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FINAL REPORT
ON
UNCERTAINTIES IN THE DETECTION,
MEASUREMENT, AND ANALYSIS OF
SELECTED FEATURES PERTINENT TO
DEEP GEOLOGIC REPOSITORIES

PURCHASE ORDER NO. 9010603

MASTER

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ABSTRACT

Uncertainties with regard to many facets of repository site characterization have not yet been quantified. This report summarizes the state of knowledge of uncertainties in the measurement of porosity, hydraulic conductivity, and hydraulic gradient; uncertainties associated with various geophysical field techniques; and uncertainties associated with the effects of exploration and exploitation activities in bedded salt basins. The potential for seepage through a depository in bedded salt or shale is reviewed and, based upon the available data, generic values for the hydraulic conductivity and porosity of bedded salt and shale are proposed.

KEYWORDS: Uncertainties, measurements, hydrology, bedded salt, shale, permeability, porosity, modeling, radioactive waste disposal, geophysical field techniques

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1. INTRODUCTION

The participation by GEI in the waste management program of Lawrence Livermore Laboratory, prior to the initiation of this particular phase of the investigation, consisted primarily of the acquisition of data necessary for modeling the performance of a depository located in bedded salt. This included information on such factors as the hydraulic conductivity and porosity of salt, the stratigraphy and groundwater regime of salt basins and the development of geological features that could have a major effect on the integrity of a repository.

In the process of developing and using a data base to characterize the containment properties of bedded salt it became apparent that the study should be expanded to include consideration of the magnitude and potential effect of uncertainties associated with the input data to the flow-path model. Therefore, this investigation to study input data and selected model uncertainties was authorized and initiated under Purchase Order 9010603 of the University of California dated November 2, 1977.

The uncertainties which were investigated in this study deal primarily with the technical limitations associated with the exploration of a site, i.e., the acquisition of data and the interpretation of such data in terms of characterizing the site. The sources of uncertainty that were considered included (1) measurement errors, both laboratory and in-situ, of various geotechnical parameters; (2) the spatial variation of parametric values and the degree to which measured values are representative of the site; (3) limitations in the state-of-the-art of site exploration by means of drilling and geophysical techniques; and (4) activities associated with the exploration and exploitation of the mineral resources.

At the outset of this investigation, it was anticipated that the results of both completed and on-going studies directed by the DOE at the WIPP site in New Mexico would be utilized. Of particular interest were data associated with the spatial variation of parametric values in areas of bedded salt. Very few in-situ measurements have been performed, however, because of both the costs and difficulties associated with field hydrologic measurements on rocks with low

permeabilities at depths of more than 500 m and the preliminary nature of the studies performed to date at the WIPP site. Therefore, the spatial variation of parametric values and the degree to which measured values are representative of a site are not treated in this report.

In addition to preliminary data from WIPP, several laboratory data on bedded salt were generated during Project Gnome (located several miles south of WIPP), Project Salt Vault, and during several proprietary investigations (see Section 6.0).

The uncertainties associated with the three other topics listed above were studied and the results are presented in the next three sections of this report which are entitled:

3. Uncertainties Associated With Selected Geotechnical Measurements
4. Uncertainties Associated With Geophysical Exploration and Drilling
5. Uncertainties Associated With Exploration and Exploitation of Mineral Resources.

Concurrent with these studies, certain of the assumptions and geotechnical data were reviewed relative to the potential movement of groundwater in the depository layer as predicted by the flow-path model. This review included consideration of such factors as the applicability of Darcy's Law, values of effective porosity of salt and permeability of salt and shale, the time required for resaturation of the depository following decommissioning, and the potential for downward flow in the depository layer. The results of this portion of the study are presented in the section entitled:

6. Potential Groundwater Flow In the Depository Layer

Certain results from this investigation, e.g., those presented in Section 6.0, consist of numerical values of certain parameters and can, therefore, be incorporated directly into the flow-path model. Other results, e.g., those presented in Sections 3.0, 4.0 and 5.0, consist primarily of a description of the topic, its significance relative to the performance of a repository, and a discussion of the magnitude and potential consequences of the uncertainty. It is anticipated that the results of these three sections may provide the basis for estimates of the magnitude of uncertainties associated with particular sources. In addition, such results may be helpful to NRC in their formulation of site suitability guidelines and criteria.

2. EXECUTIVE SUMMARY

2.1 Introduction

This report, prepared under Purchase Order 9010603 of the University of California, dated November 2, 1977, describes the uncertainties associated with selected geotechnical measurements, geophysical surveys and drilling, and the presence of mines and wells. In addition, the uncertainties associated with modeling flow through the depository layer are investigated, and based on available data, revised baseline values for the hydraulic conductivity of salt and shale and the porosity of salt are proposed.

2.2 Uncertainties Associated With Selected Geotechnical Measurements

2.2.1 Porosity

- a. Laboratory measurements of effective porosity can be made to within several percent of the actual value by choosing a sufficiently large sample size. These measurements are representative of field conditions only where interstitial porosity is much larger than fracture porosity, such as in a porous sandstone.
- b. Field determinations of porosity can be made with borehole logging devices or by tracer tests. Logging devices sample only a small zone near the borehole, and no quantitative analysis of total measurement uncertainty has been published. Tracer tests can be used only where the hydraulic conductivity is greater than 10^{-6} to 10^{-7} cm/sec, because test periods range from months to years for less permeable rocks. No quantitative analysis of test errors has been published. Grove and Beetem (1971) report that a variation of 8% in the measured value produces an unacceptable match of the data to the best fitting type-curve. Typically, no test uncertainty is reported with field determinations of porosity.

2.2.2 Permeability

- a. Although laboratory measurements of permeability are useful in locating potential repository sites,

detailed field measurements must be performed to confirm site suitability. Marine (1967) shows that for one area in granite terrane permeability is 1,000 times the laboratory permeability (because most of the field permeability is due to fractures). In petroleum-producing areas, however, shale may be plastic enough to close fractures at depth so that, fracture permeability may be a relatively small component of total permeability, as shown by lab and field permeability tests of shale by Witherspoon et al (1967). In other areas where shale was tested for permeability, gas leakage from several storage projects has been greater than was predicted on the basis of laboratory and limited field examination (Aufrecht, 1978). Therefore, extensive geologic studies and field permeability measurements are required for the best assessment of in-situ permeability.

- b. The permeability as measured in the laboratory depends upon the in-situ stress history of the sample, the disturbance during sampling and test preparation, and the confining pressure during the test. All of these factors must be considered before laboratory data can be used to predict in-situ permeability.
- c. The permeability of many common rocks, such as salt, shale, granite, and basalt, lies below the sensitivity of many testing devices. In these cases, the test can define an upper limit to the permeability of the rock, but only if the sensitivity of the apparatus is known. This applies to both laboratory and field tests.
- d. The permeability of salt measured in the laboratory apparently decreases with time to less than 10^{-12} cm/sec (the sensitivity of one test apparatus) when saturated brine is the permeant. This phenomenon, if it occurs in the field, is of fundamental importance because it indicates that short-term laboratory tests overestimate the in-situ permeability of salt by orders of magnitude. The potential for time changes in the permeability of any medium should be considered prior to using test results to predict long-term behavior.

2.2.3 Hydraulic Gradient

Uncertainties in hydraulic gradient are due mainly to (a) errors associated with the measurement of water levels in wells, (b) spatial variations in gradient due to hydraulic inhomogeneities in the rocks, (c) the time period required for water levels to stabilize in rocks where the permeability is very low, and (d) the gradient changes due to man's removal of water, oil, and gas that may or may not result in permanent gradient changes.

- a. If the nonverticality of a borehole is taken into account, the water level in a well can be read to within 0.15 m at depths of 300 to 600 m; for wells spaced 1 km, this corresponds to an uncertainty of ± 0.00015 in the gradient, which is only 3% of the baseline gradient (.005) currently used in the model. This hypothetical error, however, is greater than the gradient in some areas (for example, the Nevada Test Site) so that unless the spacing of wells is adequate, both the magnitude and direction of groundwater flow can be indeterminant.

Predictions of the wrong flow directions would lead to incorrect assumptions about potential migration paths for radionuclides and discharge locations to the biosphere.

- b. Spatial variation in hydraulic gradient is strongly dependent upon local geology. Typically, variations of 2 to 3 times over distances of several km are common in relatively uniform sedimentary strata where petroleum and/or water production are minimal (Mercer and Orr, 1977).
- c. Time periods of months to years may be required for water levels to stabilize in wells where the rocks are relatively impermeable (Mercer, 1978). After a permanent observation well is cased and cemented, the casing is perforated at the desired stratum by firing projectiles through the casing and cement into the rock. If the rock has very low permeability, or if the permeability is due to fractures not penetrated by the projectiles, the water levels may rise very slowly.
- d. Pumping of oil, water, or gas can reduce hydraulic heads by hundreds of meters. Little is known about whether such changes can be permanent, because in most areas where heads have been artificially

lowered, pumping has never been stopped long enough for the recovery of hydraulic heads to be observed.

More significantly, in many bedded salt areas, petroleum production is so extensive, and original head data so sparse, that the magnitude of man-made changes is unknown. Caution should be used in interpreting hydraulic head data where oil, gas, or water production has taken place.

2.3 Uncertainties Associated With Geophysical Exploration and Drilling

2.3.1 Seismic Reflection and Refraction

- a. In seismic methods, a pulse or wave train is generated, and the reflections or refractions are recorded. The reflections or refractions are due to subsurface acoustic impedance discontinuities or gradients, and the resultant profile gives a two-dimensional picture of the subsurface. Seismic reflection yields more detail and results in a profile with depth in units of travel time rather than length. The profile can be cast into units of length if correlated with data from sonic well logs. Seismic refraction gives significantly less detail than reflection and is generally used for reconnaissance purposes only.
- b. Seismic reflection yields greater resolution with higher frequency source energy; however, as the frequency is increased, penetration becomes more limited. Typically, resolution is of the order of one wave length, which might be approximately three meters at depths of 600 m.
- c. Seismic methods do not endanger the integrity of potential repository layers.
- d. Seismic methods are most useful for locating anomalies in subsurface structure or stratigraphy. The anomalies can then be drilled for more accurate characterization.

2.3.2 Radar

- a. Radar techniques, specifically designed to explore relatively dry rocks such as salt, have successfully detected small water hazards, such as a brine-filled borehole, at distances of 50 to 80 m. A fault was located 400 m from a mining face.
- b. At present, radar probing is most accurately performed from mines. Borehole radar devices have been tested, but their usefulness is limited, and directional control has not yet been developed.
- c. Radar probing from the ground surface is not feasible because the radar beam cannot penetrate any soil or rock strata containing more than about 0.5% water by volume.

2.3.3 Electrical Resistivity Surveys

- a. Electrical resistivity surveys are based on a model approach, where a best fit is sought between the field data and an assumed subsurface resistivity model. The results are characterized by non-unique and commonly oversimplified solutions.
- b. Resistivity methods have performed fairly well in detecting near-surface features, as wide as seven hundred meters across, but they have failed to detect potential hazards, such as vertical columns of breccia, at depths of a few hundred meters.
- c. The resolution of the method is a complicated function of many variables, including the resistivity contrast of the target and the depth and size of the target.
- d. A target cannot be detected whose depth is greater than its lateral dimensions. Thus, a spheroidal brine cavity generally cannot be detected from the ground surface.

2.3.4 Gravity Surveys

- a. The resolution of gravity surveys is severely limited by variations in topography within the survey area. Minor variations in topography, of the order of several meters, obscure the gravity anomalies generated by small targets at any depth.

- b. Gravity surveys appear to have little value for detecting local repository hazards.

2.3.5 Magnetic Surveys

- a. Magnetic surveys, like resistivity and gravity surveys, are based on a modeling process and yield inherently non-detailed information about the geometry of subsurface structures.
- b. Because they respond principally to contrasts in the iron content of rocks, magnetic surveys are most useful for detecting igneous dikes and other intrusive features in sedimentary basins. They are generally not effective in detecting anomalies such as breccia pipes or brine cavities because these features do not create a magnetic contrast with the surrounding rocks.

2.3.6 Drilling Programs

- a. Drilling is not useful for detecting local hazards because the probability of hitting a small target is low for reasonable drilling grid spacings. For example, if it is desired to make 95% sure that there is no cavity or breccia pipe of radius 200 m or more within a 3 mi² (7.7 km²) site, a grid spacing of 167 m is necessary, and it would take approximately 300 holes to explore the site at the desired level.
- b. Drilling is most useful for characterizing potential hazards, once their presence has been indicated by remote surveys, such as seismic reflection.
- c. Drilling has the inherent limitation that it creates a potential leakage path for radionuclides.

2.4 Uncertainties Associated With Exploration and Exploitation of Mineral Resources

Features associated with resource exploitation in bedded salt basins include petroleum exploration and production wells, mineral exploration boreholes, brine wells, solution cavities, mine shafts, and underground excavations. Evaluating the hazards to a repository posed by each kind of feature has two aspects: determining the

potential effects of a given feature, and determining the location of existing features, or the likelihood of unknown features occurring near the repository site. The former problem can be approached by examining case studies, which can indicate at least a probable maximum radius of influence of each feature. The difficulty experienced in locating exploitation features and adequately demonstrating the absence of unknown features depends on several factors, among which are the kind of feature, the local exploitation history, and the state in which the study is being made. The danger of known features can be minimized by placing a repository far outside their maximum observed radius of influence. More danger is posed by unknown features.

2.4.1 Petroleum Wells

Evaluations of the desirability of a particular basin for nuclear waste disposal should include the following considerations:

- a. Degree of petroleum exploration in the basin. - Although more heavily exploited basins contain more wells, there are areas within each basin that are relatively untouched, and the time-frame of development, regulatory history and geometry of the petroleum reservoirs are probably more important considerations than the degree of exploration.
- b. Time frame of development - Those areas significantly developed before technological improvements in the early part of this century and before the advent of state record keeping and regulation are particularly likely to contain unknown and/or incompletely plugged wells.
- c. State regulatory history - The adequacy of state plugging regulations has varied greatly from state to state, even in the fairly recent past. Well-marking regulations differ between arid and agricultural states, those in arid state making location of wells easier.
- d. Location of oil within the basin - If reservoirs occur in easily-identifiable trends, early wild-cat drilling, which is liable to be poorly recorded, may be confined to the trends, lessening the possibility of unknown boreholes in areas untouched according to current records.

- e. Location of oil within the stratigraphic section - If the salt lies below shallow petroleum reservoirs within a basin, the vast majority of the wells, especially the older ones, may not even breach the salt.
- f. Information cited in this report leads to the following conclusions about the potential influence of petroleum wells that do penetrate the salt.
 - (1) Wells abandoned before the 1930's are likely to be inadequately plugged.
 - (2) Borehole plugging is a difficult operation, and plugs placed in the wells during normal operations may not be effective in preventing fluid migration. In any case, plugging has been routinely practiced only for about the last 50 years, and examples of plug longevity for longer periods do not exist.
 - (3) Fluid migration through abandoned wells is documented. However, dissolution resulting from that migration is difficult to recognize unless subsidence occurs.
 - (4) Subsidence in salt basins associated with petroleum operations is a rare event, and the largest documented subsidence zone found in this study is approximately 300 m in diameter. Most subsidence zones stabilize after the initial collapse at diameters much less than 300 m.
 - (5) All cases of subsidence documented in Kansas were associated with brine disposal, which can lead to fluid migration in at least two ways. One is that if the operation results in mixing of different brines, rapid corrosion of well casings in the area may result. The other is that brine disposal improperly practiced may lead to abnormal pressure buildups which can cause leakage through wells at least 500 m away from the associated disposal operation.

The technology for finding all old wells in a (small) field and effectively sealing them to the passage of gas has existed for the past 40 to 50 years. The task of locating the wells is facilitated in arid environments by the preservation of surface features due to drilling. Especially in such environments, the probability of an unknown well remaining undiscovered after site investigation is negligible.

2.4.2 Solution Mining

The problems due to solution-mining activities are similar in many respects to the problems due to petroleum activities. For instance, the technology of drilling, completing, and plugging brine wells is virtually the same as petroleum well technology. The same problem of poor records of old, defunct operations exists, and similar techniques are used to find old wells. There are some differences:

- a. Fewer solution-mining wells exist.
- b. Brine well fields are associated with large surface plants which are likely to be recorded or remain prominent long after the operation closes. Thus, even if well location records are completely inadequate, localities where solution mining occurred can be identified and avoided.
- c. Locating and replugging solution mining wells is necessary but insufficient to eliminate hazards as in the case of locating and replugging petroleum wells, because even if all brine wells in a field are successfully replugged, the associated solution cavities remain.
- d. The diameter of subsidence zones associated with solution mines is dependent on the shape and size of the brine cavity. The largest subsidence zone documented in this study measured 600 m in diameter on the surface. Most subsidence areas are much smaller, and all appear to stabilize after the initial collapse.

2.4.3 Mineral Exploration Boreholes

Potash exploration wells are a few orders of magnitude more numerous than petroleum wells in the Carlsbad potash (WIPP site) area, and therefore are more difficult to avoid than petroleum wells. Important observations about potash wells include:

- a. Records of potash wells have been carefully kept since exploration began.
- b. The vast majority of the potash wells in the Delaware Basin are not drilled completely through the salt layers and so, at least initially, do not establish hydraulic communication between aquifers above and below the salt.
- c. Plugged potash wells intersected by mines have proved tight, and no cases of fluid migration, dissolution, or subsidence associated with the boreholes have been reported. Thus, for the time span of experience (about 50 years), potash wells can be regarded as completely plugged.

2.4.4 Conventional Mines

There is little danger to the integrity of a repository due to conventional mining because mine locations and excavations are obvious and well-surveyed, and the effects of mining on rock integrity are limited in areal extent. Disturbances are easily avoided.

2.5 Potential Groundwater Flow In the Depository Layer

The discussion in this section is directed specifically toward the two of the groundwater models in the LLL waste transport model. Several of the model assumptions and parameters are discussed, and, where appropriate, new baseline parameter values are proposed. It is assumed that the reader is familiar with the waste transport model, which is described in detail elsewhere in reports subcontracted under the LLL Waste Management Program.

2.5.1 Recharge Model For the Depository After Decommission

a. Flow Equations

Darcian flow should be assumed for both salt and shale. In recent tests performed specifically to look for non-Darcian flow in sands, silts and clays, Russell and Swartzendruber (1971) concluded that flow was Darcian except in swelling

clays. We have found no similar tests on shale or salt, and the observed non-Darcian effects observed by Russell and Swartzendruber (1971) were small at gradients comparable to those used in the LLL model.

Saturated conditions should be assumed in salt; although there is some evidence to the contrary, proof is lacking. The assumption of saturated conditions will lead to conservative flow estimates if bedded salt at depth is unsaturated.

b. Geometry

The current one-dimensional model geometry should be modified to include the effects of both the shafts and the more permeable layers of sandstone and siltstone horizontally interbedded with the salt.

c. Model Parameters

Proposed new hydrologic parameter values are as follows:

Parameter	New Baseline Value	Old Baseline Value	Std. Log Deviation	Probability Distribution Function	Estimated Generic Limits
Hydraulic Conductivity of Bedded Salt	10^{-12} cm/sec	10^{-9} cm/sec	NA*	NA	NA
Hydraulic Conductivity of Shale (Vertical)	4×10^{-11} cm/sec	10^{-8} cm/sec	1.5	Log Normal	10^{-6} to 10^{-13} cm/sec

*NA - Not applicable, because, based on the available information, only an upper limit can be determined.

The new value of hydraulic conductivity for salt is based upon the limit of the accuracy of the most sensitive measurements performed on rock salt.

The new value of hydraulic conductivity for shale is based upon 25 published values for deep shales from petroleum producing regions.

Available data show that the hydraulic conductivity of salt decreases below measurable values in several weeks when under high confining pressures and when brine is the permeant. In one test, a hole drilled through a salt sample closed within 7 days so that the hydraulic conductivity had decreased by a factor of 26 before testing was stopped.

We recommend a revised hydraulic conductivity for salt of 10^{-12} cm/sec because this was the lowest value measurable with the apparatus used to test salt. We have no data or other basis for assigning a standard deviation, probability distribution function, or generic limits, at present.

d. Boundary Conditions

The boundary conditions of the model, the hydraulic heads in the depository and in aquifer above and below the depository layer, determine the gradient during recharge. The recharge gradient used in the model, while geologically reasonable, is about four times the corresponding value in the Delaware Basin at the WIPP site. Resaturation time predicted with the generic heads and flow length currently used in the flow path model is, therefore, roughly one-fourth that calculated with actual field data (if other parameters are held constant).

e. Independent Recharge Models

Two independent (and very approximate) determinations predict recharge times due to horizontal, interstitial flow, in excess of 10,000 years. Recharge due to vertical, interstitial flow, when the revised hydraulic conductivities for salt or shale are used, are likewise more than 10,000 years. Therefore, attention should be focused on shaft and tunnel sealing after repository decommission. This correlates with experience in salt and potash mines, where all of the permanent mine inflow is due to shaft leakage.

2.5.2 Waste Migration Through the Depository Layer

In general, the same considerations apply to the Waste Migration model as to the Recharge model, with the exceptions noted below:

a. Model Parameters

Because the flow velocity affects the time radio-nuclides first arrive outside the depository layer, porosity, which affects flow velocity, must be known. The following revised value for the porosity of salt is proposed:

Parameter	New Baseline Value (Dimension- less)	Old Baseline Value (Dimension- less)	Std. Log Devi- ation	Probability Distribu- tion Function	Generic Limits
Effective Porosity of Bedded Salt	1.4×10^{-2}	2×10^{-2}	0.3	Log Normal	10^{-3} to 10^{-1}

No new data has been obtained for the porosity of shale.

b. Boundary Conditions

The hydraulic head data for aquifers above and below the salt at the WIPP site have not yet been published, so that comparison of model and in-situ values is not possible at present. These data are scheduled for publication in late 1978.

Preliminary oral reports from the USGS in Albuquerque, New Mexico indicate that not only the magnitude, but also the direction of the gradient across the salt is unknown.

Based on these reports, the current model configuration may represent a worst-case situation. If a site is characterized by a downward hydraulic gradient through the depository layer, the transport time of wastes to the biosphere may be orders of magnitude longer than those calculated, because of longer transport distances, lower permeabilities of aquifers at greater depths, greater dispersion, and lesser human usage (caused by possible lower water quality in deeper aquifers, such as the saline Delaware

Mountain group in the Delaware Basin). The lower retardation coefficients associated with saline aquifers, however, may partially offset some of these effects.

If the data show a downward hydraulic gradient through the depository layer, modeling will require additional hydrologic data for the lower aquifer.

3. UNCERTAINTIES ASSOCIATED WITH SELECTED GEOTECHNICAL MEASUREMENTS

3.1 Introduction

The intent of this portion of the investigation was to focus attention on the sources of error and uncertainties that are associated with the measurement of certain parameters that are pertinent to the movement of groundwater. In particular, three parameters were selected for study: porosity, permeability and hydraulic gradient.

In order to assist the reader who is not familiar with the significance of these parameters in terms of groundwater flow, each is defined and the effect of each on the movement of groundwater is described. In addition, a description of the method or methods by which the particular parameter is measured is provided so that the specific sources of error and uncertainty can be understood.

The study is based on a review of the literature and contacts with knowledgeable engineers and researchers from the petroleum industry and the U. S. Geological Survey. A Northeast Academic Science Information Center (NASIC) computer search was performed for references from the NTIS and Energy data bases.

3.2 Porosity

3.2.1 Definition

Porosity is defined as the ratio of the void-space volume to the bulk volume of a material. It can be determined by measuring two of the three quantities of bulk volume, void-space volume, or solids volume. It is necessary to distinguish between absolute, or total, porosity and effective porosity. Absolute porosity is void-space regardless of pore connections, whereas effective porosity is that fraction of the void space consisting of interconnected pores. It is the effective porosity which influences the movement of groundwater.

3.2.2 Measurement Techniques and Uncertainties

Commonly used methods for the determination of porosity are described in a publication by the American Petroleum Institute (1960). They include the following:

Direct Method. The volume of the specimen is measured after which the sample is crushed to remove all pores and the volume of the remaining solids measured. This method yields total porosity.

Mercury Injection. The volume of the specimen is measured by displacement of mercury. Mercury is then forced into the void space under great pressure and the volume of mercury that enters the specimen is measured. This method yields effective porosity.

Gas Expansion Method. The sample, of known bulk volume, is placed in a container of known volume under a known gas pressure. The container is connected to a second chamber of known volume at known and different pressure, and the pressures are equalized and measured. From knowledge of the chamber volumes and pressures and from Boyle's Law the volume of the void space in the sample can be calculated. This type of measurement is widely used in the petroleum industry. It requires careful calibration of the instrument and is considered to give measurements within the range of $\pm 0.002\%$ of the pore volume (American Petroleum Institute, 1960). This method yields effective porosity.

Imbibition Method. A sample of rock, for which the total volume is known, is weighed dry, then immersed in fluid under vacuum for at least a week and weighed in water to determine the submerged weight. The difference between the submerged weight and the dry weight is used to determine the volume of interconnected pores. This method yields effective porosity.

Measurements by mercury displacement and by gas measurement apparatus are commonly performed on samples with a bulk volume of 10 to 20 cc. Volume measurements by mercury pump are considered reproducible to ± 0.01 cc. Gas measurement techniques by the double cell method yield results which have errors ranging from ± 0.003 cc to ± 0.04 cc as the volume of the solids varies from 4 to 13.5 cc (American Petroleum Institute, 1960).

The potential effect of these measurement errors on determinations of the porosity of salt is significant as shown in the following analysis. For computation purposes, examples from tests conducted by Core Laboratories, Inc. (1959) will be used. In their tests, the most sensitive case is that of Sample 54 which has the lowest porosity: 0.62%.

Using the values given above, if this particular sample had a volume of solids of 13.5 cc and if the error in the pore volume were ± 0.003 cc, then the calculated porosity would range from 0.00598 to 0.00642. This variation, due to measurement error, from the value of 0.0062 is insignificant compared with other model uncertainties. However, if the volume of solids were 4.0 cc and if the pore volume uncertainty were 0.04 cc, then the calculated porosity would range from 0 to 0.0162. This upper limit represents a value some 2.5 times the presumed actual value of 0.0062, and the lower limit would lead to (theoretically) infinite flow velocities.

It is recommended that samples with bulk volumes of from 10 to 20 cc be used for grain volume determinations.

Field measurements of porosity are made routinely by the petroleum industry by means of neutron logging sondes (Schlumberger Ltd., 1972). In this method, a radioactive neutron source is lowered down a borehole, and the collisions of emitted neutrons with hydrogen atoms in formation water or oil produce lower energy neutrons and eventually gamma rays, either of which can be counted. The neutron or gamma counts are essentially proportional to the amount of hydrogen in the formation, and because the volumetric hydrogen content is similar for both oil and water, the resulting log can be correlated with porosity (Schlumberger Ltd., 1972).

Uncertainty is introduced by a number of variables, including:

- 1) Salinity of water (hydrogen is replaced by salt)
- 2) Shale content (bound water does not contribute to effective porosity)
- 3) Rock type (various rock-forming minerals affect neutron or gamma counts differently)
- 4) Drilling fluid (water content and composition, which can vary with time and depth, affects neutron or gamma counts)
- 5) Borehole diameter (diameter affects penetration of neutrons and amount of drilling fluid present)

- 6) Temperature and pressure (affect rate of energy loss by neutrons)
- 7) Casing thickness, if any
- 8) Statistical variations in the emission of neutrons by the source

All of these sources of error can be partially corrected either automatically during the logging procedure or afterwards during interpretation, and results can be enhanced by correlation with gamma ray, density, sonic, and other logs (Schlumberger Ltd, 1972).

There apparently is no published treatment of all the sources of uncertainty that leads to a quantitative assessment of the accuracy of borehole porosity measurements.

While logging devices can be used to measure porosity only within a narrow zone around a borehole, two-well tracer tests can be used to determine the effective porosity (combined fracture and interstitial) of the volume of rock or soil between two wells. The spacing can be more than 100 m in highly permeable rock (Claassen and Cordes, 1975), but simple Darcian flow calculations demonstrate that for wells spaced only 5 m in rock with hydraulic conductivity of 10^{-9} cm/sec and porosity of 10%, a two-well tracer test with an induced gradient of 100 would require more than 25 years. Clearly, borehole logging devices provide the only practical in-situ method for determining the porosity of rocks with permeabilities less than about 10^{-6} to 10^{-7} cm/sec.

In the published descriptions of two-well tracer tests, no discussions of the sources of uncertainty are given. The test data analysis consists of a curve-matching procedure, and Grove and Beetem (1971) note that variations in porosity of only 8% caused an unacceptable match to the data. No analysis of pumping rate variations or model assumptions is provided to assess overall test uncertainties.

In order to quantify the uncertainty associated with porosity determinations, it is required that the method of measurement be described, and that the errors associated with the physical measurements be specified. This is typically not done with published data with the result that the errors associated with the values are unknown.

3.3 Hydraulic Conductivity (Permeability)

3.3.1 Definitions

Hydraulic conductivity and permeability are related terms that describe the ease with which fluids are transmitted through a porous material.

"Hydraulic conductivity" (units L/T) is the volume of water at the existing kinematic viscosity that will move in unit time under unit hydraulic gradient through a unit area measured perpendicular to the flow direction (Lohman and others, 1972). This term, used extensively in groundwater hydrology, has been used throughout the development of the flow path model to report data, with units of cm/sec.

"Intrinsic permeability," more commonly called "permeability," (units L^2) is used in the petroleum industry, and because it does not depend on the viscosity of the fluid, it is a property of the material only. A porous medium has a permeability of one darcy when a single phase fluid of one centipoise viscosity, that fills the pores of the medium, moves in laminar, viscous flow at a rate of one cm^3 per second through a cross-sectional area of one cm^2 under a pressure gradient of one atmosphere per cm (Lohman and others, 1972). The darcy equals 0.987 square micrometer (μm)², which is the term commonly used by the USGS. In the petroleum industry, permeability is generally reported in milli-darcys (md), and for groundwater at relatively low temperatures, $1 \text{ md} = 1.045 \times 10^{-6}$ cm/sec. Separate terms were developed because the viscosity of groundwater is essentially constant while that of oil is not--"hydraulic conductivity" includes the viscosity of groundwater implicitly, whereas "permeability" requires that the viscosity be entered into the flow equations explicitly.

For groundwater modeling purposes, "permeability" is synonymous with "hydraulic conductivity," and measurements reported in md can be multiplied by 10^{-6} to get the corresponding value in cm/sec. Both terms are used interchangeably in this report, except permeability only is used to describe the flow of gas or petroleum through porous media.

Hydraulic conductivity (units L/T), when multiplied by the hydraulic gradient (dimensionless), equals the "specific discharge," or flow per unit area, through a porous material. This term is sometimes confused with the flow velocity because both have units of L/T.

The velocity of a tracer introduced into a porous medium can be found by dividing the specific discharge by the effective porosity. The specific discharge is actually a volume rate of flow per unit of area (units $L^3/T/L^2$) whereas the velocity of flow as determined above is a true average velocity. (Dispersion causes some variations in velocity on a microscopic scale so that after flow through a porous medium, the concentration of a tracer at some point downstream builds up gradually as the tracer front progresses).

3.3.2 Measurement Techniques and Uncertainties

Permeability can be determined by measuring the flow of liquid or gas under a given pressure gradient through a porous medium. If a gas is used, it is necessary to perform tests at several pressures in order to determine the magnitude of the Klinkenberg effect which results from changed conditions of gas flow along pore walls (Davis and DeWiest, 1966). Klinkenberg showed that gas permeability of porous media was a linear function at the molecular free path which is inversely proportional to the gas pressure and to the square of the molecular diameter. The effect exists because the movement of gas on the walls of passageways is different from the laminar flow on which conventional calculations are based. If the Klinkenberg effect is not considered, the computed permeabilities will be higher than the actual values. For example, for a permeability of 0.5 millidarcy, the computed value would be approximately twice the actual value and for a permeability of 100 millidarcys, the computed value would be about 1.05 times the actual value.

The equipment used in permeability tests varies widely in type and construction, particularly as the effort is made to measure very small permeabilities. An excellent qualitative summary of sources of error to be considered when conducting permeability tests is found in pages 14 to 16 of RP-27, Recommended Practice For Determining Permeability of Porous Media (American Petroleum Institute, 1952). Since the equipment varies widely, calibration of the equipment, leakage, and repetition of tests are of particular importance.

Permeability tests in the laboratory have been performed on both intact and fractured material. Brace et al (1968) measured permeabilities from 4 to 350×10^{-12} cm/sec in granite on small (5 cm³) solid specimens and found that flow decreased with increased effective confining pressure. The

measurements were made at confining pressures up to 4,000 bars (1 bar = 14.5 psi). The errors were evaluated and reliability of measurement given as approximately $\pm 10\%$ for the experiments at confining pressures of 50 to 1,000 bars, and approximately $\pm 20\%$ for tests at 2,000 and 4,000 bars. The permeability was determined by the decay characteristics of a pressure change at one end of the sample. The tests were conducted for a maximum of 30 minutes because the necessary control of temperature and pressure was not possible for longer periods of time.

Reynolds and Gloyna (1960) determined the permeability of dome and bedded salt on samples with a cross-sectional area of 10 sq cm and with a length of 4 cm. The tests involved permeation by gas, kerosene and brine under a series of permeant pressures which ranged from 6.8 to 34 kg/cm² (1 kg/cm² $\approx$ 14.7 psi - 1 atm) and confining pressures that ranged up to 204 kg/cm². Values of 10^{-6} to 10^{-9} cm/sec were typical. As with most tests of permeability, leakage within the test equipment was not measured, and the results, especially those for the lowest permeabilities, are suspect. For more valid results, both influent and effluent should be measured to be sure that the equipment is not leaking.

As would be expected, the permeability always decreased when the confining pressure was increased. However, it was also found that the permeability at a particular pressure was permanently decreased by cycling the specimen to a higher confining pressure and then back down to the original pressure. For example, the permeability at 37 kg/cm² was reduced by 35 percent after the confining pressure had been increased to 190 kg/cm² and then returned to 37 kg/cm². Although not evaluated, this effect of permanent change in permeability due to changes in effective stress may have occurred during some of the tests in which the pressure of the permeant was cycled.

Another source of error in permeability measurements is the clogging of the fluid pathways by particles in the permeant, by gas that comes out of solution, or by growth of bacteria in the porous medium. Clogging occurred in some of the tests by Reynolds and Gloyna (1960) but was stopped by the installation of filters.

Core Laboratories, Inc. (1959) performed tests on salt samples with a cross-sectional area of approximately 45 to 50 cm² and a length of 20 cm. Their results were similar to those achieved by Reynolds and Gloyne (1960) in that, over a period of time, permeation with brine caused the permeability to decrease markedly. In fact, at 54 kg/cm² confining pressure, the permeability decreased several orders of magnitude over a time span of less than a thousand hours to values less than could be detected (approximately 10⁻¹² cm/sec).

Aside from errors associated with apparatus and procedures, the observations mentioned above suggest that when brine is the permeant, certain changes take place within the structure of salt which cause a substantial reduction in permeability. Although various hypotheses have been suggested, there are no published studies documenting the cause or causes of the observed decrease. Therefore, it is important that permeability data for rock, and salt in particular, be evaluated in terms of the possible errors and uncertainties that may exist.

Of more fundamental concern is the uncertainty associated with utilizing laboratory values of permeability to predict in-situ flow characteristics. This is particularly the case for those situations where the unbroken rock has a very low permeability and where the bulk of groundwater flow is along the naturally occurring fractures in the rock mass. Data obtained by Marine (1967) indicate that there may be several orders of magnitude difference between the permeability of the unbroken material and the naturally fractured rock mass. Reporting on permeabilities of crystalline rock determined from laboratory tests, Marine found that two-thirds of the measurements were less than 4×10^{-11} cm/sec which was the lowest value measurable under the conditions of the test. His study of permeabilities measured in-situ gave values for the permeability as high as 2×10^{-7} cm/sec for one well, and 1.5×10^{-8} cm/sec for the average of four other tests. Although Marine specifically states that the values are to be considered only in a qualitative manner, they clearly point out the magnitude of differences that can exist between laboratory and in-situ values.

The investigation by Marine (1967) involved the use of two methods of determining in-situ permeability: injection tests and swabbing tests. In both tests, the section of the borehole to be tested is isolated from the rest of the borehole by means of packers.

(A packer is an inflatable rubber device which is lowered to a certain depth in the borehole and expanded so as to prevent the flow of fluid within the borehole past that depth.)

In the injection tests attempts were made to pump water into the interval isolated by packers. However, the flow into most of the sections was lower than could be measured. Therefore, about halfway through the investigation the injection tests were abandoned in favor of the swabbing tests.

In the swabbing test, the water in the drill pipe that connects the packed-off interval to the ground surface is swabbed out of the hole by lowering and then raising a swab which essentially lifts the column of water out of the borehole. Following swabbing, the rate of rise of the water level in the borehole is monitored and the data are used to determine the in-situ permeability.

Leakage around poorly-sealed packers, which can obscure test results, is generally monitored with electrical devices when problematical.

Measurements of permeability using both techniques were made in three boreholes. In each case, although data obtained from the swabbing tests allowed computation of the permeability, the amount of water that was accepted during the injection tests was too small to be measured, i.e., at the low values of in-situ permeability that existed at the site, the swabbing tests worked satisfactorily whereas the injection tests did not. These results point out the need to consider the sensitivity requirements of the data that is sought when selecting the particular measurement technique and associated instrumentation.

As part of their investigations to determine the underground storage potential of aquifers, the natural gas industry has developed techniques for determining the in-situ permeability of rock strata that have very low permeabilities (Witherspoon et al, 1962a, 1962b, 1967a, and 1967b). The typical gas storage site consists of one or more aquifers in which the natural gas is to be stored, which are overlain by a "caprock" of sufficiently low permeability that the gas is trapped in the aquifer. It is the technique of measuring the permeability of the caprock that is of interest. The test requires at least three wells: one to pump water from the aquifer and the two to observe changes in the hydraulic heads within both the aquifer and

caprock at known distances from the pumping well. The field observations are plotted and compared with theoretical curves based upon the fact that, as water is pumped from the aquifer, the water pressure in both the aquifer and in the overlying caprock is reduced by amounts that depend on the permeabilities of both strata, the distances from the pumping well to the observation wells, the duration of the pumping, the thickness of the aquifer, and the distance above the aquifer to the observation well in the caprock.

The theoretical curves used to analyze the data were computed by a finite-difference mathematical model of a caprock-aquifer system. As such, there exists the inherent uncertainty associated with theoretical models of actual geological situations.

However, in two reported cases, field and laboratory measurements agreed within a factor of about 2, which is sufficiently accurate for petroleum engineering purposes (Witherspoon and others, 1962a).

The accuracy of the test technique, if the rock strata are homogeneous, depends in a large part on the accuracy of the observation well measurement. As described in detail in Section 2.4.2, water levels in deep wells can be measured within 5 to 15 cm of the true level, corresponding to a caprock permeability uncertainty of 2 to 3 times. A similar uncertainty is caused by an order of magnitude uncertainty in the permeability of the underlying aquifer.

The technique of measuring the vertical permeability of a caprock is a significant development in hydrologic testing and has potential consequences for the development of repository site suitability criteria. Before this technique was developed, the petroleum industry measured permeability with the "drill stem test (DST)." While the DST is still a commonly used field test for petroleum reservoir assessment, its lower limit is about 10^{-7} cm/sec (Demis, 1978; Correll, 1978; Griswold, 1978) and it tests permeability in essentially the horizontal plane only.

The gas storage caprock test, however, has successfully been used to measure vertical permeabilities as low as 10^{-10} to 10^{-11} cm/sec, which represents a 10^3 to 10^4 fold increase in the resolution of field permeability testing.

3.4 Hydraulic Gradient

3.4.1 Definition

Hydraulic gradient is defined as the change in hydraulic head per unit of distance in a given direction (Lohman and others, 1972). For horizontal flow along a given stratum the hydraulic gradient is usually determined by measuring the elevation of the groundwater table at two locations and then dividing the difference in elevation by the length of the flow path between the measuring points. The elevation of the groundwater table can be determined by subtracting the depth to the surface of standing water in a well or borehole from the elevation of the ground surface from which the depth was measured.

In the case of vertical flow between two points through a medium with uniform vertical permeability, the hydraulic gradient is found by dividing the difference in hydraulic head at the two locations by the vertical distance between the measurement points. The hydraulic head at each point is the sum of the pressure head and the elevation head (the distance above an arbitrary datum). In the case of vertical flow where the permeability is not constant, i.e., through a layered media where the individual strata have different permeabilities, the change in hydraulic head that occurs in a given layer must either be measured directly or computed from knowledge of the permeability and vertical dimension of the strata across which a change in hydraulic head was measured.

3.4.2 Measurement Techniques and Uncertainties

Studies drawing conclusions from measurements to water surfaces at depth should be evaluated in the light of the Garber and Koopman (1967) assessment of the problems of deep well measurements. The repeatability of measurements by steel tape, when proper calibrations were performed, was found to be 3 cm at 500 m depth. Measurements with a resolution of 0.3 cm were found possible with electric cable devices when the device was left in place between measurements. Repeatability after removal is ± 15 cm for one instrument.

Several field permeability test methods require that water levels be measured in observation wells; therefore, it is important to know the accuracy of the measurement method in order to assess the uncertainty in the test results. Reports by Marine (1966, 1967) describe fracture zones and the field methods for determining the permeability of crystalline rock at depths of 300 m. Measurements were made with an electric probe, and the error was probably of the order of 3 to 15 cm. The effects of these errors on the computed value of in-situ permeability were negligible (Marine, 1978).

Young (1963) describes problems in drilling and testing deep wells at the Nevada Test Site where steel tapes and electric cable devices were used for measurements of water levels in wells. Young indicates that a principal source of error is nonverticality of the holes. He reports that three measurements to water level of 473 m, 471 m and 470 m were corrected to 469.5 m when hole deviation and instrument correction were taken into account. The difference between true and uncorrected water levels in the Nevada Test Site wells, which were mostly in the range from 300 to 600 m deep, varied from 0.15 m to 2 m (Garber and Koopman, 1967).

Variations in barometric pressure can obscure water level readings if not taken into account. A pressure variation of one inch of mercury, for example, corresponds to a maximum water-level variation of 35 cm, which is the same order of magnitude as the variations measured in a caprock permeability test (Witherspoon and Nelson, 1962b). Therefore, conclusions drawn from subtle water-level variations are suspect if the data have not been corrected for variations in barometric pressure.

Because the depth to water in a well is subtracted from the ground surface elevation to obtain the elevation of the water level, the ground surface elevation must be accurately measured between wells where hydraulic gradients are low, such as at the Nevada Test Site. Accurate surveying is usually straight-forward in the field. Elevations from USGS topographic maps, which are generally accurate to about one contour interval, are not suitable for accurate determinations of water levels.

3.5 Summary and Conclusions

With few exceptions, no error analysis is reported with laboratory or field measurements of hydraulic conductivity, hydraulic head, or porosity because, in general, very little is known about the actual test uncertainties. Although we were unable to reach one of the goals of this study (to quantify hydrologic measurement uncertainties), we have identified the major sources of test error and have developed a semi-quantitative framework in which test results can be examined. While this framework is important for the development of reasonable site suitability criteria, it should be recognized that hydrologic test uncertainties cannot yet be put on a quantitative basis.

In the following summary, measurements of porosity, permeability, and hydraulic gradient are discussed, generally with reference to any type of rock. In certain instances, the discussion will focus on measurements in salt.

3.5.1 Porosity

The errors associated with laboratory measurements of porosity on unfractured samples are well documented. This is because the experimental techniques are simple and are, in general, similar to those used in other fields of science.

In contrast, we have found no treatment of the errors associated with field measurements of porosity, and we question whether such an analysis is possible for rocks with dominantly fracture porosity. Field measurements of porosity generally require injection of a tracer in one well and observation of the tracer concentration as a function of time in another well. For rocks with permeabilities of approximately 10^{-9} cm/sec, it would take many years to make porosity measurements between wells only 5 meters apart. Tests lasting even this long would fail to sample the large-scale inhomogeneities that would likely exist in the field.

3.5.2 Permeability

a. Although laboratory measurements of permeability are useful in locating potential repository sites, detailed field measurements must be performed to confirm site suitability. Marine (1967) shows that for one area in granite terrane permeability is 1,000 times the laboratory permeability (because most of the field permeability is due to fractures). In petroleum-producing areas, however, shale may

be plastic enough to close fractures at depth so that, fracture permeability may be a relatively small component of total permeability, as shown by lab and field permeability tests of shale by Witherspoon et al (1967a). In other areas where shale was tested for permeability, gas leakage from several storage projects has been greater than was predicted on the basis of laboratory and limited field measurements (Auffricht, 1978). Therefore, extensive field permeability measurements are required for the best assessment of in-situ permeability.

b. The permeability as measured in the laboratory depends upon the in-situ stress history of the sample, the disturbance during sampling and test preparation, and the confining pressure during the test. All of these factors must be considered before laboratory data can be used to predict in-situ permeability.

c. The permeability of many common rocks, such as salt, shale, granite, and basalt, lies below the sensitivity of many testing devices. In these cases, the test can define an upper limit to the permeability of the rock, but only if the sensitivity of the apparatus is known. This applies to both laboratory and field tests.

d. The permeability of salt measured in the laboratory apparently decreases with time to less than 10^{-12} cm/sec (the sensitivity of one test apparatus) when saturated brine is the permeant. This phenomenon, if it occurs in the field, is of fundamental importance because it indicates that short-term laboratory tests overestimate the in-situ permeability of salt by orders of magnitude. The potential for time changes in the permeability of any medium should be considered prior to using test results to predict long-term behavior.

3.5.3 Hydraulic Gradient

Uncertainties in hydraulic gradient are due mainly to (1) errors associated with the measurement of water levels in wells, (2) spatial variations in gradient due to hydraulic inhomogeneities in the rocks, (3) the time period required for water levels to stabilize in rocks where the permeability is very low, and (4) the man-made gradient changes, due

to man's removal of water, oil, and gas that may or may not result in permanent gradient changes.

a. If the nonverticality of a borehole is taken into account, the water level in a well can be read to within 0.15 m at depths of 300 to 600 m; for wells spaced 1 km, this corresponds to an uncertainty of ± 0.00015 in the gradient, which is only 3% of the baseline gradient (.005) currently used in the model. This hypothetical error, however, is greater than the gradient in some areas (for example, the Nevada Test Site) so that unless the spacing of wells is adequate, the direction of groundwater flow can be indeterminant.

Predictions of the wrong flow directions would lead to incorrect assumptions about potential migration paths for radionuclides and discharge locations to the biosphere.

b. Spatial variation in hydraulic gradient is strongly dependent upon local geology. Typically, variations of 2 to 3 times over distances of several km are common in relatively uniform sedimentary strata where petroleum and/or water production are minimal (Mercer and Orr, 1977).

c. Time periods of months to years may be required for water levels to stabilize in wells where the rocks are relatively impermeable (Mercer, 1978). After a permanent observation well is cased and cemented, the casing is perforated at the desired stratum by firing projectiles through the casing and cement into the rock. If the rock has very low permeability, or if the permeability is due to fractures not penetrated by the projectiles, the water levels may rise very slowly.

d. Pumping of oil, water, or gas can reduce hydraulic heads by hundreds of meters. Little is known about whether such changes can be permanent, because in most areas where heads have been artificially lowered, pumping has never been stopped long enough for the recovery of hydraulic heads to be observed.

More significantly, in many bedded salt areas, petroleum production is so extensive, and original head data so sparse, that the magnitude of man-made changes is unknown. Caution should be used in interpreting hydraulic head data where oil, gas, or water production has taken place.

4. UNCERTAINTIES ASSOCIATED WITH GEOPHYSICAL EXPLORATION AND DRILLING

4.1 Introduction

Several techniques of geological and geophysical exploration are applicable to the problem of detecting geological features that represent potential hazards to a nuclear waste repository in bedded salt. Exploring a proposed repository site in bedded salt is particularly aided by technological developments encouraged by the salt mining and petroleum industries. For example, radar equipment to probe salt was developed for the purpose of detecting water hazards in salt mines.

Some of the methods discussed below can be used not only to detect local hazards, but also to define regional geology. For instance, local gravity surveys may detect solution cavities, while regional surveys may reveal large-scale trends in basement rocks. Drilling programs, which may be used in an effort to detect cavities, breccia pipes, shale interbeds, or other features at a particular site, may also be used to correlate stratigraphy over wide areas and to infer large structural features. The discussion of this section is generally limited to the detection of local features.

A section on each of the following techniques is included in this report: seismic surveys, radar, electrical resistivity, gravity, and magnetic surveys, and drilling. Each section includes a brief introduction to the theory behind the technique, followed, in certain cases, by sample calculations to illustrate the limitations of the method and/or examples published in the literature describing its application to salt deposits.

4.2 Seismic Reflection

Seismic reflection methods are used to map subsurface geologic structures by measuring the time required for a seismic pulse generated at the surface to return after reflection from lithologic boundaries. The source of seismic energy used depends on the desired energy and wave-length of the pulse. Some common sources are explosives, dropped weights, and vibrating masses. Reflected signals are received by arrays of geophones, recorded, and processed by computer. The final display of information resembles a continuous cross-section of the subsurface, with a few important differences. One is that depths are presented in units of seismic travel time, not in units of depth, which

means that any variations in velocity, either vertical or lateral, will distort the "time section" relative to the actual geologic structure (Dobrin, 1976). Another source of distortion is the uncertainty in ray-path geometries of seismic propagation (Dobrin, 1976). Measurements of seismic velocity in the strata are used to solve for that uncertainty, to "migrate" the section to show true structure, and to present the section with depth rather than time on the vertical scale. Modern digital computer techniques permit determining seismic velocities from the reflection data. Borehole determinations of seismic velocity, where available, give independent values and are used to calibrate the computed values.

As a rule, seismic methods can resolve reflecting surfaces no closer than one wave-length of the seismic pulse. Thus, resolution capability is directly related to the frequency of the seismic source. The ability of seismic waves of a given energy to propagate through the subsurface is, however, inversely related to frequency. Therefore, the considerations of desired depth of penetration and degree of resolution must be balanced. High frequency sources are used for shallow, detailed investigation, while lower frequencies are used for deeper surveys and yield less resolution. No matter what frequency is used, however, resolution decreases with depth since high frequency energy is filtered out progressively with depth. For instance, the wave length of a typical seismic pulse may be on the order of 60 m after passing through 3,000 m of section (Dobrin, 1976).

The natural filtering action of the earth causes reflection time lags analogous to phase lags of electronic filters (Dobrin, 1976). In sedimentary environments where seismic velocities commonly range between 3,000 and 5,000 m/sec, the lag could represent an uncertainty of as much as 400 m in depth. This factor makes accurate determination of absolute depths to a reflector difficult. However, relative differences in depth to the same reflector at two stations can be determined if the sonic velocity characteristics of the section do not change laterally, permitting the assumption of equal lag at the two locations. If the reflection quality is good, structural relief between the points can be mapped with an accuracy of 1 to 2 ms (Dobrin, 1976). Furthermore, if velocities are laterally constant, and the seismic survey lines are "tied" to a nearby well for which velocity logs exist, the absolute depths to reflectors can be determined with similar accuracy, which translates to about 3 to 10 m (Dobrin, 1976; Griswold, 1978).

Bedded-salt basins are characterized by distinctively-layered rock strata. Sonic velocities are relatively constant within a given rock unit, and accurate seismic mapping is commonly possible. Interpretation of seismic records is somewhat an art, however, and experience is necessary to correctly determine subsurface structure from the sometimes subtle features on the seismic record. The petroleum industry has many years of experience interpreting folds and faults from seismic information, while detection of such features as breccia pipes and solution cavities is more uncertain.

Cook (1974a) describes experiments to map the outlines of a solution cavity by seismic reflection and predicts theoretical limits on the precision of the method. High seismic frequencies should be used, 100 Hz being a good compromise between attenuation and resolution considerations. Sample calculations show that cavity boundaries 300 to 2,500 m deep should be locatable with an accuracy of about 6 m (Cook, 1974a).

Griswold (1977) reports the results of both shallow and deep seismic surveys in the Delaware Basin. The shallow surveys were not successful because the attenuation of the high frequency signals was too severe. The deeper surveys were more successful, resolving not only folds, but also features interpreted as breccia pipes (Griswold, 1977; 1978).

Seismic surveys possess three major advantages over drilling programs in characterizing the subsurface at a repository site: seismic methods are cheaper, they do not breach the salt, and they give a two-dimensional picture of the subsurface rather than the one-dimensional picture given by a borehole. Drilling and seismic methods used cooperatively are particularly useful, as boreholes can be used to calibrate the seismic information, and, in turn, the seismic records provide a means for interpolating between boreholes. In addition, the seismic records can identify anomalies which can then be investigated in detail by boreholes.

There is another method, called seismic refraction, which measures arrival times of seismic waves refracted by contrasts in seismic velocity at depth. Interpretation of the data is based upon Snell's Law, which relates the angle of incidence to the angle of refraction of waves for a given contrast in velocity across a boundary. While the reflection method results in a detailed cross section of the subsurface, the refraction method yields only the depth to, and seismic velocity in, at most, four to five layers. Simple structural features, such as dips of beds, and faults, can be determined. Resolution of refraction techniques is poorer than that of reflection techniques, however.

Refraction techniques are useful in only a narrow range of geologic environments. The geologic structure must be relatively simple, and the velocity of successively deeper strata must increase for interfaces to be detectable. Refraction is particularly useful where there is a small number of horizons with wide areal extent and laterally continuous properties (Dobrin, 1976). To be detected, a horizon must be overlain by a lower velocity stratum, and the velocity contrast should be high for accurate depth determinations. Dobrin (1976) suggests that mapping the thickness of the sedimentary section in a basin is an appropriate task for refraction techniques, as the boundary between high velocity crystalline basement rocks and overlying low velocity sedimentary rocks is distinct.

Anomalous velocity profiles can lead to erroneous interpretations of the refraction record. For instance, a low velocity layer sandwiched between two high velocity zones cannot be detected at all, and the depth to deeper detectable layers is miscalculated (Dobrin, 1976). A dissolution cavity or rubble-filled breccia pipe, being such a low velocity zone, is not detectable with seismic refraction. Also, near-surface high velocity layers can mask deeper marker beds (Dobrin, 1976). This effect can be overcome by using seismic wavelengths long compared to the thickness of the masking bed; such long wavelengths may be obtained by using wide source-detector spacing, due to the filtering effect of the earth (Dobrin, 1976). In the Delaware Basin, spacing of more than 30 km was used to penetrate the salt strata and measure the depth to deep Devonian limestone at depths of approximately 4500 m (Dobrin, 1976). The detailed stratigraphy of the sedimentary rocks, which would have been recorded in a seismic reflection survey, was not obtained with the refraction survey.

4.3 Radar

Salt deposits, either dome or bedded, are generally considered to be dry. However, there are some accumulations of fluid which could be dangerous to a mine if intersected by excavations: for instance, faults, shale interbeds, brine cavities, and old boreholes. A radar system has been developed for probing salt and is now used on a regular commercial basis to detect water hazards in the vicinity of salt mines.

Regardless of the medium through which they travel, radar waves are reflected by discontinuities in the electrical properties of materials in their path (Unterberger, 1977). Radar systems use this phenomenon to detect and locate targets by measuring the time elapsed between sending a signal and receiving its reflection. If the speed of the waves in the medium is known, the distance to the reflecting target can then be computed. Reflections can be timed with an accuracy of ± 0.05 microsecond, which in salt corresponds to an uncertainty of ± 3 m (Stewart and Unterberger, 1976). The angle subtended by the radar beam in some systems permits knowing the horizontal direction of the target within $\pm 9^\circ$ (Stewart and Unterberger, 1976).

In the case of rock, electrical discontinuities can be due to lithologic changes or to local variations in the amount of water in the rock. The problem is, however, to get radar waves to propagate long distances through the earth, as moisture in rock dissipates the energy of radar signals. Moisture contents as low as $\frac{1}{4}\%$ in the rock will render radar useless (Unterberger, 1977). Most success in "looking through" rock with radar has been achieved in salt because it generally has a low moisture content (Unterberger, 1974a). Radar equipment must be used from within the mine workings to take advantage of the dry environment.

Since geologic surfaces that reflect radar waves are rough compared to the wave length of the signals, reflections of the radar beam are dispersed. Thus, the reflection does not behave like reflections from mirrors and other smooth reflectors. The dispersion enables planar features at low angles relative to the beam direction to be detected (Unterberger, 1978).

Radar does have some limitations besides being useful only in dry environments. It cannot detect faults and fractures that do not cause a change in the electrical properties of the rock. It also cannot detect healed collapse breccias, filled cavities, or healed faults, which may be more permeable than the surrounding salt but which do not contain groundwater. By itself, radar cannot ascertain what the reflector actually is. Knowledge of the local geology, plus the orientation of the reflector, may provide some clues, such as whether the reflector is a lithologic or structural discontinuity.

The same trade-off between penetration and resolution that limits seismic reflection methods also applies to radar reflection techniques. Several different kinds of radar units have been developed for use specifically in dry salt deposits.

Low frequency (230 MHz), high power units are used to detect large targets relatively far away (over 1,000 m). Intermediate frequency (440 MHz) and power are used for medium ranges. Higher frequency, low power units are used for close range work (50-500m) (Unterberger, 1977). A special microwave FM radar set, which is very accurate, has been developed for use at ranges of less than 30 m (Unterberger, 1974a). In theory, a laser radar should be a more efficient and powerful tool than normal radar, but it has not yet been developed (Unterberger 1974b).

Radar systems have detected gas- or brine-filled cavities, brine-filled porous material, and such subtle features as anhydrite layers within salt deposits. Detection of moist shale layers within the salt should be possible, although examples of this application are not documented. Reflections have been received from targets as distant as 2,000 m, but most work is done at much closer ranges, as the operators of salt mines are generally uninterested in such remote hazards (Unterberger, 1977).

In general, radar is reliable to a range of somewhat more than 300 m (Unterberger, 1978). Cook (1974b) suggests that an 8 cm fissure should be detectable at a distance of 85 m; Unterberger (1977) claims a brine-filled petroleum well could be located from up to 1,000 m away. The following is a partial list of the available details of successful attempts to locate mine hazards:

1. An old, brine-filled petroleum exploration hole was located inside a large mine pillar to within 3 m of its mapped location by measurements taken at 6 radar stations located about 50 to 80 m away (Cook, 1974b).
2. A fault was detected near a mine 400 m ahead of the mine face at which the radar was stationed (Unterberger, 1977, 1978).
3. A radar survey was performed in a dome salt mine in advance of sinking an air shaft. Looking up from the mine level 1,241 ft (378 m) below the surface, it was possible to detect the upper mine levels which existed 334 ft (102 m) and 515 ft (160 m) above the observation station. In addition, discontinuities at 630 ft (192 m), 739 ft (225 m), 1,015 ft (309 m) and 1,074 ft (327.4 m) above the radar station were detected. Excavations for the shaft have so far encountered the upper two discontinuities, which were water-bearing units at 1,069 ft (325.8 m, a 5-ft {1.5 m} error) and at 1,015 ft (309 m, no error) above the mine level (Unterberger, 1977).

4. Radar probing in a salt dome mine measured 518 ft (157.9 m) between a mine level and the salt-anhydrite contact above. The actual distance, measured in the shaft was 519 ft (158.2 m, a 1-ft (0.3 m) error). Also, reflections interpreted as anhydrite stringers in the salt were detected at distances of 335 ft (102 m) and 359 ft (109 m) (Unterberger, 1977, 1974a).
5. The short-range FM system accurately outlined a tunnel 4.5 to 10 m below the mining level from which it was used. Also, mine-related fractures oriented at a low angle to the radar beam were detected (Unterberger, 1977).
6. In two cases, radar data and seismic data were compared, and the comparisons proved the radar to be more accurate. Because radar waves are generally of shorter wave length than seismic waves, this result is expected. In one case, seismic-generated contours located the potentially hazardous flank of a salt dome 210 m from a mine perimeter. Radar probing indicated a distance of 292 m. Based upon the radar results, the mine was extended 60 m towards the flank with no harmful results (Unterberger, 1977). In another case, the top of a salt dome was mapped both by seismic and by radar methods. Drilling of the top of the dome proved the radar data correct and the seismic data erroneous where the two differed (Unterberger, 1977).
7. Radar has been tried in other kinds of rock besides salt, but minimal penetration has been attained. Reflections have been received in experiments using low power equipment through only 13 m of hard limestone and 18 m of coal. The theoretical working range in most hard (well-consolidated) rocks is on the order of 75 m (Cook, 1972).

Variations on the radar technique have been devised to overcome some shortcomings of the basic system. A sonar device has been developed to probe wet salt or other moist rock environments which radar cannot penetrate. The device is reliable to almost 250 m, although it has detected reflections from targets as distant as 400 m (Unterberger, 1977, 1978). Neither sonar nor radar work effectively from the surface because groundwater dissipates the radar energy, and air-filled voids in the unconsolidated sediments absorb sonar energy. Sonar has been tried from the surface on a few occasions, but penetration of only 6 to 10 m could be attained (Unterberger, 1978). Radar is limited to a similar range when used from the surface.

At least two borehole devices have been developed. One is a borehole radar device which, when tested in a salt dome, proved to be potentially useful. Some refinements are needed, for example, those permitting the direction of reflectors to be measured. The device accurately outlined the flank of the salt dome a maximum of 250-275 m away and detected a brine-soaked potash zone. Reflections were received at ranges up to 400 m (Holser *et al*, 1972). An important limitation of this system is that it does not yet allow determination of the direction to reflectors.

Another borehole device was developed to detect hazards in advance of tunneling. The equipment consists of an array of radio transmitters and receivers lowered down boreholes drilled in advance of tunneling operations. Although details of the performance of the device are scanty, it is known that transmissions have been received through as much as 330 m of granite. In addition, water pockets have been detected in granite (Geotechnical Engineering and Construction, 1978).

4.4 Electrical Resistivity

Electrical resistivity methods are used to detect variations in the electrical properties of the earth, by which inferences can be made about subsurface conditions. The resistivity of rock materials is governed by rock mineralogy and porosity, and by the chemistry of fluids present in the pore spaces. Resistivity generally decreases with increasing porosity and with increasing fluid salinity. In many geologic environments, resistivity is a property distinctive of individual rock formations. Resistivity can be measured in boreholes (Schlumberger, 1972, 1974), and mines (Scharon, 1963), or from the surface (Dobrin, 1976; Griswold, 1977). This discussion treats the last two applications.

Resistivity is determined in the field by introducing a known current to the earth through a pair of electrodes, and measuring the potential difference (voltage) across another pair. The depth of current penetration into the earth depends, in part, upon the electrode spacing: the wider the spacing, the deeper the penetration.

Ohm's Law governs the flow of electricity through a homogeneous body. The resistance of a body can be expressed by a form of Ohm's Law:

$$R = \frac{V}{I}$$

where R = resistance, V = the potential difference measured across the body, and I = the current flowing through the body.

The resistivity of the material in the body is expressed as the resistance of a unit cylinder of the material:

$$\rho = \frac{RA}{L}$$

where ρ = resistivity, R = resistance, A = cross-sectional area of the unit cylinder, and L = length of the unit cylinder. The earth, however, is not electrically homogeneous. Thus, the resistance measured at the surface is determined by all the different zones of resistivity penetrated by the measuring current. This measured quantity is called the "apparent resistivity" of the earth (Dobrin, 1976).

If the earth were electrically homogeneous, current flow lines for a typical pair of current electrodes on the surface might appear as in Fig. 1b. Variations in resistivity would distort the flow lines because current lines are deflected towards zones of lower resistivity and away from zones of higher resistivity (Fig. 1a). Thus, in a simple two-layer model of the earth, if the upper layer has a higher resistivity than the lower layer, the flow lines might be distorted as in Fig. 1c. By measuring the apparent resistivity of the earth at various locations, these distortions can be mapped, and subsurface structure inferred.

Resistivity measurements are acquired by the continuous profiling or the vertical sounding methods (Dobrin, 1976). In the former, an electrode array of fixed spacing is moved over the surface to detect lateral variations in resistivity above the maximum depth of current penetration. In vertical sounding, an electrode array is expanded about a fixed center to detect vertical discontinuities.

Resistivity data are interpreted by comparing field measurements to those predicted by assumed models of the earth. To interpret stratigraphy, measurements of apparent resistivity obtained by vertical sounding are plotted against electrode spacing. The resulting curves are compared with master curves predicted for two, three, or four-layer models, which have been published (Dobrin, 1976). Modern digital computers make possible the construction of a master curve for any layered sequence (Dobrin, 1976). Separate curves are needed in the case of dipping or vertical strata. The model that results in the closest approximation of the data, and is, in the opinion of the analyst, geologically reasonable, is chosen as the best approximation of the subsurface.

Resistivity anomalies due to discrete rock masses are also interpreted by the modeling approach. The target body is generalized as a geometric form (i.e., a sphere or a cylinder, etc.), and predicted measurements are compared with actual measurements. An important limitation is that a buried sphere apparently cannot be detected when its top is at a greater depth than its radius (Dobrin, 1976). In the context of bedded salt deposits deep enough to be considered for a repository, this limitation generally means that spheroidal brine cavities cannot be detected from the surface, as the depth to the salt is large compared with reasonable cavity radii. Filled sinks (depressions occurring where soluble rocks lie near the surface, caused by solution or solution cavity collapse) and some breccia pipes extending near the surface can, however, be detected.

Scharon (1963) documents two experiments, one in dome salt and one in bedded salt, in which resistivity methods were tried in salt mines. The conclusion of that report is that although resistivity methods can easily measure resistivity anomalies in salt mines due to moisture-content variations, interpretation of the data is difficult. The complicated mine-related features such as brine pits, pillars, and rooms prevented effective analysis of the results, since each introduces its own component of the measured anomalies which must be included in the interpretive model.

Applications of resistivity methods from the ground surface for the detection of features important to the siting of a repository have met with somewhat more success. For instance, a shallow buried sink in limestone, filled with shale, was detected and modeled by assuming a hemispherical shape (Fig. 2) (Dobrin, 1976; Cook and Van Nostrand, 1954). Comparison of the actual geology of the sink with the model shows that some information was lost: while the maximum diameter of the sink was closely modeled, the maximum depth was not. Also, the alluvial cover was not included in the model. In another experiment, faults interrupting an aquifer were located by resistivity methods. The fault locations were later confirmed by drilling (Dobrin, 1976; Ginzburg, 1974).

An experiment to detect dissolution in the Rustler formation of the Delaware Basin is discussed by Griswold (1977):

"The objective is to determine lithologic changes with depth, as shown by changes in electrical resistivity. The salt is highly resistive in relation to the siltstones and sandstones of the (overlying) Dewey Lake and Santa Rosa Formations. If salt and anhydrite are present in the Rustler (formation), they should show a corresponding increase in resistivity and can be de-

tected. If the salt has been removed and the anhydrite converted to gypsum, then the surveys might reflect the top of the first salt in the Salado Formation. Unfortunately, the results of the field work do not support this hypothesis. Apparently, the varying thickness of the Santa Rosa and Dewey Lake beds overwhelm the electrical response of the underlying salt beds." (Griswold, 1977).

More detailed (shallow) electrical surveys designed to investigate two known and three suspected breccia pipes, all with surface expression, were carried out as part of the same experiment. Measurements taken over the known pipes indicate that the features have easily detectable resistivity anomalies relative to the undisturbed strata. All of the three suspected pipes were detected, and the resistivity technique proved adequate to further define their geometry: two of the three structures are evidently deep-seated, and one is only a shallow sink (Griswold, 1977). Breccia pipes whose tops are buried deeper than 150 m were not detectable in this survey (Griswold, 1978).

Electrical resistivity methods appear to be useful for the detection of features that extend to, or close to, the ground surface. Resistivity work in salt basins is facilitated by the strong resistivity contrasts between brine and fresh water, between wet salt and dry salt, and between evaporite and other rock types. There are distinct limitations, however, to the modeling approach of data interpretation. One is that complex features are hard to model and interpret. Geometric simplification inevitably results in lost information and reduced accuracy. Another limitation is that the modeling of resistivity data provides non-unique solutions. Geologic and geophysical controls independent of resistivity measurements can aid in narrowing the range of possible interpretations.

4.5 Gravity Surveys

A volume of material at depth, called a target, with a density different from that of the surrounding rock, may be detectable at the surface by measuring local variations in the earth's gravitational field. The instrument precision available for measuring these gravity anomalies is ± 0.01 milligal (mgal)* for standard land gravity meters, and ± 0.002 mgal for modified portable meters (Speed, 1970). If the target is a dissolution cavity, limitations on detectability are generally set by the level of background variation in gravity measurements. A target can be located only if the gravity anomaly due to it is of greater amplitude than the amplitude of the background variations, or "noise."

*1 gal is an acceleration of 1 cm/sec^2 .

Noise is introduced to the gravity background by three principal sources: variations in local topography, earth tides and other time-variable phenomena, and inhomogeneities in the subsurface density due to bodies other than the target (Speed, 1970). Noise can be "filtered out" of the background, to some degree, by careful consideration of the variables. Of the three sources, time-variable phenomena are easiest to filter out. Careful measurements at a base station gravity meter can define the amplitude and periodicity of the variations, which can then be subtracted from exploratory measurements (Speed, 1970).

It is more difficult to filter out effects of topographic variations, and complete elimination of noise due to this source is impossible for the following principal reasons:

- a. There is a $\pm 5\%$ or more uncertainty about the bulk density of rocks making up the local topography. The error introduced by this uncertainty depends upon the amount of relief in the survey area. For 3 m of relief, about 0.013 mgal, and for 30 m of relief, about 0.132 mgal errors are introduced (Speed, 1970). The larger the area, the higher the included relief is likely to be.
- b. Topographic control for 150 to 300 m around each station is important for a "terrain correction." Accuracy in defining topography of about 0.3 m is available with aerial surveys (Speed, 1970). U. S. Geological Survey maps are generally accurate to one contour interval, which, for is 10 ft. The error introduced by imperfect control depends in a complex way upon the amount of relief in the survey area; for 3 m of relief, about 0.02 mgal is introduced; for 30 m, 0.044 mgal is introduced (Speed, 1970).
- c. Limitations in determining the latitude and elevation of the gravity meter stations introduce an error where magnitude depends upon the precision of the survey. For each meter of uncertainty in absolute elevation, about 0.225 mgal uncertainty is introduced to gravity measurements (Dobrin, 1976). In middle latitudes, 0.082 mgal uncertainty would be introduced by 100 m of north-south positional uncertainty (Dobrin, 1976). Speed (1970) suggests that highly-precise surveys could limit noise due to positional uncertainty to ± 0.016 mgal.

The total amount of noise introduced by the three sources of uncertainty in an area with surface relief of 3 m is about 0.0446 mgal and in an area of 30 m relief is about 0.187 mgal (Speed, 1970). Anomalies below these values cannot be distinguished from noise and are, therefore, undetectable.

Once the effects of background noise are eliminated as much as possible, the third problem must be considered. As with resistivity data, the interpretation of gravity data is undertaken by the modeling approach, and solutions to the data are frequently non-unique because an anomaly can be due to various subsurface features. For instance, deep structure in the crystalline basement, intrusive bodies, and other features such as lithologic changes and faults can all cause gravity anomalies. Experience, knowledge of local geology, and other geophysical information can help in distinguishing the source of the anomaly.

The following example of cavity detectability is taken from Speed (1970):

The shape of breccia pipes and some solution cavities in bedded salt may be approximated by a cylinder. The gravity anomaly produced in this case is expressed by the equation:

$$\Delta g = \frac{2\pi G(d_2 - d_1)r^2c}{z^2} \left(1 + \frac{4c^2 - 3r^2}{2z^2}\right)$$

Δg = gravity anomaly due to target cavity
 G = gravitational constant ($6.67 \times 10^{-8} \frac{\text{N m}^2}{\text{kg}^2}$)

d_2 = density of salt
 d_1 = density of brine
 r = radius of cavity
 c = $\frac{1}{2}$ height of cavity
 z = depth to center of cavity

For estimating detectability of a cavity, assume that the radius and height are small compared to the depth of the cavity. Thus, $\left(1 + \frac{4c^2 - 3r^2}{2z^2}\right)$ approaches 1; the equation

becomes $\Delta g \approx \frac{2\pi G(d_2 - d_1)r^2c}{z^2}$.

First, assume an open cavity, filled with brine but not rock debris. The density of salt is approximately 2.2 g/cm^3 , and the density of brine approximately 1.2 g/cm^3 . Thus, $d_2 - d_1 = 1 \text{ g/cm}^3$.

If the depth to a cylindrical cavity is 300 m and if the cavity has a radius of 30 m and a height of 30 m, then

$\Delta g \approx 0.0063$ mgal. (Figure 3 shows the graphical means of estimating Δg of this cavity.)

Even with only 3 m of relief, a cavity of these dimensions is not detectable (see Fig. 3, where the limits of detection are plotted in relation to cavity anomalies). In the northern Delaware Basin, although there are some 2 to 5 km² areas with less than 3 m of relief, 10 to 15 m of relief over such an area is a common minimum. Since gravity measurements are taken over a several square kilometer area, only relatively large near-surface cavities, can be detected in the Delaware Basin.

The results of experiments in the detection of breccia pipes indicates that, in practice, breccia pipes are undetectable by means of gravity techniques. Detailed gravity surveys were run over two known and three suspected pipes, all of which had surface expression. The best available instrumentation was used, and station spacing was relatively close, 30 to 60 m. No detectable anomalies were measured (Griswold, 1977).

This result is not unexpected. Although breccia pipes may extend to, or near, the surface, they are filled with rubble and are possibly healed, which greatly reduces the density contrast between the breccia pipe and undisturbed salt. Evidently, the latter effect, which tends to reduce detectability, overwhelms the former effect (i.e., proximity to the ground surface), which tends to increase detectability.

4.6 Magnetic Surveys

Magnetic surveys are used to broadly characterize the geometry of sedimentary basins, to locate igneous intrusions, and to prospect for selected mineral deposits. The following discussion shows why the method is ill-suited to explore for most types of hazards to a radioactive waste repository in bedded salt.

Magnetic surveys have much in common with gravity surveys: both methods measure variations in a natural potential field of the earth over the survey area. The data are then corrected for several measurable effects, with uncertainties usually on the order of 10-15 gammas (a gamma is the standard cgs unit of magnetic field strength used by geophysicists), and modeling techniques are used to interpret the corrected data (Dobrin, 1976). The magnetic field is measured by using one of several different kinds of magnetometer with precisions ranging from 0.005 gammas to 12.5 gammas (Dobrin, 1976). Surveys can be performed using aircraft or a grid of discrete ground stations.

The earth is not magnetically homogeneous on even a large scale, and a map of its actual magnetic field intensity shows large-scale anomalies due to deep, poorly-understood subcrustal processes (Fig. 4a). Superimposed upon these large-scale anomalies are the smaller-scale anomalies due to local variations in magnetic susceptibility at crustal depths caused by local, crustal geologic structure. Magnetic susceptibility, which is a characteristic physical property of a material, is a measure of how much magnetism is induced in the material by an externally-applied magnetic field (i.e., the earth's). Susceptibility of entirely nonmagnetic substances is zero. Typical values of susceptibility for various rocks and minerals are presented in Fig. 4b and below:

<u>Material</u>		<u>Susceptibility (cgs units)</u>
iron minerals	magnetite	300,000 - 800,000
	ilmenite	135,000
	hematite	3,000
	calcite	-1
	quartz	-1
	rock salt	-1
	dolomite	14
	sandstone	17
	basalt	680
	granite	28 - 2700
(from Dobrin {1976} and Howell {1959})		

Since greater anomalies are produced by bodies of rock having greater magnetic susceptibilities, the above information indicates that the detectability of a feature is primarily a function of its iron mineral content. The amplitude of anomalies arising from ore bodies are generally in the range of hundreds to thousands of gammas, and instrument precision and data corrections are generally not limiting factors in the detectability of these features. On the other hand, the lack of contrast in the low susceptibilities of normal sedimentary rocks means that local structures involving only sedimentary rocks are generally not detectable with magnetic surveys. Structures such as cavities or breccia pipes within a bedded-salt repository layer would not be detectable. The one exception is that salt domes may have slight negative anomalies associated with them (Dobrin, 1976). The principal use of magnetic surveys, then, is to model the configuration of the igneous and metamorphic basement beneath sedimentary rocks and to detect igneous intrusions such as basalt dikes within the sedimentary rocks. Griswold (1977) reports that magnetic surveys were used to establish the trend of a dike near the WIPP site in New Mexico.

The amplitude of the magnetic anomaly arising from a body is directly related to the amount of highly-susceptible material in the body and inversely related to the square of the distance to the body. Modeling of magnetic data is complicated relative to modeling of gravity data by such subtle factors as the orientation of the anomalous body in the earth's magnetic field and whether the anomalous body has magnetism associated with either previous orientations of the earth's magnetic field or previous orientations of the body with respect to the surface of the earth.

Airborne surveys are the most common magnetic survey technique due to their speed, economy, and accuracy (Dobrin, 1976). The altitude of the survey and the coarseness of the grid pattern strongly affect the resolution of the technique. Resolution decreases with increasing survey altitude. For instance, closely-spaced anomalies are generally not resolvable if the survey altitude above land surface is greater than the difference between the horizontal separation of the anomalies and their depth of burial (Dobrin, 1976). In one case, a survey at 1,000 ft altitude resolved two closely-spaced anomalies with amplitude of 2,400 gammas. A survey flight at 4,000 ft over the same location picked up one broad anomaly of 850 gammas, and a flight at 10,000 ft did not detect any anomaly (Dobrin, 1976). Spacing of the flight grid is also critical in detecting near-surface anomalies, since anomaly amplitude falls off rapidly with distance. For instance, line spacing of $\frac{1}{2}$ mi did not detect a 2,000 gamma anomaly that was detected by a $\frac{1}{4}$ mi grid (Dobrin, 1976). The size and shape of the target determines the effect of grid spacing on detectability. Intrusive dikes, due to their elongation, are relatively easy features to detect.

In summary, most geologic structures in sedimentary basins cannot be detected with magnetic surveys, and with the possible exception of igneous dikes, those that can be detected would also be detected in seismic reflection surveys.

4.7 Drilling

Breccia pipes and solution cavities have been accidentally discovered by boreholes in salt deposits. However, a drilling program designed to explore systematically for such relatively small features over a potential three square mile (7.7 km^2) repository site is inefficient, even though such a program is the only direct sensing method available, short of mining the repository openings.

This discussion assumes that a breccia pipe or brine cavity is always recognizable if it is intersected by a borehole, and that the features are circular in plan view. The latter assumption is for mathematical simplicity only, since the theory is perfectly applicable to elliptical targets. Also for mathematical simplicity, an infinite square drilling grid is assumed. Of course, in actual drilling programs, an infinite grid is not needed, only one that completely covers the investigation area. Treatment of the general elliptical target, to be detected by a square, rectangular, or hexagonal grid, is available (Singer and Wickman, 1969).

The case of hitting a target of radius b with a grid of spacing c is equivalent to the case of the center of the target falling within one of the circles of radius b centered on each point of the grid (Figs. 5a and b). That is, their probabilities are the same (Singer and Wickman, 1969). The probability is expressed by $p = \frac{\text{area of target circle}}{\text{area of unit grid}} = \frac{\pi b^2}{c^2}$ when $b \leq \frac{1}{2} c$ (when the grid-centered circles of the transformation in Fig. 5b do not overlap (Singer and Wickman, 1969)).

When $b > \frac{1}{2} c$, it is possible to get one or more hits. For example, in Figs. 5c and d, if the center of the target falls in area x, no hit will be recorded; in area y, one hit; and in area z, two hits will be recorded. The probability of each of these cases is as follows:

$$P(0 \text{ hits}) = \frac{\text{area of x}}{c^2}$$

$$P(1 \text{ hit}) = \frac{4(\text{area of y})}{c^2}$$

$$P(2 \text{ hits}) = \frac{4(\text{area of z})}{c^2}$$

(Singer and Wickman, 1969).

In the application to finding hazards, the probability of detection (i.e., one or more hits) is of interest.

$$P(1 \text{ or more hits}) = 1 - P(\text{no hits}) = 1 - \frac{\text{area of x}}{c^2}$$

Singer and Wickman (1969) use a computer program based upon this geometric analysis to calculate the probability of detecting various-sized targets with different grid spacings. Part of their results is excerpted in the following table (Singer and Wickman, 1969):

Diameter of Feature*	Probability of Detection				
	99%	95%	90%	50%	20%
100 m	77 m	83 m	91 m	125 m	200 m
200 m	154 m	167 m	182 m	250 m	400 m
.	.	.	.	.	.
.	.	.	.	.	.

*grid spacing and diameter of feature can be linearly scaled.

The table gives the grid spacing necessary to detect a feature of a given radius with the desired probability.

For example, if it is desired to make 95% sure that there is no cavity or breccia pipe of radius 200 m or more within a 3 mi^2 (7.7 km^2) site, a grid spacing of 167 m is necessary and it would take approximately 300 holes to explore the site at the desired level. For exploration at a higher level of certainty, or for smaller targets, the number of boreholes increases. A drilling program involving such a large number of holes would probably be counterproductive to the goal of ensuring repository integrity. A more reasonable alternative would be to locate anomalies at a site with remote-sensing devices and then to explore these limited areas by drilling.

Drilling permits the recovery of subsurface material for examination and testing on the surface. It also enables the use of down-hole geophysical sondes to measure in-situ rock properties and borehole determinations of velocity aid the interpretation of seismic data. Thus, although drilling is not useful to systematic exploration efforts for localized hazards to a repository, it is valuable as a tool for characterizing the general geology of a site. It has the serious disadvantage of creating a potential path for radionuclide migration.

4.8 Conclusion

Three classes of exploration techniques for the detection of local hazards to a repository in bedded salt have been examined in this report: direct observation, techniques based on "potential fields" (i.e., gravity and electric fields), and those employing waves to probe the subsurface. Table 1 summarizes the classes and techniques.

The only direct observation method, drilling, has the advantages of enabling core retrieval and the use of down-hole instruments to measure rock and fluid properties at depth. However, drilling is an inefficient technique for exploring for localized hazards because each well can only investigate the variation of geology with depth: i.e., only a one-dimensional view of the subsurface is obtained. Furthermore, while borehole logging measurements may be detailed and precise, they cannot measure rock properties more than a short distance from the well. The presence of numerous exploratory holes at a site may compromise repository integrity.

The "potential field" methods, on the other hand, are remote-sensing techniques and can be used from the surface without disrupting the salt. Gravity, magnetic and resistivity surveys are usually less expensive than drilling, and can provide three-dimensional information. Potential field methods, especially airborne magnetic surveys, can proceed much more rapidly than other exploration techniques. All potential fields, however, are "smooth, weak and essentially featureless at a distance from the 'source' (the target) which is large compared to its dimensions" (Cook, 1974a). Thus, methods based on potential fields are inherently

"blunt," and their limited resolution is "an inherent consequence of the basic laws of physics, without regard to the practical engineering problems or the 'noise' interferences..." (Cook, 1974a). Because of noise, only large and/or near-surface features can be detected at all, while the modeling approach to interpreting the data results in non-unique and frequently oversimplified solutions. Knowledge of local geology and rock properties is necessary to narrow down the possibilities.

Resistivity methods have performed fairly well in detecting near-surface features, but they have failed to detect potential hazards at depths of a few hundred meters. Gravity surveys appear to be unreliable in detecting local hazards at any depth, while magnetic surveys are able to detect only such local features as basalt dikes and other intrusions. Gravity and magnetics are most effective when used in regional surveys to broadly characterize depositional basins.

Exploration techniques employing reflected waves, whether seismic or electromagnetic, are, like potential field surveys, remote-sensing methods. However, resolution of the reflection methods, being dependent on the wave length of the signal used, is inherently greater than that of the potential field methods. Electromagnetic (radar) wave lengths on the order of one meter, and seismic wave lengths of a few meters are commonly used. Reflection methods "see" subsurface discontinuities in much the same way that people see objects. This method is inherently a more reliable system than the inferential modeling approach.

Seismic reflection methods do not endanger the integrity of potential repository layers, and give a two-dimensional record of the subsurface. Radar methods give two-dimensional results, which can be extended to three dimensions, but the equipment must be used from mined openings within the salt or possibly from boreholes. Both radar and seismic methods have performed well at detecting local hazards.

It is clear that a hazard-location program should employ all the methods discussed above, after geologic mapping and large-scale geophysical investigations have defined the regional geology of a potential site area. A program coordinating the several methods enhances the performance of each individual technique. For instance, borehole determinations of velocity are used to calibrate seismic records. Drilling, inefficient if used by itself, can be used to great advantage in directly sampling anomalies detected by remote-sensing. Geologic information from any source can aid the interpretation of gravity, magnetic and resistivity data.

Each method is particularly appropriate at different levels of site development. Relatively cheap remote sensing methods are useful for rapidly and nondestructively screening a wide area. As interest is focused on smaller and smaller favorable areas, resistivity and seismic surveys can be refined. Drilling can be kept to a minimum, being used to investigate geophysical anomalies near potential (relatively anomaly-free) sites. Current radar technology becomes useful at an advanced stage of site development, after mining is initiated.

5. UNCERTAINTIES ASSOCIATED WITH EXPLORATION AND EXPLOITATION OF MINERAL RESOURCES

5.1 Introduction

Bedded salt basins are a major source of salt, potash, and petroleum, and there is a potential conflict between ensuring the integrity of a nuclear waste repository located in bedded salt and exploiting these resources. Resolving the conflict has two aspects: (1) determining the locations and potential effects of disturbances of the salt and/or associated strata due to exploitation, and (2) estimating the resources lost by closing a repository site to future exploitation. This section discusses the former problem. A brief history of drilling and mining in bedded salt basins is presented to establish the geographic distribution of potentially hazardous features, and is followed by a discussion of the technology of drilling and completing boreholes to provide a basis for understanding the problems associated with plugging wells. Documented examples of the effects of wells and mines on fluid migration are provided, after which the state of records of exploitation activities is examined. Finally, the consequences of wells and mines upon waste repository siting and regulatory considerations are evaluated.

For the most part, this study focuses on the drilling and mining activities that have taken place in the Permian Basin in Kansas (the location of Project Salt Vault, an early AEC-funded repository study) and the Delaware Basin in New Mexico (the location of the Waste Isolation Pilot Plant (WIPP) site).

Wells are drilled in bedded salt basins to produce or explore for oil, natural gas, salt, potash and fresh water. The potential effect of such activities on the integrity of a nuclear waste depository situated within the salt strata depends greatly upon whether or not the well penetrates the salt. For instance, fresh water is produced from strata above the salt and any immediately-overlying impermeable rocks. As a consequence, water wells do not directly endanger a depository situated within the salt. On the other hand, oil and natural gas (hereafter referred to collectively as petroleum) may be produced from strata above or below the salt, while salt and potash, of course, occur within the salt. The potential effect of borings that do penetrate the salt strata depends upon the sealing effectiveness of the well lining (casing) and of the seals (plugs) that are placed in the well upon abandonment.

Similarly, the potential effects of mining are dependent on the geometry of the salt stratum relative to the mine openings. In particular, for those mines in which excavation results in collapse and subsidence of the overlying strata, there is the potential for fracturing and, therefore, increasing the hydraulic conductivity of the rock units in the zone of subsidence. Pathways are provided for the migration of water which may threaten the integrity of a nearby repository.

The uncertainties associated with estimates of the potential influence of wells and mines on the integrity of a repository include several factors, many of which are difficult to quantify for possible inclusion in the development of a computer model. For example, the time-frame of resource development in bedded salt areas is almost as important as the degree of exploitation because techniques of boring and sealing wells have improved with time, as have records and regulation of drilling activities. Areas significantly developed before the 1930's, prior to effective governmental regulation and record-keeping, are particularly likely to contain boreholes of unknown location and/or boreholes that are incompletely plugged. In addition, each state has its own regulations and regulatory history. Also, the workmanship of the driller, and the owner of the well are important factors, since records of older, bankrupt operations may be missing, and bankrupt or marginally profitable owners may not have been able to afford plugging their holes properly.

To a certain degree, similar, non-quantifiable factors govern the magnitude of the uncertainties associated with the potential effects of mining activities on the integrity of a repository in bedded salt.

5.2 History and Extent of Exploitation In Bedded-salt Basins

5.2.1 Petroleum (Drilling)

Bedded salt basins in the U. S. have, in general, been heavily drilled in the search for, and production of, oil and gas. Fig. 5 summarizes the number of wells and the earliest date of significant production in the major bedded-salt basins.

Exploitation of bedded-salt basins began at different times in different basins, and proceeded at different rates. For instance, in the Pennsylvania and New York portions of the Appalachian Basin, oil seeps had been noticed and used in colonial times, as had petroleum-contaminated water wells. The first wells drilled specifically for petroleum were completed in 1859 in Pennsylvania and in 1865 in New York (Landes, 1970). Production in both states reached early peaks (1882 in New York, 1891 in Pennsylvania), after which a decline in production through the early 20th century occurred. The industry revived with the introduction of new technology in the 1910's and 1920's (Landes, 1970).

Oil was discovered in Kansas in the 1860's, and first produced in the early 1890's (Landes, 1970). Not until 1923 did exploitation activities begin in earnest in salt areas of central Kansas (Walters, 1976). Likewise, oil was known to be present in Michigan as early as the 1880's, but significant production did not occur until the mid-1920's (Ells, 1971). Finally, the Williston Basin was not exploited until relatively recently, first producing petroleum in 1951 (Ashmore, 1971).

Although bedded-salt basins have been heavily-drilled in the last century, there are areas in each within which, for two principle reasons, the salt is relatively untouched. One reason is that the petroleum reservoirs may occur in readily-identifiable trends. For instance, in southeast New Mexico, the first significant production occurred in 1924 from the Artesia Field (Stipp and Haigler, 1956). Early drilling concentrated on and near the transition zone between the Delaware Basin and the Northwestern Shelf which is marked by the Capitan Reef. Not until the 1940's was drilling initiated in the northern part of the basin itself, which is the area of the proposed WIPP site (Netherland, Sewell, and Associates, 1974). On the other hand, petroleum in the Appalachian Basin does not occur in such marked trends, and drilling is more evenly distributed over the area.

The other reason is that in some basins, the petroleum may lie above the salt beds so that drilling does not disturb the salt. For instance, salt in the Permian Basin of New Mexico and Kansas lies above the petroleum reservoir rocks, and, therefore, all drilling must penetrate the salt. But in the Appalachian and Michigan Basins, the salt lies below many of the favorable petroleum rocks, and only relatively recently have drilling programs begun to explore for petroleum below the salt (Netherland, Sewell, and Associates, 1975). While there are 750,000 holes in the Appalachian Basin, many of which were drilled in the 19th and early 20th centuries, there are very few wells penetrating the salt (density about 1 per 100 mi²), and all of them are relatively new (Netherland, Sewell, and Associates, 1975).

5.2.2 Solution Mining

The history of solution mining is also disparate between salt basins. At one end of the spectrum lies the Williston Basin of Montana and North Dakota, where solution mining has yet to be practiced. There are, however, large, deep potash reserves in the Williston Basin, and solution mining is envisioned as a potentially economic way to exploit them (Singleton, 1978). Solution mining is practiced in the Canadian portion of the Williston Basin, where potash occurs nearer the surface (Singleton, 1978). On the other hand, the Kansas Permian and Michigan Basins have a long history of solution mining. In both Kansas and Michigan, a substantial industry, which is now defunct, developed prior to 1900 (Walters, 1976; Rarick, 1978). Different, modern operations continue today (see Section 4.5.2). The Delaware Basin of southeast New Mexico has a brief solution-mining history. Only two short-lived experiments were attempted and these occurred in the 1950's and 1960's (see Section 4.5.2).

5.2.3 Conventional Mining

Conventional mining is practiced in salt basins to extract potash and/or salt. Potash mining in the Carlsbad area of the Delaware Basin began in 1931. Over the years, the workings have grown to comprise 11 mines with 25 shafts and a total of 45 square miles of underground excavations (Brokaw et al, 1972). Peak production was reached in 1966, and since then, some of the mines have closed (Brokaw et al, 1972).

In the Michigan, Appalachian, and Kansas Permian Basins, conventional mining of salt began much earlier than did potash mining in New Mexico, but mine workings are generally much less extensive. For instance, there is only one conventional mine in Michigan, which opened about 1910 and whose workings amount to only about 900 acres (Walden, 1978). No other conventional mines have ever been established in Michigan (Walden, 1978). There are about five conventional mines in Kansas, all of which opened in the earliest part of this century. Two of these

are abandoned, and one is closed but in operating condition (Wilson, 1978). Workings associated with each mine amount to no more than a few hundred acres (Walters, 1976; Wilson, 1978; Lomenick, 1972).

Exploratory boreholes are associated with mining activities, both solution and conventional. These are drilled in order to detect desirable minerals, and to map the occurrence of the minerals at sufficient grade for mining so that development plans may be made. In the case of New Mexico, approximately 1,500 exploratory boreholes have been drilled in the Carlsbad area since potash was discovered there in the late 1920's (Brokaw et al, 1972).

5.3 Technology and Regulation of Drilling and Completing Exploratory and Production Boreholes

5.3.1 Technology of Drilling and Completing Wells

Familiarity with certain drilling procedures is helpful in understanding the potential instability or leakage problems associated with drill holes. Many of the procedures described below are practiced not only by the petroleum industry, but are also followed in the drilling and completion of solution mining wells and of mineral-exploration holes.

Deep drill holes, also called wells or boreholes, are drilled by large rigs and may cost hundreds of thousands of dollars each. Such holes today are usually drilled by rotary equipment, the bit being attached to the bottom of a pipe called the "drill stem." As a hole is advanced downward, the drill stem is lengthened by adding sections of pipe at the top. Drilling fluid is pumped (circulated) down through the drill stem, out the drill bit, and back up around the annulus between the drill stem and the borehole wall. The purposes of the fluid are to cool the drill bit, to remove the rock fragments ("cuttings") produced by the drilling, to prevent the caving of the hole, and to prevent the flow of fluids into the hole. Heavy mixtures of clay, water and chemicals, termed "mud," are the most common drilling fluids. The mud is constantly recirculated, and prior to its reintroduction to the borehole, the suspended cuttings are allowed to settle out in a bulldozed pit on the well site. Cylindrical core samples can be retrieved during drilling operations.

Especially where there are thick accumulations of unconsolidated sediments or large influxes of shallow subsurface fluids, a steel pipe, or "casing," is placed part way down the hole as a lining to help keep the hole open and to prevent fluid migration while deeper drilling at a smaller diameter proceeds. This "surface pipe" is generally cemented to the borehole wall along its entire length.

After a petroleum exploration hole is drilled, geophysical instruments are usually lowered into it on a cable, and various properties of the rock, such as its natural radioactivity, its resistivity, and the velocity of sound transmission are recorded on a graph as a function of depth. This is called "logging the hole," and the resulting "logs" are used to correlate rock units between different boreholes as well as to measure in-situ rock properties.

The decision to abandon a well or to "complete" it for production is based upon these and other down-hole measurements. If the hole is to be abandoned, it is plugged (see below). If the borehole is to be completed, it is cased from the surface down to the lowermost horizon from which petroleum production is anticipated, the casing being perforated opposite strata from which petroleum will be produced. The borehole below the lowest producing horizon is customarily plugged. The casing may be set in several stages, each stage, or "string," of progressively smaller diameter. Each string is cemented to the borehole wall from its lower end upward for a certain interval. Cementing is accomplished by setting a packer or similar device in the borehole just below the lower end of the casing. Concrete is pumped down inside the casing, out the bottom, and up the annulus between the casing and the borehole wall to the desired level. After the concrete hardens, the concrete plugging the wellbore is drilled out. Frequently, especially in newer holes, the casing may be cemented along the whole length of the well. Eilers (1977) discusses proper cementing techniques.

The technique of cementing the casing prevents fluids from migrating up or down the annulus between the casing and the borehole wall.

Completion of a borehole for production may include a procedure called "hydraulic fracturing" by which an open fracture is propagated from the wellbore to stimulate the flow of petroleum. Low-viscosity cement, called "grout," can be used to plug the fractures for a short

distance into the formation to prevent fluid migration into the borehole, but the fracture system as a whole cannot be sealed with current techniques.

When a hole is to be abandoned, either because enough information has been gained from it, or because no more petroleum is to be produced, some of the casing (that portion that is not cemented) can be recovered, or it may be left in the hole. Either way, the hole is plugged with cement "bridges" placed at several depths, and heavy mud is left in the intervening sections to prevent fluids from migrating up or down the borehole (see Section 4.4.1). Rarely is a hole filled completely with cement. Proper plugging is a complex operation, and good discussions of the subject are presented in Eilers (1977) and Herndon and Smith (1976).

When a petroleum reservoir is tapped, usually a mixture of brine and oil is pumped. Particularly in later stages of development, a high proportion of the pumped fluid is brine, which is disposed of in the subsurface through "brine disposal wells."

Brines may be returned to their native formations, especially if it is desired to maintain pressure in the petroleum reservoir. Other strata favorable for brine disposal are permeable horizons not containing potable water. Pressures developed by brine disposal operations can result in unforeseen brine transport (see Section 4.4.2a), but do not lead to fracturing the disposal horizon. Most subsidence problems in Kansas associated with petroleum operations are related to the disposal of brine (see Section 4.4.2a) (Walters, 1976).

Solution-mining wells are treated similarly to petroleum wells. However, potash exploration wells, through which no production takes place, and which may ultimately pose a danger to mining operations, are treated differently. The vast majority of potash wells are drilled into, but not through, the salt strata, and so are less dangerous to nearby mines than wells that do completely penetrate the salt (Jordan, 1978). Even so, the holes are carefully plugged. Recently-drilled holes by Potash Company of America (PCA) and by Amax Chemical Company (Amax) are plugged solid with cement from top to bottom (Jordan, 1978; Kirby, 1978). Those drilled by Kerr-McGee Corporation are plugged solid with cement through the salt to the top of the limestone aquifer in the Rustler formation, and then with mud to a cement surface plug (Lane, 1978). No casing is left in the holes. Older wells were plugged with mud, and cement plugs were placed at the top of the salt, opposite aquifers, and at the surface (Jordan, 1978; Kirby, 1978; Lane, 1978; Thiel, 1978).

5.3.2 Plugging Regulations

The technique of cementing the casing of a well was introduced about 1903 and was developed rapidly in the 1910's and 1920's as its value to operators was established (Herndon and Smith, 1976). However, abandoned wells, whether dry or depleted, were left completely open or literally filled with junk.

In the middle and late 1930's, states began to regulate drilling activities, including plugging and record-keeping (Walters, 1976; Herndon and Smith, 1976). It is the old holes, drilled before the advent of regulations, that represent the greatest uncertainty because the locations may be unrecorded and the plugging incomplete. In the case of the proposed site area near Carlsbad, New Mexico, petroleum development occurred late in relation to regulatory developments and the area has been relatively sparsely drilled with well-documented operations. But at the old Lyons, Kansas, repository project, the presence of 29 known old holes represented "the most serious technical objections to the site" (Boch et al, 1971).

The current status of plugging regulations is well-summarized by Herndon and Smith (1976). There are thirty-four oil-producing states, and in each state the regulatory body must be notified of the intention to plug a well for abandonment. "Of the thirty-four states considered, all but eight have specific requirements for the type and locations of plugs in the well. All of the eight who give general rules specify that a plan for plugging must be submitted and approved by the state geologist or a designated representative of the state body prior to plugging. All of the states also require an affidavit or notice of completion of the plugging for each well. Most of the states also have a representative present during the plugging, or in some manner inspect the plugging job. About half of the states require a permanent marker to be placed on the well giving details on well ownership and other pertinent data (Herndon and Smith, 1976)." Fig. 7 shows typical plugs required by most states.

Among states with large bedded salt areas, Kansas, New York, Pennsylvania, and Texas have rules specifying thickness and placement of plugs in relation to aquifers and producing zones, while Michigan, North Dakota, New Mexico, and South Dakota have rules of the more general type. Most agricultural states require surface pipe to be cut off below plow depth, while states such as New Mexico and Nevada require

a steel marker above the surface (Herndon and Smith, 1976). Appendix A summarizes the regulations applicable in each state and lists the agency responsible for enforcing the regulations.

The completion and plugging rules in New Mexico are of the general type and have remained essentially unchanged since at least 1931 (Nutter, 1978). They require wells to be plugged so as to permanently isolate all fluids in their native formations. Officials of the New Mexico State Oil Conservation Division review plugging plans on a case-by-case basis and currently inspect all operations. In addition, they witness the setting of all plugs in salt and artesian areas. In the case of wells with completely cemented casing from top to bottom, the general rules translate into requiring a shoe (bottom) plug and a surface plug, with the borehole in between filled with heavy mud (Gressett, 1978). The use of mud as a long-term plugging material would require knowledge of the rate of settling of the particulate matter in suspension. In evaporite areas, if the borehole casing is not cemented through the salt, 30 m plugs are required at the top and bottom of the salt section. This practice has been in effect at least since 1942 (Knaugh, 1978). Before that date, the plug length requirements were less strict, and plugs were emplaced using a minimal volume of cement. Many are probably inadequate (Knaugh, 1978). Since 1951, wells in the potash zones are required to be cemented solidly through the salt section (Knaugh, 1978).

These general regulations seem to have functioned better than specific regulations identifying the formations to be protected and the degree of protection to be provided. For instance, the rules in Kansas contained serious oversights which were corrected only recently. Prior to 1930, there was no regulation at all of drilling practices, casing, or plugging, and from 1930 to 1935 there was only limited county-by-county supervision (Walters, 1976). State regulations and record-keeping began in 1935, the regulations requiring only that fresh water aquifers (less than 500 ppm chlorides) be protected. Not until 1967 to 1969 were requirements revised more stringently: the rules were extended to cover any kind of borehole, not just a petroleum well, which penetrates an aquifer, whether the fluid is fresh or not (Walters, 1976). These regulations were adequate for 90% of the bedded salt area where the only aquifers are the near-surface fresh water zones (Walters, 1976). However, in up

to 10% of the salt area in Kansas, there are deeper aquifers, still above the salt, which contain undersaturated brines and, until recently, it was not required that they be protected (Walters, 1976). In one oil field, downward leakage of brine from these zones, through improperly plugged wells, has been blamed for salt dissolution and subsidence (Walters, 1976).

5.3.3 Performance of Plugs

Only one documented study of the long-term performance of plugs in the field has been found in the literature (Herndon and Smith, 1976). In Michigan, 24 wells with cement plugs were redrilled to check the plugs, and records were detailed enough for 20 of the wells to permit conclusions to be drawn. According to completion records, these 20 wells originally contained a total of 49 plugs, but 11 of them were not found during the study. Of the 38 plugs that were located, six had not hardened properly. In five wells, all the plugs were either missing or soft. Eighteen of the wells had complete records, and of these, ten had soft or missing lower plugs. In two of those ten, gas had migrated up the hole and accumulated beneath the upper plug. The top plug was missing in two wells, although in most wells the top plug was generally in the best condition of all the plugs in the well (Herndon and Smith, 1976).

The above-mentioned instances of plug failures indicate that any borehole near a repository should be suspect. However, the presence of boreholes need not necessarily rule out consideration of a site because the gas storage industry has developed techniques for locating and replugging old boreholes to assure the tightness of an old petroleum field. Examples of the application of these techniques are presented in Section 4.5.1.

Because the integrity of a waste repository depends in large part on the long-term effectiveness of the plug in the shaft(s) and exploratory drill holes of the project, a large government research effort has been directed toward determining the possibility of constructing an effective plug that will last for geologic periods of time (see for example, Eilers, 1977).

5.4 Effects of Wells and Mines On Fluid Migration

5.4.1 Leakage of Fluids Through Improperly Cased Or Plugged Wells

If a well is not properly cased or plugged, or if the casing itself, the casing cement, or the plug deteriorate, fluids under pressure can migrate up or down the hole and out into permeable formations. Examples include:

- o In southeast New Mexico, there is normally no petroleum production from Triassic rocks. However, in areas of old production from deeper zones, small accumulations of oil in the Triassic rocks have been produced. These are believed to be the result of "faulty completion" (ineffective plugging) of some of the older wells, allowing oil to migrate upwards through them to the Triassic strata (Hartman and Woodard, 1971).
- o The district supervisor of the New Mexico Oil Conservation Division stationed in Hobbs, New Mexico, observes that brines flowing to the surface around some oil wells in the Vacuum and Eunice-Monument oil fields are saturated with salt, whereas natural brines in the area are undersaturated (Sexton, 1978). The supervisor hypothesizes that the salt becomes fractured around boreholes, and in older wells without properly cemented casing, brines flow up through these fractures. No subsidence has occurred around oil wells in the area (Sexton, 1978). In southeast New Mexico, a hole was plugged solid with concrete from top to bottom. Upon inspection by the U. S. Geological Survey, it was noted that oil was seeping out around the marker pipe. The inspector suggests that ordinary concrete is an inferior plugging material because small cracks, common in ordinary unreinforced concrete, allow fluids to migrate through it (Knaugh, 1978). Mud is a superior plugging agent because it exerts a hydrostatic pressure which keeps fluids out of the hole itself (Knaugh, 1978). Also, cement prevents holes from being naturally sealed by flowage of salt and provides a relatively long-lived inhomogeneity through which fluids might migrate.

- o The National Potash Company detected oil-soaked potash zones in their mine, 60 m from an old well completed in 1928, abandoned in 1942 and plugged in 1965. Unless problems occur, 30 m pillars are left around old holes on the mine leases (Thiel, 1978). Other mines leave 50 to 60 m or larger pillars (Kirby, 1978; Lane, 1978).
- o The Potash Company of America observes petroleum seeps in some of the potash zones they are mining. Presumably the oil originates from a casing leak in the nearest well, which is about 370 m away (Jordan, 1978).
- o In Kansas, the withdrawal of more brine than was pumped in at the Cargill salt plant is thought to have caused downward migration of fluids from overlying aquifers through abandoned brine wells (Walters, 1976).
- o Abnormally low fluid pressure in the Cretaceous aquifer overlying the salt near Lyons, Kansas, was discovered by site-evaluation drilling for a proposed repository. The downward migration of fluids through inadequately plugged holes is thought to be the cause (Walters, 1976).
- o In the Gorham oil field in Kansas, disposal of oilfield brines in aquifers above the salt overpressurized the system. Brine moved laterally some 500 m or more to inadequately plugged wells, where it moved downward past the salt face. The ensuing dissolution of the salt resulted in subsidence (see Section 4.4.2a) (Walters, 1976).
- o In the construction of the Lyons gas storage field, 40 to 45-year-old steel was recovered from below the zone of oxygen availability. The steel was intact. Surface pipe cement was also still good, although downhole cement conditions ranged from good to poor (Herndon and Smith, 1976).
- o Mixtures of brines from different aquifers are, on occasion, particularly corrosive. Such mixtures can result from leakage of brine from one formation to another through improperly sealed boreholes and from brine disposal operations in which brine pumped from one formation is injected

into a different unit for disposal. In one instance, a 4.5 inch (11.5 cm) diameter steel casing (probably with 3/16 to 1/4 inch thick walls) leaked after only 18 months exposure to brines mixed by disposal operations (Walters, 1976).

- o Pasini et al (1972) relate an experiment in which four old boreholes (three drilled in the 1890's and one in 1965) were replugged so a coal operation could mine through them. The plugs in the 1965 well were tested by means of tracers and proved tight. One re-plugged 1890's well was mined by the coal operation. When the excavations were within about 10 m of the well, a crude oil odor and methane were detected. The fumes were from petroleum that exited the well through a 2 cm hole corroded in the casing and soaked surrounding coal during the time between the completion of the well and the replugging experiment. The new cement emplaced during the experiment proved tight (Pasini et al, 1972).
- o Migration of fluids through boreholes obviously depends on the local fluid pressure relationships above and below the salt. Depending on these relationships, the event of the worst case, that of a repository mining into an unknown borehole, need not be disastrous. For example, the Potash Company of America accidentally mined into an old petroleum hole (see Section 4.5.1). However, the water level in the well was below the level of mining, and no flooding resulted. The well was plugged and mining continued (Jordan, 1978). Boreholes hit by other mining operations have had more serious consequences. For instance, the American Salt Company in Lyons, Kansas, mined into an unknown borehole in 1971. Brine and drilling mud entered the workings at the rate of a few gallons per minute. The flow rapidly decreased to a "fast seep" and stopped within a few months (Lomenick, 1972). On the other hand, in England, an unknown borehole was hit by salt miners, and the mine was nearly flooded (Unterberger, 1977).

Potash exploration wells pose little threat of becoming paths for fluid migration. They are so successfully plugged (see Section 4.3.1) that some mines regularly excavate right through plugged holes without worrying about potential leakage (Kirby, 1978; Lane, 1978; Thiel, 1978). Other mines

leave small pillars, perhaps 10 m in diameter, around them (Jordan, 1978). If older holes, in which mud is used as the plugging agent in the salt portion, are intersected by mining, the mud flows out of the hole and no continued seepage occurs (Lane, 1978). In the case of wells plugged with cement in the salt section, no brine seeps occur, either through the pillars or, if the hole is intersected, into the mines (Jordan, 1978; Kirby, 1978; Lane, 1978; Thiel, 1978).

5.4.2 Formation of a Cavity, By Dissolution or Mining, That Causes Subsidence and Increases the Permeability of the Overlying Rock Strata

Cavities are formed in salt deposits by conventional mining, solution mining, and dissolution around petroleum boreholes. These cavities directly increase the permeability of the salt, and if the overlying material should collapse into the void, the cavities can indirectly increase the permeability of overlying rocks by fracturing. While cavities associated with mining are expected, dissolution around boreholes is unexpected, and is difficult to recognize, especially if the hole is cased or plugged. Usually dissolution remains undiscovered until subsidence reveals that it has occurred. Walters (1976) summarizes the methods for detecting dissolution, most of which depend on subsidence:

"Methods of detecting salt dissolution at depth after drilling ceases include: (1) changes in, or redirection of, drainage patterns, (2) presence of unusual drainage patterns foreign to the geomorphology, (3) ponding of water under certain soil conditions, (4) minor downward warping detectable by precise level surveys, (5) cracks in the ground surface, or roads, (6) cracks in the walls of buildings, (7) tilting of structures such as derricks, (8) casing leaks opposite the salt section, (9) casing failures at progressively shallow depths with the passage of time, (10) contamination of fresh water aquifers by brine from subsurface sources. Often, however, salt dissolution at depth may be undetected (Walters, 1976)."

Subsidence in rural areas may not be recognized due to lack of observation of such areas and the lack of affected man-made structures.

Subsidence features in salt basins associated with petroleum operations, solution mining, and conventional mining are reported in the literature. Subsidence associated with the first two activities is rare; subsidence associated with conventional mining in the Delaware Basin is generally expected. No subsidence has been linked to potash exploration wells.

There are no published reports on the amount by which permeability of overlying rock units is increased by mining or solution-induced subsidence.

5.4.2a Subsidence Associated With Petroleum Operations

No subsidence associated with petroleum operations in the Delaware Basin of New Mexico is reported by officials of the Oil Conservation Division (Gressett, 1978; Knaugh, 1978). However, dissolution of salt is implied around some boreholes (see Section 4.4.1), and cavity development is suspected. It is hypothesized that when overlying sedimentary rocks fall into dissolution cavities in the salt they break up into rubble which is bulky compared to the original volume, thus filling the cavity with initially permeable material but preventing subsidence of the surface (Sexton, 1978). This hypothesis has not been tested.

Subsidence associated with petroleum operations has occurred in the Kansas Permian Basin and has been exhaustively investigated by Walters (1976). Eight cases of subsidence are documented, making it a rare event, happening roughly once for every 10,000 petroleum wells (Walters, 1976). All events were associated with brine disposal wells, and all but two appear to have stabilized after the initial event. Slow, gentle movement occurs in areas underlain by a thin cover of unconsolidated material, while rapid movement is associated with areas of thick alluvial cover (Walters, 1976). Table 2 summarizes the eight occurrences.

Two causes for the subsidence are proposed for the different events:

1. Hilton, Berscheit, Panning events: Casing in the brine disposal wells corroded, allowing undersaturated brines to leak through the casing and dissolve salt while flowing down past the salt layers. The ensuing cavity collapsed and caused subsidence of the ground surface (Walters, 1976).

2. Crawford and Witt Sinks: In the Gorham field, undersaturated brine aquifers lying above the salt were used for brine disposal from 1941 to 1967. Until the middle 1960's, these aquifers were not protected by state plugging regulations, and the overpressure resulting from brine disposal operations forced downward flow of undersaturated brine through improperly plugged holes. Dissolution, collapse, and ground subsidence resulted (Walters, 1976). A similar case, without the serious consequences, is noted in the Delaware Basin, where a well "broke through" (leaked) due to increased pressure from brine disposal below the salt. No subsidence occurred (Sexton, 1978).

A theoretical discussion of dissolution around boreholes during and after drilling was presented in a previous GEI report (Geotechnical Engineers Inc., 1977b). Documentation of post-abandonment dissolution of salt around three old boreholes that did not lead to subsidence is provided by Walters (1976).

5.4.2b Subsidence Associated With Solution Mining

Cases of subsidence associated with solution mining are documented in the Kansas Permian and Michigan Basins. Walters (1976) stresses that brinefield subsidence is a rare event, only four incidents having been documented in Kansas, where solution mining has been extensively practiced since 1888. A summary of the events appears in Table 3.

In all subsidence cases, the top of the salt unit lies between 100 and 200 m and deepest production is from less than 400 m. Apparently, where mining occurs at deeper ranges, surface subsidence does not occur (Rarick, 1978). Subsurface fracturing, however, could still occur.

Prior to the 1960's, solution mining operations employed the single-well method: brine was introduced and extracted through the same borehole. This method permitted uncontrolled growth of the resulting cavity and unstable roof conditions could result. In addition, cavities from adjacent wells in a brinefield could coalesce, leading to large areas

of unsupported rock, and resultant subsidence (Walters, 1976; Terzaghi, 1970). The single-well method is still employed in several operations (Walters, 1976).

In the 1960's, the two, or multiple-well method was developed. This technique involves drilling a pair of wells and connecting them through the salt by a hydraulically-induced fracture. Brine is introduced through one well, and extracted through another, limiting dissolution to a narrow zone around the fracture. Cavity development is controlled and can be engineered for stability (Walters, 1976).

Terzaghi (1970) and Walters (1976) both suspect that the coalescence of adjacent solution cavities in single-well fields led to collapse of the overlying unsupported rock, while each proposes different causes for the coalescence and instability. Terzaghi believes that in the Sandwich field, a classic, old single-well operation, roof rocks slowly sagged and loaded the pillars of salt remaining after the coalescence of adjacent cavities. Continued removal of salt by mining resulted in weakened pillars and collapse (Terzaghi, 1970). Walters suggests that old brine wells in Kansas, improperly plugged, leaked fresh water from an overlying aquifer into underpressured solution cavities, resulting in excessive and unrecognized dissolution (Walters, 1976). The problem of effective borehole plugging, which might have prevented this failure, is discussed elsewhere in this report.

5.4.2c Subsidence Associated With Conventional Mines In the Carlsbad Potash Area

Subsidence above mine workings in the Carlsbad area is summarized in the literature as being nearly 100% of mined height where mining has been completed (Brokaw et al, 1972). However, inquiries made for this study indicate that subsidence is generally somewhat less than 100% depending upon such factors as the depth to the workings, and the amount of material removed, which depends upon the excavation technique used (see Table 4). Where high extraction rates (high percent of material removed) are practiced, subsidence is expected.

Subsidence is reflected in the overlying surface by the development of gentle depressions (Brokaw et al, 1972). Surface fractures approximately 10-14 cm wide are reported in the subsidence zone. The cracks propagate upward from the edges of the mined-out areas at angles ranging from 0° to about 45° from the vertical, and the maximum angle recorded is 52° (Kirby, 1978; Lane, 1978). Over mines where two-cycle mining is practised in which high extraction ratio is attained in the second cycle, subsidence follows closely after the second cycle is complete (Kirby, 1978). Fluids migrating upward through these fractures have not been observed at the ground surface.

A previous GEI report (Geotechnical Engineers Inc., 1977b) indicated that "subsidence (over potash mines) probably causes extensive fracturing of the post-salt units, as demonstrated by the anomalously high salinities of aquifers overlying the mined areas." However, in certain instances, the salt itself appears to settle as a cohesive block (Brokaw et al, 1972; Kirby, 1978). Amax is currently mining over a subsided, mined-out zone, and encounters no fracturing of the salt except at the edges of the subsided zone. These cracks are tight: they weep brine for only a "short while" (Kirby, 1978). Flow ceases presumably because the fractures heal by plastic deformation of the salt (Kirby, 1978). Detailed investigation of the phenomenon has not been carried out.

Two instances of post-abandonment enlargement of salt mine shafts in Kansas are documented. The shaft of the Little River Salt Mine (Rice County), abandoned in 1938, was left open (unsealed). By 1975, solution of salt and sloughing of overlying shales had enlarged the shaft up to four times the original volume at some intervals. However, no surface collapse resulted, and the shaft was modified for the storage of liquified petroleum gas (Walters, 1976).

The other case occurred at Kanopolis in the shaft of the Crystal Salt Mine, abandoned in 1949. A concrete plug was set in the shaft at a depth of 40 m, and rubble fill was placed above it to the surface. In 1972, rapid subsidence began, resulting in a crater which, when it stabilized, had dimensions of 40 m x 30 m by 20 m deep. Volumetric calculations show that a volume of salt approximately four times the volume of the original shaft had been removed during the 23 years since the mine was abandoned (Walters, 1976).

5.5 Determining the Locations of Abandoned and Active Mines, Exploratory Wells, and Production Wells

5.5.1 Petroleum Wells

The completeness of records of petroleum operations should be assessed on a basin-by-basin basis. In the Delaware Basin, both State and Federal record-keepers and the potash miners, who use the records to avoid old boreholes, are confident of the records (Nutter, 1978; Kirby, 1978; Lane, 1978; Van Sickle, 1978). One official is of the opinion that New Mexico has among the best borehole records in the country (Sexton, 1978). The Oil Conservation Division of the Department of Energy and Minerals of New Mexico (until recently called the Oil Conservation Commission) was established in 1935 to supervise petroleum operations in the state. Prior to that date, the State Geologist was responsible for record-keeping. Post-1935 records are good, while pre-1935 records may be somewhat less complete (Nutter, 1978). In the Carlsbad area, the late date of petroleum development relative to record keeping advances has led to especially good records. In other areas of the country, especially those which, like the Appalachian Basin, experienced very early production peaks, followed by an early decline, records are deficient. For instance, many holes in Texas drilled in the 1910's and 1920's are not recorded or located on any map. These were commonly plugged by just driving wooden plugs into the hole. Some such wells are discovered during oilfield repressurizing operations when the plugs blow out and the well starts flowing (Knaugh, 1978). In Lyons, Kansas, the American Salt Company mined into an old well that was not on any records (Lomenick, 1972).

In New Mexico, state inspectors witness or inspect all borehole plugging operations, and driller's and completion logs are kept on each well (Nutter, 1978). At least since 1950, a 4-ft-high pipe has been required to mark the surface location of each borehole. Although gaps in the record may exist because of lost or misplaced files, officials are confident that "99.9%" of the wells are known and correctly located (Nutter, 1978). Occasionally,

a previously unknown well is discovered, but the district supervisors of the Oil Conservation Division in Artesia and Hobbs, New Mexico, cannot remember any such incidents in the northern Delaware Basin during the past 20 years (Gressett, 1978; Sexton, 1978). In one incident, a potash mining operation encountered a petroleum hole not included on company maps. However, the well was included on State and Federal records (Jordan, 1978).

Herndon and Smith (1976) estimate that a search of all available records (i.e., not only drilling permits and public records, but old leases, tax records and company records) should disclose up to 90% of the petroleum wells in a typical area. Other techniques useful in locating old mines and well sites are interviews with long-term residents, hydrocarbon detector surveys, magnetic locator surveys where surface pipe or metal debris are left just below the surface, and aerial photographs (Herndon and Smith, 1976; Johnston et al, 1973). Aerial photographs are especially useful in arid climates, because under such conditions, refuse and surface disruptions due to drilling are commonly visible many decades after abandonment of the site (Griswold, 1978). On-site searches with excavating equipment may be necessary for the final effort of locating the actual surface pipe.

The technology for finding and plugging old wells has been developed over the last 40-50 years by the gas storage industry which must find and plug all holes that might cause leakage of the gas that is injected into subsurface rock strata for storage. An example of the successful application of the technology is the commissioning of the Webb Storage field in Oklahoma, where 25 old wells were located, primarily by record searches, and re-plugged (Herndon and Smith, 1976). Construction of the Lyons storage field in Kansas involved the location and re-plugging of 18 wells. There, a record search was found less useful than aerial photography in locating wells, and some post-1945 wells were located by magnetic detection of the surface pipe (Herndon and Smith, 1976). Finally, opening the Jackson field in Mississippi necessitated the location and plugging of 80 wells drilled in the 1930's, many of whose records were missing or inadequate. In some cases,

the buildings of Jackson had been constructed over the wells, or the wells were buried under as much as 3 m of earth. The project was ultimately successful (Herndon and Smith, 1976).

5.5.2 Solution Mines

Records of solution mining operations exist in varying stages of completeness. The two extremes are illustrated by the Carlsbad area, where records are excellent, and the Kansas Permian Basin, where they are poor. In New Mexico, the good condition of the records is due to the brevity and late date of solution mining efforts. The area has not, as yet, been mined for salt, and there have been only two solution mining attempts, these to experiment with the brine extraction of potash (Brokaw et al, 1972). One experiment occurred in the 1940's and 1950's, and one in the mid-1960's. Borehole locations of both operations are accurately known, and the tabular cavity produced in the later experiment was found to be 90 m x 24 m x 2 to 3 m high (Brokaw et al, 1972).

In Kansas, on the other hand, a substantial solution-mining industry was developed from 1889 to 1893: 23 plants, each with an associated well field, were producing salt in 1890 (Walters, 1976). However, in 1893, a financial panic and, in 1894, a flood, put many operations out of business (Walters, 1976). There are no known surviving records of these defunct operations, but it is known that the wells were commonly left unplugged (Walters, 1976). In addition, wells drilled in the early 20th century may be inaccurately located on records. In many instances, their locations are given by word descriptions inadequate to provide mappable locations. A map of one plant's wells, based upon incorrectly-plotted sections and word descriptions, drawn up for its sale in 1972, was incorrect (Walters, 1976).

A similar situation exists in Michigan. There, the Michigan Geological Survey has fairly good records of solution-mining activities extending back to 1929-1930 (Rarick, 1978). However, a substantial industry developed prior to 1900 around the edges of the Michigan Basin where the salt is 300 to 600 m deep (Rarick, 1978). In some areas, state geologists

know that mining occurred, but they have no control on the actual well locations (Rarick, 1978). All wells in the deeper portion of the basin are known, since development there occurred later (Rarick, 1978).

Techniques for finding and replugging old boreholes are applicable to solution-mining wells.

5.5.3 Potash Exploration Wells

Approximately 1,500 potash exploration holes have been drilled in the Carlsbad area of New Mexico since potash was discovered there in 1926 (Brokaw et al, 1972). The mining companies keep complete records of all borehole locations, depths, logs, and plugging, which, by law, must be submitted to the U. S. Geological Survey (USGS), in New Mexico, or to the State Department of Energy and Minerals, depending on the jurisdiction (Kirby, 1978). Mining engineers are extremely confident of the completeness of their records, although the USGS, in compiling a map of potash wells, is somewhat less confident of the accuracy of reported borehole locations (Kirby, 1978; Lane, 1978; Thiel, 1978; Van Sickle, 1978). The USGS believes that all wells are reported in some fashion, and that the lack of adequate information, which extends to only a few identifiable holes, is due to errors in the transmission of data. The correct information on each borehole is believed available from the particular mining company that drilled it (Van Sickle, 1978).

5.5.4 Conventional Mines

Conventional mines in bedded salt basins are generally so deep that the excavation of their shafts constitutes a major construction project. Records of the shafts are available, and there is a negligible chance that, after a careful survey of existing records, the existence of a mine in a given study area would be missed. Also, mining companies carefully survey and map their underground workings to make sure their operations are confined to the proper lease tracts and to avoid hazards at depth which are visible on the surface (i.e., oil and gas holes).

5.6 Conclusion

Features associated with resource exploitation in bedded salt basins include petroleum exploration and production wells, mineral exploration boreholes, brine wells, solution cavities, mine shafts, and underground excavations. Evaluating the hazards to a repository posed by each kind of feature has two aspects: determining the potential effects of a given feature, and determining the location of existing features, or the likelihood of unknown features occurring near the repository site. The former problem may be approached by examining case studies, which can indicate at least a probable maximum radius of influence of each feature. The difficulty experienced in locating exploitation features and adequately demonstrating the absence of unknown features depends on several factors, among which are the kind of feature, the local exploitation history, and the state in which the study is being made. The danger of known features can be minimized by placing a repository far outside their maximum observed radius or influence. More danger is posed by unknown features.

5.6.1 Petroleum Wells

Evaluations of the desirability of a particular basin for nuclear waste disposal should include the following considerations:

1. Degree of petroleum exploration in the basin - Although more heavily exploited basins contain more wells, there are areas within each basin that are relatively untouched, and the time-frame of development, regulatory history and geometry of the petroleum reservoirs are probably more important considerations than the degree of exploration.
2. Time frame of development - Those areas significantly developed before technological improvements in the early part of this century and before the advent of state record keeping and regulation are particularly likely to contain unknown and/or incompletely plugged wells.
3. State regulatory history - The adequacy of state plugging regulations has varied greatly from state to state, even in the fairly recent past. Well-marking regulations differ between arid and agricultural states; those in arid state making location of wells easier.

4. Location of oil within the basin - If reservoirs occur in easily-identifiable trends, early wildcat drilling, which is liable to be poorly recorded, may be confined to the trends, lessening the possibility of unknown boreholes in areas untouched according to current records.
5. Location of oil within the stratigraphic section - If the salt lies below shallow petroleum reservoirs within a basin, the vast majority of the wells, especially the older ones, may not even breach the salt.

Information cited in this report leads to the following conclusions about the potential influence of petroleum wells that do penetrate the salt.

1. Wells abandoned before the 1930's are likely to be inadequately plugged.
2. Borehole plugging is a difficult operation, and plugs placed in the wells during normal operations may not be effective in preventing fluid migration. A satisfactory method of checking plug conditions downhole has not been devised. In any case, plugging has been routinely practised for only about the past 50 years, and examples of plug longevity for longer periods do not exist.
3. Fluid migration through abandoned wells is documented. However, dissolution resulting from that migration is difficult to recognize unless subsidence occurs.
4. Subsidence in salt basins associated with petroleum operations is a rare event, and the largest documented subsidence zone found in this study is approximately 300 m in diameter. Most subsidence zones stabilize after the initial collapse at diameters much less than 300 m.
5. All cases of subsidence documented in Kansas were associated with brine disposal, which can lead to fluid migration in at least two ways. One is that if the operation results in mixing of different brines, rapid corrosion of well casings in the area may result. The other is that brine disposal improperly practiced may lead to abnormal pressure buildups which can cause leakage through wells at least 500 m away from the associated disposal operation.

The technology for finding all old wells in a (small) field and effectively sealing them to the passage of gas has existed for the past 40-50 years. The task of locating the wells is facilitated in arid environments by the preservation of surface features due to drilling. Especially in such environments, the probability of an unknown well remaining undiscovered after site investigation is negligible.

5.6.2 Solution Mining

The problems due to solution-mining activities are similar in many respects to the problems due to petroleum activities. For instance, the technology of drilling, completing, and plugging brine wells is virtually the same as petroleum well technology. The same problem of poor records of old, defunct operations exists, and similar techniques are used to find old wells. There are some differences:

1. Fewer solution-mining wells exist.
2. Brine well fields are associated with large surface plants which are likely to be recorded or remain prominent long after the operation closes. Thus, even if well location records are completely inadequate, localities where solution mining occurred can be identified and avoided.
3. Locating and replugging solution mining wells is necessary but insufficient to eliminate hazards as in the case of locating and replugging petroleum wells, because even if all brine wells in a field are successfully replugged, the associated solution cavities remain.
4. The diameter of subsidence zones associated with solution mines is dependent on the shape and size of the brine cavity. The largest subsidence zone documented in this study measured 600 m in diameter on the surface. Most subsidence areas are much smaller, and all appear to stabilize after the initial collapse.

5.6.3 Mineral Exploration Boreholes

Potash exploration wells are a few orders of magnitude more numerous than petroleum wells in the Carlsbad potash (WIPP site) area, and therefore are more difficult to avoid than petroleum wells. Important observations about potash wells include:

1. Records of potash wells have been carefully kept since exploration began.
2. The vast majority of potash wells in the Delaware Basin do not extend below the salt strata, and so, at least initially, do not establish hydraulic communication through the salt.
3. Plugged potash wells intersected by mines have proved tight, and no cases of fluid migration, dissolution, or subsidence associated with the boreholes have been reported. Thus, for the time span of experience (about 50 years), potash wells can be regarded as completely plugged.

5.6.4 Conventional Mines

There is little danger to the integrity of a repository due to conventional mining because mine locations and excavations are obvious and well-surveyed, and the effects of mining on rock integrity are limited in areal extent. Disturbances are easily avoided.

6. POTENTIAL GROUNDWATER FLOW IN THE DEPOSITORY LAYER

6.1 Introduction

In this chapter, selected parametric and process assumptions used in the LLL waste transport model are discussed with reference to the observed hydrogeology of sedimentary basins. It is assumed that the reader is already familiar with the model, which is described in detail elsewhere (Golder Associates, Inc., 1977; TASC, 1978):

The model comprises a series arrangement of barriers to radionuclide migration as outlined below:

<u>Barrier</u>	<u>Description</u>	<u>Discussed In This Section</u>
1. Resaturation	Total time required: (1) for the depository to recharge after decommission, and (2) for the natural groundwater flow regime to repressurize so that dissolved radionuclides can migrate away from the depository	Yes
2. Dissolution	Rate at which radionuclides are incorporated into the groundwater flowing past waste canisters in the depository	No
3. Migration	Rate of flow of radionuclides through the depository layer (salt or shale)	Yes
4. Aquifer Transport	Rate of flow of radionuclides through the subsurface once the depository barrier is breached	No
5. Water Usage Patterns	Surface hydrology and water use patterns that affect the intake of radionuclides by humans	No

In this analysis of flow through the depository layer, only the Resaturation and Migration barriers are discussed. Discussions of the other three barriers appear in other reports subcontracted under LLL's waste management program.

To model a hydrologic system, it is necessary and sufficient to specify the following four aspects of the system:

1. Flow equations - The hydraulic equations governing flow, dispersion, diffusion, and retardation.
2. Geometry - The physical boundaries of the system including the locations of all openings and interfaces.
3. Hydraulic parameters - The hydraulic properties of the media in the system, which may vary with time, including hydraulic conductivity, porosity, gradient, dispersion, and diffusion constants, and retardation coefficients.
4. Boundary and initial conditions - The values of all potentials fixed in space and time, and the initial values of all time-varying parameters.

Using the above framework, the discussions in this section focus on the adequacy of the resaturation and migration modeling by LLL with regard to the four aspects of each hydrologic subsystem. Discussions of dispersion, diffusion, and retardation are excluded because values for these parameters have been obtained on this project by other subcontractors.

6.2 Resaturation Time

Resaturation time is the period after a nuclear waste repository is decommissioned until (1) the depository is recharged, or filled with seeping groundwater, and (2) the formation is repressurized so that essentially steady-state flow is established through the depository. In the present model configuration, dissolution and leakage of waste begins at the end of the resaturation time.

6.2.1 Flow Equations

Rates of flow into a decommissioned depository have been calculated by assuming that flow can be described by Darcy's Law (Golder Associates, Inc., [GAI], 1977). Although some deviations from Darcy's

Law have been observed in materials with very low permeability (Von Engelhardt and Tunn, 1955; Lutz and Kemper, 1959; Hansbo, 1960), one set of extremely sensitive measurements designed specifically to look for such deviations leads to the conclusion that laminar flow in porous media is Darcian except in swelling clays (Russell and Swartzendruber, 1971). In none of the soils tested, including swelling clays, were "threshold" gradients observed, below which no flow occurred (Swartzendruber, 1971). The causes of the deviations in swelling clays remain uncertain (Swartzendruber, 1978) but many researchers believe they are due to non-Newtonian fluid effects in the electrical double layer surrounding clay particles (Lutz and Kemper, 1959).

We are aware of no permeability tests for materials with hydraulic conductivities in the range of 10^{-9} to 10^{-12} cm/sec where the test gradient was as low as 0.1 to 1.0 as is the case in the LLL repository model and where non-Darcian effects, if they exist, become significant. Pending further research in this field, we recommend that Darcian flow be assumed for both salt and shale as long as the depository layer is both saturated and does not contain a significant proportion of swelling clay.

There is evidently some question, based on exploration at the WIPP site, whether the interbeds in the salt of the Salado formation are everywhere saturated. Because of the extreme difficulty of making accurate measurements at depths in the range of 600 m, no definitive conclusions were reached. However, some drilling fluid may have been lost to the Salado formation during drilling (which indicates some permeability (Griswold, 1978)) and yet, when drill stem tests were conducted, no water flowed into the hole in up to 24 hours (Griswold, 1977). The combination of permeability which would be indicated by a loss of drilling fluid, with no fluid flow, implies unsaturated conditions. However, because the information is unconfirmed at present, our opinion is that saturated conditions in the salt interbeds should be assumed because the calculated flows will be greater than actual if the interbeds are unsaturated.

Repressurization, the time required for the depository layer to replace the water lost from storage during use and recharge of the depository, has been

calculated on the basis of the one-dimensional consolidation equation from soil mechanics literature (Golder Associates, Inc., memo, April 1978). Their analysis is not reviewed in this discussion.

6.2.2 Geometry

In the current model configuration, recharge has been assumed to occur from three sources: (1) vertical flow from the upper and lower aquifers, (2) horizontal flow through the interbeds within the salt, and (3) leakage from the shaft (GAI and TASC oral presentations at June 1978 project meeting). While all three processes could be active in depository recharge, the experience in potash mines in the Delaware Basin of New Mexico suggests that leakage from vertical interstitial flow and horizontal interbed flow for a salt repository is nil. Commonly, no moisture is observed to collect on the roof of the mines except where roof bolt holes have penetrated interbeds, and flow of water from the interbeds exposed in the walls of the mines always decreases to nil after several months. The cause of the decreasing flow is uncertain, although some believe that that water may be connate, or fossil, water squeezed from the interbeds by the stress concentrations around the mine openings (Griswold, 1978; Hale, 1978). A more complete discussion of water conditions in the Delaware Basin potash mines is included in Appendix B.

In summary, the assumed geometries are valid for the generic model and can be used to determine lower limits to the resaturation time due to interstitial flow.

Leakage down the shafts from overlying aquifers, which constitutes an important leakage path, has been treated separately in computations by GAI.

Other potential leakage paths due to catastrophic events, such as faults and breccia pipes, have been discussed in previous reports (Geotechnical Engineers Inc., 1977a, b).

6.2.3 Hydraulic Parameters

For calculations of flow based on Darcy's Law, hydraulic conductivity is the controlling parameter. Porosity, which affects the velocity with which a tracer moves through a porous medium in saturated flow, does not affect the specific discharge, or volume of flow per unit area. Therefore, porosity does not influence resaturation time and is not discussed in this section.

At present, the baseline vertical hydraulic conductivity of salt and shale have been assumed to be 10^{-9} cm/sec and 10^{-8} cm/sec, respectively. In reviewing the uncertainties associated with baseline parameter values, we have obtained several additional data on the hydraulic conductivity of both salt and shale. These data are summarized below, and, based on them, we propose new baseline values.

6.2.3a Hydraulic Conductivity of Salt

Measurements of the hydraulic conductivity of salt are extremely rare because for most practical purposes, salt is considered to be impermeable below depths of 300 m (Baar, 1977). We are aware of only two sets of field measurements.

1. Golder Associates (Plum, 1978) measured hydraulic conductivity in a salt dome and found that values were below 10^{-9} cm/sec, the estimated lower limit of detectability of the test apparatus.
2. Sandia Laboratories performed 10 Drill Stem Tests to measure the hydraulic conductivity of bedded salt at the WIPP site and found that the salt yielded no fluid to the measurement test well. Based on shut-in periods ranging up to 24 hours, they calculated horizontal hydraulic conductivities on the order of 5×10^{-9} cm/sec for intervals ranging from 12 to 77 m (which included interbeds) (Griswold, 1977). Values for vertical hydraulic conductivity would be at least 10^2 to 10^3 times lower than the corresponding measured horizontal values because of the relatively high permeability of the interbeds (Griswold, 1978). The reported values are based on the poor field data, however, and they should not be used as hard numbers for the hydraulic conductivity of bedded salt (Griswold, 1977).

A 1959 unpublished report by Core Laboratories Inc. describes the results of laboratory tests on the hydraulic conductivity of both bedded and dome salt. In all four tests performed at a confining stress of 54 kg/cm^2 * where saturated brine was used as the fluid, the hydraulic conductivity decreased to "zero" within 36 days. William Aufricht (1978) said that the apparatus would have detected values of 10^{-12} cm/sec or greater. Therefore, the samples could be considered to have values of less than 10^{-12} cm/sec .

In another test, the sample was sawed in half lengthwise prior to testing to simulate a fracture in the salt. Within 8 days, the hydraulic conductivity had decreased 3 orders of magnitude.

In yet another test, a small hole was drilled lengthwise through the sample. Within 7 days the hydraulic conductivity had decreased by a factor of 26. We assume that further reductions in hydraulic conductivity would have occurred if testing had continued.

Gloyna and Reynolds (1961) measured the permeability of salt and also observed that when brine was the permeant, the values decreased about one order of magnitude within three to four days. Because they did not specify the lower limit to the sensitivity of their apparatus, we have not used their values in determining a baseline hydraulic conductivity for salt.

Indirect field data suggest that salt may have essentially no permeability. Nitrogen-brine pockets, under surface-flowing artesian pressures, are found in bedded salt deposits throughout the world (Baar, 1977; Griswold, 1977). Because these accumulations have been in existence for geologic periods of time, it can be inferred that the pressures, in excess of those of aquifers above or below the salt, should long ago have dissipated if salt had significant permeability.

The apparent hydraulic conductivity of salt can be approximated from field evidence from the potash mines of the Delaware Basin. Brine seeping through the salt evaporates and leaves stalactites or a fine layer of precipitated salt on the walls of

*Roughly equivalent to a depth of 250 to 450 m, depending upon pore pressure.

or roof of the mines, especially where interbeds are present or where pressure release holes or roof bolt holes have been drilled.

Using the amount of precipitated salt as a measure of the total flow through the salt, a relationship for the approximate hydraulic conductivity can be derived.

Assumptions

1. All of the salt dissolved in water seeping into the mine is precipitated on the mine walls. (Vaporization of saline water is a common form of desalinization.)
2. Brine seeping into the mine is salt-saturated and has a concentration of 300,000 ppm NaCl. (While minerals other than NaCl will be present in a brine, we chose an NaCl solution as a first approximation.)
3. Based on a visit to several potash mines, we estimate an average thickness of precipitated salt of 0.01 to 0.1 mm over the extent of the mine walls. (A sheet of paper is approximately 0.1 mm thick.) While telephone conversations with several mine operators within the Delaware Basin have indicated that salt precipitation is commonly nil, except near interbeds and drill holes, we have chosen a conservatively large thickness to calculate an upper limit to the hydraulic conductivity of salt.
4. The mined areas have been open five years. (This assumption, while reasonable, is arbitrary.)

We assume a constant hydraulic gradient in both space and time between the mine wall and the final radius of influence given by Bear's (1972) equation, which is a special case of the modified Theis equation for unsteady flow toward a well in a confined aquifer. While assuming a fixed gradient, based on the final radius of influence, is only a rough approximation, it turns out to be a conservative one because using a time varying radius of influence would lead to a higher average gradient and thus a lower hydraulic conductivity for the same total flow ($q = KI$). In addition, the actual hydraulic gradient,

if plotted in space, would be greater near the mine wall than the average gradient extending to the radius of influence. Thus, both in space and time, the assumed hydraulic gradient leads to a conservatively high value of hydraulic conductivity.

The expression for the hydraulic conductivity of salt is obtained by simultaneous solution of equations of Darcy's Law, hydraulic gradient, and Bear's equation for the radius of influence as follows:

Darcy's Law states that:

$$q = -KI, \quad (1)$$

where q = specific discharge
 K = hydraulic conductivity
 I = hydraulic gradient

The thickness of precipitated salt is a function of the specific discharge, the density and concentration of the brine, and the time:

$$b = q\gamma ct \quad (2)$$

where b = thickness of precipitated salt
 γ = specific gravity of salt - 2.2 g/cm³
 c = concentration of the brine - 300,000 ppm
 t = flow period

The spatially averaged hydraulic gradient is:

$$I = \frac{h_1 - h_0}{\Delta L} \quad (3)$$

where h_1 = hydraulic head in depository ≈ 0
 h_0 = hydraulic head in formation beyond "radius of influence"
 ΔL = "radius of influence"

The radius of influence is given by Bear (1972):

$$\Delta L = 1.5 \sqrt{\frac{Kt}{S_s}} \quad (4)$$

where S_s = specific storage

Combining (1), (2), (3) and (4) we derive a relationship for the hydraulic conductivity of salt:

$$K = 4 \times 10^{-6} \frac{b^2}{S_s t h_0} \quad (5)$$

where K = hydraulic conductivity - cm/sec
 b = observed thickness of precipitated salt, not including salt precipitated at interbeds - cm
 S_s = specific storage of salt - cm^{-1}
 t = age of underground workings - yr
 h_0 = original hydraulic head in salt - cm

Substituting the following values:

$b = 10^{-2}$ to 10^{-3} cm (10^{-2} cm is the approximate thickness of this paper)
 $S_s = 3.3 \times 10^{-8} \text{ cm}^{-1}$ (GAI memo of April 1978 project meeting at LLL)
 $t = 5$ yr
 $h_0 = 3 \times 10^4$ cm (approximate pressure plus position head, based on Culebra dolomite aquifer above salt in the Delaware Basin)

We calculate hydraulic conductivities in the range of 3×10^{-14} to 3×10^{-12} cm/sec. The value of S_s represents the largest uncertainty in the equation, in our opinion; however, we have seen no data on which to base another value. The calculated values of hydraulic conductivity are based on flow through salt only and do not consider flow through the interbeds, because the horizontally-layered interbeds do not materially affect the vertical hydraulic conductivity of salt.

Baar (1977, 1978) cites several examples where no observable flow has occurred through salt at depths greater than about 300 m, but no quantitative analyses are given.

Based on the results of Core Laboratories Inc. and the above computations, we propose a revised baseline value for the hydraulic conductivity of salt below depths of 300 m:

Revised Baseline Hydraulic Conductivity
of Salt: 10^{-12} cm/sec

In our opinion, this represents a maximum value because the available data indicate that the hydraulic conductivity decreases with time below this value. In addition, we feel that a generic range for this parameter is inappropriate because there are evidently no data to indicate a range of measured values. Some researchers argue that they have seen no data suggesting that the hydraulic conductivity of salt at depth is greater than zero (Hale, 1978; Griswold, 1978; C. Baar, 1977; G. Barr, 1978). Therefore, until more measurements are performed, we recommend the fixed baseline value for the hydraulic conductivity of salt.

The proposed value is for homogeneous salt only, because the interbeds commonly found within bedded salt deposits may increase the horizontal hydraulic conductivity of salt. Values for the hydraulic parameters of the interbeds are given in a previous GEI report (1977b).

Relevant experience from the potash mines of the Delaware Basin is reported in Appendix B. The data reported are qualitative and are unpublished; they were obtained from discussions with mine operators for each of the six potash mines. In general, the mines experience no permanent seeps of water through the salt beds. Minor inflow through interbeds decreases to zero after periods ranging from days to months, and the water from high pressure nitrogen-brine pockets, when hit by the miners, ceases flowing and evaporates rapidly.

6.2.3b Hydraulic Conductivity of Shale

Table 5 lists data for the hydraulic conductivity of shale. These data are for relatively deep shales in petroleum-producing area only and do not include test data for near-surface shales. The quality of the data is varied, and few details of test procedures are available; moreover, some reported results are the average of several tests. There are not enough data from any one location to assess the typical variation within a site.

If the logarithms of the data are plotted on probability paper (Figure 8), the data fall essentially along a straight line, with the exception of one anomalously permeable sample.

Based on these data, we propose revised values for hydraulic conductivity of shale:

Baseline value: 4×10^{-11} cm/sec
Geometric standard deviation: 30
PDF: log normal
Generic limits: 10^{-6} to 10^{-13} cm/sec

Although most of the data are for intact laboratory specimens, the mean of the three field values is close to the mean of the lab values. In addition, for two areas where lab and field tests were conducted on the same rock, the values agreed within a log factor of 0.3. Therefore, fracture flow is evidently relatively unimportant in some deep shales where hydrocarbons have been trapped. Apparently, shale deposits can be found where the magnitude of fracture flow is less than that of interstitial flow. We propose that the generic data given above be used for combined fracture plus interstitial flow in shale.

6.2.4 Initial and Boundary Conditions

The initial and boundary conditions in the recharge model are the hydraulic heads in the depository and in the aquifers above and below the depository layer, which are used to calculate the vertical hydraulic gradient through the depository layer.

For recharge calculations, the gradient has been assumed to be the vertical head drop between the upper or lower aquifer and the depository, divided by the flow distance. The divergence of flow lines at the edges of the depository has been neglected which is valid as long as the horizontal hydraulic conductivity is not greater than 10^4 times the vertical hydraulic conductivity. At ratios much greater than this, the effective width of the depository shrinks by a factor of more than 10^2 (Cedergren, 1967), and the depository acts more like a vertical slot rather than the assumed horizontal slot.

Because the pressure head in the aquifers can be measured within about 1/3 meter (Mercer, 1978), the apparent hydraulic gradient during recharge, assuming saturated interstitial flow, should be one of the most accurately known parameters in the model.

The recharge gradient used in the current model configuration, which is approximately 5, results from the dissipation of pressure plus elevation

head of approximately 400 m + 100 m ($\sim$ 500 m) over a flow path of 100 m into the recharging depository. This gradient, while geologically reasonable, is close to four times the corresponding gradient at the WIPP site (Griswold, 1977; Mercer and Orr, 1977). If other factors are held constant, the LLL model, using the generic gradient, predicts a recharge time that is four times shorter than that using actual head data from the Delaware Basin.

For a salt repository, if the salt contains unsaturated zones, as discussed in Section 5.2.1, or if the salt is totally impermeable at the prevailing gradient, calculations based on the assumed hydraulic gradient would fail to represent field conditions. Under these circumstances, shaft leakage would be the only form of recharge.

6.2.5 Independent Calculations of Horizontal Recharge

6.2.5a Recharge Calculations Based on Salt Precipitation In Mines

Using the framework developed in Section 5.2.3a, the thickness of precipitated salt in the potash mines of the Delaware Basin gives an indication of the specific discharge through the salt. This specific discharge can be used directly to compute the recharge time for a nuclear waste repository.

Assumptions

1. All of the salt dissolved in water seeping into the mine is precipitated on the mine walls. (Vaporization of saline water is a common form of desalinization.)
2. Brine seeping into the mine is salt-saturated and has a concentration of 300,000 ppm NaCl. (While minerals other than NaCl will be present in a brine, we chose an NaCl solution as a first approximation.)
3. Based on field inspection of the Duval Nash Draw Mine, we estimate an average thickness of precipitated salt of 1 mm over the extent of the mine walls, including salt due to flow through interbeds. (The inflow is directly proportional to thickness and 1 mm is considered to be a conservatively large thickness. Telephone conversations with several mine operators within the Delaware Basin have indicated that salt precipitation is commonly nil.)

4. The mine has been open 5 years. (While arbitrary, this assumption is conservative.)
5. The depository is assumed to be square, 5 square kilometers in total area, with an extraction ratio of 33% and a height of 5 meters.

Results

Depository Resaturation Time - based on salt precipitation in potash mines.

<u>No Backfill</u>	<u>Backfill, 20% Porosity</u>	<u>Type of Flow</u>
125,000 yr	25,000 yr	Horizontal, Interstitial

6.2.5b Recharge Calculations Based On Steady State Well Flow Equation

Horizontal recharge can also be estimated by analyzing the depository as a circular well with steady-state recharge. The steady-state radial flow equation is:

$$Q = \frac{2\pi Kb(h - h_o)}{\ln (R/r_w)}$$

where Q = flow

K = hydraulic conductivity

b = height of depository

h = head in the depository = zero

h_o = head in the depository layer outside the radius of influence

R = radius of influence

r_w = equivalent "radius" of depository

Assumptions

1. Depository is circular with area of 5 km².
2. Height of depository is 5 m, extraction ratio is 33%.
3. Horizontal hydraulic conductivity of salt plus interbeds is 10⁻⁷ to 10⁻⁹ cm/sec. Vertical hydraulic conductivity is zero; shaft leakage is zero.

4. Total head outside the radius of influence is 300 m.
5. The radius of influence is twice the depository radius. (This is very conservative because no drawdown is assumed outside the radius of influence; if drawdown did occur outside the assumed radius of influence, the actual flow rate would be less than that calculated.)

Results

Depository Resaturation Time (yr) - based on steady-state well equation.

Assumed Hydraulic Conductivity (cm/sec)	No Backfill	Backfill 20% Porosity	Type of Flow
10^{-7}	19,000 yr	4,000 yr	Horizontal, Interstitial
10^{-8}	190,000 yr	40,000 yr	Horizontal, Interstitial
10^{-9}	1.9 million yr	400,000 yr	Horizontal, Interstitial

6.3 Migration Through the Depository Layer

The flow of fluids through the depository medium, once resaturation is complete, is governed by essentially the same considerations as discussed in Section 5.2. Deviations from Section 5.2 are discussed below.

6.3.1 Flow Equations

No change.

6.3.2 Geometry

No change.

6.3.3 Hydraulic Parameters

6.3.3a Hydraulic Conductivity

No change.

6.3.3b Effective Porosity

The effective porosity, or the fraction of interconnected pore space within a porous medium does not affect the quantity of flow through the medium. It does affect the rate at which a given particle is transported through the medium, however, and thus directly influences the time of first arrival at an overlying aquifer of radionuclides originating at the depository.

Porosity measurements of salt are rare because salt is essentially impermeable for mining or most other engineering purposes. Several data have been obtained by Gard (1968), Gloyna and Reynolds (1961) and Core Laboratories Inc. (1959). These data, which are for bedded salt, are listed in Table 6 and are shown plotted on probability paper in Fig. 9. Because the hydraulic conductivity of salt decreases with time when brine is the permeant, these values may not be representative of long-term effective porosity. In addition, sampling may fracture the salt and increase its porosity. Therefore, the laboratory data probably indicate only an upper limit to the in-situ porosity of salt.

Based on the data in Table 6, we propose the following generic values for the porosity of salt:

Baseline value: 0.01
Geometric standard deviation: 2
Generic limits: 0.001 to 0.1
Probability distribution function: log normal

We have obtained no additional data on the effective porosity of shale.

6.3.4 Boundary Conditions

After resaturation, migration of fluid through the depository layer is directly influenced by the direction and magnitude of the hydraulic gradient through the salt or shale depository layer. To date, the LLL model has assumed a head drop of 61 meters between the lower and upper aquifers. While this value is geologically reasonable for either shale or salt, it should be noted that at the WIPP site, where a large field effort has centered on determining the value of this parameters, the USGS

indicates that the gradient is still uncertain.*

At the WIPP site, the salt formations (Salado and Castile formations) are underlain by a partially saline aquifer (the Delaware Mtn. group) and are overlain by two fractured dolomite aquifers, all of which are confined, rather than water table, aquifers. The preliminary results are (Mercer, 1978):

1. The heads in the upper and lower dolomite aquifers above the salt are about 60 m and 85 to 90 m below the ground surface, respectively. Thus, flow between the dolomite aquifers would probably be downward.
2. The equivalent freshwater head in the saline aquifer below the salt is between those of the two dolomite aquifers. But because the density of the saline water is approximately 1.13, the actual head is about 150 m below the other two.

Based on this information it appears that flow between aquifers above and below the salt could potentially be downward, although, according to the USGS, field relationships are still relatively indeterminate.

It should be noted that according to Mercer and Orr (1977, pp. 16 and 23) the freshwater head in the aquifer below the salt is almost exactly 61 meters above that in the aquifer immediately above the salt of the Salado formation at the WIPP site. However, a note on the potentiometric map for the lower aquifer (Delaware Mountain Group) states:

"The contours express a generalized regional head considered to be representative for the Delaware aquifer during the period 1960 to 1970...Considerable judgment was used in contouring data points."

*Publication of these data is scheduled to coincide with publication of the "Draft Generic Environmental Impact Statement On Commercial Waste Management," being prepared for the U. S. Department of Energy by Battelle Pacific Northwest Laboratories. (Office of Waste Isolation, 1978).

Mercer and Orr (1977) carefully document their interpretations with the available data. When the report was prepared, however, virtually no data were available in the vicinity of the WIPP site, and Mercer (1978) and Orr (1978) both indicated that gradients across the salt deposits at the WIPP site at the time of publication were largely indeterminant.

Until additional data become available, the current model configuration may represent a worst-case situation. If a site is characterized by a downward hydraulic gradient through the depository layer, the transport time of wastes to the biosphere may be orders of magnitude longer than those calculated, because of longer transport distances, lower permeabilities of aquifers at greater depths, greater dispersion, and lesser human usage (caused by possible lower water quality in deeper aquifers, such as the saline Delaware Mountain Group in the Delaware Basin). The lower retardation coefficients associated with saline aquifers, however, may partially offset some of these characteristics.

6.4 Summary and Conclusions

Darcian flow should be assumed for both salt and shale. In recent tests performed specifically to look for non-Darcian flow in sands, silts, and clays, Russell and Swartzendruber (1971) concluded that flow was Darcian except in swelling clays. We have found no similar tests on shale or salt, and the observed non-Darcian effects observed by Swartzendruber (1971) were small at gradients comparable to those used in the ILL model.

Saturated conditions should be assumed in salt; although there is some evidence to the contrary, proof is lacking. The assumption of saturated conditions will lead to conservative flow estimates if bedded salt at depth is unsaturated.

Proposed new hydrologic parameter values are as follows:

Parameter	New Baseline Value	Old Baseline Value	Geometric Standard Deviation	Probability Distribution Function	Estimated Generic Limits
Hydraulic Conductivity of Bedded Salt	10^{-12} cm/sec	10^{-9} cm/sec	NA*	NA	NA
Hydraulic Conductivity of Shale (Vertical)	4×10^{-11} cm/sec	10^{-8} cm/sec	30	Log Normal	10^{-6} to 10^{-13} cm/sec
Effective Porosity of Bedded Salt	10^{-2}	2×10^{-2}	2	Log Normal	10^{-3} to 10^{-1}

*NA - Not applicable, because, based on the available information, only an upper limit can be determined.

The recharge gradient used in the model, while geologically reasonable, is roughly four times the corresponding value in the Delaware Basin at the WIPP site. Resaturation time predicted with the generic heads and flow length currently used in the flow path model is, therefore, roughly one-fourth that calculated with actual field data (if other parameters are held constant).

Two independent (and very approximate) determinations predict recharge times due to horizontal, interstitial flow, in excess of 10,000 years. Recharge due to vertical, interstitial flow, when the revised hydraulic conductivities are used, are likewise more than 10,000 years. Therefore, attention should be focused on shaft and tunnel sealing after repository de-commission. This correlates with experience in salt and potash mines, where all of the permanent mine inflow is due to shaft leakage.

Available data show that the hydraulic conductivity of salt decreases below measurable values in several weeks when under high confining pressures and when brine is the permeant. In one test, a hole drilled through a salt sample closed within

7 days so that the hydraulic conductivity had decreased by a factor of 26 before testing was stopped. We recommend a revised hydraulic conductivity for salt of 10^{-12} cm/sec because this was the lowest value measurable with the apparatus used to test salt. We have no data or other basis for assigning a standard deviation, probability distribution function, or generic limits, at present.

Based on preliminary, unpublished data from the Delaware Basin, the magnitude and direction of the gradient through the evaporate deposits at the WIPP site are indeterminate at present. Downward flow through the salt appears to be a distinct possibility; if this were the case, modeling would require additional hydrologic data for the lower aquifer.

TABLE 1 - SUMMARY OF GEOLOGICAL EXPLORATION TECHNIQUES APPLIED TO HAZARD DETECTION

<u>Class</u>	<u>Method</u>	<u>Method Is Based Upon</u>	<u>Advantages</u>	<u>Disadvantages</u>
Direct Observation	Drilling	Direct observation of subsurface materials	The only direct observation method short of actual mining; enables coring and geophysical logging	Can only detect variations with depth approximately within radius of borehole; breaches repository layers
Potential Field	Gravity	Detecting local variations of the Earth's gravitational field due to local density differences at depth	Does not disturb subsurface	Inherently poor resolution; uses modeling approach; can only detect large and/or near-surface cavities; cannot detect breccia pipes
	Magnetics	Detecting local variations in the Earth's magnetic field due to variations in magnetic susceptibility at depth	Does not disturb subsurface; easily detects intrusive bodies	Inherently poor resolution; uses modeling approach; cannot detect hazards involving only sedimentary rocks in a basin
	Resistivity	Detecting variations in induced electric field due to local resistivity differences at depth	Does not disturb subsurface; can detect breccia pipes extending near surface and distinguish them from sinks	Inherently poor resolution; uses modeling approach; not reliable in detecting features at depth
Wave	Radar	Reflections of radar waves from electrical discontinuities in rock	Good resolution; very accurate and reliable	Must be used from mine or possibly from borehole; limited to dry environments
	Seismic Reflection	Reflections of seismic waves from physical discontinuities in rock	Does not disturb subsurface; good resolution and accuracy; reliable	Data should be "tied" to nearby borehole; somewhat poorer resolution than radar
	Seismic Refraction	Refractions of seismic waves by physical discontinuities in rock	Does not disturb subsurface	Inherently poor resolution; unable to detect solution cavities, breccia pipes, or other low-velocity hazards, does not give record of detailed stratigraphy

TABLE 2 - LIST OF LAND SUBSIDENCE AREAS ASSOCIATED WITH
INADVERTENT SALT DISSOLUTION IN OIL AND GAS
HOLES, CENTRAL KANSAS
(From Walters, 1976)

Page 1 of 2

Crawford No. 12 Crawford No. 16 Gorham Oilfield Russell County, Kansas	These twin wells, 50 ft (15 m) apart, are the site of more than 26 ft (8 m) of settling affecting both lanes of Interstate Highway I-70. The Kansas Highway Commission drilled a test hole between these wells. The area is precisely surveyed, intensely studied, and affords conclusive evidence that subsidence is due to dissolution of salt in old oil and gas test holes. As of 1976, area was 300 m across and 8 m deep. Subsidence continues.
Witt No. 1 Gorham Oilfield Russell County, Kansas	The Witt No. 1 is next to the south right-of-way fence of U.S. I-70. Subsidence of 17+ ft (5+ m) the well makes a gathering basin for rainwater which drains directly off the highway into the well bore, exposed in a gully. As of 1976, area was 230 m in diameter, 5 m deep. Subsidence continues.
Hodge No. 2 Welch-Bornholdt Oilfield Rice County, Kansas	There is a mature shallow dished depression with a small pond at this location, apparently due to settling of the ground around the old disposal well.
Hilton No. 6 Hilton No. 7 Chase-Silica Oilfield Rice County, Kansas	Abandoned oilfield brine disposal wells 200 ft (61 m) apart. Well 6 was used until Oct. 1951, and Well 7 until June 1965. The subsidence area around these holes appears stabilized. There is a shallow fresh water lake in the gentle depression. Total subsidence of 6 m occurred over an area 160 x 190 m.
Berscheit Heirs No. 14 Chase-Silica Oilfield	At the time this disposal well was plugged in 1972, the ground was sinking. Slow subsidence (about 5 m total) occurred over an area approximately 140 m x 120 m. The area is now considered essentially stable.
W. M. Panning No. 11 Chase-Silica Oilfield Barton County, Kansas	On April 24, 1959 at 9:00 a.m., the landowners observed a cavity forming around this well. It developed into a pit 300 ft (91 m) in diameter within a few hours' time. At present the site is a fenced freshwater lake (20 m deep) used as a game preserve.

TABLE 2 - LIST OF LAND SUBSIDENCE AREAS ASSOCIATED WITH
INADVERTENT SALT DISSOLUTION IN OIL AND GAS
HOLES, CENTRAL KANSAS
(From Walters, 1976)

Page 2 of 2

Daisy E. Pierce No. 5
Burrton Oilfield
Reno County, Kansas

Disposal into this shallow well in 1968 caused about four feet of settling of the section line road. Depth to salt is about 400 feet (122 m). Well abandoned. Road rebuilt. Appears stable.

Lovett SWD No. 2
Groveland South Oilfield
McPherson County,
Kansas

This shallow brine disposal well, drilled in 1958, encountered salt at 489 ft (150 m) total depth, with 7 - inch casing set at 487 ft. Brine was introduced directly into the salt section within the zone of natural salt dissolution. Subsidence area, about 100 feet (30 m) in diameter, is east of the section line road and north of the creek. The disposal well and all adjacent oil wells are now abandoned. The area is considered stable.

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TABLE 3 - EXAMPLES OF SUBSIDENCE ASSOCIATED
WITH SOLUTION-MINING CAVITIES

<u>Basin</u>	<u>Area (Company)</u>	<u>Characteristics</u>
Michigan Basin	Sandwich	Slow subsidence (600 m diameter) from 1948-1954. Rapid collapse in 1954 resulted in sinkhole 150 m in diameter, 8 m deep. Subsidence ceased naturally (Terzaghi, 1970).
Permian Basin (Kansas)	Hutchinson (Morton)	Initial rapid subsidence in 1914 resulted in sinkhole 50 m across and at least 2.5 m deep. The brine wells were plugged, and subsidence ceased (Walters, 1976).
	Hutchinson (Carey)	Gentle, slow, subsidence over an area 200 m in diameter was noticed only because it occurred under a city. Maximum depression was less than 1 m, and cessation of brine operations resulted in stability (Walters, 1976).
	Hutchinson (Barton)	In 1952, slow subsidence occurred with at least 3 m of relief which was associated with a well about 300 m away. The plant is still operating, and slow subsidence continues (Walters, 1976).
	Hutchinson (Cargill)	In 1974, after a period of slow, gentle subsidence, a rapid subsidence formed a sinkhole 100 m across and 20 m deep. The area is now stable (Walters, 1976).

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TABLE 4 - SOME CASES OF SUBSIDENCE ASSOCIATED WITH
POTASH MINING IN THE DELAWARE BASIN, NM

<u>Company</u>	<u>Technique</u>	<u>Geometry</u>	<u>Maximum Surface Subsidence</u>
National Potash Company	High extraction (90%) subsidence expected	1525 ft (500 m) deep; 5.5 ft (1.7 m) high rooms	1.8 ft (0.5 m)
	High extraction (95-100%) subsidence expected	850 ft (260 m) deep; 7 ft (2.1 m) high rooms	4 ft (1.2 m)
Potash Company of America	High extraction (80-90%)	650-750 ft (198-229 m) deep; 53-60 in (1.3-1.5 m) high rooms	A few cm
Duval (Nash Draw Mine)	Moderate extraction, subsidence avoided		None
Amex Chemical Company	92% extraction, subsidence expected	900-950 ft (275-290 m) deep; 6-7 ft (1.8-2.1 m) high rooms	3.4 ft (0.9-1.2 m)
Kerr-McGee Corporation	80% extraction, subsidence expected	1,600-1,700 ft (488-518 m) deep; 5 ft (1.5 m) high rooms	3 ft (0.9 m)

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TABLE 5 - HYDRAULIC CONDUCTIVITY
MEASUREMENTS OF SHALE

Source	Hydraulic Conductivity (cm/sec)	Type of Test	Confining Pressure (psi)	Permeant
1. Gondouin and Scala (1958)	2 x 10 ⁻¹² 3 x 10 ⁻¹⁰ 6 x 10 ⁻¹⁰ 7 x 10 ⁻¹² 8 x 10 ⁻¹⁰ 2 x 10 ⁻⁶ 10 ⁻¹² 9 x 10 ⁻¹¹ 4 x 10 ⁻¹⁰ 4 x 10 ⁻⁹	Lab Lab Lab Lab Lab Lab Lab Lab Lab Lab	N.A.** N.A. N.A. N.A. N.A. N.A. N.A. N.A. N.A. N.A.	0.2 N NaCl Solution 0.02 N NaCl Solution 0.02 N NaCl Solution 0.2 N NaCl Solution 0.2 N NaCl Solution 0.2 N NaCl Solution 0.2 N NaCl Solution 0.2 N NaCl Solution 0.02 N NaCl Solution 0.2 N NaCl Solution
2. Marine (1974)	3.4 x 10 ⁻¹⁰ 4.5 x 10 ⁻¹²	Field Field	~1300 ~1300	N.A. N.A.
3. Olsen and Martin (1976)	2 x 10 ⁻⁹ 1 x 10 ⁻¹⁰ 2 x 10 ⁻¹¹	Lab Lab Lab	N.A. N.A. N.A.	N.A. N.A. N.A.
4. Schenck (1955)	2.4 x 10 ⁻¹¹ 1.3 x 10 ⁻¹¹ 4.4 x 10 ⁻¹¹	Lab Lab Lab	N.A. N.A. N.A.	N.A. N.A. N.A.
5. Witherspoon et al. (1962a)	3.2 x 10 ⁻¹¹	Field	N.A.	N.A.
6. Witherspoon and Nelson (1962b)	1.8 x 10 ⁻¹¹ (Average ~10 ⁻¹¹)	Field Lab	N.A. N.A.	N.A.) Same area N.A.)
7. Witherspoon et al. (1967a)	7 x 10 ⁻¹¹ (Average ~1.8 x 10 ⁻¹⁰)	Field Lab	N.A. N.A.	N.A.) Same area N.A.)
8. Young et al.* (1964)	3 x 10 ⁻¹² 4.3 x 10 ⁻¹³ 3 x 10 ⁻¹² 5.3 x 10 ⁻¹¹ 1.4 x 10 ⁻¹² 1.7 x 10 ⁻¹³	Lab Lab Lab Lab Lab Lab	515 2,030 6,400 0 2,400 1,500	3.5% NaCl Solution 5.8% NaCl Solution 3.5% NaCl Solution 3.5% NaCl Solution 3.5% NaCl Solution 5.8% NaCl Solution

*Where two labs tested the same sample, the higher value is reported.

**N.A. - Not Available.

TABLE 6 - LABORATORY DATA ON POROSITY
OF BEDDED SALT

<u>Reference</u>	<u>Porosity (%)</u>	<u>Source</u>	<u>Method</u>
Core Laboratories Inc. ¹⁾ (1959)	1.33	Hutchinson, KS	Gas Expansion
	1.04		Brine Saturation
	1.21		Gas Expansion
	1.00		Brine Saturation
	1.00		Gas Expansion
	0.77		Brine Saturation
	1.22		Gas Expansion
	1.15		Brine Saturation
	0.62		Gas Expansion
	0.38		Brine Saturation
	0.71		Gas Expansion
	0.41		Brine Saturation
	0.67		Gas Expansion
	0.57		Brine Saturation
Gard (1968)	1.29	Gnome Site, NM	Gas Expansion
	1.14		Brine Saturation
	2.7		Kerosene Saturation
	1.1		Kerosene Saturation
	5.1		Kerosene Saturation
	1.2		Kerosene Saturation
	7.1		Kerosene Saturation
	1.7		Kerosene Saturation
	0.8		Kerosene Saturation
Gloyna and Reynolds (2) (1961)	3.2	Hutchinson, KS	Kerosene Saturation
	2.7		Kerosene Saturation
	0.59		Gas Expansion

Notes: (1) Two independent test methods were used. For analysis, the average of results by the two methods was used.

(2) Average of six determinations.

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- a) Distortion of current flow lines by bodies having (A) anomalously high or (B) anomalously low conductivity.

- b) Hypothetical flow lines in case of homogeneous earth.

— Lines of current flow
 --- Equipotential lines

- c) Hypothetical flow lines in case of layered earth, with schematic of typical circuitry.

Fig. 1 - Current flow lines and electrical inhomogeneities

Fig. 2 - Comparison of observed and theoretical horizontal resistivity profiles over filled sink: a) observed field curve with geologic cross-section (confirmed by drilling), b) theoretical field with assumed data points only at electrode positions. Assumed value of $\rho''/\rho' = 1/5$ (after Cook and Van Nostrand, 1954; as cited in Dobrin, 1976).

Fig. 3 - Anomalous gravity at point above center of mass for cavities of various radii, depths, and thicknesses. Example shown of cavity of radius 100 ft (30 m), height 100 ft (30 m) and depth 1,000 ft (300 m). Minimum detectable anomalies with 10 ft (3 m) and 100 ft (30 m) of surface relief are also shown (after Speed, 1970).

a) Total magnetic intensity over earth in 1965. Contour intervals in thousands of gammas.

b) Average magnetic susceptibilities of surface samples and cores as measured in the laboratory.

Fig. 4 - Some aspects of the earth's magnetic field (after Dobrin, 1976).
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a)

b)

c)

d)

Fig. 5 - Geometric representation of probabilities of hitting a target with a drilling grid

Fig. 6- Petroleum exploitation in bedded-salt basins

4' X 4' STEEL PIPE WITH MARKER
OR PIPE CUT OFF BELOW PLOW DEPTH

Fig. 7 - Schematic of typical plugs required by
most states. (From Herndon and Smith,
1976)

Fig. 9 - Log Normal Cumulative Probability Plot - Porosity of bedded salt

APPENDIX A

(From Herndon and Smith, 1976)

SUMMARY OF STATE PLUGGING REGULATIONS

Regulations were obtained from each oil producing state pertaining to abandonment and plugging of oil, gas or water wells. In every state, the regulations specify that the body shall be notified of the intention to plug and abandon a well. Most states have forms for this purpose, detailing the information desired.

1. Alabama - State Oil & Gas Board, Rule B-7 thru B-14

Cement plug from bottom of hole to 50 feet above top of each producing formation. Bridge plug and 50 feet of cement above top of producing formation also acceptable. Plug (50 ft minimum) approximately 50 feet below all fresh water strata. Surface plug not to interfere with soil cultivation. Mud between cement plugs.

2. Alaska - Department of Natural Resources - Division of Oil and Gas - Regulation 25

Same plugs as above for Alabama except that surface will be marked with 4-foot high steel marker set in concrete, instead of cutting off casing below ground.

3. Arizona - Oil and Gas Conservation Commission - Rules 201-204

Cement plug from bottom of hole to not less than 50 feet above each producing formation open to wellbore. Cement plug from 50 feet above to 50 feet below each fresh water strata. Surface plug not less than 20 feet, with a steel marker to locate well. Mud between cement plugs.

4. Arkansas - Oil and Gas Commission - Rule B-6 thru B-11

Cement plug from bottom of hole to 30 feet above each producing stratum. Cement plug 50 feet minimum at about 50 feet below fresh water-bearing stratum when not behind surface casing. If water is behind casing, place 30-foot cement plug inside casing. Mud between cement plugs.

5. California (Onshore) - Division of Oil and Gas - Title 14 - Article 3, Rules 1723 - 1723.7

Inside casing - cement plug across producing zone and minimum of 100-foot cement plug above each zone if possible, plug above shoe or intermediate casing and from 100 feet above to 100 feet below base of fresh water strata.

5a. California (Offshore) - Title 14 - Rules 1745 - 1745.10

In uncased hole, cement plug shall extend from total depth (or 100 feet below producing zone) to 100 feet above shoe. If open hole below casing, cement plug shall be from 100 feet above casing shoe to 100 feet below. Cement plug opposite all perforated intervals to 100 feet above. Cement plug extending 100 feet below base of fresh water (or casing stub) to 100 feet above. Surface plug of 100 feet minimum with the top 50 to 150 feet below ocean floor. Plug must be tested by 10,000 pounds weight.

6. Colorado - Department of Natural Resources - Oil and Gas Conservation Commission - Rule 327

Place plugs in such a manner that oil, gas, water or other substances are confined to their original reservoirs. Well can be marked with steel marker, or casing cut off below ground and capped.

7. Florida - Department of Natural Resources - Rules 16C - 2.07 thru 16C - 2.11

In uncased portions, plug shall extend from 100 feet below to 100 feet above producing zones. Place 100-foot cement plug opposite any formation known to produce hydrocarbons within 10 miles of well. If casing is in well, place plug 100 feet above and below casing shoe or casing stub. Cement plug opposite all perforated intervals. Surface plug of 25 feet cement on land; or 150 feet under water.

8. Georgia - Department of Natural Resources - Geologic & Water Resources Division - Rules B-7 thru B-12

Cement plug from bottom of hole to 15 feet above each producing formation. Place 50-foot cement plug at 50 feet below fresh water strata. Cement plug at surface in manner not to interfere with soil cultivation.

9. Iowa - Iowa Geological Survey - Chapter 84 - Code of Iowa

Plug well with mud, cement or plugs, singly or in combination as may be approved by State Geologist. If no log available, well to be plugged with cement from bottom to top. Cut off casing below plow depth.

10. Illinois - Department of Mines and Minerals - Division of Oil and Gas - Rule XI and XI-A

Log must be furnished or well plugged completely with cement. Otherwise, place cement plug opposite producing formation to 20 feet above. If partially cased, place cement plug from below casing seat to 20 feet above. Protect each coal seam over 30 inches thick (above 1,000 feet depth) by cement plug from 100 feet above seam to 50 feet below. Cement plug from 10 feet below surface casing to 15 feet above base. Cut off surface 2 feet below ground and cap with cement.

11. Indiana - Department of Natural Resources - Division of Oil and Gas - Rule 33

When a well is ready for plugging, a State Department field representative is called, and he tells the well owner where to place the plugs. Generally, cement plugs are placed to protect the fresh-water strata, to seal off the production zones and to plug the surface. Surface casing is cut off below plow depth. If coal seams 24 inches or thicker are present above 1,200 feet depth, a cement plug is placed from 50 feet below the seam to 100 feet above.

12. Kansas - State Corporation Commission - Rule 82-2-302 to 304

Cement plug from bottom of well to top of each formation with a 25-foot minimum at top of each producing formation with heavy mud below. Place 25-foot cement plug about 25 feet below each fresh-water strata. Balance of hole filled with drilling mud not less than 36 viscosity (API Full Funnel Method). Cement plug at top of surface casing cut off to permit soil cultivation.

13. Kentucky - Department of Mines & Minerals - Division of
Oil & Gas Rule 1.06 and 1.07

Cement plug from bottom of hole to 15 feet above each producing formation. Place cement plug of 15 feet immediately below each fresh-water strata. Cement plug at surface placed so as not to interfere with soil cultivation. Uncased rotary hole plugged with mud to base of surface casing, then place 15-foot cement plug. Cap casing as given above.

14. Louisiana - Department of Conservation - State Order No.
29-B, Section XIX

Plugging program shall be approved by Commissioner of Conservation prior to plugging. Cement plugs 100 feet minimum length shall be placed across perforated interval. Place 100-foot minimum cement plug from 50 feet below shoe of surface casing to 50 feet above. Cement plugs shall be from 100 feet below deepest fresh-water sand to at least 150 feet above sand base. Place 30-foot cement plug in top of surface casing. On land, cut off casing 2 feet below plow depth; on water, cut casing ten feet below mud line. Balance of well filled with mud.

15. Michigan - Department of Natural Resources - Geological Survey
Division - Circular 9, Rules 801-811

Plugging instructions will be specified by the State Supervisor of Wells. Plugging must confine oil, gas or water to the formation in which they occur. Surface pipe will be cut off below plow depth and capped.

16. Mississippi - State Oil and Gas Board - Rule 27 and 28

Uncased holes - place cement plugs of 50-foot minimum length to protect each producing formation and at about 50 feet below all fresh-water sands. Place 50-foot cement plug at bottom of surface casing and at surface in manner not to interfere with cultivation.

17. Missouri - Department of Natural Resources - Oil and Gas
Section - Rule 50 - 2.060

Well shall be plugged in a manner that will permanently confine all oil, gas and water in the separate strata originally containing them. Plugging shall be accomplished using mud, cement and plugs singly or in combination as may be approved by the State Geologist. Producing formations shall have cement plug from base of formation to 25 feet above top formation. Specific directions given if radio-active source is left in hole.

18. Montana - Oil and Gas Conservation Division - Rule 232

Plugging program must be submitted by operator and approved by the State Petroleum Engineer prior to plugging. Wells shall be marked with a permanent marker rising 4 feet above ground or cut off for cultivation if land owner desires.

19. Nebraska - Oil & Gas Conservation Commission - Rule 3(30)

Plugging program must be submitted and approved by Commission, but plugging must be done so that oil and gas or water will be confined to the reservoir in which it originally occurred. Mud, cement or a mechanical plug may be used.

20. Nevada - Oil and Gas Conservation Commission - Rules 200 thru 207

Plugs can be mud, cement and plugs, used singly or in combination, as may be approved by the Commission. Cement plugs shall be a minimum of 25 sacks of cement. A plug will be placed every 1,000 feet in uncased holes to prevent mud settlement, and at the base of any casing left in the hole. A steel well marker is placed at the surface.

21. New Mexico - Oil Conservation Commission - Section D - Rules 201-204

Well shall be plugged in a manner which will permanently confine all oil, gas and water in the separate strata originally containing them. Plugging shall be accomplished by mud, cement and plugs, singly or in combination, as approved by the Commission. Location of well shall be shown on steel marker above ground surface.

22. New York - Department of Environmental Conservation - Title 6 - Chapter 5, Part 555

Well owner must give notice of plugging and State Department will send representative to witness plugging. Cement plug will be placed from bottom of hole to 15 feet above shallowest producing formation. A 15-foot plug will be placed at bottom of any casing left in hole and about 50 feet below deepest potable water sand. Mud to be in well between cement plugs. Cap casing so it will not interfere with cultivation.

23. North Dakota - The Industrial Commission of North Dakota - Rules 201-204

Well shall be plugged in a manner which will confine permanently all oil, gas and water in the separate strata originally containing them. This shall be done using mud, cement and plugs, singly or in combination as may be approved by the Commission. Surface casing shall be cut off below plow depth.

24. Oklahoma - The Corporation Commission - Oil & Gas Conservation Division - Rules 3-400 thru 3-408

Well will be plugged under the supervision of a representative of the Conservation Division. In uncased hole, cement plugs shall be placed from 50 feet below each productive zone to 50 feet above base, and from a point 50 feet below top of the formation to 50 feet above the top of the zone. If producing zone is cased and properly cemented, a bridge plug capped with 10 feet of cement may be set at top of formation. All fresh water strata shall be protected by a cement plug 50 feet below and 50 feet above casing shoe, or 50 feet below lowest fresh water sand to 50 feet above surface casing shoe. Any uncased hole below any casing shall be filled with cement to at least 50 feet above casing shoe. Well location and data shall be permanently marked on the surface.

25. Ohio - Department of Natural Resources - Division of Oil and Gas - Rule 1509.14 - 1509.19

Well shall be plugged by filling hole with sediment or properly prepared clay to a point above the producing zones. One or more seasoned wood plugs (or a lead plug) shall be driven on top of sediment. Then 100 feet above the plug shall be filled with sediment or clay. After withdrawing surface casing, wooden plug or iron ball shall be placed on the casing seat and covered with 50 feet of rock sediment or prepared clay. Any fresh-water strata shall be plugged in like manner. Coal seams shall be sealed in like manner from 50 feet below the seam to 20 feet above, then a wooden plug placed and the hole filled for 30 feet more. A well through a mine must leave casing from 30 feet below mine floor to 15 feet above roof, and fill with concrete from 100 feet below mine to top of casing. A wooden plug is placed at lower point and at top of casing, with another 20 feet of concrete placed on top wooden plug.

26. Pennsylvania - Department of Environmental Resources - Oil and Gas Division - Article II - Section 205-207

For wells not underlaid by coal seam, well shall be filled with sand dumpings or mud, as Division may approve, from bottom of well to a point 20 feet above top of lowest production zone. At this point, place a plug of cement for at least 20 feet. Between this cement plug and 20 feet above highest production stratum, fill in same manner described above. Place a bridge approximately 30 feet below water casing and put 10-foot cement plug on top of bridge. Withdraw casing and then place final plug from 10 feet below surface casing to surface using mud or sand dumpings.

In a well passing through coal seams, production zones shall be plugged as described above. A plug shall be placed 10 feet below bottom of smallest coal protecting string and hole filled with 20 feet of rock or gravel. Vent pipe shall be placed on gravel to

remove any free gas. Space around vent pipe shall be filled with cement to 25 feet above highest workable coal seam.

27. South Dakota - Department of Natural Resource Development - Chapter 52:02:04

Wells shall be plugged by following a plugging schedule approved by the office of the State Geologist. Well shall be marked with a marker showing well information.

28. Tennessee - State Oil & Gas Board - Chapter 1040-2-9

Wells shall be plugged with a mud fluid of sufficient weight to off-set the hydrostatic pressure of any formation penetrated. Cement plugs shall be so placed to prevent the co-mingling of oil, gas or water from one zone to another, and to isolate potentially minable coal seams and other potentially extractable minerals. All downhole plugs must be touched to insure they have been properly placed.

29. Texas - Texas Railroad Commission 051.02.02.014 - Rule 14

All oil, gas or geothermal resource bearing formations must be protected. Place a 100 foot cement plug immediately above the upper-most perforated zone or produced horizon. If screen or perforated liners cannot be removed, place plug across zone to 100 feet above top of liner. If production casing is removed, place a cement plug from 50 feet below surface casing shoe to 50 feet above. If fresh-water horizons are exposed, place cement plug from 50 feet below base of lowest sand to 50 feet above top of sand. This plug must be checked for location by landing. Place 10-foot cement plug at surface. Use mud of 9.5 lbs/gal or better in other portions of well.

30. Utah - Department of Natural Resources - Division of Oil, Gas and Mining - Title 40-6 - Rules D-1 thru D-4

Cement plug placed from bottom of well to top of producing formation, and a cement plug of 100 feet placed immediately above each producing formation. Place cement plug from 50 feet below fresh water zone to 50 feet above zone. A 50-foot cement plug shall be placed at the base of the surface string, and a 100-foot cement plug shall be centered across any casing stub. Place 10 sacks of cement at surface of well. Fill between plugs with heavy mud-laden fluid.

31. Virginia - Department of Labor and Industry - Mining Laws -
Article 4, Rules 45.1 - 128 thru 131

Well shall be plugged in same manner as specified for Pennsylvania.

32. Washington - Department of Natural Resources - Oil & Gas
Conservation Commission - Rules 23-26

Place cement plug from bottom of cased hole to 15 feet above perforations open to producing zones. A 15-foot cement plug shall be placed at approximately 50 feet below all fresh-water strata. Place cement plug at surface so as not to interfere with cultivation. Fill between plugs with approved heavy mud. An uncased hole shall be plugged between salt and fresh water zones. Mud may be used to a surface string covering fresh-water sands, but a 15-foot cement plug will be placed in lower part of surface casing. Weld steel plate to top of casing at surface.

33. West Virginia - Department of Mines - Oil and Gas Division -
Chapter 22-4 - Rules 2.11 - 2.14

Well shall be plugged in such manner as to prevent migration of oil, gas or water to any strata other than their original strata. Cement or other suitable plugs may be used. Location and length of plugs to be approved by Department.

34. Wyoming - Oil & Gas Conservation Commission - Rules 312-315

Well will be plugged in a manner sufficient to protect all fresh-water bearing formations and possible or probable oil or gas bearing formations. Plugging plans must be approved by the State Oil and Gas Supervisor before plugging is done.

APPENDIX B

WATER CONDITIONS REPORTED IN POTASH MINES OF THE DELAWARE BASIN

General

This appendix, based on contacts with engineers from six potash mining companies in the Delaware Basin, describes sources and relative amounts of water inflow to the mines.* In general, mine inflows are due to one of the following:

- Brine Pockets
- Interbeds
- Shaft Leakage

We conclude that shaft leakage is the only permanent source of leakage into the mines.

It is important to point out that the following discussions are qualitative because few measurements are available. It is frequently difficult for a mining engineer to be specific about the amount of water inflow due to the various sources because most of the flows are so small that minimal attention is paid them.

Reports for the six mines vary, in part because even though all of the mines are similar, the geologic conditions range from place to place within the potash deposits.

What information was obtained is summarized below:

*The six mining companies contacted were the following:

1. Amax Chemical Company
2. Duval Corporation
3. Kerr-McGee Corporation
4. Mississippi Chemical Company
5. National Potash Company
6. Potash Company of America

Brine Pockets

Brine pockets are inclusions of brine, commonly with nitrogen gas, within evaporite deposits that range in size from microscopic to thousands of gallons. The frequency with which mines in the Delaware Basin hit brine pockets varies from mine to mine. For instance, National Potash Company hasn't hit any (Thiel, 1978). Other mines have hit small water deposits and have experienced no problems as a result. When brine pockets are hit, they trickle "for a while," some under pressure that rapidly decreases. The miners keep excavating after hitting a brine pocket because the flows always stop in a relatively short period of time (Kirby, 1978).

Kerr-McGee reports hitting a brine pocket which leaked 1.5 million gallons into the mine. The leak, accompanied by some nitrogen gas, began under pressure. After seven to eight days, the flow was reduced to a "trickle" and the inflow stopped soon thereafter. All the fluid evaporated within one month (none was pumped out) (Lane, 1978).

Interbeds

Interbeds, commonly called clay seams, are present to various degrees within the different ore zones being mined. Amax reports 1-2% clay in the zone being mined; others report closer to 10% (Jordan, 1978; Kirby, 1978; Lane, 1978; Thiel, 1978). Some mines drill ahead to relieve fluids and pressure (for instance, National, Mississippi, Duval, Amax); some don't (for instance, Potash Company of America). The various companies that do drill describe the purpose of their drilling in two ways: to intersect nitrogen pockets which "blow for a bit" and leak no water or to relieve pressure and fluids contained in clay seams. When clay seams are intersected, various events may happen. Sometimes no fluids leak out, or brine may trickle out very slowly and build up salt stalactites around the hole. Kerr-McGee reports that brine may trickle out for as long as one week, and amount to 10-15 barrels at most (Lane, 1978). National reports that "air" (probably nitrogen) and water sometimes come out under pressure for one to several hours. The pressure subsides and water continues trickling for as long as the mined area is open to observation (Thiel, 1978).

Amax pays no attention to seepage that occurs at holes drilled into the mine roof or walls because the flow is so slow that the mine engineers cannot determine if it ceases or not (Kirby, 1978).

In the immediate vicinity of the mine openings, the stress concentrations cause water to be squeezed from clay seams. The flows are proportional to the thickness of the clay seams and the magnitude of the stress concentrations.

For example, where National Potash Co. mines at a 95% extraction ratio, as much as one foot of water collects in the mined-out areas. Subsidence is rapid, and detailed investigation of the water flows is impossible because the areas cannot be re-entered (Thiel, 1978). Amax, with only one to two percent clay in its ore, has no compressed clay problem; where the Potash Company of America mines at 80 to 90 percent extraction, at most one liter of water drips out of compressed clays (Kirby, 1978; Jordan, 1978).

Shafts

Most mines report that the underground workings are "perfectly dry," and that water inflows are seen only at brine pockets or interbeds, except for leakage down shafts. Shaft conditions in the Delaware Basin are summarized by Brokaw and others (1972): "At several of the shafts, pumping is no longer required, and at others the amount of water pumped is minimal. The effectiveness of the methods emphasized to control the water in the shaft areas is evidenced by the fact that the records show that no water has entered the mine workings."

For instance, Amax reports a generally dry shaft in which the concrete occasionally weeps. Some water does collect in the bottom of the shaft, mostly due to condensation and to a minor amount of water that leaks down the outside of the shaft. A total of one to two gallons per minute is pumped out (Kirby, 1978). Potash Company of America reports that its old shaft, sunk in 1932, leaked because of improper cementing. The shaft was repaired, but still leaks, currently about 20 gpm. This inflow is due partly to condensation and partly to surface water from the refinery (Jordan, 1978). Potash Company of America's new shaft, sunk in 1950 with modern freezing techniques, is so dry that no pumps were even installed (Jordan, 1978). A Saskatchewan potash mine shaft, completed in 1958 by use of freezing techniques, was leaking 40 gpm by 1959. Leakage peaked at 300 gpm, when corrective measures were taken. It was discovered that water was migrating down the outside of freeze tube casings from upper aquifers; grouting was successful in halting the inflow (Parsons, Brinckerhoff, Quade, and Douglas, Inc., 1976).

APPENDIX C

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