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MEETING PAPER

TRANSIENT ANALYSIS FOR THE MULTIMECHANISM-DEFORMATION PARAMETERS OF SEVERAL DOMAL SALTS

by

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ABSTRACT

Use of Gulf Coast salt domes for construction of very large storage caverns by solution mining has grown significantly in the last several decades. In fact, a nationally important Strategic Petroleum Reserve (SPR) storage occurs in large cavern arrays in some of these domes. Although caverns have been operated economically for these many years, these caverns have a range of relatively poorly understood behaviors, involving creep closure fluid loss and damage from salt falls. It is certainly possible to postulate that many of these behaviors stem from geomechanical or deformational aspects of the salt response. As a result, a method of correlating the cavern response to mechanical creep behavior as determined in the laboratory could be of considerable importance. Recently, detailed study of the creep response of domal salts has cast some insight into the influence of different salt origins on cavern behavior. The study used a simple graphical analysis of the limited non-steady state data to give a bound, or an approach to steady state, as an estimate of the steady state behavior of a given domal salt. This permitted the analysis of sparse creep databases for domal salts. It appears that a shortcoming of the steady state analysis was in masking some of the salt material differences. In an attempt to overcome the steady state analysis shortcomings, a method was developed based on the integration of the Multimechanism-Deformation (M-D) creep constitutive model to fit the transient response. This integration process essentially permits definition of the material sensitive parameters of the model, while those parameters that are either constants or material insensitive parameters are fixed independently. The transient analysis method has proven more sensitive to differences in the creep characteristics and has provided a way of defining different behaviors within a given dome. Creep characteristics, as defined by the transient analysis of the creep rate, are related quantitatively to the volume loss creep rate of the caverns. This type of understanding of the domal material creep response already has pointed to the possibility of establishing various distinct material spines within a given dome. Furthermore, if the creep databases for domal salts can be expanded, one could expect additional definition of domal geology and structure.

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INTRODUCTION

Often in solution mined salt cavern construction projects, because of both financial and time constraints, geotechnical data availability may be quite limited. As a consequence, it is essential that the use of these limited data be optimized. Such an optimization of data analysis has proven possible in the mechanical creep behavior of salt domes where the construction of massive storage caverns is relatively common. To some extent, the knowledge provided by the data analysis is retrospective since the domal salt site acquisition and cavern construction normally begins prior to any possible availability of geomechanical testing specimens. However, extant collections of data from a given dome or domal site could be instructive in future cavern site acquisition and construction. Moreover, even post construction knowledge of domal salt response may prove beneficial to the understanding of differences in cavern behavior and operation characteristics.

A basis for the steady state analysis of sparse creep databases was established in an earlier work [Munson, 1998]. This analysis was aimed at determination of the steady state creep rate from limited amounts of creep data. Fundamentally, the common framework for behavior of salt is the micromechanical mechanisms controlling creep deformation. This framework alone, in fact, governs the functional form of the constitutive equations of creep. A constitutive model that formalizes this behavior is the Multimechanism-Deformation (M-D) model proposed by Munson and Dawson [1982] and Munson et al. [1989]. Within this framework, the only differentiation permitted among salt materials is in the values of just a few of the important parameters of the model. All other parameters of the model are either physically determined constants or material insensitive values. Because one of the important material parameters is the steady state creep rate, this parameter was the first to be studied. The functional form of the model was used by Munson [1998] to suggest that any set of creep rates obtained from testing of a given uniform material will determine a bound that approaches the steady state rate. This bound is independent of the type of creep test, either conventional or incremental, and depends only on the specimen material. A conventional creep test is one performed at a constant stress and temperature; whereas, an incremental test consists of creep over several distinct time intervals, each separated by step-wise changes in either stress or temperature, all on the same specimen. The database of creep results used to determine the bound cannot, however, include incremental stress drop data; these increments must be ignored. Using this rule, it was possible to determine the steady state bounds for seven domal salts where creep results were available [Munson, 1998]. A marked difference was found between the creep rates of the salt of the various domes. In fact, two distinct types of salt creep behaviors were identified: creep resistant (hard) salt and less creep resistant (soft) salt. The steady state rate of the soft salt appeared to be some eight times greater than the hard salt. While this alone is an extremely interesting result, it was made more so through a comparison to a quantification of cavern volume loss based on field data.

Cavern closure rates were determined for the caverns of the Strategic Petroleum Reserve (SPR) based on field data accumulated over nearly a decade of operation. Creep closure is responsible for a gradual cavern pressure increase with time. The relatively quiescent caverns of the SPR are routinely monitored for pressure build-up, and periodically bled-down as necessary to maintain the proper operating pressure range. Technology, in the form of a numerical program called CAVEMAN, was developed from the M-D model to obtain best fits to historical data of operational pressure variations and to separate expected pressure build-up response from abnormal cavern pressure behavior [Ehgartner, 1995]. The technology determines four cavern related material, shape, and stress parameters, which can then be used to extrapolate an expected future cavern pressure response. Because the pressure build-up is directly related to volume closure of the cavern, effective cavern creep rates can be obtained. When results of the independent steady state analysis of the SPR sites were compared to the CAVEMAN cavern creep rates, it was clear in most cases that at least a crude correlation existed between the steady states rates determined in the laboratory and the cavern creep rates. However, the comparison also highlighted discrepancies that uncovered defects in the steady state analysis method. Specifically, if one of the caverns, or actually one of the wells of a cavern, has a salt with a very low steady state rate, it can mask those caverns or wells with a less resistant salt. These analysis defects can be corrected, in part, through a more extensive analysis procedure involving integration of both the transient and steady state portions model to fit the creep data [Munson, 1999]. For simplicity this will be called a transient analysis.

The purpose of this work to present the methodology for transient analysis of salt creep databases, to utilize the analysis for the domal salts, and to compare the results to cavern creep rates. We begin by developing the transient analysis framework based on the Multimechanism-Deformation (M-D) model of creep [Munson and Dawson, 1982; Munson et al., 1989; Munson, 1997]. This is followed by the procedure used to integrate the model and the scheme for the actual analysis. Then, results of the transient analysis are given, together with fits to multi-increment creep curves of the relevant databases. Implications are discussed of the manner in which the values of the parameters change with stress and temperature. After discussions of the comparison to the cavern creep closure results and geological implications, some final remarks summarize the work.

MULTIMECHANISM-DEFORMATION MODEL

To visualize the concepts of transient analysis, it is beneficial to begin with a schematic of a raw conventional creep curve, as shown in Figure 1. This creep curve would result from a creep test in which a specimen is held at constant stress and temperature, and the creep strain recorded as a function of time. Typically, at the time of stress loading, strain is rezeroed to eliminate the loading strain. As the schematic illustrates, the total creep strain can be decomposed into the steady state strain, ε_s, and the transient strain, ε_t, components. As indicated, the steady state strain grows at a constant rate. However, the evolutionary process controlling the transient strain during primary creep causes a diminishing rate with continued straining, which eventually saturates at some maximum value given by the transient strain limit, ε^*_t. Thereafter, further strain accumulates only at the steady state creep rate. Often, and for various reasons, usually cost, creep tests are terminated in the primary stage of creep, well before the development of steady state creep. Fortunately, the steady state creep contribution is unique to a given creep curve, as is the transient contribution. This uniqueness makes the fitting, even of abbreviated portions of the primary transient, possible, although not entirely easy.

Even though the above description is sufficient to properly visualize the transient analysis method, some additional information is necessary to interpret the more complicated incremental creep tests. If one were to plot the time differential (instantaneous strain rate) of a conventional creep curve of Figure 1 against the amount of transient strain, ε_t (here in terms of the internal state parameter, ζ) one of the curves of Figure 2 would result. In Figure 2, several curves, each at constant stress, of the family of such curves are shown. Incremental creep tests impose different stress loading and temperature conditions for various time intervals successively on the same specimen. Here, each increment may have transient behavior that the model accounts for through the evolution of the state parameter. A hypothetical incremental test is illustrated in Figure 2, where specimen history follows the appropriate curve for the initial stress, σ_1, and temperature, T_1, with the strain rate decreasing with increasing state parameter magnitude. An abrupt change in stress causes the material to move, with a constant state parameter magnitude, to another curve

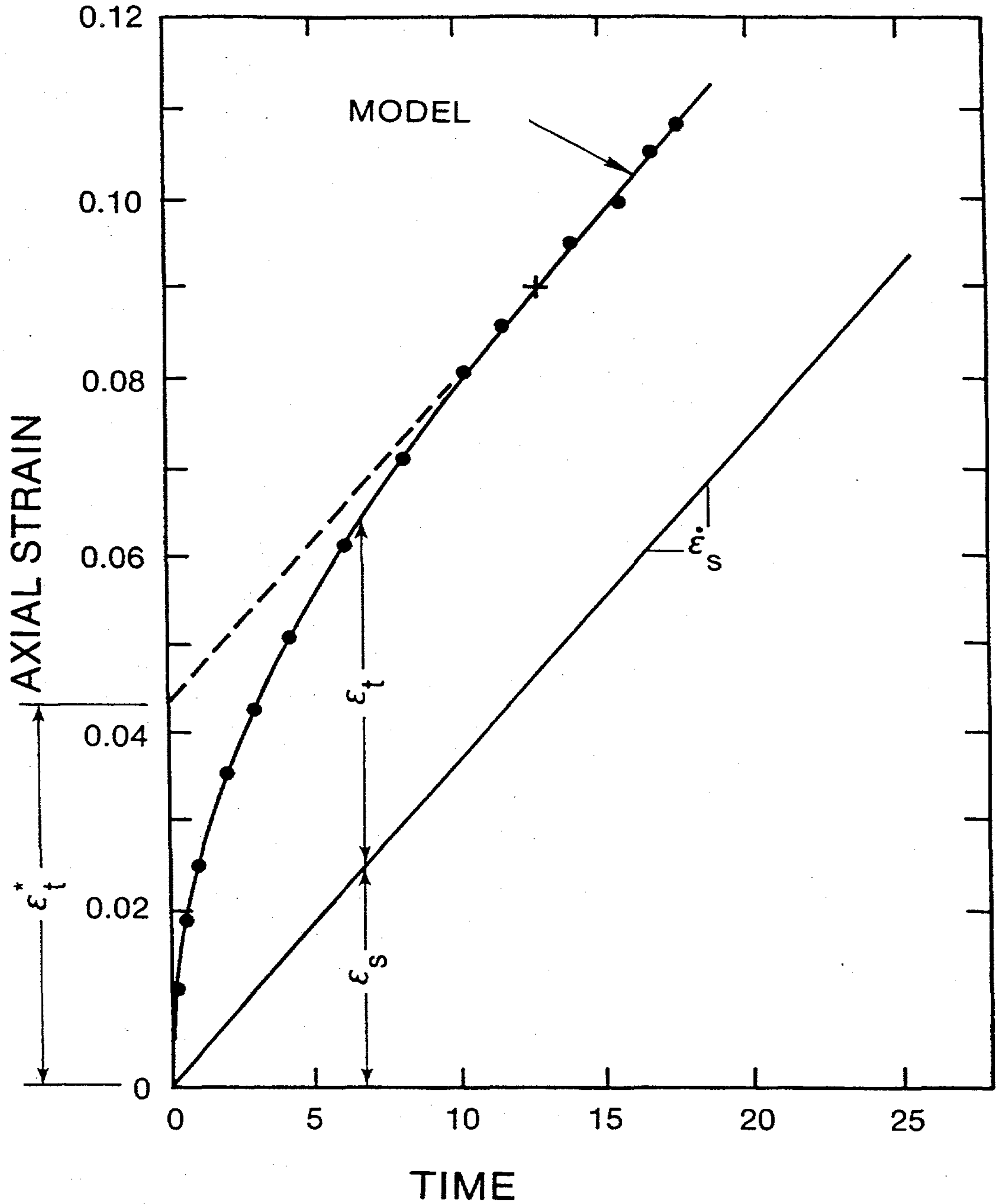

Figure 1. Artificial Separation into Steady State and Transient Creep Components.

appropriate to the new stress. Again the strain rate moves along this curve until another change in conditions occurs. For strain rate states above steady state (ordinate axis), the material is workhardening (increasing state parameter values). For states below the steady state, the material is in recovery (decreasing state parameter values). A feature in the model is the introduction of an internal state parameter related to the changes in the internal defect structure. The state parameter always moves toward the steady state condition, which occurs when the state parameter, ζ, is equal to ε^*_t. The rate of change is related to higher order kinetic equations. We have now defined the three fundamental features of a creep curve that must be described if a curve is to be fitted: (1) the steady state creep rate, (2) the transient strain limit, and (3) the workhardening or recovery time rate of change (curvature). The analysis method that we will use

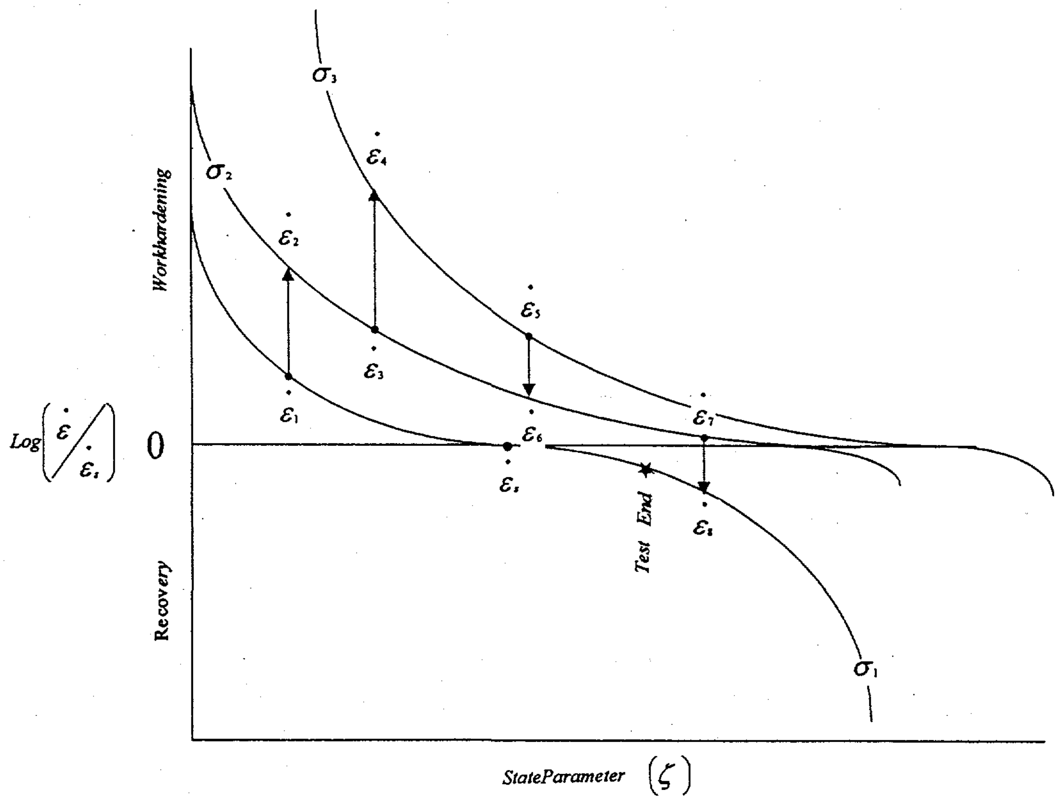

Figure 2. Transient Curves Showing Incremental Test Path [Munson and Dawson, 1982].

in this work is based on an exact fitting of conventional and incremental transient creep curves. Such analysis is necessitated by the very limited amount of data available for any one material. In fact, the analysis method makes use of essentially all the points along the entire single creep curve to define the parameters. In contrast, the conventional manner analysis method is to use a much larger database to determine the parameters by compiling multiple values of the parameters from many specimens to determine not only the appropriate value but also the uncertainty. The difference in the two methods is that the both the material and testing uncertainty cannot be seen in the transient analysis because it inherently involves only one specimen. As a consequence, it must be understood that the transient analysis of sparse databases carries a potentially large risk of uncertainty.

With the general concept in mind, we can now develop the mathematical descriptions that make up the M-D constitutive model [Munson, 1997] of salt creep. Through these mathematical equations, it is possible to define all of the necessary material parameters. However, as with any constitutive model, there are some restrictions that define the ranges over which the model is accurate. In developing the constitutive description, we concerned ourselves only with the temperature and stress ranges encountered in mining and storage cavern operations, typically these are low temperature and low to moderately high stresses. For these conditions, creep is envisioned as arising from contributions of three appropriate micromechanical mechanisms as determined from the deformation mechanism-map [Munson, 1979]. These mechanisms are (1) a dislocation climb controlled creep mechanism at moderate temperatures and low stresses, (2) an empirically specified but undefined mechanism at low temperatures and low stresses, and (3) a dislocation slip controlled mechanism at high stresses [Munson et al., 1989]. Each of these mechanisms is thermally activated, which defines the form of the temperature dependence. The respective steady state creep rates for the three individual mechanisms are given by:

$$\dot{\varepsilon}_{s_1} = A_1 e^{\frac{-Q_1}{RT}} \left(\frac{\sigma}{\mu(1-\omega)} \right)^{n_1}$$

$$\dot{\varepsilon}_{s_2} = A_2 e^{\frac{-Q_2}{RT}} \left(\frac{\sigma}{\mu(1-\omega)} \right)^{n_2} \qquad 1$$

$$\dot{\varepsilon}_{s_3} = \left| H(\sigma - \sigma_0) \right| \left(B_1 e^{\frac{-Q_1}{RT}} + B_2 e^{\frac{-Q_2}{RT}} \right) \sinh \left[\frac{q\left(\frac{\sigma}{1-\omega} - \sigma_0 \right)}{\mu} \right]$$

where the numerical subscripts refer to the appropriate mechanism, the A's and B's are structure factors, Q's are activation energies, R is the universal gas constant, T is the absolute temperature, μ is the shear modulus, q is the stress constant, σ_0 is a stress limit, and H is a Heaviside step function with argument ($\sigma - \sigma_0$). It has been shown [Munson, et al., 1989] through multiaxial experiments that the proper flow law, or equivalent stress measure, is $\sigma = |\sigma_I - \sigma_3|$, expressed in terms of principal stresses. The structure factors are the fitting parameters of interest.

These mechanisms act in parallel, which means the individual steady state creep rates can be summed over the three mechanisms to give the total steady state creep rate, as follows:

$$\dot{\varepsilon}_{s} = \sum_{i=1}^{3} \dot{\varepsilon}_{s_i} \qquad 2$$

The equivalent total strain rate is treated through a multiplier, F, on the steady state rate, given by

$$\dot{\varepsilon}_{eq} = F \dot{\varepsilon}_{s} \qquad 3$$

The three branches of F, representing workhardening, steady state, and recovery, respectively, are as follows:

$$F = \begin{cases} e^{\Delta\left(\left(1 - \frac{\zeta}{\varepsilon_t^*}\right)^2\right)} & ; \zeta < \varepsilon_t^* \\ 1 & ; \zeta = \varepsilon_t^* \\ e^{-\delta\left(\left(1 - \frac{\zeta}{\varepsilon_t^*}\right)^2\right)} & ; \zeta > \varepsilon_t^* \end{cases} \qquad 4$$

Here, Δ is the workhardening parameter, δ is the recovery parameter, ζ is the state parameter, and ε^*_t is the transient strain limit. It is important to note that Equation 4 defines the curvature as well as the strain magnitude of the transients in the creep curve. The strain magnitude is determined by ε^*_t, and the curvature is defined by Δ or δ, depending upon whether the transient is workhardening or recovering.

The kinetic equation for the state parameter is given by

$$\dot{\zeta} = (F-1)\dot{\varepsilon}_s \tag{5}$$

The transient strain limit is defined by

$$\varepsilon^*_t = K_0 e^{cT}\left(\frac{\sigma}{\mu(1-\omega)}\right)^m \tag{6}$$

where K_0 and c are constants and m is a material constant. In terms of the transient analysis, the fitting parameter of interest is K_0.

The workhardening, Δ, and recovery, δ, parameters are described through linear functions, as follows:

$$\begin{aligned} \Delta &= \alpha_w + \beta_w \log\left(\frac{\sigma}{\mu(1-\omega)}\right) \\ \delta &= \alpha_r + \beta_r \log\left(\frac{\sigma}{\mu(1-\omega)}\right) \end{aligned} \tag{7}$$

where the α's and β's are constants. Although for our purposes here it is taken as zero throughout these equations, ω is the damage parameter. Here, we see the fitting parameter for the curvature of the creep curve is either α_w or α_r. However, because the recovery parameter is not used in the fitting process here, but is taken as a constant, we may simplify the fitting parameter to just α_w.

The earlier work, Munson [1998] discussed the implications of a model based on micromechanical mechanisms. All total, there are 17 parameters to be evaluated, not counting the damage parameter and the elastic constants. Fundamentally, salt creep behavior has common micromechanical constitutive features regardless of the origin of the salt, all that differs is the exact value of the parameters. In particular, those critical parameters that primarily distinguish one salt material from another are the steady state responses as represented by the structure factors (A's and B's) and the transient strain rate limits (ε^*_t) as represented by K_0. And, Δ, which represents the curvature of the workhardening process as represented by α (a permitted simplification of α_w), may also be material sensitive.

As noted previously, the remaining M-D model parameters are either independent of the exact salt material being considered or are insensitive to material variations. This results from the fact that many of these parameters are related to the salt physical properties and processes at an atomic level. This is true of the micromechanical mechanisms of self-diffusion controlled dislocation climb and dislocation interactions during slip. The activation energies, Q, are related to atomic diffusion processes and, therefore, are not physically sensitive to the origin of the various salt materials. Similarly, the stress exponents, n, are also related to local atomic processes and are insensitive to different salt materials. As a result, the same precise values of Q's and n's that were determined for Waste Isolation Pilot Plant (WIPP) clean salt [Munson et al., 1989] will be used for the domal salts. Values of the stress limit, σ_0, and the stress constant, q, are not, in general, sensitive to the salt material. As a consequence, the values of these parameters, σ_0 and q, from the WIPP clean salt will also be used for the domal salts. The value of m is a theoretical constant, independent of material. The non-critical value of c is related to an activation process and is assumed to remain unchanged with different materials.

ANALYSIS METHODOLOGY

In the earlier work, the M-D model was used in a passive sense in the analysis, specifying only the form of the steady state creep response with stress and temperature. The approach was based upon the fact that the micromechanical mechanisms do not vary with the origin of the salt. As a result, this form is the same for all domal salt materials and can be used in determining the bound of the creep rates from a test or group of tests. However, the approach for the analysis proposed in this work is significantly different. Both steady state and transient parameters must be obtained from very limited data, perhaps a single creep curve. This means, in contrast to the steady state analysis procedure of the previous report, the transient analysis requires direct integration of the M-D equations themselves. The integration, however, is a simple, forward Euler method for the internal state parameter, ζ, evolutionary equation and the creep strain, ε_c, equation. The fitting parameters in the process are the three material sensitive parameters already identified, the steady state creep rate through proportionality to A_2, the transient strain limit through K_0, and the rate of workhardening through α. A complete fit to the experimental creep data can be obtained by trial and error variation of these three parameters.

The procedure was initiated by the selection of the parameters as obtained from the earlier steady state analysis method [Munson, 1998], together with the proper independent inputs for the stress and temperature of the test. Based on the results of this initial fit, and the relative contributions of the steady state and transient as visualized in Figure 1, both the A_2 structure factor (with the remaining A's and B's, always taken in proportion to A_2), and the value of K_0 were adjusted. From the comparison of the integrated creep curves with the experimental data, an estimate was made of the required change in α to obtain the proper curvature. Subsequent adjustments of these three parameters were made, as necessary, until the fit was deemed adequate. For creep data obtained from multiple increments, each increment was integrated in succession using the appropriate conditions of stress and temperature. Both the internal state transient strain and the creep strain values from the previous increment were carried forward to the following increment.

Even though the process is straightforward, a number of uncertainties can degrade the quality of the fit. Undocumented experimental errors lead to non-systematic discrepancies in the fitting, whereas the utilization of parameters beyond their "range" lead to systematic discrepancies. An example of an experimental error is the determination of the loading strain caused by "slack" or misalignment in the mechanical system. These errors can also be encountered during changes in stress and temperature during incremental testing. Perhaps the most difficult source of error is related to equipment hysteresis where material straining is masked by apparent gradual removal of mechanical slack from the system. Such experimental errors can lead to unusually large initial strain offsets and abnormal transient responses. When the analysis results are compared to the experimental data, these experimental difficulties will become evident. An example of a "range" error is that which occurs when a given parameter is actually a function of an input condition, such as temperature, that has not been specifically evaluated for variations in that input condition. Such a systematic deviation between experimental results and model prediction was found because α was initially evaluated only at a single temperature.

DOMAL SALTS RESULTS

Because of the adequate conventional databases for the Weeks Island (WI) and Avery Island (AI) salts, transient analysis of these data is unnecessary. In all of the other cases, however, there were insufficient data to evaluate the parameters directly. These databases, Bryan Mound (BM), West Hackberry (WH), Bayou Choctaw (BC), Big Hill (BH), Moss Bluff (MB), and Jennings Dome (JD), may consist of standard creep tests terminated before steady state or of multiple increment tests. The database may consist of the results from only one creep specimen or from several creep specimens and the specimens themselves may be from cores taken from different wells or from different locations in the same well. Test nomenclature gives the salt dome, the well number, and the depth, in feet, of the core in the well from which the specimen was taken.

The Weeks Island [Mellegard and Pfeifle, 1996; Munson and Ehgartner, 1997] and Avery Island [Mellegard, 1983; DeVries, 1988] databases permit essentially complete parameter determinations. For these two materials, the parameters that were initially determined by Munson [1998] will be used. Some of these parameter value results for Weeks Island and Avery Island salts are repeated in Table I. However, one must refer to the original report for the complete set of parameter values.

All of the remaining databases, which are extremely sparse, will be analyzed by the transient method. Because of space restrictions, only a few typical comparisons between data and analysis can be shown, complete comparisons are given in Munson [1999]. The database for Bryan Mound consists of ten tests, involving four different wells with up to as many as five separate coring locations in a given well. The early data [Wawersik et al., 1980a] was in the form of standard creep tests involving material from two different wells, 107A and 107B, of the same cavern. Analysis began by using the steady state creep analysis parameter values as input to the integration process. Trial and error adjustment of the three fitting parameters finally produced the type of fit shown in Figure 3 for BM2 (107A) and BM4 (107C). In Figure 3 the calculated fit to BM2 appears extremely good; however, the fit to BM4 data has some obvious problems (as well as a non-obvious problem). If the BM4 data are examined carefully, the data initially follow the fit and BM2 data very closely; but at about 10 hours, the BM4 data are displaced sharply upward. Although we have no way to know definitely, these types of offset displacements, which can be relatively common, are probably mechanical (not creep) effects related to testing machine or gage behavior. Thereafter, the measured rate decreases markedly until it eventually becomes the same as the calculated fit and the BM2 data. Thus, it appears that initially a non-creep related offset in strain occurred, followed by machine or gage hysteresis. This mechanical hysteresis effect eventually gives away again to the creep related strain behavior. Although not shown, BM1 (107A) produced an excellent fit with the same parameter values. However, BM3 (107C) appeared to have too little initial strain, perhaps due to a relatively common strain loss problem during rezeroing. Unfortunately, even then, the agreement depends upon making an arbitrary change to the reported temperatures of the BM2 and BM3 tests, assuming essentially that they were transposed between the values of 60°C and 22°C when reported. Unless this is assumed, no logical fit can be obtained. In further support, it seems unlikely that two specimens from the same well would be tested under identical conditions. Under the assumptions described, a single set of fitting parameters could be determined for BM1, BM2, BM3, and BMN4, as given in Table I.

Table I. Transient Analysis M-D Model Parameters for Domal Salts Creep Tests.

Specimen	$A_2(x10^{12})$ #	---------Factor	$K_0(x10^5)$	---------Factor	$\alpha(T(^oC)$	--------------Factor	Closure (%/yr.)
BASELINE	9.672	1.00	6.275	1.00	-17.35(25)	1.00	WIPP Clean Salt
AVERY ISLAND DOME (Direct Analysis, Parameters Determined by Munson [1999])							
	6.869	0.71	1.342	0.21	-13.20(25)	0.76	??
WEEKS ISLAND DOME (Direct Analysis, Parameters Determined by Munson [1999])							
	5.706	0.59	6.275	1.00	-17.35(25)	1.00	??
BRYAN MOUND DOME							
			Cavern 113				
BM10 113-4225	**11.32**	1.17	**4.393**	0.70	**-13.37**(60)	0.54	0.12 (Very Soft)
					-9.37(80)	0.42	
			Cavern 107				
BM5 107B-3324	**2.647**	0.27	**3.640**	0.58	**-13.37**(22)	0.77	0.02 (Hard)
					-9.37(60)	0.54	
					-6.37(100)	0.37	
BM9 107C-2508	**0.2965**	0.03	**4.050**	0.65	**-13.37**(30)	0.77	(Very Hard)
					-9.37(60)	0.54	
					-7.37(80)	0.42	
BM8 107C-2506	**0.2965**	0.03	**3.640**	0.58	**-9.37**(60)	0.54	(Very Hard)
BM7 107C-2516	**0.2965**	0.03	**2.904**	0.46	**-13.37**(22)	0.77	(Very Hard)
					-9.37(60)	0.54	
BM6 107C-2517	**0.2965**	0.03	**2.904**	0.45	**-9.37**(60)	0.54	(Very Hard)
BM4 107C-2504	**0.2609**	0.03	**1.335**	0.21	**-13.37**(22)	0.77	(Very Hard)
BM3 107C-2507	**0.2609**	0.03	**1.335**	0.21	**-9.37**(60?)*	0.54	(Very Hard)
BM2 107A-3965	**0.2609**	0.03	**1.335**	0.21	**-13.37**(22?)*	0.77	(Very Hard)
BM1 107A-3966	**0.2609**	0.03	**1.335**	0.21	**-9.37**(60)	0.54	(Very Hard)
WEST HACKBERRY DOME							
			Cavern 6C				
WH1 6C-2243	**11.32**	1.17	**9.777**	1.56	**-17.37**(22)	1.00	(Very Soft)
WH3 6C-2225	**11.32**	1.17	**9.777**	1.56	**-17.37**(22)	1.00	(Very Soft)
WH2 6C-2201	**11.32**	1.17	**9.777**	1.56	**-17.37**(80?)*	1.00	(Very Soft)
WH4 6C-2196	**11.32**	1.17	**9.777**	1.56	**-17.37**(80?)*	1.00	(Very Soft)
			Cavern 108				
WH5 108-2267	**11.32**	1.17	**8.512**	1.36	**-13.37**(60)	0.77	0.145 (Very Soft)
			6.275**	1.00	**-9.37**(80)	0.54	
WH6 108-3652	**11.32**	1.17	**8.512**	1.36	**-13.37**(60)	0.77	0.145 (Very Soft)
			6.275**	1.00	**-9.37**(80)	0.54	
BIG HILL							
			Cavern 106				
BH1 106B-5465	**11.32**	1.17	**6.275**)	1.00	**-13.37**(60)	0.77	0.09 (Soft)
					-9.37(80)	0.54	

Table I (Cont.). Transient Analysis M-D Model Parameters for Domal Salts Creep Tests.

Specimen	$A_2(x10^{12})$ #	Factor	$K_0(x10^5)$	Factor	α(T(°C)	Factor	Closure (%/yr.)
			Cavern 108				
BH2 108B-2517	**15.85**	1.64	**8.512**	1.36	**-13.73**(60) **-9.37**(80)	0.77 0.54	0.15 (Very Soft)
BH3 108B-3516	**15.85**	1.64	**8.512**	1.36	**-13.73**(60)	0.77	0.15 (Very Soft)
BAYOU CHOWTAW							
			Cavern 19A				
BC1 19A-2577	**2.250**	0.23	**6.275**	1.00	**-13.73**(60) **-9.37**(80)	0.77 0.54	0.06 (Hard)
MOSS BLUFF							
			Well MB				
MB1 MB2-3349	**6.770**	0.70	**8.964**	1.43	**-13.73**(60)	0.77	(Soft)
JENNINGS DOME							
			Well LA1				
JD1 LA1-3927	**1.222**	0.13	**1.308**	0.21	**-13.73**(60)	0.77	(Hard)

The quoted factor is just the ratio of the domal salt material A_2 parameter value to that of the WIPP clean salt baseline value. In order to form a complete set of parameters for a material, this factor must be used to generate, where necessary, the remaining A and B values.

* Appears to be some uncertainty in the reported values.

**These are very high stress increments, perhaps causing a change in K_0.

These results indicate the type of "range" error mentioned previously. In very early data analysis of WIPP salt, Munson and Dawson [1982] had shown that K_0 is a function of temperature and this variation was eventually incorporated into the model [Munson et al., 1989]. However, at the time, there was no indication in these early results that Δ was influenced by temperature because this parameter was determined at only one temperature. Even though there is no provision in the M-D model for the temperature dependence of the α parameter, better fits are often obtained when this parameter is changed systematically with temperature for a given material. As α decreases, the magnitude of Δ also decreases, and the curvature (workhardening rate) increases.

In a later study [Wawersik and Zeuch, 1984], additional specimens of Bryan Mound salt were tested in incremental tests. Transient analyses were made for tests BM6, BM7, BM8, and BM9, all on material taken from Well 107C. In these multiple increment tests, while the steady state creep rate remained unchanged from the earlier analysis results, it was necessary to increase the transient strain limit by more than a factor of two. In these results we see a continuation of the fitting difficulties. Some individual increments appear to be offset from the calculated curves. Without major changes to the parameters within the same test, the analysis appears unable to fit all aspects of these tests. In the case of BM6, it appears that individual increments fit the shape and

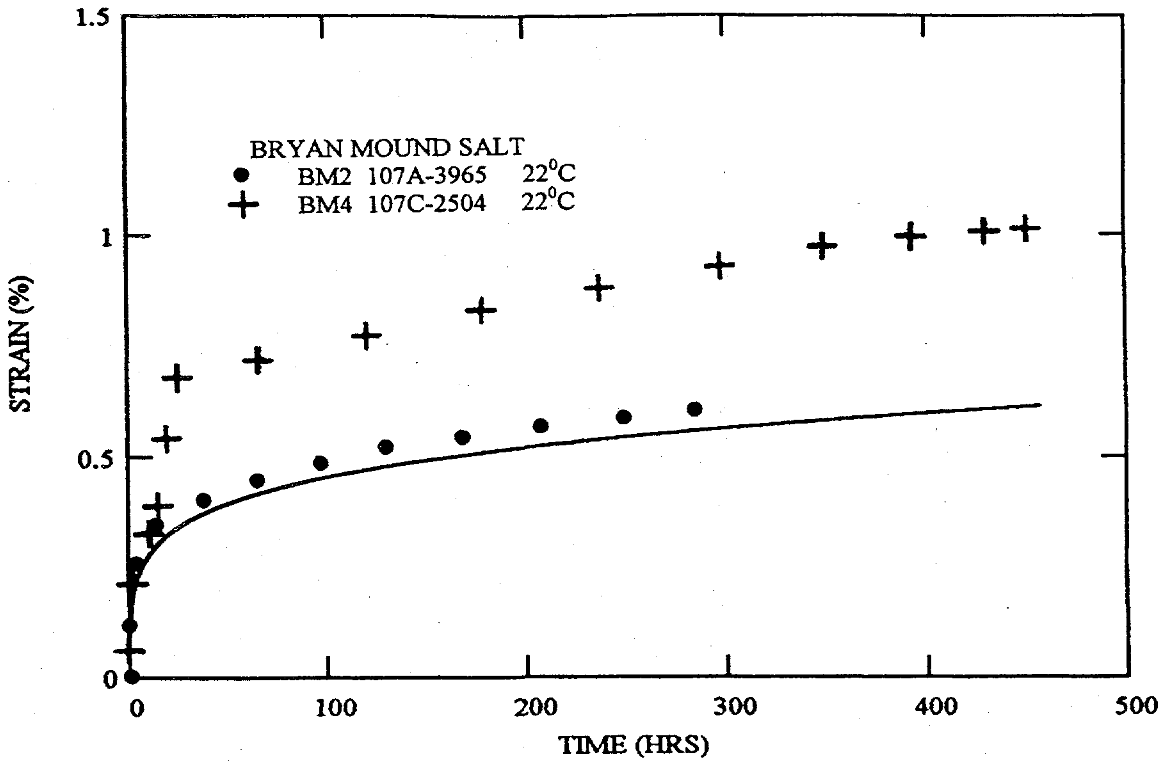

Figure 3. Calculated Fit (Solid Line) to Bryan Mound Salt BM2 and BM 4 Creep Data.

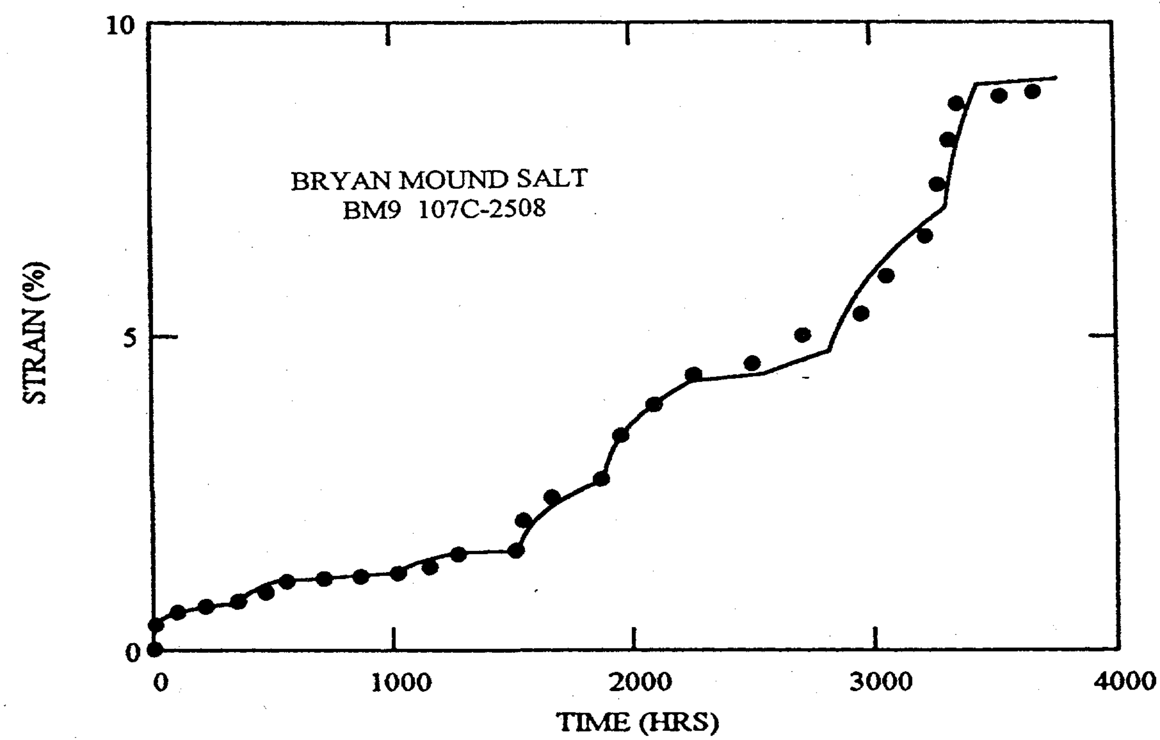

Figure 4. Calculated Fit (Solid Line) to Bryan Mound Salt BM9 Creep Data.

the strain rates of a given increment calculation, provided they can be arbitrarily displaced vertically in strain. In the case of BM7, the second increment has the appearance of machine hysteresis. In the case of BM8, the calculation and experiment are initially in good agreement, only to give way to a slow, abnormal looking, transient increase in creep strain. The vertical offset apparently continues throughout the final increment of the test. In the end, a set of parameters, as given in Table I, was obtained that gave the best "shape" regardless of the vertical offsets necessary to fit a given increment, without proof such offsets are permitted. The 14-increment BM9 test comparison results are shown in Figure 4 and illustrate the closeness of fit, even though some discrepancies are evident. Apparently, the cores from Wells 107A and 107C all correspond to "hard" salt, with the only variation being a rather modest change in the transient strain limit.

At this point there are only two remaining Bryan Mound creep tests to discuss, BM5 and BM10. The core for these two specimens came from wells distinct from those discussed previously. BM5 is from Well 107B, and as shown in Figure 5 is a six-increment test. The first three increments are under nearly identical conditions of stress and temperature, with only a change in confining pressure between increment one and two, at about 150 hours. The initial three increments appear to have a vertical offset, which appears to be eliminated by mechanical hysteresis during the third increment. The experimental results show a vertical shift at the time of a confining pressure change from 6.9 MPa to 13.8 MPa, but the creep rates remain almost unchanged, as they should, after this perturbation has passed. As the results in Table I indicate, BM5 was found to have a higher steady state creep rate, increased by a factor of 10, from those tests previously presented. This suggests that the salt of Well 107B is not as creep resistant, at least from this depth, as the salt from the other two wells of the cavern. The wells were initially separated laterally by 15 to 35 m. Regardless of these differences in the creep characteristics of the salt specimens from the three wells of this cavern, the salts would all still be considered as "hard" or creep resistant.

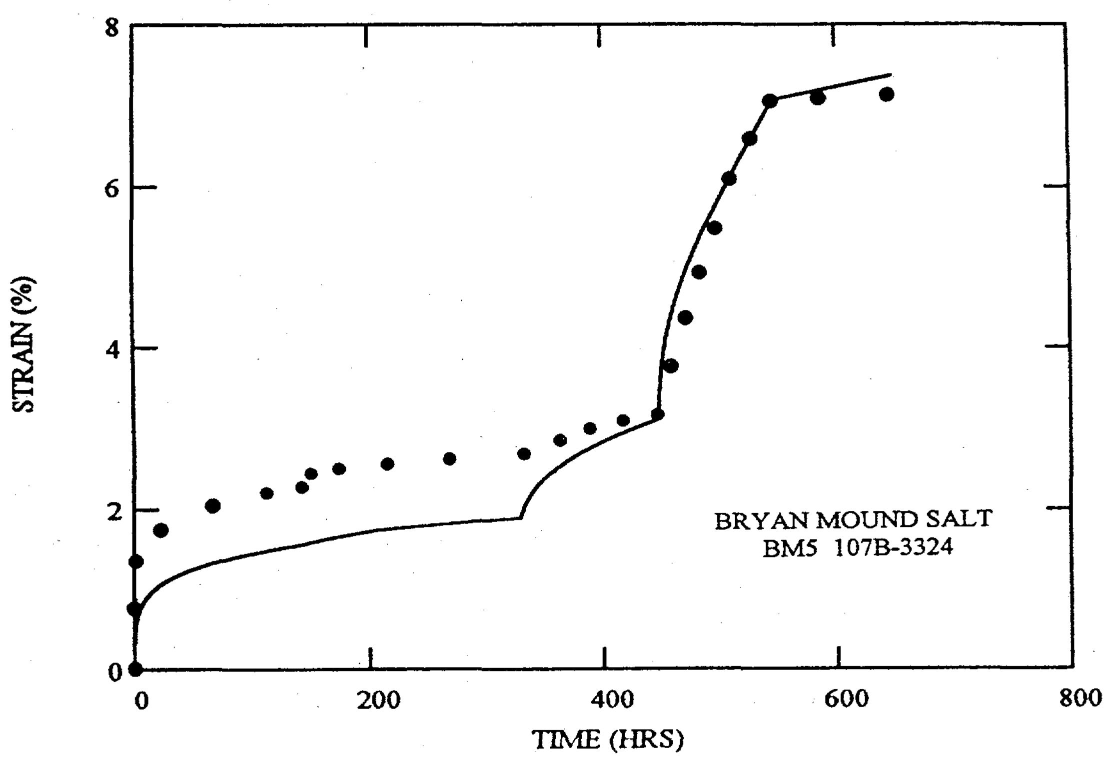

Figure 5. Calculated Fit (Solid Line) to Bryan Mound Salt BM5 Creep Data.

Test BM10 was a ten-increment test on specimen material taken from Well 113. This test was quite well simulated by the calculation, as shown in Figure 6. The parameters necessary to obtain this fit are given in Table I. It is clear that this BM113 salt material is very "soft" and has much less creep resistance than the material from BM107. This difference is also reflected in the relative values of the CAVEMAN volume loss creep rates, as given in the table.

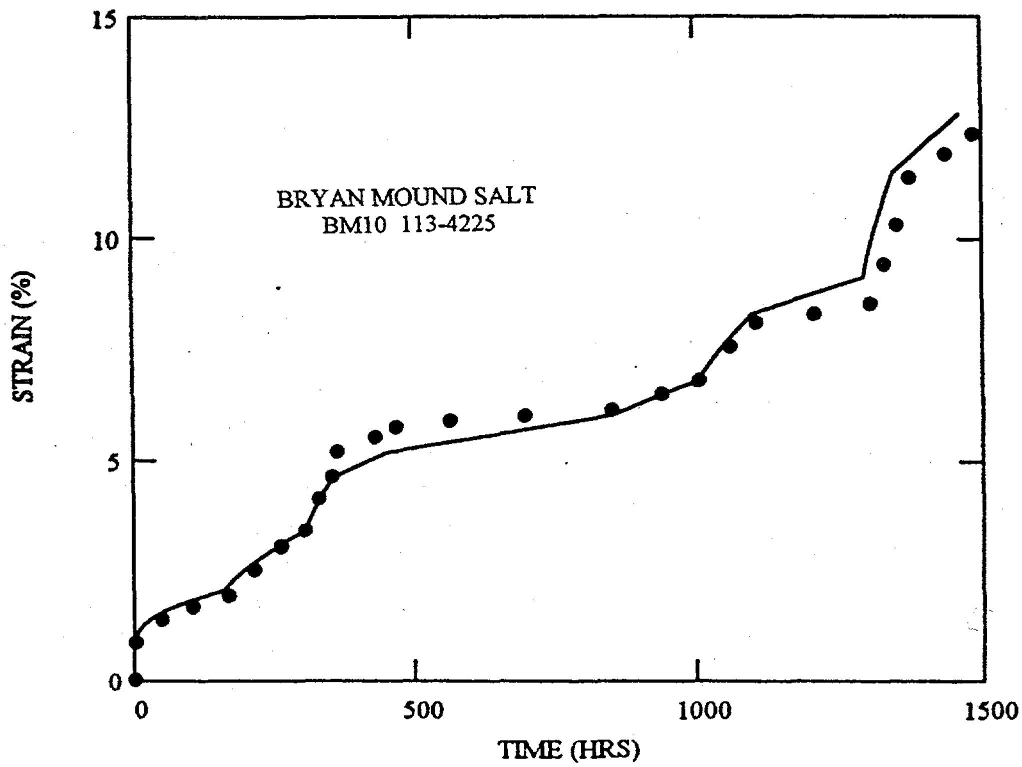

Figure 6. Calculated Fit (Solid Line) to Bryan Mound Salt BM10 Creep Data.

The creep database for the West Hackberry SPR facility [Wawersik et al., 1980b; Wawersik and Zeuch, 1984] consists of some six separate specimens from two different wells, 6C and 108. The 6C cavern was an existing commercial cavern purchased by the SPR Program, as a result its construction was not well controlled and it differs markedly in configuration. Cavern 108 was purpose-constructed by the SPR Program and is a well-configured, cylindrical cavern with the nominal dimensions of the other purpose-constructed SPR caverns. As we shall see, the creep results from the West Hackberry creep tests are extremely consistent, much more so than the Bryan Mound data discussed above.

The four tests on the Well 6C materials were all conventional creep tests, terminated prior to attaining steady state. The two tests on Well 108 material were multiple increment tests, involving two separate specimens. The calculated integrated fits as compared to the experimental data are very straightforward (almost) for the first four tests. WH1 and WH3 data at 22°C were essentially identical to each other and to the fit. Using these same parameters determined at 22°C, the tests, WH2 and WH3, at the higher temperature were simulated. Interestingly, the calculated fits for these higher temperature tests did not match the data. In fact, a logical set of parameters could not be developed unless the test temperature of these tests was assumed to be 80°C. The results are

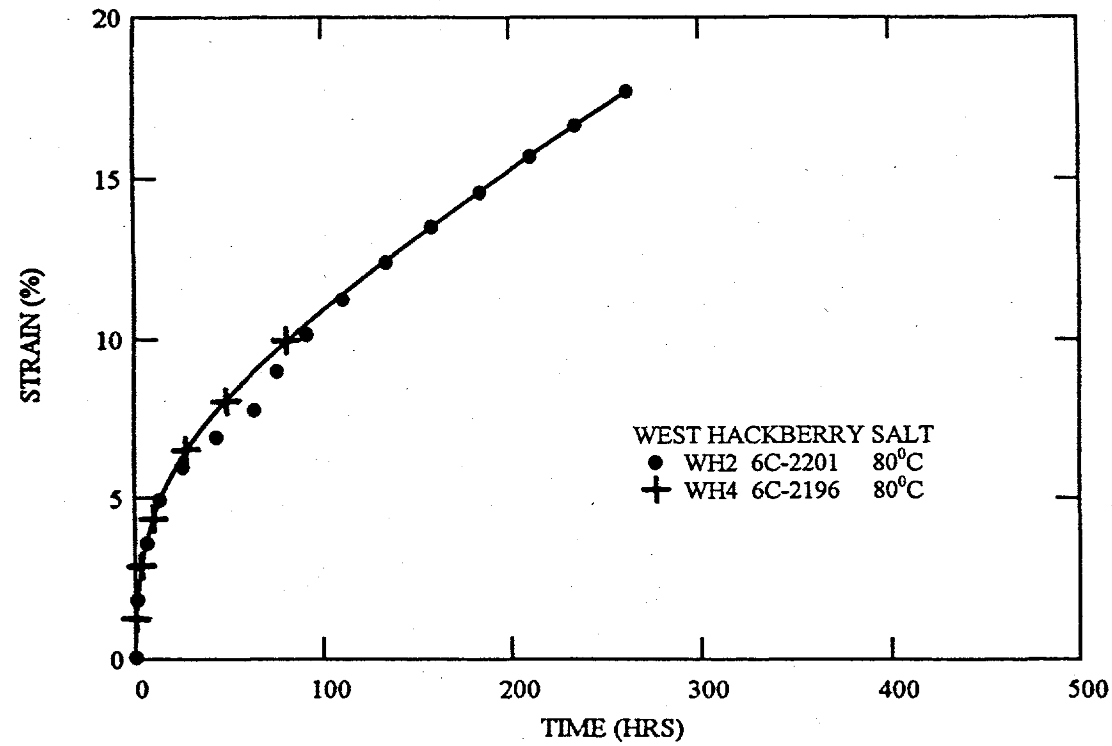

Figure 7. Calculated Fit (Solid Line) to West Hackberry Salt WH2 and WH4 Creep Data.

shown in Figure 7. While it is probably inappropriate to assume the reported temperatures are in error, the fitting procedure certainly suggests this may be a possibility.

Test WH5, as shown in Figure 8, consists of five increments, primarily descending through successive stress drops from the initial stress condition. Integration to obtain a good fit was possible using the same steady state rates as in the first four tests, but with a slightly smaller value of K_0. The fitting parameters are given in Table I. The calculated response seems to under predict all of the stress drops of this experiment suggesting δ may be incorrect. However, as initially noted, the recovery parameter, δ, is not taken as a fitting parameter in this analysis. Even then, considering the small magnitude of the discrepancies, the current analysis appears to be adequate.

Test WH6 consists of six increments. Using the same steady state parameters and the same K_0 as for WH5, the integration gives quite an acceptable simulation of the experimental data. While the results are not shown, the fitting parameters are given in Table I.

All of fits to the creep data from the four specimens obtained from two wells at West Hackberry were quite reasonable, with consistency obtained in the fitting parameters. Moreover, the West Hackberry database is adequately represented, with only minor variations, by one set of fitting parameters, which is in contrast to the Bryan Mound data where the database can not be fit with one set of parameters. It is clear that the West Hackberry salt, at least on the basis of the specimens from the two wells tested, is a very soft salt. This is directly confirmed by the comparable CAVEMAN measures of cavern creep closure, as reproduced in Table I.

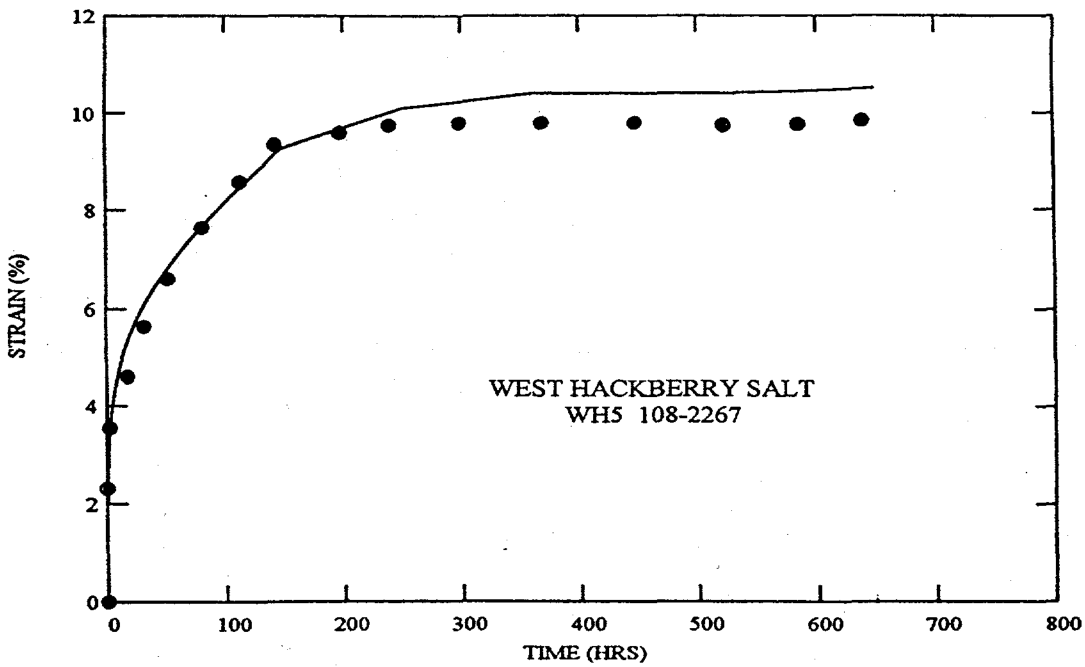

Figure 8. Calculated Fit (Solid Line) to West Hackberry Salt WH5 Creep Data.

For the Big Hill SPR facility, the geomechanical test data [Wawersik, 1985] from two different wells are available, with multiple tests from the specimens of one of the wells. Test BH1 is a four-increment test from Well 106B. Tests BH2 and BH3 are four-increment and six-increment tests, respectively, from Well 108B. These test results are interesting. Although the fits are acceptable, there are indications of some growing discrepancy at high strains and long times where the data almost suggest the development of a tertiary creep behavior. In fact, this same general response is found in all of the Big Hill data. Based on what is known about the suppression of fracture for confining pressures above 5.5 MPa, the 13.8 MPa confining pressure on these tests certainly should be adequate [Chan et al, 1998]. In any event, the form of the experimental curves is clearly different than one would expect. Parameter values obtained from the fits for these tests are given in Table I and indicate the Big Hill salt is quite soft, with little creep resistance. The CAVEMAN creep closure data support this contention.

Only a single specimen was tested from material at the SPR Bayou Choctaw facility [Wawersik and Zeuch, 1984]. Test BC1 was a 13-increment test on a specimen taken from core of Well 19A. Cavern 19 was a commercial cavern purchased for use by the SPR Program. Because of its commercial beginnings, it has an irregular geometry considerably different than the cylindrical symmetry of the SPR constructed caverns. Because of the large number of increments, the integration process proved to be difficult for these data. While there remain some discrepancies, the parameters used for the calculated fit appear to be adequate. The salt is seen to be moderately creep resistant, but not equivalent to the very hard salt of the Bryan Mound dome. The cavern creep volume closure from the single purpose-built SPR cavern, BC101, at the Bayou Choctaw facility indirectly collaborates this observation.

A four-increment creep test was performed on a single specimen from Well MB at the Moss Bluff dome [Wawersik, 1992]. The specimen is from Well MB2. Although this dome is not the site of a SPR facility, it is located in the state of Texas, somewhat near the Bryan Mound dome. The site is used for commercial storage operations. The MB1 test results compared to the calculated parameter integrated fit are given in Figure 9. The fit could be considered quite good. As the parameter values given in Table I suggest, the Moss Bluff salt is relatively soft, although somewhat more creep resistant than the WIPP baseline salt.

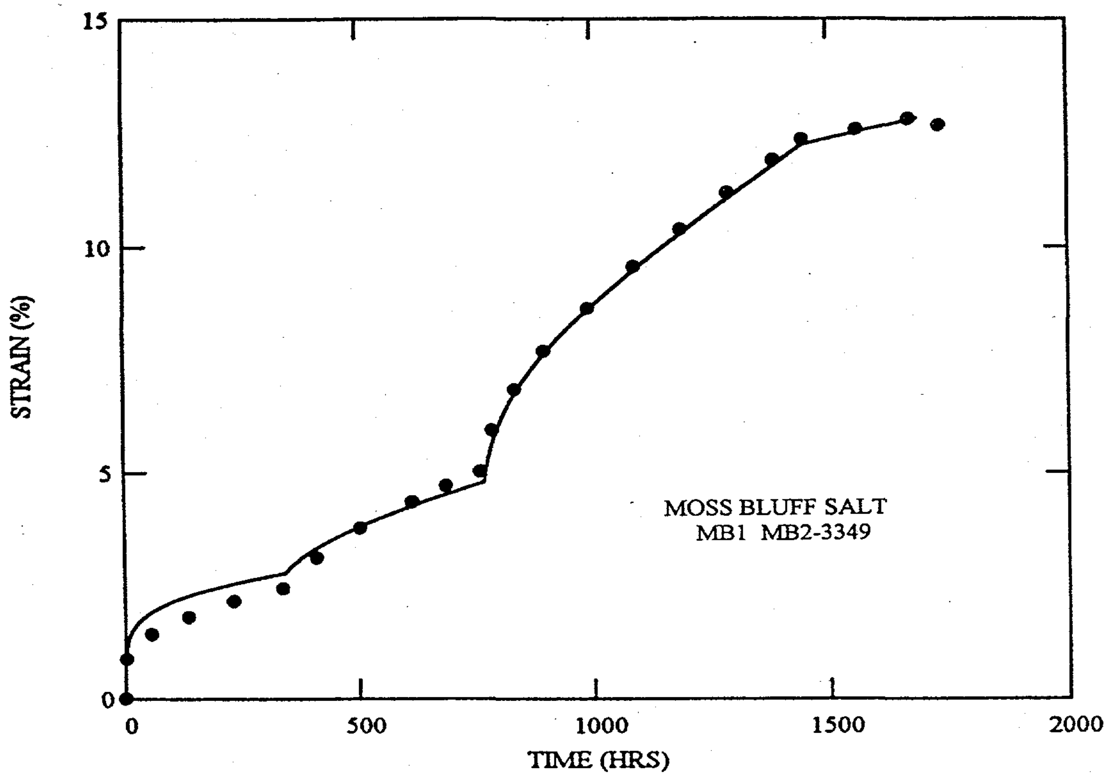

Figure 9. Calculated Fit (Solid Line) to Moss Bluff Salt MB1 Creep Data.

The well at the Jennings Dome, Well LA1, provided a single test specimen, JD1 [Wawersik and Zimmerer, 1994]. This dome is located in the state of Louisiana near the location of the West Hackberry dome. The dome is used for commercial storage. This specimen was used for a five-increment test. Parameters given in Table I provided an adequate representation of the data, even though some offsets, both positive and negative, were apparent. Based on this single test result, the salt from the Jennings Dome appears to be quite creep resistant.

DISCUSSION

Perhaps the most significant consequence of the ability to determine the relative creep response of the domal salts is the possible quantitative correlation to the field behavior of caverns. While it is recognized that most existing caverns have operated adequately in the absence of any detailed geomechanical understanding of the salt, incorporation of this new knowledge into processes of siting and operation may be of benefit. Certainly, it offers another tool to aid the operator in further optimization, if possible, of a cavern operation. To establish the correlation to field behavior, we first present the CAVEMAN [Linn, 1998] results of analysis of SPR cavern creep closures. Then, correspondence is made to the results of the transient analysis to determine the relative creep response of the domal salts. This then suggests an interpretation about the large-scale geological structure of the domes themselves.

CAVERN VOLUME CLOSURE

During standard operation of the SPR caverns, which is relatively quiescent, cavern pressure gradually increases because of the creep closure of the cavern. Periodically, the pressure is reduced by removal of fluid to maintain the operating pressure within the range acceptable good practice and the requirements of state regulations. In an extensive study of the pressure build-up in the caverns of the SPR, Ehgartner et al. [1995] developed an interpretation of historical cavern operation. Interestingly, the material behavior component of method is based on the M-D constitutive equations. The ensuing tool is called CAVEMAN. Through an inversion process, functions describing the geometry, stress, and material behavior that involved four adjustable parameters could reproduce the pressure build-up history. This amounts to a fitting process of the historical pressure record of a cavern. The parameters determined in the fitting process then become the basis for prediction of future cavern behavior. Deviations between expected and actual behavior may be attributed to cavern sealing problems and other abnormal events. One of the outputs of CAVEMAN is a value of the creep closure rate of the cavern. This is an "effective" creep rate that is some kind of average of the actual point-by-point closure rates,

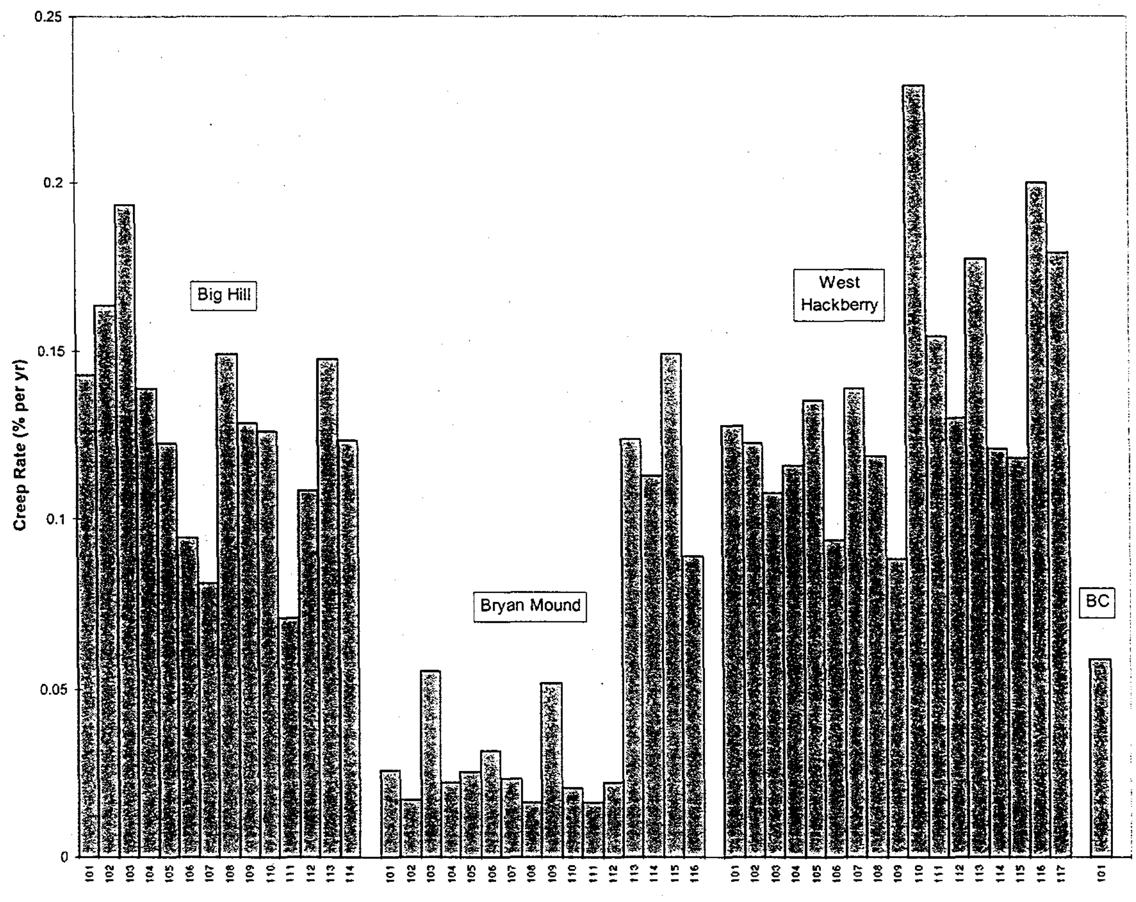

Figure 10. CAVEMAN Volume Creep Closure Rates for SPR Caverns [Linn, 1997].

which are strongly dependent upon vertical location within the cavern and the salt dome. The effective creep closure rates of the purpose-built SPR caverns based on CAVEMAN are given in Figure 10. The four relevant salt domes for the SPR facilities are clear from the figure.

There is considerable information contained in Figure 10. Not only are the general closure rates significantly different between the facilities of the different domes, but also there are marked differences between the cavern closure rates within a given dome. Clearly, Big Hill and West Hackberry domes have the largest closure rates, while Bryan Mound and Bayou Choctaw domes have smaller closure rates. However, even here, for example, the closure rates of the caverns in Big Hill span a considerable range, approaching as much as a factor of two. The range in closure rates of the Bryan Mound caverns is even more pronounced, varying quite sharply by over a factor of four.

Certainly the quantitative closure data give a strong indication not all caverns respond the same within a dome, much less from one dome to another. However, the fact that the closure rates differ does not necessary, in itself, mean that the effect is the result of material behavior. This results from the nature of height averaging in determining the effective closure rate. One of the CAVEMAN parameters is essentially a stress parameter. This stress parameter is some measure of the cavern depth within the salt dome. It reflects not only the cavern height but also the amount of overburden above the cavern. One of the other CAVEMAN parameters concerns the "effective" shape of the cavern. While this effect is difficult to visualize, the closure rate of equal volume caverns with different shapes could be different. That is a conical shape would give different answers depending upon whether the apex is up or down. As a consequence, closure rates can be correctly compared only if the caverns have roughly the same geometry and have nearly the same amount of overburden. Fortunately, the geometry and overburdens of those caverns purpose-built for the SPR are nearly identical. This of course does not apply to those existing commercially constructed caverns purchased for SPR use. As a result, the differences between closure rates of the caverns shown in Figure 10 are probably the result of only the differences in material response.

CLOSURES AS RELATED TO MATERIAL REPONSE

While it is clear that we have established that the characterization of the mechanical behavior of the domal salts can be quantified through analysis of the creep data, this perhaps can be extended to a broader characterization. As indicated previously, we are interested in establishing the link, if possible, between laboratory material testing and the behavior of caverns in a dome, and to carry this even further to the geologic material characterization of the dome itself. Although the creep database is extremely limited, it is still possible to plot for any given cavern the values of the steady state creep parameter, A_2, obtained from the transient analysis against the CAVEMAN deduced cavern volume creep rate. This plot is given in Figure 11. Even for such a small data collection, it is clear that the cavern volume loss rate is related directly to the steady state creep rate. Moreover, the trend is entirely logical. Admittedly, there is considerable scattering of results. However, within the limitations of the quantity and quality of the creep databases available, it is remarkable that such a good correlation between laboratory data and field behavior has been obtained. It is somewhat unfortunate that more geomechanical laboratory creep data were not obtained as a routine part of cavern construction. The noted success of the preceding analysis would strongly suggest the desirability of requiring at least limited creep data for new cavern construction and of recovery of any creep data from existing caverns. In fact, it would be extremely challenging to collect creep information from all facilities in a given dome. One of the interesting aspects of being able to quantify the creep response of individual caverns is that they represent a discrete location within the greater salt dome.

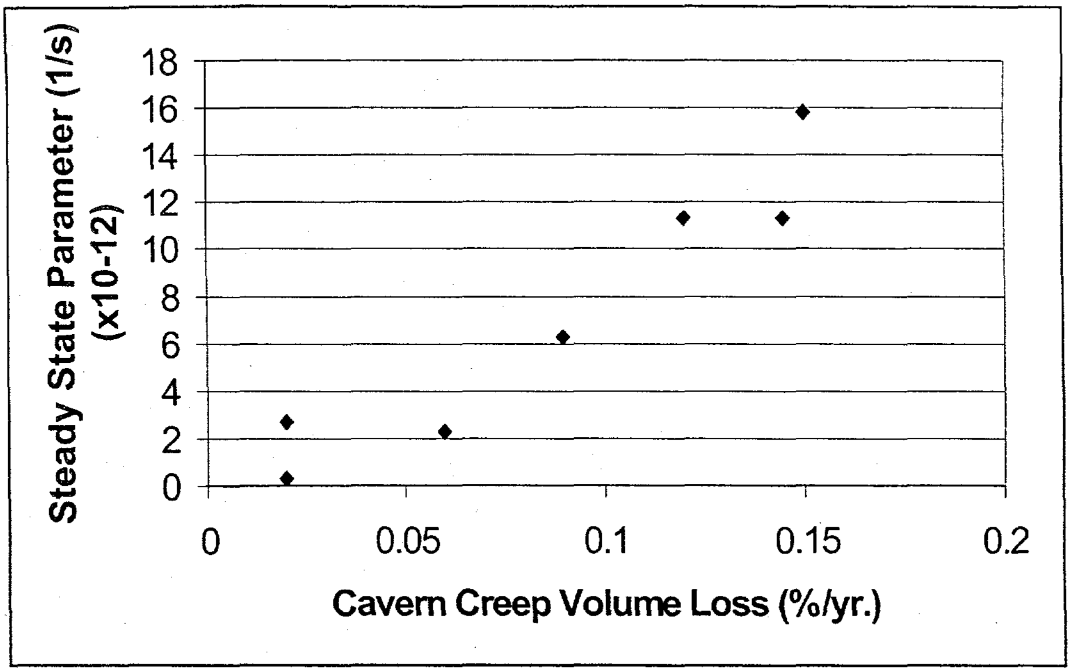

Figure 11. Steady State Creep Parameter A_2 and Cavern Creep Volume Loss.

GEOTECHNICAL CHARACTERIZATION OF A DOME

The next step in examining how the mechanical response of caverns in a salt dome is organized is to note the relative differences in cavern volume creep loss on the plats of the facilities. While Munson [1999] did this for Bryan Mound and West Hackberry, we will only repeat the results for Bryan Mound. The SPR caverns are located in the dome as shown in Figure 12. Here, the shaded cavern locations are the purpose-built caverns with large (greater than about 0.8 %/yr.) volume creep rates. All of the other purpose-built caverns, which have small (averaging less than 0.4 %/yr.) are shown as unfilled, outlined locations. A dashed line has been drawn which separates the southern limb of the dome that contains all of the caverns with high creep volume losses, specifically caverns BM113 through BM116, from the low creep volume loss caverns to the north.

If we examine the transient analysis information on the values of A_2 for the Bryan Mound dome, it becomes clear that the caverns with the "soft" salt are the ones with the large volume closure rates. This occurs without exception based on the very limited data available. The grouping of the less creep resistant caverns in an east-west arc along the southern portion of the dome may indicate that a very significant geologic feature of the Bryan Mound dome. In fact it suggests the possibility of two distinct spines in the dome, a soft material spine to the south of the line of separation and a hard material spine to the north. It is also possible to make a further conjecture. Although it is easy to make generalizations, those caverns immediately to the north of the dashed line seem to be subject to a number of "unusual or abnormal" conditions. These conditions range from having a number of damaged (hanging string) casings probably as a result of salt falls to significant accumulations with time of salt on the cavern bottom, and further to indications of gassy conditions during construction. In Figure 12, these caverns include BM112, which experiences the greatest number of casing damage incidences and bottom accumulations, and

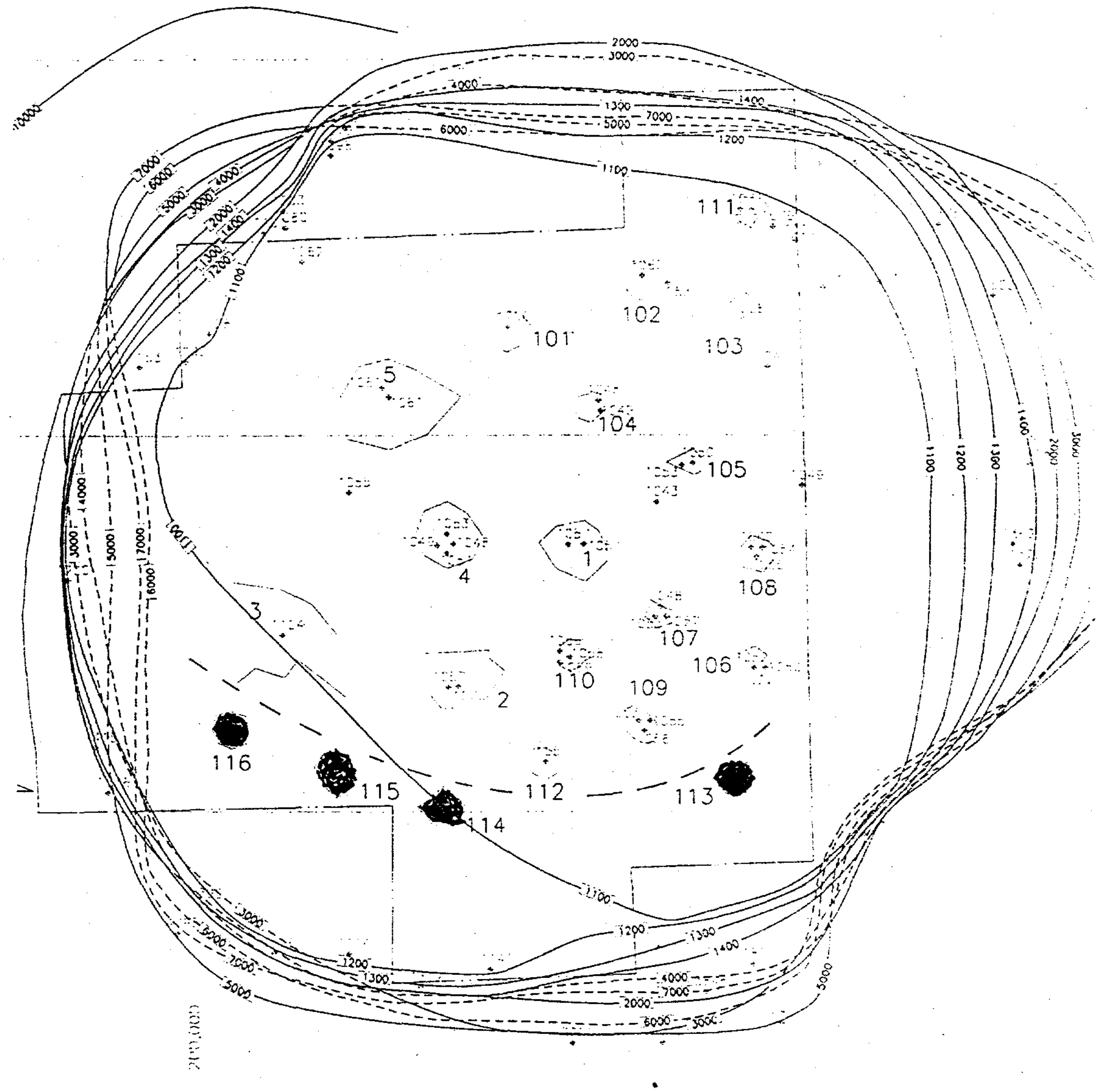

Figure 12. Plat of Bryan Mound, High (Shaded) and Low Volume Creep Caverns.

BM109 and BM106, which experience somewhat fewer incidences and accumulations. The spine to the north adjacent to the line of separation may also have a concentration of impurities that have been postulated to cause these salt falls and bottom accumulations [Munson et al., 1998]. Other caverns further removed to the north from the dashed line may have similar, but less severe, condition histories.

While the above arguments are perhaps logical for the "hard" and "soft" salts of the Bryan Mound dome, when they are applied to West Hackberry dome the results are not nearly as clear. Based on the limited amount of steady state creep data, it appears that the entire dome should be considered as "soft" salt. As a result, so even though there are +/- 50% differences in the West Hackberry volume creep losses, these are much smaller relative differences than the factor of four for the Bryan Mound dome. Therefore, it should be noted that West Hackberry rates are not as distinctly separated as are the two markedly different groups of Bryan Mound caverns. With this in mind, the five purpose-built SPR caverns with volume creep loss values, in excess of 0.15%/yr. were arbitrarily chosen as possible candidates for another spine. This cut off point is only 10% greater than the top value of the remaining caverns. While four of these purpose-built SPR caverns, WH 110, WH111, WH113, and WH116, appear along the outer rim of the north-east portion of the dome, the remaining high volume loss cavern, WH117, is found almost in the center of the dome, somewhat surrounded by caverns of lower volume loss. Consequently, although, we can still suggest that the material involved in these five high volume loss caverns may be different than the others, it is impossible to suggest that they belong to a separate spine.

At this point, the picture is extremely mixed of how material properties, in our case the creep properties, reflect the structure of a salt dome. Clearly, various locations in the dome can have markedly different creep characteristics, as appears to be the case in the Bryan Mound dome. Here, the creep resistant salt seems to be concentrated in one region of the dome and the less creep resistant salt in another, to form what may be distinct spines. For West Hackberry it appears volume creep rates vary by a factor of two over the dome. Even though some of the highest volume creep caverns occur in an arc along the rim of the dome, there doesn't seem to be enough difference to suggest a separate spine.

CONCLUSIONS

From the framework provided by the Multimechanism-Deformation (M-D) constitutive description of salt creep, it is possible to obtain the model parameters through trial and error fits to very limited creep databases. Initially, the framework provided only the form of the steady state creep response as the bound for conventional and incremental test data. The results of the steady state analysis suggested that domal salts were either "hard" or "soft" salts depending upon their creep resistance. However, shortcomings of this steady state analysis method permitted some data to obscure the actual steady state response of other data. Consequently, it was necessary to develop a more detailed transient analysis method based on the direct integration of the M-D equations. Using this detailed method, individual creep tests, either conventional or incremental, could be fitted through trial and error to obtain the material sensitive parameters best describing the test material. Although there are numerous model parameters that must be considered, only three are significantly material sensitive to become involved in the fitting technique. These parameters are the steady state creep rate as specified through the structure parameter, A_2, the transient strain limit as determined by K_0, and the workhardening curvature as given by α. When this transient analysis was completed, the same "hard" and "soft" salt designations were observed as previously; however, the range of behavior was greater and the distinction blurred. These transient analyses of laboratory creep data supports the cavern volume creep closure results found from the analyses of CAVEMAN, a fitting program for using the history of pressure build-up in quiescent caverns to predict future cavern response. Results of the transient analysis of very sparse laboratory creep databases suggest that these data may be a valuable tool in the selection of candidate cavern locations for new caverns or in the understanding of the operational characteristics of existing caverns.

With knowledge of the creep volume closure and laboratory creep response of the various SPR caverns, it was possible to place this information in the geological context of the salt dome. As a consequence, it is believed that the Bryan Mound salt dome consists of at least two spines, one of creep resistant salt and one of less creep resistant salt. This is supported both by relative creep volume closures and relative creep resistance of the salts. The West Hackberry SPR caverns, while showing some deviation in the creep response, never-the-less are all in soft salt, with little apparent possibility of spines. Likewise, the other SPR facilities in the Bayou Choctaw and Big Hill salt domes suggest a more uniform material makeup, possibly equivalent to West Hackberry.

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