognized that the analyses provided in this report are to be taken only as a hypothesis, which remains to be proven. On the basis of this hypothesis, however, conceptual analyses suggest why some caverns have a propensity for salt falls. This current evaluation is preliminary in nature and is being developed further. This work concludes with a summary of a number of analyses and suggests possible operational changes to mitigate the extent of damage to casings and loss of hanging string pipe.

2.0 Review of Individual Site Characteristics and Salt Falls

There are presently four individual domal salt sites containing SPR facilities: Bryan Mound (54 events, 43 string failures), West Hackberry (11 events, 9 string failures), Bayou Choctaw (5 events, 2 string failures), and Big Hill (1 event, 1 string failure), listed in order of the total number of events observed to the date of this report. The total number of events include those that occurred in both Phase I caverns which were pre-existing caverns purchased for SPR use, and the more recent Phase II and Phase III caverns that were constructed specifically for SPR use. An event denotes observed casing damage, which may or may not have resulted in loss of hanging string casing. Note that some of the string failures are reported as lost pipe without identifying the direct cause of failure. While each string failure is presumed to be uniquely related to a salt fall, it is not necessary that every salt fall will cause a string failure, either because it merely damages the pipe string or misses the string altogether. Thus, other salt falls may have occurred but were not detected because they did not cause damage or pipe loss. All of the events reported for Phase II and Phase III caverns at the SPR sites are shown in Figure 1; this figure details the number of events plotted as a function of the elapsed time (years) since the beginning of solutioning. The initial construction authorization was termed the Phase II effort, while the second construction effort was denoted as Phase III. Since we have no record of the event history in the Phase I caverns prior to purchase, these caverns add additional uncertainty. As a result, in the following report data are primarily used from the events in Phase II and Phase III caverns. The very sparse database makes statistical evaluation impossible. Nevertheless, one can make some reasonable predictions and comments. During the cavern solutioning process, usually over the first two years, several sites experienced events. These solution-related events may arise from different causes than the later events that occur in the quiescent, operating caverns. Thereafter, for some period of time, only Bryan Mound experienced salt falls. However, in recent years, other sites have begun to experience additional events, notably West Hackberry.

It is believed that all of the Gulf Coast salt domes, including those domes containing the SPR facilities, are a related chain of domes or diapirs commonly derived from the same Jurassic “mother” salt formation, the Louann salt. Although the sites share general characteristics of diapirs formed from the base salt formation, it is probably more of the individual character within each dome that will eventually lead to the propensity for salt falls within a given cavern. For example, geological examination has led investigators to suggest that all of the domes appear to have “anomalous zones” in the salt and traces of faults intersecting their surfaces. West Hackberry is thought to have at least two such anomalous zones crossing at relatively high angles, Bayou Choctaw and Big Hill each appear to have one anomalous zone [Neal et al., 1993a], while Bryan Mound may have one anomalous zone and one possible anomalous zone [Neal et al., 1994]. Postulated anomalous zones are defined by Kupfer [1990] as a collection of three or more anomalous features. They may be associated with graben or shear faults in the cap rock. The zones in some instances are believed to separate distinct salt spines or lobes in the dome [Kupfer, 1963]. Because the spines potentially have had different rates of uplift, anomalous zones may also

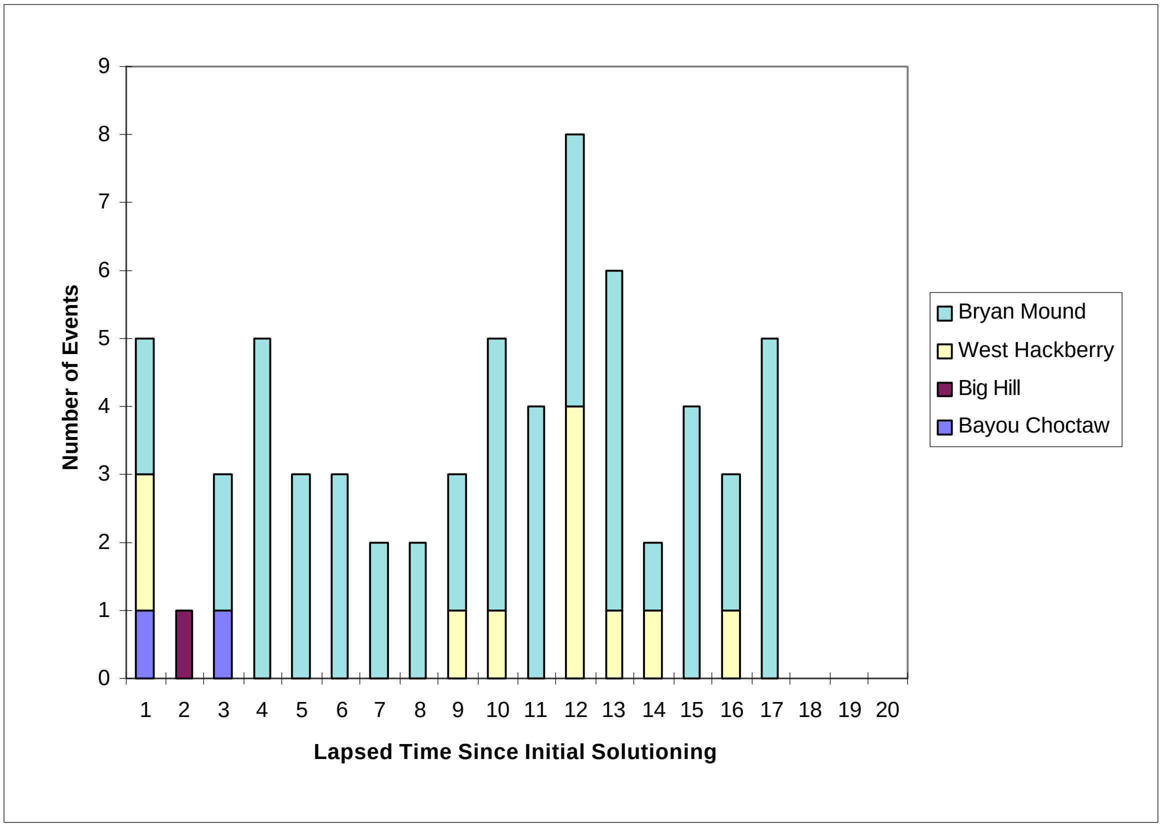

Figure 1. Frequency of Phase II and Phase III Cavern Events for All Sites.

be zones of shear. These zones are usually depicted as vertical planes with surface traces that go essentially straight across the dome. Multiple zones do not appear to be coplanar, but are typically shown as intersecting at relatively large angles to each other. Due to possible shear, the anomalous zones appear to contain slightly larger amounts of insoluble impurities, normally sand, shale, or limestone, drawn into the zone. In addition, it is thought that the zone may potentially be a region of gassy salt, with occluded pockets of gas. It must be noted that there is another type of impurity structure possible in salt domes. It is possible to speculate that the intrusion of the initially bedded salt that forms the foundation or mother body into the overlying strata can carry non-salt materials, other minerals, and interbedded material layers in concentric arcate bands up into the dome with the salt. The bands are the possible relics of the bedding of the mother salt formation. Potential interaction of these bands with the shear zones between spines may cause offsets and marked local changes in the detailed band structure. In fact, the interbeds can be thought of as localized concentration zones of impurities. These arcate concentrations of impurities would appear to intersect the line of the shear zones at right angles. They would also be folded and truncated by shearing of the dome and loss of salt, especially at the dome edges, during the formation of the dome. Some confirmation of these types of band structures was found by Jackson et al. [1990] in near ground surface domes that have been exposed and truncated by erosion.

2.1 Bryan Mound

The SPR facility at Bryan Mound consists of 20 caverns, four of which were existing caverns purchased in 1977 and 1978 by SPR in Phase I of the storage operation and filled with oil between 1980 and 1981. The remaining 16 caverns were developed for the SPR in Phase II of the storage operation. These were constructed between 1980 and 1984 and filled between 1982 and 1986, making them the oldest of the SPR developed caverns.

The Bryan Mound caverns are located in a salt stock that is postulated to contain one major anomalous zone and at least one other possible anomalous zone, as noted by Neal et al. [1994]. These authors also suggested that numerous faults exist in the cap rock that are believed to be somewhat congruent with the anomalous features in the salt stock and which mark the occurrence of the anomalous zones. Evidence indicates that the Bryan Mound dome contains significantly more shale and probably less anhydrite than the other SPR sites to the east. In Bryan Mound, black shale is a common impurity. Apparently, little sylvite is found in this dome and less anhydrite than at Big Hill. However, based on core analyses and other observations obtained from the wells drilled at Bryan Mound, this site is possibly the best characterized in terms of impurities and gas occurrences.

During its operational history, Bryan Mound has had the greatest number of casing events and hanging string failures. A summary of the events and hanging string failures at Bryan Mound since the beginning of operation is given in Table 1, where operation is defined as the time after initial solutioning began. As will be described, considerable differences exists in the nature of Phase I, Phase II, or Phase III caverns, particularly in their uniformity of shape. Table 1 contains considerable information about the status of the caverns, including: the year of initial solutioning, the year of completion of solutioning, the number of wells used during solutioning, the current operation wells, the type of crude stored, depth to the top of salt, depth to the cavern top, the height of the cavern, and the date and location of events and string failures. Often completion of solutioning coincides with the beginning of filling. However, in some of these caverns filling occurred simultaneous with the later stages of solutioning. As is apparent, there have been a total of four detected events in Phase I caverns and 50 detected events, with 43 resulting in loss of some portion of pipe, in the Phase II caverns. The events include pipe damage without pipe loss. In the subsequent accounting of the events at any site, only those occurring in the Phase II and Phase III caverns are given, principally because of the unknown early history of the Phase I caverns. The frequency of damage and pipe loss in Bryan Mound Phase II caverns as a function of lapsed time of cavern operation is shown separately in Figure 2. Perhaps because of the sparse database, it is not possible to ascertain any increase of frequency with time, at least over the current life span of these caverns.

Some of the caverns, especially Cavern 106 (11 events, 7 string failures) and Cavern 107 (9 events, 5 string failures), have had the dominant share of the salt falls. Cavern 109 has now experienced 7 events, all resulting in string failure; however, two of these string failures appear to have occurred simultaneously in the two hanging strings, perhaps as the result of a single salt fall. Cavern 112 and Cavern 103 each have had 5 string failures. Cavern 108 has had three string failures (4 events). Cavern 101, Cavern 102, Cavern 113, and Cavern 116 each have had two. Cavern 111 has had one. The primary question is why do these caverns experience the hanging string events?

Table 1. Bryan Mound Site Hanging String Events.

No.	(Wells)Typ.	Start-End (year)	Salt. Cover (ft.)	Depth to Roof (ft.)	Cav. Height (ft.)	Cav. Diam. (ft.)	Casing No.	Failure Date	Casing Loss (ft.)	Casing Depth (ft.)	Impact	Notes
BM 1	(2) Sour	42(78)	1213	2349	413	383						
BM 2	(2) Swt	42(78)	380	1450	220	453						
BM 4	(3) Swt	42(77)	1430	2495	581	504						
BM 5	(3) Sour	57(77)	1012	2102	1171	481	5	10/78	456	2817	B	SF
							5	08/88	204	3069	S	SF
							5	06/90	458	2815	S	SF
							5C	07/92	530	2743	S	SF
BM 101	(2)Sour	82-84G	936	1998	2161	193	101C'	10/83	226	3903	B	SF
							101C**	08/07	Damg.	3713	D	UC
BM 102	(2)Sour	80-84	1136	2203	2034	201	102B	07/83	817	3420	B	SF
							102B'	07/90	747	3490	S	SF
BM^103	(2)Sour	82-84G	1059	2122	2021	201	103C'	08/87	156	3977	S	SF
							103C'	11/87	343	3790	S	SF
							103C'	10/90	284	3849	S	SF
							103C*	08/96	624	3670	S	SF
							103C**	03/97	300	3500	D	UC
BM 104	(3)Sour	80-83	1050	2108	2055	202						
BM^105	(2)Sour	80-83	986	2050	2143	195						
BM 106	(3)Maya	80-82	1041	2106	1905	216	106A'	05/86	1027	2984	P	SF
							106C'	01/88		3340	D	SF
							106A'	07/90		3340	D	SF
							106C*'	11/90		3046	D	PC
							106A	03/91	1080	2931	S	SF
							106C	04/91	1248	2763	S	SF
							106A	05/92	561	3450	S	SF
							106C	05/92	431	3580	S	SF
							106C*	05/93	896	3101	S	SF
							106C*	11/95	327	3620	D	SF
BM 107	(3)Sour	80-83G	1077	2150	1947	205	107C	08/84	1232	2865	S	SF
							107B	09/84	Damg.	?	D	SF
							107A'	06/86	297	3800	P	SF
							107A'	04/89	924	3174	D	PC
							107A	06/92	1125	2972	S	SF
							107A	09/93	?	(3500)?	D	UC
							107C	09/93	?	(3100)?	D	UC
							107C**	07/97	623	?	UC	DG
							107C**	08/97	Damg.	3904	R	DG
BM 108	(3)Sour	80-85	1093	2166	1964	211	108A'	04/84	767	3363	B	SF
							108B'	04/84	41	4089	B	SF
							108B'	01/87	620	3510	S	SF
							108A*	10/96	Damg.	3720	D	UC
							109B'	11/84	305	3871	S	SF

Table 1. Bryan Mound Site Hanging String Events. (continued)

No.(Wells)Typ.	Start-End (year)	Salt. Cover (ft.)	Depth to Roof (ft.)	Cav. Height (ft.)	Cav. Diam. (ft.)	Casing No.	Failure Date	Casing Loss (ft.)	Casing Depth (ft.)	Impact Notes
BM 109 (3)Sour	80-83G	1047	2132	2044	201	109C	07/83	97	4079	B SF
						109B’	11/84	305	3871	S SF
						109A’	11/87	268	3908	S SF
						109B*	07/95	988	3164	D SF
						109A**	11/96	130	?	L SF
						109A**	03/97	694	3424	UC DG
						109B**	03/97	1464	?	D UC
BM 110 (3)Sour	80-82	1065	2140	1982	203					
BM 111 (2)Sour	83-84G	1052	2130	1998	200	111B*	06/94	584	3547	S SF
BM 112 (2)Sour	80-84G	1001	2065	2040	196	112A	08/85	769	3336	S SF
						112A’	12/86	1371	2734	S SF
						112A’	06/89	1304	2801	S SF
						112A’	11/90	992	3113	S SF
						112A	01/93	1563	2542	S SF
BM 113 (2)Swt	84-86	1068	2134	2066	156	113B*	10/96	89	4129	S SF
						113B**	04/97	Damg.	3751	D UC
BM 114 (2)Swt	84-87	1056	2130	2036	170					
BM^115 (2)Swt	84-86	1067	2146	1984	193					
BM^116 (2)Swt	84-86	1014	2100	1845	204	116B*’	08/85	337	3963	D UC
						116B*	04/95	1243	2731	P SF

Underlined = Those caverns that have been or will be degassed. Except for 113 which was a closed loop operation, raw water was added in bottom of cavern. Order of degassing: 113 (closed loop oil into 116 & 114, brine into 113), 2 (oil to 113), 114 (oil to 2), 1 (oil to 114), 101 (oil to 110 and 1), 109 (oil to 101), 103 (oil to 109), 107 (oil to 103), 111 (scheduled next), 112, 106. All exceed gas criterion, 114 very gassy.

’ Taken from Boeing Petroleum Services, DOE SPR Constructed Cavern History, Rev. 2, January 1991.

* New events reported by individual cavern reports, private communication Harry Lombard.

** New events from individual cavern engineers.

^ Participated in Sale ’90 test.

G Gas reported in one or more of the brining wells, Strategic Petroleum Reserve (SPR) Geological Site Characterization Report Bryan Mound Salt Dome, Ed. R. G. Hogan, SAND80-7111, Sandia National Laboratories, Albuquerque, NM, October 1980.

Well 109B potential damage observed (3/97) by operator as a dull thud and pressure variations at well head.

B = Brine solutioning	P = Depressurization	SF = Salt fall
S = Static operation	L = Loss of pipe	PC = Pipe collapse
W = Workover operation	D = Damaged pipe	UC = Unknown causes
R = Raw water partial fill	DG = Degassing	

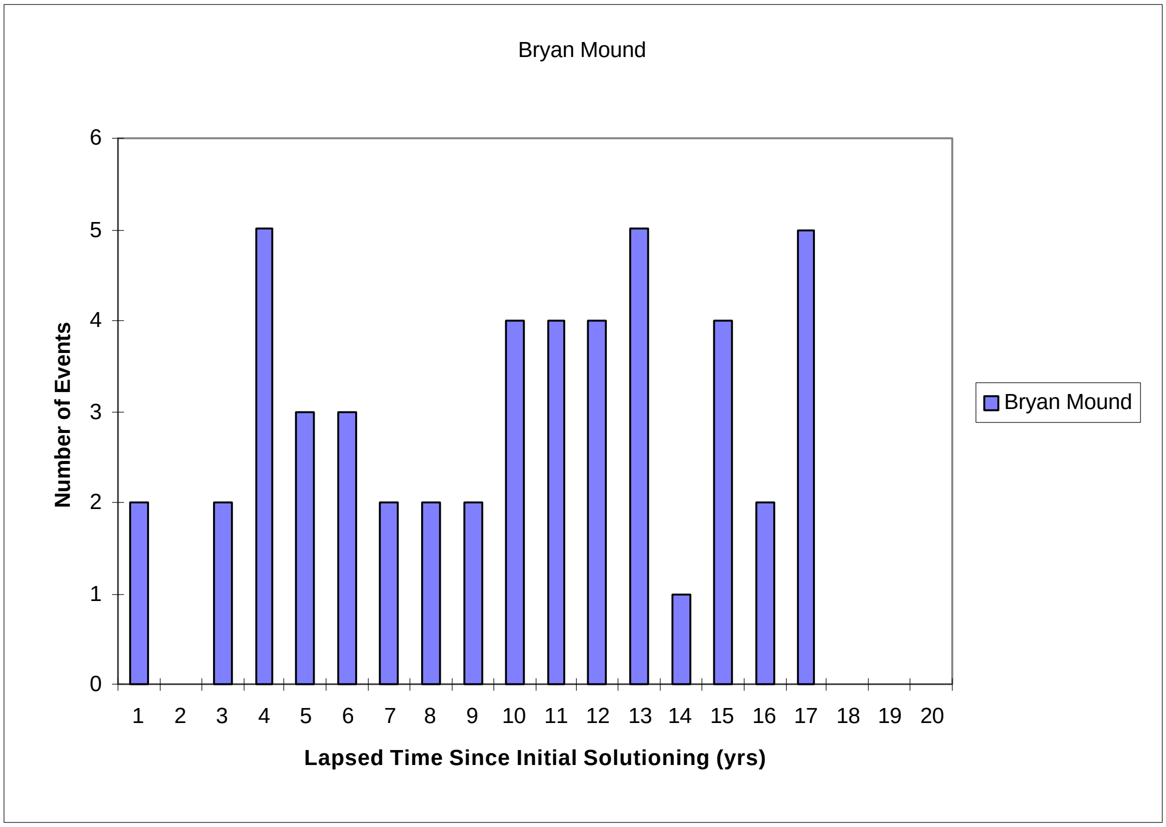

Figure 2. Frequency of Phase II Events at Bryan Mound.

Nine of the events are recent and coincide with the degassing operations at the site, although it is not clear that the salt falls and degassing operations are related. In the degassing operation, the cavern is emptied of oil using a raw water injection. The oil is placed in a previously emptied and degassed cavern, with subsequent disposal of the displaced brine. Repeating this process, the affected caverns have been degassed in turn, with Cavern 113 first, followed in the order by Caverns 2, 114, 1, 101, 109, 103, 107, 111, 112, and 106. Displacement of the oil with raw water has provided sufficient new storage volume that Cavern 112, which is extremely gassy, is planned to remain empty of oil, if operationally possible.

The spatial distribution of the salt falls over the height of the cavern can be partially determined by noting the amount of pipe which is lost, then relating that to the location within a cavern. The side view cross-section profiles of the Bryan Mound caverns relative to depth in the dome have been given by Neal et al. [1994]. When these profiles are combined with the observed damage location or pipe loss of the events, as in Figures 3a and 3b, a good measure of failure location with respect to the cavern is obtained. The cavern geometries were obtained in some detail from sonar surveys, although some portions (those with rather smooth boundary lines) are constructions using minimal angular data. The profile views shown in Figures 3a and 3b are very instructive because they indicate qualitatively the geometrical irregularities, if any, of the caverns and the relationship to the casing damage events and failures. Severity of the geometric irregularities has often been used as an indirect indicator of the trends of impurity concentrations in the

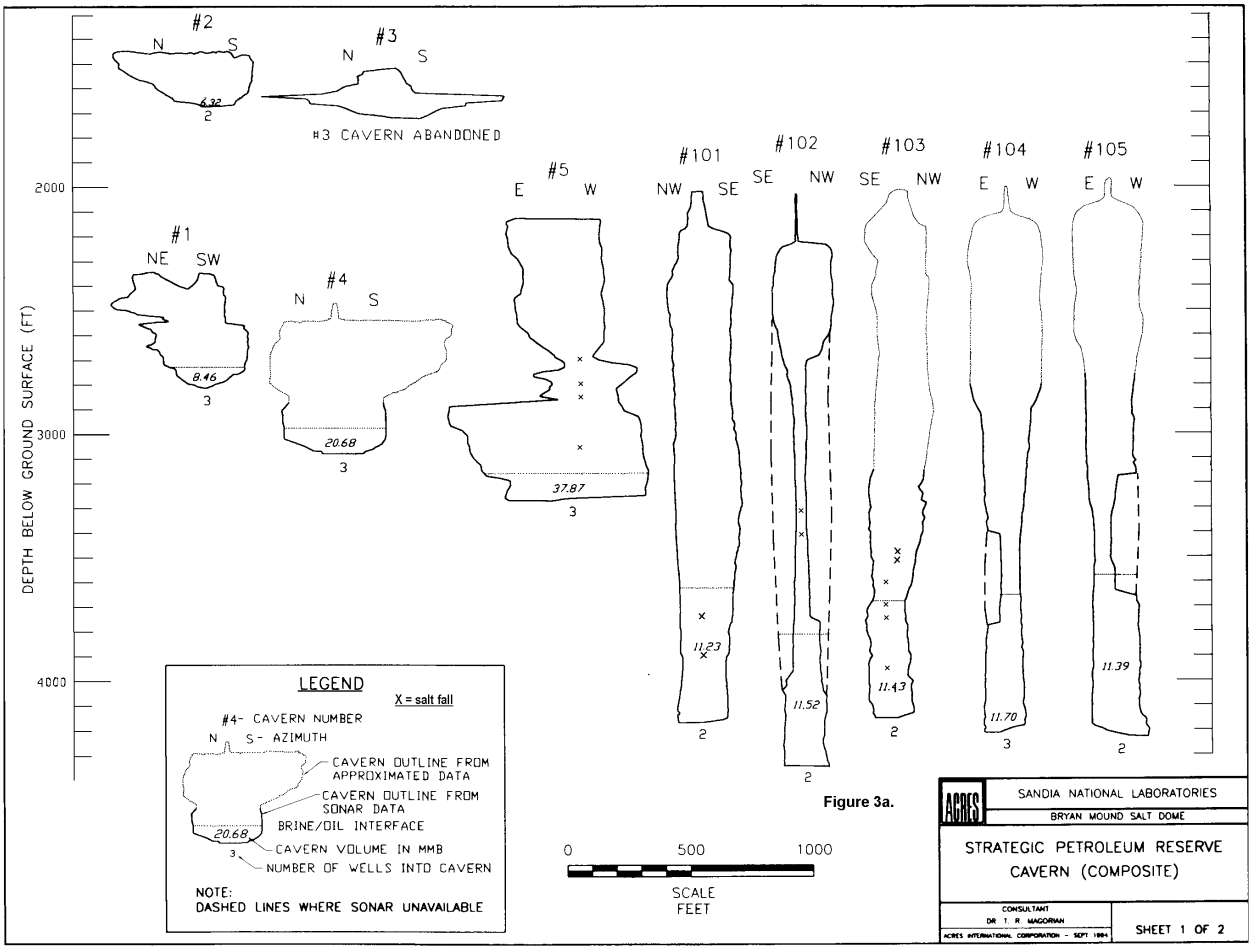

Figure 3a. Profiles and Event Locations for Bryan Mound, Caverns 1 - 105.
[adapted from Neal et al., 1994]

dome [Hogan et al., 1980, Section 6.5]. Obviously, the cavern visualization shown in Figures 3a and 3b are quite simplistic and possibly misleading. In fact, the changes in geometry in the two-dimensional profiles are actually changes in the cavity diameter as indicated by the sonar survey of a specific well. Configurations of this type certainly add complexity to the interpretation of salt falls. Also, many of the earliest caverns were being filled with crude at the same time as cavern construction solutioning was occurring. Later caverns, even in Bryan Mound, do not appear to have such marked geometric irregularities. The Bryan Mound facility was the first facility to have Phase II caverns solution mined for the SPR. The solutioning method was rather distinct because it used either two or three wells to speed solutioning. Thus, multiple chimneys were formed in the early stages of solutioning. As these chimneys coalesced, there was a potential to form splines of undissolved material in the interstice between wells and a cavern shape in the form of a “club” or “mouse ears” cross section. Although it was possible for these splines to fall, there is little evidence of brine string failures during development of the chimneys. As noted by the events marked “B” in Table 1, some events occur in the later stages of cavern construction, well after coalescence of the chimneys. Also, as the cavern dimension increases with respect to the well spacing, the tendency is for the cavern to become more cylindrical. In the completed caverns, the regions

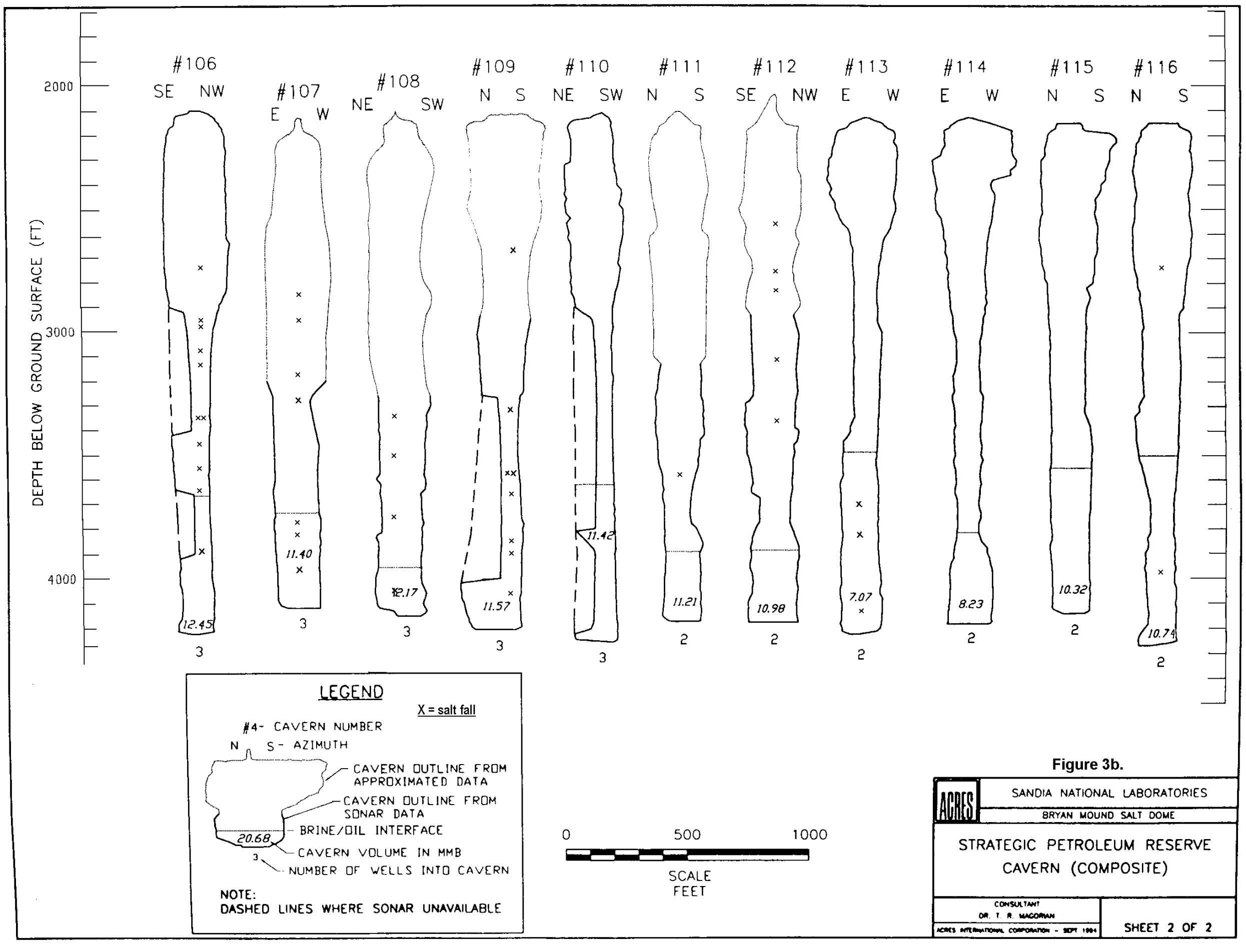

Figure 3b. Profiles and Event Locations for Bryan Mound, Caverns 106 - 115.
[adapted from Neal et al., 1994]

of concern are not the solutioning splines which are removed during the coalescence of the chimneys, rather they are regions of marked changes in cross section area or shape which may produce ledges and overhangs, and narrow, constricted areas depending upon how the cross section changes. As a result, combined sonar surveys of all of the wells would show discrete cavities around each of the wells which may be linked over certain regions to produce a single cavity. Solutioning practice was such that the wells were often, but not always, linked at the bottom and the top of the cavern. To picture the cavern shape from the top, the cavern would look like a pair of two- or three-legged trousers with joined flare bottoms.

Location of the caverns are shown in the plan view of Figure 4, together with a relative indication of insolubles, potash, and gas as determined in the solutioning wells and, eventually during solutioning of the cavern [Neal et al., 1993b].

In Figures 3a and 3b, the number of wells used in solutioning is indicated beneath the outline of the cavern. Of those caverns (6) with apparent complex geometries, including major cross sectional variations somewhere in the cavern, there are nearly as many two-well caverns (2) as three-

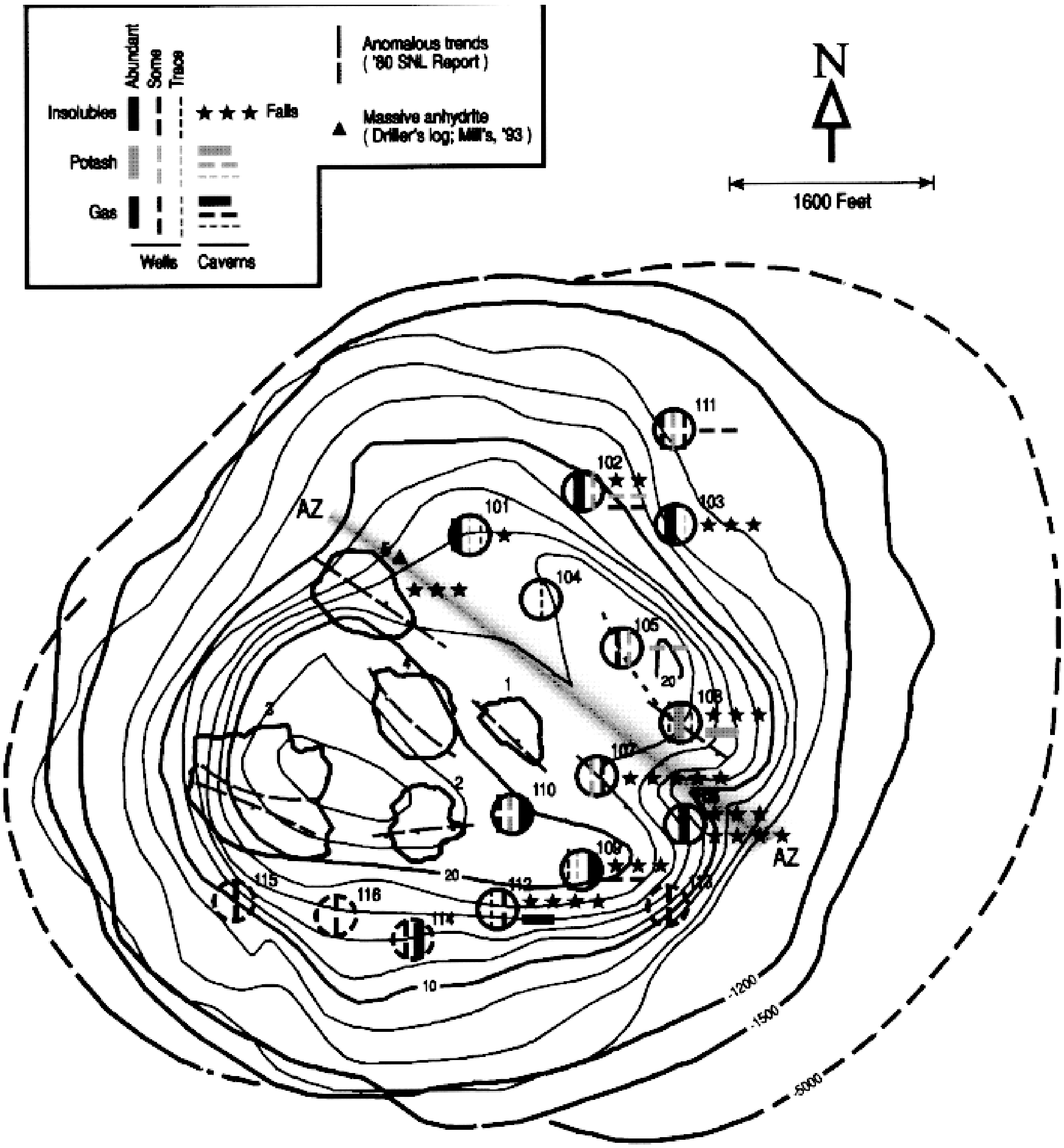

Figure 4. Plan View of Bryan Mound with Estimates of Impurities.
[after Neal et al., 1993b]

well caverns (4) exhibiting these features, with the two-well caverns actually more severe in extent of the irregular cross section formation. Cavern 102, 106, and 109 show the most complex geometries, with narrow, highly elliptical cross sections, perhaps caused by preferential solutioning along some vertical planar feature or by control problems of the solutioning/filling requirements. However, the remaining caverns (10), again of both two- and three-well types, are quite cylindrical. Interestingly, although Cavern 106 has strong geometric irregularities and exhibits the greatest number of events, the events seem to occur in more caverns (7) without geometric features than in caverns (3) with geometric features. Again, while the data base is too small for statistically meaningful comparisons, the data above suggest that the control over the solutioning process is more important than the number of wells involved in determining the geometric variations in a cavern. Some caverns were leached while filling with oil. They also suggest that nearly cylindrical caverns are as prone to salt falls as irregularly shaped caverns; if the geometry has an effect, it appears to be secondary to some other more primary cause.

2.2 West Hackberry

The SPR facility at West Hackberry consists of 22 caverns, five of which were existing caverns purchased in 1977 for Phase I of the SPR and filled with oil in 1978. The remaining SPR caverns, except for Cavern 117, were constructed during the Phase II, or initial construction phase, primarily between 1981 and 1985, with construction of four caverns extending into 1987 and 1988. Cavern 117 is a Phase III cavern, which were caverns constructed by SPR in the follow-on phase. The caverns were filled after completion of construction, between 1983 and 1988. As is apparent from Table 2, the sixteen Phase II caverns in this facility are all single-well caverns constructed following the development of the Bryan Mound Phase II caverns. The single Phase III cavern is a two-well type.

During its operational history, West Hackberry has experienced 11 events, all in Phase II caverns. This total is considerably fewer than Bryan Mound over approximately the same time frame. Nine of the events resulted in hanging string failures. Most of these events have been quite recent, occurring between 1992 and the present. Table 2 gives a summary of all Phase I, Phase II, and Phase III cavern events. As previously described, the table lists a number of other items relevant to the caverns at this facility.

The caverns are located in a salt dome that is thought to contain at least two postulated anomalous zones, which Magorian et al. [1991] described as probable shear zones. Many minor faults are located in the cap rock which may not extend into the salt. The shear zones are defined by increased amounts of anhydrite contained within them. There was very little coring of the wells at West Hackberry, with the result that little can be determined about the impurity contents. From the cavern construction, it may be speculated that the insolubles were noticeably greater in Caverns 107 and 110, as evidenced from excessive solids buildup in the sumps.

From just 11 events it is not possible to determine any true significance about salt fall frequency. The events occurred in Caverns 102, 103(3), 107, 108(2), 109(2), 110, and 113. Events in Caverns 109 and 113 damaged just the end of the strings. These caverns are not directly associated with each other, nor are they the caverns thought to have greater insolubles. Moreover, only one, Cavern 108 in the east-west zone, is included within the shear zones defined for this salt stock [Neal et al., 1993b]. Even though Cavern 113 seems to be very well removed from any anomalous zone and from the other caverns, it exhibited an event. Here, again, several other caverns that do not exhibit salt falls are found in the anomalous zones.

Table 2. West Hackberry Site Hanging String Events.

No.	(Wells)Typ.	Start-End (year)	Salt. Cover (ft.)	Depth to Roof (ft.)	Cav. Height (ft.)	Cav. Diam. (ft.)	Casing No.	Failure Date	Casing Loss (ft.)	Casing Depth (ft.)	Impact Notes
WH 6	(3)Sour	46(78)	1300	3249	141	662					
WH 7	(3)Swt	46(78)	560	2552	942	315					
WH 8	(1)Sour	46(78)	415	2450	999	272					
WH 9	(3)Sour	47(78)	1113	3213	342	454					
WH 11	(3)Sour	62(78)	866	2951	804	276					
WH 101	(1)Swt	81-83	505	2555	1885	206					
WH 102	(1)Swt	82-83	565	2628	1870	206	102*	09/95	Damg.	4433	D UC
WH 103	(1)Swt	81-84	629	2667	1756	205	103*’	07/82	188	4215	B L UC
							103*	05/95	476	3927	P L UC
							103*+	05/97	161	4242	L UC
WH 104	(1)Swt	81-84	549	2625	1921	206					
WH 105	(1)Swt	81-84	582	2640	1969	204					
WH^106	(1)Sour	84-87	491	2556	1790	212					
WH 107	(1)Swt	81-84	527	2585	1971	204	107*’	11/82	300	4234	B L PC
WH 108	(1)Swt	82-84	543	2596	1844	212	108*	05/94	860	3573	P L UC
							108*	09/94	143	4290	L UC
WH 109	(1)Sour	84-87	526	2583	2061	204	109*	10/93	40	4573	D UC
							109**	12/96	217	4396	D L R
WH 110	(1)Swt	82-85	495	2567	2001	200	110*+	03/96	Damg.	4425	P W UC
WH 111	(1)Sour	82-88	937	2622	1974	196					
WH 112	(1)Sour	83-87	512	2562	1970	203					
WH 113	(1)Swt	82-85	714	2827	1865	216	113	11/92	40	4630	D UC
WH 114	(1)Sour	82-85	447	2520	2029	200					
WH 115	(1)Sour	84-87	467	2540	2094	201					
WH 116	(1)Swt	82-85	552	2640	2078	199					
WH 117	(2)Sour	85-88	509	2560	2049	211					

Underlined = Caverns that participated in the recent 1996 oil sale, partial oil removal using raw water insertion. Order of draw down is 109, 115, 114, and 112.

\+ Taken from West Hackberry Weekly Report, December 26, 1996, P. Hetznecker to L. Johnson.

’ Boeing Petroleum Services, Inc., DOE SPR Constructed Cavern History, Rev. 2, January 1991.

* New events reported by individual cavern reports, private communication Harry Lombard.

** New events from individual cavern engineers.

B = Brine solutioning	P = Depressurization	SF = Salt fall
S = Static operation	L = Loss of pipe	PC = Pipe collapse
W = Workover operation	D = Damaged pipe	UC = Unknown causes
R = Raw water partial fill		

There appears to be only fragmentary evaluation of the relative impurity contents of the initial West Hackberry wells, with very little core recovered. From these cores, however, it was determined that the single major impurity was anhydrite, approximating about 3% [Whiting et al., 1980, Section 6.6]. In general, the initial wells and the resulting caverns are not gassy. This observation is especially interesting because it implies again that salt falls occur in the absence of gas inclusions in the salt, at least in this salt stock.

Cavern profiles, or side views, are shown in Figure 5 [Magorian et al., 1991] for all of the West Hackberry SPR caverns, Including Phase I, II, and III. Also indicated on these profiles are the locations of the casing damage and failures in the hanging strings. The profiles are the result of sonic surveys taken during construction, or at the time of purchase. In general, the Phase II cavern profiles all appear to be uniformly cylindrical and free of major perturbations or irregularities in cross section. These regular cross sections appear to be the product of the single solutioning well construction method. This lack of geometric irregularities in the West Hackberry caverns is in marked contrast to the caverns of Bryan Mound. As a result of this comparison, one might conclude, as we have done previously from the results of Bryan Mound alone, that marked geometric irregularity is not necessarily a requirement for the development of salt falls or the occurrence of casing damage.

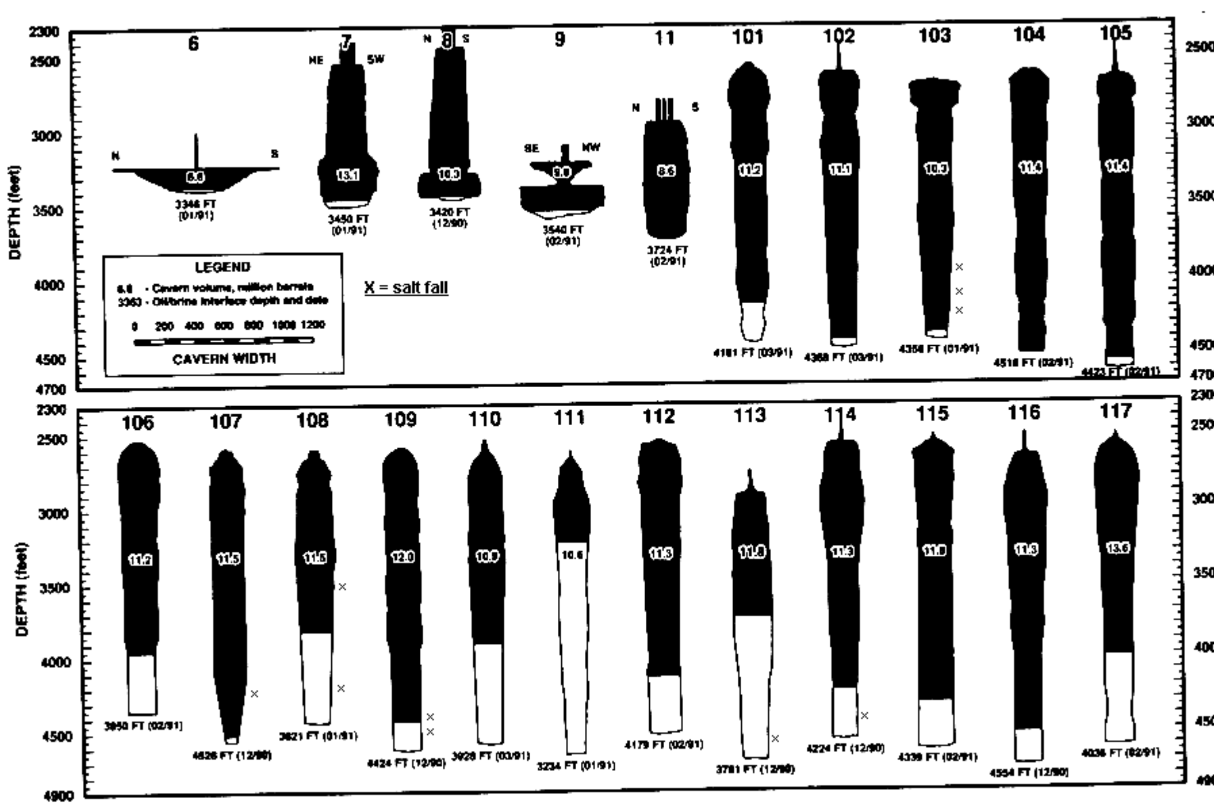

Figure 5. Profiles with Event Locations for West Hackberry.
[adapted from Magorian et al., 1991]

2.3 Bayou Choctaw

The dome at Bayou Choctaw contains five Phase I caverns and one Phase II cavern. The Phase I caverns were existing caverns purchased for SPR use between 1977 and 1985. These caverns were filled over the same general time span. The Phase II cavern was leached between 1987 and 1990 and subsequently filled. Another cavern, Cavern 102, was leached by the SPR under a brine supply and cavern exchange agreement with Union Texas Petroleum; this cavern was not retained. The Bayou Choctaw dome is thought to contain one anomalous zone running in an east-west direction and located somewhat in the southern part of the dome [Neal et al., 1993a]. These authors have described this feature as a probable shear zone separating salt spines which reflects a fault feature in the cap rock.

The dome has a long history of use for storage caverns and contains some 22 older caverns. The development of 10 of the earlier caverns was at relatively shallow depths, from 1000 to 2000 feet. Cavern leaching for brine stock in the shallow caverns appeared to be uncontrolled with cavern irregularities and thin to non-existent salt roof thicknesses. However, the remainder of the earlier caverns were much deeper, between 2000 and 4000 feet. A number of the deeper caverns are geometrically quite regular, perhaps as the result of adequately controlled leaching. Many of the shallow caverns have been abandoned or are inactive. Cavern 7 collapsed in 1954 to form Cavern Lake. Cavern 4 may be metastable [Neal et al., 1993c], although monitoring has shown no subsidence.

There appears to have been a total of five events at this facility, only two of which caused loss of pipe in the hanging string. A summary of the events reported for this site is given in Table 3. Both of the pipe losses were in Cavern 101, with one of the losses occurring very early in the leaching process. The cavern appears to have few geometrical irregularities. It is located quite close to, if not directly in, the anomalous zone. Specific impurity content information is not available from well data for the Bayou Choctaw cavern development.

The remaining three events were in Cavern 20, a Phase I acquisition. It is not possible to determine a frequency distribution from these limited data. This cavern is within the anomalous zone and very near (about 130 feet) to the southwest edge of the dome [Hogan et al., 1980, Section 6.7]. This cavern is also quite deep, situated between 3000 and 4000 feet, and geometrically very irregular. Both the depth and the irregularities would suggest susceptibility to salt falls.

2.4 Big Hill

The Big Hill facility is the most recent of the SPR facilities to be developed. Leaching at Big Hill began in 1987, with the storage operation beginning in 1990. It contains 14 Phase III constructed caverns, all utilizing the two well leaching method. Based on the initial sonic surveys obtained during construction [DOE/SPR, 1991], all of the caverns are nearly cylindrical, with few, if any, major geometric irregularities.

Even though a large number of caverns are involved, only one rather recent event has been experienced at this facility. This loss of pipe through unknown causes occurred in Cavern 114 early in its operation. While the lack of events at this site may be due to the relatively short life history, one would suppose if all sites were comparable that a number of events should have taken

Table 3. Bayou Choctaw Site Hanging String Events.

No.	(Wells)	Typ.	Start-End (year)	Salt. Cover (ft.)	Depth to Roof (ft.)	Cav. Height (ft.)	Cav. Diam. (ft.)	Casing No.	Failure Date	Casing Loss (ft.)	Casing Depth (ft.)	Impact	Notes
BC 15A	(2)	Sour	53(80)	1979	2695	691	412						
BC 17	(2)	Sour	55(85)	1952	2600	1423	238						
BC 18	(2)	Swt	67(78)	1320	2125	2094	244						
BC 19	(2)	Sour	70(78)	2078	2935	1257	380						
BC 20A	(2)	Swt	79(78)	3130	3830	395	514	20*”	??/81	Damg.			
								20A*”	??/81	Damg.			
								20*”?	??/83	?			
BC 101	(2)	Sour	87-90	1824	2550	2290	201	101B*’	12/87	118	4838	L	UC
								101A*’	03/90	1445	3874	B	SF

” [1988] Taken from D506-1788-09, author unknown, February 1988.

’ [1991] Taken from Boeing Petroleum Services, Inc., DOE SPR Constructed Cavern History, Rev. 2, January 1991.

* [1996] New events reported by individual cavern reports, private communication Harry Lombard.

B = Brine solutioning   SF = Salt fall

L = Loss of pipe   UC = Unknown causes

place. This difference in propensity for casing damage between sites certainly suggests that the factors causing hanging string damage and failure is very site dependent. A summary of the event history is given in Table 4.

Neal et al. [1993b] proposed a probable anomalous zone or shear zone traversing the dome in the north-south direction. Numerous faults exist in the cap rock, with some suspected of continuing into the dome. Significant faults occur above the anomalous zone. Three of the caverns, Cavern 103, 108, and 113, are within the anomalous zone. None of these appears to have experienced events or salt falls. Although none of the Big Hill caverns are currently reported as being gassy, at least two of the caverns, Caverns 108 and 114, showed signs of gas evolution during development. Cavern 114, an extremely gassy cavern, also showed production of hydrocarbon condensate.

General descriptions of the impurity content of the dome [Hart et al., 1981, Section 6], taken from sources other than the Phase III wells, have suggested about 3% insolubles, based on minimal data. There have apparently been no specific evaluations of anhydrite. These wells were fundamentally not characterized for impurities.

Table 4. Big Hill Site Hanging String Events.

No.(Wells)Typ.	Start-End (year)	Salt. Cover (ft.)	Depth to Roof (ft.)	Cav. Height (ft.)	Cav. Diam. (ft.)	Casing No.	Failure Date	Casing Loss (ft.)	Casing Depth (ft.)	Impact	Notes
BH 101 (2)Swt	88-90	634	2265	2180							
BH 102 (2)Swt	87-90	655	2289	2241							
BH 103 (2)Swt	87-90	658	2280	2050							
BH 104 (2)Swt	87-90	647	2276	2174							
BH 105 (2)Sour	87-90	650	2283	2297							
BH 106 (2)Sour	87-90	667	2297	2256							
BH 107 (2)Sour	87-90	630	2265	2215							
BH 108 (2)Sour	87-90	(736)	2334	2126							
BH 109 (2)Sour	87-90	639	2266	2334							
BH 110 (2)Sour	87-90	656	2277	2195							
BH 111 (2)Sour	88-90	618	2248	2162							
BH 112 (2)Sour	88-90	653	2290	2128							
BH 113 (2)Sour	88-90	640	2274	2076							
BH 114 (2)Swt	88-91	697	2327	2070		114A*’	06/90	600	3006	L UC	

” [1988] Taken from D506-1788-09, author unknown, February 1988.

’ [1991] Taken from Boeing Petroleum Services, Inc., DOE SPR Constructed Cavern History, Rev. 2, January 1991.

* [1996] New events reported by individual cavern reports, private communication Harry Lombard.

B = Brine solutioning   SF = Salt fall

L = Loss of pipe   UC = Unknown causes

3.0 Possible Factors in Producing Casing Damage

Although it appears reasonably certain that salt falls have caused damage to hanging strings, it is important to confirm this logic. As a result, an analysis of the dynamics of a falling salt mass through a viscous medium was performed. Because such analyses are not exact and require significant assumptions about conditions, uncertainty in the potential velocities of a falling mass remain large. Ehgartner [1997] has determined the dynamics of a falling salt mass through crude oil. The assumptions involved in this special analysis are of a flat plate falling vertically, edge on, through the oil. The analysis indicates that a 1.0 ft-thick salt slab, 5.0 ft wide and 10.0 ft long (3.35 tons), achieves a velocity of 40 miles/hour within 160 ft of travel, 75 miles/hour within 500 ft, 90 miles/hour within 1000 ft, and 97 miles/hour within 2000 ft. A salt mass half this weight (1.68 tons) will achieve a velocity of 40 miles/hour in 200 ft of travel and 67 miles/hour in 2000 ft. If the salt mass is twice this weight (6.7 tons), it attains a velocity of 40 miles/hour in 150 ft and 130 miles/hour in 2000 ft. As is apparent, a relatively small slab of salt (1 ft by 5 ft by 5 ft), which weighs about the same as an automobile (1.68 tons), attains high speeds while falling within a cavern, and can impart significant momentum on impact. However, actual velocities would be expected to be much less than for the ideal assumptions used in this analysis.

In a less ideal situation, the slabs could fall much as a leaf from a tree, oscillating with considerable lateral motion. The resulting vertical velocities would be less. On the other hand, very small particles would probably fall at the other extreme of velocity, settling at only a slow rate. Based on the assumption that the larger salt masses would fall at reasonable velocities, Munson [1997a] has suggested a scenario based upon impacts of a salt mass on a hanging string to explain the forms of damage observed on recovered pipe.

A rather large number of factors could contribute to the observed hanging string casing damage and salt fall events in storage caverns. The most reasonable factors, listed in Table 5, will be examined and a logical argument developed to determine the primary factor, if possible. Each factor is categorized according to whether it is the result of a *natural* condition or an *imposed* condition. *Natural* conditions are those primarily related to special features of a dome and involve materials and properties, with the principal natural conditions being domal structure (anomalous zones), salt mass creep and fracture properties, thermal response, and impurity type and quantity. *Imposed* conditions are either operational or geometric. Operational conditions considered include the leaching method (1, 2, or 3 wells, as well as oil-fill while leaching), type of crude stored, cycling of crude between caverns as required or for degassing of storage, workovers, operating pressures, etc. Geometric conditions include roof span, depth, irregularities in leaching profile, spacing, and location within the dome. Each factor can also be categorized according to the geometric area or extent applicable. As a result of the application area, some of the factors can be considered as general, while the remainder are local. A general designation suggests that the factor is present in all domes where the SPR facilities are sited. Local conditions suggest that not all domes are affected equally, or that all portions of a given dome behave similarly. These factors comprise a rather large number of variables, all of which could possibly influence the development of salt falls. The number of variables, when coupled with the rather small

Table 5. Major Factors Considered in Evaluation Process.

Factor	Condition	Application	Comments	Cause
Anomalous Zones	Natural	General	Possibly a secondary factor.	Secondary
Crude Type	Imposed	General	Possibly a secondary factor.	Secondary
Leaching Method	Imposed	Local	Linked to geometry irregularities.	Secondary
Operational:				
Operation Procedure	Imposed	Local	Time-independent failures	Secondary
Depressurization	Imposed	Local	Linked to stress.	Secondary
Geometrical:				
Location in Dome	Imposed	Local	Cavern spacing, dome edges.	Secondary
Cavern Depth	Imposed	Local	Linked to stress magnitude.	Secondary
Cavern Shape	Imposed	Local	Roof span, geometry irregularities.	Secondary
Material:				
Creep Properties	Natural	General/Local	Deformation processes.	Secondary
Fracture Properties	Natural	General/Local	Salt fracture, link to impurities.	?Primary?

database available on salt falls, creates an obvious problem for analysis. There are insufficient data to statistically determine the most probable cause of salt falls. As a result, an attempt must be made to eliminate logically some of the variables in some systematic manner. In the "Cause" column of Table 5, the most probable contribution (i.e., primary or secondary) of the factor to casing damage and salt falls is given.

Only two of the general factors apply to all four sites:
(1) the presence of anomalous zones in the dome; and,
(2) the type of crude stored.

The first general factor, anomalous zones, concerns the natural condition of a salt dome structure. Anomalous zones, as postulated by geological investigations, are presumed to occur in all four of the domes having SPR facilities, and in fact have been proposed to be a general characteristic of all the Gulf Coast salt domes (not just those with SPR caverns). As noted earlier, anomalous zones may be zones of shear between spines moving differentially, with possible incorporation of impurities and gas in the zones. If the existence of an anomalous zone itself is the critical factor, each of the facilities should experience similar event rates, correlated with the caverns most affected along the anomalous zone. These zones are thought to be at most a hundred feet in thickness [Neal et al., 1993a]; in fact, where direct observation is possible, identified shear structures appear to be less than this thickness. With thicknesses on this order, affected caverns would certainly have to be almost directly in the anomalous zone. In the West Hackberry dome, there are thought to be two possible shear zones at nearly right angles to each other [Magorian et al., 1991]. The north-south zone transects the facility and potentially involves four caverns, and the east-west zone touches the southern boundary of the facility and involves three caverns. None of the caverns in these zones has experienced events or salt falls. At Bayou Choctaw, two of the six caverns are near what is thought to be a single anomalous zone [Neal et al., 1993a] involving shear, and both caverns have experienced events. At Big Hill there is thought to be a single anomalous zone with shear [Magorian and Neal, 1988], which at the extreme of several hundred feet wide may involve six of the caverns. The only event at this facility does take place in a cavern near the anomalous zone. Bryan Mound dome is thought to contain one definite anomalous zone, with another possible zone oriented nearly at right angles to it [Neal et al., 1994]. There are eight caverns (six Phase II and two Phase I) along the trend of the anomalous zone, five of which have casing damage events. While this may suggest a correlation, there are four caverns away from the zone that show events. If the second, postulated anomalous zone is present, it incorporates potentially ten caverns, only two of which have exhibited events. Certainly, in the Bryan Mound facility, one might make a case for the influence of the anomalous zone on producing the conditions for salt falls, with five, and potentially seven, of the seventeen caverns near anomalous zones. However, if all of these caverns are to be influenced by the anomalous zones, the effective width of the zones would have to be many times the apparent width of observed zones. Furthermore, if the anomalous zone influence were a primary factor in determining salt falls, all of the facilities would experience salt falls within the involved areas. Clearly not all facilities do. Although it is possible that the anomalous zones have a secondary effect on producing salt falls, it seems reasonably certain that they do not have a primary effect.

The second factor, the type of oil stored, addresses the concern that the sour crude is more reactive with either the pipe string or the salt than the sweet crude. Both the physical evidence on recovered pipe and a metallurgical study, which eliminated hydrogen embrittlement [Scientific Testing Laboratories, 1993] of the pipe, suggest that the crude does not interact significantly with the pipe. However, there are no data available on the influence, if any, of the crude type on the fracture of salt. Because each of the facilities have some caverns with sour and some with sweet crude, if the type of crude were the only or primary influential factor, one would expect each facility to have salt falls in proportion to the number of caverns with sour crude. Although the conclusion is not completely clear, this appears not to be the case. If we look at all of the sites, then 37 caverns contain sour or Mayan crude and 25 contain sweet crude, for a ratio of 1.48 sour/sweet storage. If the sites are neutral, then this ratio could be expected to apply to the events both collectively and at individual sites. Taking all of the sites and caverns, there are 54 events in sour caverns and 17 events in sweet caverns, giving a ratio of 3.18 sour/sweet events with the possible implication that the events occur disproportionally in sour storage caverns. (If the Bryan Mound Cavern 106 storing Mayan crude, which seems extremely prone to events, is eliminated, the overall site ratio becomes 2.76, a marked change). However, this conclusion appears to be misleading. If the Bryan Mound results are excluded, then only six events occur in sour caverns and 13 events occur in sweet caverns, with a sour/sweet event ratio of only 0.46, which indicates a greater tendency for sweet crude failures. These results suggest the type of crude is not a principal factor in creating events, rather they seem to indicate that the site itself is the more important factor.

A third, local factor is often expressed as a potential cause of different cavern responses; it is the number of wells or solutioning method used in the initial solutioning of the cavern. Upon close examination, the influence of the solutioning method is to produce differences in geometry at various stages of the cavern construction. It is true that the geometric complication of the final cavern is related to the number of solutioning wells used, with the three well caverns the most likely to have complicated geometries and the single well caverns to have simple cylindrical geometries. However, because it is possible for a three well cavern to also have a simple geometric shape, it is the geometry and not the number of wells involved in the solutioning method that is important. As a result, the number of solutioning wells is certainly secondary in nature, with only an indirect influence through the geometry produced during solutioning.

Whenever casing damage occurs, there is always a concern that the operational procedures are a factor and may have contributed to the problem. These are the instances where observation suggests there is no evidence of impact damage, so that the cause cannot be due to salt falls [Shourbaji, 1997]. The operational procedures of concern are related to the typical workover operations at a site. Potentially, workover operations can involve either direct damage to casing through the operational procedures and methods used, unintentional impacts of the pipe string against geometric irregularities in the cavern, or indirect influence through the reduction of pressure during the workover. Depressurization during fluid transfer (down to about 200-400 psig) is fundamentally similar to the depressurization during workover (down to 0 psig).

In order to examine these factors, it is necessary to observe that the action of each is fundamentally different. Direct damage during workovers leads to a time-independent process, whereas, the indirect effects of depressurization during workover or fluid movements affect some other process to increase the propensity for casing damage and is a time-dependent effect. Direct damage would involve setting of casing where impact damage of joints or miss-coupling of joints could occur. Such problems may or may not be immediately apparent. However, both could be checked quickly after completion of the workover. Damage causing loss of integrity of the casing or couplings would result in rapid indication through oil sightings in the brine pond. Casing impact damage, although not evident through indirect means, could be checked through running of a casing diameter gage immediately after completion of the setting of the casing.

In the casing damage records available to date, there is little evidence to indicate that casing damage can be identified immediately during the workover activity. This does not mean, however, that damage has not occurred during workover. It means simply that the damage must not be severe enough or is of a type that goes undetected at the time of the workover.

The other operational activities that occur are the depressurizations of the caverns during workovers and transfers of fluids. Even though these are operational activities, they cannot affect the casing directly. In fact, the influence is on the stress level in the caverns, as will be discussed later. In the casing damage records available to date, there appears to be no immediate one-to-one correlation between depressurization and observed events. As a consequence, if the depressurization does influence casing damage and loss, it must be an effect delayed in time.

In any discussion of geometric factors, it is reasonable certain that these can have a strong influence on the propensity for salt falls, and hence casing damage. The geometric influence is primarily through the evolution of stress fields and their magnitudes. In terms of the potential deformation and fracture response, the depth of the cavern within the dome is of considerable importance. This is the result of the very strong dependence of the deformation (creep) on the applied stress (stress is directly proportional to depth) [Munson et al., 1989]. The Phase II and Phase III caverns tend to have relatively uniform thicknesses of overburden, typically some 2000 ft, with a roof thickness of at least 500 ft of salt. Also, the new caverns are quite consistent in their general size, with about 200 ft roof spans and 2000 ft heights. The deepest part of the caverns are, thus, at about 4000 ft. Because of their similar dimensions and overburdens, the stresses around all Phase II and III caverns are nearly identical. Although the stresses associated with these depths are appreciable, they are reduced significantly because of the fluid content of the cavern. At zero well head pressure, with brine fill, the stresses are approximately halved. Equivalent stresses with oil fill are somewhat greater. Moreover, caverns in static operation normally maintain a well head pressure on the oil approaching 1000 psi, which further reduces the effective stresses in the cavern. Because of the differences between lithostatic and hydraulic pressure gradients, the caverns still undergo relative creep deformation. With the elevated oil pressures at the well head, the amount and distribution of creep closure is altered. In this condition the bottom parts of the cavern will continue to close but the top parts will undergo little closure with time. Even then, the rather uniform cavern overburden depths and dimensions suggest that the cavern stresses alone are not significantly different and, therefore, are probably not a primary factor in determining the different potential among Phase II and Phase III caverns for salt falls. In fact, if it were, because the caverns are about 20% deeper, then one would actually expect somewhat more events in West Hackberry than in the shallower Bryan Mound caverns.

The Phase I caverns present a considerably different picture than the Phase II and Phase III caverns, in that they are typically geometrically irregular and are at various depths in the salt stock. At Bryan Mound, Cavern 5, by far the largest SPR cavern, is both very geometrically complex and very deep, whereas the other four caverns are irregular but shallow. Cavern 5 exhibits a number of events. At West Hackberry, only Phase I Caverns 6 and 9 are severely irregular; the other Phase I caverns (Caverns 7, 8 and 11) are quite regular. All of these caverns are at moderate depth and none have experienced hanging string events. At Bayou Choctaw, the Phase I Caverns 18 and 19 are more typical of the shape and dimensions of the Phase II caverns, Caverns 15 and 17 are regular but closely spaced, and Cavern 20, with a number of salt falls, is both irregular and deep. As these results tend to support, the depth is important as is the non-uniformity of the stress caused by the irregularities in geometry.

Although the Phase I cavern failures would suggest that geometry is an important factor, the relative importance may not be as strong as thought. If the failures are examined with respect to irregularities in cavern shape in the Phase II caverns, the number of events in Bryan Mound caverns with geometric irregularities is less (20 events) than in caverns with well defined shapes (30 events), as illustrated in Figures 3a and 3b. As a consequence, it appears that while geometric irregularities are important, some other more primary factor actually controls the process.

At this point, we can address the potential for roof falls, as contrasted to salt falls from the walls of the caverns. Using the relative locations of the hanging string failures and damage in Figure 3 for Bryan Mound and Figure 5 for West Hackberry, it is clear that all the damage locations in the Phase II caverns are at appreciable depths in the caverns. None of the failures are near the cavern roof. In the Phase I caverns, where the geometric irregularities and the largest roof spans occur, there are also no string failures near the roof of the caverns. In the only Phase I cavern to show failures, Bryan Mound Cavern 5, all of the failures are in the mid-cavern region. While roof falls could of course occur without impacting the hanging string, especially in the caverns with large roof spans, the fact that no hanging string damage or failures appear near the roof strongly suggests that most, if not all, of the salt falls must be from the cavern walls.

Sometimes it is necessary to fully depressurize a cavern; this in turn alters the stresses and promotes an increase in creep deformation. In fact, prior to the degasification cycles started in late August 1995, only three of the 45 events at Bryan Mound and two of the 10 events at West Hackberry appear to be associated with depressurizations. It is clear that most often the events occur under the conditions of long-term static (non-changing stress) operation, but occasionally an event occurs shortly after a short-term depressurization. This suggests a possible correlation even though the event is not actually simultaneous with the depressurization. If the depressurization does in some manner trigger the event, the event must be the result of a time dependent process that is sensitive to the stress. Recently 10 caverns at Bryan Mound were degassed, which required depressurization. There were, as a result, also 10 caverns that did not require degasification. If the event rate were neutral to the depressurization, we would have expected an split of events among those caverns requiring degasification and those that did not. Of the 13 events at Bryan Mound that have occurred since the beginning of degasification, 10 have occurred in caverns involved in the degasification process. While these events suggest a possible connection, it is not a simple connection because not all degassed caverns showed events. Also, clearly, at this time there is not a one-to-one correlation between a depressurization and damage event causation, which implies depressurization is a secondary effect, at best.

Before examining the remaining factors, a brief summary of the logic to this point seems appropriate. It appears that the propensity for salt falls is not a general (i.e., global) problem, although all of the facilities have experienced salt falls to some degree. At least, it is not a general problem so far as a major imposed factor of oil type is concerned. It also does not appear to be general in the sense of major salt dome structures in the form of anomalous zones. The geometry plays some role, as does stress, but neither appears to be a dominant factor. If those general and imposed factors are not the dominant factors in the development of salt falls, then the problem and resolution becomes more difficult because it becomes site specific, involving local factors. Examination does not show a definitive factor separating those caverns with salt falls from those without salt falls. However, it is clear that individual sites have differing propensities for development of salt falls. Certainly, Bryan Mound is the most susceptible to events, with West Hackberry somewhat less likely to experience events.

4.0 Material Related Factors and Interpretation

At this point, all of the factors initially proposed have been examined in a logical manner, except for those related to material responses. As a result of the logic, each of the examined factors have been determined to be secondary, at best, in causing cavern events. The remaining factors, all of which relate to materials and their mechanical and physical properties, must now be examined. Although we would suspect, by elimination, that material factors must be the dominant factor in both causing cavern events and salt falls, this remains to be demonstrated. This examination will be more difficult because it requires us to postulate a model of material behavior which properly explains all of the ramifications of casing damage and salt falls. While we can begin the process of postulating a model, the complete evaluation of such a model is somewhat beyond the scope of this current effort. However, we will begin the process here.

The specific material factors are creep deformation, fracture, and localized impurity composition. Clearly, all salt domes are composed principally of rock salt, or halite, which governs the long-term deformation of the dome, including its formation. The inclusion of impurities, principally in the form of anhydrite, other evaporites, second phase particles, and clay, are also ubiquitous to the domes. However, these tend to be localized conditions, with variations in impurity concentrations. They also reflect the variation evident in the layered salt "mother" deposit as deformed throughout diapir formation. Consequently, the specific parameters of the salt constitutive description may vary, as may the local concentrations and types of impurities, both among the different domes as well as within a given dome. Thus, these factors are general in the sense that they apply to all domes, but they are actually local because of the variation possible between domes and within domes.

4.1 Possible Model of the Generation of a Salt Fall

From an understanding of creep and fracture, a model can be proposed to explain many of the observed cavern phenomenon, at least qualitatively. Moreover, for material response effects it is necessary to establish some reasonable model framework as an analysis aid. Existence of the cavern in the salt mass of the dome causes the development of significant stress fields in the salt around the cavern. The salt will deform or creep under the action of cavern stress fields. Specifically, the deviatoric, or shear, component of the stress field causes the deformation. As would be expected, the deviatoric stress is also the driving force for the formation of microfractures or damage in the salt. This creep deformation leads to the cavern walls moving inward with time and to the possible growth of microfractures, which can eventually coalesce, leading to spall formation. In any cavern, the deviatoric stress magnitude is greatest at the wall of the cavern and diminishes with radial depth into the salt. Because of the nature of the stress field around a cavern, the propensity to spall is most pronounced at the wall of the cavern. Creep is a very strong function of the stress, with the steady state rate increasing as the stress to a power. Moreover, the stress at any vertical position in the cavern is also directly related to the amount of overburden or depth to that point in the cavern. As a result, the possibility of spallation can be expected to increase with depth in the cavern. Fluid pressure within the cavern decreases the magnitude of the deviatoric stress, as is the case for the SPR caverns. Typical operating conditions require additional applied fluid pressures above hydrostatic pressure which in turn decreases the magnitude of the deviatoric stress even further. In addition, a critical aspect of the fracture and spall process is the sensitivity of the generation of microfracture damage to the amount of second phase impurity particles in the salt. Thus, the tendency to form fractures and spall will depend significantly upon the impurity content of the salt in the cavern walls. Because the impurity content is very localized and known to vary from site to site and from cavern to cavern, the variation in local impurity contents may be the key to the differing salt fall propensity in the caverns. While this is presently only a supposition, it will be the principal thrust of the modeling effort.

Deformation of salt is defined by constitutive relationships of the Multimechanism Deformation (M-D) creep model [Munson, 1997b]. This creep response is a general factor in the sense that all salt exhibits this behavior. In general, the creep response is similar among the various salt domes, and the differences are readily accounted for by the material parameters of the constitutive model. Moreover, steady state creep response is relatively insensitive to second phase impurities such as small crystals of polyhalite or anhydrite or clay inclusions in the salt, as shown for clean and argillaceous salt by Munson et al. [1989]. However, the fracture behavior of salt is strongly affected by the impurity content, as shown for argillaceous salt by Chan et al. [1996].

The creep behavior of the SPR domal salts has been studied [Wawersik and Zeuch, 1984] and, while differences exist, the behaviors are quite similar. A reanalysis of original creep data [Munson, 1997c] for one of the Gulf Coast salt domes, Weeks Island, suggests a response closely related to that of the Salado Formation (although this is bedded, rather than domal salt). This may apply, with some exceptions, to the salts of the SPR domes and a number of other non-SPR sites.

Fracture response of salt is such that deformation under certain conditions of confining pressure and deviatoric stress leads to accumulation of microfracture damage and results in tertiary creep through the relationships of the Multimechanism Deformation Coupled Fracture (MDCF) model [Chan et al., 1991, 1995]. Eventually, fracture of the salt occurs. In the walls of any cylindrical cavity such as a cavern, the stress conditions exist for the possible accumulation of damage and the development of spalls. Again, whether or not damage accumulates for any given stress condition, also depends upon the second phase impurities in the salt. Relatively small amounts of second phase particles or small voids enhance the fracture process [Chan et al., 1996].

In the domal salts of the SPR sites, the impurities are not of a single type but potentially of many different types. Impurities can be in the form of anhydrite or polyhalite second phase grains within the halite, stringers or particles, such as remnants of interbeds of anhydrite, polyhalite, sylvite, and clay, and potential incorporation of clays, shales, limestone, and other overburden particles in shear zones between spines. Occluded gas impurities are also present in certain locations. Although quantification of the amount and precise locations of the impurities is quite difficult and in the SPR caverns their locations are generally not quantified, there is considerable direct evidence of such impurities. However, in the constitutive model for fracture, and hence for the development of salt falls, the composition of the impurity is unimportant. This is because the model agent that enhances fracture is the inclusion cavity and not the inclusion. The inclusion cavity modifies the local stress field to facilitate microfracture formation in the adjacent salt. As a result, any of the solid inclusions produce the same effect. For a gaseous inclusion, the response may be somewhat altered. There is in this case the possibility that the gas pressure in the inclusion cavity further aids in the formation of microfractures in the salt, so that the spallation process may be accelerated. The model potentially explains the differences in the various caverns which exhibit salt falls, and the potential association with impurity content and gaseous caverns.

We need to determine if possible, two aspects of cavern character or behavior based on existing operational data. First, it may be possible to evaluate the inclusion content of the dissolved salt of a cavern through determination of the quantities of undissolvable material in the cavern sump, with the sump dimensions determined from sonar surveys. The question is whether the accuracy of such a determination is adequate to make relative evaluations of the caverns. Second, it may be possible to evaluate salt falls quantitatively by determining the accumulation of material falling in the caverns from routinely collected wireline measurements of the rise in floor level with time.

4.2 Analysis of Available Cavern Data for Insoluble Inclusion Content

An attempt to differentiate between caverns with high concentrations of impurities and those with low concentration of impurities has been made primarily for the caverns of Bryan Mound [Magorian and Neal, 1985], as summarized in Figure 5. In some cases, the insolubles were determined from recovered core and in other cases from peripheral evidence of gas generation and brine pond contents. Although some quantification of impurity content occurred at Bryan Mound, determination of salt and impurity material characteristics did not receive high priority in the development of any of the storage sites. This was to be expected because these characteristics play only a very minor role in the operational location and solutioning of caverns. However, anecdotal evidence suggests that the other SPR sites contained less insolubles and impurities than the Bryan Mound site. Recent degassing efforts also indicate that Bryan Mound has a number of gassy caverns (see Table 1) with Cavern 112 considered the most affected. West Hackberry and Big Hill also have gassy caverns, but perhaps not to the extent of Bryan Mound.

It was decided as a part of this current study to examine available sonar survey and operating data from the sites, especially Bryan Mound, and to evaluate, if possible, relative impurity contents of the dissolved salt mass through estimates of the amount of insolubles remaining in the cavern sump. In a preliminary attempt to evaluate the insoluble content, the sump volume was determined by taking the sump profile given in the completion reports as a volume of revolution about a vertical axis. The sump volume was then normalized by the cavern volume based on sonar survey determinations, to give a percentage of insolubles in the dissolved salt. Sump shapes were not available for all of the caverns, possibly because of insufficient early sonar data. Because the sump volume represents porous material, it was assumed that the solids constituted 55% of the volume, as is often the case for untamped particles. Table 6 shows the insolubles estimates to be between 1.0 and 5.5%. These values appear within the bounds of known insoluble contents and seem reasonable. Unfortunately, the sump volumes could be markedly overestimated because the construction report shapes are assumed to be flat bottom rather than conical. The conical shape occurs because sump development started by solutioning at the bottom of individual wells, raising the solutioning raw water string as the well bottom accumulated insolubles. As a consequence, the configuration details of the bottom part of the sumps are difficult to determine and are probably much different than the construction reports suggest. Consequently, there

Table 6. Estimates of Insoluble Volumes - Bryan Mound.

Cavern No.	Year (as of) Sol.	Fill	Oper.	Bot.Dia. ft	Sump Geometry* all ft	Cav.Vol. ft^3x10^6	Insol.Vol. ft^3x10^6	Insol.Conc. vol.%
BM 101	82	84	96	200	200x172+1/3x200x86	63.195	6.304	5.5
BM 102	80	84	96	95	95x200	79.670	1.417	1.0
BM 103	82	84	96	170	170x232+90x70	63.741	5.711	4.9
BM 104	80	83	96	160	160x?	Insufficient completion data		
BM 105	80	83	96	240	240x182+1/2x240x91	64.090	6.175	5.3
BM 106	80	83	96	130	130x?	Insufficient completion data		
BM 107	80	83	96	180	180x?	Insufficient completion data		
BM 108	80	85	96	200	200x152	63.013	4.775	4.2
BM 109	80	83	96	260	260x?	Insufficient completion data		
BM 110	80	82	96	90	90x40+170x50	?	1.389	?
BM 111	83	84	96	160	160x127+120x120	63.197	3.910	3.4
BM 112	80	85	96	200	200x104+60x104	62.202	3.561	3.2
BM 113	84	86	96	180	180x?	Insufficient completion data		
BM 114	84	87	96	170	170x?	Insufficient completion data		
BM 115	84	86	96	150	150x?	Insufficient completion data		
BM 116	84	86	96	No completion reports found		Insufficient completion data		

* From the sketches of cavern shape in the completion reports and assuming cylindrical geometry.

appears to be a large degree of uncertainty in the results due to the assumptions made in the calculations. Eventually, solutioning was sufficient in some cases for individual wells to coalesce to form a single, larger diameter sump. Even the coalesced sump should not be cylindrical. At this point, sufficient early sonar survey data of the individual well solutioning have not been examined to permit a better evaluation of the sump volume. In fact, such data may not be available. With such large uncertainty, it is clear on evaluation that the current results given in Table 6 cannot be accurate enough to properly order the caverns according to insoluble content. In fact, no trend could be observed between the calculated insoluble impurity content and the propensity for casing damage and loss.

4.3 Estimation of Quantity of Salt Fall Material from Cavern Data

The operational data from the caverns permits us to make estimates of the volume of material that collects on the cavern floor. The assumption, which is reasonable if the cavern is not undergoing dissolution, is that the accumulation of material is from salt falls from the cavern surfaces. As a part of any normal wireline survey of a well, the tool is allowed to touch (tag) the apparent bottom of the cavern. From this information the apparent depth of the cavern is obtained. The history of the measured depths may be a direct indication of the build up of material on the cavern floor. With knowledge of the floor diameter, it is possible to calculate the volume accumulation rate. From such estimates, judgments can be made about which caverns are the most likely to have hanging string events. Table 7 summarizes the relative rate of accumulation of material for Bryan Mound caverns (except for Cavern 116 which has no completion report). In the table, the caverns have been arranged in decreasing order of the accumulation volume per year. In order to obtain the equivalent salt fall volume, a particle packing percentage of 55% and a salt density of 134 lb/ft^3 have been assumed. Cavern 112 has averaged 9,840 tons of salt falls per year while Cavern 102 produced only 78 tons per year over the same time frame.

Uncertainty in these evaluations result primarily from experimental errors in determining the change of floor location with time and the assumptions necessary for calculating the area of the cavern floor. Even though the estimates of accumulation amounts suffer from this uncertainty, they are presumably more accurate than the estimates of insolubles given previously. This is a

Table 7. Order of Caverns by Salt Accumulation Volumes and Equivalent Event Rates.

Cavern	Dia.Bot.	Dura.	Accum.	Fall Vol.	No. Events		Remarks	ECNF	
No.	ft	yrs	ft/yr	tons/yr	Tot.	Wells		Tot.	Well
BM 112	200	11	8.5	9840	5	5A	A4142’	5	5A
BM 109*	260	13	3.6*B	7043	7	3A,3B,1C	C(S),A3865’,B4267’	3	3B
BM 103	170	12	6.0	5018	5	5C	C4132’	5	5C
BM 106*	130	13	10.1	4939	11	5A,6C	A3990’,C3452’	6	6C
BM 107	180	13	3.0*C	2813	9	5A,1B,3C	A4088’,C2874’	5	5A
BM 113	180	10	2.3	2157	2	2B	B4218’	2	2B
BM 114	170	9	2.0	1672	0		B4164’	0	
BM 105	240	13	0.5	833	0		B3754’,C4179’	0	
BM 111	160	12	1.0	714	1	1B	B4131’	1	1B
BM 101	200	12	0.6	695	2	1A,1C	C(S),A4136’,C4118’	1	1A
BM 110	90	14	2.4*A	563	0		A4104’,B4092	0	
BM 108	200	11	0.4	463	4	2A,2B	A&B(S),A4120’,B3353’	1	1A
BM 115	150	10	0.7	456	0		B4093’	0	
BM 104	160	13	0.2	148	0		A3103’,B4173’	0	
BM 102*	95	12	0.3	78	2	2B	B(S),B4118’	1	
BM 116	?	10	2.0		2	2B	B4239’	2	2B

In those caverns marked *, only one of the wireline depths changed with time, perhaps indicating that cavern bottoms at the other well(s) were blocked by other debris in some manner.

Cavern 116 has no completion report or sonar survey, so the bottom configuration is unknown.

Under Remarks, the S in parenthesis indicates that the recorded event or string failure was during the solutioning phases of the cavern construction.

The Equivalent Corrected Number of Falls (ECNF) are based on the total number of falls in a cavern, less the number of falls that occurred during the solutioning phase, and then adjusted for the number of hanging strings in the cavern. The underlined well number is the representative well of the multiple well cavern.

result of the better definition of the cavern floor size through the final sonar survey at the end of solutioning and the relatively accurate wireline tagging data. However, even with the better floor dimension definition, several dimensions still appear relatively small, especially in Caverns 106, 110, and 102. Moreover, all of the data are not straightforward. In some wells of a given cavern, the wireline tagging data show no change in depth with time even though the other wells of the cavern showed an accumulation. For these cases, it is assumed that something prevents the wireline from touching the true salt accumulation surface. In these cases, as noted in Table 7, the well that showed accumulation with time was used for the calculations. All of the caverns that showed this anomalous behavior between wells had geometric changes in cross sections with separate chambers for individual wells, and often are the caverns with the greatest amount of lost hanging string pipe. As an exception, BM 110 has some unusual cross sections at the bottom of the cavern, but has no lost pipe.

In any case, we now have a more complete picture of events in a cavern. Even allowing for significant uncertainty, there appears to be a continuous accumulation of falling material, with some caverns apparently producing rather large amounts. The calculated range of the amount of salt is from 9,840 tons/year in Cavern 112 to 78 tons/year in Cavern 102. Because the amount is so large compared to the number of hanging string failures, it also appears that very little of this falling material impacts hanging strings, or that most of the material is small enough to do little damage. However, some of the falling material is apparently in larger spall pieces which can produce significant damage. Here, the damage probability is related to the amount of salt fall material. Those caverns with the greatest number of hanging string events also have the greatest values, but the relationship between accumulation and hanging string events is not one-to-one.

4.4 Corrections and Equivalent Events with Multiple Strings

In Table 7, one of the obvious corrections is to eliminate those events that occurred prior to the completion of the caverns, i.e., during solutioning and prior to oil filled operation of the caverns. This seems appropriate because of the possible rapid and marked transitions in cavern shape and the potential of falling splines and solution wedges. Several events were identified as taking place during the solutioning phases, as denoted by the B in the “Comments” column of Tables 1 through 4. These events were simply subtracted from the total events to give a corrected number of events during quiescent cavern operation.

Multiple hanging strings occur in several of the caverns, as noted previously. In general, the number of hanging strings in a given cavern is an operational choice and not fundamental to the question of salt falls. These strings may be long, extending to near the bottom of the cavern, or of intermediate length. If the amount of salt fall material is uniform over the cavern cross-section, then each long string has the same probability of being impacted. Thus, a cavern with two equally long hanging strings should experience twice as many hanging string events as it would if it contained only one hanging string. In fact, the number of events should be just multiples of the number of long strings in the cavern. Since the number of impacts is a function of the length of hanging pipe, intermediate length strings would have the potential for a fewer number of impacts.

In order to obtain a correct evaluation of the number of events in a specific cavern, the number of events must be normalized to account for multiple hanging strings. The normalization goal is to obtain an equivalent of one string per cavern, and the most probable number of events associated with that string. The longest string should have the greatest number of events, which is confirmed by the results of Table 7. Our choice is quite simple. Normalization here assumes that the longest string with the greatest number of events correctly estimates the likelihood of a string being damaged in the flux stream of that specific cavern. The equivalent well string selected is noted by underlining it in the last column of the table.

Using the equivalent, corrected number of events as given in Table 7, it is apparent from the ordering of the caverns according to the amount of salt fall accumulation per year that the highest number of equivalent events occur in caverns with the greatest amount of salt fall accumulations. A note of caution is necessary here. Because of the uncertainty in defining the salt fall quantity, the order shown could be slightly modified if more accurate salt accumulation data were available. Never-the-less, it is believed that we have established a significant relationship between salt accumulation and hanging string events.

For a uniform distribution of flux over the cavern cross-section, a single, long, hanging string in a cavern will have a certain probability of being damaged, depending upon the magnitude of the flux and the spall size distribution in the flux. The probability in this case does not depend upon the location of the hanging string in the salt fall stream. However, if the stream is not uniform, but is concentrated along the walls of the cavern, then proximity of the string to the wall will increase the probability of damage. A preliminary effort was made to determine the closest approach of hanging strings to the cavern walls. As could be expected, this is not a simple task because of the quantity and variation in sonar survey data. In some caverns, the sonar survey data was not taken in all of the wells, which leaves the geometry picture incomplete. A separate study is now in progress to obtain three-dimensional plots of cavern shapes using sophisticated plotting packages, which may aid in the current evaluation.

5.0 Preliminary Model Simulations of Cavern Fracture

A preliminary simulation of an idealized cavern condition [Chan et al., 1996] has been possible using the Multimechanism Deformation Coupled Fracture model of salt behavior. This model predicts the time dependent evolution of microfracture damage in the salt around the cavern. The amount of microfracture damage can be related to failure of the salt. Continued evolution of the microfracture damage eventually leads to discrete cracks and spallation.

In this simulation, a 200 foot diameter cavern, 2000 foot high, with a 2000 foot overburden depth was modeled. An axisymmetric finite element calculation was performed with the SPECTROM-32 code [Callahan, et al., 1989]. In the calculation, the mesh was a thin, “pineapple slice” obtained under the assumption of axisymmetric symmetry. The slice was located at an equivalent depth of 4000 ft, with a far-field boundary located at a distance of 10,000 ft. Cavern construction was handled in the simulation by excavation of the cavern material instantaneously at time zero. Fluid pressure in the cavern was approximated by placing equivalent overburden and fluid pressure forces on the appropriate mesh surfaces. Fluid pressure was assumed to be the hydrostatic pressure of brine at the depth of the simulation mesh, this is equivalent to assuming that the fluid filled cavern was depressurized. Model parameters were those developed for argillaceous salt from the Salado Formation by Munson et al. [1989] and Chan et al. [1993]. The Salado Formation salt is a bedded salt which in the argillaceous form contains small clay particle inclusions. In the calculations, it was assumed that the equivalent impurity content of the domal salt was 2.9%., which is about the average clay content of the argillaceous samples used in determining the model parameters. The simulation was carried out to a time of 10 years, nearly equivalent to the current operating period of the actual caverns.

Figure 6 shows the results of this very simplistic simulation. Damage is maximum at the cavern surface and decreases with distance into the salt. Here, distances are given in terms of multiples of cavern radii. The results indicate that the micromechanical damage extends well into the salt surrounding the cavern, to about a distance of 45 ft. Damage also increases with time, as would be expected. However, the damage levels attained in this simulation are quite low, with a maximum at the cavern surface at 10 yrs of 0.00032. This level can be compared to a the level of 0.15 normally associated with failure. Such low levels of damage are not unexpected. They arise because of the very stable cylindrical cavern configuration assumed in the simulation. It is unlikely that perfect cylindrical configurations actually exist in the caverns. In fact it is more likely that local geometric irregularities occur which can cause stress concentrations, and hence increased damage. These local areas would then be the source of spalls and salt falls. Idealized forms of the local geometric perturbations can be modeled and additional modeling efforts are planned to explore their influence.

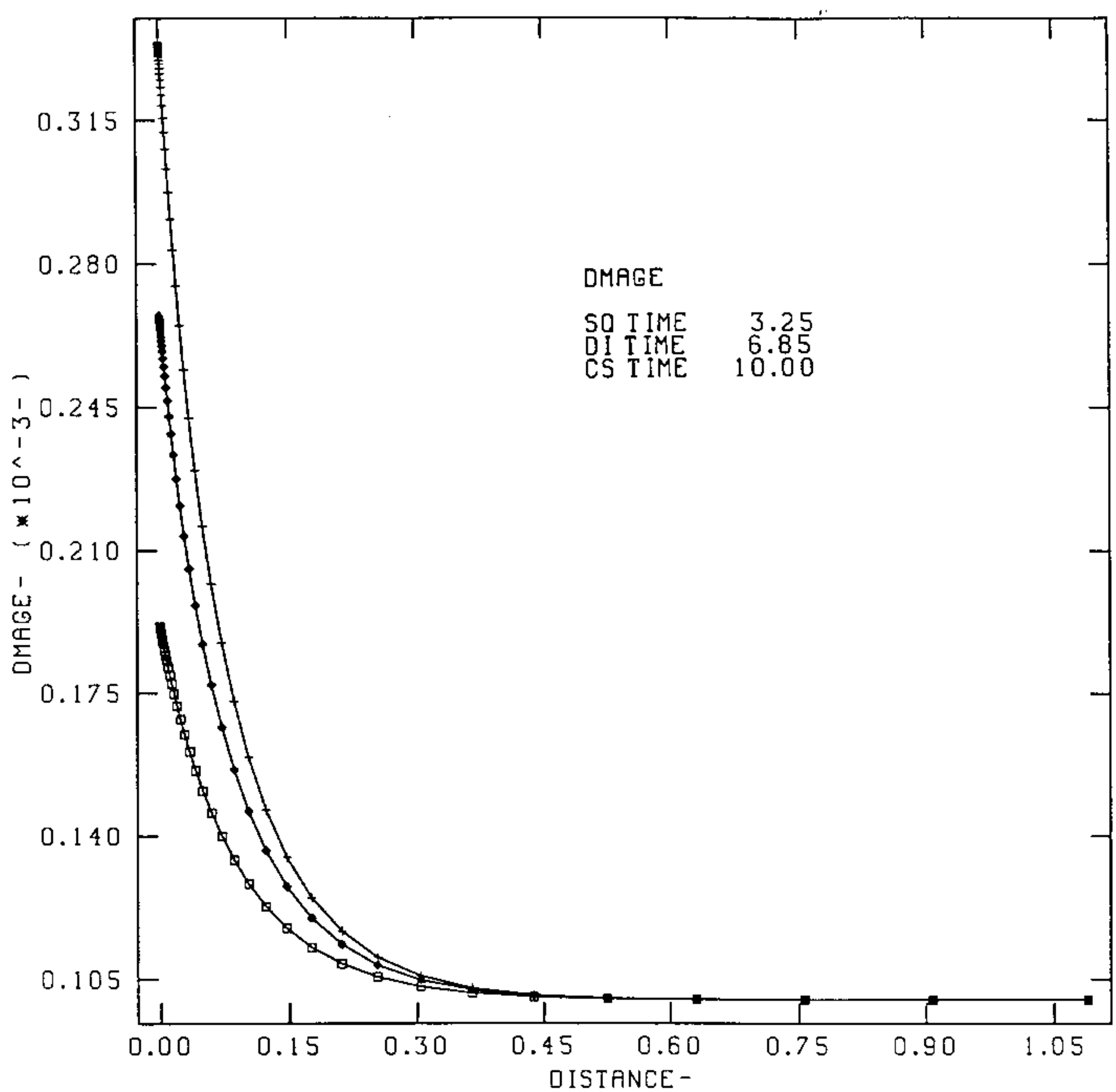

Figure 6. Calculated Damage at Bottom (4000 ft) of Perfectly Cylindrical Cavern.

6.0 Summary and Preliminary Suggestions

We have updated and compiled the Strategic Petroleum Reserve caverns hanging string damage and failure events and presented a study of potential factors influencing salt falls. As a result of this study, a summary with preliminary suggestions is presented as follows:

1. The major factors that have been identified that may contribute to processes resulting in the damage of casing and hanging string failures are: anomalous zones in the salt dome, crude type, leaching method (1, 2, or 3 wells, and/or fill while leaching), operating procedures or depressurization, cavern details (location in dome, depth, and geometry), and material properties (creep and fracture).
2. Based on a logical evaluation of these factors, it appears that all major factors *except* the material properties can be described as secondary, not primary, causes of cavern events.
3. It is then postulated that the propensity for a cavern to experience casing damage and salt falls may be related primarily to the presence of localized impurities in the salt, including insoluble materials and gas inclusions.
4. A constitutive model of salt behavior which describes both creep and fracture, in the presence of inclusions, could appreciably aid in a description and analysis of the general process.
5. If the model is accurate, it suggests that suppression or mitigation of salt falls requires that the operating pressures remain high and depressurization cycles in a cavern be minimized.
6. It is possible to estimate from operational data the accumulation rate (in ft/yr) of falling salt material in a cavern, and this accumulation correlates reasonably well with the number of observed hanging string events.
7. In some caverns, the salt fall accumulation volume is extremely large, approaching 10,000 tons/year.
8. Multiple hanging strings in a cavern, with a uniform flux, can be expected to experience a greater number of hanging string events than the same cavern with only one hanging string. Thus, efforts to minimize the number of hanging strings would result in workover cost savings.
9. Location of the hanging string events can be made with respect to the cavern oil/brine interface. This potentially would permit a shortening of the strings to remove them from danger, or, in other cases, the current excess storage capacity could permit adjustment of the oil storage volume in a given cavern and a shortening of the strings to remove them from danger.
10. Preliminary fracture analysis was made using the Multimechanism Deformation Coupled Fracture model of salt behavior, for a 2000 foot-high cylindrical cavern, with a 2000 foot overburden depth, and filled with brine, but not pressurized. The analysis showed that little microfracture damage occurs for these highly symmetrical conditions even at the bottom of the cavern (most severe conditions) at 10 years.
11. 11. Additional studies are in progress to more carefully examine the impurity calculations and the details of salt spalls. Also studies will continue to examine the effect of geometric irregularities on the propensity to cause damage.

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