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GROUNDWATER RECHARGE AND DISCHARGE SCENARIOS FOR A NUCLEAR WASTE REPOSITORY IN BEDDED SALT

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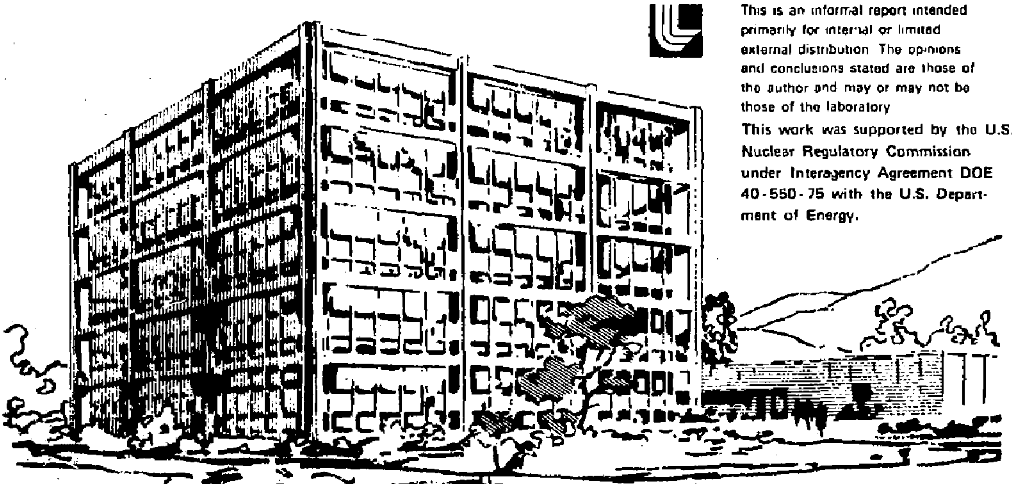

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FOREWORD

This report on groundwater recharge and discharge scenarios for a nuclear waste repository in bedded salt was prepared as part of the Nuclear Regulatory Commission Waste Management Program at Lawrence Livermore Laboratory under Task 2 in support of the Basic Order Agreement.

The ideas presented in this document were discussed at a meeting in Livermore during January 1979. The following people contributed to these discussions: N. Bonner, D. Carpenter, H. Lutz, R. Martin, T. Naymik, W. O'Connell, M. Revelli, T. Steinborn, W. Sutcliffe, and J. Wagoner of LLL; J. Cogan and D. Sokol of International Engineering Company, Inc.; J. Ashby of Golder Associates, Inc.; and B. Ross of The Analytical Science Corporation. T. Naymik of LLL provided additional geohydrological information for this report.

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ABSTRACT

Twelve potential scenarios have been identified whereby groundwater may enter or exit a nuclear waste repository in bedded salt. The 12 scenarios may be grouped into 4 categories or failure modes: dissolution, fracturing, voids, and penetration. Dissolution modes include breccia pipe and breccia blanket formation, and dissolution around boreholes. Fracture modes include flow through preexisting or new fractures and the effects of facies changes. Voids include interstitial voids (pores) and fluid inclusions. Penetration modes include shaft and borehole sealing failures, undetected boreholes, and new mines or wells constructed after repository decommissioning. The potential importance of thermal effects on groundwater flow patterns and on the recharge-discharge process is discussed. The appropriate levels of modeling effort, and the interaction between the adequacy of the geohydrologic data base and the warranted degree of model complexity are also discussed.

INTRODUCTION

The migration of nuclear waste from a deep geologic repository depends on three sequential events. Water must enter the repository, the waste form must be leached or dissolved, and the waste must migrate away from the repository. This document describes 12 scenarios whereby water may enter the repository and/or waste may migrate from the repository. The assumptions that have been made are: 1) the repository is located in a bedded salt layer in a sedimentary basin, and 2) waste can only leave the repository dissolved in groundwater or in colloidal form.

This document describes the 12 failure modes as a basis for future development of numerical models and provides descriptions of related geologic processes that may be important in repository evaluation. The most direct application of these scenarios will be to provide a basis for repository refill and local migration modeling in the Repository Design Performance task. These scenarios will also serve as a basis for systems model development.

It should be emphasized that, while the existence of an entry for water into a nuclear waste repository will likely result in eventual resaturation and repressurization of the repository, nuclide escape is not necessarily a consequence of water entry. For escape to occur (except by the very slow process of diffusion), a flow path must develop, that is, a means of entry and exit must exist, and a hydraulic gradient must be present in the system. The hydraulic gradient must be such that groundwater will migrate outward from the repository.

FAILURE MODES

The 12 different means of entry or exit of water into a nuclear waste repository in bedded salt may be grouped into 4 categories or failure modes: dissolution, fracturing, voids, and penetration.

Descriptions and sketches of the 12 potential failure pathways are presented in the following sections.

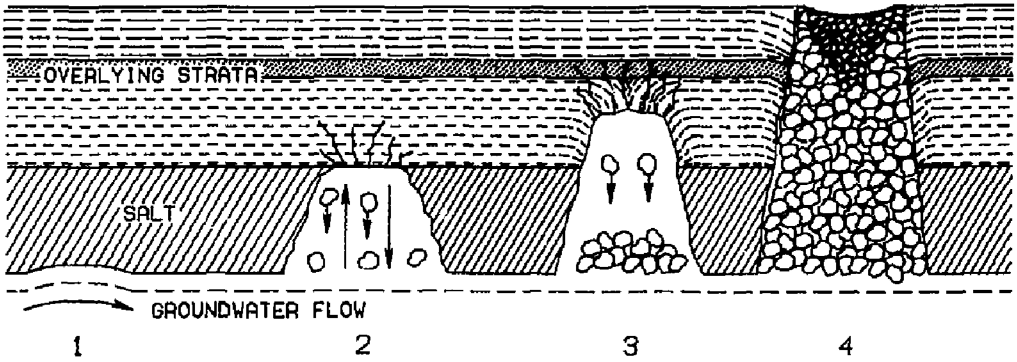
DISSOLUTION MODES

Breccia Pipe Formation

Water flowing through aquifers adjacent to salt formations is usually not saturated with salt (Geotechnical Engineers, Inc., 1977a). If this water comes in contact with salt, dissolution will occur. If the contact is made at the base of the salt unit, the dissolution process will cause the development of cellular flow, and the resulting cavity will grow upward through the salt (GEI, 1977a).

Cellular flow may be envisioned as a process whereby density differences in the brine within the cavity result in the development of discrete, vertically oriented fluid cells. Within a given cell, denser, more saturated brines sink in certain portions of the cell, while less dense, less saturated brines move upward in other portions of the cell. This type of cavity development promotes formation of collapse chimneys or breccia pipes as a result of progressive loss of support for overlying beds. An idealized sequence for breccia pipe formation is shown in Fig. 1.

It should be noted that complete development of the breccia pipe (stage 4 in



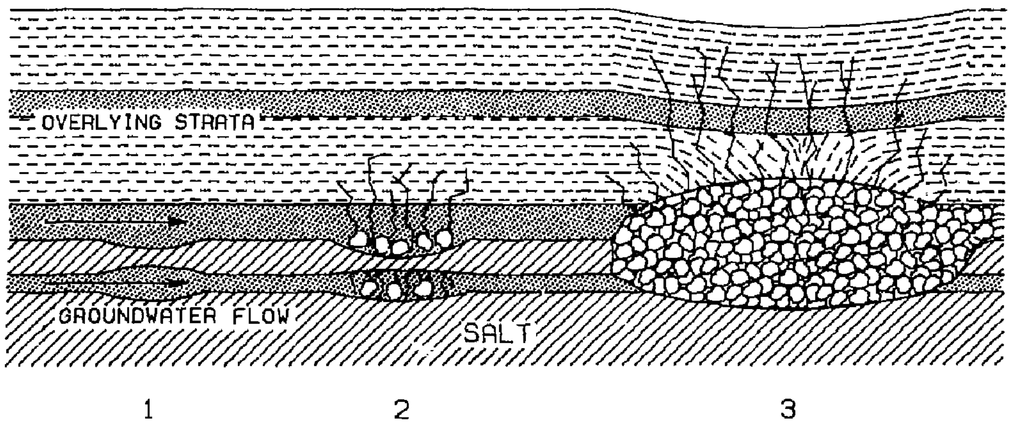
1. Initial cavity develops when salt is dissolved by moving groundwater in an underlying permeable unit.
2. With continued solution, caving begins.
3. Caving front migrates upward through overlying formations.
4. Breccia pipe may reach ground surface.

FIG. 1. Progressive development of a breccia pipe (adapted from Geotechnical Engineers, Inc., 1977a).

Fig. 1) is unnecessary before the pipe may serve as a recharge or discharge pathway. Once the growing pipe reaches the base of the repository, a pathway to an underlying aquifer will exist. Further growth would create an interconnection with an overlying aquifer. The breccia pipe need not reach the ground surface to result in hydrologic communication.

Breccia Blanket Formation

If groundwater flow occurs in an aquifer in contact with the top of a salt formation, dissolution will promote formation of very wide, shallow, flaring cavities (GEI, 1977a). This will occur because the groundwater will be denser, containing more dissolved salt, at the base of the aquifer than higher in the section. Therefore, the ability of the groundwater to leach downward will be reduced, and dissolution will be concentrated on the top surface of the salt layer. The resulting shallow cavities will eventually coalesce and cause a loss of support for the overlying strata. These undermined strata can fracture and form rubble that will progressively fill the cavity until adequate support is restored. Surface subsidence over broad areas may result. Normal faults may develop near the margins of subsided areas in response to increased stresses imposed on the materials overlying the zone of breccia blanket formation. These stresses will be created by the loss of support resulting from salt dissolution. An idealized sequence for breccia blanket formation is illustrated in Fig. 2.



1. Initial groundwater flow in permeable unit within or at top of salt initiates dissolution.
2. Solution of overlying or underlying salt bed continues.
3. Overlying unit collapses.

FIG. 2. Progressive development of a breccia blanket (adapted from Geotechnical Engineers, Inc., 1977a).

Dissolution Around Boreholes

Abandoned or inadequately sealed boreholes that penetrate salt formations can provide pathways for dissolution as water migrates through the borehole in response to pressure differences between aquifers. This process is the natural equivalent of solution mining, where water is forced down a hole into the salt stratum, dissolution occurs, and the resulting brine is then pumped to the surface for recovery of the resource. GEI (1977b) has reported that test holes are commonly enlarged to about three times the bit diameter where they penetrate salt strata and that similar or greater enlargements can reasonably be expected along old wells or boreholes drilled during past exploration for salt, natural gas, and oil. Older holes represent the greatest risk, because past record keeping was poor or nonexistent and because sealing was either not attempted or incomplete.

The risks associated with dissolution along an old well or borehole are of two kinds: (1) an encounter with such a hole during repository mining can result in a large inflow, or (2) continued dissolution along an undetected hole located near repository workings can eventually compromise repository integrity. A sketch of an idealized solution pathway along a well or borehole is shown in Fig. 3.

FRACTURE MODES

Flow Through Existing Fractures

At contemplated repository depths (1000 m), salt is expected to behave as a plastic substance (GEI, 1977a) and, therefore, should not be expected to sustain fractures. However, Baar (1977) has reported the presence of fractures in salt that have permitted groundwater flows into some European mines. In a few cases, these inflows have increased as a result of salt dissolution until mines have been flooded. Therefore, the possibility of groundwater entering a repository in salt through existing fractures cannot be entirely dismissed.

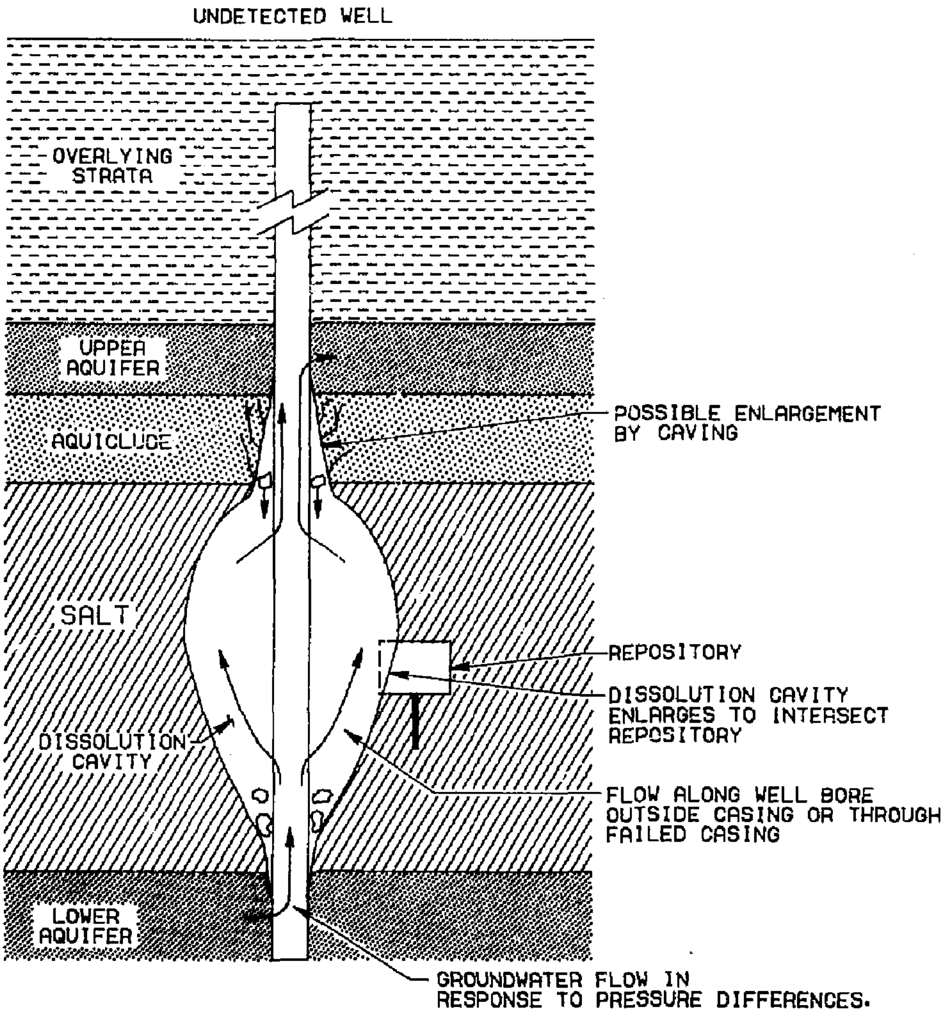


FIG. 3. Dissolution along a well or borehole penetrating salt.

Fracture networks such as bedding planes, joint systems, shears, old faults, and random fractures are common in shaly aquicludes above or below salt deposits. These fracture systems may significantly reduce the effectiveness of the aquicludes as groundwater barrier layers. Similar fracture networks may persist in brittle beds within the salt sequence, such as shale interbeds (clay seams) and anhydrite or polyhalite beds. Figure 4 shows how groundwater may enter a repository through fracture networks.

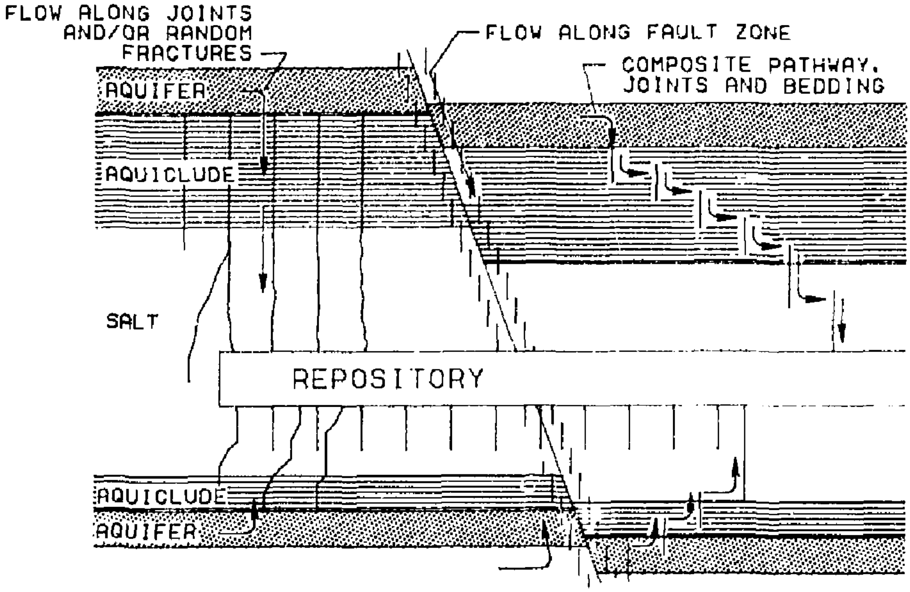
Flow Through New Fractures

Mining of a repository will change the stress field in the enclosing rock mass, and the resulting strains could induce development of new fractures. In extreme cases, large-scale failures such as a roof collapse may occur and cause repository flooding.

New fractures may develop in rocks overlying repository workings in response to a loss of support caused by salt creep into repository openings. GEI (1977a) reports increased salinity in aquifers over potash mines as evidence for this process. A measured surface subsidence of 3 ft, caused by high-extraction potash mining at a depth of 1600 ft, is cited as evidence for propagation of stresses throughout the entire overlying section (GEI, 1978). At the lower extraction ratios contemplated for a nuclear waste repository, the potential for stress propagation is considerably less. During the scenario meeting, Cogan described a salt mine in which fractures developed in the floor, permitting the entry of water from an underlying artesian aquifer.

Natural processes may also create new fractures. Haimson and Kim (1972) found that long-term cyclic loading (as by repeated earthquakes) may cause fatigue failure in intact rock. The development of a new fault through a repository as a result of future tectonic activity is a geologic event that must be considered, although it is of extremely low probability.

Thermal stresses may also play an important role in the development of new fractures in rocks surrounding a nuclear waste repository. Altenbach (1979) analyzed thermal effects in a potential repository room-pillar configuration and discovered that temperatures may reach 1250°F (676°C) near the pillar



Flow paths may be either downward in response to gravity or upward in response to artesian pressure within a confined aquifer.

FIG. 4. Groundwater inflow through existing fractures.

surface after 50 y in an unventilated case. A temperature of about 440°F (232°C) was predicted at a depth of 44 ft (13.4 m) into the pillar under the same conditions. Assumptions of ventilation for various periods led to lower predicted temperatures, but even if continuous ventilation was provided for 25 y prior to room backfilling, a temperature of 344°F (173°C) was predicted at pillar centerline 50 y after canister emplacement. Possible thermal effects are summarized below.

Rock Weakening and Failure.

- Heat lowers salt and rock strength, leading to caving, floor cracking, and/or subsidence.

- Heat induces melting of salt.
- Heat-induced chemical alterations lead to reduced strength in salt.
- Greater expansion of some beds causes tensile fracturing in other beds with less expansion.
- Differential heating across faults causes differential movement between the two sides, opening flow paths.
- Differential expansion between beds creates permeable cracks along bedding surfaces.
- Differential expansion between rock, salt, seal, and plug materials creates fractures in seals and plugs.
- Steam causes hydrofracturing of rock (unlikely at depth).

<u>Creep.</u> Heat induces high creep rates, leading to distortion of salt beds.

- Distortion exposes canisters to aquifers.
- Distortion induces fracturing in salt and other rocks.

<u>Paths Formed by Differential-Temperature Water Processes After Emplacement.</u>

- Cold water enters hot, dry repository.
  (1) Sudden cooling of rock promotes shrinkage accompanied by fracturing, caving, and/or subsidence.
  (2) Steam forms and builds up pressure, forcing contaminated water from repository.
  (3) Cold water contacts hot shaft and borehole seals and fractures them.
- Hot water from repository contacts cool rock.
  (1) Hot water contacts cool rock and causes expansion. Effects are unknown.
  (2) Hot water contacts cold shaft and borehole seals. Effects are unknown.
  (3) Hot water leaks from repository and flashes to steam, increasing permeability.

Flow paths associated with new fractures are the same as for existing fracture systems, shown in Fig. 4.

Facies Changes

Bedded salt deposits typically contain interbeds of claystone, anhydrite, and polyhalite, with occasional interbeds of siltstone and sandstone (GEI, 1977b). Redfield (1967) has described rapid lateral changes from anhydrite and gypsum to carbonate rocks (mainly dolomite), with a further lateral gradation downdip from carbonate facies to siltstone. At the site investigated, the lateral shift from evaporites to carbonates was essentially complete within a distance of 4500 ft (1.4 km).

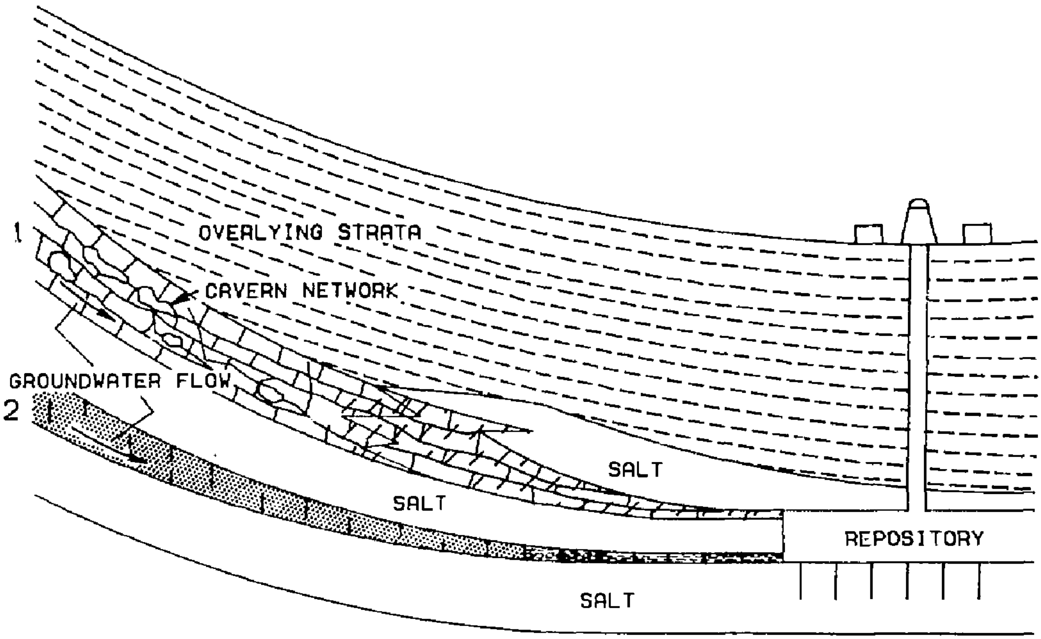
These interbeds and lateral variations in sedimentary facies provide potential pathways for water seepage into repository workings. The pathways may be composite; for example, interstitial permeability in a sandstone aquifer may feed fracture systems in shale beds deposited at the distal end of the clastic zone. As another example, water flowing in cavernous limestones may reach a repository by flow through joints in anhydrite beds that were deposited contemporaneously with the limestone in other portions of the evaporite basin. Sketches of possible facies changes are shown in Fig. 5.

VOIDS

Voids, as the term is used in this document, are open spaces between or within grains or crystals. Voids that have developed in evaporite or carbonate facies as a result of dissolution were discussed on pages 2 through 5.

Interstitial Voids

Voids or pores occur to some extent in all sedimentary rocks. However, before flow can occur, interconnections must exist between voids, and the voids must be of sufficient size to allow water molecules to migrate without being adsorbed by charged clay mineral surfaces present on the walls of the voids. Effective porosity is, therefore, that fraction of the total void space that permits flow through the rock mass. GEI (1977b) has estimated average values of 0.01% and 0.07% for salt and included or adjacent shale beds, respectively. Potential inflows to a repository based on an assumed hydraulic gradient of 0.005 were calculated to range from 6.9×10^{-6} to 8.2×10^{-6} cm^3/s for salt and from 7.7×10^{-5} to 2.8×10^{-6} cm^3/s for shale. These are very



1. Carbonate facies grading laterally to gypsum-anhydrite sequence.

2. Clastic facies: sandstone grading to fractured shale.

FIG. 5. Groundwater inflow through interbeds and facies variations.

small quantities and would by themselves contribute negligible amounts of recharge to a nuclear waste repository. A sketch of hypothetical voids in a sedimentary rock is given in Fig. 6(a).

Inclusions

Brine-filled inclusions are common in salt deposits and range from a few microns in size to pockets containing as much as 100 000 gal (GEI, 1977b). Studies of fluid inclusions in single salt crystals show that those with less than 10% vapor will migrate toward a heat source (Holdoway, 1973). As shown in Fig. 6(b), migration is accomplished by preferential dissolution on the warmer side and deposition on the cooler side.

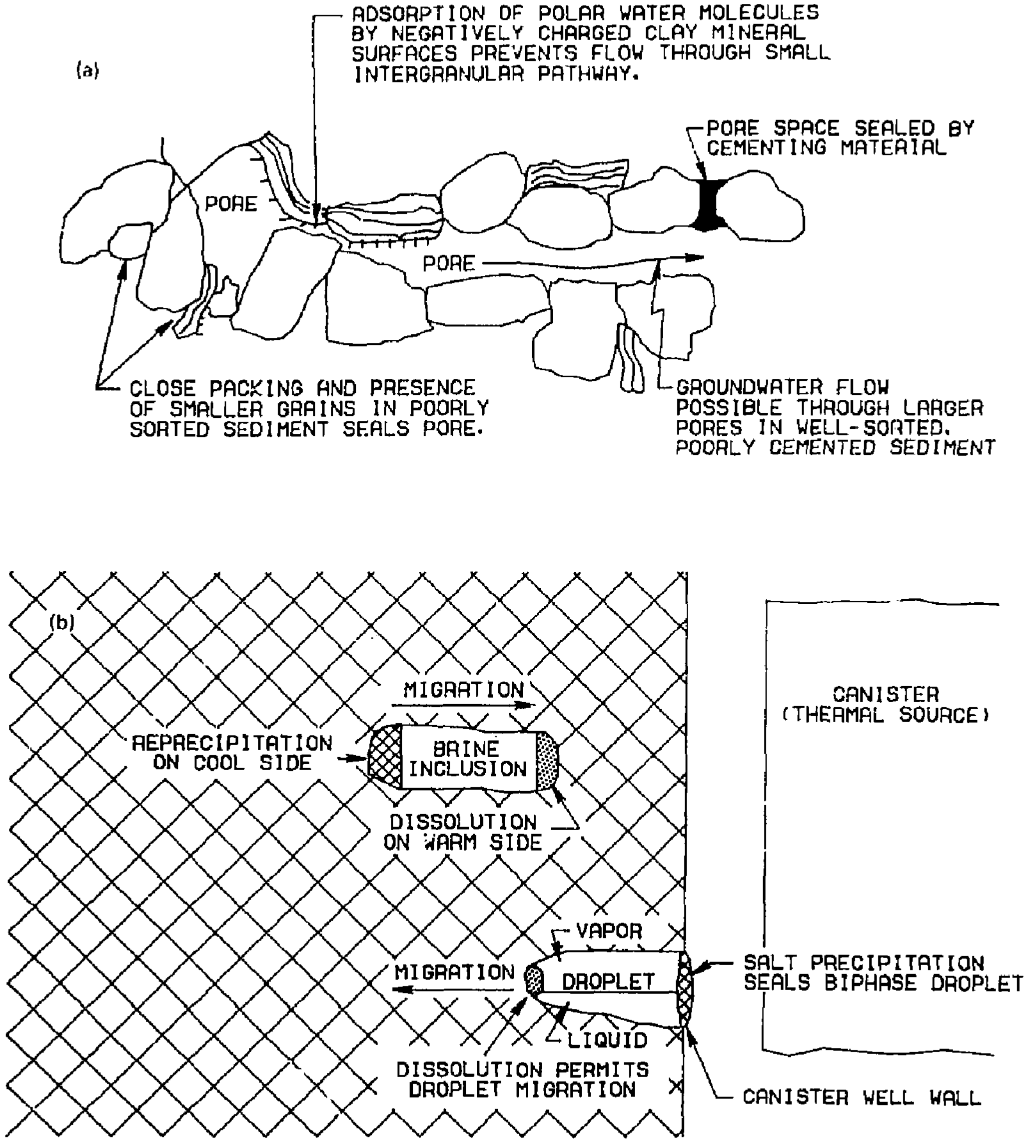


FIG. 6. (a) Porosity and effective porosity in a sedimentary rock;
(b) Migration of brine inclusions in salt.

Biphase droplets (>10% vapor) migrate away from a heat source; therefore, it is possible for a transport mechanism to develop as a result of the movement of fluid inclusions in salt. GEI (1977b) suggested that such a transport mechanism would be an inconsequential pathway for radionuclide escape, because high canister temperatures are expected to persist for relatively short periods and because the canister heat affects only a limited area. Migration over long distances, out of the salt unit, was considered improbable.

In view of the findings of Altenbach (1979), a reassessment of the opinion expressed by GEI (1977b) appears to be in order, and the effects of repository-generated thermal fields on waste migration through fluid inclusions should receive further analysis.

PENETRATION MODES

Borehole Sealing Failures

GEI (1978) has determined that all of the conterminous United States in which oil and gas are produced enforce regulations that require the sealing of wells and boreholes prior to abandonment. However, the long-term effectiveness of any well sealing and plugging system has not been demonstrated, and a study by Herndon and Smith (1976) indicated that existing well plugs and seals must be suspect. Furthermore, a zone of increased fracturing may develop about a well or borehole, either as a result of drill action or in response to changes in the local stress field caused by the presence of the hole. The fractures around a hole would provide pathways for fluids to bypass seals. Such fracture zones may also result from reservoir stimulation efforts, such as hydrofracturing.

Variations in hole diameter are also common. As noted earlier, holes in salt are commonly enlarged to about three times the bit diameter, providing a ready pathway for fluid migration between the hole wall and casing wherever hole backfilling is incomplete or ineffective.

Repository thermal effects may contribute to borehole sealing failures in several ways. Leaching or chemical alteration of sealing materials can lead to loss of strength and subsequent failure. Fracturing of seals as a result of steam pressure, and bypassing of seals as a result of dissolution of evaporites by hot water or differential expansion of borehole walls relative to seals can also cause failures.

Examples of potential well and borehole sealing failures are shown schematically in Fig. 7.

Shaft Sealing Failures

Potential shaft seal failures are of the same type as those for wells and boreholes. The problem is complicated by the large size of the shaft relative to a well or borehole. The failure can thus develop in a much larger volume of material. However, the larger size of the opening may also make failure less likely, since better quality sealing may be achieved; for example, the backfill can be mechanically compacted in thin lifts.

Excavation of a large-diameter shaft can currently be accomplished only by conventional mining methods (for example, by using explosives in rock), but the size of shafts that can be mined by boring methods is steadily increasing. As a result of blasting, a zone of increased fracturing develops around a shaft. This problem could be mitigated in part by grouting fractures in aquifer zones and/or by lining the shaft to safeguard subsequent excavations and operations against hazardous water inflows and rock falls. However, complete sealing may not be achieved, and grouts and shaft linings may deteriorate with time. Thermal effects could contribute significantly to shaft sealing failures; potential modes are the same as for borehole seal failures. Therefore, leakage through shafts must be considered an important pathway whereby water may enter a nuclear waste repository. Potential shaft sealing failures are shown schematically in Fig. 7.

Undetected Boreholes

Salt dissolution caused by an undetected borehole was discussed on page 5. Undetected boreholes and wells can also provide pathways for groundwater movement into a nuclear waste repository, independent of dissolution. Since

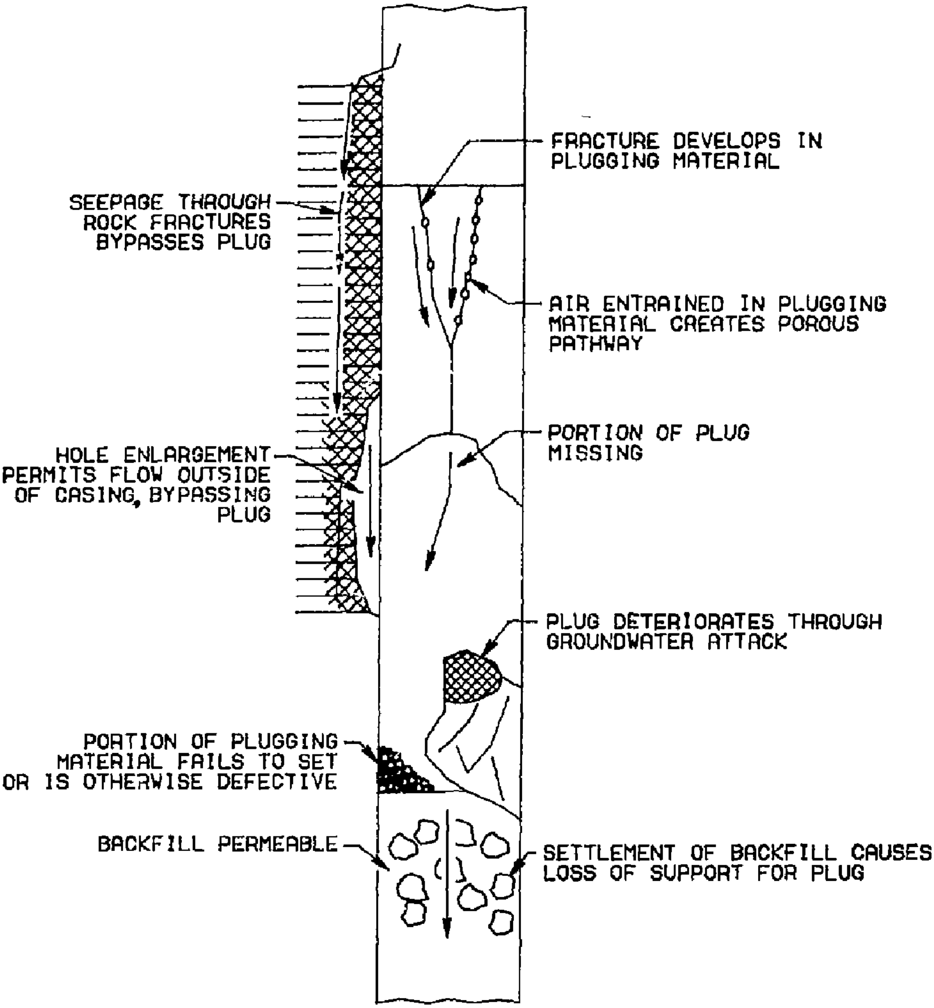


FIG. 7 Well, borehole, or shaft sealing failures.

most unknown wells or boreholes are old and were drilled either before state permit procedures existed or without coming to the attention of permit authorities, such wells are likely to be inadequately sealed or not sealed at all.

Unrecognized wells and boreholes will probably exist near nuclear waste repositories, but techniques have been developed to facilitate the search for them. Development of these techniques has received impetus from the need to seal old wells to permit effective pressurization of underground gas storage facilities. Herndon and Smith (1976) have reported efforts that have led to the successful location of old wells under buildings and as much as 3 m of earth.

New Wells or Mines

Bedded salt and associated evaporites represent mineral resources that may be exploited in the future. The radioactive elements in a waste repository may also represent an attractive future resource, especially as man depletes his supply of fossil and nuclear fuels. If a repository is penetrated by future man with full knowledge of its existence, the act becomes one of judgment based upon an assessment of risk. If knowledge of the repository is lost, however, inadvertant intrusion is possible, and the probability of such an event is a matter to be assessed by social scientists taking into account the persistence of records, the stability of societies, and the ability of societies to preserve and communicate information during periods of grave social upheaval.

The risk of intrusion as a result of water-well drilling would be significantly reduced where highly saline groundwaters overlie repository sites. The presence of high salinities would discourage further drilling, and since the level of total dissolved solids often greatly exceeds seawater concentrations, desalination of brackish aquifers and of seawater would likely provide large water supplies long before future man would be driven to exploit hypersaline brines for water supplies. Exploitation of the salt resource or a search for hydrocarbons in strata below the salt deposits are much more likely to lead to inadvertant intrusion.

MULTIPLE PATHWAYS

Hybrid modes of water inflow to repositories are probable. For instance, water may leak down a well located beyond the repository site and then flow to the repository along a permeable interbed. Other combination inflow paths are possible. Among the more likely are those involving combinations of bedrock fracture systems (for example, bedding and joint networks) and those in which wells and shafts provide interconnections between aquifers or between an aquifer and the repository.

Other hybrid pathways could be activated thermally. In addition to differential expansion effects (see page 9), heating can cause migration of fluid inclusions. A large inclusion could approach a repository in such a way that dissolution along the advancing inclusion front causes weakening of the roof or a wall of a repository room. Roof or wall collapse could then occur, resulting in a large "cathedral" void. The cathedral void will cause a redistribution of stresses about the room, and the redistributed stress field could promote further failures.

Certain types of hybrid modes appear to be of only slight importance. For instance, a later borehole could successively penetrate a large brine pocket and the repository layer, thereby permitting the brine pocket to discharge into the repository. However, even in the case of the 100 000-gal brine pocket cited on page 11, the volume discharged would only fill a space approximately 20 by 20 by 60 ft--less than one contemplated repository room.

RECHARGE AND DISCHARGE MECHANISMS

When a nuclear waste repository is closed, the repository will be at atmospheric pressure, and the local hydraulic gradients created by dewatering or evaporation will be toward the repository. The repository will also be a significant heat source. Thermal analyses by Altenbach (1979) indicate that temperatures above the boiling point of water at 1 atm will exist in canister rooms and into the walls for at least 6 m (19.5 ft). Higher temperatures and larger volumes of rock heated above the boiling point of water would exist in unventilated or early-backfilled repositories. Therefore, when the repository recharge-discharge process begins, the repository will be a hot hydrologic sink.

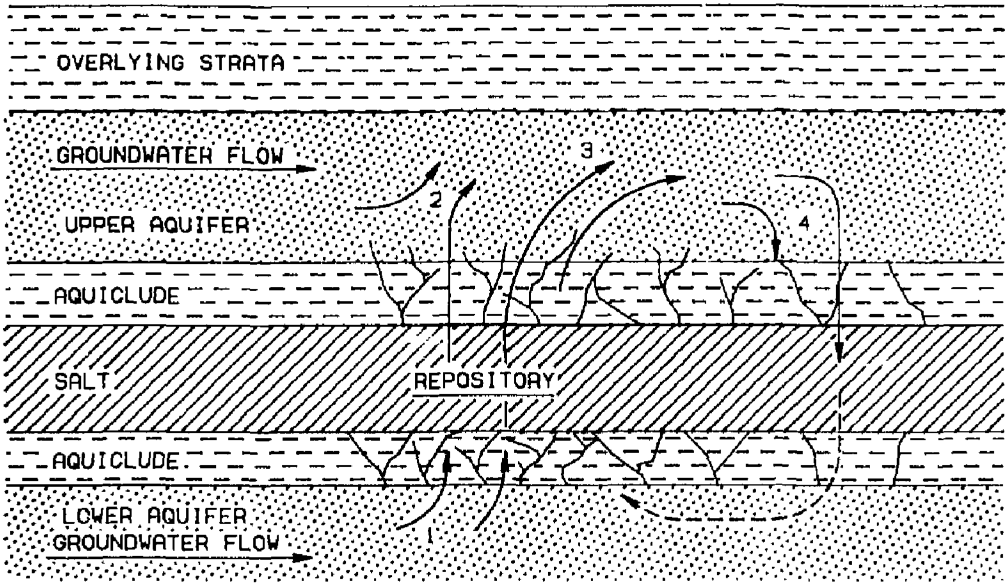
If open pathways exist, water will migrate toward the repository from an overlying aquifer by gravity and will enter the repository from an underlying aquifer if the head in the underlying aquifer exceeds one atmosphere. As water flows into the repository, the head within the repository will increase, producing a decrease in the hydraulic gradient and thereby reducing the flow. Inevitably the head at the repository will increase to equal the head of either the overlying or the underlying aquifer, whichever is lower. The direction of flow will then reverse between the repository and the aquifer with the lower head. Thereafter, water will flow through the repository. The flow will be upward if the head in the lower aquifer is higher than the head in the upper aquifer, and the flow will be downward if the head in the upper aquifer is higher.

The rates at which water will move into and out of the repository will depend upon the extent and efficiency of the pathways caused by one or more of the failure modes described in the preceding section; for example, the number and openness of fractures through surrounding aquicludes. Water can enter by three different modes: sudden inflow through an open pathway, intermittent or periodic inflow, or slow seepage inflow through pores or fractures over a long period of time.

As groundwater approaches the repository, it will be heated by the repository's thermal field. Calculations by Altenbach (1979) indicate a high probability of steam formation, at least during the early period following repository closure. Flow velocities will increase as the water is heated and is eventually converted to steam. Also, the potential for dissolution and enlargement of fractures and voids (either pores or around boreholes and shafts) will increase because of the higher solubility of evaporites in hot water. However, if the water flashes to steam, dissolved materials will remain in the brine, because the ability of steam to transport nongaseous ionic species is very low. This could create a complex pattern of dissolution and possible reprecipitation as groundwater moves into the zone heated by the repository.

Within the repository, steam formation will provide a means for conveying water from areas of high heat energy (for example, canister rooms) to cooler areas, such as former workshops and shaft locations. These movements may not follow ordinary hydraulic gradients and could have unanticipated effects. Moisture and gaseous radionuclides could concentrate at potential weak points, such as shafts and areas where less attention had been paid to rock integrity because of an absence of waste. As water pressures in the repository increase and as the thermal load falls, steam formation will be retarded. If leaks occur, the hot water or steam will flow along the escape path, and the total head will decrease. This will tend to prolong the period during which steam will be present.

In the region around the repository, a complex convection pattern will develop as a result of the thermal cell created by the repository. Qualitatively, cooler water approaching the repository along the regional hydraulic gradient will be warmed and will rise through and over the repository. As cooling occurs, the water will sink in the aquifer, completing the convection cell. The rising water will be deflected downstream by flow in the overlying aquifer so that a distorted convection cell will form. A sketch of the convection cell based on preliminary thermal analyses by Dames and Moore, Inc. (1978), is shown in Fig. 8.



1. Groundwater flow in lower aquifer is deflected upward in response to pressure-density differences.
2. Water heated by repository rises into upper aquifer as thermal plume.
3. Plume is sheared by groundwater flow in upper aquifer; warmer water is deflected downstream.
4. Water cools and sinks in upper aquifer, completing convection cell.

FIG. 8. Idealized thermal convection pattern (adapted from Dames and Moore, Inc., 1978).

As during the recharge process, a complex pattern of dissolution and reprecipitation may be expected. Dissolution will enlarge pathways and increase flow, while precipitation of materials from cooling groundwater will tend to plug voids and fractures, thereby further perturbing flow patterns.

GENERAL MODEL CONSIDERATIONS

The failure modes described in this report involve several coupled physical processes. This complex situation places a heavy burden on the accumulation and assessment of the needed data for the models to be used. Several of the failure modes will probably require careful evaluation of the theoretical foundations of the processes involved. Furthermore, adequate models may not exist for some of the potential failure modes.

A fundamental question that must be answered is how much detail to include in the models of the failure modes: will simple semianalytic models suffice, or are large detailed models necessary? The answer depends on the amount and reliability of the data available and the depth of understanding of the processes involved. The complexity of the models should reflect the state of knowledge. Continued development and refinement of both modeling and data collection techniques should be pursued.

The question of using a simple or detailed model depends additionally on whether a generic or a specific site is to be considered. In a generic study, a detailed model has serious drawbacks, which are introduced by the ranges and uncertainties in the parameters used in the generic evaluation. When a specific site is to be investigated, detailed models become more suitable. Even in this case, however, one must consider each process individually when deciding on the appropriate level of complexity.

The question of model verification is always a difficult one to address adequately. Comparisons with field measurements are needed to assess a model's strengths and weaknesses. This process also serves to isolate those mechanisms whose future theoretical development is most important to add to the level of knowledge upon which the model building is based.

The failure modes described in this report can be roughly divided into two categories: those for which reasonably adequate models exist and those where pertinent mechanisms remain in doubt.

In the case of a shaft failure or an intersecting fault, the mechanisms are relatively well understood, and computer codes exist that can do some justice to the models. These problems are inherently three-dimensional and should be treated as such unless an axis of symmetry can be defined. If the air initially present in the repository can be neglected and minimum steam formation assumed, several adequate porous-flow codes are available. However, if these assumptions prove inadequate, a two-phase code will be necessary. The boundary and initial conditions, as well as the characteristics of the shaft or fault, remain to be specified. For the shaft problem, two permeability functions must be defined, in addition to the permeabilities of the in situ material. First, the permeability of the shaft itself must be described as a function of time. This could reflect a slow deterioration or a sudden collapse of the shaft backfill material. Second, in the material surrounding the shaft, a spatial variation of permeability must be defined that accounts for damage to the rock caused by the presence of the shaft.

A fault through the repository poses additional problems. Careful consideration of the entire geologic setting is necessary, including such matters as the probability and orientation of the fault and the effects of displacement on the aquifer system, as well as the characterization of the fault zone. For the fault itself, information is needed as to size, permeability, and effect on the local flow field. It may also be desirable to consider the behavior of the fault as a function of time, including permeability variations. The use of these types of information could enable parameter studies to be carried out to determine a fault's contribution to repository fill time.

General consideration must now be given to the second category of failure modes--those for which the mechanisms are cloudy or not understood. For some failure modes, it may be possible to calculate certain elements numerically, but not to model them in detail. In these cases, simple models may be all that can be expected at the present time.

A partial list of potentially necessary models can be provided. Codes exist that can treat some of these effects in detail; however, complete coupling has probably not been done. Models sufficient for detailed calculations would include some or all of the following processes: porous flow, fracture flow, dissolution of salt, subsidence, heat flow, chemical effects, and two-phase flow. Flow in open pipes and cavities may also have to be considered. Finally, because of dissolution and possible precipitation it may be necessary to allow flow regimes for a particular point in space to vary with time. These effects are coupled to one degree or another, and each depends upon the particular failure mode being considered.

Clearly, the calculation of these failure modes will be very complex. The difficulties may be compounded when data are sought to validate the models and the proposed codes. An additional concern is the determination of the appropriate boundary and initial conditions. In the absence of reliable information in these areas, care must be exercised in the interpretation of results. Additional field measurements and studies will serve to improve the situation, and this will justify development of a series of progressively more detailed models for these failure modes.

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