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DEVELOPMENT OF SITE SUITABILITY CRITERIA FOR THE HIGH LEVEL WASTE REPOSITORY FOR LAWRENCE LIVERMORE LABORATORIES

P.O. 6115603

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CONSULTING MINING AND GEOTECHNICAL ENGINEERS

June 30, 1977

University of California
Lawrence Livermore Laboratories
P.O. Box 808
Livermore, California 94550

ATTN: L.A. COLE, L-127

Gentlemen:

We are pleased to submit our final report to the University titled "Development of Site Suitability Criteria for the High Level Waste Repository for Lawrence Livermore Laboratories". This work was performed in accordance with the University Purchase Order 6115603. Our technical director on the project was Dr. Donald Towse of Lawrence Livermore Laboratory Earth Sciences Department.

Very truly yours,

GOLDER ASSOCIATES, INC.

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FOR THE
HIGH LEVEL WASTE REPOSITORY
FOR
LAWRENCE LIVERMORE LABORATORIES

Summary

General

This report presents the results of our mining, geological and geotechnical studies provided in support of the development of site suitability criteria for the high level waste repository. This work was performed in accordance with our unsolicited proposal to LLL dated January 1977 and authorized by the University Purchase Order 6115603. The primary purpose of our work was the identification and development of appropriate geotechnical descriptors and coefficients required for the Site Suitability Repository Model. This model was developed by The Analytic Sciences Corporation (TASC) of Reading, Massachusetts and will not be described in this report.

Data Base Study

In order to provide credible geotechnical descriptors and coefficients, it was necessary to initiate a geotechnical data base study. This work involved an initial definition and evaluation of geotechnical information considered significant to site suitability. It was not the intent to complete an exhaustive state-of-the-art study. The enormous amount of information available in these areas combined with the intensive research and development work presently being funded by ERDA clearly makes such a comprehensive study beyond the scope of

our contract. Rather the intent was to provide a basic framework of geotechnical data and, interfacing with the TASC model, further investigate those areas which appeared to most significantly affect site suitability. Figure 1 indicates the overall structure of the data base work and depicts its relationship with the TASC model and site suitability criteria. Since the main pathway considered by the model for radiation contamination to the biosphere is through the ground water, the data base study generally relates factors to their effect on potential ground water contamination pathways.

In general, the work consisted of three main topics: ground water hydrology, geology, and mining/rock mechanics. Each section was generally subdivided into: Factors, Available Information, and Technology. Factors present a compilation of conditions, parameters and phenomenon pertinent to site suitability. The Available Information is a brief review of available field data based on a literature survey. The Technology section summarizes the general numerical and analytical tools currently available for analyzing critical site suitability factors.

The data base information was also used to develop geologic and hydrologic generic models which formed the basis for the TASC model. This consisted of a compilation of regional geologic and hydrologic data which was synthesized into appropriate generic models. This work formed an essential part of our contract since the credibility of the TASC model is fundamentally dependent on these generic models. Development of any TASC models which are not founded on known geology and hydrology would have little meaning and be an obvious weakness which may discredit the model.

Descriptors and Coefficients

The analytical descriptors and coefficients required for the TASC model and provided to the university were generally related to the following main catagories as presented in our original proposal:

1. Mechanisms and probabilities of any subsurface excavation and bore hole failure.

2. Seismic probabilities vs. area types excluding regions which are on the edge of tectonic plates.

3. Seismic response of specific rock mass characteristics vs. severity.

4. The effect of undetected voids.

5. The dissolution of the repository and rock media near to the repository.

6. The effect of loss of administrative control.

7. The hydrological response vs. climatic variations.

8. The erosion modification of phenomenologic models.

As the overall project effort developed, certain critical areas requiring more detailed evaluation were delineated. Thus, through Dr. Don Towse of LLL our technical director, we were instructed to expand some items while abbreviating others. The general results of our work related to these original catagories are summarized below. Due to the revision of emphasis in many of these original catagories, the format of the main body of the report deviates from this original framework.

1. Mechanisms and probabilities of any subsurface excavation and bore hole failure

Descriptors and coefficients characterizing the hydrological affect of fracture zones around subsurface excavations and bore hole seal failures were evaluated. This evaluation included a preliminary analysis of the size, porosity, and permeability of the fracture zone around the shafts and tunnels of a nuclear repository. The occurrence and properties of potential bore hole seal failures were also considered. The evaluation concerned only new bore holes drilled for the subsurface investigation of the repository site and assumed that state-of-the-art sealing techniques would be implemented. The evaluation provides an estimate of the hydraulic properties of a bore hole seal failure and a probability of their occurrence.

2. Seismic probabilities vs. area types excluding regions which are on the edge of tectonic plates

In conjunction with the data base study, regional seismicity data was compiled and is summarized in the regional geology sections of this report. This information includes seismic history, fault data, and general tectonic setting. The actual seismicity descriptors and coefficients used in the TASC model evaluation were provided by LLL.

3. Seismic response of specific rock mass characteristics vs. severity

LLL provided data on the rate of formation of new faults. The evaluation was based on the criteria that "faulting" is an event that induces changes in water table, fracturing or cracks in the ground, and is caused by earthquakes of intensities of VIII or higher on the Modified Mercalli scale. The work presented in this report consists of evaluating the characteristics of new faults or recurrent movement along old faults caused by these major seismic events. The evaluation provided estimates of fault width, porosity, and permeability and their variation with time.

4. The effect of undetected voids

This report presents a summary of potential undetected voids and anomalies which might affect the integrity of the repository. These features include both man-made, (mines and wells), and natural (facies changes, reefs, solution zones, fractures, erosion features, etc.). The occurrences and characteristics of the features are related to known regional geologic data and present resource uses. Analytic techniques are also present to evaluate the hydrologic effect of these features and incorporate into the TASC model.

5. The dissolution of the repository and rock media near the repository

The anticipated nuclear waste/rock interaction and the long-term structural effects of the repository construction are discussed to a level consistent with the requirements of the TASC model. This work includes preliminary analyses of fracture zones around shafts and tunnels, the potential thermal effects of the waste cannisters on the surrounding rock, and the projected mechanical and hydrologic characteristics of the backfill. The preliminary descriptors and coefficients describing these behaviors are presented in a format which is readily incorporated into the TASC model analysis.

6. The effect of loss of administrative control

Since it is necessary to evaluate the integrity of the repository over thousands or even hundreds of thousands of years, consideration was given to the effect of loss of administrative control. This would include the drilling of bore holes, drilling of wells (freshwater, brine, oil, gas, etc.), and the excavation of deep mines both at and near repository site. The probability of these occurring and their potential effects are conceptually discussed in the report. Due to revision of emphasis as the project developed, we were instructed by Dr. Don Towse our technical director not to provide coefficients or descriptors relating to loss of administrative control for the TASC model.

7. and 8. The hydrologic response vs. climate variations and the erosion modification of phenomenologic models

As the project developed, the need for detailed evaluation of existing hydrologic conditions became apparent. As discussed above under the Data Base Study, the credibility of the TASC model is fundamentally dependent on the generic hydrologic model. Thus the majority of our effort for these tasks related to the evaluation of regional hydrologic information and the effect of variations on these hydrologic regimes. These variations included the effects of repository construction and abandonment, existing geologic anomalies, future geologic changes (faults, breccia zones, etc.) and future man-made changes (wells, mines, etc.). The results of this work is presented in the form of general information (Data Base Study) and specific coefficients and descriptors required for the TASC model study. Based on preliminary climatological study performed by LLL, we also present some general comments on the effects of climate variations including affects of erosion.

1.0 PURPOSE AND SCOPE

This report presents the results of our mining, geological and geotechnical studies provided in support of the developing of site suitability criteria for the high level waste nuclear repository. This work was performed in accordance with our unsolicited proposal to LLL dated January 1977 and authorized by the University Purchase Order 6115603. The primary purpose of our work was the identification and development of appropriate geotechnical descriptors and coefficients required for the Site Suitability Repository Model. This model was developed by The Analytic Sciences Corporation (TASC) of Reading, Massachusetts and will not be described in this report. A secondary purpose of this study was to present a preliminary geotechnical data base. This work was necessary in order to define significant geotechnical factors and develop credible descriptors and coefficients.

The scope of our work involved literature research, preliminary evaluation of geotechnical factors, development of specific geotechnical descriptors and coefficients for two cycles of the TASC model relating to salt and shale repositories, and geotechnical guidance to the overall LLL site suitability work. In addition to the work presented in this report, we attended numerous working project meetings involving LLL and their other consultants. We presented preliminary findings at a two-day joint NRC-LLL meeting in Livermore on March 22-23. We also made several other trips including two visits to Washington D.C. to confer directly with NRC and a visit to Sandia Laborators to obtain information on their work for NRC.

2.0 GEOTECHNICAL DATA BASE

2.1 General

This section presents the results of our geotechnical data base study. The purpose of this work was to provide an initial definition and evaluation of geotechnical factors needed to assess site suitability criteria. The work consisted of three main topics: ground water hydrology, geology, and rock mechanics/mining. It was not the intent of our work to complete an exhaustive state-of-the-art study. The enormous amount of information available in these areas combined with the intensive research and development work presently being funded by ERDA clearly makes such a comprehensive study beyond the scope of our contract. Rather the intent is more realistically to provide a list of basic geotechnical factors with appropriate preliminary comments. It is hoped that this work becomes the basic data framework for future geotechnical site suitability assessments.

Due to the wealth of available information and the relative level of NRC's expertise in the two areas, the ground water hydrology and geology sections emphasize assessment of factors and the development of appropriate models for analyses. The rock mechanics/mining section is on a somewhat different level due to the limited available information coupled with NRC's lower level of expertise on the subject. Thus, this latter section emphasizes basic principles and theories. Each major section is generally subdivided into Factors, Available Information, and Technology. Factors present a list of conditions, parameters, phenomenon, and variables pertinent to site suitability with a preliminary discussion of the more significant topics. The available information is a brief review of available field data based on a literature survey. The technology section discusses some of the general numerical and analytical tools currently available for analyzing critical site suitability factors. Figure 1 indicates the overall structure of the data base work and depicts its relationship with the TASC model and site suitability criteria.

The only pratical pathway for radiation contamination to the biosphere considered by the TASC model is through circulating ground water. Thus, the data base study generally relates factors to their effect on the ground water regime and on potential ground water contamination pathways.

2.2 Ground Water Hydrology

2.2.1 Factors

Some of the more important contamination pathways include those from both existing geologic conditions future geologic events and man-made conditions. In general, the pathways due to existing and man-made conditions are relatively more significant than those due to future geologic events. This appears to be a reasonable premise based on the low probability of the most significant future geologic events combined with the sharp decrease in radiation effect after approximately 600 years (LLL, 1977). Thus, although long-term events extending over many tens of thousands of years must be considered, in our opinion, the current ground conditions in conjunction with the effects of the repository construction should be emphasized.

The primary initial pathways considered for this study include ground water flow through the overall bedrock formations, flow through major structural discontinuities such as faults and breccia zones, and flow through man-made pathways such as mines, wells, or those created by the repository itself. The critical characteristics of these pathways include the velocity of water flow and its direction. To transmit radiation, these pathways require a source of water and a driving gradient. The primary sources of water would be an adjacent aquifer and/or effective recharge zone while the primary driving gradient would be the natural ground water gradients. Numerous secondary water sources must also be considered such as injection wells, or brine inclusions, but would generally be less significant than the primary modes. Gradients induced by the heat of the HLW cannisters must also be evaluated.

Although not considered by the present TASC model or evaluated in this report, potential gas pathways must also be evaluated.

The following is a preliminary list of ground water hydrology factors as related to site suitability.

A. Primary Parameters/Properties
   1. Permeability - interstitial, fracture, combined.
   2. Porosity - interstitial, fracture, connected.
   3. Dispersion coefficients.
   4. Specific yield/specific retention.
   5. Infiltration/runoff factors.
   6. Nature and composition of pore fluids.
      a. Water chemistry.
      b. Composition of other fluids - gases, oil, etc.
      c. Degree of saturation.

7. Rock/soil chemistry.
8. Sorption/retardation factors.
9. Bulk density.

B. Primary Phenomena - Existing Conditions

1. Piezometric levels.
2. Primary pressure gradients.
3. Flow velocities and direction.
4. Diffusion phenomenon.
5. Sorption/retardation phenomenon.
6. Water cycle balance recharge/discharge phenomenon.
7. Secondary induced pressure gradients - thermal, electrical, osmotic, capillary, swell, chemical, others.

C. Long-Term Natural Variations

1. Climate.
2. Surface geologic changes - erosion, deposition, glacier action.
3. Subsurface geologic changes - tectonic activity, solution/precipitation, stress and chemical changes, thermal changes, etc.
4. Glaciation.
5. Frost action.
6. Sea level fluctuations.
7. Surface hydrology - drainage, lakes, ponds, etc.
8. Vegetation - effect on water balance.

D. Man-Made Variations

1. Effect of repository construction.
2. Effect of repository abandonment: ground water regime will re-establish its original condition, thermal affects, steam generation.
3. Long-term effects of repository.
4. Short-term ground water and surface water management: use of aquifers - water, disposal, oil and gas wells.
5. Short-term land use - mining, construction, excavations, etc., in general area affecting ground water regime.

6. Long-term land and ground water use - future acts of man which would affect ground water regime.

A detailed discussion of each factor is beyond the scope of this report. However, a brief discussion of some of the more significant factors is presented below.

2.2.1.1 Permeability

Permeability is a fundamental parameter in any site suitability assessment since it is the basic measure of a formations ability to transmit water. It is a controlling factor in all ground water related behavior including flow velocity, flow direction, flow quantities, and mine dewatering conditions. Since permeability is generally not an easy parameter to accurately measure and its value can vary over many orders of magnitude in a single geologic formation, the assessment of permeability will present a major concern to both site suitability and site selection evaluations.

The permeability of a real formation can be composed of flow through the openings between individual grains (interstitial permeability) and flow through fractures or other flaws in the rock (fracture permeability). In many types of formations, the overall permeability is controlled by the fracture permeability. Thus permeability values based on laboratory core samples generally represent a lower bound value and would not reflect fracture permeability. Therefore permeability data based on field tests such as full scale pumping tests which more adequately reflect the actual in situ permeability are much more creditable.

In general, theories and practices in ground water hydrology have been developed for homogeneous, isotropic, porous media and not for non-homogeneous, fractured media. It is important to consider the limitations of applying the classic ground water techniques to more complex fracture and/or non-homogeneous media.

2.2.1.2 Porosity

Porosity is a measure of the relative amount of pore space in a porous medium. It is a fundamental parameter in any site suitability assessment since it is one of the controlling factors in determining flow velocity. In simple terms, the velocity of flow is equal to the Darcy discharge velocity divided by the appropriate porosity factor. As with permeability, meaningful porosity values are generally difficult to measure and can exhibit a significant variation. Thus, the evaluation of porosity will also present a major concern to both site suitability and site selection evaluations.

Porosity of real formations can be composed of interstitial porosity consisting of the void spaces between mineral grains of the rock and/or fracture porosity consisting of larger scale openings such as vugs, fissures and joints. Interstitial porosity or primary porosity is an inherent characteristic of the rock and is simply the ratio of pore volume to the total volume. This is a relatively easy parameter to measure in the laboratory and generally exhibits only minor variations for a given rock type. The vast majority of data reported in the literature refers to interstitial porosity only. Fracture porosity, which is often referred to as secondary or induced porosity, is a complex parameter and generally can only be determined from field tests. For evaluation of fracture flow velocity, only the interconnected fracture porosity is pertinent since unconnected fractures do not affect the flow.

2.2.1.3 Dispersion Coefficients

Dispersion or the gradual spreading of a dissolved concentrate in a porous media has a significant effect on the concentration distribution of the waste as it is transported in the ground water from the repository toward the biosphere. The coefficient of mechanical dispersion, D, appearing in the dispersion equation is a complex factor and has the units L^2T. It depends on flow patterns, actual flow velocity, characteristics of both the fluid and porous media, and the relative significance of molecular diffusion versus hydrodynamic (mechanical) diffusion. The coefficient varies with direction and is described using both a lateral (perpendicular to average flow direction) dispersion coefficient and a longitudinal (in the average flow direction) dispersion coefficient.

Based on previous work, it appears that hydrodynamic dispersion is the major factor controlling dispersive behavior. Assuming molecular dispersion to be insignificant, the coefficient of hydrodynamic dispersion, D, equals:

$$D = I\ V$$

Where: I: dispersion constant or characteristic dispersion length, units of length

V: flow velocity, normally taken as the Darcy discharge velocity divided by the effective porosity, units of length/time.

Although the dispersion constant is a convenient mathematical quantity, it is difficult to assign a physical significance to the parameter. Mathematically it is equivalent to the mean free path in the diffusion equation.

The evaluation of dispersion coefficients is a very complex problem and is not well understood. The sketchy data reported comes from a very limited number of field and laboratory tests. In fact, the technology to determine the coefficients for two or three dimensional dispersion behavior in an anisotropic media may not presently even be available. To further complicate the problem, the available data applies only to flow through media possessing interstitial permeability or porosity. The dispersion coefficients applicable to a fractured medium, particularly if the orientation of the fractures are strongly anisotropic and widely spaced, may be entirely different from those presently reported in the literature. Thus, considerable effort may have to be given to a better understanding of these coefficients.

As discussed by Robertson and Barraclough (1973), "The most speculative of these inputs are the dispersity and distribution coefficients. No effective way of measuring these coefficients in the field is presently practical because of the large scale inhomogeneities."

2.2.1.4 Nature and Composition of Pore Fluid

Occurrence of ground water can be divided into zones of aeration and zones of saturation. Within the zone of aeration, the voids are occupied partially with air and partially with water. The water is held by molecular and capillary forces. In the zone of saturation, all the voids are filled with water or other fluids under hydrostatic pressure. The upper limit of the zone of saturation is commonly referred to as the ground water table or phreatic surface, although the actual zone of saturation may extend slightly above this due to capillarity. Although the depth to the ground water table varies from the surface to several hundred feet in the U.S., any repository depth considered viable will undoubtedly be below the ground water table. Therefore, this section will emphasize the nature and composition of the pore fluids below the ground water table.

At some limiting depth, the in situ overburden stresses combined with the natural geothermal temperature are great enough to cause rock to flow plastically and close any effective pore space. Thus, theoretically there is a lower limit of ground water since below the zone of plastic behavior there could be no effective porosity and no free ground water (Meinzer, 1923). The depth of such a theoretical lower limit depends on the rock type and probably exceeds tens of miles for harder rock types. The actual lower limit is probably much shallower than the theoretical depth due to creep effects, closing of joints and fractures, and other complex effects. In general, the depth to zero effective porosity in rock types such as crystalline rocks, which rely on fracture porosity to transmit ground water, is probably much less than for rocks such as sandstones which have considerable primary porosity. The depth to an effective lower limit of free ground water is of considerable interest to any site suitability evaluation.

It is believed by many well drillers and some hydrologists that at depths well below the ground water table there are porous formations whose voids are empty. The evidence for the occurrence of such zones generally include observations of drilling water behavior during deep well drilling and not well documented hydrologic testing results. Theoretically it is difficult to understand the existence of these zones (Meinzer, 1923). Clearly, however, should such formations exist it would be of significance to a site suitability evaluation.

Virtually all of the fluid occupying the voids below the ground water table is water. However there are many other fluids which locally may be extensive. These fluids, which generally occur in sedimentary formations, include petroleum, natural gas (generally methane), and to a much lesser extent, other gases such as carbon dioxide, hydrogen sulfide, helium, and steam. Since these fluids constitute a major part of our natural resources, a nuclear repository must not jeopardize them. Therefore, a site suitability evaluation must adequately consider the occurrence of these fluids and the potential impact of the repository on these resources.

All ground water contains salts carried in solution with the kind and nature of the salts depending on the environment, movement, and source of the ground water. These salts generally originate from solution of rock materials (primarily associated with sedimentary formations), sea water intrusion, and connate waters. The water chemistry has several significant impacts on the ground water regime relating to site suitability evaluations. The water chemistry is fundamental in determining its present and future freshwater resource values. It effects the density of the water which may alter the general ground water pressure gradients and flow directions. Variations in water chemistry can also induce water movement through differential ionic pressures. The concentrations of dissolved salts has a major effect on the water's potential to dissolve rock, such as in salt formations where the location and growth of dissolution features are strongly influenced by salinity. Of particular significance to the nuclear repository evaluation is the effect of salinity on retardation factors. Preliminary evaluations by LLL indicate that the retardation factors for some of the radioactive ions could differ by several orders of magnitude between freshwater and salt water (those factors associated with salt water being much lower). Although not related specifically to site suitability, water chemistry may be a valuable tool in evaluation of the overall ground water regime during the site selection phase.

For purposes of this study, the salinity of the ground water will be the primary consideration relating to ground water chemistry. The following classification adopted from Robinove (1958) is suggested:

Classification	Dissolved Solids (milligrams per liter)
Fresh	Less than 1,000
Slightly saline	1,000 to 3,000
Moderately saline	3,000 to 10,000
Very saline	10,000 to 35,000
Brine	More than 35,000

2.2.1.5 Rock Chemistry

The chemistry of the bedrock formations has many similar effects on the ground water regime as the chemistry of the water. In many ways the two are inter-related since the salts dissolved in the ground water often originate from dissolution of the rock. For purposes of this site suitability study, the primary influence of rock chemistry is its effect on ion retardation factors. Certain rock types, such as shales, by virtue of their large surface area and high ion exchange capacity, would tend to increase the retardation factor. Other rock types, such as salt, would lower the retardation factors due to their effect on the salinity of the pore water. This subject is being considered in detail by LLL.

The chemistry of the rock may also be of importance as related to minimum or threshold gradients. Due to physiochemical interactions, ground water flow may not occur in certain rock types until a threshold gradient is surpassed. In certain clay soils threshold gradients have been measured exceeding 20 to 30 (Scott, 1963).

2.2.1.6 Pressure Gradients

As expressed by the classic Darcy equation, ground water moves from levels of high pressure or energy to levels of low pressure or energy. The pressure distribution is commonly referred to as the pressure gradient and can be expressed mathematically as a change in pressure per unit change in distance. The pressure gradient determines the direction of flow, and in conjunction with permeability and porosity, the flow velocity. The pressure gradients in real ground water regimes can be quite complex exhibiting significant three-dimensional variations. The complexity of these gradients is often not so much caused by complex pressure sources, but rather reflects the natural variations in the permeability of the geologic media. In general, primary pressure sources are relatively simple and are induced by elevation differences between the recharge areas and discharge areas. In deep multi-aquifer systems, other potentials can be quite significant. These potentials might include osmotic potentials, thermal potentials, chemical potentials and density potentials (Bredehoeft and Hanshaw, 1968). Density and osmotic potentials are discussed in more detail below.

In the deep sedimentary basins considered for the repository, most of the deep ground waters are saline and often brine (more than 35,000 mg/l dissolved solids). Any basic flow concept in which these high density, saltwaters migrate upward into lighter, fresh ground waters must be reviewed with respect to these other potentials. The temperature gradients produced by the canisters may also alter the ground water flow pattern. In addition, as previously mentioned, the concept of minimum or threshold gradient, which is known to be significant in certain clay soils, should be examined.

2.2.1.7 <u>Osmotic Potential</u>

Clay minerals in shale beds may act as semipermeable membranes resulting in an osmotically induced potential gradient. Clay particles have fixed negative charges resulting from the dissociation of positively charged cations. In compacted clays or shales the negatively charged clay particles tend to exclude the passage of anions but allow the passage of adsorbed cations and neutral water molecules. An electric streaming potential is set up between the two sides of the clay membrane and cations cannot continue to pass through the membrane without increasing the electrical imbalance. Thus, the membrane is permeable to water but does not allow the passage of dissociated ions and an osmotic pressure potential gradient will exist that forces water in the direction of greater ion concentration.

The magnitude of the osmotic pressure can be calculated. Hanshaw and Zen (1965) use the following equation to calculate osmotic pressure, π, for a clay member:

$$\pi = P_{II} - P_{I} = \frac{RT}{V} \quad \frac{a_{I}}{a_{II}}$$

Where I and II denote the two sides of the membrane system, R is the gas constant, T is the absolute temperature, V the mean molar volume of water in the pure state averaged over the pressure range, and "a" is activity of water. The pressures P_{II} and P_I are corrected for elevation differences in depth below a given datum.

Shale will undoubtedly not act as an ideal membrane, however, the existence of an osmotic gradient may cause anomalous pressures within saline aquifers. Thus it is possible that a higher head (as measured by a piezometer for instance) in a saline aquifer than in an underlying or overlying freshwater aquifer will not result in flow from the saline to the freshwater aquifer if an intervening shale bed is acting as a semipermeable membrane. To flow from the saline to the freshwater aquifer, water must overcome the osmotic gradient which acts opposite to the normal piezometric head gradient. These osmotic pressures can be very significant. I.W. Marine (1973) reports measured excess pressure heads in a deep Triassic basin in South Carolina exceeding 200-300 feet above the overlying coastal plain aquifer. In his opinion, these pressures are most likely caused by osmotic potentials. The existence of osmotic pressure gradients may have significant implications on the flow regime within a repository layer and should be investigated in detail.

2.2.1.8 Density Gradients

Many aquifers, particularly those in deep sedimentary basins, contain water of variable density. If variations in density are not considered, predictions of flow direction and velocity can be in error. A difference in piezometric head between two points within a constant density aquifer is indicative of the potential for flow between these points. In a variable density aquifer, a difference in piezometric head may not indicate flow unless the head differences caused by density changes can also be evaluated. Water within a variable-density aquifer must overcome gravitational forces due to density variations as well as the viscous forces normally considered in constant-density flow. Bond (1973) defines the head available between points P_1 and P_2 to cause flow, ψ_p, by:

$$\psi_p = (H_{F2} - H_{F1}) - \int_{P_2}^{P_1} (\rho-1)\, dz,$$

Where: H_F is the static head in terms of freshwater, ρ is the relative density of a given sample of aquifer water (ratio of measured density of aquifer water to that of freshwater at $75^{\circ}F$ and 1 atm. pressure), and Z is the elevation above a datum.

To evaluate the integral portion of this equation, the variation of density with elevation must be known or estimated. The potential for flow between P_1 and P_2 will depend upon the relative values of the two terms in the above equation.

The gravitational effects in a variable-density aquifer depend upon the complexity of the flow paths due to structures such as impermeable layers, anticlines, synclines, domes, saddles, etc. In aquifers with complex structure, conclusions about flow made by mapping a potentiometric surface may be completely invalid. Bond (1973) reached the following conclusions regarding gravitational effects:

> "In moderately complex aquifers, for example, sandstones that contain tilted shale stringers, gradients in head up to about 5 ft./mi. can be expected to be caused by gravitational effects. In aquifers that have more complex lithology and structure or that show rapid changes in water density, gravitational gradients up to 10 ft./mi.

or more can occur. Only in aquifers where the observed gradient is large, on the order of 50-100 ft./mi., can the gravitational effects of troughs and structure be neglected; gradients of this magnitude are found only in intermontane basins (Hubbert, 1953). Thus, the results of many flow studies based on potential measurements are open to question. The conclusions that are derived from such studies are valid only if all of the gravitational effects have been evaluated and taken into account or if they can be proved to be negligible."

The effects of variable density flow may be significant with respect to flow of contaminants from a waste repository. The existence of density gradients which can significantly influence the flow pattern should be investigated wherever waters of varying density are encountered. Flow patterns deduced from potentiometric maps should be viewed with caution.

2.2.1.9 Effect of Repository Construction and Abandonment

The construction of the repository may in itself represent a major threat to the integrity of the overall geologic isolation. The repository shafts could provide a direct hydrologic link between the repository layer and overlying aquifers and the ground surface. The flow could occur in the mine backfill and/or within fracture zones around the openings induced by stress release. This flow could allow for a rapid saturation of the mine after abandonment and/or create a rapid pathway for potentially contaminated water to travel out of the repository zone. Clearly, a major technical requirement of an acceptable repository should include detailed evaluation and development of appropriate repository construction and backfill techniques.

After mine abandonment, time will be required to re-establish the original ground water regime and saturate the mine area. Until this occurs, probably no ground water will flow out of the repository zone although gas and steam pathways may be significant. The time required for re-saturation depends on the nature of the original ground water regime, the effectiveness of the shaft seal, and the porosity and permeability of the backfill and tunnel fracture zones. The re-saturation time could become very significant as it might exceed several hundred years for suitably designed and constructed repositories. This effect could in itself represent a major safety feature to water flow paths.

Requirements for dewatering during the 30-year repository operation must be carefully considered. Some dewatering may be required due to leaks through the shaft or from the repository zone itself (many otherwise acceptable formations may require some dewatering during mine operation although exhibiting no circulating ground water after repository abandonment). However the discharge from the dewatering system may become contaminated by radiation from the HLW canisters during the operational phase and provide a quick pathway for contamination to reach the biosphere.

2.2.1.10 Effect of Mines and Wells

In our opinion, the effect of both existing and possible future mines and wells may prove to be of major significance to site suitability. In order to perform any credible evaluation of their effects, it is imperative that the nature and occurrence of existing mines and wells be properly understood. Development of any models which are not consistent with known resource uses and their hydrologic effects will have little meaning and be an obvious weakness for which to discredit the entire model. Data which must be properly incorporated into the model includes the size, depths and locations of existing mines and wells, the nature of well hydrology, and their measured effects on the overall ground water regime.

A detailed survey of known mines and wells (including freshwater, oil and gas, brine, and injection) should be a criteria for any site selection program.

The hydrologic effects of existing and future mines and wells must be evaluated in order to be properly incorporated into the TASC model. These effects can be divided into two general catagories: the direct affect on the ground water regime and pathways to the biosphere resulting from well operation and mine dewatering; and the permanent secondary alterations to the strata caused by deformation, stress changes, leaky seals, etc.

2.2.1.11 Effect of Bore Holes

Since test borings themselves may represent a significant threat to the integrity of the repository, it is important to assess the relative merit of the information obtained from borings versus their liability. This evaluation is particularly urgent since OWI is presently performing subsurface explorations at perspective repository sites.

The general approach should involve evaluation of the negative effects of borings versus the negative effects of undetected anomalies. Similar to the problem of repository backfill, development and implementation of proper sealing of bore holes drilled for the repository exploration phase will constitute a major technical requirement of an acceptable repository.

2.2.2 Available Information

This section presents a partial summary of available information on the hydrology of sedimentary basins. In general, we have concentrated on major mid-continent sedimentary basins which include both salt and shale. This is consistent with the overall TASC model effort which concentrated on salt and shale repositories. The data presented below is divided into shale and salt. General comments about each formation type is presented with brief discussions of specific basin hydrology. The data includes general regional hydrology, and reported measurements of permeability, hydraulic gradients, and salinity. This work in conjunction with the available geologic information summarized in Section 2.3.2 was incorporated into the generic shale basin model and salt basin model presented in Section 2.4. The stratigraphic units referred to in this section are discussed in Section 2.3.2.

Ground water flow within sedimentary basins can be extremely complex. The effects of geology and topography have been shown to be important (Hitchon to 1969). In order to reduce the complex flow in a basin to a system which can be reasonably modeled, the general ground water regime can be presented by three types of gravity flow. Figure 2 illustrates these three idealized basin flow systems. Flow system A will occur if the basin is tilted causing a head difference between the recharge area and the discharge area. This is the flow system thought to occur in the Williston Basin where ground water appears to flow from higher elevation recharge areas in the southwest and west to lower elevation discharge areas to the east and northeast. The Delaware Basin may also follow this flow pattern to some degree. Flow system B consists of a very symmetrical basin being recharged at its margins and discharged at an elevation low within its center. Flow systems of this kind are common where water is recharged from high areas on either side of a river valley. Flow of this nature is occurring along major river valleys in various sedimentary basins but it has not been demonstrated to occur on a basin-wide scale in the basins so far considered. Flow system C is a reversal of system B. The potential for this flow pattern may exist within the Michigan Basin which attains its maximum elevation near the basin center. However, the sketchy available information indicates that seepage of water into the deep aquifers and resulting flow towards the basin margins (i.e. the Great Lakes) may not actually occur.

2.2.2.1 Shale

Shale is considered as a potential host rock for a waste repository due primarily to its low permeability. Shales are generally poor fluid transmitters making water or oil extraction through wells extremely difficult. This lack of interest in shales for water and oil wells also results in a lack of in-situ measurements of their important hydrologic parameters, specifically permeability and porosity. Exceptions occur in highly fractured shales in which fluids are readily transmitted along open fractures. Most highly fractured shales are found associated with faults or other tectonic activity. It is generally thought that these permeable shales must be relatively close to the surface to keep fractures from closing due to mechanical deformation. In most areas shales act as aquitards confining more permeable aquifer forming rocks.

Porosity, and to a large extent permeability, depend upon the degree of compaction of a shale. Athy (1930) reported porosities of surface clays ranging from 40-50% and porosities of 4-20% for shales subjected to deep burial. He found a definite relationship between pressure (due to burial) and porosity. He concluded that reduction in pore space due to high confining pressures is largely due to mechanical deformation until a porosity of about 10% is reached. Beyond this, the decrease in porosity is very slight and takes place slowly and only with large increments of pressure. He interprets this as the point at which mechanical deformation is largely complete and recrystallization assumes the dominant role. The pressures at which this occurs are on the order of 6,000 $lbs./in.^2$. A reduction in permeability can also be expected due to the reduction in porosity. Archie (1950) gave porosity-permeability plots for several petroleum-bearing formations. For the poorly sorted, shaley sands of the Nacatoch sandstone, a reduction in porosity of only 15% (from 40% to 25%) caused a reduction in permeability of nearly four orders of magnitude. Shale will also experience a reduction in permeability with a decrease in porosity.

Shale is deposited in individual beds which may contain varying amounts of coarser-grained sediments. Sandstone lenses are commonly found in even the thickest shale deposits. This results in a highly non-homogeneous media, at least on a small scale. Permeability is generally greater in the direction of bedding than perpendicular to it. This results in anisotropy or directional permeability. On a large scale, i.e. an entire shale sequence, it may be possible to "average" the variations in permeability and represent a shale by a homogeneous media with maximum permeability parallel to bedding. The various porosities must also be represented by an "average" value.

A major concern in any shale sequence considered for a repository site will be the width and spacing of open fractures, if they exist at all. Most authors have assumed that "undisturbed" shale will not contain open fractures at depths over one or two hundred meters due to do closure by plastic deformation. Undisturbed, in this context, means that there has been little or no tectonic activity (folding, faulting, etc.) subsequent to original deposition and burial of sediments. This condition most commonly occurs in the large mid-continental sedimentary basins. However little data is available on the fracture characteristics in deep shale deposits because shales are generally not productive reservoirs for water or petroleum. There is a definite need for further study into the characteristics of fractures in deep shale deposits.

Shale exhibits other important characteristics which include clay swelling, ion retardation, threshold gradients, and osmotic pressures. The high temperature produced by the high level waste canisters may have adverse affects on shale which is temperature sensitive due to its mineralogy.

The hydrology of three sedimentary basins in which thick shale deposits are known to exist were examined. The purpose of this work was to provide base information required to construct a generic shale model. This model is presented in Section 2.4. The basins studied include the Williston Basin containing the Pierre Shale, the Michigan Basin containing the Devonian-Mississippian Ellsworth and Mississippian Coldwater shales, and the Appalachian area containing the Devonian Ohio Shale in central and northern Ohio and the Ordovician shales in central and western New York.

Figure 3 shows the locations of the basins and Figures 4-6 indicate typical stratigraphic sections and information on basin resource use. Many other sites contain sufficiently thick shale deposits, however, they are thought to be less suitable for underground placement of waste due to tectonic activity, fractures, or various other reasons (Merewether, et al., 1973). The amount of information obtained and reviewed relative to the above basins was extensive but by no means complete. Rated according to the completeness of information available, the Williston Basin was studied in the greatest detail with the Appalachian Basin studied in the least detail. A summary of the information reviewed is presented in Appendix A.

2.2.2.2 Salt

Salt, as a potential host rock for a waste repository, exhibits several favorable hydrologic characteristics. It occurs primarily in thick bedded deposits associated with sedimentary basins or in salt domes formed by diapirism. Bedded salt and dome salt are very similar in composition but differ significantly in their hydrologic environments.

Bedded salt deposits are usually found in sequence with limestone, dolomite, and anhydrite which can isolate them from percolating waters by acting as seals. Bedded salts commonly contain impurities and thin shale seams. Dome salts are generally surrounded by a layer of caprock which tends to seal the salt from the surrounding aquifer waters. Brine inclusions, some under high pressure, are found in both bedded and domed salt.

Permeability tests have been made on laboratory samples of both bedded and dome salts. Gloyna and Reynolds (1961) concluded that if flow occurs in a rock salt specimen, it must occur through fractures or intercrystalline planes and not through the salt crystals. They measured intrinsic permeabilities for dome salt from effectively zero to 1.5 x 10^{-9} cm^2 and for bedded salt from effectively zero to 2.3 x 10^{-13} cm^2. (10^{-5} cm^2 is approximately equal to 1 cm/sec for pure water at 20^oC). These values were increased using a non-reactive fluid (helium or kerosene). Permeabilities decreased with increased stress and also with time. Many of the fractures which transmitted fluid initially were thought to be caused by stress relaxation when the samples were removed from their in-situ environment. These fractures start to close with increased pressure and continue to do so over time. Bedded salt was found less permeable than dome salt which Gloyna and Reynolds attribute to the larger amount of impurities present in the bedded salt. Permeabilities measured using brine were highly variable but averaged only 32% of the non-reactive fluid permeabilities. Effective porosities varied from 1.71% in the dome salt to .59% in the bedded salt. Katz and Coats (1968) report intrinsic permeabilities of rock salt from effectively zero to 10^{-9} cm^2 and porosities from 0.6 to 2.0%. It seems possible that overburden pressure will cause permeability channels in salt to heal resulting in little if any permeability. Based on this preliminary literature review, no reliable in-situ permeability tests in salt have been documented. Since the in-situ permeability of salt is very important, clearly a better understanding of the in-situ behavior is needed.

Productive salt mines in bedded salt and dome salt commonly exhibit some brine inflow. This inflow is usually attributed to brine which is contained in inclusions or shale layers. It flows into the mine because of pressure release and usually continues for a relatively short time. Some salt mines have had much larger inflow attributed to connection with aquifers due to poor shaft sealing, leaky bore holes, or fractures caused by mining which allow communication with aquifers. These inflows may increase with time and may eventually dissolve large volumes of salt forming breccia pipes and other solution and collapse features.

Hydrologic characteristics of salt, as presently known, appear favorable to a waste repository site. Permeability is low as measured in lab tests and may be even lower under in-situ conditions. For instance Gloyna and Reynolds (1961) state:

> "Although the measured permeabilities are real, the permeability in-situ must obviously be much less than that measured in the laboratory; the laboratory tests did not involve the extended consolidation that would occur over a geological time period; also the laboratory specimens were fractured when they were removed from the mine."

If fractures heal easily and quickly, as is suspected, the major concern for radioactive release from a repository would be natural solution features associated with salt or man-made pathways.

Evaporite sequences occur in most sedimentary basins, including both the Williston and Michigan Basins described for shale. These occur at greater depths than do the shales considered previously but the same general basin hydrology pertains. The Delaware Basin, actually a sub-basin of the much larger Permian Basin, is considered as a major candidate for a waste repository in bedded salts. The basic hydrology of the Permain Basin, the Delaware Basin, the Williston Basin, the Michigan Basin, and salt domes are presented in Appendix A. Figure 3 shows the locations of these basins and Figures 4, 5 and 7 indicate stratigraphic sections.

2.2.3 Technology

The following is a partial list of ground water related technology that would be required to evaluate site suitability:

1) Dispersion Behavior Analyses
2) Retardation Behavior Analyses
3) Evaluation of Secondary Pressure Gradients
4) General Theoretical Ground Water Transport Analyses Methods
5) General Numerical Ground Water Transport Analyses Method
6) Mine Ground Water Evaluations - Dewatering, Leakage, Recharge Time
7) Evaluation of Nuclide Movement Within Repository Zone
8) Evaluation of Significant Parameters - General Procedure for Determining, Accuracy, Probable Variations
9) Evaluation of Undetected Features Through Pumping Tests
10) Lower Limit of Circular Groundwater
11) Predictions of Climatology Effects - Including Glacier, Changes in Recharge and Discharge Characteristics, etc.

A discussion of each of these topics is beyond the scope of this report. However, ground water transport and theory and numerical modeling techniques are briefly discussed below. These topics are considered critical areas to the site suitability evaluation.

2.2.3.1 Transport of Nuclides by Ground Water Theory

The theory of contaminant transport by ground water, largely ignored up until about 1960, has been a subject of growing interest over the last decade. The complex natures of the physical/chemical processes involved are only beginning to be understood, and present accepted theories may no longer by considered valid in a few years. In the following section we will briefly discuss the state-of-the-art of contaminant theory. A useful general review may be found in Cherry, Gilham & Pickens (1975) or in Borg et al. (1976).

There are three distinct processes that contribute to transport: convection, mechanical dispersion, and diffusion. The latter two processes are often lumped under the term hydrodynamic dispersion. Chemical interaction of the contaminant with the solid medium (sorption) can significantly impede the rate of transport due to each of the three transport phenomena. Convection refers to contaminant transport due to the average bulk flow of the ground water. Mechanical dispersion is the process whereby the contaminant concentration is diluted due to the intermingling of flow paths. Diffusion is the process whereby the contaminant is spread due to molecular motion. Each of the three transport processes can dominate, depending on the rate of fluid flow and the nature of the medium (Bear, 1972). They are discussed separately below:

Convection

Convection is determined by the ground water velocity. The ground water velocity is usually determined by Darcy's law, which states that the mass average flow velocity is the product of the fluid weight density, the permeability tensor and the potential gradient, all divided by the fluid viscosity. The actual pore velocity is found by dividing the mass average velocity by the effective porosity. Darcy's law is generally considered valid for reasonably low head gradients provided the surface activity of the formation materials is not high (as in some clays). Darcy's law applies to a continuum, and its validity for sparsely-jointed rock may be questionable.

Of the parameters required to determine the ground water velocity, the fluid weight density and viscosity are usually fairly easily defined functions of pressure, temperature and salinity. The permeability tensor, however, is substantially more difficult to assess and may be highly anisotropic and nonhomogeneous. Similarly, the effective porosity is difficult to measure and may vary throughout the formation.

The fluid potential (energy) is the force which drives the water through the formation. It is generally considered to be primarily a function of elevation, density and pressure (Remson, Hornberger & Molz, 1971) but is also affected by ionic concentration (salinity), temperature and electric potential. Salinity, in particular, appears to be able to have a major effect on the fluid potential (Hanshaw & Zen, 1965) which is not incorporated in present flow theory.

Mechanical Dispersion

Mixing occurs in flowing ground water due to the multitude of non-uniform, non-parallel flow paths. The rate of dispersion is conventionally assumed to be the product of the coefficient of dispersion (a second order tensor) with the concentration gradient of the contaminant. The coefficient of dispersion is the product of the seepage velocity and some power of the medium's dispersivity. A general discussion of dispersion may be found in Bear (1972) or Scheldegger (1961).

Due to the complexity of the relations outlined above and the difficulty in obtaining the large number of material parameters required, it is common to assume that the dispersivity is isotropic, and that the coefficient of dispersion in the product of the seepage velocity varies with the first power of the dispersivity. These assumptions lead to a simple longitudinal (parallel to the flow) and transverse (perpendicular to the flow) coefficient of dispersion.

The accuracy with which the simplified theory can simulate dispersion in bedrock aquifers is not well established. Studies conducted to date (Webster, Proctor & Marine, 1970; Robertson & Borraclough, 1973, etc.) generally indicate that given appropriate parameters the theory can predict at least the general trend of dispersion.

Diffusion

The movement of contaminants by diffusion is usually considered negligible in aquifer flow. A repository, however, would presumably be located in material of very low permeability. In such a case transport by diffusion through the rock pores might be significant.

Sorption

Interaction of the contaminant with the formation can substantially impeded the transport process, depending on the chemical nature of the formation and the concentration of various species in the water. Shales, in particular, can have high sorption capacities due to the large fraction of clay minerals.

There is commonly assumed to be a linear relationship between the concentration of an ion in solution and the amount sorped. The distribution coefficient reflects the ratio between the amount sorped and the amount in solution, at constant temperature. The effects of concentration, temperature, pressure and competing ion species on the distribution coefficient for a given ion are complex, only partially understood, and difficult to measure.

In shale beds which act as semi-permeable membranes, the majority of the nuclear ions may be completely impaired from moving through the shale.

Summary

The transport of nuclides by ground water involves several processes, all complex and none well understood. The material parameters involved are difficult to measure and can be expected to vary substantially over relatively short distances. The uncertainty resulting from these factors is significant, and it must be assumed that any predictions of regional transport of nuclides released from a repository are liable to order-of-magnitude errors.

On the other hand, we do understand the general nature of all the transport processes and we do have simplistic theories describing them. With these tools we can assess the parametric importance of different factors on transport and identify repository types which are relatively safe and types which are clearly unsafe.

2.2.3.2 Computer Modeling of Nuclide Transport Via Ground Water

With the development of powerful digital computers it has become possible to numerically model ground water transport of pollutants with increasing sophistication. In the last decade general finite difference and finite element codes have been produced. None of these is so powerful as to include all aspects of transport, but the capability exists to create more-or-less accurate numerical models for a considerable range of problems.

Limitations on the solution accuracy can be considered to stem from three sources: limitations in the transport theory itself, limitations on the complexity of the flow/transport regime being studied, and limitations on the numerical algorithm accuracy. As discussed above there are at present limitations in the theory available to describe each of the four main processes involved in transport (convection, dispersion, diffusion and sorption). Most of the presently available programs avoid the theoretical weaknesses by being restricted to special classes of problems. For example, most programs are restricted to cases where the pollutant concentration is low. In this way the effect of the pollutant on the fluid density and on the fluid flow potential is neglible. Other fundamental weaknesses in flow/transport theory cannot be readily dismissed. Questions as to the applicability of the available theories to sparsely-jointed rock aquifers, with the possible presence of strong salinity concentration gradients and substantial thermal effects, will tend to limit the believable accuracy of any program. Limitations on the complexity of the flow/transport regime being studied are inevitable for two reasons: it is never possible to completely determine the nature of a geologic system, and even the largest computing budgets are overwhelmed by massive three-dimensional models. Finite-difference models in particular are usually rather weak at modelling geometrically complex boundaries and interfaces, and at extending their grids to distant boundaries. In general there is a payoff between the complexity of the model and the cost of computing a solution. The number of spatial dimensions (1, 2 or 3) represented in the model is a dominating factor, as the cost of a one-dimensional solution could be squared for a two-dimensional solution and cubed for a three-dimensional solution.

Limitations on the numerical algorithm accuracy arise due to the complex nature of the differential equations. "Numerical diffusion" in finite difference codes and numerical instability in finite element codes are the symptoms of fundamental limitations in the algorithms used. Any program must be used with careful regard to its numerical limitations.

State-of-the-Art Programs

In our review of available programs we located three packages which were suitable for modeling aspects of the transport of nuclides from a deep repository to surface waters. Other programs are available (Appel & Bredehoeft, 1976) but are probably less effective than the three described below.

1) "Waterloo" Program

This program was written by John Pickens at the University of Waterloo, Ontario. It is described in Pickens and Lennox

(1976). The least ambitious of the three programs discussed here, it solves two-dimensional transient transport in a steady flow field by a finite element method. Solute concentrations are presumed to be small, and the effects of variable temperatures and salinity concentrations are ignored. The program is written for IBM 360/370 series computers.

2) "Pinder" Program

This program was written under the direction of George F. Pinder at Princeton University. It is a general-purpose finite element program which can be adapted to a multitude of problems. In solute transport form it can solve coupled transient solute-concentration/flow problems in one, two or three dimensions, but cannot include thermal effects. Due to its increased flexibility, it requires more input information than the Waterloo program. The Pinder program was written for IBM 360/370 series computers, and is presently being converted to CDC form at Lawrence Livermore Laboratories.

3) INTERCOMP Program

This is a two/three dimensional finite difference program written by INTERCOMP Resource Development and Engineering, Inc. under contract to the U.S. Geological Survey (INTERCOMP, 1976). The program can perform transient pollution-transport/heat-transport/flow analyses and includes coupling due to induced density changes (but not direct coupling due to chemical and thermal potential changes). The program is apparently free from "numerical diffusion" due to the choice of the second spatial-difference algorithm. The program is written for CDC computers, and is available from NTIS. As written, the program does not simulate sorption or radioactive decay of the contaminant. An upgraded version of the program with these capabilities is presently being developed by INTERCOMP under contract to Sandia Laboratories.

2.3 Geology

2.3.1 Factors

The primary affect of geology on site suitability is its relationship to potential ground water flow paths. Thus, the geologic conditions are, in essence, secondary to the primary hydrologic factors discussed in Section 2.2.1. Listed below is a preliminary list of geologic factors which would have to be considered in a site suitability evaluation. Due to the scope of this report and since most of these factors are self-explanatory, a discussion of the individual items is not presented. This preliminary list includes:

1.0 Lithology - Rock Type Characteristics, Chemistry, Physical Behavior, Thermal Properties, etc.
- 1.1 Sedimentary.
- 1.2 Igneous.
- 1.3 Metamorphic.
- 1.4 Unconsolidated.

2.0 Stratigraphy - Geometry, Configuration, Bed Thickness, Uniformity, Zones of Alteration and Weathering, Unconformity, Nonconformity, Bed Dip.

3.0 Structure
- 3.1 Primary.
  - 3.1.1 Sediments - grain size and distribution, voids, depositional related features, bedding.
  - 3.1.2 Igneous - lineation, foliation, form, uniformity, texture voids, primary porosity.
  - 3.1.3 Metamorphic - lineation, foliation, form (layering, dyke-like, injection, etc.), uniformity, texture, primary porosity.
- 3.2 Secondary.
  - 3.2.1 Flaws or joints, faults, fractures, dykes, etc.
  - 3.2.2 Alterations.
  - 3.2.3 Solution and depositional features.
- 3.3 Tectonic.
  - 3.3.1 Folding.
  - 3.3.2 Faulting.
  - 3.3.3 Others.

4.0 Geomorphology - Surface Phenomenon

5.0 Tectonic Phenomenon

5.1 Setting - province, crustal stability, etc.
5.2 Seismicity - historic, factors affecting anticipated ground movement, predicted events, depth of event.
5.3 Results of event - related to rock type, existing rock structure, existing stress conditions.

6.0 Potential Resource Value - Related to Rock Types

7.0 Glaciation

2.3.2 Available Information

This section presents a partial summary of available information on the geology of sedimentary basins. This data, in conjunction with the hydrologic data, was incorporated into the generic basin models presented in Section 2.4. The general format and specific areas discussed are similar to those discussed in the hydrology Section, 2.2.2 and Appendix A.

2.3.2.1 Shale

The shales and mudstones outbulk all other types of sedimentary rock and have accumulated in a wide range of environments. These sediments consist mostly of the end products of chemical decay which are the clay minerals and the oxides of iron, manganese and aluminum. They may also include finely-divided particles of a wide variety of other minerals, particularly quartz, calcite and organic matter. The low permeability, relatively high plasticity, large ion-exchange capacity, thickness, and widespread distribution of shale, mudstone and claystone sequences are desirable properties in host rocks for underground waste emplacement. These rocks, however, may also have characteristics that may not be desirable. Some of the most extensive undeformed shales with relatively high plasticity contain much montmorillonite that may cause major mining problems and may release water when gently heated. Other shales contain organic matter that may yield combustable carbon compounds when heated. Limestone rich or calcium carbonate cemented shales may yield carbon dioxide when heated to very high temperatures.

Shales of marine origin have received more study during this investigation than non-marine shales because marine sediments are more uniform in composition, thickness and greater aerial extent. They are less likely to contain unexpected coarser-grained water-bearing beds and thus are less permeable as a unit. All shales are interbedded with various units including siltstone, sandstone and limestone. Commonly clay shale represents only 80 percent of the overall shale unit.

Those regimes containing abundant faults, folds or seismic activity have received little study. Folding and fracturing creates rocks with significant secondary porosity and thus greater permeability. Regions characterized by frequent earthquakes or faults of Quaternary age are more likely to be subjected to significant diastrophism during the next several hundred thousand years. It does not follow that safe repository sites cannot be selected within these regions, only that greater care and discrimination will be required in their selection.

As discussed in the hydrology section, the geology of three sedimentary basins were reviewed. These include the Williston Basin, the Michigan Basin and the Appalachian Basin. Figure 3 shows the locations of these basins. This information is summarized in Appendix B.

2.3.2.2 Bedded Salt

Evaporites have been chemically precipitated from hypersaline sea water trapped in a structural low area that was cut off or restricted from the open ocean. The sequence of deposition of evaporites from a desiccating water body and their volumes are controlled by the chemical composition of the water-salt system involved. In sea water, calcite and dolomite are deposited first. Then, after evaporation has increased the concentration of dissolved salts some three times or more, calcium sulfate (gypsum and anhydrite) begins to deposit. This is followed in turn by halite, polyhalite and the other less abundant salts. The solubility of a given salt and, therefore, its deposition, are affected by temperature and the presence of other salts in the system. Changes in temperature and salinity during evaporation may cause reversals in the sequence of deposition. Bedded salt is usually a sequence of halite, thin clay seams, and anhydrite.

Structures in salt are related to their plasticity and solubility. Folds form from plastic flow of the salt reacting to tectonic stresses. The most common structure, however, is some kind of dissolution feature. These may range from channels, sink holes and caverns, to total removal of salt and resultant failure of the overlying rock.

The term dissolution front is used to describe the zone of active solution of the salt. This zone requires circulation of fresh ground water because salt saturated ground water may actually act as a barrier to further solution. One mechanism for solution collapse features is the change of Anhydrite ($CaSO_4$) to gypsum ($CaSO_4 \cdot 2H_2O$). There is a 30% to 58% increase in volume creating pressures between 300-10,000 psi. One uplift analyzed in the field gave 35-42% volume increase and 2,000 psi uplift pressure (Brune, 1965). Buckling of beds during hydration will cause cracking and open waterways for subsurface solution. This uplift seems to be restricted to moderate depths around 500 feet. At greater depth in the area investigated, rock overburden pressure was sufficient to reasonably contain the expansion pressures.

Solution features are not restricted to the presently active dissolution front or zone. Hydration, solution and the related overlying slumping and subsidence may have occurred during a variety of erosion cycles in the past. Dissolution, which is not restricted to a single front, may be active along a series of zones. Buried solution features may be healed by recrystallization of salt or by plastic flow into the void areas. They also may be partially open with the subsiding formation forming a cap that seals the salt from circulating water.

Within the salt body itself large pockets of brine may exist. Some mines have experienced brine inflow of up to 100,000 gallons when they drilled into such a pocket. This may be connate water or water that was trapped when the salt healed a flaw. Small bubbles of brine may be included within the salt crystals as in the Hutchinson salt of Kansas. Pockets of gas also exist within salt bodies. Both the brine inclusions and the gas may be under great pressure.

Salt deposits are widely distributed in 24 of the 50 states. Some of the deposits have a lateral extent of several hundred miles. The Silurian salt deposits of the northeastern states underlie parts of

New York, Pennsylvania, West Virginia, Ohio, and Michigan. The greatest aggregate thickness of salt is in the previously described Michigan Basin. The combined thickness of all the salt beds ranges from about 1,800 feet in the central part of the basin to about 500 feet on the margins. In New York the maximum thickness is about 800 feet with rapid thinning away from the center. Figure 3 shows the locations of the major salt basins. Geologic information on the Permian Basin, Delaware Basin, Williston Basin, Michigan Basin, and salt domes are presented in Appendix B.

2.3.3 Technology

The following is a partial list of the geologic related technology that would be required to evaluate site suitability.

1. Evaluation of Type, Probability, and Affect of Undetected Features
2. Evaluation of the Type, Probability, and Affect of New Features: Seismic, Geomorphological, Glacial, Solution
3. Evaluation of Future Seismicity
4. Predictions of Climatological Effects Including Glaciers
5. Evaluation of Physical Variations Along Existing and Future Flaws: Especially Faults
6. Evaluation of Fracture Occurrence

2.4 Generic Basin Models

Based on the information presented in Sections 2.2 and 2.3, and Appendices A and B, generic salt and shale basin models were developed. The purpose of these models is to incorporate the features commonly encountered in major mid-continent basins which might affect site suitability.

These generic models would then be synthesized into the TASC model, enabling realistic geologic and hydrologic conditions to be credibly evaluated.

2.4.1 Generic Shale Basin Model (See Figure 8)

The general geology and hydrology of the stratigraphic units are:

A. Recent Deposits

A surficial group made up of weathered zones of all formations plus transported sediments from erosional processes (alluvial, glacial, wind).

Generally contains water table aquifers, may be locally confined. Permeability varies widely, depending primarily upon particle size and sorting. Well-sorted sands and gravels will have highest permeabilities, poorly-sorted till material will have the lowest permeability. Most productive aquifers located in alluvial valleys and glacial outwash areas. Water quality variable depending upon location and amount of circulation. Used for domestic water, stock, irrigation.

B. Clastic Sequence

Upper: A series of variable thickness layers of sandstone and shale. Individual beds are discontinuous pinching out or changing facies within short distances; i.e., a sandstone may change to a shale within 1 to 2 miles.

Various confined aquifers in sand zones, areally discontinuous. Permeabilities range widely in vertical and horizontal directions from one location to another (non-homogeneous, anisotropic). Fracturing may allow some hydraulic connection between various aquifer layers. Water quality will generally be good and aquifers may be an important source of water locally.

Middle: A thick shale sequence with a variety of individual layers. Some carbonate, organic and silty or sandy zones exist within beds.

Shale will have low permeability with some more permeable zones due to interbedded sandstone or limestone. Very little water movement will occur unless shale is fractured, allowing flow. Water velocities may be very significant if open and connected fractures are present.

Lower: A thin sandy sequence of alternating sandstone, shaley sandstone and siltstones.

Forms a confined sandstone aquifer, fairly continuous over much of the basin. Water is too deep and of too low a quality to be important for domestic, stock or irrigation uses. Lowest quality is found near the center of the basin.

C. Carbonate-Evaporite Division

These rocks reflect sedimentation in a variety of carbonate depositional environments. The sequence is interrupted by beds of relatively high clay or sand content and evaporite beds of anhydrite and salt.

Contains a number of confined aquifer zones in sandstone or cavernous limestone. Some of these aquifers may be continuous over large areas. Aquifers near evaporites may contain brines with concentrations of 100,000 to 300,000 mg/l total dissolved solids. Fracturing, if present at these depths, may allow some hydraulic connection between various aquifers.

D. Basal Clastic Sequence

A series of fine to coarse grained quartzose sandstones replaced upward by siltstones and shales.

Forms a confined sandstone aquifer, may be fairly permeable due to poor cementation. Forms the lowest permeable formation.

E. Basement

A Precambrian erosion surface of granite and metamorphic rocks.

Considered relatively impermeable over most of the basin. May form an aquifer at outcrops due to fracture permeability.

2.4.2 Generic Salt Basin Model (See Figure 9)

The general geology and hydrology of the stratigraphic units are:

A. Recent Deposits

Surficial windblown dune sand, playa lake silts and sands, alluvial sands and gravels, bottomed by caliche.

Little or no water contained in dune sands. Unconfined aquifers found near some large playa lakes but are generally not an important water source. Unconfined aquifers in alluvial deposits may yield significant water for stock, irrigation and domestic use. Quality is generally fair to good in alluvial aquifers.

B. Upper Clastic

A series of terrestrial red beds consisting of shale, siltstone and sandstone containing thin veins of secondary gypsum.

Areally discontinuous aquifers, confined or unconfined, found primarily in sandstone layers. Various aquifers generally exhibit some degree of hydraulic connection between them. Permeability variable (non-homogeneous, anisotropic). Quality is variable, water is used for stock and domestic purposes where quality allows.

C. Evaporite Sequence

Upper: Dominantly anhydrite with a few silty layers and several 10-40 ft. thick dolomite beds. The structure is complicated by the anhydrite altering to gypsum and solution collapse. The base of this unit is a solution breccia.

Several aquifers with fracture and/or solution porosity in dolomite layers. Confined above and below by anhydrite and siltsone. Water is slightly to moderately saline but may constitute an important aquifer for water wells. Basal breccia zone is permeable and contains very saline water. Vertical connection between aquifers can occur at fault or fracture zones.

Middle: A thick salt section with salt and anhydrite in the form of thick beds and inclusions making up 10 to 25% of the formation.

Contains virtually no aquifers or moving ground water. Inclusions may contain brine.

Lower: An interlaminated white anhydrite and brownish limestone section with several beds of relatively pure salt. The salt beds range in thickness from a few feet to over 700 feet but average less than 250 feet thick. They are separated by beds of anhydrite - limestone 50 to 500 feet thick.

Contains little or no moving ground water. Some brine may be found in limestone beds and inclusions.

D. Lower Clastic Section

A sandstone sequence with minor interbeds of limestone and shale. It grades laterally into carbonate reef deposits at the margin of the basin.

Confined sandstone and limestone aquifers containing saline water or brine. Permeability is fairly low but may increase significantly near reef deposits. Vertical communication exists between some aquifer layers.

E. Carbonate Sequence

A thick marine limestone section containing several thick shale beds near the center of the sequence. This section contains at least three erosional unconformities. The lithology and thickness of individual units is relatively uniform over wide areas.

Contains a number of confined aquifers in fractured or cavernous limestone. Aquifers can be continuous over most of the basin. Water is very saline with concentrations over 150,000 mg/l total dissolved solids common.

F. Basement

Largely granitic, although it may consist of metamorphics and volcanics locally.

Considered relatively impermeable although it may contain some stagnant water in fractures. Forms an aquifer only at outcrop areas.

2.4.3 Anomalies

Geologic formations are not uniform homogeneous bodies with infinite boundaries. The normal case is one of change within a few feet to a few miles. For this model anomalies are those geologic features that affect the flow of ground water through rocks in a sedimentary basin. Only the major features altering ground water flow will be discussed.

Primary anomalies are those features that formed with the deposition of the sediments themselves. There are two major sedimentary environments, marine and non-marine. The marine environment is characterized by a more uniform deposition than the non-marine or terrestrial environment. For example, floodplain deposits normally include silt and clay spread widely beyond the channel during flood, and relatively linear bodies of sand or gravel representing the channel fill and natural levees. In the sea, sand is normally spread in sheets, since there are no confining channels. Facies change thus varies with the environment of deposition. The sea also sorts sediments into even-grained groups, where streams tend to lump sizes together.

Reefs or bioherms are features associated with the marine environment and evaporite deposition. They formed a barrier creating a backreef lagoon where salt accumulated, while in the forereef area, reef talus and limestone were being deposited. Reefs are generally located at the margins of a basin because they require shallow water for the various organisms to grow. If the basin is subsiding slowly and the sea is shallow, then reefs are not restricted to the margins but may form pinnacles or knolls anywhere the water is shallow enough. Due to wave action eroding the reef, there is usually a reef talus deposit of high porosity making reefs prolific water sources and traps for oil and gas. The Capitan Reef in the Delaware basin is about 3 to 4 miles wide and 2,000 to 3,000 feet thick. It grew laterally covering its own talus. This has made it a major source of oil and a freshwater aquifer. Reefs in the Michigan and Williston Basins grew vertically and are only about one mile wide and 4,000 to 5,000 feet high. These reefs can significantly alter local ground water flow due to their relative high permeability.

Secondary geologic anomalies include anything that has happened to a formation after its original deposition. Frequently formations have been subjected to multiple periods of erosion creating uneven surfaces, talus piles, stream and river channels and other erosional features. Karst topography is developed in regions where soluble rocks are close to the surface and subject to circulating fresh ground water. Solution caverns follow joint patterns with sink holes and pipes or chimneys occurring through overlying formations. In salt, these pipes may become healed, due to salt flow and recrystallization after reburial. Limestone and dolomite caverns probably do not heal though they may be sealed with debris.

Tectonic forces act on formations causing faults, folds, and joints. Faults are usually oriented along some structural feature such as the margin of the basin or flexures in the basement rocks. These flexures can cause gentle folding and associated faulting as found in the Williston and Michigan Basins. Joints may not exist in an open state much below 500 feet, but because they are open at near surface depths, they can significantly alter the ground water flow. Joints occur in much greater number than faults because they relieve stress in only a very local area. An average spacing for joints in the mid-continent area is about 10 feet as measured in Kansas, Nebraska, Oklahoma and part of Missouri.

Tectonic activity while causing folds and fractures may also have volcanism associated with it. There are some dikes intruding the salt in the Delaware Basin that are probably associated with volcanic activity outside the basin. Volcanic activity in the Williston Basin is restricted to the western marginal area.

Sedimentary basins are a major source for oil and gas, coal, potash, salt and numerous other raw materials. Oil wells, both exploration and producing, can interconnect aquifers. In addition, secondary recovery techniques often involve pumping large volumes of water from one aquifer into another. Some wells are used as brine wells creating a solution cavity at great depth. Wastewater and toxic chemicals are being pumped into deep formations. Freshwater is being extensively utilized from near surface wells. All of these wells create openings and cause artificial recharge or discharge areas altering the local ground water flow pattern.

Potash mines are possible sources of solution activity in evaporite areas. The mine might flood from the shaft seal and overlying aquifers causing an artificial dissolution front. Mines, in general, create large interconnected openings which may eventually collapse due to overburden load. This collapse and resulting fractures may have a major effect on the ground water flow patterns.

2.5 Rock Mechanics/Mining

2.5.1 General

As with geology, the primary concern of rock mechanics/ mining on site suitability is its relationship to potential ground water flow paths. These flow paths would include fracture zones around openings, the shaft and/ or tunnel backfill, large-scale deformation above the repository causing changes in formational permeability, the affect on the ground water regime of dewatering during and after mine operation, and gradients and flow paths induced by the thermal effects of the canister heat. Thus, rock mechanics/mining considerations are, in essence, secondary to the primary hydrologic factors discussed in Section 2.2.1.

The rock mechanics/mining considerations which influence the suitability of an underground repository relate to stability of the repository during its initial operational phase and disturbance (and associated permeability changes) during the construction, operational and storage phases.

The initial factor determining the level of disturbance of a repository site is the method of excavation. The level and type of underground support for the operational phase of the repository will be determined by operational stability requirements and the resulting degree of rock mass disturbance in the immediate vicinity of the excavation. The sequencing and timing of support placement in relation to the excavation program is also an important factor influencing the stability and resulting disturbance.

In deep underground structures in rock, the primary requirement for stability is that the rock mass be basically capable of supporting itself. The function of artificial support (rock bolts, steel sets) is therefore limited to nearsurface stabilization, while the major load supporting role must be attributed to the rock mass itself. The ability of the rock mass to satisfactorily fulfill this load support requirement depends on a complex interaction of factors such as strength of the rock mass, deformability characteristics of the rock mass, geometry of the repository, and applied loading including in-situ ground stress, earthquake and thermal loading.

The size of the overstressed zone for a fixed geometric opening in a fixed stress field is a function of the strength/stress ratio. Similar considerations apply for other types of loading such as earthquake and thermal loads. The size of the overstressed zone for a fixed geometry and fixed material strength grows substantially as the relative horizontal stresses increase in magnitude. For any given in situ stress field, there is an optimum shape of openings which will result in minimum disturbance to the rock mass. This will be generally achieved when the ratio of the major and minor axes of the opening (oriented parallel to the principal stress directions) is equal to the ratio of the corresponding principal stresses.

In the storage phase of the repository operation, the long term support will be provided by backfill. The extent of additional disturbance which develops in the vicinity of the repository during this period will be dependent primarily on the relative stiffness of the backfill in relation to the rock mass stiffness. This will be related to the practicalities of establishing a viable backfilling procedure with a minimum of remaining voids. The long term permeability characteristics of the backfill itself will also influence the ultimate suitability of the repository.

The above discussion has briefly introduced the rock mechanics/mining considerations which are of concern in establishing suitability criteria for an underground nuclear waste repository. Each of the factors generally falls into one of two major subdivisions: natural factors and man-made factors. In the following sections, these factors, together with the items of principal importance in influencing or modifying the factors, are discussed in general terms. The following general outline will be used:

<u>Natural Factors</u>

Geomechanical Properties of Rock Masses

(i) Strength of Rock Masses

(ii) Deformability Characteristics of Rock Masses

(iii) Density of Rock Masses

In-Situ Loadings

(i) In-situ Stress Field

(ii) Earthquake Loadings

Man-Made Factors

(i) Method of Excavation

(ii) Geometrical Layout

(iii) Type of Support: Short-Term - open cavern support,
Long-Term - backfill support

(iv) Thermal Loadings

Due to the concentration in effort by OWI in using salt for a repository, we have completed a detailed evaluation of the physical properties of rock salt. This work is summarized in Appendix C.

2.5.2 Natural Conditions

2.5.2.1 Strength of Rock Masses

Rock mass strength characteristics are used in conjunction with the stress field prediction of analytical models in order to assess the extent of failure zones surrounding an underground excavation. This has implications regarding the excavation stability together with the associated permeability characteristics which are dependent upon the degree of rock disturbance.

The strength of a rock mass depends on the characteristics of both the intact rock material and the discontinuities present within the mass. The intact rock material is that component of the rock mass considered to be physically continuous for design purposes, although strength testing must be carried out on samples of sufficient dimensions to account for the inherently discontinuous nature of the material. The strength properties of the "discontinuities" such as joints or faults must be determined separately. These features, together with the rock material, constitute the rock mass.

Rock failure can occur by either a tensile mechanism or a shear mechanism. Tensile failure of interparticle bonds is undoubtedly involved in the shear failure process, but on a macro-scale the two types of loading induce widely different responses within rock material. The capability of a rock mass for transmission of direct tensile loading is generally considered to be limited. The shear or compressive strength of rock material and rock discontinuities is therefore of major concern. A principal determinant of the shear strength of a rock mass is the applied state of stress, and failure criteria for rock are initially discussed in terms of this variable. The influence of other factors such as rate of loading, temperature, existence of pore pressure and presence of moisture, which assume variable importance depending upon operating conditions and rock type, must also be considered.

Kvapil (1959) has reported the influence of a radiation dose of $7.6\text{x}10^8$ r/cm^2 of fast neutrons and gamma radiation, on the strength characteristics of three limestone and one rock salt specimens. For comparison purposes, similar strength testing was also carried out on specimens of similar but non-irradiated rocks. The effect of the radiation dose was to result in a drop in the unconfined compressive strength of 20 to 41 per cent for the limestone and a corresponding strength decrease in the rock salt of almost 45 per cent.

2.5.2.2 Deformability Characteristics of Rock Masses

The deformability characteristics of a rock mass, in conjunction with the level of applied loading, determine the stress distribution around any given underground opening. The level of the developed stresses in relation to the rock mass strength will in part determine the degree of rock disturbance accompanying the formation and maintenance of the mine opening.

In general terms, rock failure is merely a specific stage in the deformation history of an overloaded zone of rock. The resulting macrodeformations which may occur when the strength is reached should be considered as part of the describable deformation characteristics of the rock. In practical terms, the pre-failure behavior is generally moderately well defined and is approximated by appropriate simplified models.

Temperature will affect the deformation properties of rock material in two specific ways. First, higher temperatures are consistent with the development of plastic or ductile behavior at lower levels of confining stress for any particular rock type. Thus, the higher temperatures permit deformation by flow to occur when fracturing would result under loading at lower temperatures. This is of particular interest for repository design in rock salt, since the temperature in the vicinity of the waste containers will be such as to change significantly the stress-deformability characteristics of the salt. Second, experimental work has shown that increased temperature results in a marked acceleration of creep strain rates for any given ambient stress conditions.

Kvapil (1959) subjected three limestone samples and one salt specimen to a radiation dose of 7.6×10^8 r/cm^2 of fast neutrons and gamma radiation. At fixed levels of stress, the per cent increase in deformation of irradiated specimens as compared with the deformation of non-irradiated specimens ranged from 30 to 240 per cent for the limestones and was 290 per cent for the rock salt.

2.5.2.3 Density of Rock Masses

The most important consideration in relation to rock mass density is the buoyancy force exerted on an embedded container of waste when temperatures in the immediate vicinity of the canisters are sufficient to melt the rock or cause plastic behavior. Under these circumstances, there will be a tendency for the waste canister to migrate upwards or downwards, depending on the relative densities of the waste package and the molten repository rock. Since this type of behavior is not desirable, the requirement is to ensure that temperatures in the vicinity of the canisters do not result in complete loss of shear strength in the adjacent rock. The temperatures should be limited to values which will enable the rock to develop sufficient shear stress to maintain the waste canisters in their correct location.

2.5.2.4 In-Situ Stress Conditions

The pre-existing state of ground stress must be determined before the stress distribution around any man-made excavation can be calculated. Various attempts at a theoretical solution to this problem have been made, but they have been shown to be of limited usefulness as a result of the simplifying assumptions which bear little relevance to the complex geologic processes. Recognizing this fact, recent developments have therefore concentrated on the measurement of in-situ stress rather than upon its theoretical determination. A variety of instruments have been developed for this purpose, the most useful of which provide the complete three-dimensional state of stress from a single measurement and rely on monitoring strain changes induced during stress release of a region of in situ loaded rock.

The measured vertical stresses are generally in good agreement with the simple prediction which equates vertical stress to the weight of overburden. It should be noted, however, that stresses in unusual geological environments may exhibit significant variations. Such as the stress levels at relatively shallow depth may be sensitive to the surface topography and the vertical stress at the toe of a major escarpment may be well in excess of overburden.

Figure 10 shows the variation of K (average horizontal stress/vertical stress) with depth below the surface. For shallow depths below 500 meters, the average horizontal stress may be well in excess of the vertical stress, with K values of 3 being not uncommon. At greater depths, the average horizontal stress and the vertical stress tend to equalize as suggested by Heim (1912). This trend is to be expected since the very high deviator stresses which would be implied by high K values at considerable depth would lead to induced fracturing, plastic flow and time-dependent deformation in the rock. All of these processes tend to reduce the difference between the horizontal and vertical stress. Much higher K values have been measured in regions of high tectonic activity, but these have not been included on Figure 10 as the results are not regarded as typical of "undisturbed" rock masses.

The wide variations in measured stresses emphasizes the uncertainty which is inherent in any attempt to predict the in situ stress field on the basis of simple theretical concepts, and the absolute necessity for in situ stress measurements.

2.5.2.5 Earthquake Loadings

Documented evidence on the influence of comparatively severe earthquakes on the stability of underground openings is quite limited. For earthquakes with significant surface intensity, underground experience ranges from heavy noise and vibration with failure of loosened rocks to no effect at all. It is probable that the range of observations may be directly attributed to variations in the rock structure. Despite the fact that pronounced earthquake vibrations can extend to considerable depths within mines, there appears to be comparatively little rock material damage associated with them.

In order to examine possible dynamic magnificiation effects in the vicinity of an underground complex, the repository system could be modelled numerically. Initially, the rock medium would be idealized as a linear elastic system and the response characteristics of any variable will be a function of the frequency of the applied dynamic steady-state disturbance. In any numerical application, the description of the boundary conditions must be handled carefully in order that damping effects are accurately modelled. Having determined the response characteristics of any system parameter as a function of excitation frequence, these functions can be applied to a theoretical earthquake spectral function. Utilizing standard procedures of random variable theory and probability theory, the maximum expected response can be determined for any random earthquake input which has been statistically defined. Such analyses will be undoubtedly idealized, but conservative assumptions can be made to provide an upper bound on the estimate of likely disturbance to an underground repository.

Considering the relatively modest levels of ground stress associated with in-situ earthquake waves together with the unlikelihood of significant dynamic magnification effects, it is probable the structural damage to a repository as a result of earthquake loading will be limited to comparatively minor surface effects.

2.5.3 Man-Made Conditions

2.5.3.1 Method of Excavation

Blasting: The traditional method of excavating tunnels in rock is to use explosives placed in a pattern of holes drilled ahead of the advancing face of the tunnel. If the blasthole pattern and the detonation sequence is carefully designed, an excavation can be created with minimum disturbance to the rock mass. On the other hand, a carelessly executed blast can cause considerable damage to the rock mass. The drill and blast method of excavating tunnels is more than 100 years old. Since its introduction in a mechanized form around 1860, it has been subjected to many major improvements in drilling equipment and techniques as well as in explosives and in blasting methods. Each improvement has resulted in safer construction and generally in increased rates of advance. Because of its continued use, the drill and blast method is now well-known and quite reliable. It has been tested and has proven successful in nearly all rock types and has also been shown to be easily adaptable to widely variable rock conditions.

The most obvious advantage of the drill and blast method is the experience gained by contractors and engineers from its very wide application in the past. With the recent introduction of the smooth wall blasting techniques, the method has reached a stage of near-ultimate development and because of its continued use, well-trained labor is easily available. From a technical point of view, the drill and blast method is attractive because it can produce any shape of tunnel without special difficulties or costs. In particular, tunnels which are horseshoe-shaped can be produced directly and large masses of concrete are not required as would be the case for full-face machined tunnels. Finally, the major advantage of the drill and blast method is its adaptability to practically all rock conditions.

This advantage is not as important where rock conditions are known to be relatively uniform, but it becomes overwhelming where the rock conditions are variable. Indeed, in terms of present technology, the drill and blast method is the only possible means of excavating tunnels through rocks which vary greatly in strength, or through rock masses containing faults or shear zones. As a result, the method is frequently used as the last remaining solution when other mining methods have failed.

A problem associated with the drill and blast method is the lack of detailed control on the size and shape of the excavation. To eliminate so-called "tight spots" (rock projecting into the designed tunnel opening, which has to be chiselled off by hand methods), drill patterns are selected to produce overbreak. This results in increased quantities of muck to be hauled out of the tunnel and in the case of concrete-lined tunnels, to significant increases in concrete quantities. The drill and blast method also produces an unavoidable loosening of the rock surrounding the tunnel opening, and as a result the rock requires more support to remain stable. It is estimated that the increase in the amount of support required can be as high as 20 per cent.

Machine Excavation: The primary requirement of a repository will be the need to contain the waste in isolation from man's environment and therefore the excavation methods used must cause as little disturbance to the rock mass as possible. This would disfavor drilling and blasting as an excavation method.

In recent years tunneling machines have found increasing use in the creation of underground excavations. Such machines are frequently used in soft rocks such as mudstones and shales and are also being used increasingly in harder rocks.

Very little damage to the surrounding rock mass would normally occur with tunneling machine operations. As an alternative, one of two types of tunneling machine would be suitable: a full-face or part-face tunnel boring machine. Both could excavate with ease in rock salt or shale and both would form tunnels with minimal disturbance to the rock mass.

2.5.3.2 Support of Excavations to Prevent Rock Deformation

In any excavations made for the repository, deformation of the surrounding rock mass must be minimized to restrict the flow of ground water through open fractures. Since any deformation that occurs will be irreversible, it is necessary during the operational period of the repository to provide support to any potentially unstable rock. It is possible that, if the repository were sited in strong, crystalline rocks with few fractures, then little advantages would be gained by installing substantial support because deformation would be minimal.

Salt and shale will require considerable support in certain critical areas such as shaft bottom sumps, junctions of tunnels and shafts. Since heat will accelerate creep rate, the approach should be to calculate the anticipated closure during the operational life of the repository and to excavate oversize openings to accommodate this closure. Where it is necessary to provide complete support, then either of the following two approaches should be adopted: place massive concrete junction eyes, shaft plugs, etc.; or place "normal" thickness concrete combined with a compressible zone at the interface between the concrete and salt/shale.

When storage of the canisters is complete and the repository is to be abandoned, it will be necessary to completely backfill all openings and shafts to minimize long-term deformation as the rock support system deteriorates due to natural weathering and the effects of heat.

2.5.3.3 Geometrical Layout of Repository

Because of the great variability in geological, geomechanical and hydrological conditions, the geometrical layout of the repository should be appropriate to the conditions at a selected site. This section discusses some alternative layouts which may be considered, under various conditions, to minimize the disturbance produced by the repository in the surrounding rock.

The single-level repository with vertical shafts is best suited to geological formations in which the two horizontal dimensions are considerably greater than the vertical dimension. This design is best suited to horizontally bedded deposits such as salt and shale, with operational problems minimized if the formation is near-horizontal. This is the sort of design being considered by OWI in salt (Parsons, et al., 1976).

The multi-level repository with vertical shafts is best suited to geological formations in which the vertical dimension is greater than the horizontal dimensions. By concentrating the disposal rooms around the shaft, the underground transportation distance is minimized. However, it is probable that heat dissipation will be slower with this design than a single-level repository, and this would be a significant factor in materials which are susceptible to heat damage. This design is best suited to salt domes or intrusive pluton formations in crystalline rocks.

A third alternative is to have a single-level or multi-level repository with access through inclined shafts or ramps. The length of the access tunnels will be greater than that of a vertical shaft for a repository at the same depth, and the actual length will depend upon the grade. The maximum grade for rubber-tired vehicles would be about 5 per cent to 8 percent and for conveyors about 15 percent.

Although it may be preferable at some sites to locate the repository at great depth so as to maximize its distance from overlying aquifers, there are certain restraints to the maximum practical depth. These restraints are as follows:

(a) Heat - The ambient temperature of the rock increases with depth. It is generally found that the rate of increase of temperature with depth is about $1^{\circ}C$ per 100 ft. of depth, although greater and lesser rates of temperature increase do occur. Greater rates may be found in areas of volcanic activity, and lesser rates in recently-deposited sedimentary formations. High rock temperatures will produce operating problems and also reduce the rate of heat dissipation from the waste canisters.

(b) Rock Stress - As previously discussed, the in-situ rock stress increases with depth. The rock in which the repository is excavated must be able to withstand the high stresses around the opening without causing operational problems and significant rock fracturing. The behavior, under high stress of ductile materials such as salt and weak shales, differs significantly from that of brittle rocks such as granites. Salt will creep, at a rate which increases with the applied stress, and under sufficiently high stress the opening may eventually close. However, brittle rocks which are subjected to high stress will fracture rather than creep. In some cases the stored strain energy will be released explosively as the rock fractures.

2.5.3.4 Backfill Considerations[1]

The selection of a suitable fill will depend upon its satifactory performance against the following criteria:

(a) The fill should preferably have a design life equal to that of the repository. The minimum design life would be about 1,000 years, which appears to be the most critical containment period.

(b) The fill should have sufficient strength to prevent closure of the openings. The ideal situation of the fill preventing all closure is only possible if it has the same modulus as the rock. Thus, some closure will probably occur as the fill consolidates.

(c) The fill should have a low permeability to prevent circulation of groundwater.

The following are general comments on present mine backfill techniques:

Hydraulic Fill

(a) This type of backfill is most commonly used in the mining industry:
- The backfill is used to fill large openings that would otherwise fail and cause surface subsidence and/or hinder adjacent operations.
- When pillars are to be recovered next to an already mined stope, it is necessary that the

[1] References: A major source of references on backfilling is the proceedings of the Jubilee Symposium on Mine Filling sponsored by the Australian Institute of Mining and Metallogy at Mount Isa Mines in August, 1973. This is probably the most up-to-date and comprehensive summary of backfilling in underground mines. In addition, information on concrete behavior can be obtained from: A.C.I. Publication SP-39 entitled "Behavior of Concrete Under Temperature Extremes". This volume was developed from a symposium held in Ottawa, Canada in October, 1973.

fill in this stope be sufficiently strong to remain intact during pillar recovery. That is, the fill must not fail and flow into the new excavation.

- Occasionally fill has been placed underground because there is no suitable location for surface disposal.

(b) The fill used in underground mining operations is usually concentrator tailings mixed with water to form a slurry containing about 70 percent solids by weight which is transported to the disposal site in wear-resistant pipes. The slurry is flooded into the area to be filled and the water drains out to form a compact sand with a water content of between 15 and 20 percent.

(c) Work has been done at the Cobar Mine in Australia (by Aitchison, Kurzeme and Willoughby), in Sweden (by Mattson) and in the Coeur D'Alene Mine District in Idaho (by Corson and McMay) on the action of hydraulic fill in the limitation of closure of an opening. It is generally concluded that this type of fill is not sufficiently stiff to resist movement until strains of about 20 percent have taken place. As the excavation closes, strains occur in the fill and when the induced stress reaches several hundred psi there is a distinct increase in the stiffness. In the case of the repository, it is essential that the fill be in intimate contact with the back of the rooms if the fill is to inhibit deformation of the rock above the room.

(d) There are two major disadvantages of the use of hydraulic fill for a repository backfill:

- Hydraulically placed fill will shrink as the water drains from the sand and this will produce a void at the back.
- The water which drains from the fill may be contaminated with radioactivity and may have to be treated before disposal. It is estimated that about 30 gallons of water will be produced for each cubic yard of fill placed underground. This could be overcome by re-cycling the water. The normally used hydraulic fills have a relatively high permeability.

Concrete

The apparent advantages of using concrete are as follows:

(a) It may be possible to use the mined-out material as an aggregate for the concrete and thus reduce disposal problems.

(b) The mixing and transportation of the concrete in pipelines will be fairly straightforward since it is already standard practice in construction.

(c) The concrete, when set, will be significantly stronger and stiffer than a hydraulic fill.

(d) The concrete will have a much lower permeability than normal hydraulic fills.

Pneumatically-Placed Fill

A relatively new method of placing backfill is to transport it from a stockpile in a pneumatic pipeline and then discharge it at high velocity from a nozzle into the excavation that is being filled. This system has been developed by Radmark Engineering and is being used at Cominco in British Columbia, the Grants Mine in New Mexico, and the President Steyn Mine in South Africa. It has also been tested by the U.S.B.M. in Spokane.

The pneumatic system operates as follows:

(a) The waste material is crushed to minus 3 in. size and transported to the blower unit, either on a conveyor, under gravity down a borehole, or from a hopper.

(b) The lower unit introduces the waste into the stream of air which is moving at about 90 mph at a flow rate of 3,000 cfm. The feed pressure is about 8 psi.

(c) Water is added at the nozzle to control dust and to improve compaction of the waste. Cement could be added to increase the strength of the fill if necessary.

The apparent advantages of the pneumatic backfilling method are:

(a) This equipment is well suited to handling waste rock from tunneling machines, so the same waste handling equipment could be used for both excavation and backfilling.

(b) The waste rock could be placed back underground with virtually no reprocessing and the addition of only a minimal amount of water.

(c) The relative density of the resultant backfill can be as high as 80 percent compared to the density of the intact rock.

(d) Use of the system in production shows that the waste can be closely packed against the roof of the excavation.

The apparent disadvantages of the system are:

(a) The resultant fill contains air voids so that it will not be a good conductor of heat.

(b) The fill is permeable.

Obviously a great deal of research and development will be necessary in order to design and implement adequate backfill methods for the repository openings.

2.5.3.5 Thermal Loadings

In addition to the influence of high temperatures on the mechanical properties of rock masses (reduced strength, increased ductibility), thermal loadings will be induced as a result of the expansion of the rock mass in a relatively confined environment. The nature of the thermal stress distribution will be dependent upon the geometrical layout of the underground repository, the magnitude and distribution of the developed temperatures, and the thermal and mechanical properties of the rock.

The temperature distribution within the repository will be dependent upon the distribution and power generation of each of the high level waste canisters, together with the thermal properties of the medium. The convection affects of circulating air (prior to backfilling) and circulating gas and/or water (after backfilling) may also have a significant impact. Heat balance may be significantly altered by medium phase changes such as water to steam.

For any given distribution of temperature within a repository zone, the developed thermal loadings will depend on the coefficient of thermal expansion and on the parameters describing the stress/strain response of the rock mass. These thermal and mechanical properties of the rock will be dependent upon the temperature, and hence a non-linear numerical analysis will be generally required. In addition, the thermal conductivity values will be dependent upon the conditions of the rock mass, and an iterative solution procedure between the heat flow analysis and the thermal stress analysis may be required. Such a procedure will ultimately be instrumental in defining maximum permissible temperatures which can be tolerated in the zone of the repository.

One of the primary concerns of thermal loading is the potential areal ground heave and formational fracturing which might occur above the repository.

2.5.4 Available Information

An initial review of available information on rock mechanics/mining as related to site suitability is presented below. Due to the limited scope of this report, the information discussed is in essence only a general format of the appropriate available information.

2.5.4.1 Literature Survey on Rock Properties and Rock Mass Behavior

Data on rock properties and behavior which is relevant to the design of underground openings should be collected manually and via available literature retrieval system. Three literature searches have been identified:

- KWIC: Rock Mechanics Section of Imperial College, London
- GEODEX: Geotechnical Abstracts
- CINDAS: Dept. of Civil Engineering, Purdue University

The data should include the following topics: creep, moisture effects, radiation effects, heat transfer properties, data on rock strength, and underground instrumentation in mines and civil and engineering caverns.

Creep

Much effort has been exerted by many researchers to establish mathematical relationships between creep strain and the ambient stress and temperature in a particular situation. These factors, together with the elapsed time are the main influences on the amount of time-dependent formation of rock around a storage cavern.

Two equations are commonly used to relate creep strain and time for given constant conditions of stress and temperature.

1. Strain $=$ $A \log t$

and 2. Strain $=$ At^b

where t is the elapsed time; and, A and b are constants depending on the particular material. No evidence has been found so far which suggests that these equations cannot be used for all crystalline rock types, including rock salt. Some authors consider them appropriate for some non-crystalline rocks such as shale. Equation (2) is more widely used and is frequently expanded to include the effects of stress and temperature as follows:

$$\text{Strain} = B\,\sigma^c\,T^d\,t^b$$

In this equation, σ is the deviator stress (proportional to the maximum shear stress), T is the absolute temperature, t the elapsed time, and c, d, and b are constants.

From the sources investigated, the range of values of these exponents deduced from experimental testing of rock salt is as shown in Table 1.

TABLE 1

VALUES OF CREEP EXPONENTS FOR ROCK SALT

Exponent			
t(time)	c(stress)	d(temp)	Source*
0.35	3.2	10.9	Bradshaw, Lomenick (1966)
	1 to 2		("low" stress) Heard (1972)
	2 to 3		("high" stress)
0.36	2.98		Zienkiewicz (1975)
	1.9		Robertson (1964)
0.4	3.1		Bradshaw
0.51			Dreyer (1972)
0.168 to 0.771			Le Comte (range for 17 tests)
		9.5	McClain, Bradshaw (1970)

* For source references see Hoek (1977).

Misra and Murrell (1965) have concluded that, for rocks generally, simple logarithmic or power laws are not in themselves sufficient to represent creep. They believe that the logarithmic law should be used at lower temperatures and confining pressures while the power law is appropriate at higher values.

The transition from one law to another depends on rock type as well as temperature and stress levels and is approximately 0.5 times the melting temperatures at low stress levels. Based on experimental results they conclude that creep behavior of rocks is very similar to that for metals.

Effect of Trapped Moisture and Radiation Effects: According to Bradshaw (1968), trapped moisture in rock salt may be of great significance in the design of nuclear waste repositories. In experiments they found that trapped moisture can cause shattering of rock salt specimens at temperatures above 200^{o} to $250^{o}C$. In triaxially confined specimens, they conclude that serious loss in strength would occur at temperatures over 200^{o}C due to expansion of moisture.

Underground Instrumentation: A main area of investigation should be in the results from reported underground instrumentation schemes. Many such investigations have been reported in the literature but the vast majority of these are inappropriate because of the geologic characteristics which usually involve disturbed and fractured strata such as would not be found in an underground repository. For this study six case histories have been reviewed which include measurements in evaporites and intact igneous rocks. The main purpose of these investigations was to measure the time-dependent closure of the cavities. In all cases movement was still continuing when measurements ceased. The longest period of measurement recorded was for three years (Hebblewhite, Miller, and Potts, 1977) in the case of a shaft through rock salt. These measurements were made at a depth of 3,100 ft. Approximately 45mm radial closure had been recorded up to this time in the 7.6m diameter shaft.

2.5.4.2 Literature Survey of Water Inflow into Mines

A survey was made of about 30 papers on ground water conditions in mines; these references were taken from the SME Mining Engineering Handbook, Chapter 26, in which a total of 126 references are listed.

The following conclusions have been drawn from the survey.

(a) Ground water inflow problems are most usually associated with carbonate rock types (dolomite and limestone);

approximately one-third of the mines described experienced flows from these rock types.

(b) Ground water flows in carbonates usually occurred suddenly when a cavity in the carbonate formation was intesected and high volume flows were experienced. For example, during shaft sinking at the Friedensville Mine in Pennsylvania, a sudden flow of up to 8,000 gpm occurred in the shaft bottom despite pre-grouting of the walls of the shaft ahead of sinking. The cavities and fractures in the dolomite were often filled with clay which made grouting difficult (S.M.E. Ch. 26, Ref. (4)).

(c) Another third of the inflows occurred in mines in highly fractured rock; the fracturing is probably associated with the formation of the ore-body. For example, at the San Manuel block caving operation in Arizona, flows of up to 1,300 gpm have occurred during excavation of development drifts (S.M.E. Ch. 26, Ref. (110)).

(d) High flows of water are often experienced near faults. The fault itself will often prevent transverse seepage due to the presence of low permeability gouge in the fracture plane. However, the rock on either side of the fault is often fractured as a result of the relative movement across the fault, and this rock is likely to be several orders of magnitude more permeable than the fault. At the Naica Mine in Mexico holes drilled through the fault produced a total flow of 7,000 gpm (S.M.E. Ch. 26, Ref. (14)).

(e) Water bearing formations such as limestone, sand and till often occur in salt basins. Grouting and freezing were required during shaft sinking for the potash mines in New Mexico and Saskatchewan. In Carlsbad, New Mexico two shafts were abandoned when grouting was unsuccessful, and in Saskatchewan freezing was required to control artesian flows of about 1,000 gpm from a drill hole in the center of the proposed shaft, (S.M.E. Ch. 26, Ref. (38)).

(f) There is some evidence that small inflow quantities can be expected into excavations in undisturbed argillaceous rocks. For example, at the Iron River Mine in Michigan the footwall is composed of slate and greywacke and little inflow occurs through this formation compared to that which occurs through the iron formations and till (S.M.E. Ch. 26, Ref. (22)).

In addition, at the Wabana Iron Mine in Newfoundland, where the iron formation is overlain by shales and mining takes place up to 1,000 ft. below the sea bed, little water inflow is experienced. Room and pillar mining is carried out at 55% extraction ratio with care being taken that no subsidence occurs. Total flow is reported at 250 gpm but most of this is apparently from surface runoff and drilling (S.M.E. Ch. 26, Ref. (45)).

(g) The majority of documented ground water studies of underground excavations concern conditions where excessive flows occurred. Very little is written about effectively dry excavations which would correspond to the type of formations being considered for the repository. In these effectively dry mines, it would be necessary to carry out a water balance calculation which included the moisture in ventilation system, dust control system, and hydraulic backfill operation. It is important to realize that a mine considered "dry" to a mining engineer may be unsuitable for a repository.

3.0 DESCRIPTORS AND COEFFICIENTS

3.1 General

As part of this study, specific descriptors and coefficients were developed for two cycles of the TASC site stability model. The basic model is presented in Figure 11 and indicates the general geologic and hydrologic conditions assumed in the model. In general, the model is a simple layered system with water flowing vertically upward from a lower aquifer under higher pressure, through the repository zone, and to an upper aquifer. Once in the upper aquifer, the water flows horizontally to discharge in a river or lake.

The primary purpose of these two model cycles was to determine the relative importance of each variable. This was accomplished through sensitivity analyses in which the radiation dose impact on man was evaluated over various ranges of factor coefficient values. The factors evaluated included: permeability, porosity, pressure gradients, geometry, retardation factors, faults, breccia pipes, bore hole seal failures, mine backfill dissolution, and fracture zones around shafts and tunnels.

At the writing of this report cycle 1 was complete and cycle 2 was being performed by TASC. The reader is referred to "Site Suitability Criteria for Solidified High Level Waste Repositories", A Preliminary Report Prepared for the Waste Management Program, NRC presented at LLL on March 22-23 by LLL for a description of the cycle 1 model and results.

Golder Associates, Inc. was responsible for developing descriptors and coefficients for the TASC model hydrologic analog; permeability and porosity values for the goelogic formations (excepting salt); occurrence and properties of the bore hole seals, backfill, and mine fracture zones; and properties of seismically induced faults. All data was presented with a preferred value and maximum credible range. These values related to a generic repository in a sedimentary basin and not a specific site. Thus, the parameters are inherently "guesstimates" and should not be construed in any way to be actual computed or measured values. This is consistent with the overall generic site suitability model philosophy which was to evaluate relative importance of variables and not to determine absolute numerical values. The approach used in developing our input data reflected this approach and was primarily based on experience, available field information and judgement rather than detailed theoretical analysis.

The descriptors and coefficients are described by two sets of data corresponding to cycle 1 and cycle 2. This information was presented to LLL in two memos in February and May 1977, and are reproduced below for this report. Where deemed appropriate, a discussion of the rationale for data is presented in Appendix D.

3.2 Cycle 1 Model Data

1. Permeability and Porosity

Layer	Permeability (cm/sec) (Horizontal) Ave.	Range	Porosity (effective)
1	10^{-6}	10^{-5} to 10^{-7}	0.02
2	10^{-4}	10^{-3} to 10^{-5}	0.1
3	10^{-6}	10^{-5} to 10^{-7}	0.02
4	10^{-8}	10^{-7} to 10^{-9}	0.01 (Shale Repository Only)
5	10^{-6}	10^{-5} to 10^{-7}	0.02
6	10^{-4}	10^{-3} to 10^{-5}	0.1

Vertical Perm. = 0.1 Horizontal Perm.

2. Natural Horizontal Gradient

   Layers 1, 2, 6 $i = 0.005$ (average)

   $i = 0.0005$ to 0.05 (range)

   Layers 3, 4, 5 $i = 0$

3. Artesian Head Between Layers 2 and 6

   Average - 200 ft. (excess in Layer 6)

   Range - 10 to 1,000 feet

4. Fracture Zone Around Shafts and Horizontal Tunnels:

   a. Geometry: Fracture zones around shafts and horizontal tunnels are estimated not to exceed twice the diameter plus 6 meters without a seismic event and three times the diameter plus 6 meters with a seismic event. For this preliminary model, assume shafts and tunnels have a 10m diameter.

   b. Occurrence: For this initial model, assume that the probability of the fracture zone occurring is 100%. To be conservative, use the fracture zone with a seismic event. Since the fracture zone would probably stabilize within about 100 years, assume it forms immediately and is not time variable.

   c. Permeability and Porosity: Ave. Permeability of Fracture Zone: $K = 10^{-5}$ cm/sec.

   Range of Permeability: 10^{-6} to 10^{-3} cm/sec.

   d. Hydrologic Model - See Figure A

   Path e-d: Length: thickness layer 5

   Perm. & Porosity: layer 5

   Area: horizontal area of repository, use 10×10^{6} m^2

   Path d-c: Length: half thickness layer 4

   Perm. & Porosity: layer 4

   Area: 10×10^{6} m^2

Path c-b: Length: average path of 1500 m
Perm. & Porosity: $K = 10^{-5}$ cm/sec.
$n = 0.02$
Area: 30,000 m^2

Path b-a: Length: half thickness of layer 4 and thickness of layer 5
Perm. & Porosity: $K = 10^{-5}$ cm/sec.
$n = 0.02$
Area: 1900 m^2 (assumes two shafts)

5. Subsidence: It is recommended that as a first approach, until quantified limits can be derived, that it be assumed there will be no subsidence due to the excavation of the shafts or tunnels.

This can be justified on the assumption that horizontal separation of the storage tunnels will be greater than or equal to ten times the diameter of the tunnels and that their depth of burial is not less than 300m, and that all tunnels and shafts are completely backfilled.

6. New Faults with Fracture Zones Around Shafts and Tunnels:
   a. Geometry: For this initial model, it is assumed that all faults are vertical, intersect the repository, and are continuous between layers 2 and 6.
   b. Occurrence: LLL will supply data on probability of occurrence of seismic events. Conservatively it should be assumed that each event can produce a fracture zone which is 0.5 meters in width.
   c. Permeability and Porosity
      Ave. Permeability: $K = 10^{-3}$ cm/sec.
      Range of Permeability: 10^{-4} to 10^{-2} cm/sec.
      Porosity: $n = 0.1$
   d. Hydrologic Model - See Figure B
      1. Unfaulted Fraction of Repository:

Path e'-d'-c': Length: thickness of layer 5 plus half thickness of layer 4

Permeability and Porosity: See (c) above

Area: 1,500 m^2 for each pervious fault

Path e-d: See 4(d)

Path d-c: See 4(d)

Path c-b: See 4(d)

Path a-b: See 4(d)

2. Faulted Fraction of Repository: (This applies only to those cannisters directly intersected by the fault; unless the fault becomes very wide this pathway may be insignificant).

Path g-h: Length: Total thicknesses of layers 3, 4, 5

Permeability and Porosity: See (c) above

Area: 1,500 m^2 for each pervious fault

7. Faults and Shaft Fracture Zone Without Horizontal Tunnel Fracture Zone:

To consider these cases, input the following for pathway c-b:

Length: 3,000 m

Permeability: Horizontal of layer 4

Porosity: Layer 4

Area: 30 x 10^3 m^2 (10 meters by 3,000 meters)

8. Mine Backfill Deterioration:

a. Geometry: Assume total area of vertical shafts is 157 m^2 and the total area of the horizontal tunnels is 5000 m^2.

b. Occurrence: Initially the mine backfill has a permeability equal to the in-situ repository rock. After 1000 years, the fill begins to deteriorate to essentially a fine sand after another 2000 years.

c. Permeability and Porosity:

1) Initially to 1000 years - same as in-situ rock (no affect)

2) 1000 to 3000 years: On a natural scale of time versus log of permeability, K linearly increases from initial to 10^{-3} cm/sec. Porosity linearly increases from initial to 0.1

d. Hydrologic Model - See Figure A

Essentially identical to the case of Fracture Zone Around Shafts and Horizontal Tunnels except for:

c-f: Length - average path of 1500 m
Perm. & Porosity - See (c) above
Area - 5000 m^2

f-g: Length - half thickness of layer 4 and thickness of layer 5
Perm. & Porosity - See (c) above
Area - 157 m^2

(Note: In the limiting case after 3000 years, the pathways through the fracture zone around the shafts and tunnels can be ignored. Assume complete mixing at nodal point c.)

9. New Borings:

The most critical limiting case would involve the tunnel backfill intersecting the borings. Should the borings become uniformly pervious, water would flow upward to the backfill, be somewhat dispersed, and flow out up through the borings. This limiting case is shown on Figure C and discussed below. We recommend for the initial model run that this case be analyzed.

a. Geometry: Assume all borings have an effective diameter of 0.3 meters and extend from the surface to layer 6. Consider five borings (minimum program) and 50 borings (expanded program).

b. Occurrence: For this preliminary model, assume that all borings are properly sealed initially and remain intact for 1,000 years. After 1,000 years the seals gradually deteriorate to essentially a fine sand after another 2,000 years.

c. Permeability and Porosity:

1. Initially to 1,000 years: $K = 10^{-6}$ cm/sec.
   $n = 0.01$

2. 1,000 to 3,000 years: On a nature scale of time versus log of permeability, K linearly increases from 10^{-6} cm/sec. to 10^{-3} cm/sec. Porosity linearly increases from 0.01 to 0.1.

d. Hydrologic Model Without Shaft and Tunnel Fracture Zone: Virtually no effect on basic model.

e. Hydrologic Model with Shaft and Tunnel Fracture Zone - See Figure C.

Path f-c: Length - Thickness of layer 5 plus half thickness of layer 4.
Perm. & Porosity - See (c) above.
Area - 1.5 m^2 (minimum)
15 m^2 (maximum)

Path c-g: Length - Thickness of layer 3 plus half thickness of layer 4.
Perm. & Porosity - See (c) above.
Area - 1.5 m^2 (minimum)
15 m^2 (maximum)

Other Paths: Identical to basic model with fracture zone around shaft and tunnels.

(Note: Assume complete mixing at nodal point c).

10. Bedrock Pathways:

For simplicity, the models shown do not show a pathway from the repository up to layer 2 through the undisturbed bedrock layers. All models should have a pathway from the repository to layer 2 as follows:

Repository to Layer 3:

Length - Half the thickness of layer 4

Perm. & Porosity - Layer 4

Area - 1×10^7 m^2

Layer 3 to Layer 2:

Length - Thickness of layer 3

Perm. & Porosity - Layer 3

Area - 1×10^7 m^2

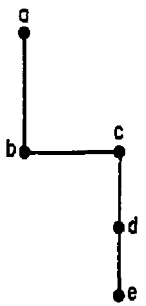


Fig. A

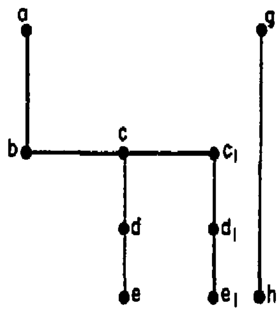


Fig.B

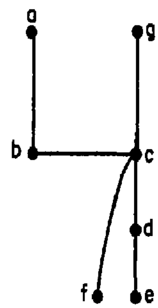


Fig.C

3.3 2nd Cycle Input Data

1. General: This information relates to the basic six-layer model with layers 2 and 6 being a sandstone aquifer; layers 3 and 5 being a sandstone, siltstone, shale sequence; and layer 4 either shale or salt. Layer 6 is under a greater hydraulic head than layer 2; thus, water flows from layer 6 up through layers 5, 4, 3 to layer 2. The water in layer 2 then flows horizontally to a lake or river. This model is identical to the cycle 1 model. Although useful in indicating trends, in our opinion it does not adequately reflect realistic geologic or hydrologic conditions. We understand that the third generation model will represent more realistic conditions.

A brief discussion of the rationale for the fracture porosity and permeability data, the fracture zone data, and the fault data, are presented in Appendix D.

2. Formation Permeability and Porosity: It is not feasible to generalize for a generic model whether ground water flow will be through fractures, interstitial pore space or both. Thus, the model should be run with two sets of values for layers 3, 4, 5. Parameters for layer 4 applies only to shale; salt data is provided by others.

a. Values for Interstitial Flow

	Horizontal Permeability (cm/sec.)		Porosity	
Layer	Preferred	Range	Preferred	Range
2	10^{-4}	10^{-2} to 10^{-6}	0.10	0.02-0.20
3	10^{-6}	10^{-4} to 10^{-8}	0.05	0.01-0.10
4	10^{-8}	10^{-6} to 10^{-10}	0.05	0.01-0.10
5	10^{-6}	10^{-4} to 10^{-8}	0.05	0.01-0.10
6	10^{-4}	10^{-2} to 10^{-6}	0.10	0.02-0.20

b. Values for Fracture Flow

	Horizontal Permeability (cm/sec)		Porosity*	
Layer	Preferred	Range	Preferred	Range
2	10^{-4}	10^{-2} to 10^{-6}	0.10	0.02-0.20
3	10^{-5}	10^{-3} to 10^{-7}	10^{-4}	10^{-3} - 10^{-5}
4	10^{-7}	10^{-5} to 10^{-9}	10^{-5}	10^{-4} - 10^{-6}
5	10^{-5}	10^{-3} to 10^{-7}	10^{-4}	10^{-3} - 10^{-5}
6	10^{-4}	10^{-2} to 10^{-6}	0.10	0.02-0.20

*NOTE: When performing combined permeability and porosity sensitivity analyses on layers 3, 4, 5 for fractured flow, the following porosity values should be used:

Preferred Permeability Value:

Preferred Porosity: 10^{-5}

Maximum Permeability Value:

Preferred Porosity: 10^{-4}

Range: 10^{-4} - 10^{-3}

Minimum Permeability Value:

Preferred Porosity: 5×10^{-6}

Similar values should be used for layers 3, 5.

c. Vertical Permeability

Preferred: $K_V = 0.1\ K_H$; Range $K_V = K_H$ to $0.01\ K_H$

NOTE: For purposes of the model analysis use $K_V = 0.1\ K_H$ for all cases. The range in vertical permeability values is effectively modeled by the given ranges in horizontal permeabilities.

3. Gradients

a. Horizontal

Layers 2, 6	i = 0.005 (preferred)	
	i = 0.0005 to 0.05 (range)	
Layers 3, 4, 5	i = 0	

b. Vertical Head Between Layers 2, 6

Preferred = 200 ft. (excess in layer 6)

Range = 10 to 500 feet

4. Fracture Zone Around Shafts and Tunnels

a. General:

For our evaluation it was necessary to assume some general mine layout; these parameters relate to a mine layout similar to the preliminary design presented in the "Waste Isolation Facility Description" by Parsons, Brinckerhoff, Quake & Douglas dated September 1976. The underlying assumption for the stress analysis is that the openings are sufficiently spaced so that there is minimal stress interaction between openings.

b. Parameters:

The following table indicates the guesstimated radius of anticipated fracture zone around shafts (vertical) and tunnels (horizontal). The maximum fracture zone relates to a repository constructed in low strength rock with a high in-situ stress field and a poorly placed and/or non-rigid backfill. The minimum fracture zone relates to a repository in high strength rock with a low stress field and an ideal rigid backfill placed under pressure. Since the permeability within the general fracture zone decreases exponentially with distance from the tunnel or shaft face, the effective size of the fracture zone (using the peak permeability at the face) is only about 20% of the actual fracture zone.

Fracture Zone	Layers 3, 4 (shale) Shaft Deep	Shaft Shallow	Tunnel	Layer 4 (salt) Shaft	Tunnel
Intensely Fractured Zone					
1. Width					
Preferred	None		1.05R	None	None
Minimum	-		None	-	-
Maximum	-		1.12R	-	-
2. Properties					
Perm. (cm/sec)	-		10^{-1} (10^{0}-10^{-2})	-	-
Porosity	-		0.1(0.01-0.2)	-	-
General Fracture Zone					
1. Width					
Preferred	1.25(R+½m)	1.1(R+½m)	2(R+½m)	2.7(R+½)	2.7(R+½)
Minimum	R	R	1.45R	1.15R	1.15R
Maximum	3.3(R+1m)	3.3(R+1m)	4(R+1m)	3.5(R+1)	3.5(R+1)
2. Properties (all cases)					
Perm. (cm/sec)	10^{-4}		(10^{-3} to 10^{-6})		
Porosity	10^{-3}		(10^{-2} to 10^{-4})		

NOTE: R = radius of ½ width of opening; thus, area of fracture zone would be $\Pi R_2^2 - \Pi R_1^2$ (R_2: radius of fracture zone R_1: radius of opening).

c. Transition Times:

The above values relate to the maximum size of fracture zone which will develop in less than 50 to 100 years after repository backfilling. We estimate that the fracture zone in shale will not change significantly with time. In salt, we estimate that with time much of the fracture zone may heal. For this model, assume that the permeability of the fracture zone will decrease to 1% of its original value in 50 years (preferred); 20 to 200 years (range).

d. Hydrologic Model - see Figure A

Path a-b: Length = layer 5
Perm & Por = layer 5
Area - horizontal area of repository
use 5×10^6 m^2

Path b-c: Length - half thickness L-4
Perm & Por - L-4
Area - 5×10^6 m^2

Path c-d: Ditto above (b-c)

Path d-e: Length - L-3
Perm & por - L-3
Area - 5×10^6 m^2

Path c-f: Length - 1200m (½ length of HLW)
Perm & Porosity - See fracture zone table for tunnels; if a highly fractured zone exists (preferred and maximum in shale) ignore the negligible flow increase contribution fror the general fracture zone.

- Areas (shale highly fractured) for tunnels
  Preferred - 316 m^2
  Min - 0 Max - 785 m^2
- Areas (shale - general effective)
  Preferred - 1900 m^2
  Min - 580 m^2
  Max - 7950 m^2
- Areas (salt effective)
  Preferred - 3300 m^2
  Min - 290 m^2
  Max - 6400 m^2

Path f-g: Length - 440m (preferred)
200m - 6000m (range)
Perm & Por - see fracture zone table for tunnels
Areas - use 6% of above areas

Path g-h: Length - ½ L-4
Perm & Por - see fracture zone table for shafts
- Areas (shale effective)
  Preferred - 10 m^2
  Min - 0
  Max - 100 m^2
- Areas (salt effective)
  Preferred - 60 m^2
  Min - 4 m^2
  Max - 110 m^2

Path h-i: Length - L-5
Perm & Porosity - see fracture zone table for shafts
Area - Preferred: 5 m^2
- min, max - ditto g-h (shale)

5. Mine Backfill Deterioration

a. Utilized Preliminary Parson design to estimate area of tunnels & shafts.

b. Occurrence of Deterioration:

Deterioration will be a function of host rock type, groundwater flow, backfill type, placement methods and time. It is clearly impossible to project such an occurrence without some knowledge of backfill type and placement method. Thus, the parameters and transition rates presented below are only educated guesses. Preliminary backfill concept (OWI) for the salt repository is to use salt. Suitable backfill material for shale has not been evaluated at this time. Due to mechanical creep combined with precipitation and recrystallization, a properly placed salt backfill may result in a very low risk of deterioration

For this cycle we recommend that two basic cases be examined. Case 1 assumes that a backfill technique is developed which produces an effectively impervious backfill with some time-related deterioration uncertainty. Case 2 assumes that the backfill is relatively pervious initially and remains so.

c. Parameters:

Case 1:

Assume that initially backfill has the same hydrologic characteristics of parent rock. With time there is a given probability that the fill may deteriorate with time.

Layer	Probability of Deterioration		Transition Rate		Final Properties			
					Perm. (cm/sec)		Porosity	
	Preferred	Range	Preferred	Range	Pref.	Range	Pref.	Range
L-3	50%	20%-80%	500	50-5000	10^{-4}	10^{-5}-10^{-3}	10^{-2}	10^{-1}-10^{-4}
L-4 (shale)	40%	20%-50%	500	50-5000	10^{-4}	10^{-5}-10^{-3}	10^{-2}	10^{-1}-10^{-4}
L-4 (salt)	10%	5%-60%	500	50-5000	10^{-4}	10^{-5}-10^{-3}	10^{-2}	10^{-1}-10^{-4}

Case 2:

Permeability: 10^{-3}, range 10^{-1} to 10^{-6} (cm/sec)

Porosity: 10^{-1}, range 2×10^{-1} to 10^{-3}

Consider at least the following:

- Tunnel backfill perm.: 10^{-3}
  Shaft backfill perm.: 10^{-3}
- Tunnel backfill perm.: 10^{-3}
  Shaft backfill perm.: 10^{-6}
- Tunnel backfill perm.: 10^{-1}
  Shaft backfill perm.: 10^{-6}

d. Hydrologic Model - see Figure A
Identical pathways to fracture zone model except permeability and porosity are given above and areas as follows:

Path c-f: Area 33,000 m^2
Path f-g: Area 1,620 m^2
Path g-h, h-i: Area 64 m^2

6. Boring Seal Dissolution (borings taken for repository investigation only)

a. Geometry: Assume 50 borings (preferred) with 5 to 100 borings (range). Assume an effective diameter of 6 inches, 20% of the holes extend from the surface through layer 6; 80% extend from the surface to just below the repository zone.

b. Occurrence of Seal Dissolution: As with the backfill dissolution, it is clearly impossible to project the seal dissolution characteristics without some knowledge of sealing method. Although OWI has funded several research contracts to develop sealing procedures, no one method has been chosen. Thus, the parameters and probabilities presented below are only educated guesses. There is a certain probability that any boring seal will be improperly installed and effectively fail immediately. There is also a probable transition time in which the bore hole seals will deteriorate. Obviously, this depends on sealing procedure and quality of work.

c. Parameters: Assume that initially the borehole seal is effective and with time there is a given probability the seal may deteriorate.

BORE HOLE PARAMETER - (per bore hole)

	Immediately	0-500 yrs.	500-1000 yrs.	Never
Probability of Deterioration	10%	20%	20%	50%
Transition Time				
Final Perm:				
Preferred	10^{-4} (cm/sec)			
Range	10^{-6}-10^{-2} (cm/sec)			
Final Porosity:				
Preferred	10^{-2}			
Range	10^{-4}-10^{-1}			

d. Hydrologic Models - Figure B

The hydrologic affect of the bore holes cannot be generalized since it is a function of the vertical gradient distribution within layers 3, 4, 5 and within the bore hole itself. For bore holes which extend through to layer 6 water may flow from the bore hole into the repository, from the repository into the bore hole, or there may be no flow at all between the boring and the repository. Thus, the models presented below are grossly simplified solutions intended to represent upper and lower bound approximations. The areas of the flow paths are 0.02 m^2 times the number of failed bore holes. The permeabilities and porosities are given above.

<u>Worst Case</u> (complete mixing)
Path j-c (deep boring): Length L-5, ½ L-4
Point c: complete mixing
Path c-k (deep boring): Length ½ L-4, L-5
Path c-l (shallow boring): ditto

<u>Best Case and Preferred</u>

(1) Repository not affected by borings (reduce total area)
  Area: Preferred: 100% - 0.5% N times total area
  Minimum: 100% - 0.05% N times total area
  Hydrology: Same as base cases.

(2) Repository affected by borings
  Area: Preferred: 0.5% N times total area
  Minimum: 0.05% N times total area
  Where: N = number of failed borings
  Hydrology: Path a-b-c-d-e: ditto base case but with area equal to .5% N or 0.05% N of total area.
  Path i-c (deep borings): length - L-5, ½ L-4, borehole properties.
  Point c: (Complete mixing)
  Path c-k (Deep boring): ½ L-4, L-3, borehole properties.
  Path c-l (shallow boring): ditto

7. Event-Induced Faults

a. Occurrence:

This section applies to new faults or recurrent movement along old faults caused by a major seismic event of intensity VIII. The probability of occurrence of the event is given by LLL. For a given seismic event, we estimate a 90% probability it will be caused by movement along a pre-existing fault zone and a 10% probability it will be caused by a new fault unrelated to any previous faulting.

b. Transition Rates:
The increasing stress field leading up to an event will open fractures within zone around the fault and increase the permeability. The event itself will result in a release of stress with a subsequent closing of many of these fractures. Thus, the permeability of the zone affected by the event will increase with time to some maximum value, then decrease with time after the actual event to some residual value.

c. Parameters:
Tables 1 and 2 indicate the permeability, porosity, width and transition rates for both new faults and movement along old faults. The residual salt permeability should relate to a possible solution opening along the fault zone and incorporate breccia pipe probabilities.

d. Hydrologic Model - See Figure C:
The hydrologic effect of a fault has many of the same uncertainties as the affect of bore hole seal deterioration. In fact, a very large fault could depressurize the lower aquifer and effectively stop upward flow of the waste. The models presented below are gross simplified solutions intended to represent upper and lower bound approximations. The area of the affected zone should be taken as 2500m times the width of affected area. The width, permeability and porosity is given on Tables 1 and 2. As shown on Figure C, the repository should be subdivided into two general regimes as follows:

(1) Repository not affected by the fault

Area: Preferred: 98%

Range: 100% to 75%

(reduce total area)

Hydrology: Base case

(2) Repository affected by the fault

Area: Preferred: 2%

Range: 0% to 25%

Hydrology: Path a-b-c-d-e: ditto base case but reduced area

Path f-g: fault in L-5

Path g-c: fault in L-4

Point c: complete mixing

Path c-h: fault in L-4

Path h-i: fault in L-3

e. Preliminary Modeling Recommendations:

Due to the complexity of the above faulting parameters combined with the anticipated sensitivity of these refinements, we recommend several simplifications for the actual model evaluation. These recommendations include:

1. Assume that any new fault movement will be along an existing fault (Table 1).
2. To assess the effect of faulting, a base case with an existing fault with initial properties shown in Table 1 should be evaluated.
3. The change in fault permeability with time can be simulated by a simple step function. The time the fault is open should be taken as total transition time, while the permeability of the fault should be conservatively assumed equal to the peak permeability.

4. For all cases use a porosity of 10^{-3}.
5. *Assume a fault in salt either closes immediately* or develops into a breccia pipe. This would incorporate the breccia pipe parameters developed by GEI.

8. Ground Water Recharge

After mine abandonment time will be required to re-establish the original ground water regime and saturate the mine area. Until this occurs, probably no ground water will flow out of the repository zone, although gas and/or steam may escape. The length of time required for recharge depends on the nature of the original ground water regime, the effectiveness of the shaft seal, and the porosity and permeability of the backfill and tunnel fracture zones. This affect should be incorporated into the model by not allowing any waste release after repository abandonment for the following delay periods:

Preferred: 100 years
Range: 20-1000 years

9. Recommended Base Case

The general base case should include the fracture zone around the shafts and tunnels and the ground water recharge delay period.

MODELS

Figure A

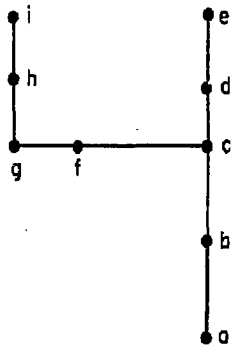


Figure B

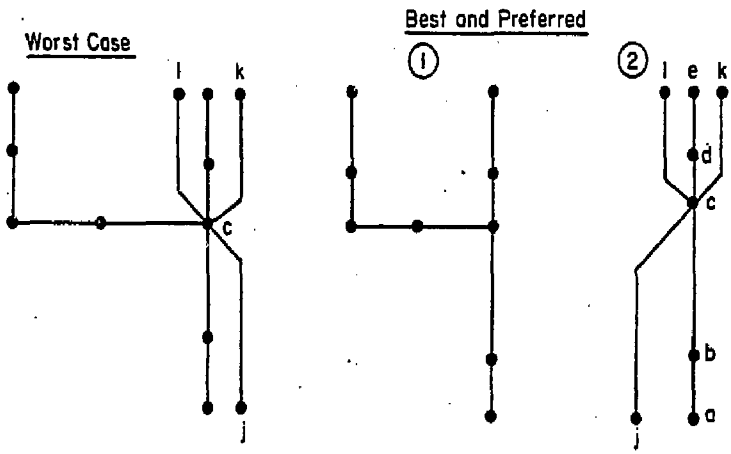
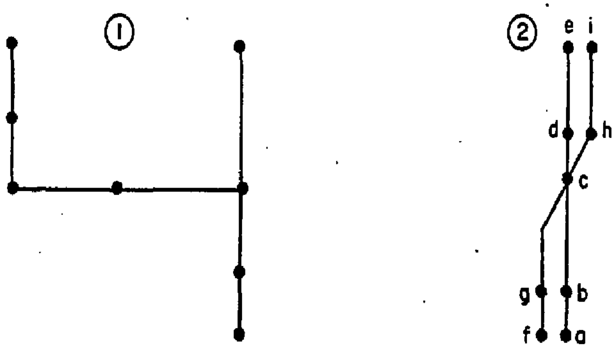


Figure C



3.4 Future Model Cycles

Although not part of this contract, we have given consideration to the general geotechnical work we feel appropriate for future TASC model cycles. These tasks should include:

1. Groundwater Flow Modeling

The present TASC model, strictly speaking, only considers one-dimensional groundwater flow and does not consider lateral dispersion. The general modeling concept has involved an analytical and/or numerical groundwater analysis performed exterior to the TASC model. Due to the hydrologic simplicity of the initial models, the analog evaluations have been relatively simple being adequately derived from basic analytical flow relationships. However, as more complex models are developed, more sophisticated two-dimensional (or even three-dimensional) methods may be required to develop the flow analog and validate the basic TASC model solution.

The results of these models would then be incorporated into the future cycle TASC models. The resulting TASC model analog might be similar to a suggested third cycle format presented below in item 11. Should this future work indicate that significant errors may be introduced through the present TASC model, these problems would have to be resolved and/or the model altered.

2. Existing Mines and Wells

In our opinion, the effect of both existing and possible future mines and wells may prove to be of major significance to site suitability. In order to perform any credible evaluation of their effects, it is imperative that the nature and occurrence of existing mines and wells be properly understood. Development of any models which are not consistent with known resource uses and their hydrologic effects will have little meaning and be an obvious weakness which may discredit the model. Data which must be properly incorporated into the model include the size, depths and locations of existing mines and wells, the nature of well hydrology and the measured effects of the overall groundwater regime.

The hydrologic effects of existing and future mines and wells must be evaluated in order to be properly incorporated into the TASC model. These effects can be divided into two general catagories: the direct effect on the groundwater regime and pathways to the biosphere resulting from well operation and mine dewatering; and the permanent secondary alterations to the strata caused by deformation, stress changes, leaky seals, etc.

3. Heads and Gradients (Including Salinity Variations)

In normal shallow freshwater aquifer systems, the movement of the groundwater is usually controlled by hydrostatic pressure and elevation potentials. However, in deep multi-aquifer systems other potentials can be significant. These potentials may include osmotic potential, thermal potential, chemical potential, and density potential. In the deep sedimentary basins considered for the repository, most of the deep groundwaters are saline and often brine (more than 35,000 ppm dissolved solids). The basic TASC model concept of these high density, saltwaters migrating upward into lighter, fresh groundwaters must be reviewed with respect to these other potentials. The temperature gradients produced by the canisters may also alter the groundwater flow pattern. In addition, the concept of a minimum (threshold) gradient, which is known to be significant is certain clay soils, should be examined. Due to physiochemical interactions, groundwater flow may not occur in certain rocks until a threshold gradient is surpassed.

4. The Effects of Exploration vs. Undetected Anomalies

Since test borings themselves may represent a significant threat to the integrity of the repository, it is important to assess the relative merit of the information obtained from borings versus their liability. This evaluation is particularly urgent since OWI is presently performing subsurface explorations at perspective repository sites. The general approach would involve evaluation of the negative effects of borings and the negative effects of undetected anomalies. Properly integrated into the TASC model, the results should provide significant information for site exploration criteria.

In our opinion, the undetected anomaly problem should also be considered for at least two stages after the repository construction has begun. These recommended stages would include: after the main shafts and corridors are constructed and monitored, and just prior to backfill after completion of the repository when some 30 years of monitoring information is available.

5. Mine Saturation

After mine abandonment, time will be required to re-establish the original groundwater regime and saturate the mine area. Until this occurs, no groundwater will probably flow out of the repository zone. The time required for re-saturation depends on the nature of the original groundwater regime, the effectiveness of seals, and the porosity and permeability of the backfill and mine fracture zones. We have made a preliminary assessment of this effect for the second cycle TASC model. This work should be continued to refine the data for future cycles.

6. Gas Pathways

The TASC model only considers potential groundwater pathways to the biosphere. Since the radiation decay of the high level waste canister will produce gas, potential gas pathways should also be evaluated. Other gas sources might include existing natural gas, the entrapped air after mine abandonment, and steam produced from the canister heat. Potential steam pathways may be very significant during the period prior to complete mine saturation.

9. Thermal Effects

The heat from the high level waste canisters will result in a significant temperature gradient around the repository. This temperature gradient may affect various phases of the repository including groundwater flow, gas flow, mechanical behavior of the host rock and backfill material, dissolution behavior, inducement of ground heave, and other effects. Although OWI has completed several studies related to the temperature, the problem is quite complex and has not yet been clearly delineated. Clearly, substantial work is required in this area in order to adequately consider the thermal affects. Many researchers feel that thermal affects may be the single most significant problem in the repository concept.

10. Tectonic Effects

All potential tectonic effects were evaluated using a criteria of a seismic effect of intensity VIII. Although this approach was reasonable for the initial TASC model cycles, the entire approach must be reconsidered for future models. Clearly, the subject of tectonic related changes incorporates a wide range of geologic phenomena including those caused by lower intensity seismic events and those not associated with seismic events at all.

11. Refined Model Geometry

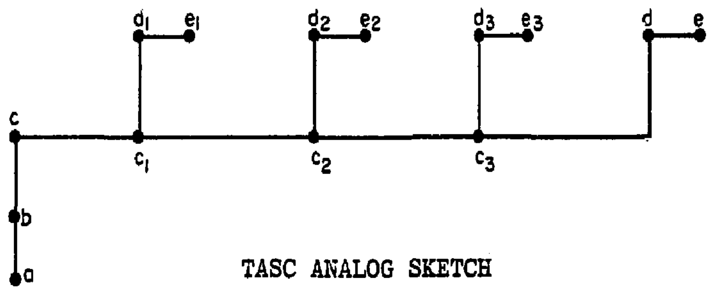
The initial TASC models represented a relatively specific, although conservative, geologic and hydrologic situation. Future models should begin to incorporate more realistic geologic and hydrologic conditions based on the results of detailed regional analyses of actual known conditions. The generic shale and salt basin models presented in Section 2.4 of this report represent the results of such studies and should be incorporated into future models. A suggested format for a third cycle and TASC model reflecting a generic shale basin model might include the following (see TASC Analog sketch and Figure 8):

1. Large sedimentary basin; repository in thick shale sequence.
2. Layers (from surface).
   A-1: Upper non-indurated sediments.
   A-2: Lower non-indurated sediments.
   B-1: Sandstone aquifer.
   B-2: Thick shale deposit (repository zone).
   B-3: Sandstone aquifer.
   C: Thick evaporite sequence.
3. Groundwater Regime
   A-1: Groundwater aquifer, hydraulically continuous with surface waters.
   A-2: Aquitard.
   B-1: Artesian aquifer, generally higher pressure than A-1, fresh to saline, may include wells, locally connected to A-1 where A-2 is absent or at anomalies.
   B-2: Aquitard.
   B-3: Artesian aquifer, higher pressure than B-1, saline, may include oil or gas wells.
   C: Aquifer-aquitard sequence, saline to brine, may include oil or gas wells.

   Basin recharged along one end and discharged at the other.
4. Unflawed Repository: Multi-Pathways (see sketch).
   a-b-c: Upward flow from B-3, through repository to B-1.
   c-d-e: Ultimate discharge from basin at discharge area, c-d through B-1, d-e in A-1 to surface water, pathway large (over 50-100 miles) with considerable dillution.

$c_n-d_n-e_n$: (Multi-pathways) Various pathways out of B-1 to A-1 (c_n-d_n); hence to local surface waters (d_n-3_n). Pathways caused by local anomalies (faults, strata change, reefs, etc), pinching out of A-2, minor leakage through A-2, and/or lateral (vertical) dispersion.

Due to dilution and dispersion, the concentration decreases with distance from the repository. However, the probability of the pathway existing would increase with distance. The final distance d_n-e_n would be a function of surface water environment (arid, wet, etc.). The number and characteristics of these pathways could be made relatively complex to simulate real geologic conditions.



TASC ANALOG SKETCH

5. Flaws
   a. Drinking water wells: A-1, B-1 (layers).
   b. Oil and gas wells: B-3, C (layers).
   c. Mines: C (layers).
   d. Fracture zone around shaft and tunnels.
   e. Borings
   f. Faults
6. Other shale configurations may be required to simulate different overall groundwater flow regimes.

12. Other Rock Types

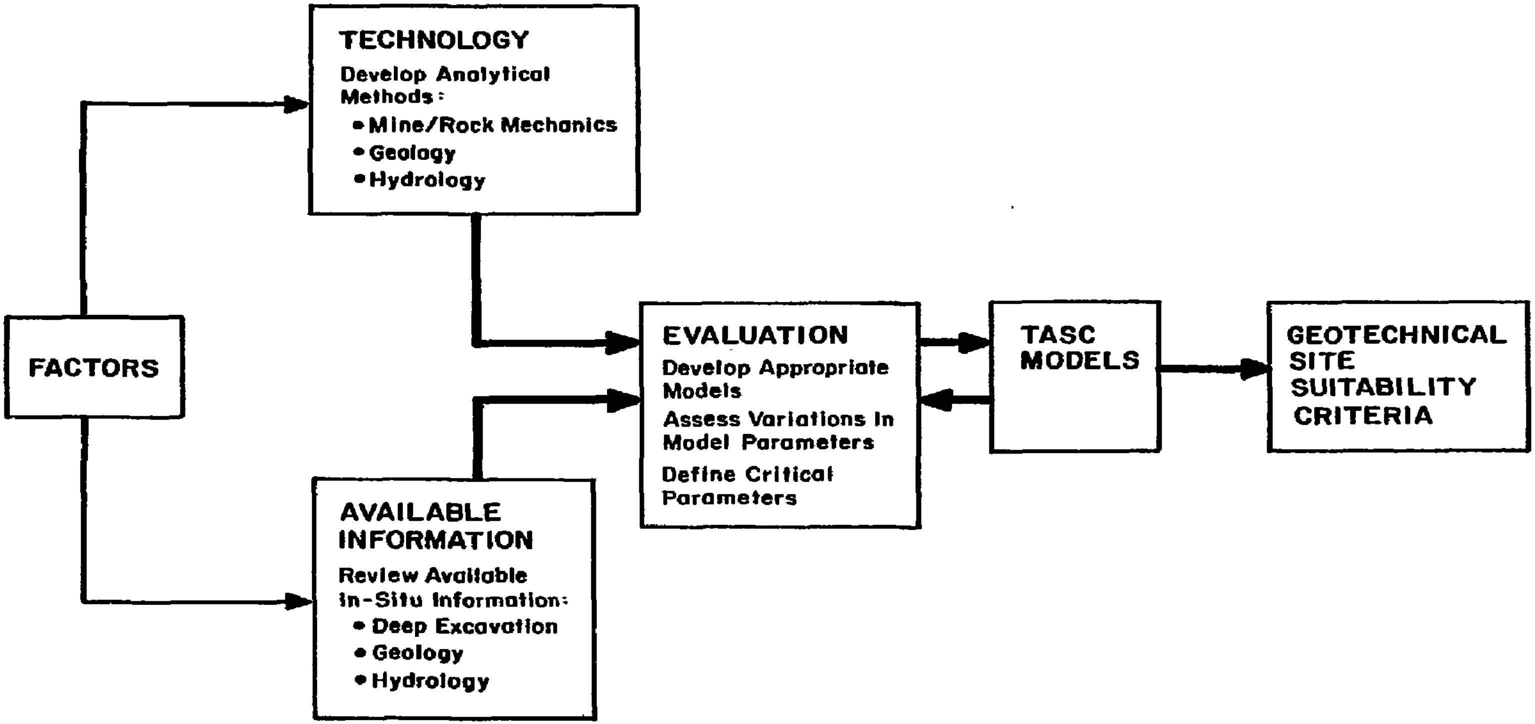
The initial TASC models reflect only shale and bedded salt. Clearly other rock types will also have to be considered in detail. Of particular interest would be massive crystalline rock and domed salt.

Respectfully submitted,

GOLDER ASSOCIATES, INC.

for D. Pentz

R. Plum



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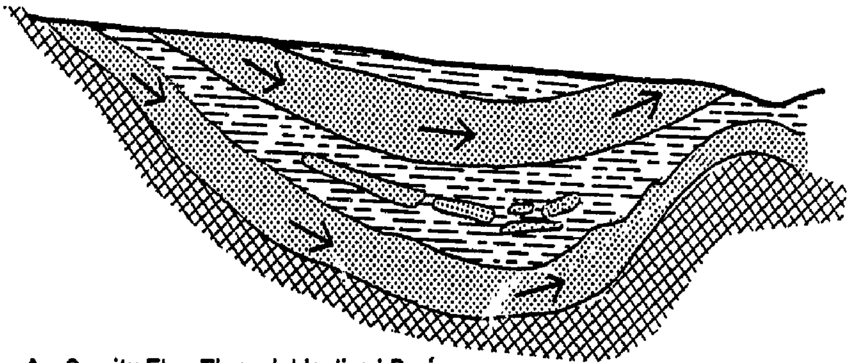
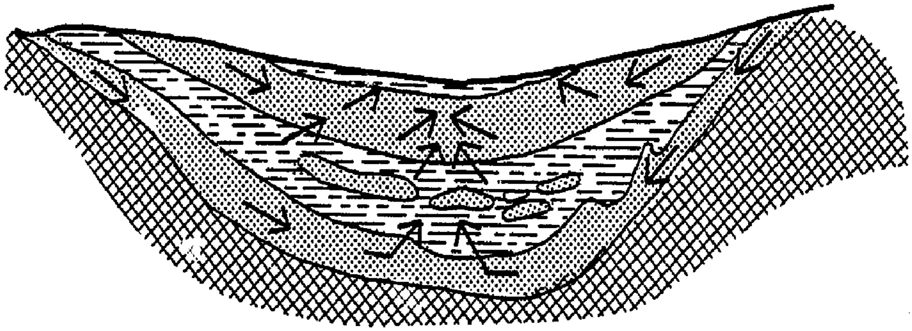
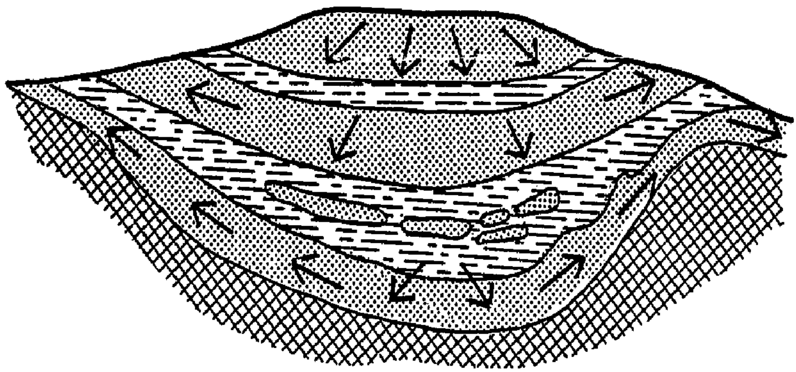


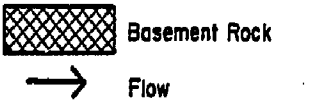
A. Gravity Flow Through Idealized Basin



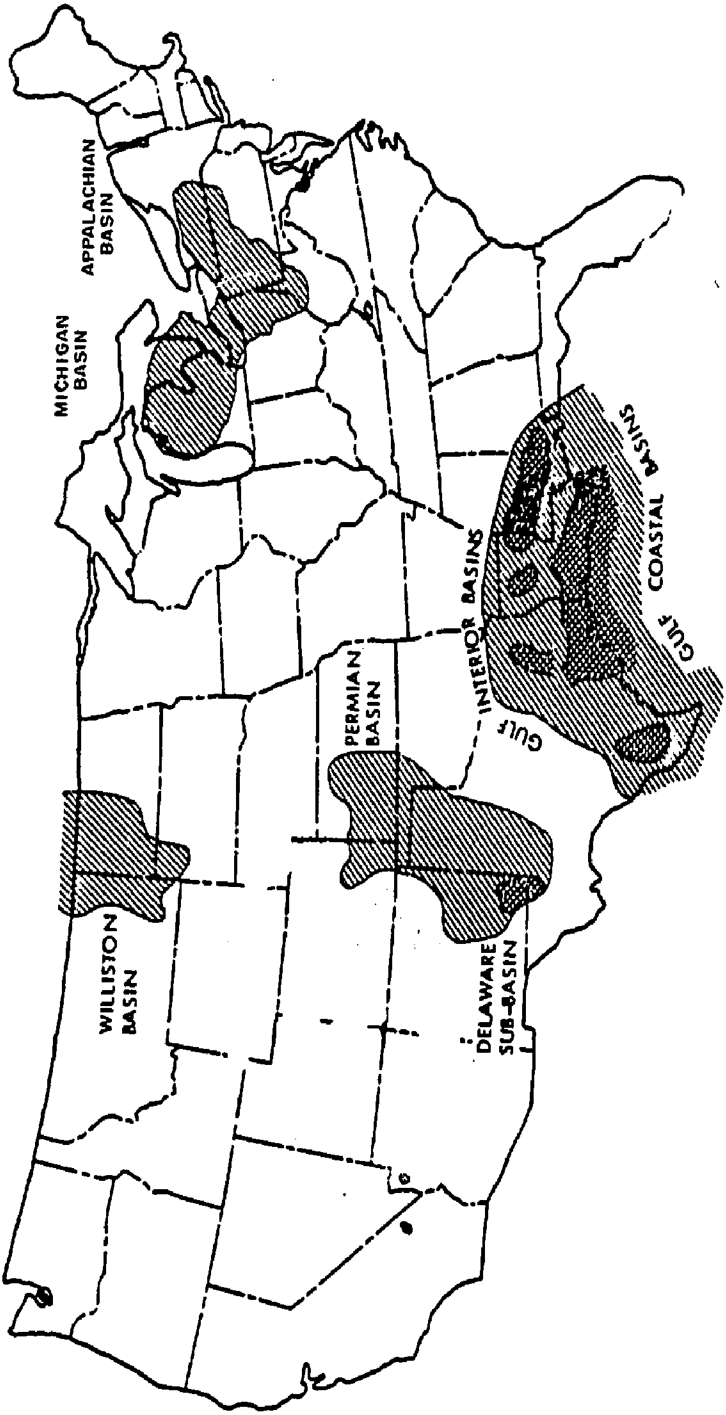
B. Gravity Flow Toward Center of Basin



C. Gravity Flow Toward Sides of Basin



Reference : Modified from Drescher (1965).



Reference: Pierce and Rich, USGS Bull. 1148

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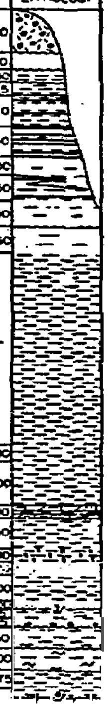
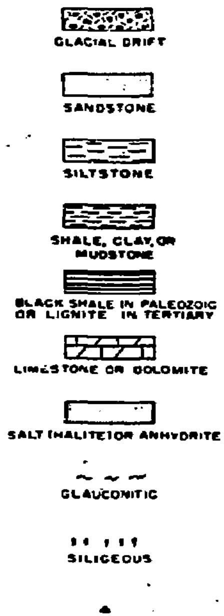
1

ERA	SYSTEM	SERIES	GROUP	FORMATION	MEMBER	THICKNESS IN FEET 1/
CENOZOIC	QUATERNARY	PLEISTOCENE		GLACIAL DRIFT		0 - 500
	TERTIARY	MIOCENE		ARIKAREE FORMATION		0 - 300
		OLIGOCENE		WHITE RIVER FORMATION		0 - 400
		EOCENE		GOLDEN VALLY FORMATION		0 - 175
		PALEOCENE		FORT UNION FORMATION	SENTINEL BUTTE MEMBER	0 - 950
					TONGUE RIVER MEMBER	0 - 650
					CANNONBALL MEMBER	0 - 300
					LUDLOW MEMBER	0 - 350
MESOZOIC	CRETACEOUS	UPPER		HELL CREEK FORMATION		100 - 550
			MONTANA GROUP	FOX HILLS SANDSTONE		150 - 350
				PIERRE SHALE		1500-2300
			COLORADO GROUP	NIOBRARA FM		100 - 200
				CARLILE SHALE		200 - 500
				GREENHORN FM		50 - 200
				BELLE FOURCHE SHALE		150 - 450
		LOWER		MOWRY SHALE		50 - 200
				NEWCASTLE SS		0 - [illegible]
				SKULL CREEK SHALE		200 - 300
			DAKOTA GROUP	FALL RIVER FM		[illegible]
				[illegible] FM		[illegible]
				LAKOTA FM		[illegible]
	JURASSIC	UPPER		MORRISON FORMATION		0 - 250
				SWIFT FORMATION		350 - 400
				RIERDON FORMATION		125 - 475

GENERALIZED LITHOLOGY



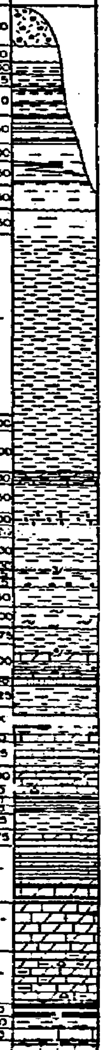
EXPLANATION



IC SECTION OF SEDIMENTARY ROCKS IN CENTRAL WILLISTON BASIN

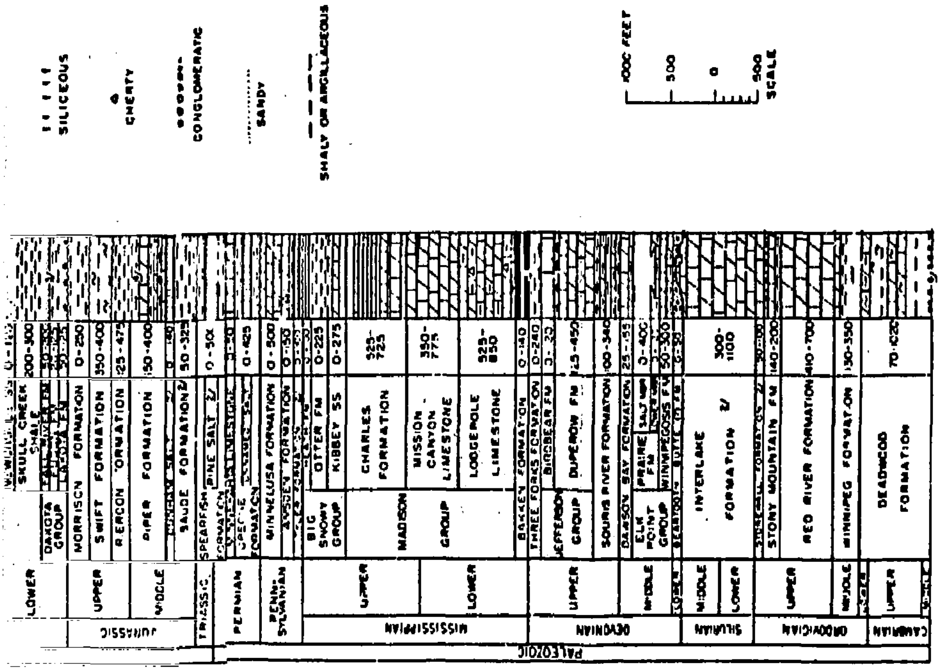
2

Era	System	Series	Group	Formation / Member	Thickness in feet 1/
CENOZOIC	QUATERNARY	PLEISTOCENE		GLACIAL DRIFT	0 - 500
	TERTIARY	MIOCENE		ARIKAREE FORMATION	0 - 300
		OLIGOCENE		WHITE RIVER FORMATION	0 - 400
		EOCENE		GOLDEN VALLY FORMATION	0 - 175
		PALEOCENE	FORT UNION FORMATION	SENTINEL BUTTE MEMBER	0 - 950
				TONGUE RIVER MEMBER	0 - 650
				CANNONBALL MEMBER	0 - 300
				LUDLOW MEMBER	0 - 350
MESOZOIC	CRETACEOUS	UPPER		HELL CREEK FORMATION	100-550
			MONTANA GROUP	FOX HILLS SANDSTONE	150-350
				PIERRE SHALE	1500-2300
			COLORADO GROUP	NIOBRARA FM	100-200
				CARLILE SHALE	200-500
				GREENHORN FM	50-200
				BELLE FOURCHE SHALE	150-450
		LOWER		MOWRY SHALE	50-200
				NEWCASTLE SS	0 - [illegible]
				SKULL CREEK SHALE	200-300
			DAKOTA GROUP	FALL RIVER FM	[illegible]
				[illegible] FM	[illegible]
				LAKOTA FM	[illegible]
	JURASSIC	UPPER		MORRISON FORMATION	0-250
				SWIFT FORMATION	350-400
				RIERDON FORMATION	125-475
		MIDDLE		PIPER FORMATION	150-400
				[illegible] SALT 2/	0 - 140
				SAUDE FORMATION 2/	50-325
	TRIASSIC		SPEARFISH FORMATION	PINE SALT 2/	0 - 500
PALEOZOIC	PERMIAN			[illegible] LIMESTONE	0-50
			OPECHE FORMATION	[illegible] SALT	0-425
	PENNSYLVANIAN			MINNELUSA FORMATION	0 - 500
				AMSDEN FORMATION	0 - 50
				[illegible] FORMATION 2/	[illegible]
	MISSISSIPPIAN	UPPER	BIG SNOWY GROUP	[illegible] FM	0 - 30
				OTTER FM	0-225
				KIBBEY SS	0-275
			MADISON GROUP	CHARLES FORMATION	325-725
		LOWER		MISSION CANYON LIMESTONE	350-775
				LODGEPOLE LIMESTONE	325-850
				BAKKEN FORMATION	0 - 140
				THREE FORKS FORMATION	0-240
			JEFFERSON	BIRDBEAR FM	0 - 20



EXPLANATION

- GLACIAL DRIFT
- SANDSTONE
- SILTSTONE
- SHALE, CLAY, OR MUDSTONE
- BLACK SHALE IN PALEOZOIC OR LIGNITE IN TERTIARY
- LIMESTONE OR DOLOMITE
- SALT (HALITE) OR ANHYDRITE
- GLAUCONITIC
- SILICEOUS
- CHERTY
- CONGLOMERATIC
- SANDY
- SHALY OR ARGILLACEOUS

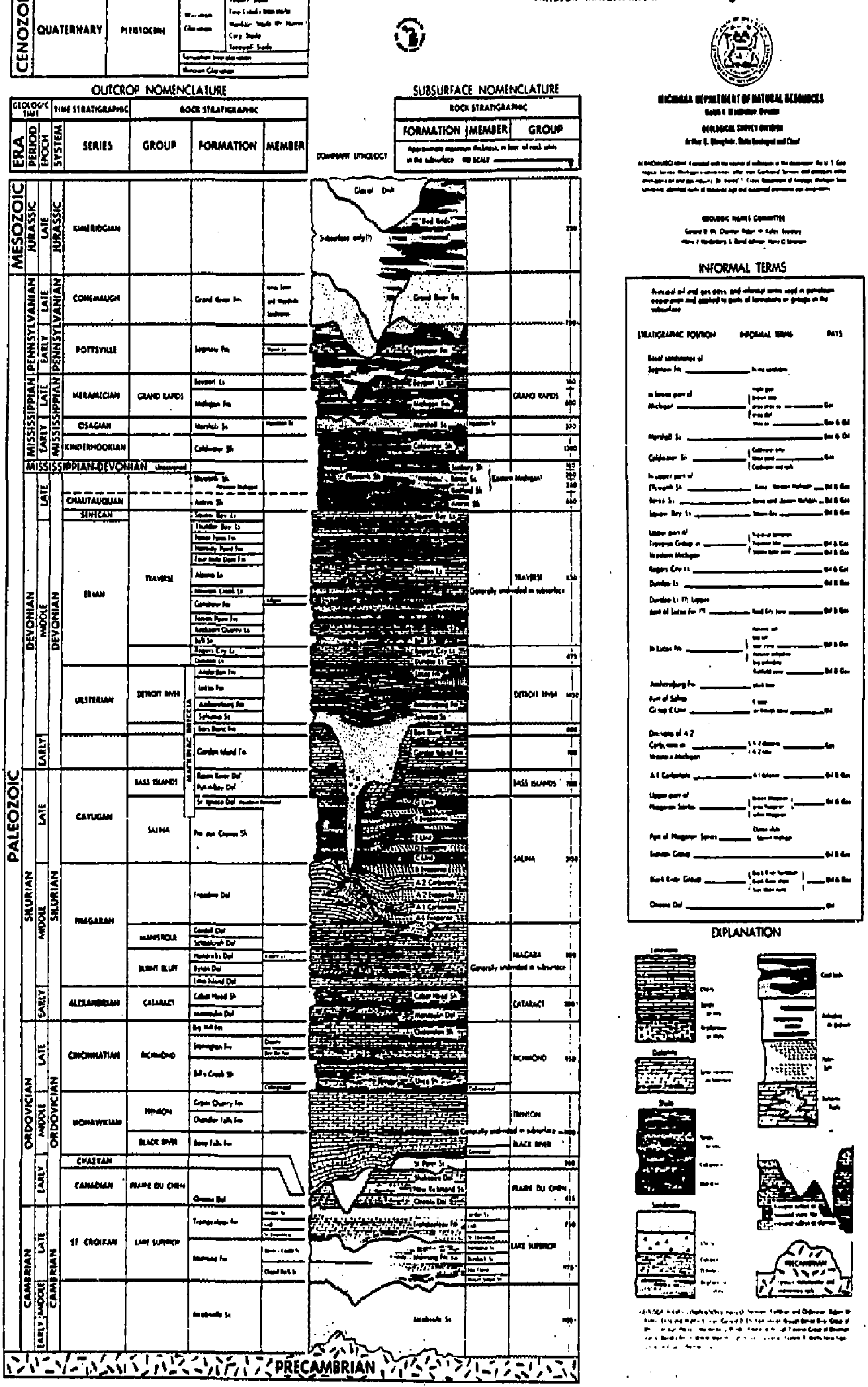

SILICEOUS
CHERTY
CONGLOMERATIC
SANDY
SHALY OR ARGILLACEOUS
1000 FEET
500
0
500
SCALE
SKULL CREEK SHALE
200-500
DAKOTA GROUP
MORRISON FORMATION
0-250
SWIFT FORMATION
350-400
RIERDON FORMATION
25-475
PIPER FORMATION
150-400
SAUDE FORMATION
50-325
SPEARFISH FORMATION
PINE SALT
0-500
MINNELUSA FORMATION
0-500
AMSDEN FORMATION
OTTER FM
0-225
KIBBEY SS
0-275
BIG SNOWY GROUP
CHARLES FORMATION
325-725
MISSION CANYON LIMESTONE
350-775
LODGEPOLE LIMESTONE
325-850
MADISON GROUP
BAKKEN FORMATION
0-140
THREE FORKS FORMATION
0-240
BIRDBEAR FM
JEFFERSON GROUP
DUPEROW FM
SOURIS RIVER FORMATION
DAWSON BAY FORMATION
PRAIRIE FM
ELK POINT GROUP
WINNIPEGOSIS FM
50-300
INTERLAKE FORMATION
300-1100
STONY MOUNTAIN FM
140-200
RED RIVER FORMATION
WINNIPEG FORMATION
150-350
DEADWOOD FORMATION
70-1020
LOWER
UPPER
MIDDLE
JURASSIC
TRIASSIC
PERMIAN
PENNSYLVANIAN
MISSISSIPPIAN
DEVONIAN
SILURIAN
ORDOVICIAN
CAMBRIAN
PALEOZOIC

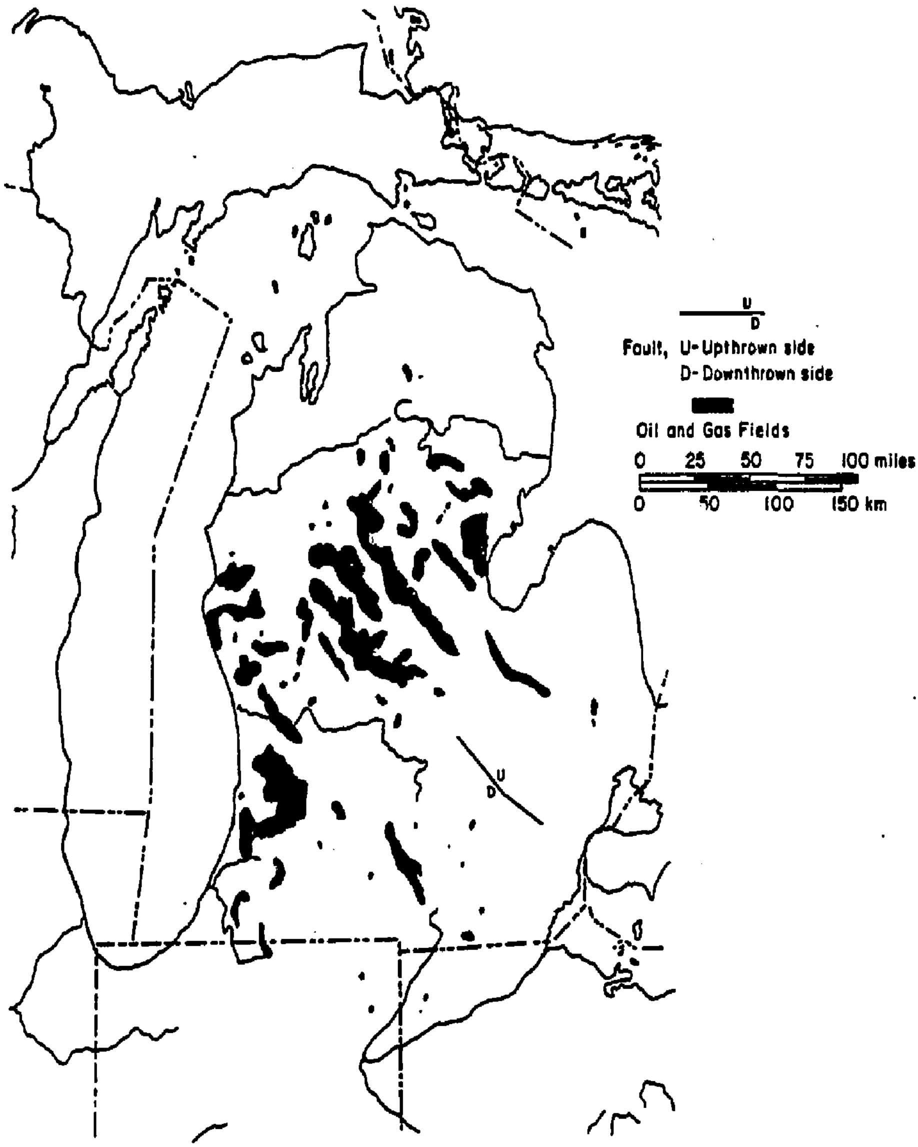
3

STRATIGRAPHIC SUCCESSION IN MICHIGAN

PALEOZOIC THROUGH RECENT

Figure 5





Reference: Merewether and Others, 1973

REPRESENTATIVE STRATIGRAPHIC SECTION OF THE DELAWARE BASIN BASED ON PROJECT GNOME SITE

Figure 7

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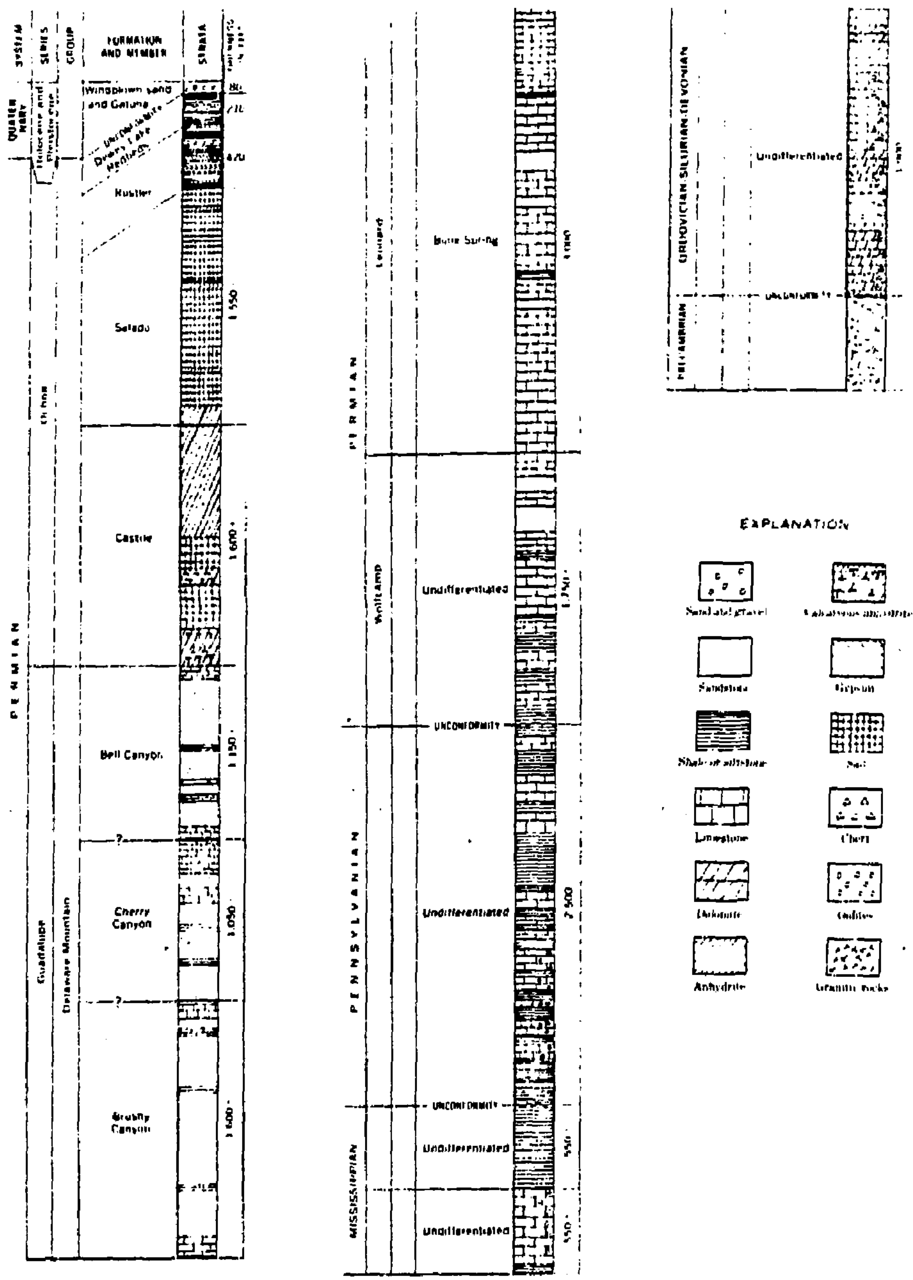

Reference: Cooper and Glanzman, 1971

GENERIC BASIN MODEL FOR SHALE

Figure 8

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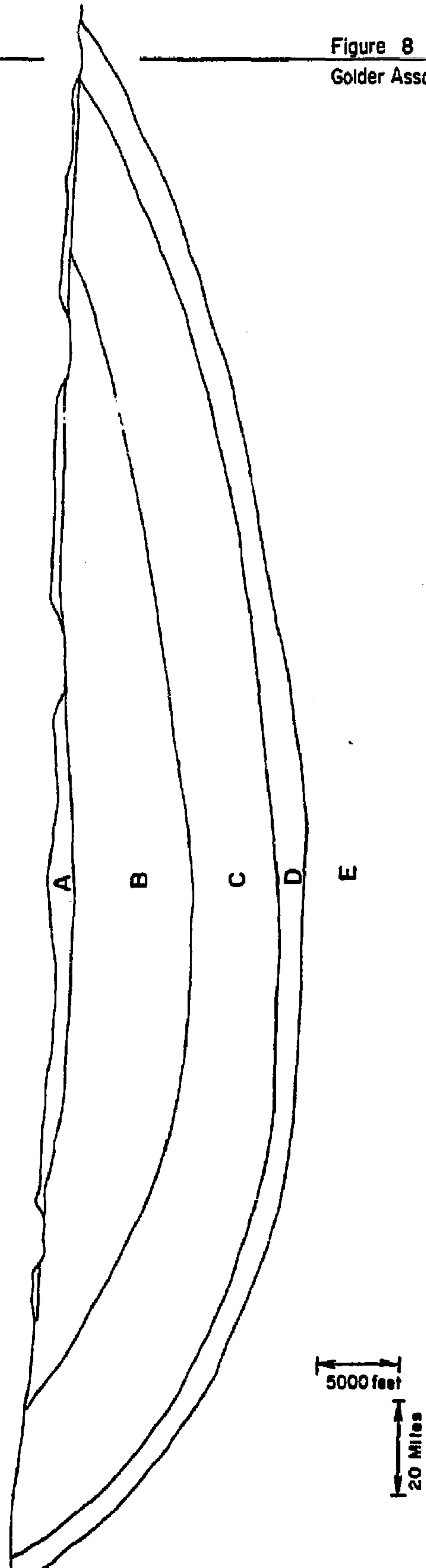

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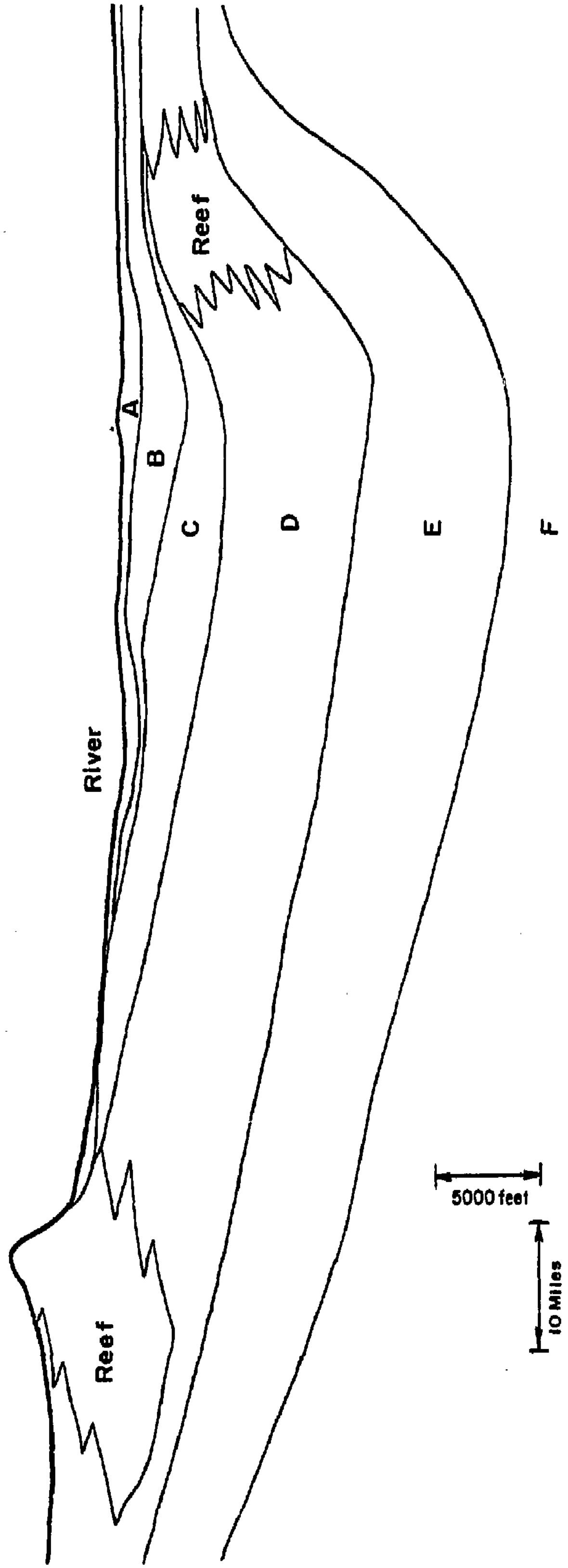
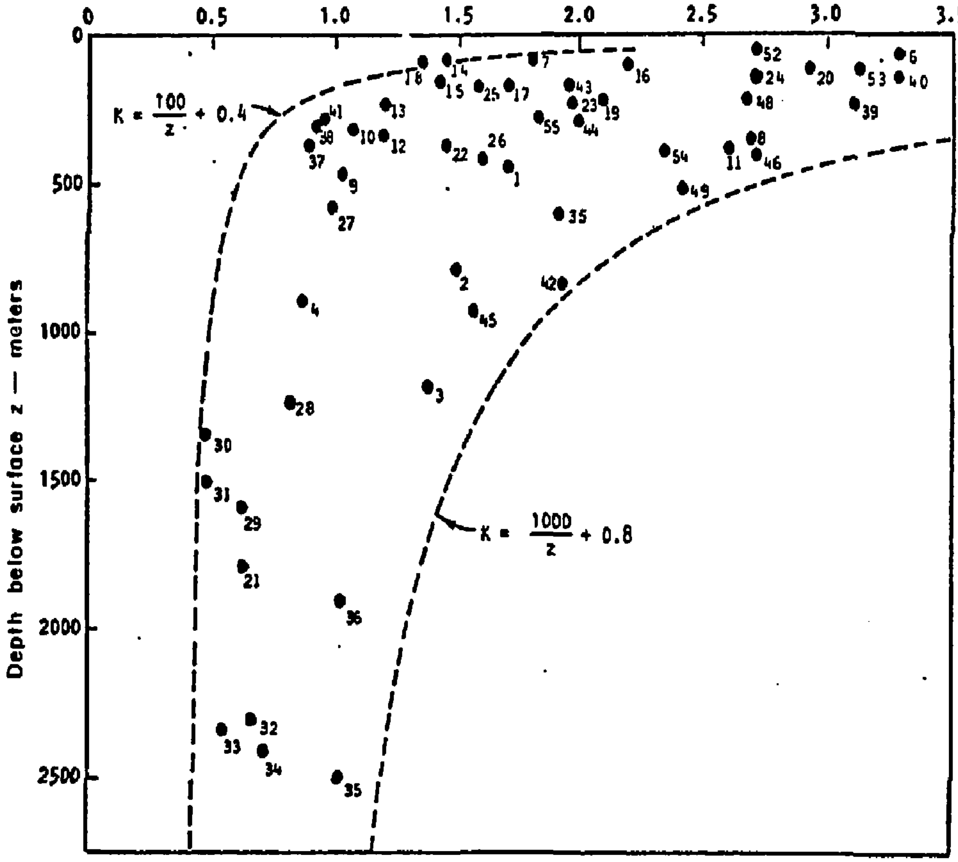
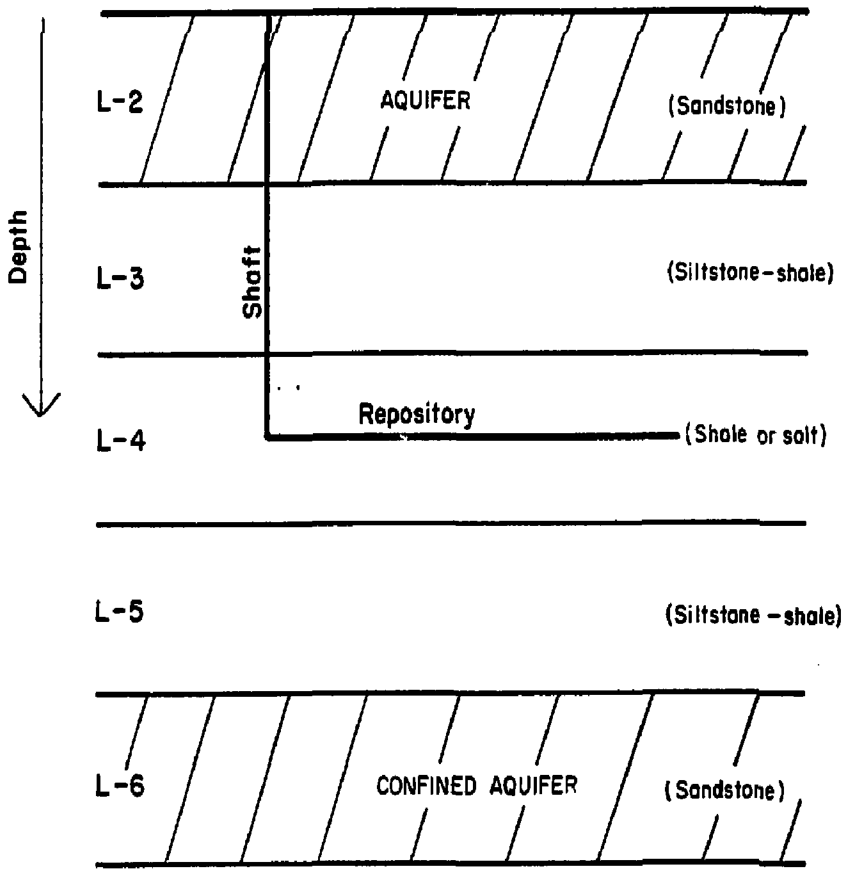


$$K = \frac{\text{Average horizontal stress}}{\text{Vertical stress}} \quad \frac{\sigma_{h.av.}}{\sigma_v}$$



Reference: Hoek and Brown in Preparation


Depth
L-2
AQUIFER
(Sandstone)
L-3
Shaft
(Siltstone-shale)
L-4
Repository
(Shale or salt)
L-5
(Siltstone-shale)
L-6
CONFINED AQUIFER
(Sandstone)

APPENDIX - A
HYDROLOGY OF SELECTED SEDIMENTARY BASINS

A-1 - Shale

Williston Basin

The geology, stratigraphy, and structure of the Williston Basin is described in Appendix B of this report. This section is devoted to a description of the surface and subsurface hydrology of the Williston Basin, particularly with reference to a possible repository located within the Pierre shale.

1) Surface Water: The Williston Basin, located primarily in North Dakota, is transected by a major surface drainage divide running approximately from the northwest to the southeast corner of North Dakota. Surface water to the southwest of this divide is drained by the Missouri River and eventually reaches the Gulf of Mexico. The area to the northeast of the divide is drained by the Red River of the North which flows to Hudson Bay.

Surface runoff is generally low over most of the Basin. Annual precipitation ranges from over 20 inches in the Black Hills of South Dakota and along the eastern border of both North and South Dakota, to about 13 inches in northwestern North Dakota and eastern Montana. Over most of the basin the mean annual surface runoff is only .5 to 1 inch. It is extremely variable both seasonally and annually. Many areas within the basin do not contain integrated drainage systems due to the complex glacial terraine. Other areas contain well defined drainages eroded in glacial or alluvial deposits.

The Missouri River forms the major drainage in the Williston Basin. Its major tributaries include the Yellowstone, Little Missouri, Knife, Heart, Cannonball, Grand, Jones, and

Moreau Rivers. Smaller tributaries, generally occupying large glacial runoff valleys, drain the area to the east and north of the Missouri River. The flow in the Missouri ranges from over 400,000 cfs to less than 2,000 cfs with an average of approximately 20,000 cfs. Most of the major tributaries have maximum flows of from 10,000 to 50,000 cfs but generally average from 50-200 cfs. They may completely dry up during part of the year. The Red River forms the eastern drainage boundary in North Dakota but is, itself not flowing over the Williston Basin. Its tributaries include primarily the Cheyenne and Souris Rivers. Maximum flows are from 5,000-10,000 cfs in these tributaries with an average of about 100 cfs. These tributaries can also completely dry up for some time during the year.

River water is used primarily for irrigation and stock watering and secondarily for municipal and recreational purposes. The two major rivers and many of their tributaries have been dammed for flood control, irrigation, power generation, and recreation. These reservoirs constitute an important source of water in an otherwise relatively dry area. Lakes and ponds are also found scattered throughout the basin with the greatest concentration occurring in the glacial terraine to the north and east.

North Dakota is covered by 1385 $mi.^2$ of standing surface water which is about 2% by area of the state. South Dakota has 1091 $mi.^2$ of standing surface water or about 1.4% of the state (Geraghty, et al., 1973). The Oahe Reservoir in South Dakota and the Garrison in North Dakota, both on the Missouri River, are third and fourth in total storage capacity for all reservoirs in the United States. A more detailed description of surface water in the Williston Basin can be found in Bulletin 63 of the North Dakota Geological Survey (1973) and Bulletin 16 of the South Dakota State Geological Survey (1964).

2) Ground Water: Ground water occurs in aquifers throughout the sedimentary rock strata above the Pre-Cambrain basement of the Williston Basin. Aquifers often do not follow the same boundaries as stratigraphic units and thus are rather difficult to define. Many rock units within the basin are subject to facies changes over relatively short distances which affect aquifer properties. The formations described below should not be considered uniform with characteristic permeabilities, heads, and gradients. Rather the hydrologic properties will, in many instances, vary greatly in both vertical and horizontal directions even within the same formation. Figure 4 shows a stratigraphic section and indicates the aquifer locations.

Pre-Cambrian Aquifer

The Pre-Cambrian crystalline rocks underlie all of the Williston Basin and outcrop only at the extreme basin edges. They may yield small quantities of water from fractures near the southern and eastern perimeter of the basin. They are considered to be functionally impervious over the remainder of the basin.

Paleozoic Aquifer

Ground water occurs in confined Paleozoic aquifers throughout the Williston Basin to depths of over 13,500 feet below sea level in northwestern North Dakota. Data on these aquifers is limited and thus areal extent, thickness, and interconnection of these aquifers cannot be determined in many localities. The Paleozoic aquifers are generally treated as one unit in the deeper areas in the Williston Basin. Water is found in fine sandstones which generally yield small quantities and porous cavernous limestones, which may yield very large quantities. Oil well exploration throughout the basin and water wells (particularly near the basin edges) have yielded some information on the Paleozoic aquifers. Confined aquifers yielding or capable of yielding water in the South Dakota section of the Williston include the Readwood, Winnipeg, Red River, and Minnelusa Formations along with the Madison Group (South Dakota State Geological Survey, 1975). Brine is produced in conjunction with oil in many formations. Oil is currently being recovered from reservoirs in the Red River, Interlake, Winnipegosis, Duperow, Bakken, Madison, Tyler, and Spearfish Formations (Borchert, 1977).

It is probably not possible to define a piezometeric surface for the Paleozoic aquifers. In general, heads seem to decline towards the northeast indicating flow in that direction.

Water quality within the Paleozoic aquifers is generally low. Brines produced with oil may contain over 300,000 mg/l total dissolved solids. Quality generally deteriorates toward the center of the basin with the highest quality found near the basin margins where the aquifers are recharged. Typical water quality ranges from 14,000 to 54,000 mg/l in eastern North Dakota, from 58,000 to 140,000 mg/l in north-central North Dakota, and from 200,000-330,000 mg/l in western North Dakota.

Dakota Aquifer

The Dakota aquifer consists of interbedded quartzose sand and shale, with sand predominating in the east and shale predominating in the west. The aquifer underlies most of the Williston Basin and ranges in depth from 100 feet along the eastern margin to over 5,600 feet in the center of the basin. The Dakota aquifer is not uniformly permeable but consists of from two to seven permeable zones. The lowest zone generally has the highest head. Poor hydraulic connection between the individual beds is evidenced by variations in head along a vertical section through the Dakota aquifer (Swenson, 1968).

The Dakota is under artesian pressure which is high enough to cause flow at the surface along the eastern margin of the Williston Basin. Aquifer development has resulted in an uneven piezometric surface. Withdrawal for stock, irrigation, and domestic use has caused a pressure decline in the eastern side of the basin. In the north central and western region of North Dakota, water has been pumped from the Dakota into deeper formations to maintain oil field pressures. Brine produced with oil has also been reinjected into the Dakota thus overpressurizing it at some locations, particularly north of Minot, North Dakota. The piezometric surface of the Dakota aquifer generally slopes eastward from the Black Hills and the mountainous terrain forming the boundaries of the Williston Basin in Wyoming and Montana. This surface is not well determined but indications are that gradients range from 2.5 to 16 ft./mi. with an average of 10 ft./mi.

Water quality within the Dakota, although variable, is usually higher near the basin margins (recharge areas) and lower near the basin center. Quality near the margins ranges from 1,000 to 10,000 mg/l. The lowest quality found in the basin center is about 11,000 mg/l.

Several aquifers probably exist both below the Dakota (but above the Paleozoic sequence) and between the

Dakota and the Pierre Shale. These aquifers have been recognized in South Dakota and may also exist in North Dakota. They include the Sundance Formation below the Dakota aquifer and the Greenhorn Limestone and Niobrara Formation above the Dakota aquifer. These latter two aquifers need closer evaluation since they would lie directly beneath a repository site within the Pierre shale.

Pierre Shale

The Pierre Shale is thought to be an aquitard with low permeability. It is the primary formation considered for a possible repository site in the Williston Basin. In some localities where it outcrops, the Pierre Shale is an aquifer. The only source of water is from fractures which extend down several hundred feet. These fractures generally do not yield significant water much below 100 ft.

The hydrologic characteristics of the Pierre Shale are not well known where it occurs buried at depth. Values of permeability and porosity have not been adequately evaluated. The degree of fracturing at depth and whether open fractures exist at all is not known. These are important factors which presently must be estimated since direct measurements are not available.

The water quality of the Pierre near outcrops is extremely variable ranging from 700-12,500 mg/l. The water quality at the Pierre near the central portions of the basin has not been measured.

Fox Hills - Hell Creek Aquifer

The Fox Hills - Hell Creek aquifer consists of interbedded sand, clay, silt, and lignite. It contains many individual sand lenses, generally medium to fine-grained, which extend only a few miles areally. These individual permeable layers are found in both the Fox Hills and Hell Creek Formations. However, since there appears to be hydraulic connection, they are treated as one aquifer. The depth to the top of the aquifer (saturated, pervious rock) increases from several feet near outcrop areas to more than 1,400 feet at the center of the basin.

The Fox Hills-Hell Creek aquifer is generally confined. The piezometric surface slopes towards the east at a gradient of 3.5 to 40 ft./mi. with an average of about 11 ft./mi. The piezometric surface is reversed where the formations have been eroded by the Missouri River in southern North Dakota and South Dakota.

Fort Union Aquifer

The Fort Union aquifer overlies the Fox Hills-Hell Creek aquifer. It is formed by interbedded sand, silty clay, clay, and lignite beds, with most beds traceable over less than one mile. The aquifer is confined, except at outcrops, and may be over 1,100 ft. deep near the basin center. Several local aquifers probably exist within the Fort Union at any point but they are considered as one unit.

The slope of the piezometric surface is not known but probably slopes at about 10 ft./mi. towards the east.

Water quality within the Fort Union ranges from 200-6,700 mg/l total dissolved solids. The high dissolved solids concentrations are found in areas covered with glacial drift, usually at depths of 300 ft. or less.

Glacial and Alluvial Aquifer

Glacial drift aquifers are scattered throughout the glaciated parts of the Williston Basin. They form the most important source of ground water in many areas and are generally unconfined but may be locally confined by silt and clay layers. Water level elevations are dependent upon local variations in topography and follow no regional pattern. Water quality varies widely. Surficial outwash deposits generally contain less than 1,000 mg/l in areas with sufficient discharge for adequate flushing. In small enclosed glacial-fluvial deposits or areas of low topography, water quality is lower, sometimes exceeding 5,000 mg/l. Along the eastern margin of the basin water in glacial drift may contain as much as 26,000 mg/l total dissolved solids although it is usually less than 10,000 mg/l. This is thought to indicate contamination from the underlying Paleozoic and Dakota aquifers along the eastern edge of North Dakota.

Alluvial aquifers are also present along modern and ancient buried stream channels. These may constitute an important local source of water, but the aquifers are of limited depth and areal extent. Water levels are generally closely related to the level of the river or stream in the valley. Quality is generally good due to constant flushing by the river. Buried stream valley aquifers range from 400-2,500 mg/l in dissolved solids.

3) Water Movement

Vertical Movement

In general the deeper aquifers within the Williston Basin exhibit higher piezometric heads than the overlying aquifers. This indicates a possible upward gradient for flow of water from the Paleozoic and Dakota aquifers to the overlying Fox Hills-Hell Creek and Fort Union aquifers. Upward vertical flow through the various confining layers has not been demonstrated in the central Williston Basin. Swenson (1968) gives evidence for upward movement of water from the Madison group to the overlying Dakota sandstone along the eastern edge at northern South Dakota and North Dakota. This movement is made possible by a thinning of the intervening strata along the eastern margin of the Williston Basin. High dissolved solids concentrations in glacial till along the eastern edge of North Dakota also point to upward flow of water from the deeper saline aquifers.

Regional Flow

On a regional basis, water in the confined aquifers within the Williston Basin seems to be flowing in a northeasterly direction. Recharge takes place around the western and southwestern perimeter of the basin where older rocks outcrop. Some recharge to the artesian aquifers also occurs along the eastern and southeastern margins of the basin.

The major discharge point for deep Paleozoic aquifers seems to be near Lake Winnipeg in Canada where Paleozoic rocks outcrop. Land surface elevation is around 700 feet, thus, this region represents a natural topographic low and corresponding discharge point for northeasterly flowing water. It is estimated that 50,000 ton/yr. of salt is brought to the surface here (Gorrell and Alderman, 1968). Water from the Dakota aquifer may naturally discharge along the eastern margin of the basin. Pumping in this area has reduced the piezometric levels so that many wells which originally flowed at ground surface no longer do so.

It is not possible to represent real flow within the Williston by a simple recharge-discharge flow pattern. Hitchon (1969) has pointed out many flow complexities resulting from density variations, topography, geologic changes (both lithologic and structural) and osmotic effects within the Canadian portion of the Williston. He concludes that topography exerts a major influence on regional flow as do geologic changes which result in lateral and vertical variations in permeability. He also noted drawdown effects to depths of 5,000 feet at some major rivers.

Michigan Basin

The stratigraphy and structure of the Michigan Basin, described in the Geology section of this report, is similar to that of the Williston Basin. The subsurface hydrology of the Michigan is examined here with reference to a repository site within the Coldwater or Ellsworth shales.

1) Surface Water: The major surface water features associated with the Michigan Basin are the Great Lakes which bound the lower Michigan Penninsula to the east, north, and west. Rivers flow radially from the center of the basin towards the Great Lakes. Small glacial lakes and swampy areas, common in poorly drained glaciated regions, are also found.

Precipitation averages about 30 inches per year with from 10-15 inches of surface runoff occurring annually. Most meteoric water circulates within a layer of glacial deposits which range from 50-800 feet thick. Rivers and streams are constantly fed by groundwater from these surficial glacial deposits.

River water and shallow wells in the glacial drift supply most of the water used in Michigan for domestic supplies, irrigation, and stock. The state of Michigan is covered by 1,398 $mi.^2$ of standing surface water which constitutes 2.4% by area of the state (Geraghty, et al., 1973).

2) Ground Water: Ground water occurs in numerous aquifers within the Michigan Basin. Aquifers within the Michigan Basin are subject to the same types of areal variations in thickness, permeability, and porosity as described in the Williston Basin. There are no deep freshwater wells in the Michigan Basin. Figure 5 shows a stratigraphic section through the basin.

Pre-Cambrian Rocks

Pre-Cambrian crystalline rock underlies the Michigan Basin. This rock is considered functionally impervious except at outcrops where it may contain water within fractures or weathered zones.

Cambrian-Ordovician Aquifers

The Cambrian-Ordovician aquifers are formed by sandstone and carbonate rocks at depths to over 13,000 feet below sea level. Very little is known of these aquifers although additional information may be attainable from petroleum exploration and production. The water is generally thought to be saline. Where these aquifers occur closer to the surface in the upper Michigan Peninsula, water flows above ground surface in many wells. These aquifers are probably also under relatively high artesian pressure near the central Michigan Basin.

Silurian-Devonian Aquifers

Numerous aquifers exist in limestone and dolomite rocks. Some of these aquifers are hydraulically connected (Allen, 1977), however, evaporites and shales are present which will form confining layers for many of them. All aquifers are under relatively high pressures with the piezometric head probably increasing with depth.

Water in these aquifers is saline and may contain dissolved solids concentrations greater than 200,000 mg/l due to contact with evaporites. Some freshwater exists in the Silurian-Devonian aquifers near outcrops at the basin margins.

The Traverse Group, comprised of various carbonate formations including limestone rocks, forms the lower boundary of overlying Ellsworth shale. No information at this time has been found relating to existing heads or brine concentrations in the Traverse.

Ellsworth and Coldwater Shales

The hydrologic characteristics of these shales are not known. The Ellsworth Shale appears fairly uniform within its lower portions, however, its upper portions grade into the Berea Sandstone towards the eastern half of the Michigan Basin. Oil and gas production has been noted in the upper Ellsworth in western Michigan and from the Berea in eastern Michigan. The Coldwater Shale contains interbedded limestone and sandstone which also produce some gas.

Marshall Aquifer

The Marshall Sandstone aquifer immediately overlies the Coldwater Shale. It consists of well-cemented sandstone and minor amounts of siltstone, shale, and limestone. Permeability is largely derived from fractures. The Marshall aquifer is the most productive bedrock aquifer in Michigan, supplying water for municipal and industrial use particularly along its southern subcrop area. The aquifer flows at land surface over much of this southern area.

The Marshall aquifer becomes increasingly saline towards the center of the basin. It is also thought to be saline in the northern subcrop area (Allen, 1977) where it is covered by a great thickness of glacial drift. Oil and gas has been produced from some reservoirs located within the Marshall sandstone.

Saginaw Aquifer

The Saginaw aquifer consists of interbedded sandstone and shale with minor amounts of limestone, coal, and gypsum. It includes the Saginaw Formation and possibly portions of the Grand River Formation. Permeability is a function of both interstitial and fracture flow. The aquifer is confined above by shale beds or, where they are absent, glacial drift. The Saginaw flows at land surface in portions of southern and eastern Michigan where the aquifer occurs relatively near the surface.

Water in the Saginaw is generally high quality in the southern and eastern subcrop areas but becomes saline near the basin center. Oil field data indicates the water is also saline in the northwestern subcrop areas. Where fresh, the Saginaw aquifer is used for municipal and industrial purposes.

Glacial Aquifers

The glacial drift which overlies most of Michigan supplies water to streams, lakes, and deeper bedrock aquifers. The permeability of the drift will vary widely. In some areas it will allow water to infiltrate into underlying bedrock aquifers while in other areas it may serve as a confining layer.

Flowing wells are common within the glacial drift. Water quality is generally high.

3) Water Movement

Vertical Movement

Piezometric head generally increases with depth in the Michigan Basin (Piper, 1972). It is uncertain whether this indicates a potential upward vertical flow of water throughout the basin since the effects of salinity, osmosis, and possibly other factors are not known. Evidence does not indicate contamination of overlying aquifers by those underneath. The areal extent of saline water decreases in aquifers occurring in younger rocks. For instance, saline water is found in the Silurian-Devanian aquifer system over nearly all of the lower Michigan Peninsula. The areal extent of saline water decreases in the Marshall aquifer until only that portion of the Saginaw aquifer near the center of the basin contains saline water.

Regional Flow

The regional flow pattern within the Michigan Basin is not readily apparent. Water from the Great Lakes may serve to recharge some of the deeper aquifers within the basin, however, there seems to be little or no place for such recharge to flow. It may be that there is no large scale regional flow within the basin. Withdrawal of brine and oil from deeper aquifers may induce some lateral flow into the depleted aquifers.

Aquifers occurring above the level of the Great Lakes will be recharged by water penetrating the glacial till. It is also possible these aquifers are relatively static except near their subcrop areas. Saline water will sink towards the lower portions of the aquifers near the basin center. A static situation can exist if this saline water does not escape from the aquifers by flowing vertically.

Localized flow systems will occur where aquifers come in contact with permeable glacial drift at the subcrop areas. These local flow systems may account for the flowing wells found at the subcrops of the various aquifers described. Present data is not sufficient to accurately evaluate the regional flow, if any, in the Michigan Basin.

Appalachian Basin

The Devonian Ohio shale in central and northeastern Ohio and the Ordovician shales of central and western New York are only briefly examined in this report. They exhibit low permeability and may constitute a suitable host rock for a waste repository.

1) Surface Water: The major drainages in the Ohio area include the Ohio River and its tributaries, the Allegheny, Muskingum, and Kanawah Rivers. Lake Erie forms the northern boundary of the area. Surface waters in the New York area include the Oswego, Seneca, and Genesee Rivers, flowing north into Lake Ontario, and the Susquehanna and Mohawk Rivers flowing east. Lake Ontario bounds the area to the north and Lake Erie to the west. The numerous Finger Lakes are scattered over much of the region.

Precipitation ranges from about 30 to 40 inches per year over both areas. Surface runoff averages 10 to 15 inches in central and northern Ohio and 15 to 20 inches in central and western New York. Much of the area in Ohio is rural and agricultural land with that in New York being agricultural and forest land.

2) Ground Water: Little information has been reviewed concerning the ground water aquifers, heads, gradients, water quality, and regional flow within the Appalachian

Basin area. In general, the Appalachian Basin contains various sandstone and carbonate aquifers. Saline water with concentrations of 1,000 to 3,000 mg/l total dissolved solids is found at depths of less than 500 feet over much of the basin. Higher salinity will occur in aquifers adjacent to Silurian salt deposits.

Abundant oil and gas wells have penetrated the shale in central and northeastern Ohio. Few bore holes have been drilled through the shale in the New York region where oil is found in overlying Silurian and Devonian strata.

Regional flow within the basin was not studied. Deeper ground waters are probably not in good connection with the shallower waters. The high dissolved solids content of deeper ground waters indicate little flushing by high quality surface and shallow subsurface water.

A-2 - Salt

Permian Basin

The Permian Basin includes parts of southeast New Mexico, northwest Texas, western Oklahoma, and southwest Kansas. Several sub-basins contain thick salt deposits. The Deleware Basin, considered as one of the most favorable sites for a waste repository, is considered in more detail in the following section. A brief general description of other areas in the Permian Basin is given here.

1) Kansas Area

The Hutchinson Salt Member of the Wellington Formation is relatively pure and up to 420 ft. thick. It is overlain by a shale member of the Wellington and underlain by interbedded anhydrite and shale also of the Wellington. These upper and lower members are relatively impermeable and tend to seal the salt from circulating water (Bayne and Brinkley, 1972).

Salt solutioning has occurred where this seal has not been effective. Sinks may be caused by either natural or man-induced solutioning of salt, gypsum, chalk, or limestone. Solutioning, even if not originating within the salt, may result in collapse thus destroying the integrity of the shale seal. Brine wells have been known to cause large collapse features. The Mead Salt Well formed a central sink and fracture zone 175 feet in diameter upon its collapse in 1879 (Bachman and Johnson, 1973).

Active salt mines and brine wells are found in or near the Kansas area. There are numerous oil fields within the eastern half of the area with fewer in the western half. Petroleum is being produced from strata both above and below the Wellington Formation.

2) Oklahoma-Texas Area

The Oklahoma-Texas area, within the Anadarko Basin, contains several salt-bearing formations including the Hutchinson salt. An overlying shale unit and underlying anhydrite unit may tend to seal the salt from ground water.

Several major streams drain eastward from this area. They include the Canadian River, North Canadian River, and North Fork of the Red River.

The ground water movement in the area has not been investigated in this report. Salt springs and sink holes in Oklahoma-Texas area indicate active dissolution of bedded salts.

3) Clovis Area

The Clovis area, part of the Palo Duro Basin, contains bedded salts in the San Andres Formation and the Artesia Group. The salt is often found interbedded with anhydrite, shale, and dolomite in the San Andres. It is interbedded with anhydrite and red beds within the Artesia Group.

Most surface drainage is to the east although a small portion of the area drains west into the Pecos River. Playas and sinkholes are common where water flows into closed basins.

Ground water was not studied in detail. It is known that sandstone beds within the Artesia Group contain water (Jones, 1974). There is also a sandstone aquifer underlying the salt-bearing San Andres Formation which contains saline water.

4) Colorado-Kansas Area

Permian salts occur in this area although they are not well known. Surface drainage is largely to the east and streams include the Arkansas River. No information was reviewed on ground water in this area.

Delaware Basin

The geology, stratigraphy, and structure of the Delaware Basin is described in Section 2.3.2.2. Figure 7 shows a general stratigraphic section through the Delaware. The hydrology of the Delaware Basin has been most extensively studied in southern Lea and Eddy counties, New Mexico. Cooper and Glanzman (1971) studied the geohydrology of this area as a part of Project Gnome sponsored by the AEC. Their objective was to study the effects upon the geohydrology of a nuclear device detonated within the Salado Formation. Brokaw, et al., (1972) summarized the available geologic and hydrologic information on the Carlsbad, New Mexico potash area on behalf of the AEC. The most recent study in the area was done by Claiborne and Gera (1974) for the AEC and related to a potential radioactive waste repository, known as the WIPP Site (Waste Isolation Pilot Project), within the bedded salts of the Salado Formation.

1) Surface Water: The Pecos River serves as the major surface drainage in the Delaware Basin. It flows to the southeast from New Mexico and is the only throughgoing perennial stream in the basin. Surface drainage is poor over much of the basin with playa lakes and salt flats common. The Black River, south of Carlsbad, forms a perennial tributary to the Pecos. Most other streams flow intermittently and many drain into playas or surface sinks formed by evaporite solution and collapse.

Precipitation is low over the Delaware Basin ranging from about 10 inches in the middle of the basin to slightly over 20 inches in the surrounding mountains. The average surface runoff is less than .25 inches per year.

Several small reservoirs are located on the Pecos River. Other small lakes, some man-made, are found within the basin. Only a few contain water for the entire year.

2) Ground Water: The Delaware Basin contains saline water in various carbonate and sandstone aquifers. Variations in aquifer properties can be expected due to facies changes, particularly as rocks grade into the large carbonate reefs which encircle the basin. The Pre-Cambrian basement rock is considered the lower limit of permeability within the Delaware Basin. Heads are given in terms of freshwater elevation above sea level unless otherwise indicated. Basin-wide heads and salinities are primarily from McNeal (1965).

Ellenburger

The Ellenburger dolomite is the basal aquifer. The potentiometric surface dips from west to east dropping from about elevation 4,000 to elevation 3,000 ft. Water quality ranges from about 50,000 mg/l near the edges of Delaware Basin to over 200,000 mg/l near the center. At the WIPP Site the Ellenburger has a saline water level of 1,705 feet above sea level with a salinity of 150,000 mg/l. This converts to a freshwater head of 3,198 ft. (Datum is mean sea level).

Devonian

The Devonian is a limestone-dolomite aquifer. Its potentiometric surface is slightly higher than the Ellenburger, ranging again from about elevation 4,000 to elevation 3,000 ft. Salinity varies from 50,000 to 200,000 mg/l. At the WIPP Site the Devonian exhibits a head of 3,198 feet and a salinity of 50,000 mg/l. This gives a freshwater head of 3,706 ft.

Mississippian

Data for the Mississippian limestone aquifer is too sparse to determine potentiometric and salinity trends.

At the WIPP Site, the Mississippian aquifer has a saline elevation head of 3,198 ft. or 3,706 ft. of freshwater head. The salinity is 50,000 mg/l, equal to the underlying Devonian aquifer. This indicates it is possibly in hydraulic connection with the underlying aquifer.

Strawn

Basin-wide potentiometric and salinity data are also lacking for the carbonate Strawn aquifer. At the WIPP Site the saline water level is elevation 2,296 ft. and salinity is 150,000 mg/l. This gives a freshwater head of 3,280 ft.

Wolfcamp

The potentiometric surface of the limestone Wolfcamp aquifer dips from west to east ranging from about elevation 3,600 to 3,000 ft. Salinity data on the Wolfcamp is sparse but indicates an increase towards the east from less than 50,000 to over 150,000 mg/l. The saline water level at the WIPP Site is 2,296 ft. and salinity is 150,000 mg/l which produces a freshwater head of 3,280 ft.

San Andres

Basinwide, the potentiometric surface of the sandstone and carbonate San Andres aquifer dips from west to east, ranging from about 4,000 to 3,000 ft. Salinity increases towards the eastern edge of the basin from 50,000 to over 200,000 mg/l. At the WIPP Site the saline water level is 3,100 ft. with a salinity of 50,000 mg/l. This yields a freshwater head of 3,198 ft.

Delaware

The Delaware aquifer, composed primarily of sandstone but with some carbonates, ranges from over 4,000 to 3,000 ft. in potentiometric surface elevation, dipping from west to east. Salinity increases towards the east from under 50,000 mg/l to over 300,000 mg/l. Saline water rises to 2,755 ft. at the WIPP Site with a salinity of 200,000 mg/l. The freshwater head is 3,198 ft. The Delaware aquifer immediately underlies the evaporites of the Castile formation which contribute to the high salinity.

Salado

The bedded salts of the Salado formation are considered a major candidate for location of a waste repository. Circulating ground water has not been reported within the Salado in the potash mines or drill holes scattered throughout the Project Gnome area (Cooper and Glanzman, 1971). Some pockets of entrapped water have been encountered during mining. Pockets of non-flammable gas have been encountered in drill holes which are under sufficient pressure to cause geysering or blowouts of drilling fluids to heights of 10 ft. or more above ground surface.

The Salado is being subjected to solutioning along the Pecos River and possibly in areas near the buried Capitan Reef.

Rustler

Several aquifers are present in the Rustler formation near the WIPP Site. These include the solution breccia zone at the base of the Rustler at its contact with the Salado, the Culebra Dolomite Zone, and the Magenta Dolomite Zone. The continuity of these aquifers over the entire basin is not known. The Culebra is the major freshwater aquifer at the WIPP Site. It is generally considered to be in hydraulic connection with overlying aquifers, being recharged from above (Claiborne and Gera, 1974). The freshwater head stands at about elevation 3,346 ft., higher than any of the aquifers underlying the evaporite sequence. This implies that water would tend to move down within the Salado.

Although not part of the Rustler formation, the Santa Rosa Sandstone is hydraulically connected with it. It yields small quantities of water in the area of the WIPP Site but its importance as an aquifer in the remainder of the basin is not known at present.

Surficial Aquifers

Various other aquifers are found in the Delaware Basin. These include the Ogallala and Gatuna Formations, sand dune deposits, playa lake deposits, and alluvial deposits adjacent to the Pecos River. These aquifers may be in hydraulic contact with the underlying Rustler aquifer. They can be under confined or water table conditions. Salinity probably varies with location. The alluvium near the Pecos River yields the greatest quantity of high quality water from surficial aquifers.

Barrier Reefs

Near the margins of the Delaware Basin is the Capitan reef complex including the Capitan and Goat Seep Limestones. It is important primarily for its oil production capacity. The reefs may allow vertical communication between various aquifers near the basin margins. They also influence the regional flow of water within the basin as shown later. Water in the Capitan aquifer is relatively high quality although saline water is also found at some locations.

3) Water Movement

Vertical Movement

The potential for vertical water movement generally seems to be downward at the WIPP Site (Claiborne and Gera, 1974). This seems to be true over the remainder of the Delaware Basin although data is too sparse to allow accurate prediction of vertical movement over many portions of the basin.

Active dissolutioning is taking place in the Salado along the Pecos River near the Gnome and WIPP Sites. Groundwater in the formations above the Salado moves generally southward and southwestward towards the Pecos River. This water is thought to discharge into the Pecos River near Malaga Bend. It is estimated that during the past 5 million years the salt has dissolved laterally at a rate of 3.5 to 4 miles per million years (Brokaw, et al., 1972).

Regional Flow

Potentiometric contours (McNeal, 1965) indicate flow from west to east within aquifers below the Castile formation. Hiss (1975) agrees with a general west to east flow pattern, but points out the effects of the Pecos River on the San Andres and Delaware aquifers and upon flow within the Capitain aquifer.

The Pecos River has intercepted much of the flow occurring in the north-plunging Capitan aquifer on the northwest margin of the Delaware basin. Flow in the east portion of the Capitan aquifer is thought to be north toward its lowest point. Flow within the San Andres and Delaware aquifers in the eastern half of the basin is towards the Pecos River. Flow within the western half of the basin is also towards the Pecos until, at some point, it reverses and eastward flow is again established.

Flow within the deeper aquifers is thought to be towards the east. Potentiometric surfaces of these aquifers have probably been altered by oil production.

The direction of flow within the Rustler has been estimated near the Gnome and WIPP Sites in southeastern New Mexico. It moves generally southward and southwestward eventually discharging into the Pecos River near Malaga Bend, New Mexico.

Williston Basin

Evaporite sequences are found in the Paleozoic and early Mesozoic strata within the deeper regions of the Williston Basin. These aquifers are described in Appendix A-1. Present information does not warrant a more detailed description.

The thickest salt is found in the Prairie formation which is underlain by an aquifer in the Winnipegosis formation. The other salt beds are also located adjacent to aquifers. The high salinity of the deep aquifers within the Williston Basin and the salt springs observed at the supposed discharge area of the deep aquifers near Lake Winnepeg in Canada point to active solutioning of at least some of the evaporite layers. Collapse features in Canada also indicate evaporite solutioning.

Michigan Basin

Salt in Silurian and Devonian strata of the Michigan Basin may constitute a potential waste repository site. The hydrology of the Michigan Basin, described in Appendix A-1 pertains to salt as well as shale.

Little information is available on the Silurian-Devonian aquifers. Head generally increases with depth although information is not available to ascertain the head difference between aquifers underlying and overlying the evaporites.

These aquifer waters are generally very saline. Water flow is not known to occur except in response to pumpage from oil or brine wells.

Salt Domes

Salt domes occur within the Gulf Cost Province of the United States as shown in Figure 3. Individual domes have been studied in relationship to salt mining and oil production. The geohydrology of the Tatum salt dome in Mississippi was studied extensively prior to and after the Salmon Event, a nuclear detonation which occurred in 1964 (Taylor, 1971). From a preliminary review of information, it is apparent that various salt domes are similar in their hydrology.

1) Surface Water: The Gulf Coast region is drained by a number of rivers, among them the Mississippi, which drain directly into the Gulf of Mexico. Precipitation varies from about 25 inches per year in southern Texas to over 60 inches per year in southern Mississippi. Surface runoff ranges from about 1 inch to over 30 inches per year.

2) Ground Water: Numerous aquifers are found throughout the thick sequence of unconsolidated sediments surrounding the Gulf Coast salt domes. Generally, water is fresh except near the coastline where pumping has resulted in sea water intrusion at some localities. The aquifers are generally confined and their piezometric surfaces slope gently towards the south on the order of several feet per mile or less. Some aquifers locally exhibit northward sloping piezometric surfaces where pumping up-gradient has been sufficient to cause reversal of the natural southward flow.

The domes are usually shrouded in a relatively impermeable caprock which tends to isolate them from the surrounding aquifers. Some domes develop salt water plumes downgradient from them when the caprock seal is imperfect. Others develop no plume and are considered hydrologically stable. Salt within a stable salt dome has no flowing water although pockets of gas or brine are commonly encountered, especially along ancient shear zones. If the caprock seal is broken due to mining or improperly sealed drill holes and shafts, the salt can dissolve very quickly causing flooding and collapse.

APPENDIX - B
GEOLOGY OF SELECTED SEDIMENTARY BASINS

B-1 - Shale

WILLISTON BASIN

1) General: The Pierre shale and its lateral equivalents, the Bearpaw, Clagett, Lewis, and Steele shales, are representative of most of the Cretaceous shales of the western interior of the United States. The Pierre has a volume of about 175,000 cubic miles, an outcrop area of about 90,000 square miles, and is concealed beneath younger strata in an area of about 370,000 square miles (Tourtelot, 1962). It consists of thick sequences of claystone, shale, bentonitic mudstone, and many thin beds of bentonite ranging from less than 500 feet thick in the eastern Dakotas to more than 5,000 feet thick in southeastern Wyoming and central Colorado (Tourtelot, 1962). The Pierre is largerly devoid of aquifers though it yields a little water locally to near surface wells.

The typical mineralogy of the Pierre shale is 65-80% clay minerals, 15-25% quartz and a few percent feldspar, with traces of calcite, dolomite, biotite, pyrite, gypsum, clinoptilolite, jarosite and organic material. The clay minerals consist of 25-40 percent montmorillonite, 35-45 percent mixed-layer illite-montmorillonite, 15-25 percent illite, and about 5 percent each of kaolinite and chlorite (Tourtelot, Schultz, and Gill, 1960).

The Pierre shale and its lateral equivalents are found in a number of structural basins just to the east of the Rocky Mountains. The most prominant are the Denver Basin in eastern Colorado and western Nebraska, the Powder River Basin in Wyoming, and the Williston Basin in western North Dakota, eastern Montana and northwestern South Dakota. The Williston Basin is the southern end of a series of basins continuing into Saskatchewan and Manitoba. This study considers only the 110,000 square miles of the Williston Basin wholly within the United States as shown on Figure 3.

2) Stratigraphy: The sedimentary rocks that fill the Williston Basin attain a maximum thickness of about 16,700 feet and include parts of every geologic system from Cambrian to Quaternary. This thick sequence rests on an erosion surface of Precambrian metamorphosed igneous rocks at elevations ranging from 500 to about 13,900 feet below sea level. The sequence comprises three distinct lithologic assemblages. Rocks of middle Cambrian through middle Ordovician age are about 1,200 feet thick in the central Williston Basin and consist of clastic rocks, largely shale and sandstone with interbeds of limestone and limestone-pebble conglomerate. Rocks of late Ordovician through Pennsylvania age comprise a carbonate sequence about 7,500 feet thick. They consist largely of limestone and dolomite but include one thick salt bed, seven thinner salt beds, and several thin beds of shale. Rocks of Permian through Tertiary age are about 8,000 feet thick. These beds consist predominantly of shale. Connecting interbeds and lenses of sandstone and siltstone exist in the lower and upper part of the sequence and near the base are three thin salt beds. Figure 4 shows a stratigraphic section through the basin.

3) Structure: Rocks at the surface generally appear to be flat-lying because regional dips from the margins to the basin center are 1° or less. Most of the major folds are on the west side of the basin. The east and south sides contain only minor wrinkles. Dips on the flanks of the major folds average from 1° to 3° except for the steep west flank of the Cedar Creek anticline, while those in the interior never exceed 2°. The major folds in the Williston

Basin are the Cedar Creek and Nesson anticlines, the Poplar and Bowdoin domes, and the Sheep Mountain and Blood Creek synclines. The important secondary folds are the Camp Crook, Plevna, and Sanish anticlines, the Freedom dome, and the Coburg syncline.

The Cedar Creek anticline is a 125 mile long, northwest-plunging, asymmetrical anticline with a steep west limb. It tends N. 30° W. from northwestern South Dakota to east-central Montana. Dips on its west limb range from about 4° to 30° SW. But locally the surface rocks are nearly vertical where they reflect a subsurface fault (Sandberg, 1962). The Plevna anticline branches from the Cedar Creek anticline and parallels its west limb. The Sheep Mountain syncline borders the Plevna anticline to the west while the Camp Crook anticline connects the southern part of the Cedar Creek anticline to the Black Hills uplift. The Nesson anticline is a 75-mile long, 15-mile wide anticline that plunges southward just east of the basin center. It has a subsidiary fold, the Sanish anticline that trends southeast. The Poplar dome is an elliptical feature 25 miles long by 15 miles wide that is located just north of the end of the Cedar Creek anticline. Two domes and two synclines form the north-central Montana boundary for the Williston Basin. The Bowdoin dome is the largest feature being about 65 miles long east to west and 50 miles wide. The dips rarely exceed 1° and it is connected to the Little Rocky and Bearpaw Mountains by a steeper dipping syncline, the Coburg. South of the Bowdoin dome are the Blood Creek syncline and the associated Freedom dome which connect the basin to the central Montana uplift.

The latest deformation of the Williston Basin resulted largely in gentle folding and faults are rare in the surface rocks. The only two known major surface faults are the Brockton-Froid fault zone and the Weldon fault. Several large faults have been recognized however in the subsurface associated with ancestral anticlines. The Brockton-Froid fault zone is half-a-mile wide and extends northeast for 35 miles from the east end of the Poplar dome. Displacement is about 75 to 200 feet with the north side downdropped (Colton and Bateman, 1956). The Weldon fault also trends roughly northeast and is located midway between Freedom and Poplar domes. Its surface length is about 8 miles, but it seems to be part of an older long fault zone parallel to the Brockton-Froid fault zone. Subsurface exploration for oil and gas have delineated several buried faults or monoclinal structures having the same general trend as the Weldon and the Brockton-Froid faults.

The largest fault in the Williston Basin is the subsurface fault off-setting the steep west limb of the Cedar Creek anticline. It trends roughly northwest and may be as much as 125 miles long. Oil and gas exploration indicate that this fault is a zone along which several types of fault movement have occurred in at least four episodes between the Pre-Cambrian and Tertiary periods. Several other subsurface faults exist, but they are local in extent and all are associated with the major fold structures.

The Williston Basin and its surficial structural features were shaped by Laramide Orogeny during latest Cretaceous and early Tertiary time. Most major structural features did not originate, however, during the Laramide Orogeny but had already formed in Pre-Cambrian time. These ancestral features were reactiviated during several subsequent orogenies, of which the Laramide is the latest.

4) Resource Uses: Oil is the most important natural resource of the Williston Basin. Lignite is rapidly becoming a major resource and may eclipse oil in commercial importance. Gas, uranium, salt, gravel, sand, clay and other resources are relatively unimportant. Oil is produced from deep formations in the Williston Basin. The producing formations range from the Ordovician Winnipeg formation to the Cretaceous Newcastle sandstone, excepting a Permian-Triassic redbed-evaporite sequence. Lignite is mined in the Williston Basin area largely by stripping. Commercial beds of lignite up to 40 feet thick are abundant and widely distributed in the Fort Union formation of Paleocene age. Stripable reserves of up to 2 billion tons exist.

The basic economy of the basin has been agricultrual, relying on dry land wheat farming and stock grazing. The average population density has been 4.7 people per square mile. Due to the increase in coal and petroleum exploitation, boom towns exist and population densities may vary widely. Three-quarters of the oil production has come from oil fields located on only three major structural features and coal from only two significant areas.

MICHIGAN BASIN

1) General: The Michigan Basin is a sedimentary basin covering about 122,000 square miles in parts of five states and the Province of Ontario as shown on Figure 3. It contains about 108,000 cubic miles of sedimentary rock, largely of Paleozoic age. The rocks are thickest in the central part of the Southern Penninsula of Michigan where they are 14,000 feet thick. Approximately one-fourth of the surface is covered by Great Lakes Erie, Huron, and Michigan. The maximum surface elevation in the Southern Peninsula is about 1,700 feet and the maximum depth below sea level is in Lake Michigan, about 350 feet.

2) Stratigraphy: Four general lithologic sequences are recognizable in the basin. Each sequence is characterized by lithology that is indicative of several closely related environments of deposition. Figure 5 shows a stratigraphic section through the basin.

The Cambrian clastic sequence is composed of sandstone and siltstone that accumulated in near-shore and shelf environments. This unit is about 3,000 feet thick.

The carbonate-evaporite sequence is the major unit within the Michigan Basin and is 6,000 to 7,000 feet thick. It ranges in age from Early Ordovician to Middle Devonian. The sequence is composed largely of marine carbonate rocks. At times bioclastic or reef limestone accumulated in the shallow water, while at other times chemically precipitated limestone and dolomite were deposited. During Late Silurian and Middle Devonian time, periods of restricted hypersaline seas and an arid climate are indicated by very thick layers of gypsum, anhydrite and salt interbedded in the carbonate rocks.

The next higher unit is a 3,000-foot thick shale-siltstone sequence of Late Devonian and Mississippian age, composed mainly of illite clay shale and silty shale, although sandstone, sandy limestone and evaporites are present locally within the sequence. Some shales are rich in organic matter when circulation was restricted. Deltaic sandstones were deposited on the margins of the basin particularly during Mississippian time.

Following the shale unit is a 1,500 foot-thick sequence of continental clastic rocks commonly containing coal. These deposits consist of intertonguing lenticular sandstone and shale in which the tracing of individual units over any distance is very difficult to impossible.

Overlying the Paleozoic rocks is a mantle of unconsolidated glacial drift and alluvial sediments up to 1,000 feet thick.

3) Structure: The Michigan Basin is roughly elliptical in plan view and is about 460 miles long by 380 miles wide. The bedrock of this relatively simple structure dip gently toward the center of the basin at less than 1^{o}. Locally the regional dip is modified by small anticlines, commonly with less than 200 feet of closure (de Witt, 1960). Anticlines trend northwest and lie en-echelon throughout much of the basin. The general parallelism of trend suggests that the small folds in the sedimentary rocks are the surface manifestations of deep-seated faulting in the basement complex. Normal faults are commonly associated with the anticlinal folds.

The largest fault in the basin is a normal fault on the west flank of the Howell anticline with a displacement of about 1,000 feet.

Collapse structures, local zones of complex faulting and beds of sedimentary breccia are present near the outcrop of formations containing soluble evaporites of Silurian, Devonian, and Mississippian age.

4) Resource Use: The Michigan Basin contains large reserves of oil, gas, salt, high-grade limestone, and dolomite as well as smaller amounts of coal, gypsum, glass sand, and clay. Most mining exists in or near the outcrop of a formation near the basin edges. Oil and gas, however, have been found in the deeper formations throughout the entire basin area. Figure 6 shows oil and gas fields in the Michigan Basin.

APPALACHIAN AND OTHER BASINS

Shales from several other areas have been considered but not studied in any depth. These are briefly discussed below.

Central and eastern Ohio and western New York contain a thick section of undeformed shale and argillaceous limestone. This section is in a series of three belts that parallel the Appalachian Mountains. The belts are buried about 1,000 feet deep in central Ohio but become much deeper toward the east. The presently known mineral resources are oil, gas, and salt and are generally produced from overlying rocks. Overlying these ordovician shales are Devonian-Mississippian shales with about the same general aerial extent. These shales, however, have been extensively penetrated by oil and gas wells, salt mines, brine wells, and a few coal mines.

Within the Appalachian Mountains from Massachusetts-Connecticut area to central North Carolina are a series of Triassic basins. These basins were a series of fault troughs filled with conglomerates, sandstones, siltstones, and shales interbedded with flows of basic lava. The thickness varies from 2,000 to 20,000 feet. The section is highly variable with poorly sorted and irregularly bedded sediments. The sediments are thickest and coarsest in the eastern part of the basin. Structurally these basins are complicated by later complex faulting.

The Atlantic coastal plain sediments consist of interbedded and interfingering sands, clays, and calcareous materials. The beds dip gently and thicken toward the sea. Thick clays are uncommon and the dominant clay mineral present is montmorillonite. Sediments are saturated with water and are generally unconsolidated until buried by more than 2,000 feet of other sediments.

Another large area of unconsolidated sediments is the Gulf Coast. This area has much the same characteristics as the Atlantic Coast but some thick clays do exist. These clays are in a thick section of sands, silts, and clays. Freshwater is produced from sands as deep as 3,000 feet.

There are several thick shale sequences in California, Oregon and Washington, but these areas are structurally complex. The clays are derived largely from volcanic rocks including ash, and are montmorillonitic. Seismic activity may result in moderate to major damage. The intermountain plateaus of California, Nevada, Utah, and New Mexico also contain structurally complex shales with moderate to high seismic risk. These shales have interbedded permeable sandstone and limestone together with numerous faults.

Shales from the interior plains are ususally interbeds within a limestone sequence. They frequently contain coal along with sandstone and siltstone. The clay mineral present in most of these shales is illite. Structurally they range from near horizontal, undeformed to intensely folded and faulted. Most areas have been tested for oil and gas, coal and salt.

B-2 - Salt

PERMIAN BASIN

The Permian Salt Basin includes several connected smaller basins and uplifts. These features were well established before Permian sedimentation began and crustal stability has been maintained since Permian time.

The salt deposits of the Permian Basin underlie areas of Kansas, Colorado, Oklahoma, Texas, and New Mexico and have a linear extent of 650 miles and a width of 150 to 250 miles. In Texas, New Mexico and Oklahoma, abundant gypsum and anhydrite are in close association with the salt. In Kansas little anhydrite or gypsum is interbedded with the salt although thick deposits of gypsum are reported from both higher and lower beds. The thickest and most extensive salt beds in the Permian basin are in the Castile, Salado, and Rustler formations of the Ochoa series in southeastern New Mexico and southwestern Texas.

DELAWARE BASIN

1) General: The Delaware Basin represents the area of maximum subsidence of the Permian basin and contains the thickest Permain strata. It is a deep asymmetric trough west of the Central Basin Platform in the vicinity of Pecos, Texas. The basin extends in an arc for more than 200 miles in a north-south direction and has more than 20,000 feet of structural relief.

The Capitan reef grew around the margin of this subsiding basin in Permian time, separating the marine strata of the basin from the lagoonal and evaporite strata of the backreef or shelf area. The reef is exposed from Carlsbad southwestward to Guadalupe Peak and El Capitan in

Texas. East of Carlsbad it rings the Delaware Basin and is buried by younger rock stratigraphy.

2) Stratigraphy: The sedimentary rocks of the area are, in descending order, Quaternary, Triassic, Permian and Pennsylvanian to Cambrian in age as shown in Figure 7.

Quaternary deposits generally are thin, although locally they reach a maximum thickness of about 400 feet. They consist of alluvial deposits of clay, silt, sand and gravel, playa deposits, caliche, and dune sand.

The Triassic rocks are a series of red siltstone, shale and fine-grained sandstones and the Santa Rosa sandstone. Below these rocks are the Permian Dewey Lake Redbeds which are another series of red shales and siltstones.

The late Permian evaporites reach a thickness of about 4,900 feet in the Delaware Basin (Jones 1959). They are divided, in descending order, into the Rustler, Salado, and Castile formations. The Rustler formation is composed dominantly of gypsum rock hydrated from anhydrite. It ranges from 100 to 370 feet in thickness. The formation is divided into five parts. They are in descending order: the Forty-niner, a gypsum with siltstone, claystone and sandstone; the Magenta dolomite, containing some anhydrite; the Tamarisk, gypsum with some shale; the Culebra dolomite; and a lower sandstone member. There are a few thin discontinuous salt beds near the base of the Rustler.

Conformably underlying the Rustler formation is a thick, lithologically complex deposit of salt known as the Salado formation. The Salado has an average thickness of 1,650 feet but varies from about 200 feet to a maximum of slightly over 2,000 feet. It is characterized by thick persistent units of rock salt alternating with thinner units of anhydrite and polyhalite. Thin seams of claystone underlie virtually all the anhydrite and polyhalite units. There are also a few thin beds of sandstone or siltstone at long intervals. The middle member of the Salado contains potash salts. The salt comprises 75% to 90% of the total formation. Much of the salt is grayish in color from admixed black mud and clay. The Castile formation is the bottom formation of the Permian evaporite sequence. It is divisable into three units. The upper unit grades into the Salado. This unit is 700-800 feet thick and consists of interlaminated anhydrite-limestone, massive anhydrite, rock salt, and minor amounts of dolomite and magnesite. The middle member is a 550 to 1,000-foot thick salt rich unit. Predominantly rock salt, the member is divided into two salt beds by a 100-foot thick layer of interlaminated anhydrite-limestone. The upper salt also contains several of these layers which are two to five feet thick. The lower salt bed does not contain any anhydrite-limestone layers. The lower member is 200 to 400 feet thick and is largely interlaminated anhydrite-limestone with a few beds of limestone.

The evaporites overlie a thick clastic sequence consisting mostly of sandstones. There is up to 3,800 feet of sandstone with a few limestone beds before a very thick sequence of limestones up to 9,000 feet thick. A thick shale section is included near the base of this section.

3) <u>Structure</u>: In spite of its extreme depth, faulting is apparent only near the boundry with the Central Basin Platform. This faulting occurred before deposition of salt. Salt solution and resulting collapse features have created many shallow faults, but no deep-seated faults are known that have vertical displacements of more than 20 feet in the

evaporites within the area (Jones, 1959). The salt beds are disturbed little structurally except for a slight eastward tilt of less than two degrees.

4) Resource Use: The Permian Basin is one of the most prolific oil and gas producing areas in the United States. The production is from formations beneath the salt. Exploration is continuing with new and deeper fields being found. The area is also a major producer of potash from the middle member of the Salado formation. Many potash exploration drill holes exist in addition to those for oil and gas. There are several active underground mines. A possibility exists in the future of solution mining not only the rich sylvite potash zones but the low grade polyhalites as well.

WILLISTON BASIN

1) General: The Williston Basin is a large sedimentary and structural basin underlying a part of southern Canada, most of North Dakota, the eastern part of Montana, and the northwest and central parts of South Dakota. The general structure and stratigraphy is discussed in Appendix B-1 on shale and therefore only an outline of the salt bearing formations will be presented here.

Oil and gas exploration has disclosed 11 salt beds in the Williston Basin. The oldest and thickest is the Prairie formation of Middle Devonian age. In the overlying beds of Mississippian age seven salt beds have been recognized. Other beds of salt are found in the Opeche formation of Permian age, in the Spearfish formation of Permian and Triassic age, and near the base of the Jurassic sequence. The stratigraphic position of the salt beds is shown in Figure 4.

2) Stratigraphy: The oldest and most deeply buried evaporite sequence is called the Prairie formation. It ranges in thickness from less than a foot to almost 500 feet. Found in the deepest part of the basin, it consists of two members. The lower one with a maximum thickness of 120 feet consists mostly of anhydrite and dolomite interbedded with thin beds of shale and salt. The upper member is largely salt with thin stringers of dolomitic shale.

The 700-foot thick Mississippian Charles formation contains massive salt beds, anhydrite, limestone, and dolomite. Six individual beds have been recognized with a seventh located in the upper part of the underlying Mission Canyon formation. Most of the Mississippian salt formations are 5,000 to 9,000 feet below the surface.

The salt of Permian age occurs in the Opeche formation. This 400-foot thick formation consists of red shale, salt, anhydrite and some siltstone. The depth to the 100-foot thick salt is 5,700 to 7,500 feet.

The youngest and least deeply buried salts are found within a red-bed sequence of shale, siltstone, and fine-grained sandstone called the Spearfish formation. These two salts range in thickness from 100-300 feet and are buried 4,000 to 8,000 feet deep.

3) Structure: See Appendix B-1.

4) Resource Use: See Appendix B-1.

MICHIGAN BASIN

1) General: Extensive Silurian rock salt deposits underlie large areas of New York, Pennsylvania, West Virginia,

Ohio, Michigan, and southwestern Ontario. Silurian salt had its greatest development in the Michigan part of the Salina Basin. The combined thickness of all the salt beds is over 1,600 feet at the center of the basin, but it thins out toward the margins. The depth to the top of the salt varies considerably. Salt lies at about 800 feet near Detroit and 500 feet at the borders of the basin but at 6,500 feet near the basin center. The general structure and stratigraphy of the Michigan Basin is described in Appendix B-1 on shale; thus an outline of only the salt formations will be presented here.

2) Stratigraphy: Landes (1945, 1951) has divided the Salina formation into seven units designated A through G. His generalized stratigraphic column of the Salina-Bass Island Evaporite Section is shown in Figure 5.

Unit A is the basal unit of the Salina formation. It ranges from 100 feet thick at the margin to about 1,100 feet thick in the center of the basin. It consists of dolomite and shaly dolomite at the basin margins but contains more salt toward the basin center. This salt contains numerous paper thin laminae of anhydrite and dolomite. The maximum thickness is 872 feet thick with a 58-foot medial separation of dolomite. Unit B is 90% to 100% salt and is 240-275 feet thick over most of the basin. It contains a few laminae of anhydrite. Unit C is shale to shaly dolomite with some anhydrite and is 60 to 160 feet thick. Unit D is a nearly pure salt 80 to 160 feet thick. Thin dolomite beds may exist locally. Unit E is a thin shaly unit 90-125 feet thick. It contains red shale, shaly dolomite and anhydrite. Unit F consists of thick salt beds separated by shales, dolomite, and shaly dolomite. The salt content varies from about 50% to 100% with highest salt content near the north edge of the basin. The thickness of the unit varies from near zero at the margins of the basin to over 1,200 feet at the center of the basin. Unit G is primarily dolomite with a little anhydrite. It is about 80-100 feet thick.

In addition to the salt in the Salina formation, there is a 400-foot salt section within the Lucas formation of the Detroit River group. This section may contain as many as 8 separate salt beds with the thickest exceeding 100 feet. It is buried 1,300 feet at the northeast edge of the deposit to 4,300 feet near the basin's center.

3) Structure: See Appendix B-1.

4) Resources: Michigan produces one-fifth of the salt in the United States. Brine is extracted from the Devonian salts for the extraction of magnesium, bromine, calcium, potassium, and iodine. Silurian salt is mined near Detroit and oil and gas are produced from dolomites within the evaporite sequences.

SALT DOMES

1) General: More than 300 salt domes are distributed randomly throughout the Gulf Coast area shown on Figure 3. In plan, most of the domes are more or less circular with diameters of less than one mile to more than four miles. The burial depth is quite variable. Domes less than 4,000 feet are considered shallow. Those from 4,000 to 10,000 feet are termed intermediate, and those more than 10,000 feet below the surface are considered deep. Those near surface domes may have penetrated as much as 25,000-30,000 feet of overlying sediments.

2) Stratigraphy: A cap rock, composed primarily of anhydrite, gypsum, and limestone is found on top of many salt domes. It is commonly found on shallow domes, and is thin or non-existent on deep domes. Cap rocks are formed by residual accumulation as the salt is removed by solution. They are normally 300-400 feet thick but some cap rocks exceed 1,000 feet in thickness.

In addition to cap rocks, some domes have a shale or clay sheath around the sides of the dome. The material resembles fault gouge and is formed during the upward movement of the salt stock.

Salt in the salt domes is almost pure sodium chloride with anhydrite in black bands as the principal impurity. Occasionally pieces of sediments, through which the salt was intruded, are found as inclusions in the salt.

3) Structure: The internal structure of a salt dome is one of complex folding with the axis of the folds almost vertical. The relationship of this piercement structure to the enclosing sediments is also complex. These strata may be arched gently or steeply, ruptured and pierced by the salt, complexly faulted, or any combination of these.

4) Resource Use: Salt domes form structural traps for large accumulations of oil and gas. Exploration has been concentrated, however, to the margins of the dome and there has been little actual penetration of the salt structure itself. Along with oil and gas, domes have been mined for salt, gypsum and sulfur. Some domes are presently being used to store liquid hydrocarbon products in both mined and solutioned cavities.

APPENDIX C

ROCK SALT PROPERTIES AND BEHAVIOR WITH REGARD TO HLW REPOSITORY

TABLE OF CONTENTS

Task limitation

Properties, behavior and specific phenomena of rock salt, collected in this brief report, are limited to the area of possible influence on the definition of HLW site selection criteria.

1. Density of natural salts at normal temperature

According to Lotze (1957) and Robertson (1962), the average values of density are as follows:

Material	Density (g/cm^3)
Carnalite	1.60
Sylvite	1.98
Kainite	2.10
Halite	2.16
Gypsum	2.31
Anhydrite	2.90

(In engineering calculations in Germany, the average density of rock salt is approximately 2.20 g/cm^3).

2. Salt density versus temperature

Gussow (1968) has compiled data of salt density versus the temperature, as shown in Figure 2-1.

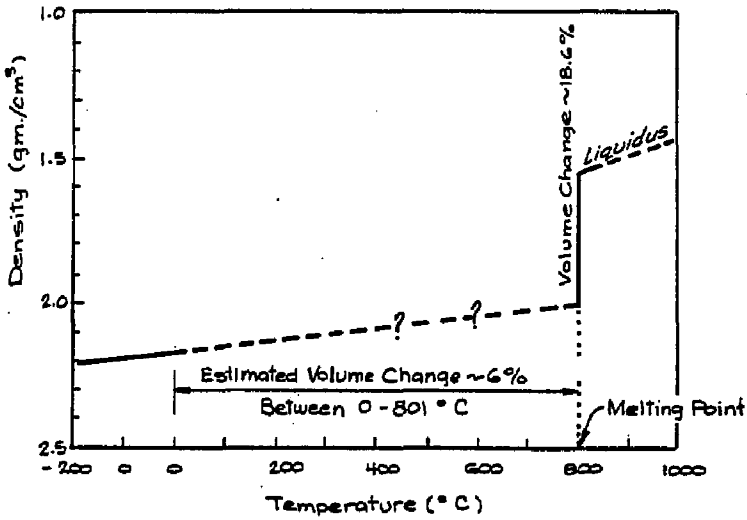


Figure 2-1: Salt density as a function of temperature

3. Properties and behavior of rock salt as a function of acting factors

The theoretical basis for understanding the properties and behavior of rock salt is in principle characterized by the physical processes of the deformation of ionic crystals, caused by different factors.

Our comments will be limited mainly to the influence of major external factors, especially heat and/or pressure and time.

3.1 Phase diagram

It is known that rock salt deposits contain brine (Gussow, 1968) and the phase diagram at 1000 bars for the system H_2O in NaCl is shown in Figure 3-1-1, modified by Gussow (1968) (redrawn after Wyllie and Tuttle).

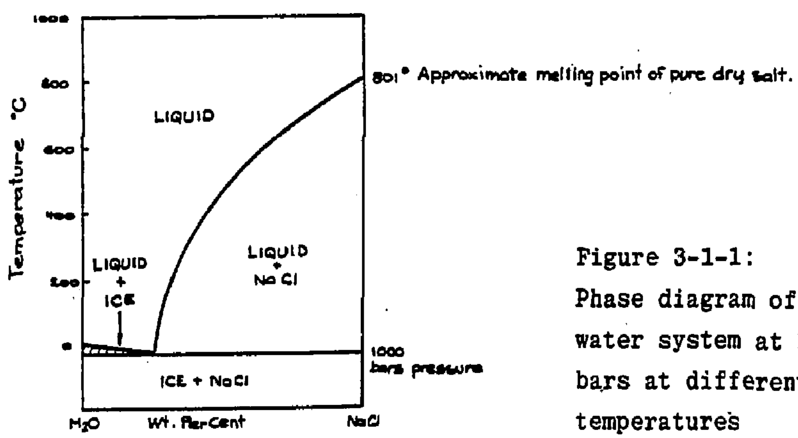


Figure 3-1-1: Phase diagram of salt-water system at 1000 bars at different temperatures

(Remark: 1 bar = 10^6 dynes/cm^2 = 1.02 kg/cm^2
1 kg/cm^2 = 14.22 psi, 1 kilobar = 14,500 psi)

According to Wyllie and Tuttle's (1960) estimation, the mixture of 90% of NaCl and 10% of water at 100°C, 14% is liquid. At 400°C, 20% will be liquid. At 650°C, 50% would be liquid.

3.2 Compressibility

Bridgman (1940) and Stephens (1964) have defined the relationship between hydrostatic pressure at 25°C and the compressibility of an NaCl crystal (see Figure 3-2-1).

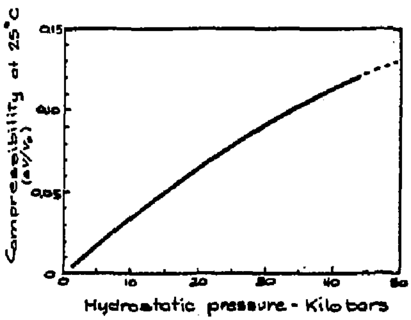


Figure 3-2-1: Diagram shows clearly that up to a hydrostatic pressure of about 46 kb, no phase change occurs in the salt. Therefore, it can be said the behavior of rock salt will be relatively more dependent on heat (and time) than on loading.

3.3 Creep behavior

With certain simplification it can be said that the creep mechanism is caused by movement and generation of dislocations in a crystal.

According to Andrade (1914), we can distinguish three stages of the creep flow process:

- Transient stage, in which the creep rate decreases continuously with time;
- Steady-stage in which the creep rate is constant;
- Tertiary stage in which the creep rate increases and the process results in rupture. (Knowledge is very limited concerning the mechanism of tertiary creep in rock salt.)

It is well known that the temperature is a very important factor in salt behavior. This is evident from Figure 3-3-1 after Handin and Hager (1958).

Figure 3-3-1 shows stress-strain curves for halite single crystals at 1000 and 2000 bars confining pressure at different temperatures ranging from 24°C to 300°C.

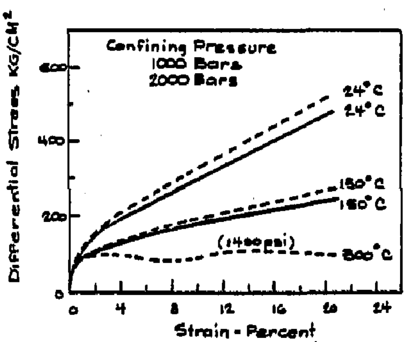


Figure 3-3-1: Stress-strain on a single dry halite crystal under confining pressures of 1000 and 2000 bars.

From Figure 3-3-1 it is evident that the main effect is caused by temperature.

Creep effects are known from mining operations in rock salt mines, usually as a slow flow over a long time period.

For example, in Hallstatt mines in Germany (Lees, 1931), every 18 to 20 months the drifts and tunnels were repaired because of the creep of the surrounding rock salt mass. Original vertical stress in intact rock was about 160 kg/cm^2. Naturally the creep effects are increased with greater depth of the opening below the surface, where also the temperature of rock salt mass is higher.

Serata and Gloyna (1959) published the results of in-situ measurements, using convergence measurements between the roof and floor of a drift, located 700 feet below the surface at the Grand Saline Mine. See Figure 3-3-2.

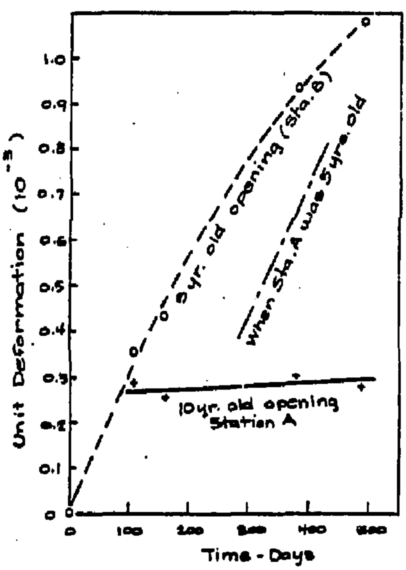


Figure 3-3-2: Creep rate measured by convergence in a drift in Grand Saline mine 700 feet below the surface.

Using the floor and roof convergence in a 10-year old drift (Odé 1968) as a steady-state creep, the creep rate is about 0.9 m.m./year.

Assuming, for simplification, a circular shape of the opening, the equivalent viscosity of rock salt for this case (connected with Figure 3-3-2) can be calculated by the equation

$$\eta = \frac{-2pR}{3\frac{du}{dt}},$$

where η = viscosity, p = external pressure, R = radius of a drift with circular section, then according to Odé is $R = 3.3 \times 10^2$ cm, $p = 5 \times 10^7$ dynes/cm^2, $\frac{du}{dt} = \frac{0.09}{3155} 10^{-7}$ cm/sec and then $\eta = 4 \times 10^{18}$ poises approx.

Some data on viscosity (compiled by Odé) are shown in the following table 3-3-I.

TAB. 3-3-I

Type of Rock	*Viscosity (poises)*	*Source of Data*	*Remarks*
Rock salt	10^{18}	Weinberg (1927)	Torsion plastometer.
Sylvite	2.7×10^{11}–1.1×10^{12}	Höier (1958)	Creep at atmospheric pressure. Load ±200–360 bars. Load ±200–360 bars.
Rock salt of Grand Saline, Texas	4×10^{18}	This report	Very inexact method of creep closure of holes.
Rock salt of Neustassfurt, Germany	2×10^{16}–2.3×10^{17}	This report	Same inexact method. Data from Busch (1907); low value at 500 m, high at 300 m depth.
Halite, single crystal	2.6×10^{17}	Griggs (1939)	Conventional creep test at atmospheric pressure, 60 bars, at 18°C.
Halite, single crystal	2×10^{18}	Handin and Hager (1958)	Triaxial test, 2,000 bars confining pressure, 1 per cent strain per minute, 10^8 dynes/cm^2 load.
Halite, single crystal	8×10^{13}–4×10^{14}	Kendall (1958 thesis)	Confining pressure 140 bars. At 70 bars load, high viscosity; at 250 bars, low viscosity.
Powdered NaCl	0.2×10^{15}–6.1×10^{15}	LeComte (1960 thesis)	Various confining pressures and load.
Salt from Grand Saline, Texas	1.6×10^{15}–3.5×10^{16}	Serata and Gloyna (1959)	Creep test at 50, 70, and 140 bars uniaxial load.
Rock salt	10^{15}-10^{17}	Meinhold (1956)	Derived from equation (3) (factor 3 omitted). No other data given.
Dry gypsum	10^{16}	Griggs (1940)	Creep test at atmospheric pressure. Load 400 bars.
Water-saturated gypsum	0.4×10^{14}–14.4×10^{14}	Griggs (1940)	Creep test at atmospheric pressure. Load ranging from 125 to 300 bars.
Water-saturated gypsum	6.4×10^{13}–1.4×10^{16}	Griggs (1940)	Creep test at 1,000 bars confining pressure.

It has been defined by Reynolds and Gloyna (1961) that:

a) The creep rate increases with the depth of the opening below the surface and with the size of the opening.

b) The rate of creep increases at higher temperature - fine grained materials at low temperature are more creep-resistant than coarse-grained materials. This effect is reversed at higher temperatures.

Dellwig and Snyder (1960) executed measurements of convergence at the depth of 650 ft. in the Hutchinson mine. In one drift, about 30 years old, the horizontal convergence rates were 9.9×10^{-4} in/year. In another drift, only nine months old, the averages were 16.5×10^{-4} and 4.2×10^{-4} in/year. The actual vertical deformations were more or less the same.

Some Examples of the Creep Flow in Mines

Höfer, Berthold and Menzel (Germany) have executed convergence measurements showing the change of the diameter in Ø3m horizontal circular drifts at various orientations and for different depths.

The results are in Figures 3-3-3, 3-3-4, 3-3-5 and 3-3-6.

Measurement in the rock salt executed by Barron, Toews (1963) in the Esterbarg Mine, Saskatchewan in the shaft (18 ft. diameter) at a depth of 3,079 feet is shown in Figures 3-3-7 and 3-3-8.

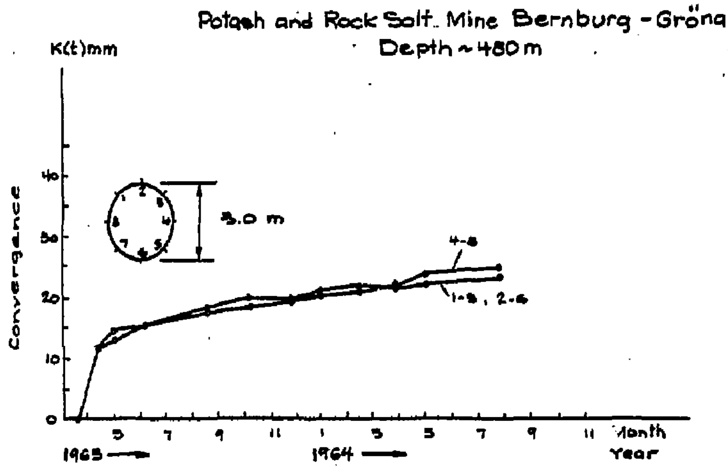


FIGURE 3.3-3 Change in drift diameter with time, mine Bernburg - Gröna, Germany.

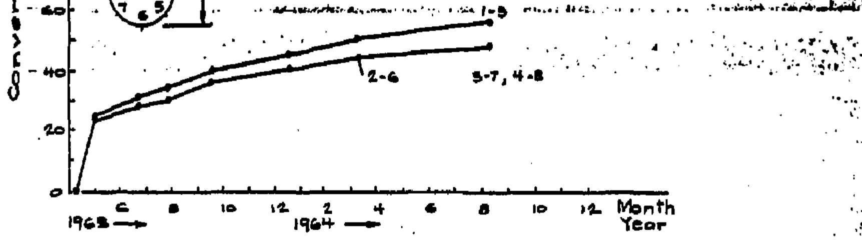


FIGURE 3.3-4 Change in drift diameter with time, mine "Gluckauf" Sondershausen, Germany.

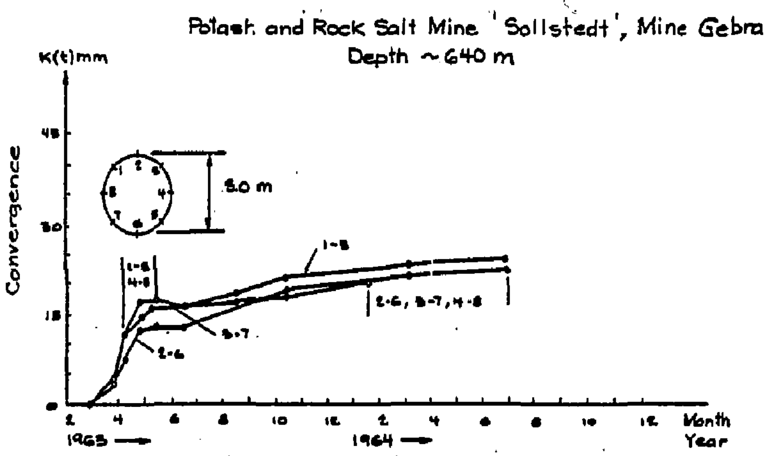


FIGURE 3.3-5 Change in drift diameter with time, mine Sollstedt, Germany.

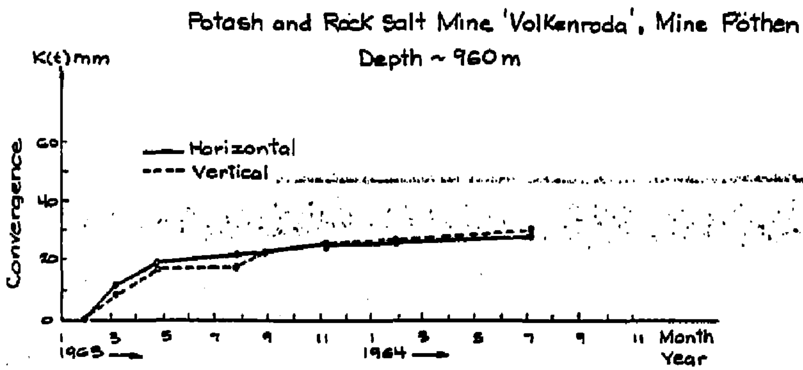
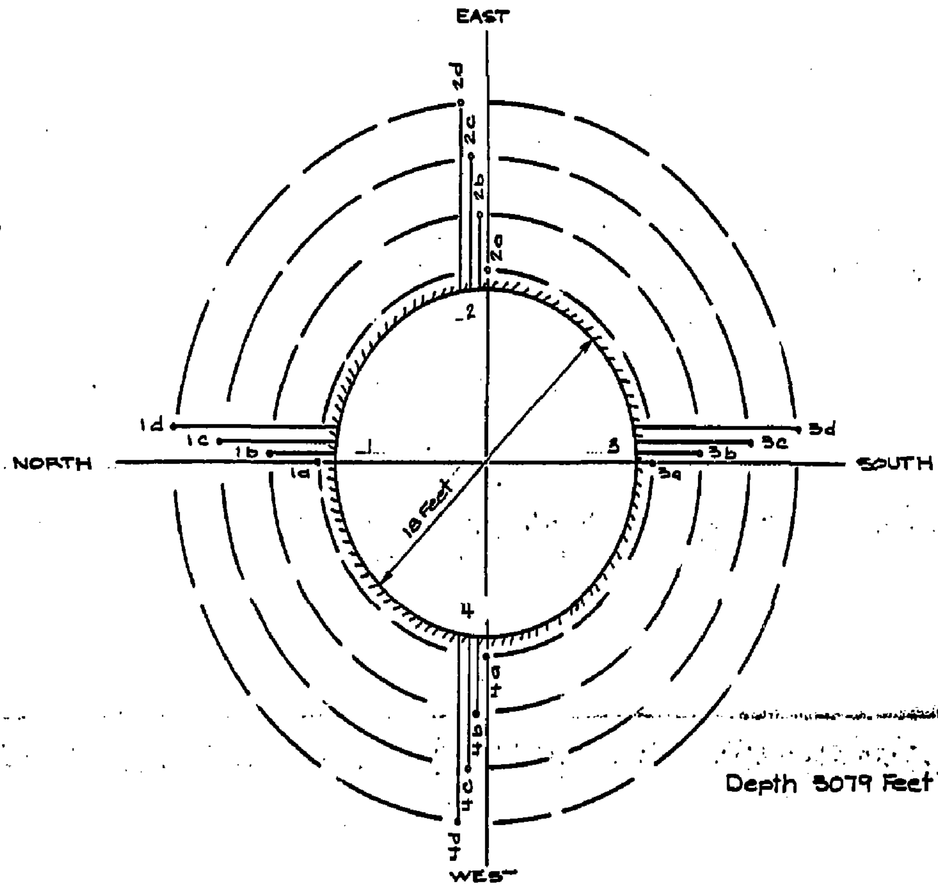


FIGURE 3.3-6 Change in drift diameter with time, mine Volkenroda, Germany.

Remark: Figures 3.3-3, 3.3-4, 3.3-5 & 3.3-6
After Hoefer, Berthold and Menzel.



NOMENCLATURE:
2 - Station number identification
4c - Station & depth identification

a - anchors at 6" deep
b - anchors at 4' deep
c - anchors at 7' deep
d - anchors at 10' deep

FIGURE 3.3-7 Shaft Geometry and Instrument Locations. (After Barron & Toews)

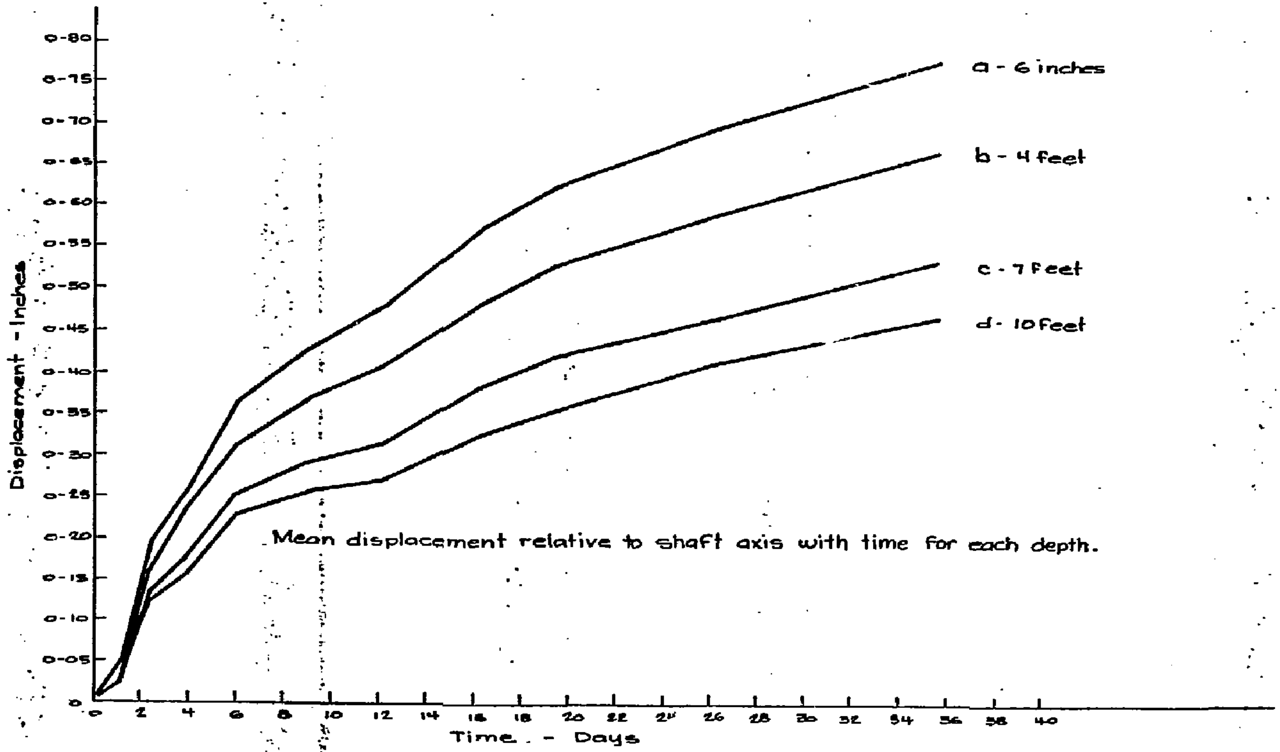


FIGURE 3.3-8 Displacement Data (After Barron and Toews)

3.4 Plastic Behavior of Rock Salt

Flow of rock salt in creep or in plasticity is mainly influenced by three principal factors (Kvapil 1961, 1963):

- loading
- time
- heat (and other radiation energies)

A shortage in one factor can be replaced by a surplus in one or both remaining factors, to obtain the same result - for example, the same quality of the flow.

An explicit, physical analysis of salt for understanding the plastic behavior has been worked out by Joffé (1928), using the x-ray measurements method for definition of elastic limits. The result is shown in Figure 3-4-1.

The average strength of rock salt is approximately 44 kg/cm^2 (see line D in Figure 4-3-1). For a single crystal Joffé has proved that the strength is constant in the temperature range - 196°C (liquid air) up to +650°C, as shown in Figure 3-4-1. The curves of elastic limit A, B and C in the same figure represent the crystallographic directions (100), (110) and (111) of applied stress.

As is evident from the Figure 3-4-1, the elastic limit depends upon temperature and upon crystallographic direction.

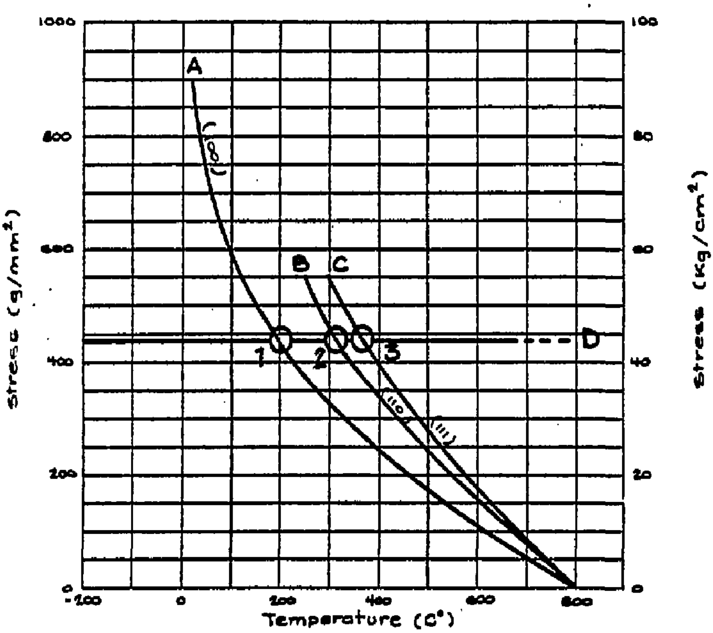


Fig. 3-4-1: Joffé's (1928) diagram, modified by Gussow (1968)

Salt plasticity depends on crystallographic direction. Intersections 1, 2 and 3 of elastic limit curves A, B and C with strength D represent the beginning of plasticity. Salt becomes plastic in crystallographic direction (100) at a temperature of 200°C (intersection 1), in direction (110) at a temperature of 300°C (intersection 2) and in direction (111) at 350°C. By 350°C salt is completely plastic.

In other words, salt starts to be plastic at temperatures of 200°C and at 350°C is completely plastic.

At a temperature of 300°C salt flows plastically in direction (100) under a stress differential of 33 kg/cm^2 and in direction (110) under a stress differential of 44 kg/cm^2.

Under confining pressure of about 2000 bars, the salt is ideally plastic at 300°C. See Fig. 3-3-1 after Handin and Hager (1958).

Brown and Jessen (1959) executed tests on rock salt at temperatures ranging from 90 to 400°F and under pressures between 1000 to 16,000 psi. Flow of salt and creep rate changes abruptly with temperature increases and above 300°F the temperature is a very important factor.

By temperatures above 200°C (400°F) the rock salt flows without rupture, is plastic, and (according to Gussow - 1968) "can be extruded readily, very much like toothpaste or soft paraffin wax".

At higher pressures temperatures above 20°C up to approximately 155°C have a big influence on the creep rate of the salt.

3.5 Comments, conclusions and suggestions

1. At temperatures above 350°C the salt is completely plastic. The salt can be ideally plastic also at temperature of 300°C under higher confining pressures.

Excavation of underground openings will generate a stress concentration in the surrounding rock salt mass, which has a similar effect to confining pressure.

In certain zones around the high level waste canister the temperature will probably be much above 350°C; it means the rock salt will be ideally plastic. If the density of the canister will be higher than the density of plastic salt, the canister will sink downwards. If its density will be lower than rock salt and the tunnel is open (not filled), the canister will move upwards (see Figure 2-1). The speed of movement downwards or upward will depend from the temperatures (above 350°C) and from the viscosity of salt in the plastic states.

It seems to be desirable to analyze the effect of buoyancy, in ideally plastic rock salt at temperatures above 350°C and 300°C. (How big is the zone around the canister with temperatures higher than 350° (or 300°)C?)

2. Because even at temperatures slightly above 200°C and confining pressure the rock salt flows without rupture, it is very important to define the possible size, shape and limits of the zone, in which the temperature will be 200°C (see intersection 1 in Figure 3-4-1) and more. This temperature, together with the stress concentration around the opening, will represent a very important factor for the behavior and stability of the tunnels, because the salt will plastically flow in this zone.

3. The next clearly important zone is the temperature between about 150 to 200°C, because already temperatures above 150°C have big influence on the creep flow.

Conclusion from points 1, 2 and 3:
In principle we can, for rock salt, distinguish the following zones, influenced mainly by temperatures.

Zone 1 - ideally plastic flow at temperatures above 350°C (see intersection 3, Fig. 3-4-1).
Zone 2 - plastic flow at temperatures above 200°C up to 350°C (see intersection 1 in Fig. 3-4-1).
Zone 3 - creep flow at temperatures above 150°C up to 200°C.

Zone 4 - <u>normal creep</u> at temperatures below 150^{o}C.

Naturally, this classification is not complete because the same qualities of plastic flow or creep can be reached also by lower temperatures but by higher confined pressures and longer time.

Nevertheless, this classification can be used as a "first approach" input for analyses of the behavior of rock salt masses around the tunnels.

It would be favorable to analyze more the simultaneous influence of temperature and confining pressure and depth on the plasticity and creep of rock salt around the tunnels and to define the acceptable limits for construction of a safe repository.

(The sources of the confining pressure are in our case generated by natural stresses, caused by the weight of overburden and by stresses induced by execution of the openings and also by stresses caused by the heat expansion of salt. See Figure 2-1 and the paper of Bradshaw, Lomevick, McClain, Epson concerning the influence of thermal expansion of rock salt.)

The analyses should determine:

a) What is the optimum shape of the transversal section of tunnels;
b) What is the maximum depth still acceptable for location of a safe repository in rock salt;
c) How large a creep deformation of tunnels can be expected
   - at different depths;
   - at various times.

The behavior of rock salt is different in different deposits; therefore it is not possible to define exact and generally valid classifications.

Based on the experience of mining operations in rock salt (and potash) deposits, it can be said that down to about 500m below the surface the damage of openings is usually characterized by fracturing of the rock salt mass, partially influenced by creep.

At depths of about 1000m and deeper, the difficulties in drifts and other openings are often mainly caused by creep flow of the rock masses around the openings and in pillars.

Naturally, higher heat, generated by the canisters, will result in the increasing of creep or plastic flow, supported also by greater natural and induced stresses, dependent upon the depth, geometry and dimensions of the underground structure of openings and pillars.

(Extreme: Below about 7km salt flows indefinitely as an ideally plastic material.)

4. Some characteristic failure phenomena in salt mines

Most deposits of bedded rock salt are characterized by a layered structure with layers of clay of variable thickness between the salt layers.

The quality on contact surfaces between the different salt layers can be different, and they often represent planes of easy separation. The layers of clay (or other types) can be hard, with the same or higher strength as rock salt, or can be plastic when water is present.

Under the condition that rock salt layers can separate relatively easily, the roof is characterized by the occurrence of Weber's cavities, as shown in Figure 4-1, in the roof of the tunnel. The progressive bending of layers results in the failure of the roof and creation of a new, often stable, roof in the form of a natural arch.

At greater depths below the surface the development of Weber's cavities can also occur in the floor of the opening, as schematically shown in Figure 4-2.

The mechanism of the bending of layers in the roof and/or floor of a tunnel and creation of Weber's cavities can be intensified by plastic layers of clay between the rock salt layers.

The plastic layer of clay is a very important factor which controls the behavior of openings and pillars. The influence of a plastic layer can be most simply explained on a pillar which has on the upper (contact with the roof) and lower (contact with the floor) loading surfaces a plastic layer.

The plastic layer has influence (Kvapil 1957) on:

- deformation of the pillar
- accumulation of stress energy in the pillar
- fracturing pattern in the pillar
- bearing capacity of the pillar
- failure type of the pillar

Comparing the different behavior, when: (A) the pillar has total friction on the loading surfaces; and (B) the pillar has plastic layers on loading surfaces is shown in Figure 4-3 and 4-4 (after KVAPIL (1958)).

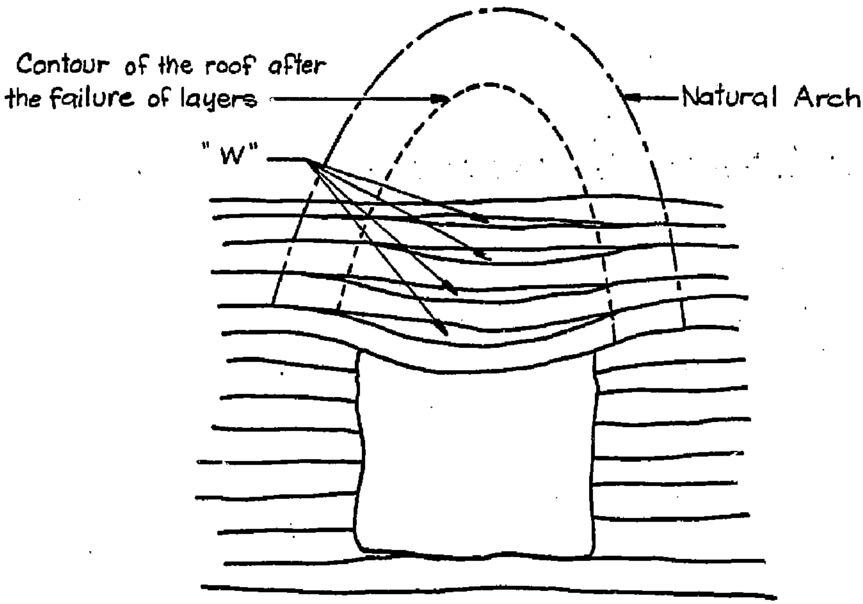


FIGURE 4-1 Weber's Cavities "W" in the Roof of an Opening in a Rock Salt Mine

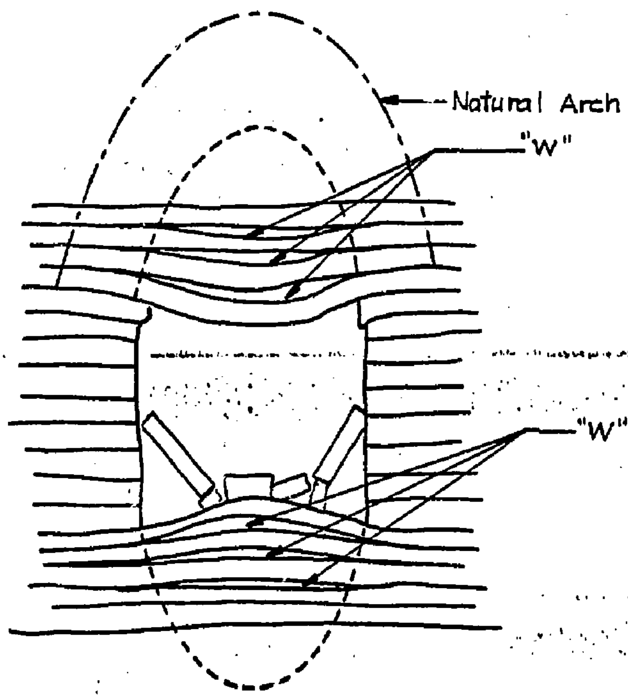


FIGURE 4-2 Weber's Cavities "W" in the Roof and Floor.

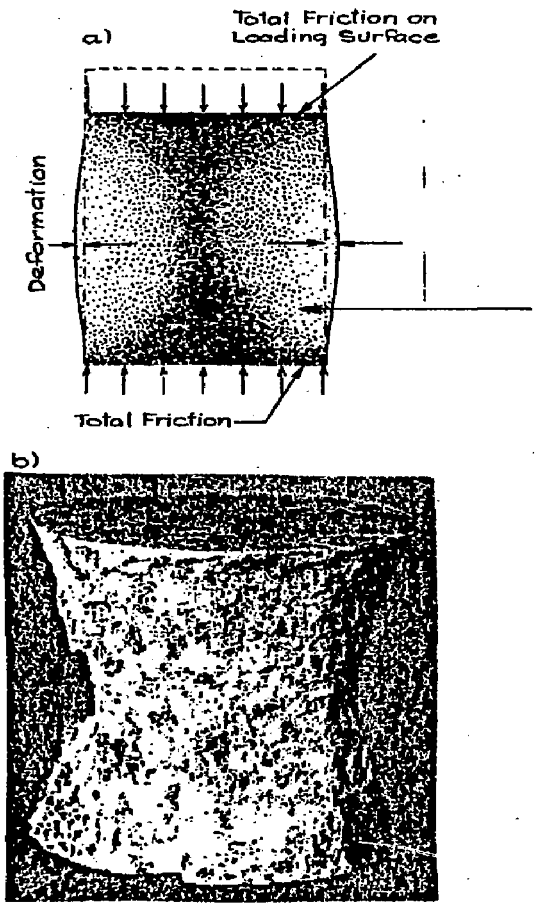
Figure 4-3 is the case with total friction on loading surfaces. Figure 4-3A represents the principle of deformation and the pattern of accumulation of the potential stress energy. Maximum lateral (horizontal) deformation is at a point at half of the height of the pillar. Density of points in Figure 4-3a is proportional to the quantity of accumulated stress energy. High stress energy accumulation in two cones (Fig. 4-3a) is caused by full friction on loading surfaces. This pattern of stress energy accumulation results in a characteristic shape of fracturing of the body of the pillar (or specimen) as evident from Figure 4-3b.

Figure 4-4 represents in principle the other case, when plastic layers are on upper and lower loading surface of the pillar (or specimen).

Under loading, the plastic material flows out from the joint and generates tensile stresses on both loading surfaces of the pillar. The lateral deformations (horizontal) are the same over all the height of pillar and therefore the pattern of potential stress accumulation is parallel with the walls of pillar as shown in Figure 4-4a.

The fracturing pattern follows the levels of the same quantity of accumulated stress energy. Because the stress energy accumulation forms a vertical pattern of the same levels of energy, the cracks in the pillar are vertical (perpendicular to the loading surfaces). Characteristic failure of the pillar (or specimen) with plastic layers on both surfaces is shown in Figure 4-4b.

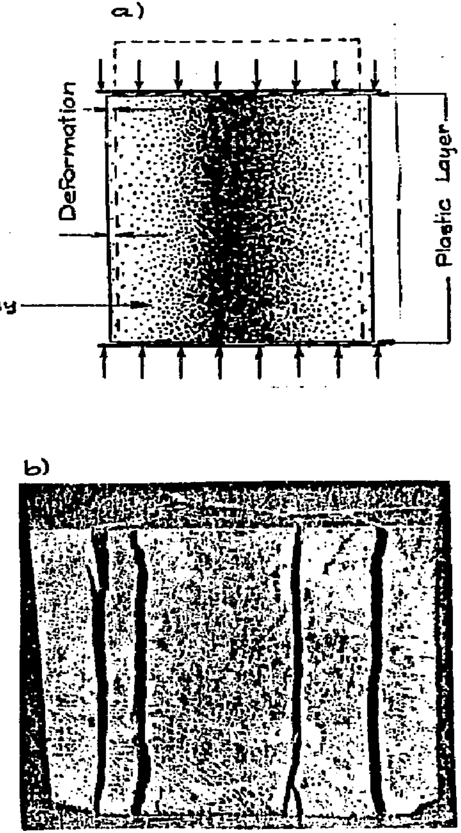
Under the same geometry (shape and dimension) and the same rock mass, the pillar with plastic layers on both surfaces



Characteristic Failure

FIGURE 4-3 PRINCIPLE OF A PILLAR WITH TOTAL FRICTION ON LOADING SURFACES

(KVAPIL)



Characteristic Failure

FIGURE 4-4 PRINCIPLE OF A PILLAR WITH PLASTIC LAYERS ON LOADING SURFACES

(KVAPIL)

will have the bearing capacity down to 50% less than the pillar with total friction on loading surfaces.

The principle of the influence of the plastic layer on the behavior of the rock mass can be applied for the understanding of many phenomena observed in underground mines in pillars, walls, roofs and floors of openings. Naturally, the knowledge of this principle should be utilized in engineering design with the goal to minimize the damaging effects of plastic layers on the underground openings. This means that special care should be given to the determination of the most favorable location of an opening with regard to the bedded structure of salt layers and especially with regard to the relative location of plastic joints.

It has been observed many times in German salt mines that an originally dry clay layer has been changed to a plastic structure merely by absorption of the humidity from ventilation air. Its plasticity has then induced the phenomena described above.

Considering the importance of the phenomena it seems to be very desirable to analyze in detail all physical and mechanical properties of the layers which are or can be plastic and to develop a system of testing and classification of such layers. This can be very significant as the input for formulation of site selection criteria, and also, as important data for the detailed design of the repository.

Generally rock salt is considered as a plastic type of material. In fact, under certain conditions and circumstances, the salt can be highly brittle, so that intensive rockbursts can occur in the mines. See KVAPIL (1961) and KVAPIL AND PFORR (1961). One of the biggest rockbursts was in the Merkers salt mine in Germany, July 8, 1958.

DISPLACEMENTS AND THE FRACTURE CONE AROUND THE SHAFTS AND TUNNELS OF THE HLW REPOSITORY

Shafts:

Assumptions: Layers of rock salt deposit are more or less horizontal and therefore the stress around the circular shaft is characterized by a lateral pressure $P_L = f(\phi)$.

The shaft has a concrete lining, which has the function of a circular support.

The deformation ϑ (see Figure 4-5) in the direction toward the center S of the shaft has the general form:

$$\vartheta = \frac{\sigma_t}{E} \cdot a,$$

where σ_t is the tangential stress and E is the modulus of elasticity of concrete.

For calculation of tangential (and radial) stress, the classic equations of FENNER or KIERSCH can be used. For higher safety of the shaft construction, it is usual to assume that the rock salt is partially plastic. The deformation ϑ of the shaft lining can be controlled by the construction of this lining (quality and thickness of the material).

The shafts for HLW repository should avoid or minimize the danger of fracturing around the shaft, which could result in the creation of vertical connections for the transport of liquids.

Under the condition that instead of drilling and blasting, the shaft sinking will be executed by rock cutting and a heavier lining will be used, then it is possible to assume, that the deformation ϑ can be in the order of some 3-5^{o}/oo

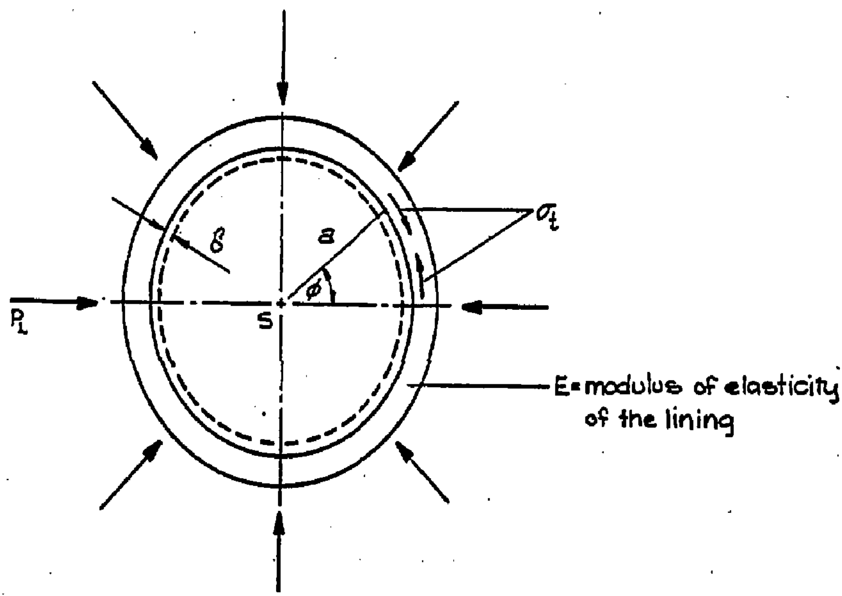


FIGURE 4-5

of the shaft radius. Such a small deformation will exclude in practice the creation of any fracture zone around the shaft for the time period at least 30-35 years, which is sufficient for the time of operation of the repository. After this time the shaft will be filled. The filling will have the function of sealing and at the same time of a highly efficient support for the old concrete wall of the shaft. Therefore the situation can be considered stable.

HORIZONTAL TUNNELS

We have two phases: operational phase 30-35 years, and the second phase, which means the situation after the first 35 years, when the openings are filled and sealed.

Operational Phase

Repository must be located not more than 500m below surface. The dimensions of the tunnels, about 5-6m wide and about 5m high, can be stable for the period of 30-35 years under the condition, that the tunnels are located in a favorable geo-structure of the bedded salt deposit. From other mining operations, it is known that curved corners and arched roofs are very efficient factors for long-term stability. The excavation must be executed by cutting (no drilling and blasting). If the geo-structure allows the utilization of an arched roof, then the arch height, h_A, should be about 40% of the width, W_T, of the tunnel. More exact determination of the shape of the roof can be worked out by finite element method (or other methods), with respect to the real conditions and situations in-situ.

In some cases the roof stability can be improved by adequate reinforcement.

Post Operational Phase

When the operational function is finished, the tunnels will be filled.

The behavior of the surrounding rock mass will depend on the behavior of the fill. Ideal conditions are characterized by the situation, that the fill has the same resistance against compression as the surrounding in-situ rock mass.

The more compressible the fill, the greater will be the zone of fracturing of the rock masses mainly above the roof. Any more precise solution needs extensive analyses.

As a first approach (based on mining experience in other salt mines), we can assume the following:

The rock mass above the tunnel will fracture. The fracturing results in loosening. The weight and loosening of fractured material will compress the fill. This process will be finished when equilibrium is reached between the fracturing and loosening of rock mass and compression of the fill.

The rock mass above the tunnel will create a natural arch, which represents a new element of stability. Rock will be fractured only below this arch.

The approximate span, S_A, of this arch (see Figure 4-6) in salt is about 1.6 x W_T, when the height and width of the tunnel are more or less the same. (KVAPIL: New aspects in the theory of rock mass pressure..., SNTL, PRAGUE, 1956.)

The height of the arch, H_A, is then about:

$$H_A = 0.8 \times S_A \text{ . approximately}$$

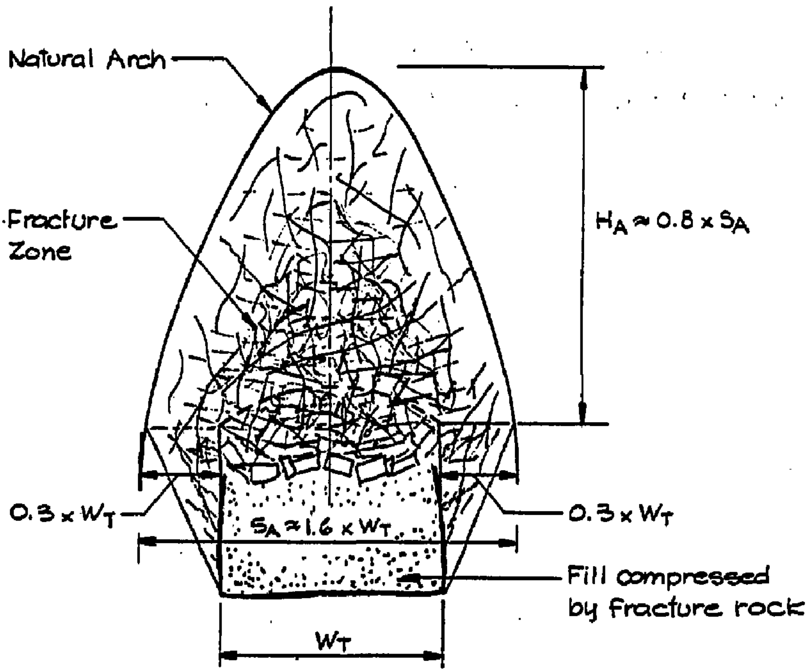

Natural Arch
Fracture Zone
$H_A \approx 0.8 \times S_A$
$0.3 \times W_T$
$S_A \approx 1.6 \times W_T$
$0.3 \times W_T$
Fill compressed by fracture rock
W_T

FIGURE 4-6

With additional compression of the fill and decreasing of the loosening of fractured rock, the span S_A and particularly the height H_A of the natural arch will increase.

Such determination of dimensions of the natural arch (and fracturing and loosening zone) above the tunnel, filled with compressible coarse material is approximate for normal conditions in a salt mine and can be used as an estimation in the complex of mine planning, especially in the section of evaluation of zones which have been mined out and filled. Naturally this determination of fracturing zone is not complete, because only the rock masses above the tunnel are considered to be active. In reality the processes are occurring also in the floor and wall zones of the tunnel, but when the mining has been finished and the opening filled, the main interest in the mining operation is concentrated on the processes in the roof and the behavior of lower zones is usually of minor importance.

In the second phase works of the HLW repository, it will be necessary to analyze in more detail the complete behavior of rock mass zones around the tunnel, especially with regard to the effects of heat generated by HLW canisters. In principle, these effects will have a multilateral influence on stress distribution, fracturing, creep and plasticity of rock masses around the tunnel, both without filling (first 30-35years) and with filling.

The best filling material can be selected only when function (or functions) are defined in the structure of acting effects in rock masses around the tunnels.

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APPENDIX D
DISCUSSION OF MODEL COEFFICIENTS

D-1 Fracture Porosity and Permeability Rationale

This information is an explanation of the permeability and porosity values for fracture flow. Data relating to these parameters, particularly fracture porosity, are few. Fracture porosity must be generally measured indirectly since representatively fractured rock masses are much too large for laboratory anlaysis. Permeability in fractured rock is generally not measured unless the fractures are extensive enough to yield substantial water or oil. The values we have given for these parameters are, however, based on actual hydrologic bore hole tests in conjunction with theoretical considerations.

Fracture permeabilities have been compiled from numerous sources; however, very few of these permeabilities are thought to be representative of the type of rock and fractures assumed for layers 3, 4, and 5. Information on fracture spacing and width seldom accompanies measured values of permeability. We feel that the values of fracture permeability chosen for these layers are representative of the information currently available but they may be modified after further study.

Fracture porosity is also a difficult parameter to measure. We have used a method for estimating fracture porosity from measured values of permeability and fracture spacing developed by Snow (1967). Among the basic assumptions made by the method are:

1. Isotropic fracture permeability.
2. Three mutually orthoganal and similar sets of fractures (cubic fracturing).
3. Numbers of open fractures intersected by equal lengths of random drill holes obey a Poisson distribution.

Computer study by Snow indicated that for a rock of given permeability, the fracture porosity is most dependent upon the fracture spacing and average aperture width, and is less dependent upon variations in the aperture widths and fracture orientations. The computer model indicated errors of less than 20% in computing average porosity from a series of permeability measurements, regardless of the aperture distribution. Snow's study incorporated data from 5,532 bore hole pressure tests on 35 dam sites. Granite, gneiss, and metavolcanics were well represented with slate, phyllite, schist, cemented sandstone, and shale having fair representation. He concluded that neither aperture width nor fracture spacing are notably different from one rock type to another, nor are the porosities and permeabilities which depend upon the former parameters.

Snow found that fracture porosity decreases approximately logarithmically with depth. The upper porosity limit is .05% near the surface, decreasing to .0005% at 400 ft. In only a few cases did fracture porosity decrease less rapidly than an order of magnitude per 200 ft. The minimum spacing of open fractures increased from 4 ft. to 14 ft. in this interval. Only fractures in competent rock were considered, thus excluding weathered zones, fault breccia, overburden, etc. Fracture openings range from 400 to 75 microns in the upper 30 feet, but decrease to from 150 to 50 microns at depths of 50 to 200 feet.

Only a few additional references on fracture porosity have been found after review of the current literature available to us. Webster, et al., (1970) found two types of fractures common in crystalline rock (predominantly chlorite-hornblende schist and gneiss) at the Savannah River plant near Aiken, South Carolina. The first type pervades the entire rock mass but transmits very little water. The second type is restricted to definite zones and transmits substantial quantities of water. Permeability of the entire rock mass (including both types of fractures) is 5 x 10^{-5}m/sec. as determined from a two-well tracer test. Fracture porosity is calculated to be .08%. The fracture porosity of the rock containing only the first type of fractures is thought to be .01% or less.

Several calculations of fracture porosity and fracture width are given below using Snow's analysis. Permeabilities in the range given for layers 3, 4, and 5 are assumed together with a wide range of probable fracture spacings.

Obviously, a significant assumption in this analysis is the fracture spacing. Our preferred values reflect fracture spacing of about 100 to 200 cm, which we feel is reasonable. A study conducted by Ward (1968) of joint patterns in gently dipping sedimentary rocks in south central Kansas agrees with these assumptions. The formations studied were composed primarily of limestone, cherty limestone, and shale beds. The length of the joints varied from a few feet to 100 feet or more with a spacing of one to as much as 25 feet apart. A common distance was 5 to 10 feet (150cm to 300cm). The majority of joint surfaces had dips greater than 85°. Dips as small as 46° were observed but were not common. Two prominent joint sets (75% of all joints) were present, one striking northeast and one striking northwest. Various minor joint sets (25%) of all joints were found clustered around the major sets. Ward interpreted the two major joint sets as resulting from shear, whereas the minor joints are believed to be caused by tension.

COMPUTED VALUES OF POROSITY AND FRACTURE WIDTH FOR GIVEN PERMEABILITIES AND FRACTURE SPACINGS

Intrinsic Permeability (cm^2)	Permeability (cm/sec)	Fracture Spacing (cm)	Fracture Porosity	Aperture Width (cm)
10^{-14}	10^{-9}	10	2.5×10^{-5}	8.4×10^{-5}
10^{-14}	10^{-9}	50	8.7×10^{-6}	1.4×10^{-4}
10^{-14}	10^{-9}	100	5.4×10^{-6}	1.8×10^{-4}
10^{-14}	10^{-9}	500	1.9×10^{-6}	3.1×10^{-4}
10^{-12}	10^{-7}	10	1.2×10^{-4}	3.9×10^{-4}
10^{-12}	10^{-7}	50	4.0×10^{-5}	6.7×10^{-4}
10^{-12}	10^{-7}	100	2.5×10^{-5}	8.4×10^{-4}
10^{-12}	10^{-7}	500	8.7×10^{-6}	1.4×10^{-3}
10^{-10}	10^{-5}	10	5.5×10^{-4}	1.8×10^{-3}
10^{-10}	10^{-5}	50	1.9×10^{-4}	3.1×10^{-3}
10^{-10}	10^{-5}	100	1.2×10^{-4}	3.9×10^{-3}
10^{-10}	10^{-5}	500	4.0×10^{-5}	6.7×10^{-3}
10^{-8}	10^{-3}	10	2.5×10^{-3}	8.4×10^{-3}
10^{-8}	10^{-3}	50	8.7×10^{-4}	1.4×10^{-2}
10^{-8}	10^{-3}	100	5.5×10^{-4}	1.8×10^{-2}
10^{-8}	10^{-3}	500	1.9×10^{-4}	3.1×10^{-2}

D-2 Fracture Zone Rationale

Introduction

The construction of an underground repository will inevitably result in a degree of disturbance to the rock mass, and this will influence the inherent ability of the repository to prevent the escape of radionuclides to the environment via the ground water system.

The nature and extent of rock mass disturbance will be a function of:

(i) damage inflicted as a result of the excavation process
(ii) magnitude of the in situ stress field
(iii) strength and deformability characteristics of the rock
(iv) geometrical layout of the repository
(v) damage due to thermally induced loadings
(vi) earthquake induced disturbance
(vii) performance of operational and long term support or reinforcement (backfill).

The results have been presented as a preferred value and a range of values, since the results are applied in a generic sense. There are many circumstances in which rock mechanic considerations would prevent the development of a suitable repository, but these design criteria have not been indicated here. The correct interpretation to place on the data provided, therefore, is that the specified range of zones of disturbance will encompass all possible results, given that the repository can be satisfactorily constructed.

Two basic rock formation types have been considered: shale and bedded rock salt.

Technology

Simple hand calculation technology based on elasticity theory and general rock mechanics experience has been employed. The applicability of the elastic assumption in the range past failure has been allowed for by taking a strength/stress ratio of 3 as indicating the extent of the zone of disturbance. This allows for stress re-distribution processes which will occur when local failure develops.

The incorporation of the effects of time-dependent deformation (particularly for rock salt of higher temperatures) has been handled in an entirely empirical manner for the purpose of this study. Of concern in relation to the nature of the disturbance zone is the type of failure which develops - brittle fracture with crack formation or ductile flow which maintains the integrity of the material.

Geometrical Layout

The geometrical layout considered consists of a vertical shaft and horizontal tunnels, located some 500 meters below ground level (Parsons, et al., 1976). For analysis purposes, the opening here has been taken to be circular in shape, and it has also been implicitly assumed that the horizontal repository chambers are sufficiently separated that the concentration fields do not interact to any significant extent.

Excavation Disturbance

The depth of excavation disturbance has been taken to range from effectively 0 meters to a depth of 1 meter. This covers a range of excavation methods from tunnel boring mechanics to drill and blast methods. Thus, the effective radius of the excavation that must be considered for assessing the depth of disturbance resulting from high stress levels ranges from r to (r + 1) meters, where r is the actual excavated radius.

In Situ Stress Field

From a study of available in-situ stress data obtained from tectonically quiet and topographically simple locations, the following range of stress values was taken as appropriate to the particular depth of repository considered.

A. Repository Tunnels:

	Vertical Stress (psi)	Horizontal Stress (psi)
Lower	1300	1300
Preferred	2180	3260
Upper	2190	6380

B. Shaft in Vicinity of Repository:

	Horizontal Stress (psi)	Horizontal Stress (psi)
Lower	1300	1300
Preferred	2180	3260
Upper	2190	6380

C. Upper Shaft at Approximate Depth 100m:

	Horizontal Stress (psi)	Horizontal Stress (psi)
Lower	174	522
Preferred	435	1305
Upper	1595	4780

In addition, for prediction of failure zones, two cases of pore water pressure were considered: dry and pressure equal to overburden head.

Rock Mass Strength

Shale:

The generic shale model was considered to be an intact, horizontally bedded formation, demonstrating pronounced strength anisotropies. The strength for failure by shearing across the bedding was taken as:

$$\sigma_{Df} = \sigma_c \left(1 + \frac{\sigma_3'}{\sigma_c}\right)^{\frac{1}{2}}$$

where:

σ_{Df} = maximum principal stress difference of failure

σ_c = unconfined compressure strength

$\sigma_{3'}$ = effective minor principal stress

The shear strength for failure along the bedding was described by:

$$\sigma_f = 0.1\,\sigma_c + \sigma_{n'} \tan \phi \qquad (\phi = 25^{\circ})$$

where:

σ_f = shear stress or failure

$\sigma_{n'}$ = effective normal stress or failure

These strength parameters indicated that the minimum unconfined compressive strength for critical orientation of the bedding plane of weakness would be approximately one-third of σ_c (the unconfined compressive strength for loading normal to the bedding). The strength values were thus characterized by:

	Unconfined Compressive Strength σ_c (psi)
Lower	3,625
Preferred	7,250
Upper	10,875

Bedded Salt:

During the initial construction phase, the bedded salt has been assumed to fail in a brittle manner and the strength characteristics have been taken as homogeneous and essentially nonfrictional:

$$\sigma_{Df} = \sigma_c$$

The strength values were taken as:

	Deviator Strength σ_{Df} (psi)
Lower	2900
Preferred	4350
Upper	5800

Depth of Disturbance Due to High In-Situ Stress

The depth of disturbance due to high in-situ stress was determined by comparing the stress concentration fields (equivalent to the specific in-situ stress fields) with the given strength data, in the manner previously described. The zone of rock lying within the strength/stress ratio of 3 was considered to characterize the region of disturbed material, and this area was indicated by an equivalent radius of disturbance.

The lower limit of disturbance was determined by examining the influence of the lower in-situ stress field upon the upper strength value, and the upper limit of disturbance was similarly calculated by combining the upper in-situ stress field with the lower strength level.

Influence of Temperature Induced Stresses

The influence of thermally induced stresses around the shale repository was examined by assuming the long-term temperature distribution of 190°C at the repository, decreasing exponentially to 60°C at 240m from the repository. The assumption is grossly simplified, and it is emphasized that consideration of the influence of thermal stresses is very tentative at this stage.

The thermal stress distribution was added to the stress field resulting from in-situ loading, and the extent to overstress again examined. This indicated that the influence of the thermal loadings is to increase the effective radius of disturbance by approximately 15 percent. Thus, this factor has been applied to the radius of the disturbance zones calculated for shale.

At the temperatures in question, while thermal loadings will tend to develop within salt, the physical properties of the salt will alter so significantly that additional disturbance will not occur. In fact, the development of high temperatures will result in partial healing of the disturbance zone enacted during the excavation and operational phases, when temperatures in the vicinity of the repository were comparatively low.

<u>Earthquake Loading</u>

Additional disturbance as a result of earthquake loading has not been included, because of the comparatively minor effects that dynamic earthquake loads will produce within the repository.

<u>Operational Support</u>

The calculation of the levels of disturbance surrounding an underground repository have been undertaken on the implied assumption that operational support will be adequate to prevent progressive deterioration of the roof and upper sidewalls of the repository. This is a design problem.

<u>Disturbance Zones Prior to Backfilling</u>

The above procedure has allowed the determination of a range of zones of disturbance for the salt and shale repositories and associated shafts. The nature of the disturbance within these zones is considered to be characterized by the given permeability and porosity values ranging from maximum disturbances in the vicinity of the excavation to original undisturbed in-situ conditions at the extremity of the specified zone.

Disturbance Following Backfilling

Shale:

Following backfilling, the operational support will eventually deteriorate and the backfill must be capable of providing the required support. The optimum backfill would be of stiff material which has been placed under pressure, such as post-placement high pressure grout which would provide support without further disturbance to the rock.

Alternatively, the placement of a soft, unpressurized backfill in the repository tunnels will require support pressure. The process will consist of local roof collapse and bulking of the failed material until sufficient backfill support has been mobilized to stabilize the situation. The volume of the moderately disturbed and bulked material (typically 10 percent porosity) has been determined and expressed as an equivalent radius of intensely fractured zone.

No intensely fractured zones are considered to develop within the vertical shaft.

Salt

During the post backfill phase of the bedded salt repository, the high temperatures developed will permit additional closure without fracturing and will essentially result in the healing of fractures indicated in the vicinity of the repository, prior to backfilling.

D-3 Fault Data Rationale

Faults are fractures in the crust along which there has been displacement parallel to the fracture plane. In contrast, joints are fractures along which there has been no displacement parallel to the rupture surface. They can vary in size from a few inches to hundreds of miles in length and corresponding minor to major displacements. The movement and size of the fault depend on the size and orientation of the stress field and the competency of the rocks involved. For a new fault to form, totally unrelated to pre-existing features, would require a stress field building up a magnitude great enough to fail the rock mass rather than just overcome frictional resistance on a pre-existing fracture. Faults once formed thus tend to be reactivated even under a different set of stress conditions than formed the original rupture.

This recurrent movement is well documented. The fault on the west flank of the Cedar Creek Anticline in the Williston Basin in North Dakota has had repeated movement since Precambrian Time. In this case, both normal and high-angle reverse faulting have occurred. During the Precambrian the west side was downthrown. Later in the Devonian-Mississippian, the east side was lifted up and over part of the west block. In post-Permian time, high angle reverse faulting moved the west block higher than the east block. This movement was reversed by down-faulting of the west block associated with the Cretaceous Laramide Orogeny. The San Andreas Fault shows repeated movement. Its movement, although mostly horizontal strike-slip, sometimes exhibits vertical movement. The period of major movements is about 50 to 100 years. Minor movement and adjustments occur almost constantly with very small seismic magnitudes. Associated faults tangential to the San Andreas also show repeated movement. Their stress field is probably directly related to movement along the San Andreas. Even though this fault is a very special case involving a plate boundary, it can be used as a "worst case" example.

A fault can act as a water barrier or as a water conduit. The cataclastic zone can vary from clay gouge to a fractured rock zone. Due to the plastic behavior of many shales, faults in shale are commonly water barriers. Associated with faults are a set of near-perpendicular feather joints. These tensional fractures form during creep movement along the fault. As the stresses increase beyond a strength threshold they will open up, but once stress is relieved by movement they will close rapidly.

The numbers generated reflect a small to medium fault in plastic to semiplastic rocks. The fault plane may or may not be permeable. Assuming a relatively tight fault, the major water movement will occur through the feather fracture zone only when shear stresses are highest. There will be a long slow buildup but, after movement, a very rapid closure. The range of values given includes the possibility for the fault to remain fully permeable after the event.

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