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Reference Stratigraphy and Rock Properties for the Waste Isolation Pilot Plant (WIPP) Project

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ABSTRACT

A stratigraphic description of the country rock near the working horizon at the Waste Isolation Pilot Plant (WIPP) is presented along with a set of mechanical and thermal properties of materials involved. Data from 41 cores and shafts are examined. The entire stratigraphic section is found to vary in elevation in a regular manner, but individual layer thicknesses and relative separation between layers are found to have no statistically significant variation over the one mile north to south extent of the working horizon. The stratigraphic description is taken to be relative to the local elevation of Anhydrite b. The material properties have been updated slightly from those in the July '81 Reference Stratigraphy. This reference stratigraphy/properties document is intended primarily for use in thermal/structural analyses. This document supercedes the July '81 stratigraphy/properties document.

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I. INTRODUCTION

There are many structural analysts in several organizations who have been and presently are performing thermal/structural analyses of shafts, drifts, and rooms at the WIPP site. The details of the stratigraphy and materials have been found to be important in these analyses. Rather than have each analyst build a model of his/her own, it was decided in mid 1979 to study the available data and collectively decide on an appropriate reference model of the stratigraphy and a set of materials properties. The initial reference set was particularly valuable since only cores and corehole logs were available at that time to define the stratigraphy and the interpretation of these was subjective so that choice of a set required some judgement. Analysts, geologists, geophysicists, and mining engineers all had useful inputs to interpretation of the data and definition of a reference stratigraphy/properties. It was recognized from the outset that this reference set must be updated as new data became available. These updates could hopefully be made in a controlled manner so that analysts could always use a reference set without having to use ad hoc modifications to the reference with a different set of modifications used by each organization or analyst.

Early work on a reference stratigraphy was documented in internal memos [1,2] at Sandia National Laboratories. There were probably similar memos written by structural analysts in other companies associated with the WIPP. A meeting was held on November 15, 1979, with attendees from WPO/DOE, Bechtel, the TSC/D'Appolonia, and Sandia, and the first reference stratigraphy and properties were set down [3,4,5]. This was then declared by the project office to be used for all structural calculations[6]. It was called the "November '79 Reference Stratigraphy" and was used for some time [7].

The November '79 Reference Stratigraphy was updated in July, 1981, when more data became available [8]. The material properties in particular were revised at that time. Since this was prior to construction of the shafts, no attempt was made to revise the stratigraphy. This document was used [9,10] as the reference until the present time.

When the shafts were constructed and logged, it became apparent that the July '81 Reference Stratigraphy should be updated. Analysts began using updates to the stratigraphy which accounted for new observational data [11]. A meeting was held between analysts, project geologists, and geological properties scientists at Sandia to consider updates to the reference stratigraphy [12]. Because other analysts are involved, it was obvious that a consensus of everyone, not just Sandia, was needed to define a useful reference.

On July 7, 1983, a meeting was held with attendees from Bechtel National, the TSC/D'Appolonia, Sandia National Laboratories, and the DOE/WIPP Project Office. The meeting notice, meeting schedule, and minutes are included in Appendix A. Action items resulting from the meeting and recorded there include clearing up some questions about correlation between the core, core logs, and tests on insolubles content. Another was a bringing together of suggested reference stratigraphies submitted by Bechtel [13] and the TSC/D'Appolonia [14] and Sandia into a documented reference stratigraphy/properties that would be accepted by everyone. This is the resulting reference stratigraphy/properties document.

A suggestion was made at the meeting documented in Appendix A that three stratigraphic descriptions would be useful as noted on page 43. The present document is a combination of two of the suggested models. The third model would cover a 900m (3000 ft) depth and would be used for regional studies. Due to time constraints, this is not covered here.

The present document is not intended to be a final report on this topic. It is expected that as more data become available, then this document will be revised or superceded.

II. INTENT OF REFERENCE STRATIGRAPHY/PROPERTIES

The intent of this report is to set down a consensus stratigraphy and set of material properties which are suitable for structural analyses of the underground WIPP site. The first part is a presentation of the model which is local to the underground WIPP horizon (near a depth of 655 m (2150 ft)), and is to be used for drift and room calculations. Next, the properties of the rocks listed in the stratigraphy are presented which are generally those presented in the July '81 Reference Stratigraphy. The report concludes with a short summary.

III. STRATIGRAPHY

A. Shift in Reference Depth

The stratigraphy near the underground WIPP horizon has been characterized by examining 41 cores and core logs [10(App C,D,E),15]. These cores were taken throughout the site as it existed in the summer of 1983. The locations of the various coreholes [15] are shown in Figure 1. The layers are fairly planar but dip to the south somewhat. This is shown in Figure 2 taken from reference [15]. Stein, Sandia organization 6331, made quantitative tests on the insolubles at various layers in the core from DH 52,53. It was found that visual estimates of the percentages of impurities listed in the core logs were in error. As an action item from the stratigraphic meeting on June 15, 1983, a group of geologists reexamined the core from four boreholes including DH 52,53. With the measured insolubles as a point of reference for visual estimates, the estimates of impurities listed on the core logs were revised. These four revised core logs were then used by Bechtel National [13] and the TSC/D'Appolonia [14] to identify what they felt were the stratigraphic features which are important to structural analyses. The Sandia National Laboratories input was not documented. All three inputs had generally the same features. These features were then identified on all the 41 logs available. The logs were then shifted to a zero level at anhydrite b above the drifts. Anhydrite b was chosen because of its proximity to the drift and its lack of waviness. The height of the various layers above anhydrite b as well as their thicknesses were then listed as shown in Table I.

B. Layer Thicknesses

Average thickness of the anhydrite layers and their standard deviations are listed as entries in Table I. Note the considerable variation in the thicknesses of the anhydrite layers. Fortunately, these variations are not very important in a structural analysis because most of the layers are thin.

Table I. Heights and Thicknesses of Distinct Layers Measured with Respect to the Base of Anhydrite b. All Entries are in Meters

Core Number	Location of Corehole	Elevation of Anhydrite b	Anhydrite c		Anhydrite MB 139		Unit 4		Anhydrite b	Anhydrite a		Anhydrite MB 138	
			Btm	Thk	Btm	Thk	Btm	Thk	Thk	Btm	Thk	Btm	Thk
DH 227,228	S3656 E147	382.25	-16.09	.06	-8.47	.64	-3.69	.55	tr	1.77	.24	8.78	.15
DH 223,224	S3079 E154	385.05	-15.97	.09	-8.35	.94	-3.96	.82	tr	1.83	.30	9.05	.21
DH 219,220	S2422 E162	388.41	-16.28	.06	-8.50	.67	-3.66	.79	.01	1.98	.18	9.17	.24
DH 215,216	S1960 E153	389.96	-16.82	.06	-8.93	1.01	-3.60	.64	.06	2.01	.15	9.27	.18
DH 211,212	S1320 E163	389.63	-16.92	.09	-8.90	.58	-3.72	.91	.03	2.04	.18	9.20	.15
DH 207,208	S697 E155	386.65	-17.16	.06	-9.02	1.07	-3.61	.82	.05	2.13	.21	9.27	.24
MB 139-2, DO-229	S410 E150	386.58	---	---	-9.14	.98	-3.81	.88	.03	2.26	.21	9.57	.15
Vent Shaft	S410 E25	386.91	---	---	-8.87	1.06	-3.93	.76	.06	2.10	.24	9.40	.18
DO 201,202	S406 W19	387.07	-17.16	.12	-8.81	.85	-4.15	.94	.06	2.16	.21	9.33	.18
MB 139-3	S101 E157	---	---	---	---	.70	---	.70	---	---	---	---	--
MB 139-4	S99 W17	---	---	---	---	1.04	---	.94	---	---	---	---	--
Expl. Shaft	N0 E0	390.37	-17.28	.11	-8.99	.85	-3.88	.91	.08	2.16	.23	9.39	~ .15
MB 139-1	N79 W6	---	---	---	---	.67	---	.94	---	---	---	---	--
DO 52,53	N146 W4	391.88	-16.70	.06	-8.44	1.13	-3.66	1.01	.06	2.04	.15	9.51	.12
DO 45,46	N254 E147	393.92	-16.70	.06	-8.81	1.25	---	---	.03	2.77	.18	9.91	.18
DO 203,204	N624 E140	398.13	-16.18	.06	-8.29	.79	---	---	.06	1.89	.24	8.81	.21
DO 56,57	N621 E0	397.64	-16.64	.09	-8.75	.64	-3.90	1.01	.06	2.10	.18	9.05	.15
DO 63,64	N1110 E0	401.45	-15.79	.18	-8.66	.67	-3.53	.98	.06	2.16	.37	9.02	.21
DO 67,69	N1265 W231.5	401.45	-15.91	.09	-8.26	.94	-3.29	.64	.08	2.13	.27	8.93	.12
DH 77,79	N1270 W364.5	400.75	-16.00	.06	-8.38	.98	-3.41	.76	.08	2.04	.09	8.90	.30
DO 88,90	N1265 W497.5	400.23	-16.22	.05	-8.17	.93*	-3.62	.76	.07	2.13	.15	8.84	.26
DO 91,93	N1275 W630.5	399.91	-15.88	.09	-8.29	1.04*	-3.52	.79	.05	2.16	.21	8.90	.21
DO 205,206	N1410 E0	403.13	-15.76	.06	-8.84	.40	-3.63	.85	.06	2.04	.21	8.93	.24
Average			-16.41	.08	-8.63	.86	-3.70	.83	.06	2.10	.21	9.16	.19
Std. Deviation			.51	.03	.30	.21	.21	.13	.02	.20	.06	.30	.05

*This includes an adjacent polyhalite layer

The thickness of MB139 is important because of its proximity to the drift and its considerable stiffening effect. It is known to be very non-uniform in thickness as shown in Figure 3 for the variation around the shaft [10(App C)]. Note from the figure that if a small diameter core were to have been taken from the areas shown, the thickness might have been measured as 0.61 m to 1.06 m (2.0 to 3.5 ft) in the exploratory shaft [10(App C, Fig. 4] and from 0.53 m to 1.08 m (1.7 to 3.5 ft) in the ventilation shaft [10(App D)]. The local variation in thickness of MB139 must be averaged out over a considerable bedding area in order to make plane strain drift calculations. The layer thicknesses found from the core are essentially values found at a point in the plan view of the site. In Table II, the average thickness of MB139 and its standard deviation have been determined for the data taken on the two shafts, for the data in Table I, and for two subsets of the Table I data. Note that the average value is not a strong function of north/south position. Note also that as data from larger areas are used, then the standard deviation becomes larger. The relation between standard deviation of the thickness of MB139 S and averaging area A is roughly

$$S = 0.1\ A^{0.06} \qquad (1)$$

where S is in meters and A in square meters. This seems to indicate a long range variation in thickness as well as the short range variation shown in Figure 3. For a 10 m room width, it would not be unreasonable to average the bed thickness over a $400m^2$ area centered on the drift at the station of interest. The standard deviation expected over this area would be given from Eqn (1) as 0.14 m so that the variation would be roughly that seen in Figure 3. A careful study of the statistics could probably produce an expected average thickness as a function of position over the site. At this point in time, it does not seem reasonable to pursue this approach for three reasons: (i) the confidence in the results would be low because of the small sample size, (ii) it is presently necessary to assume that the thickness variation is isotropic[1] and homogeneous[2], (iii) it appears from Table II that the variation over the site would not be large enough to significantly affect structural behavior of the drifts in any case.

The thickness of MB139 as averaged over a 10 m^2 area or larger is a reasonable characterization of the layer in that region. It also appears that layer thicknesses averaged over the entire site are the best values to use at every location on the site. This conclusion is based on the study included as Appendix B. In that study, the thicknesses and relative depths of the anhydrite layers were assumed to vary in a linear manner from north to south. The least square fits to the data, however, showed very little regular variation from north to south. Furthermore, it was found that the variations in the variables were not statistically significant. More concisely, based on the data in Table I, one cannot even determine whether

1. If the shape of the thick and thin places are not generally directional like a plowed field, then the variations are said to be isotropic.

2. If the variation is the same everywhere, i.e., there are no areas which are smoother than others, then it is said to be homogeneous.

TABLE II. VARIATION IN THICKNESS OF ANHYDRITE MB139

Location	Average Thickness (m)	Standard Deviation (m)	Averaged Area (m)
Ventilation Shaft	1.06	.15	1.8 m dia = 10.5 m^2
Exploratory Shaft	.85	.11	3.6 m dia = 42. m^2
Entries, Table I	.86	.21	240 x 1540 = 370,000 m^2
S Entries, Tbl. I	.90	.21	55. x 1190 m = 66,000 m^2
N Entries, Tbl. I*	.80	.22	235. x 240 m = 56,000 m^2

*Last eight entries in Table I.

any layer thickens or whether it thins from north to south, much less quantify the variation. Thus, averages of layer thicknesses over the entire site are used here to determine the reference stratigraphy.

The mixed layers are more difficult to identify and abstract for the reference stratigraphy. Some of these layers are present in one core but not the other or they have shifted position with respect to the anhydrite layers. Fortunately, the mixed layers are not adjacent to the drift and it is estimated in the next section that the properties are not drastically different from pure rock salt. Several argillaceous layers are identified near MB138 on the logs from the southern end of the site which have 3-4% clay. Only one smaller thickness layer of this type is seen in the log of D079 taken from the north end. The logs of eight coreholes from the northern end of the site (the last eight entries in Table I) were then compared in the region between anhydrite a and MB138. All the clay seams, breaks, and partings from the logs are identified in Figure 4. Clusters of clay discontinuities and/or argillaceous halite layers are noted in all the logs. Their general locations are not significantly different from those found at the southern end of the site. For this reason, it seems that although D079 has fewer impurities than are found at the southern end of the site, it is far from pure and it would not be unreasonable to include clay discontinuities or argillaceous layers in a model at the clustered regions shown in Figure 4. The thicknesses of the argillaceous layers in this region were taken as a subjective average of that seen in DH227, DH215, D052, and from Figure 4.

Unit 4 in Table I has been mapped in all the drifts at the site. For consistency, these maps were used at locations nearest each of the corehole locations in Table I and the resulting values entered in the table.

C. Locations and Identification of Layers

The locations and identifications of each of the layers for the September '83 Reference Stratigraphy are shown in Figure 5. Averages over the entire site which are listed in Table I have been used for most of the layers.

The layers above clay L were taken from the logs of the ventilation shaft and exploratory shaft. The average height of the layers above mid-height of MB138 was taken from the shaft logs and this same elevation difference was used to construct Figure 5.

The layers below anhydrite c were taken from the logs of ERDA 9. In Table III, the significant layers from the geologic log of ERDA 9 are compared to the position of layers from Table I. We note that the two stratigraphic columns are very similar. This is used to justify the use of the ERDA 9 log to append MB140 and MB141 to the data in Table I. The distance between anhydrite c, MB140 and MB141 are taken for the Reference Stratigraphy to be the same as for ERDA 9. The values are shown in parentheses in Table III.

The thicknesses and locations of the combined layers on the ERDA 9 log denoted as MB136, MB140, and MB141 in Table III were found as follows. Adjacent layer thicknesses were added to obtain the thickness of the idealized layer. (This included three thin polyhalite layers in MB136 and one thin one in MB140 as well as a thin claystone layer in MB141. The properties are similar enough to make this a reasonable approximation). The location of the idealized layer was found by requiring the average height (first moment) to be identical to the actual layers. This averaging was necessary since the several layers in each case were interspersed with halite layers.

Anhydrite b is shown in Figure 5 but should not be included in a structural model since it is too thin to be structurally sound. Its presence as an elastic layer in a model could introduce a local stiffness that is not physically realizable.

The clay layers are designated with letters from A through M and are taken to be of zero thickness. A clay layer C was originally defined in the rough draft of this report but was subsequently removed after discussions with various participants. The remaining layers retained their original designations.

Table III.
Midheights of Significant Layers Taken from the Geologic Log of ERDA 9 as Compared with Table I.

Layer I.D.	Height Above the Datum (m)	
	ERDA 9	Table I
MB136	30.79	30.61
MB137	23.47	---
MB138	9.39	9.26
Anhydrite	5.19	---
Anhydrite a	2.20	2.20
Anhydrite b	---	.03
MB139	-8.29	-8.20
Anhydrite c	-16.76	-16.37
MB140	-28.56	(-28.17)
MB141	-52.82	(-52.43)

Note: MB136 includes 7 layers here, MB140 includes 5, and MB141 includes 4.

D. Comparison with Input from Bechtel and TSC/D'Appolonia

Bechtel, TSC/D'Appolonia, and Sandia each proposed an idealized or reference stratigraphy as outlined in Appendix A. The stratigraphies from Bechtel and TSC/D'Appolonia are compared in Figure 6 with the compromise reference described above. The principal difference is that the reference includes several clay seams not present in the others and is a single stratigraphy whereas Bechtel proposed two references, one for the southern end and another for the northern end. The justification for the single stratigraphy is given in Appendix B and discussed above in connection with layer thicknesses and will not be repeated here. The clay seams were included primarily to signal caution to a designer or stress analyst that trouble is possible if mining occurs in these horizons. These are planes (or at least zones) where slip is possible. With the coefficient of friction of 0.4 specified for these seams, most of them will not actually demonstrate slip in most calculations. Since slip planes can increase the cost of an analysis, even if they are not active, it is generally best to omit them from a model if they are not active. This depends upon their location relative to a drift or other disturbance, the coefficient of friction of the clay seam, and the time for which the analysis is to be run. Auxiliary studies can be made to identify active seams in any particular case.

IV. MECHANICAL PROPERTIES

A. Lithostatic Stress and Density

The idealized stratigraphy of the previous section does not extend up to the surface. It is necessary to apply pressure at the top (and bottom) of a structural model of this stratigraphic interval. The value of pressure to be used here is based on the weight of overburden rock above the site. An average density of 2320 kg/m^3 has been calculated [16] by integration of the mass density measured in the well log on ERDA 9 for the interval from the surface to the room horizon. The depth of anhydrite b is given from the geologic logs of the exploratory and vent shafts as 648.24 m and 652.67 m, respectively. Using an average of 650.45 m and the height of 52.87 m to the top of MB 134 (from Figure 5) we find 597.58 m of overburden at the top of the defined stratigraphy. A value of the elevation adjusted acceleration of gravity of 9.790 m/sec^2 is used then to obtain

$$p = (9.790)(597.58)(2320.)$$

$$= 13.57 \text{ MPa } (1968. \text{ psi})$$

This is to be used as the isotropic lithostatic stress state at the top of the stratigraphic section idealized here.

A constant average density over the interval of depth used in the September '83 Reference Stratigraphy can be used for convenience. The value to be used was found by adding all the layers of halite and argillaceous halite to obtain a thickness of 90.02 m. If 99% of this is pure halite, then over the 107.06 m interval studied, we have 89.12 m of halite (2163. kg/m^3) and 17.94 m of other material for which we assume the density of anhydrite (2960. kg/m^3). This mixture gives a weighted average of

$$\rho = \frac{(89.12)(2163.)+(17.94)(2960.)}{107.06}$$

$$= 2300. \text{ kg/m}^3$$

This gives a lithostatic stress at the clay seam F of 14.83 MPa (2150.psi).

B. Thermal and Mechanical Properties

Only five materials are identified in the stratigraphy and listed here. The properties of these layers are given in this section. They are generally the same properties as were identified in the July '81 Reference Stratigraphy [8] and used elsewhere [7,9,10]. This section is organized as follows. Two tables of properties are presented, one with thermal properties and the second with mechanical properties with terms defined in the text. The source of each quantity is then identified or explained.

B1. Thermal Properties

The thermal properties are listed in Table IV. Note that clay is missing from the table. Since the clay seams are generally less than 0.02m (1. in) thick, they are ignored thermally.

The density is taken to be the same value for all materials as discussed in the previous section.

Values of specific heat are also taken to be the same for all materials. The Debye temperature for salt is near room temperature so that the variation of the specific heat with temperature is small at temperatures of interest here.

TABLE IV. Thermal Properties for the WIPP Materials

Material	Density* ρ (Kg/m^3)	Specific* Heat, C_p (J/kg-K)	Coefficient of Linear Thermal Expansion, α (K^{-1})	Thermal Conductivity Parameters	
				λ_{300} (w/mK)	γ
Halite	2300.	860.	45.0 E-6	5.0	1.14
Argillaceous Salt	2300.	860.	40.0 E-6	4.0	1.14
Anhydrite	2300.	860.	20.0 E-6	4.7	1.15
Polyhalite	2300.	860.	24.0 E-6	1.4	0.35

*These values are taken to be the same for convenience in analysis. Actual values differ somewhat.

The coefficients of linear thermal expansion are measured quantities [17]. Core specimens were used for these tests with samples taken at various depths.

Thermal conductivity for the materials [17,18,19] were fitted to the equation

$$\lambda = \lambda_{300} \, (300/T)^{\gamma}$$

where T is temperature in kelvin. The thermal conductivity expression given here has been compared by Torres [20] to data for salt from West Germany where it was found that the values were within roughly ± 3% from room temperature to 200°C.

B2. Elastic Constants

Suggested values for the elastic constants of halite, anhydrite, and polyhalite [18,19,21] are listed in Table V for 25°C and 100°C. Both anhydrite and polyhalite properties show some change with temperature; however, for reference calculations the values for 25°C should be used. Argillaceous halite is considered to be similar to the "clean" halite units and, therefore, should be assigned the same elastic constants. For the present, the elastic constants for the halite and argillaceous halite units are considered to be independent of temperature, and the values indicated for 25°C should be used.

TABLE V. Elastic Constants

	Halite*	Anhydrite **		Polyhalite**	
	25°C	25°C	100°C	25°C	100°C
Young's Modulus (E)	31.0 GPa	75.1 GPa	51 GPa	55.3 GPa	46.1 GPa
Poisson's Ratio, ν	0.25	0.35	0.26	0.36	0.30
Bulk Modulus (K)	20.7 GPa	83.4 GPa	35.4 GPa	65.8 GPa	38.4 GPa
Shear Modulus (μ)	12.4 GPa	27.8 GPa	20.2 GPa	20.3 GPa	17.7 GPa

*Similar constants for Argillaceous Halite are to be used

**As determined from tests [22,23] at a strain rate of 2.1×10^{-4} sec^{-1}

B3. Creep Constitutive Properties

The constitutive models for the materials exhibiting creep behavior are described as follows [21].

The strain rate is characterized by the equation:

$$\dot{\varepsilon}_{ij} = -\frac{\nu}{E}\dot{\sigma}_{kk}\,\delta_{ij} + \frac{1+\nu}{E}\,\dot{\sigma}_{ij} + \dot{\varepsilon}^{c}_{ij} + 3\alpha\,\dot{T}\,\delta_{ij} \tag{2}$$

where

σ_{ij} are the components of the stress tensor.

ν is the Poisson's ratio.

E is Young's modulus.

T is temperature, degrees kelvin.

α is coefficient of linear thermal expansion.

δ_{ij} is the Kronecker Delta,

and the creep strain rate, $\dot{\varepsilon}^{c}_{ij}$, is given by:

$$\dot{\varepsilon}^{c}_{ij} = \left|\dot{\varepsilon}^{c}_{kl}\right| \frac{\sigma'_{ij}}{\left|\sigma'_{mn}\right|} \tag{3}$$

where σ'_{ij} are the components of the deviatoric stress tensor. Standard summation convention is implied.

For the case in which only secondary creep (steady state) is considered, the magnitude of the creep strain rate can be expressed in terms of the effective creep strain rate, $\dot{\bar{\varepsilon}}$, or the effective stress, $\bar{\sigma}$, as follows [24]:

$$\left|\dot{\varepsilon}^{c}_{ij}\right| = \sqrt{1.5}\;\dot{\bar{\varepsilon}} \tag{4a}$$

$$\dot{\bar{\varepsilon}} = D\,\bar{\sigma}^{n}\,\exp(-Q/RT) \quad . \tag{4b}$$

where $\dot{\bar{\varepsilon}}$ is defined as:

$$\dot{\bar{\varepsilon}} = \left(\frac{2}{3}\ \dot{\varepsilon}^{c}_{ij}\ \dot{\varepsilon}^{c}_{ij}\right)^{1/2} \tag{5}$$

while $\bar{\sigma}$ is

$$\bar{\sigma} = \left(\frac{3}{2}\ \sigma'_{ij}\ \sigma'_{ij}\right)^{1/2} \tag{6}$$

D, n are constants determined from data analysis.

T is temperature, degrees kelvin.

Q is the effective activation energy, cal/mole.

R is the universal gas constant, 1.987 cal/mole-K.

Values for the parameters are given in Table VI.

Table VI. Constants for Reference Creep Law
(Repository Level, Nominal Elevation 390 m)

Material	Primary Constants			Secondary Constants		
	A	B	$\dot{\varepsilon}^*$ (sec^{-1})	D ($Pa^{-4.9}/sec$)	n	Q (Kcal/mole)
Halite	4.56	127	5.39 E-8	5.79 E-36	4.9	12.0
Argillaceous Halite	4 56	127	5.39 E-8	1.74 E-35	4.9	12.0

In many cases, clay seams can be modeled by a slip line, which allows compressive but no tensile normal stresses. Transverse forces can be transmitted with the frictional coefficient given in Section B5 for clay seam mechanical response.

The creep constants are based on the analysis of data presented in References 24, 25, and 26. The expressions used here are equivalent to those in Reference 24 but have been expressed in terms of effective strain rate.

A factor of 2/3 must be used to convert the steady state shear creep strain rate ($\dot{\gamma}_s$) in a triaxial test to effective creep strain rate $\dot{\bar{\varepsilon}}$ as:

$$\dot{\bar{\varepsilon}} = 2/3 \ \dot{\gamma}_s \tag{7}$$

Reference values for secondary creep strain rates from these formulations are given in Table VII:

Table VII Secondary Creep Effective Strain Rate $\dot{\bar{\varepsilon}}$

Temperature	Effective Stress	
	5 MPa	15 MPa
300°K	7.02 E-12	1.53 E-9
350°K	1.25 E-10	2.71 E-8

If primary creep is to be included in the constitutive model, the primary creep rate is derived [26;(Eqs 27, 28, 29; p 19)] in the following manner.

The effective creep strain rate is the sum of the secondary and primary terms as:

$$\dot{\bar{\varepsilon}} = \dot{\varepsilon}_s + \dot{\varepsilon}_p \tag{8}$$

The secondary term $\dot{\varepsilon}_s$ is defined exactly as before (Eq 4b), and the primary term $\dot{\varepsilon}_p$ is obtained from the solution of the following differential equation:

$$\dot{\varepsilon}_p = (A-B\ \varepsilon_p)\dot{\varepsilon}_s \text{ for } \dot{\varepsilon}_s \geq \dot{\varepsilon}^* \tag{9a}$$

and

$$\dot{\varepsilon}_p = (A-B\ \frac{\dot{\varepsilon}^*}{\dot{\varepsilon}_s}\ \varepsilon_p)\dot{\varepsilon}_s \text{ for } \dot{\varepsilon}_s < \dot{\varepsilon}^* \tag{9b}$$

where the initial condition of $\varepsilon_p = 0$ at $t = 0$ is assumed.

The primary creep constants A, B, and $\dot{\varepsilon}^*$ are given in Table VI. Equations (3), (4), and (8) are combined to give:

$$\dot{\varepsilon}^c_{ij} = 1.5 \frac{\sigma'_{ij}}{|\sigma'_{mn}|} \left[D\bar{\sigma}^n \exp(-Q/RT) + \dot{\varepsilon}_p \right] \tag{10}$$

where $\dot{\varepsilon}_p$ is given by Eqs (9).

The argillaceous halite is not considered to be significantly different from the "clean" halite. The secondary creep constants indicated in Table VI for argillaceous halite are derived from preliminary test results [27].

The failure of halite can be described using a failure function ϕ such that when ϕ becomes positive, halite no longer supports any deviatoric stress. This function will be assumed to be given by the following:

$$\phi = \bar{\varepsilon} - 0.023 - f(p) \tag{11}$$

where p is the pressure which is positive in compression, $\bar{\varepsilon}$ is the effecive creep strain found from the integration of Eqn (3) using Eqs (4) or (10) and the expression:

$$f(p) = \begin{cases} 0.132 \text{ for } p \geq 6.0 \text{ E6 Pa} \\ p(a-bp) \text{ otherwise} \end{cases} \tag{12}$$

Here $a = 4.43$ E-8 Pa^{-1}, and $b = 3.7$ E-15 Pa^{-2}.

The relation between pressure and effective strain for $\phi = 0$ is shown in Figure 7.

B4. Anhydrite and Polyhalite Failure Criteria

The mechanical response of both anhydrite and polyhalite can be considered as isotropic and linearly elastic up until failure [22,23]. Failure is described in terms of the fracture stress or ultimate strength of the rock, which is the maximum load it can support in a stress-strain test. Ultimate strengths of both rocks can be assumed to be independent of temperature between 25°C and 100°C, and creep can also be ignored.

Fracture of both rocks can be described equally well by two fracture criteria because insufficient information exists to distinguish between the two (the differences are expected to be small) [22]. The Mohr-Coulomb criterion can be stated in terms of resolved principal stresses where $\sigma_1 \leq \sigma_2 \leq \sigma_3$ as

$$\sigma_3 - \sigma_1 = 2\tau_0 \cos\beta - (\sigma_3 + \sigma_1)\sin\beta \tag{13}$$

The Drucker-Prager is the other criterion which can be used and is stated as

$$\sqrt{J_2'} = C - aJ_1 \tag{14}$$

where $\sqrt{J_2'}$ is the second deviatoric stress invariant, and is equal to $\bar{\sigma}/\sqrt{3}$ and J_1 is the first stress invariant or the sum of the three normal stress components. Constants for these equations are given in Table VIII [22,23]. For anhydrite, there is a slight decrease in ultimate strength with decrease in strain rate of approximately 5% for every decade of strain rate change, i.e., a 10% decrease in going from 10^{-4} sec^{-1} to 10^{-6} sec^{-1}. Polyhalite ultimate strengths can be assumed independent of strain rate.

Although there is very little deviation of stress-strain curves from elastic response as the fracture stress is approached, a yield point is detectable in both rocks. The yield point is defined as the onset of dilatancy. Since some designs are based on yield rather than ultimate strength, yield stress design parameters are also listed in Table VIII. The yield point of anhydrite is consistently observed to be 75% of the ultimate strength and is 81% of the ultimate strength for polyhalite.

Table VIII. Failure Parameters* for Anhydrite and Polyhalite

Type of Failure	Anhydrite	Polyhalite
Ultimate		
Mohr-Colomb	τ_0 = 30 MPa	τ_0 = 18.9 MPa
	β = 37°	β = 51°
Drucker-Prager	a = 0.279	a = 0.395
	c = 36 MPa	c = 19.8 MPa
Yield		
Mohr-Coulomb	σ_0 = 27 MPa	σ_0 = 17.2 MPa
	β = 29°	β = 46.5°
Drucker-Prager	a = 0.226	a = 0.361
	c = 33 MPa	c = 19.3 MPa

*Data from triaxial compression tests at strain rates of approximately 2.1×10^{-4} sec^{-1} [22,23].

B5. Clay Seam Mechanical Response

Clay seams in the middle to lower part of the Salado formation at the WIPP site are described as [28]:

1. At most a few centimeters thick

2. Having nonplanar bounding surfaces

3. Having evaporite growths of halite, anhydrite, and polyhalite penetrating into them

4. Having a significant component of quartz and illite.

Thus, the clay seams tend to be simply layers of evaporites which contain higher concentrations of silicates than adjacent evaporites. Clay seams D, I and J in Figure 5 actually correspond to clusters of thin clay partings similar to those seen in Figure 4. Their combined behavior is taken to be that of a clay seam. In view of the "grit" interspersed in the clay minerals and the nonplanar bounding surfaces, a coefficient of static and dynamic friction of 0.4 is recommended for all reference calculations. This simple description of clay with a dry friction model may appear to the uninitiated as an ad hoc assumption. This is not the case however. The bulk clay might conventionally be modeled as a Mohr-Coulomb material. For the special case of a thin layer, the relation between these two models can be shown as follows.

The Mohr-Coulomb material is taken to be an elastic-perfectly plastic material with a yield stress, Y, which varies linearly with pressure, p, as given by

$$Y = \tau_0 + p \tan \phi$$

where p is positive in compression. For a set of experimentally observed yield stresses under specified pressures, the constants α and ϕ may be determined. The general yield condition is then written as

$$(a+cp)^2 = \frac{1}{2}\left[(\sigma_{11}-\sigma_{22})^2 + (\sigma_{22}-\sigma_{33})^2 + (\sigma_{33}-\sigma_{11})^2\right] + 3\left[\sigma_{12}^2 + \sigma_{13}^2 + \sigma_{23}^2\right]$$

A thin clay seam is now considered in a geologic setting where the normal stress components are roughly equal to each other, i.e.,

$$p \cong -\sigma_{11} \cong -\sigma_{22} \cong -\sigma_{33}$$

where the normal stresses are positive in tension. The coordinate system is oriented such that the x_1-direction is normal to the plane of the seam and the x_2-direction is in the direction of motion or incipient motion.

Then σ_{12} is the only non-zero term on the right side of Eqn (11) so that it may be rewritten as

$$\sigma_{12} = \frac{\alpha - \sigma_{11} \tan \phi}{\sqrt{3}}$$

If the cohesive strength is small, then Eqn (12) is the form of a dry friction law:

$$\sigma_{12} = \mu \, |\sigma_{11}|$$

Thus, Eqn (12) applies to a Mohr-Coulomb material under clay seam conditions. In spite of this correspondence between the dry friction surface model and Mohr-Coulomb bulk behavior, it is preferable to consider a clay seam as a dry friction surface. This is due to the asperity or roughness of the seam as well as its waviness. The friction factor μ is then increased to account for the seam geometry as well as the basic bulk properties of the clay.

A complete statement of behavior of the clay seam model then is:

if $\sigma_{12} < \mu|\sigma_{11}|$ then no slip occurs and if $\sigma_{12} = \mu|\sigma_{11}|$ then slip takes place and the shear stress is limited to this value. The effect of clay seams on overall behavior of the drifts in the repository has been studied in some detail [29]. Mechanical modeling [30] and numerical behavior of the model has also been of some concern [31]. These studies have shown that the seams near the drift will be active for $\mu = 0.4$, that this is a reasonable value, and that clay seam separation is unlikely unless the seam is very near the drift. The effect of these clay seams is significant in regard to room closure and is discussed in Reference 29.

V. SUMMARY

The September '83 Reference Stratigraphy has been described as shown in Figure 5. The new stratigraphy consists of one polyhalite layer, three argillaceous halite layers, eight anhydrite layers, 12 clay seams, and halite as the remaining constituent. No mixed polyhalite/anhydrite/halite layers are included. The definition of the new stratigraphy is based on Bechtel, the TSC/D'Appolonia, and Sandia interpretations of a detailed re-examination by a selected group of individuals from these concerns of core from four selected coreholes. The location and thicknesses of the various layers were then adjusted by averaging values taken from the 41 core logs listed in Table I. Logs from the vent shaft, exploratory shaft, and ERDA 9 were used for layers remote from the horizon. The uniformity of the logs, the lack of a statistical significance in bed thicknesses and elevation variation, and the expected small influence on structural behavior resulted in a decision to use the same reference stratigraphy everywhere over the site. Anhydrite b was used as the datum layer, and elevations of other layers are specified with respect to it. It is not to be included in the model because of its small thickness.

Properties of materials are listed in Tables IV through VIII and are similar to previously used properties. A change has been made in the lithostatic pressure to be used at the top of the stratigraphic interval. A change in the average density to be used for the stratigraphic section has also been made.

The reader is cautioned that the September '83 Reference Stratigraphy is intended for structural modeling and does not include many stratigraphic details. The core logs are available and should be consulted if details are important. The reader is also reminded that while the Reference Stratigraphy and Material Properties are the basis for structural calculations and by the project participants, parameteric studies and associated analyses are not meant to be precluded by this document. It is expected that this document will be updated as more data become available.

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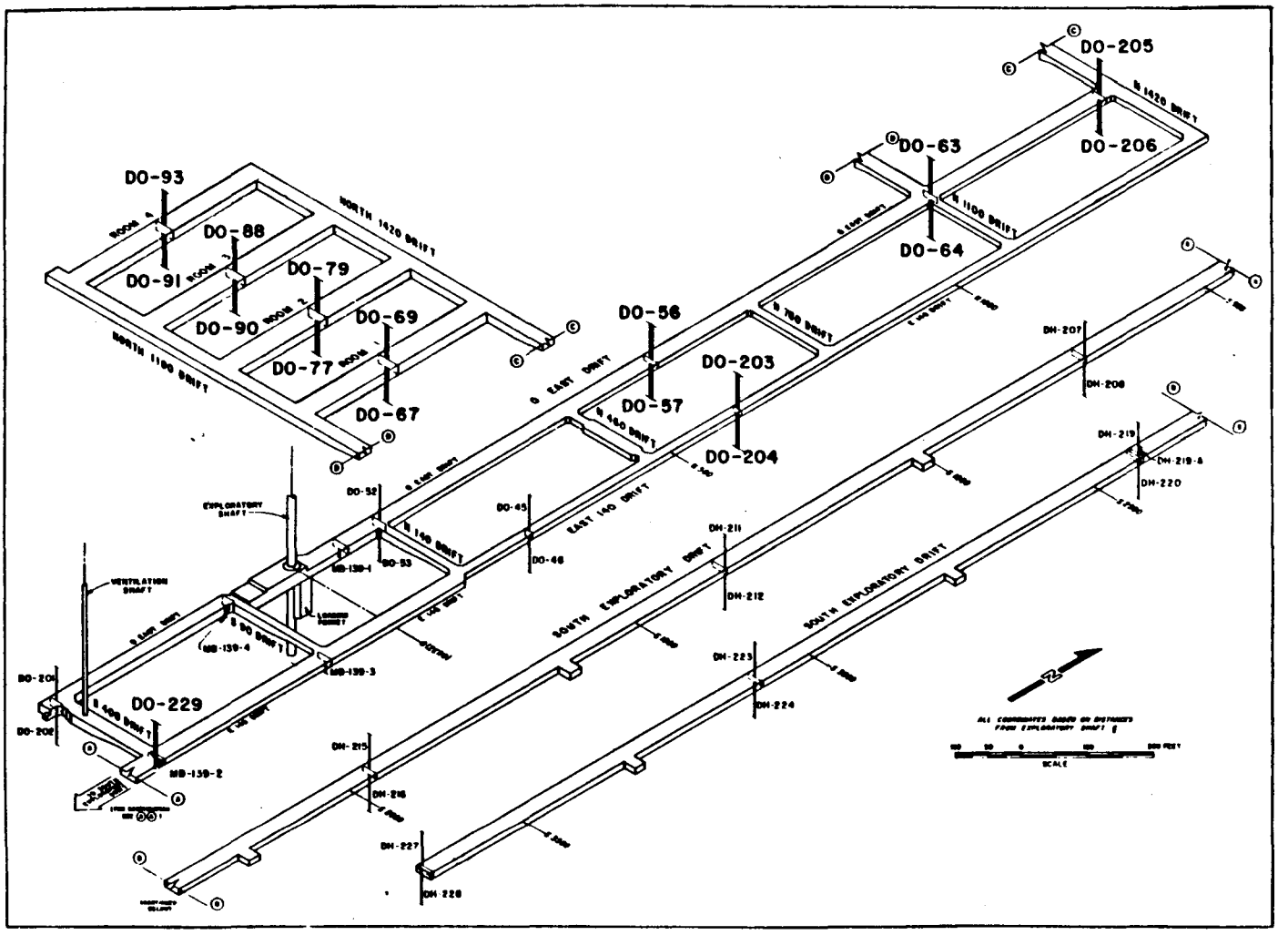

Figure 1. Location of coreholes and shafts whose geologic logs were used in construction of Table I.

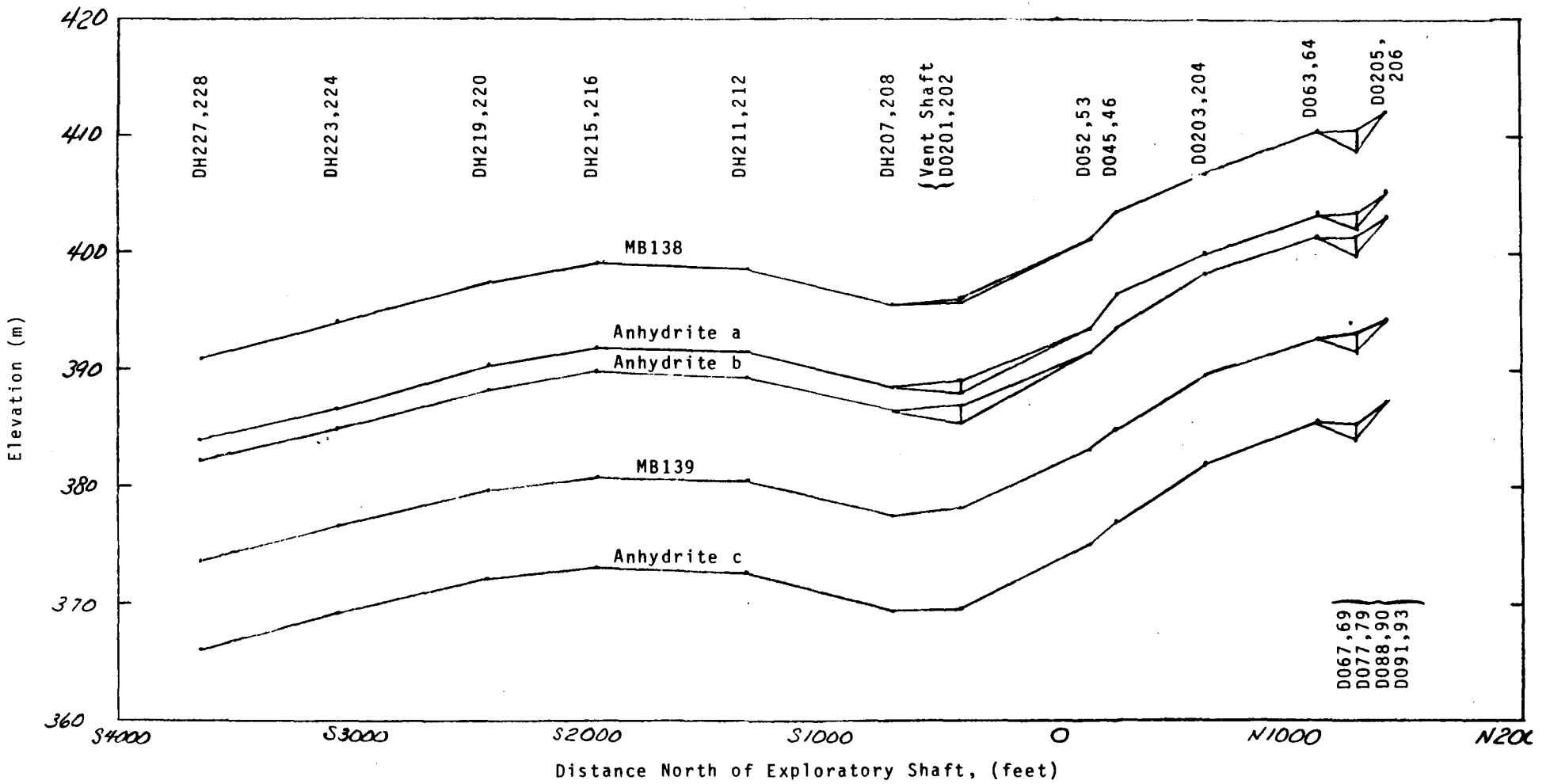

Figure 2. Elevation of the Principal Anhydrite Layers Showing Generally Parallel Layers and Dip Toward the South. Multiple Points Show E-W Spread. See Table I.

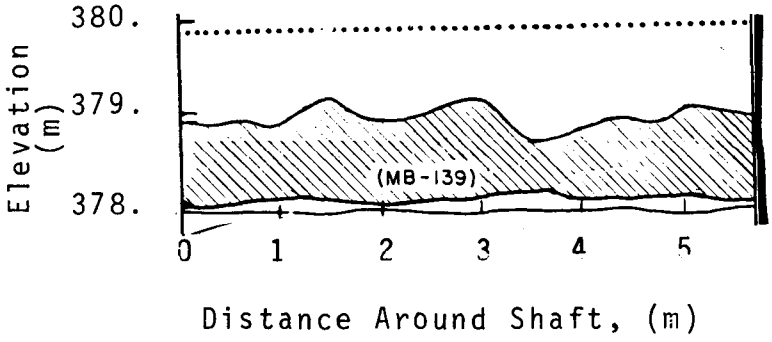

Figure 3a. Mapped shape of MB139 in the ventilation shaft.

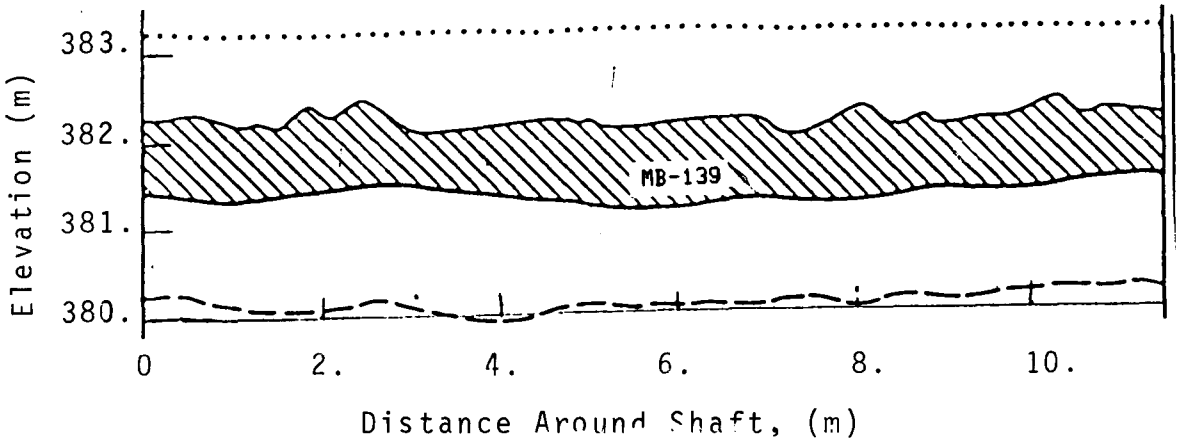

Figure 3b. Mapped shape of MB139 in the exploratory shaft.

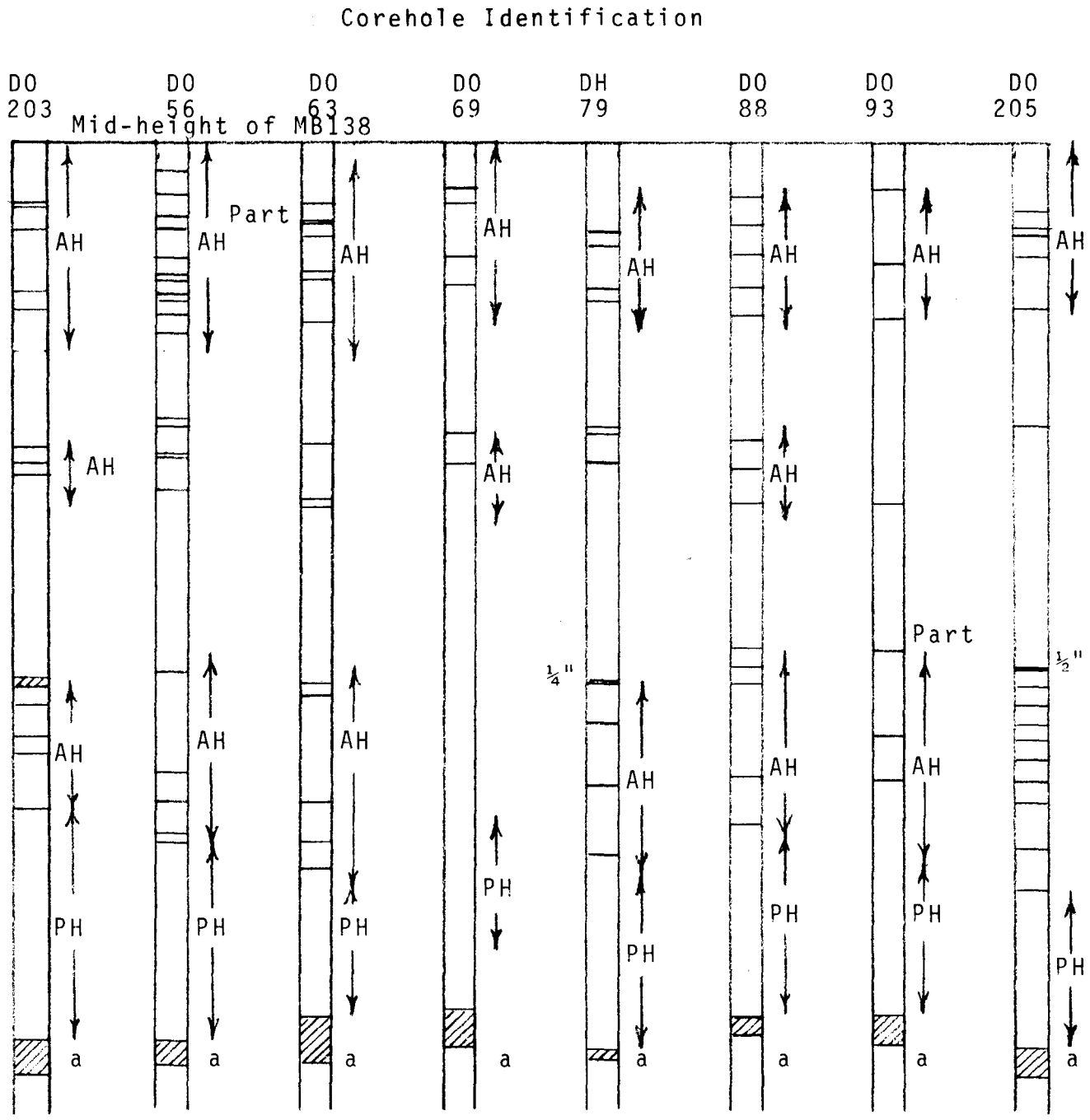

Figure 4. The clay layers are identified in the eight cores taken from the north end of the WIPP site [14]. Argillaceous halite (AH) and polyhalitic halite (PH) layers are identified also. Core logs have been shifted to the mid-height of MB138.

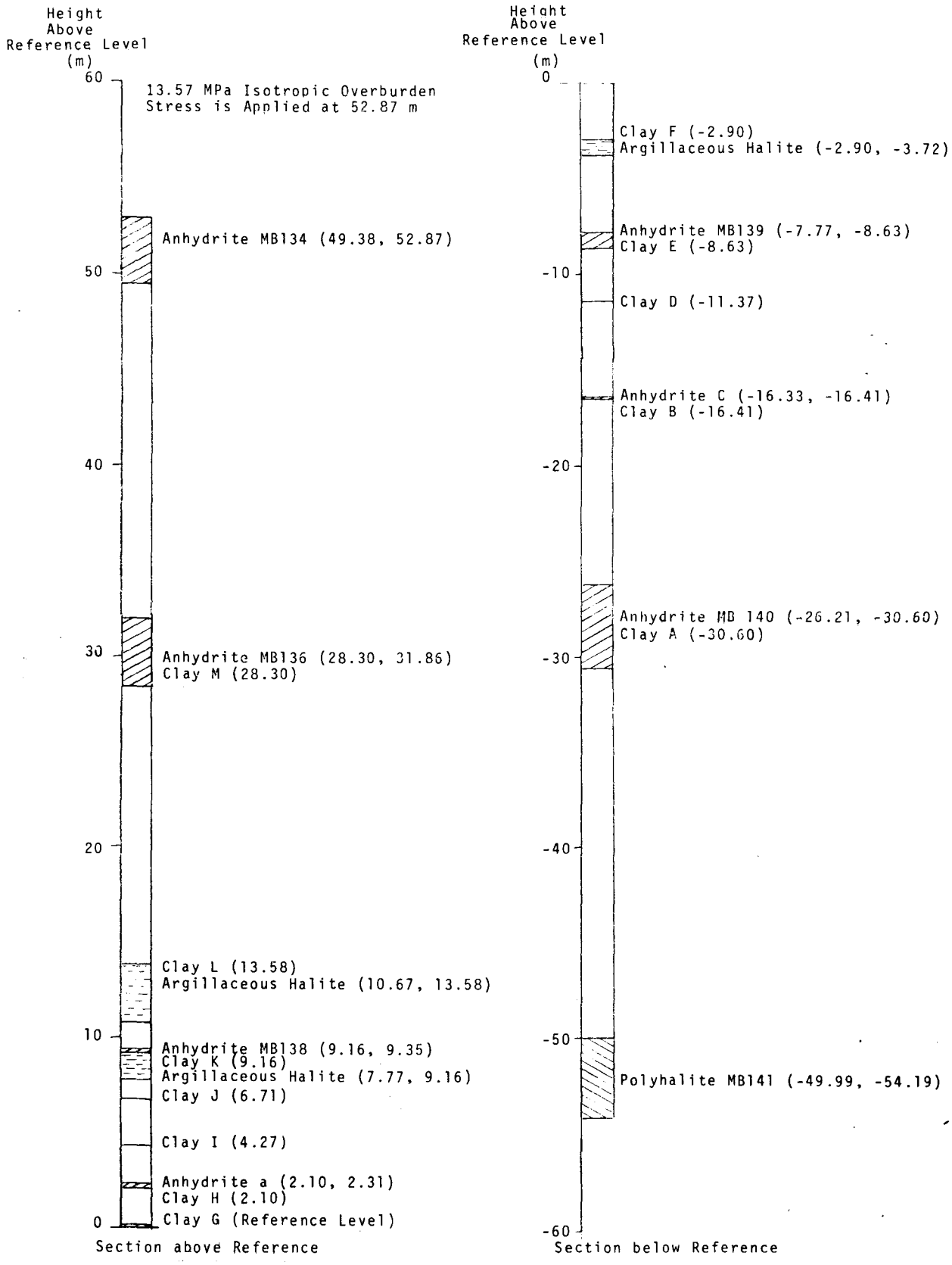

Figure 5. September '83 Reference Stratigraphy. Anhydrite b should not be used in a structural model. It is only included for reference purposes.

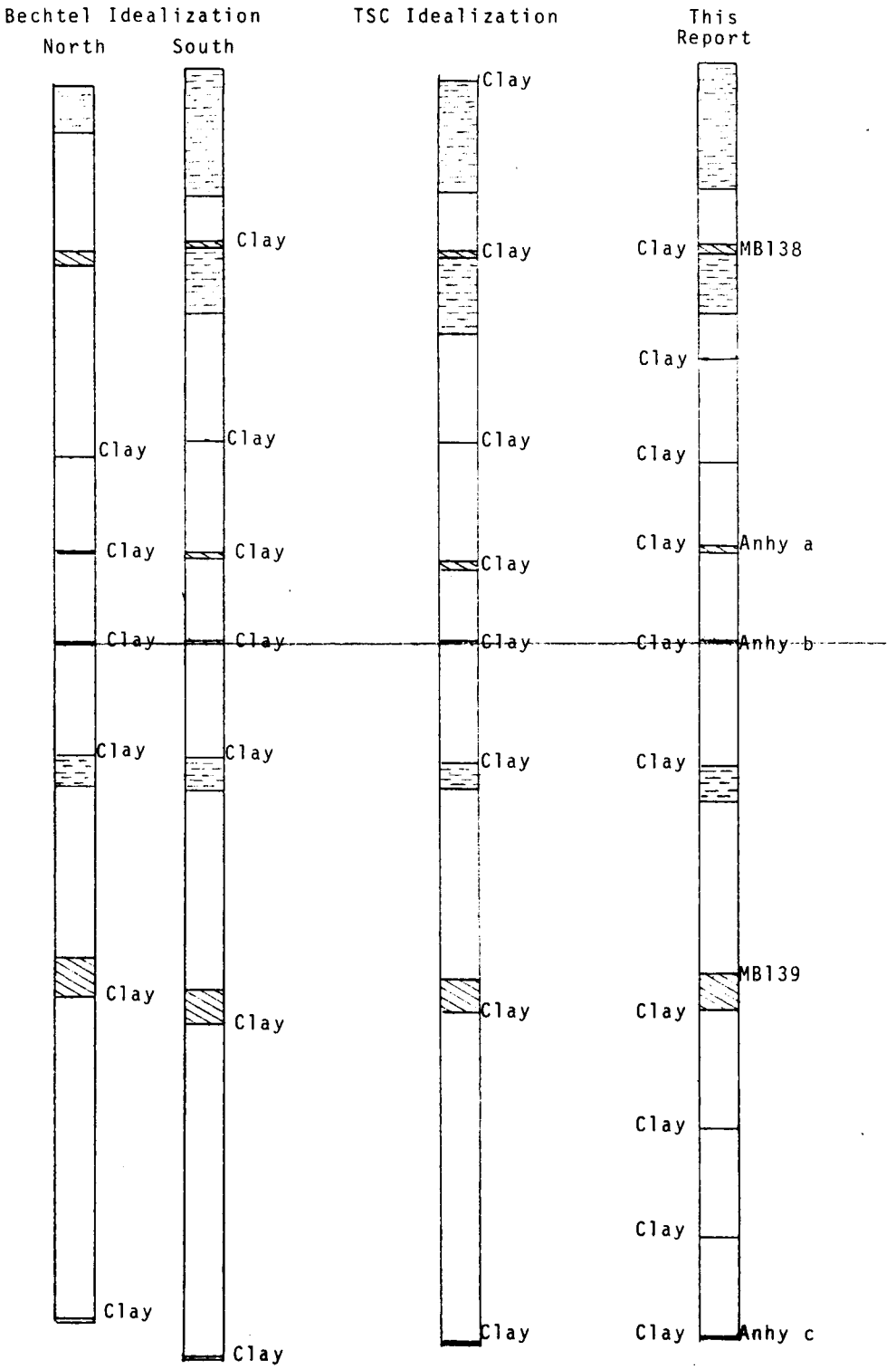

Figure 6. Comparison of idealized stratigraphies of Bechtel and TSC with the idealization of this report.

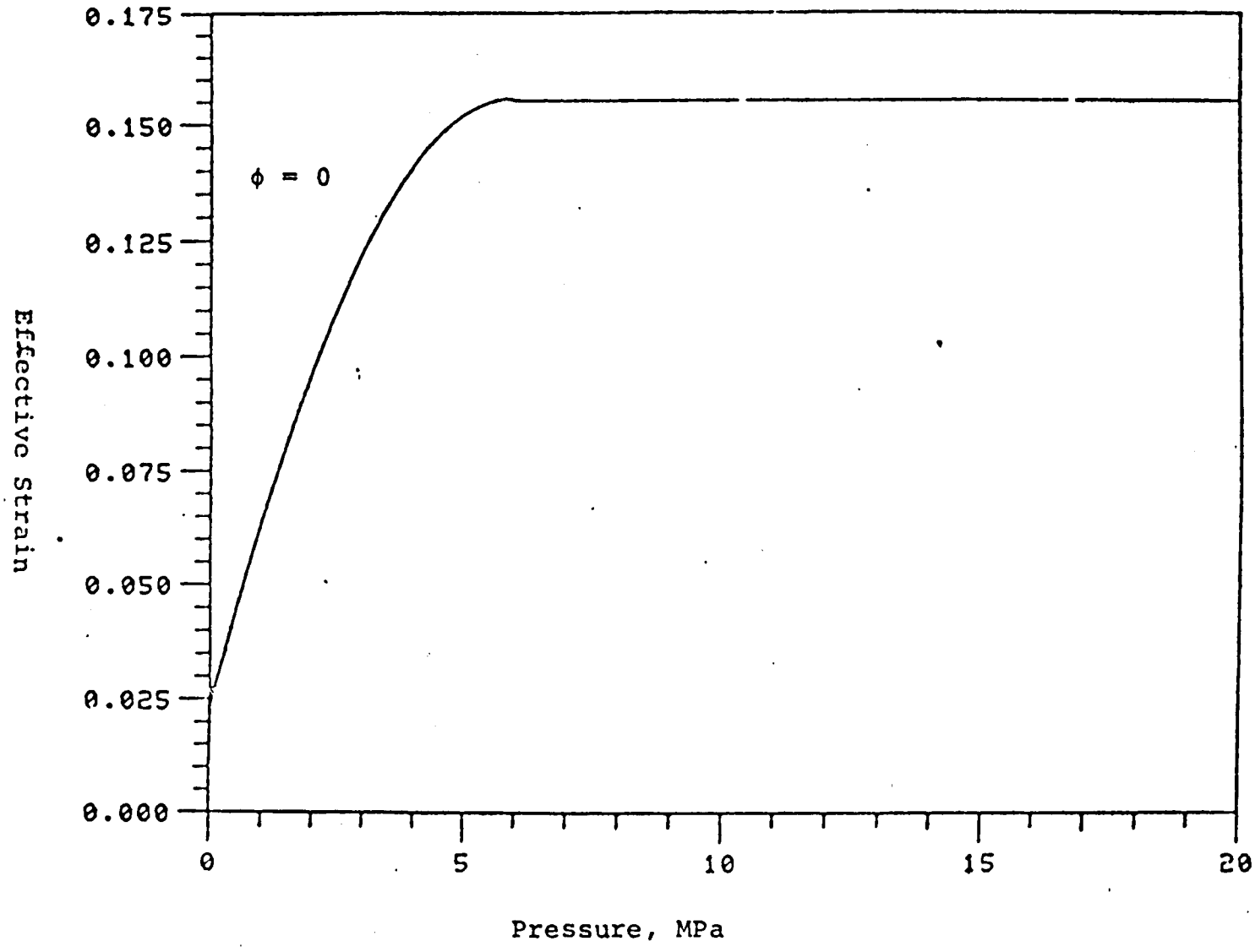

Figure 7. Failure Functions for Halite.

APPENDIX A

REVIEW MEETING ON STRATIGRAPHY AND THERMAL AND MECHANICAL PROPERTIES

Contents

- Meeting Notice
- Agenda
- Attendees
- Notes from Meeting
- Action Items

Progress Review Meeting on Stratigraphy and Thermal and Mechanical Properties Near the Working Horizon at the WIPP

July 7, 1983
8:00am - 4:30pm
Coronado Club, Room B4, Kirtland Base East
Albuquerque, NM

A standard abstracted stratigraphy and set of mechanical and thermal properties was first agreed upon by a group of experimentalists, field geologists, and structural analysts in November 1979. This has been a useful concept both for structural/thermal analyses and for design of experiments at the WIPP. The two shafts have been logged at the WIPP site and about a mile of drifts have been excavated. Some new materials tests have also been performed and some old data reanalyzed. The standard stratigraphy and set of material properties should be updated at this time to include the new information. This data base is not complete since all mechanical tests will not be completed for quite some time. However, many important calculations must be started and experimental detail decisions made prior to test completions. The new standard stratigraphy and set of properties is not meant to be a final set but rather an update.

The progress review meeting is not intended to be a showcase for the latest and greatest tools, techniques, and achievements, but rather intended to be a working meeting. The review meeting participants will collectively reach decisions which will allow an updated standard stratigraphy document to be constructed. Some participants are being asked to prepare presentations on work which directly bears on the decisions to be made by the group. Discussions and decisions on each limited topic will follow the presentation on that particular topic.

As you realize, it is difficult for a diverse group of individuals to reach decisions on anything. The success of this meeting then depends upon:

1. *an attitude of cooperation and unity of purpose, not competition and divisiveness.*
2. *conscientious preparation of "homework assignments" by participants who are asked to make presentations.*
3. *a structured program with limited scope of discussion topics.*

It is felt that these are achievable goals considering the participants who are being invited. Lunch will be served at the Coronado Club to the invitees to relieve the intensity of the meeting without rushing the meal in the time allowed.

This workshop should result in an enjoyable, tiring but satisfying day.

PROGRESS REVIEW MEETING AGENDA

Chairman: T. Hunter

8:00	*SNL, Hunter, Introduction and statement of ground rules*

STRATIGRAPHY INTRODUCTION

8:20	*Bechtel - Roberts - Concerns, needs, and uses by Bechtel for the standard stratigraphy definition and other recommendations*
8:30	*SNL, Branstetter - Sensitivity of closure in the South Drift to the initial stress state and concerns, needs, and uses by Sandia for the standard stratigraphy definition*
8:40	*TSC - Sources of data base for definition of stratigraphy*
8:50	*Directed discussion on stratigraphy, necessity for horizontal variations in the standard but no decisions on the details until properties are defined*

PROPERTIES ON ROCK SALT

9:25	*SNL, Krieg - Sensitivity of closure to variations in low stress creep behavior and other secondary creep properties, homogeneity of properties, variations in elastic moduli*
9:40	*SNL, Wawersik - Update on secondary creep description*
9:55	*Discussion on rock salt properties*
10:25	*Break*
10:40	*Decision on a standard set of properties - for rock salt*

PROPERTIES OF CLAY SEAMS

11:10	*SNL, Stone - Sensitivity of closure to clay seam friction coefficient*
11:20	*TSC - Clay seam studies*
11:30	*SNL, Butcher - Update on clay seam mechanical property studies*
11:40	*Discussion on clay seam description and decision on standard properties for seams present*
12:00	*Lunch*

PROPERTIES OF OTHER LAYERS

1:00	*SNL, Stein - Status of tests on constituents in the mixed layers*
1:10	*SNL, Wawersik - Interpretation and consequences of tests on mixed layers*
1:20	*Discussion on anhydrite, polyhalite, and mixed layers and decisions on a standard set of properties*

STRATIGRAPHY DECISION

2:00	*Bechtel - A proposed standard stratigraphy*
2:10	*TSC - A proposed standard stratigraphy*
2:20	*SNL, Krieg - A proposed standard stratigraphy*
2:30	*Discussion on stratigraphy and proposed models*
2:45	*Break*
3:00	*Decision on standard stratigraphy*
3:30	*Break*

ACTION ITEMS

4:00	*SNL, Krieg - Summary of standard stratigraphy and properties*
4:15	*Assignment of action items and conclusions*
4:30	*Closure*

Attendees

Arlen Hunt	DOE
Randy Robinson	"
Howard Taylor	Bechtel Nat'l Co.
Dale Roberts	"
Ching Wu	"
Da Lee Wu	"
William T. Li	"
Ray Krieg	1521, Sandia National Labs
Linda Branstetter	"
Hal Morgan	"
Mike Stone	"
David Webb	"
B. M. Butcher	1542, Sandia National Labs
W. R. Wawersik	"
Wendell Weart	6330, Sandia National Labs
Al Lappin	6331, Sandia National Labs
Tom Hunter	6332, Sandia National Labs
C. L. Christensen	"
Rudy Matalucci	"
Darrell Munson	"
John Stormont	"
T. M. Torres	"
Joseph Franzoni	TSC/D'Appolonia
Lubor Jarolimek	"
Roy McKinney	"
Art Moss	"
Dev Shukla	"
Dale Stephenson	

Notes from Progress Review Meeting on
Stratigraphy and Mechanical Properties Near the Working Horizon at the WIPP
July 7, 1983
Albuquerque, New Mexico

The meeting consisted of participants from Sandia, Bechtel and the TSC/D'Appolonia in the WIPP project to establish and update the reference properties to describe the rocks in the underground in the WIPP. The introduction to the meeting by T. O. Hunter consisted of a discussion of the overall purpose of the modeling and calculational effort in its relation to design. Two aspects are important in terms of this activity. One is the establishment of the technical basis for the design, and a development of the associated technology and technology demonstration as regard to WIPP's role as an R&D facility. The project is operating with a structure such that Bechtel will develop the design validation including the conclusions about the validity of the design relative to the original design assumptions. These conclusions and activities will be supported by other project participants who provide data and information supportive to that goal. Sandia will provide modeling studies and laboratory property determinations of materials which support the Bechtel design calculations. The TSC/D'Appolonia will provide interpretations of the sight geology and their impact on the development of reference, stratigraphy and properties.

The design process consists of many elements. These include the design objectives and the design basis in the actual engineering design itself. Within the engineering design are included the calculations which are necessary to form the basis for that design, as well as other empirical techniques and engineering design practices which are used to establish design of an underground facility. Two other key elements include the stratigraphy of the rocks near the working level and the assumptions about rock properties in the different geologic units. Thes two subjects, the stratigraphy and the rock properties are the subject of today's meeting. Other meetings have discussed the basis for the calculations and the basis for the design. Tomorrow's meeting will address measurement techniques and field observations that are used to correlate the design assumptions with the actual data. Finally the process consists of conclusions about the design process itself which will be part of both the design validation report by Bechtel and the conclusions regarding the R&D repository development in rock salt. The format of the meeting consists of presentations on selected subjects and focus discussions about how to develop or establish agreement on the items addressed.

The first series of presentations consisted of establishing the need in basis for development of a stratigraphy in the WIPP. The first presentation was by Dale Roberts of Bechtel.

The basis for reference stratigraphies in Bechtel's use is as a model for calculations. They are concerned about spacial variations in the stratigraphy and how it impacts design calculations. Particularly, Howard Taylor from Bechtel described how they will concentrate on calculations in the storage rooms and then associated calculations in the south drift for the design validation calculations.

Linda Branstetter, Sandia, presented a discussion of the sensitivity of the calculations to various parameters. The parameters included the density and hence the original lithostatic stress and its variation on room closure. She pointed out that it is important to establish the uncertainties in the material data and their influence on rock response. Further it was pointed out that the stratigraphic assumption should be as simple as possible, but should include the relevant mechanisms which are operative.

Dev Shukla, D'Appolonia, pointed out the basic difference between the models and assumptions about stratigraphy. He described that models and stratigraphic assumptions can be based on different views. The operational view in which one looks carefully at intervals near the drift, perhaps plus or minus 50 feet, the view of room closure or longer term room response in which one looks one looks at rock and rock performance at greater depth, perhaps plus or minus 150 feet, and finally when one looks at regional or overlying formation response, it is necessary to have general stratigraphies to depths of about 3000 feet. One conclusion that was made from the discussion by the TSC/D'Appolonia was that everyone agrees that there is good lateral continuity of the beds, the south drift variations are ranged from approximately 27 to 24 feet for the facility horizon. Hence, the uncertainty in material properties appears to be the most important parameter at the present, not the lateral continuity or variability of the beds.

An assessment of the session on introduction to stratigraphy was that we should establish what is important in terms of needs for stratigraphy. It was clear that important primers include bed thicknesses, placing location and properties, and the identification and modeling of mixed layers. Further, it appears to be important to resolve what is a special variation in the stratigraphic assumptions. Also discussed was the importance of applying this stratigraphy to the modeling in determining which primers are really important ones for the intent of the modeling. An additional discussion took place regarding the need for correlation of geophysical techniques to determine in situ rock properties from boreholes within the drift in order to simplify the assumptions about characterizing stratigraphy as well as to allow development of priorities for the testing of laboratory samples.

The second session was devoted to the properties of rock salt. Ray Krieg of Sandia described the series of parameters or assumptions which can be important in terms of the overall modeling. He described the early studies which were done with analytical formulations to decide whether or not the elastic terms were important. It was concluded that these were important in these studies and have since been incorporated in the computer modeling. Second, he described the studies on elastic properties that have been done with the finite element codes, and shows that the lowering of the sheer moduli can result in a significant impact on room closure, and, in fact, may provide a better agreement with the field data. Third, he described the effect of random properties in the studies that were done to try to look at the variation in laboratory properties on the overall impact on room closure. Fourth, he described the effect of low stress or stress cutoff on the

deformation of the rooms. It was concluded that depending on the spacial variation of stress, the existence of a low cutoff stress can be important and affect the room closure. Further, it was discussed that a correlation can be made between the existence of a cutoff stress and the long-term deformation process studies that are being done by David Borns of Sandia, and this correlation should be made. Fifth, he discussed the effect of primary creep and indicated that from Sandia's view, primary creep calculations appear to be expensive, but may be necessary if it is important to model the early time behavior. Finally, he indicated that the need and accuracy of comparing data with calculations is probably better in the long term than in the short term, and discouraged the use of equivalent parameters or factors to try to model the data, but rather emphasized a more fundamental understanding of what parameters are important and how they affect the rock response.

In the same session Wolfgang Wawersik discussed the status of secondary creep modeling in data that we have. He showed new data which indicate that Q values for example, and stress exponents may change from the reference creep law. He indicated that the new data is much higher quality and would tend to change the numbers that have been used in the past. However, from a discussion from a practical point of view, he concluded that the current model is reasonably accurate to represent a good approximation at this time. He indicated, though, that the new samples may show that two types of rocks should be considered. One is basic rock salt, primarily anhydrite, which he concluded from what he had seen in the underground at WIPP, was very similar to the assumptions of the upper level WIPP salt in the original investigations. In addition, though, there may be areas which are truly argillaceous rock salt which could exhibit a higher creep property, perhaps a factor of 2 to 5, and this should be examined further. Finally, he discussed the potential for the uniqueness of secondary creep as a equilibrium state under deformation. It is not clear if, in fact, this is exhibited by the laboratory tests and subsequent microscopic examinations. However, practically speaking, this may not be significant, but could, in fact, alter the assumptions about the reference creep law. He did indicate that there are extremely good results from strategic petroleum reserve calculations about cavern response and fluid volumes which corroborate the data correlations made for WIPP. Barry Butcher pointed out that it is important to establish a threshold about which we are not longer concerned about the impact on the predicted response. Some number like creep response within plus or minus 30% was noted as being insignificant in terms of concern about material properties.

In the same section Mr. Ching Wu from Bechtel, discussed the material concepts which he felt were needed to satisfy design validation. These included: 1) the definition of the materials, 2) the elastic constants, 3) the coefficient of friction of clay seams, 4) the unconfined compressive strength of the rocks, 5) the tensile constants, 6) appropriate failure criteria, and 7) primary creep characteristics. Mr. Li from Bechtel indicated some questions about the use of the primary creep law which may indicate typographical errors in the Sandia reference creep law. Further, he sought clarification on the use of the failure criteria for halite described in the reference creep law.

The next section consisted of discussion of the properties of clay seams. Mike Stone, Sandia, presented a result of defective clay seams on room response, and indicated that previous studies showed that for certain stratigraphies that is not necessary to incorporate all of the clay seams in a particular calculation. However, it appeared that the clay seams have a significant effect on not only room closure, but also on the closure rates, which may be strongly affected. He pointed out that the determination of which clay seams are active should be decided upon by the analysis based on the reference stratigraphy.

Franzoni of TSC/D'Appolonia reviewed the data from clay seam performance obtained in supporting document 12 in the SPDV experiment document. He discussed the Atterberg limits test, the tensile test and the direct shear test, the latter of which indicated that the coefficient of frictions ranged from 0.2 to 0.7 and significant cohesion around 100 psi was observed in the test from the data fitting. Finally, he indicated that tensile strengths of greater than 100 psi
were observed in some of the clay samples taken.

Barry Butcher discussed the prior data in assumptions about clay seam characterization and indicated that a reasonable categorization should be established for what kind of clay seams are actually present, whether they are uniform flat slipping, clay seams which have significant undulations, or in fact consist of mixed layers with intergranular clay which exhibit a similar response.

The discussions of properties of other layers indicated that we should in fact deal with four major rock types. The rock salt, the clay seams, major anhydrite ore, stiff elastic members and finally a mixed unit which is principally argillaceous rock. Carol Stein reviewed the mineralogical investigations which had been performed on drill holes near the WIPP drifts which show that the maximum impurity content for all of the samples throughout the sequence within 50 feet of the drift is about 5% water insoluble impurities, hence the clay content or the anhydrite polyhalite content is limited to just a few percent. It was concluded that more samples need to be taken and a better correlation of the mineralogical analysis with the SPDV data logging should be undertaken. Finally, it was observed that there is no evidence for either mixed polyhalite or mixed anhydrite units which would be significant. Wolfgang Wawersik pointed out that based on his qualitative interpretation he had not observed any mixed layers except perhaps the argillaceous units which would provide any different material response than we had observed in the upper level layers assumed in the original statistical study of creep properties.

The next discussion revolved around the stratigraphy which should be adopted as a reference for the WIPP project. Bechtel, TSC/D'Appolonia and Sandia presented proposed stratigraphies. Bechtel's Howard Taylor indicated that they were concerned about clay seams very near the room including the definition of argillaceous units as perhaps clay partings. The TSC/D'Appolonia Dale Stephenson, indicated that they had adopted three proposed stratigraphies, one about 3,000 ft in extent, one about 300 ft. in extent, and one about 100 ft. in extent.

They based their referencing on the anhydrite units which are very near the rooms and indicated that those, in fact, are continuous in most cases, although reasonably thin and can be used as a basis for the stratigraphy. Ray Krieg, Sandia, compared the original 1979 stratigraphy which was adopted in 9/82 and discussed the possible variations which should be considered.

At that point a general discussion followed on the importance of various layers to the reference stratigraphy. It was pointed out that all of the argillaceous layers may contain clay seams and hence should be considered as possible slip planes or points of extreme weakness. Consequently, further consideration should be given to examining those cores. Some discussion took place on the halite-halite contacts observed above the rooms. It was concluded that these were local details and not sufficiently wide-spread to be considered in the reference stratigraphy. Further discussion on materials properties was that at this point we can concentrate on intergranular impurities, principally those associated with the argillaceous material to establish a difference in creep response for the various materials.

At that point Ray Krieg presented the underlying assumptions for a reference stratigraphy, and indicated that he would take the three proposed stratigraphies, match them up and provide a common reference stratigraphy for all participants to review.

A summary of the modifications to the reference stratigraphy and material properties is as follows:

> In terms of the material description it was concluded that the primary creep assumptions will remain unchanged at this point. The secondary creep assumptions will remain unchanged, the elastic moduli based on unloading will remain the base case, but the analyst will be allowed to determine whether or not these moduli or moduli based on the secant modulus will be used in conjunction with the secondary creep models. It was suggested that a model which seems reasonable would be to leave the bulk modulus constant and to lower the shear modulus by a factor of four. It was further concluded that the failure models for rock salt will remain the original formulation of the reference creep law based on pressure and total strain.

The polyhalitic halite will be modeled as rock salt and no distinction will be made for polyhalite in conjunction with halite as a different material.

The anhydrite will be modeled with the same elastic properties and the same failure criteria if used as was developed by Sandia and available literature on the subject, and this will be presented in the new reference creep law. The argillaceous halite will require separate action but should be considered as a different material. Two aspects must be considered: 1) whether or not each argillaceous layer should be considered as a slip plane, and 2) whether or not the argillaceous material is sufficiently different mineralogically to introduce different creep properties. These will be evaluated by the creep testing matrix and mineralogical studies being conducted by Sandia.
Finally a list of action items was developed of items which should be done to support the development of a reference stratigraphy. These are outlined in the following list.

ACTION ITEMS

July 7, 1983

1. Compare and correlate mineralogical analyses results (especially argillaceous halite) with stratigraphic section - C. Stein.

2. Evaluate overburden density to surface from drill hole or geophysical (gravity and uphole velocity) data, perhaps comparing structure contour of anhydrite B with surface topography - A. Lappin.

3. Evaluate geophysical techniques for correlating stratigraphic/physical properties information in drill holes from drifts. - TSC/D'Appolonia.

4. Develop further tests to investigate clay seam properties in drill holes considering drilling techniques, drying out, etc. - TSC/D'Appolonia.

5. Develop a referring or characterizing method for clay seams. B. Butcher, C. Stein.

6. Obtain samples of argillaceous rocks from drifts for creep tests (per original test matrix). - C. Christensen.

7. Obtain samples from MB 139 and other anhydrites for quasistatic tests. - C. Christensen.

8. Reinterpret a north/south drill hole combination for comparison of logging data and mineralogical analysis. - Sandia/TSC/D'Appolonia/-Bechtel.

9. Compare proposed reference stratigraphies and develop a new reference for project review. - R. Krieg.

10. Compile and publish a document with reference constitutive models, stratigraphy, and common data base. - R. Krieg and T. Hunter.

APPENDIX B.

Statistical Proof of the Non-Significance of Spacial Variations

The anhydrite layers in Table I have been characterized by their thicknesses and elevations above anhydrite b. We note a considerable variation in the values of these parameters in any given column. The rows are arranged such that the most southerly core is at the top of the table and the most northerly at the bottom. Looking over the columns, we see a consistent variation from top to bottom in the absolute elevation of anhydrite b but little regularity in other parameters with the possible exception of the thickness of anhydrite b. Variations in the anhydrite layers listed then appear to be due to ripples or short range, rather than to long range variations. A consequence of this would be that a local measurement would not be as indicative of a mean local region thickness or height as an average value from Table I would be. We need not rely on intuition for this decision since we can statistically examine the quantities in the table.

Each column was considered individually. If X is the north-south location of the core as given in the second column of Table I with south considered to be negative, and if Y is thickness or elevation above anhydrite b, as given in one of the columns, then we make the usual statistical assumptions. We assume that a linear north-south variation does exist and the X locations of the core holes are known. The Y values are assumed to be random variables normally distributed around the assumed linear north-south variation.

If (X_i, Y_i) for i = 1, n are the values from the table, then average values $\overline{X}$ and $\overline{Y}$ are computed to be

$$\overline{X} = \sum_{i=1}^{n} X_i$$

$$\overline{Y} = \sum_{i=1}^{n} Y_i$$

A least squares fit to the data gives the curve:

$$Y = a + bX \tag{B1}$$

where a and b are found using the relations:

$$b = \frac{\Sigma(X_i - \overline{X})(Y_i - \overline{Y})}{\Sigma(X_i - \overline{X})^2} \tag{B2}$$

$$a = \overline{Y} - b\,\overline{X} \tag{B3}$$

where the summations are taken to be over the limits from 1 to n.

The values of a and b are listed in Table B-1. The variance of Y and X is denoted as $S^2_{Y,X}$ and is given as

$$S^2_{Y,X} = \frac{1}{n-2} \left[\Sigma(Y_i-\bar{Y})^2 - b\,\Sigma(X_i-\bar{X})(Y_i-\bar{Y})\right] \tag{B4}$$

This is in turn used to find the variance on the regression coefficients a and b. These variances are given by

$$S^2_b = \frac{S^2_{Y,X}}{(X_i-\bar{X})^2} \tag{B5}$$

$$S^2_a = S^2_{Y,X} \left[\frac{1}{n} + \frac{\bar{X}^2}{\Sigma(X_i-\bar{X})^2}\right] \tag{B6}$$

Another informative and useful measure is obtained by considering the fraction of the total variation in Y that is accounted for by the association between X and Y. The ratio of the sum of squares associated with the regression to the total sum of squares for Y is called the coefficient of determination and is given by

$$r^2 = \frac{\Sigma(a+bX_i-\bar{Y})^2}{\Sigma(Y_i-\bar{Y})^2} \tag{B7}$$

The variances and the coefficient of determination are all listed in Table B.

The variances and coefficient of determination are all informative, but the bottom line is simply an answer to the question of whether the north-south changes in variables in Table I are statistically significant. For this, we go to the t-distribution and consider confidence limits.

We want to know whether or not there is a linear association between X and Y, for if there is not, then there is nothing to be gained by using the X's as they will contribute nothing to the analysis of the Y's. For this, we compute

$$t = \frac{b}{S_b} \tag{B8}$$

This is compared to values for the t-distribution for (n-2) points listed in statistical tables for given confidence intervals. Values for computed and tabular values at 95% confidence interval are listed in Table B-1. The tabular values are greater than computed values for all but the thickness of anhydrite b.

The conclusion is that with a confidence of 95%, it can be said that there is no statistically significant north-south variation in any of the parameters except the thickness of anhydrite b. We further note that the most statistically significant value we can use for these variables is an average over the entire site.

Table B-1. Statistical Parameters Associated with a Spatial Variation Over the WIPP Site

Parameter	a	b	n	$S^2_{Y,X}$	S^2_a	S^2_b	r^2	t_{comp}	t_{95}
Elev Anh C	16.4	-6.76E-5	18	.265	.0150	5.96E-9	.0460	.88	2.12
Thk Anh C	.0814	3.32E-6	18	.00106	6.04E-4	2.39E-11	.0280	.68	2.12
Elev MB139	8.64	-3.05E-5	20	.0911	.00469	2.05E-9	.0246	.67	2.10
Thk MB139	.865	1.09E-5	23	.0459	.00205	1.03E-9	.00545	.34	2.08
Elev Unit 4	3.68	-4.97E-5	18	.0404	.00235	9.33E-10	.1419	1.63	2.12
Thk Unit 4	.837	2.88E-6	21	.0152	.753	3.49E-10	.1112	.15	2.09
Thk Anh b	.0528	1.29E-5	20	.000239	1.23E-5	5.38E-12	.6316	5.56	2.10
Elev Anh a	2.11	5.70E-5	20	.0339	.00174	7.61E-10	.1918	2.07	2.10
Thk Anh a	.209	-3.60E-6	20	.00381	1.96E-4	8.57E-11	.0083	.39	2.10
Elev MB139	9.16	-1.91E-5	20	.0920	.00474	2.07E-9	.0097	.42	2.10
Thk MB139	.193	5.98E-6	20	.00237	1.22E-4	5.33E-11	.0360	.82	2.10

Notes:
1. Parameters a and b are determined as in Eqs (B2) and (B3)
2. The number of samples is denoted as n
3. $S^2_{Y,X}$ is computed in Eqn (B4)
4. S^2_a is computed in Eqn (B6)
5. S^2_b is computed in Eqn (B5)
6. r^2 is computed in Eqn (B7)
7. t_{comp} is computed in Eqn (B8)
8. t_{95} is a standard tabulated 95% confidence value

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